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# LOCALIZATION OF AN EXPERIMENTAL ECOLOGICAL UNIT IN THE MARADI REGION OF NIGERIA

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LOCALIZATION OF AN EXPERIMENTAL ECOLOGICAL UNIT IN THE MARADI REGION OF NIGERIA

Report of the Second Morphodynamic Survey Mission of the Experimental Unit in Serkin Haoussa

Study of Meteorological (in Particular Anemometrical) Data (1965-1975) of the Principle Station of the Niger

Cartography of the Degrees of Reactivation of the Sandy Soils of the Niger

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16 Abstract

The report is a detailed topographical and geomorphological description of a specific ecological unit in the Maradi region of the Sahel in the Niger Republic. Sandy structures are classified into active dunes and covered dunes and an extensive vocabulary is developed to describe sub-categories. The descriptions are based on meteorological data (anemometrics and rainfall) from local weather stations, ground observations, aerial photographs and Landsat picturers. The problem of dune reactivation and desertification is discussed both from the standpoint of causes and possible counter measures.

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# LOCALIZATION OF AN EXPERIMENTAL ECOLOGICAL UNIT IN THE MARADI REGION OF NIGERIA

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The studies carried out during the first year of the /2*
DGRST [General Delegation for Scientific and Technical Research] program entitled "The Struggle Against the Effects of Aridity, Maradi Experimental Unit" in particular have made it possible to describe the locale of this experimental unit in terms of its geomorphological and lithological environment. Situated in the Sahel region, the area is exclusively sandy. These studies revealed how much the apparent monotony of forms conceals an extreme variety of nuances.

Thus the second year of this program had to be devoted first of all to solving the two major difficulties which were immediately apparent: (1) providing a simple description of forms and then (2) developing a vocabulary.

Actually, even if the topography of thessandy structures of the Sahel environment has been scantily described, no classifications or systematic studies of the origin and dynamics of these structures have been made. The structures of the Sahel Niger, which are the southernmost of the Paleosahara, were positioned during the driest phases of the current climate. This suggests that they represent only a transformation in time and space of active sandy structures.

Thus we have been led to attempt: (1) a classification of active dunes and (2) a definition, description and classification of sand structures covered with vegetation and fixed in place.

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* Numbers in the margin indicate pagination in the foreign text.

This second part was the most difficult to do because until now no systematic vocabulary had been proposed. We thus had to make up an entire vocabulary. We are not entirely satisfied with it, but it represents an initial attempt. To make things easier for our readers we have added a glossary of the terms used.

Two classification series were made, one of active dunes and one of sandy structures covered with vegetation. These series are based on studies over the last 10 years on the terrain in northern Chad, southern Algeria and a large part of the Niger Republic; and on photographic and satellite studies of coverings of northern Chad, the Niger Republic and a large part of the central and western Sahara. An initial geomorphological map of the entire erg of Fachi Bilma, between the Tibesti and the Termit massif was made, followed by a second map covering the Haussa erg between the Termit massif and the Ader Doutchi massif and the western piedmont of the Aïr. The second map relates all the decomposition parameters of the landscapes (eolian erosion, water erosion, effects of human occupation) to empahsize the mechanisms of breaking up and reactivation of the sandy mantle.

It then seemed essential to try to quantify the climatological /3 and especially anemometrical parameters of the severe drought lasting from 1969 to 1973.

Therefore a graphic analysis of the climate of the Niger in general was made. This includes (1) a standard graph of rainfall averages for 12 stations during the period 1931-1960, with -- for greater precision -- a graph of comparative rainfall for the Goulbi basins of Tarka, N'Kaba and Maradi from 1956 to 1969; (2) a graph of temperature averages for 10 station between 1951 and 1970; and (3) a graph of relative himidity in % for 10 stations between 1961 and 1970.

A special place was reserved for the study of anemometric

data. This is why we took all the meteorological measurements concerning winds between 1966 and 1975 for the main stations of the Niger.

The following wind graphs were made: (1) graphs of the average of predominating winds for 5 stations between 1961 and 1970; (2) monthly wind direction charts which take into account the direction (20 directions are distinguished), the speed and the frequency. For these same stations the average frequencies of the major winds were also studied.

An attempt was made to bring together the wind mapping data for all of the Niger which revealed the main directions of the winds.

Since Maradi was the only complete weather station close to the experimental unit, it was the object of a much more detailed study. This study included the following:

1. An annual rainfall graph comparing Maradi and Tarna for the period 1932 to 1975.
2. A monthly and annual rainfall graph for Maradi for the period 1960 to 1975.
3. A graph of maximum and minimum monthly temperature averages between 1970 and 1975 in Maradi.
4. A graph of monthly percentages of humidity from 1970 to 1974.
5. AAtable and climatological graphs for 1975 in Maradi covering rainfall, temperature, potential evaporation and amount of solar heat.
6. Charts of the average of ground winds in Maradi for the period 1951 to 1960.

Except for collecting the quantitative evidence of the climatic crisis, the study of the winds was very rushed in order

to allow the positioning of wind breaks.

Among the other tasks we focoused on was the study of all the /4 desertification, i.e. the breaking up of landscapes by reactivation of the sandy mantle.

More than a frontal advance of the edge of the desert, we were able to distinguish desertification caused by human factors; spot desertification due to over=pasturing (repeated visits to specific sites) and linear desertification along trails.

As for desertification due to physical factors -- wind, water and the combination of the two -- its location does not correspond to parallels of latitude. In fact, decomposition due to the effects of water preceds eolian desertification in the north. But the experimental unit is located in a region where we were able to show that the eolian factors are more dagerous than the water factors, with eolian reactivation capable of reaching isohyet 625 mm. The dangers due to erosion by runoff there are totally insignificant.

The research method used consisted of consulting three types of data: satellite pictures, aërial photographs and the actual terrain. We were thus assured that each set of data -- each with its own scale going from 1-1,000,000 with respect to the actual size -- included its particular information, each set differing from the other but all of them complimentary.

To back up the ground observations aalarge number of specimens was collected with three key ideas in mind:

1. Diagnosis with an aim to paleoclimatic investigation of the mechanisms responsible for the positions of the sandy material.

2. Study of the size of particles which are moveable at the present time in order to see to what extent the sands of the

experimental unit are capable of being put into motion.

3. Localization of granulometric areas in order to determine the best areas to emphasize.

For these last studies we had to extend very widely beyond the experimental square because by studying the material of the square itself it was not possible to understand how it got there.

The final step included:

1. A mapping study of the geomorphology of the Serkin Haoussa experimental unit.

The map that we made on a scale of 1:20,000 by means of photographic coverage on a scale of 1:10,000, which was specially ordered for this study, is a document which tries to show the share of morphological processes and human factors which contribute to changes in surface behavior. /5

2. A mapping study on a scale of 1:1,000,000 of various degrees of the breakup of sandy landscapes. The mapping information is based on satellite pictures and aerial photographs. The map covering the central Niger should make it possible to show where the experimental unit is situated in the scale measuring the degrees of break-up. The map of the region extending to the south western foot of the Aïr was made with the help of Unesco.

We are happy to thank the persons and organizations who authorized this work, who made it physically possible, who helped us accomplish it and those who participated in it:

- the authorities of the Niger Republic, in particular Mr. Garba Zakary, Director General of the INRANA [National Institute of Agronomic Research of Niger] at Niamey, the prefect of Maradi and Mr. Sidibe Ousseini in charge of INRAN at Maradi.

- The DGRST [General Delegation for Scientific and Technical Research] which granted us all of the necessary loans.

- The GERDAT [Study and Research Group for the Development of Tropical Agronomy], in particular Messrs. Lanfranchi and Paré

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- Mssrs. Dufraisse and Jean Hurault of the National Geographic Institute who did the photographic coverage on a scale of 1:10,000 in December, 1976.

- Mr. Piel, Director of the ASECNA at Niamey and Mr. Falola Alali, head of the Maradi weather station, who made it possible for us to collect the climate parameters; Mr. Alain Béron, who took part in the analysis of these parameters.

- Mr. Jarlaud, of the University Institute of Technology of Reims, who made the data processing program which allowed us to process the parameters collected.

- Mrs. Monique Cholet and out colleague professor P. Rognon of the University of Paris VI for making the clear copy of the 1:20,000 map.

- Finally, our most director colaborators: A.M. Chapelle, for photo interpretation and map-making; M.C. Chemin, for granulometric and morphoscopic studies done in our laboratory at the University of Reims; finally, L. Canon, to whom we are indebted for the use of the Landsat satellite pictures and also for an important mapping study.

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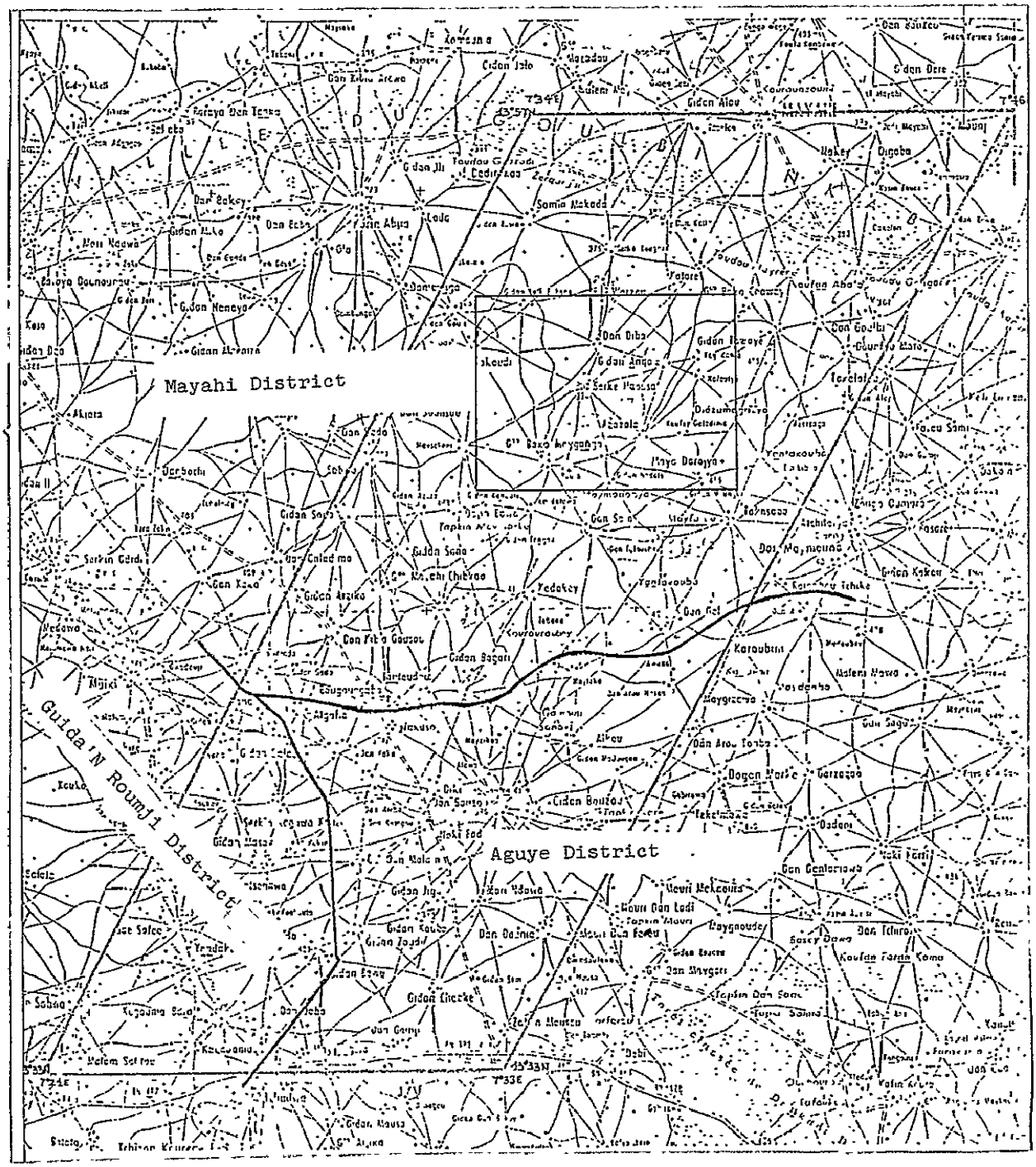


Fig. 2. Location of the Serkin Haussa experimental unit.

## Chapter I -- Proposal for Classifying Active Dunes

The small-scale picture of the earth provided by satellites,[1] makes possible a new approach to eolian sand structures and landscapes which they make up. From the initial teleinterpretation results it emerges that the dual topographical and dynamic aspects of an eolian structure cannot be captured in a single process but can only be linked together over time at various assembly levels. Before the existence of aerial photographs morphological analysis was carried out on the ground. Eolian structures were first described individually. This stage had hardly begun when aerial coverage appeared. This was a new tool which made it possible to analyze groups of structures. An aerial photograph by the National Geographic Institute on a scale of 1:50,000 measuring 18 x 18 cm covered 9 x 9 km, i.e. 81 square kilometers.

The Landsat 1 pictures brought about a new synthesis, with a single picture covering 180 x 180 km, i.e. 324,000 square kilometers.

A final step was taken with the 1:8,000,000 readings of Noaa 3 in which the indivicual structures are no longer visible. Understanding them demands the study of the largest functional units extending up to the entire northern equatorial continent for the Sahara and 3/4 of the continent for Australia.

The transition from ground observations to aerial photography, the uniting of ground observation and aerial photographs and then the access to satellite pictures -- i.e. to a smaller and smaller

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1. The doucments used are the following, lised in order of decreasing scale: (1) National Geographic Institute photographs (1:50,000); (2) Landsat 1 satellite pictures (1:1,000,000, altitude 920 km); (3) Gemini satellite pictures (1:1,000,000); (4) Pictures of the Noaa 3 satellite (1:8,000,000, altitude 1,500 km).

scale -- ends up with a more and more global view, on a continental scale, which combines not only the structures but the spaces between structures. The progress thus made is to restore a value to the "empty spaces," i.e. to the spaces where the phenomena studied are lacking (Tables I and II).

As for the dunes, specifying them according to their location, we were led to consider them, by degrees, first of all with respect to the other sandy structures of the ergs, then to reintegrate them into the entire erg and finally to observe their development in the Sahel.

While discovering the interdependence of the ergs in the Sahara, we were led to consider them in the context of three great major currents of eolian transport which sweep across the Sahara between 28°30' N and 13° N to the east and 16° N to the west.[ 5 ]. /8

The large ergs of the Sahara are arranged according to two preferential latitudes, to the north of 28°30' N and to the South of 23°30' N, between which the Sahara is poor in sandy deposits. With pictures taken by the Noaa 3 meteorological satellites it is possible to study the relationships between the two bands and to demonstrate the existence of three main sand-carrying eolian currents. The broadest of these is in the eastern Sahara, another in the western Sahara and the third follows the Atlantic coast line from 28° to 16° N then disappears in the ocean between 20° and 16° N.

The overall direction of the first two currents is NE-SW, closely following that of the trade wind. They lose their homogeneity, however, and divide into several flows while their directions bend. It is then impossible to speak of a trade wind with respect to currents which are deflected and divided by

obstacles (around Tibesti), indeed even turned back (north of the Aïr and south of the Kreb in Naga) until they become perpindicular to the initial direction (SW of the Tibesti) over more than 100 km.

Along the currents alternate sections where sometimes transport and corrosion prevail, sometimes accumulation. Transport prevails when the current is divided by an obstacle and accelerated around the same, deposit occurs when, behind an obstacle, the two currents divided by the obstacle rejoin one another then flow together and resume the initial direction of the trade wind. Each branch is accompanied with specific eolian structures and a precise mode of action.

In order to avoid any ambiguity we propose a definition of the principle terms used: erg (an Arabic term) is synonymous with adeyen in Libya, goz in the southern Sahara, koum in central Asia and nafud in Arabia. For a sandy substrate either covered or not with a deflation pavement the term specifies an extended concentration of sandy structures, either homogeneous in shape or not, united or juxtaposed according to the various degrees of organization, without any apparent organization at the edge.

It is essential to note that an erg, the main area of a deposit, is always crossed over by several transport currents, which amounts to saying that even in an erg the sand circulates. It circulates there slowly, but sand enters the erg from one side, the upstream side, and exits from the other side, the downstream side. This conclusively invalidates the hypothesis that ers are without exception a landscape modelled by the wind from a fluviatile sandy accumulation in a basin.

## I. Distinction Between Eolian Sandy Structures in General, Dunes in Particular and Suface Conditions of Sandy Layers /9

### 1. Dunes

In our definition of dunes we adopt the minimum height of 30 cm proposed by K.W. Glennie [ 3 ], adding that there must nece necessarily be a certain minimum slope value. A dune, in the strict sense of the term, possesses an active crest, directly due to saltationa and slippage on the slopes and due to the meeting of two slip faces or one deposit face and another slip face. The dunes resulttfrom a deposit in which saltation is the principal mechanism: the sand of a dune has left the ground before alighting on it.

a: Deposit dunes, mobile sandy bodies in relief, involve two different families: (1) some resulting exclusively from a deposit; shield; (2) other resulting from deposit and slippage along the face under the effects of the wind: barchans for example.

b: Erosion dunes (Australian sand ridge), stable sandy bodies, in the origin of which is involved a deflation action or even erosion in a sandy mass and which are often found in conjunction with ergs in the process of becoming established.

### 2. Surface Conditions: Ripples, Ripple Marks, Megaripples (or Zibars in Arabia)

Many classifications of eolian sand structures classify ripples amonggthe dunes, regarding them as small dunes. But there are megaripples the size of dunes which can be seen in aerial photographs at a scale of 1:50,000, and the contour of some sandy surface conditions rises as high as or above 30 cm, but the slope is so slight, distributed overaa distance of 15-20 cm, that it becomes almost imperceptible. In actuallity, it is their topography and their dynamics which make it possible to distinguish the surface conditions of dunes properly so called. In effect, the ripples do not have an active crest and are only a superficial

modification whose reptation, creep or rolling, is the main mechanism of transport of the sand which does not become detached from the ground, either because the grains are too large or because the wind has to overcome a slope, for example on the windward side of a dune.

A distinction has been made between barchan ripples, whose convex side faces the wind, and linguoid ripples whose convex side points in the direction of the wind [II]. /10

Our classification proposal is concerned only with dunes (deposit dunes and erosion dunes). There will be no question of ripples or of any other surface conditions.

Since geomorphological research was originated, in particular, to distinguish between shapes and their functions, with regard to eolian structures it has resulted in a classification based on two principles: (1) the study of an initial module and the various assembly levels; (2) the study of the dynamics of all forms topographically defined for the first time.

## II. Classification of Sandy Structures

### 1. Deposit Dunes

Our classification system is based on the simplest form making up the primary element. Complex dunes are only combinations of this primary element, and although they vary considerably, they can be classified on the basis of the primary module, which in classical terminology is the seif dune. The seif constitutes the first order.

#### a) Seif Dune (Saber in Arabic): First Order Dune

The seif is an elongated dune tapered at its downstream end with a triangular frontal section whose pointed crest generally

describes an arc. Linear or multidirectional combinations of seifs give dunes of the second order.

b) The Silk Dune or Linear Dune of the Second Order (wire in Arabic)

The silk dune as a whole is a straight string of sand, with more or less sinuous features at the microlevel due to the homogeneous justaposition of seifs along a unique direction. The sand in silk dunes behaves as alongside a railroad track which, on a surface without any topographical irregularities, could theoretically extend to infinity by the end-to-end addition of seifs.

The width of silk dunes hardly varies no matter how long they are, and in any event is completely independent of this length. This confirms that the silk is indeed a structure of the second order, resulting from the succession of a certain number of seif type modules, maintaining its scarcely variable width, while the length, with respect to width, can be as much as 100 to 500 times greater. In particular, the length can be subject to large variations, since it is only a function of the number of combined seif elements. /11

The longest silk of the Fachi Bilma erg (mission AE 56-57 NE 33 XX, photograph numbers 202, 257-258, 266-267, Merguigara sheet) passes through 19°20' E. It is 40 km long, 50-100 m wide at the upstream end, 50 m in the center and 30-50 m at the downstream end. Average silks are 2-3 km long for a width of 30-150 m. Silks are sometimes arranged in stages, in elongated systems, which can attain lengths of 30-40 km (in particular NE 33 XX and NE 33 XXI, corresponding to the Merguigara and Ehi Dohou sheets). In these stages the silks succeed each other with brief interuptions. Drift phenomena also appear from one silk to another (aerial photographs NE 33 XX nos. 381, 382, 383).

In the Fachi Bilma erg all of the silks are in festoons, sometimes without any preferential orientation of the concavities, sometimes with distinct dominant directions of the concavities, and always close to two opposite directions, north or south. Likewise the systems without preferential orientation are in fact a mixture of north orientation and south orientation. Note that in the most common case in which the winds have been effected by going around the Tibesti in the north, the north orientations correspond to concavity pointing towards the wind and the south orientations correspond to a concavity pointing downwind. Silks of different concavity are not adjacent, unless at the very head of the erg in the northern branch. Neither is there any different opening of the festoons to the north and to the south of the erg. However, towards the west, there appears a distinct dominant direction of silks with the concavity directed towards the north.

The elb is a particular type of silk. It sends out barchans leeward of the dunes. This occurs when a silk appears on a rocky substrate and with the resulting annual average wind makes a large angle of 30-45°.

Barchan Dihedrons and Barchans

These are a variant of the second order (Fig. 1) whose seifs are arranged symmetrically with respect to the axis of migration of the structure. Topographically these are crescents with the convex side pointing into the wind.

From a study of the localization of dihedrons and barchans (on Landsat 1 pictures) emerges the following definition of their dynamics: mobile dunes as a whole, making up supplies of sand which are very moveable grain by grain, which shift more slowly than the sand of the surrounding saltation mantle. Barchans are

dunes which exist only on a hard substrate, for example a rocky substrate. Thus they are peculiar to transport regions and the periphery of ergs. /12

For barchan shapes we propose the following subdivisions:

1. barchan in the strict sense of the term, original structure of the second order because it is composed of two symmetrically arranged seifs on both sides of its axis of migration.

2. Pre-barchan states of the cake and shield type, simple convexities of sand without active crests.

3. Barchan dihedrons, the result of a barchan notch on a convex pile of sand.

Thus the barchan is a complex deposit dune on the windward side and a deflation and slippage dune on the leeward side. All three mechanisms are responsible for its dynamic transport function. Thus a place should beereserved in our classification for pre-barchan stages which do not fit into the second order.

d) Ghourd or Pyramid of the Third Order with Multi-Directional Branches

The ghourd is in fact a dominant dune, often pyramidal, which sends out silks in any direction whatsoever.

Ghourds correspond to nodes in a system of staionary waves on which the sand is built up at the expense of the bulges, which correspond to sahanes.

In the case of isolated silks, the seifs as a rule are flatly arranged on a level sandy substrate, although they can climb over obstacles. They constitute the only abrupt relief. In the case of ghourds the silks diverge from the top of a sandy pyramid and thus are arranged with a steep slope.

The seifs which form the ghourds always describe a curve which is more pronounced than the curves of silks. It is this trait, even more than the convergence towards the top of a pyramid, which gives ghourds their special character. When two curved branches meet this forms the "ghorafa" or ghourd cauldrons. When the pyramid disappears or even changes and the seifs, which are always curved, form a growing number of cauldrons, a transition occurs towards the draa system, also of the third order. This transition is probably reversible. All the transition forms can be seen over short distances, although at the present time it is not possible to say which one derives from another in space or succeeds it in time, assuming there is a relationship between them.

Contrary to silks, for which there are innumerable models, the ghourd is a complex dune but there is very little variation from one to another. Thus with regard to texture the variety is to be found especially in size differences. It is on the /13
structural level that the differences are very great; ghourds are actually either arranged in semi-circles or aligned in chains of ghourds, in the first case separated by open or closed (sahane) interdune spaces and, in the second case, by coridors, or gassi, and feidj, depending on whether they are sanded over or not.

The classification of ghourds takes these arrangements into account.

e) Groups of Dunes of the Fourth Order (Photographs 6 and 7)

Third order dunes are arranged in linear groups or even more extensive groups of areas of the same behavior, such as groups of silks, semi-circular ghourds and ghourd chains which

for the fourth order. Here we turn our attention to groups of the fourth order composed of ghourds (Fig. 3).

The linear nature of the ghourd chains in the Fachi erg shows up over a lenght of 200 km and a width of 2 km. They can be marked out perfectly on the Landsat pictures at a scale of 1:1,000,000.

The feature common to the structures in this first part of our classification is the mobility of the sand.

The sand has maximum mobility in the regions where transport prevails, which are opposed to regions of dominant accumulation. In the transport sectors the sand which is displaced most rapidly is that in the saltation mantles, followed by that which is stored in the barchans. In the accumulation sectors the sand is not totally immobile. Saltation exists, but is is restricted by the roughness itself of the sandy substrate and by its sculptured relief into various dunes, e.g. silks and ghourds.

In the case of ghourd chains, the wind, which is channeled into the gassi, sweeps across them longitudinally and pulls the sand along the ghourds. Ghourd chains form the transition between mobile dunes and stable sandy structures.

## 2. Regualar Dunes or Stable Sandy Structures

Standing in opposition to the mobile dunes which we have just defined and classified, are the stable sandy structures. These are the sand ridges of the Australian geographers which make up the principle ergs in Australia. These stable structures are eolian structures for which the term "dune" cannot be retained only since their relief no longer results exclusively from deposit but from a process of even wear, i.e. erosion.

They can be defined as extensive periodic sandy waves /I5
separated by longitudinal or approxiamtely longitudinal valleys. Even if the eolian deposits are not longgitudinal because of the drift phenomena which they undergo -- phenomena which are well studied in conncetion with boat wakes -- the transport and eolian erosion are longitudinal.

A classification of stable sandy eolian structures is not conceiveable without a study of the bioclimatic environment in which they appear. We have already stressed the specific character of barchans in the transport regions and the specific

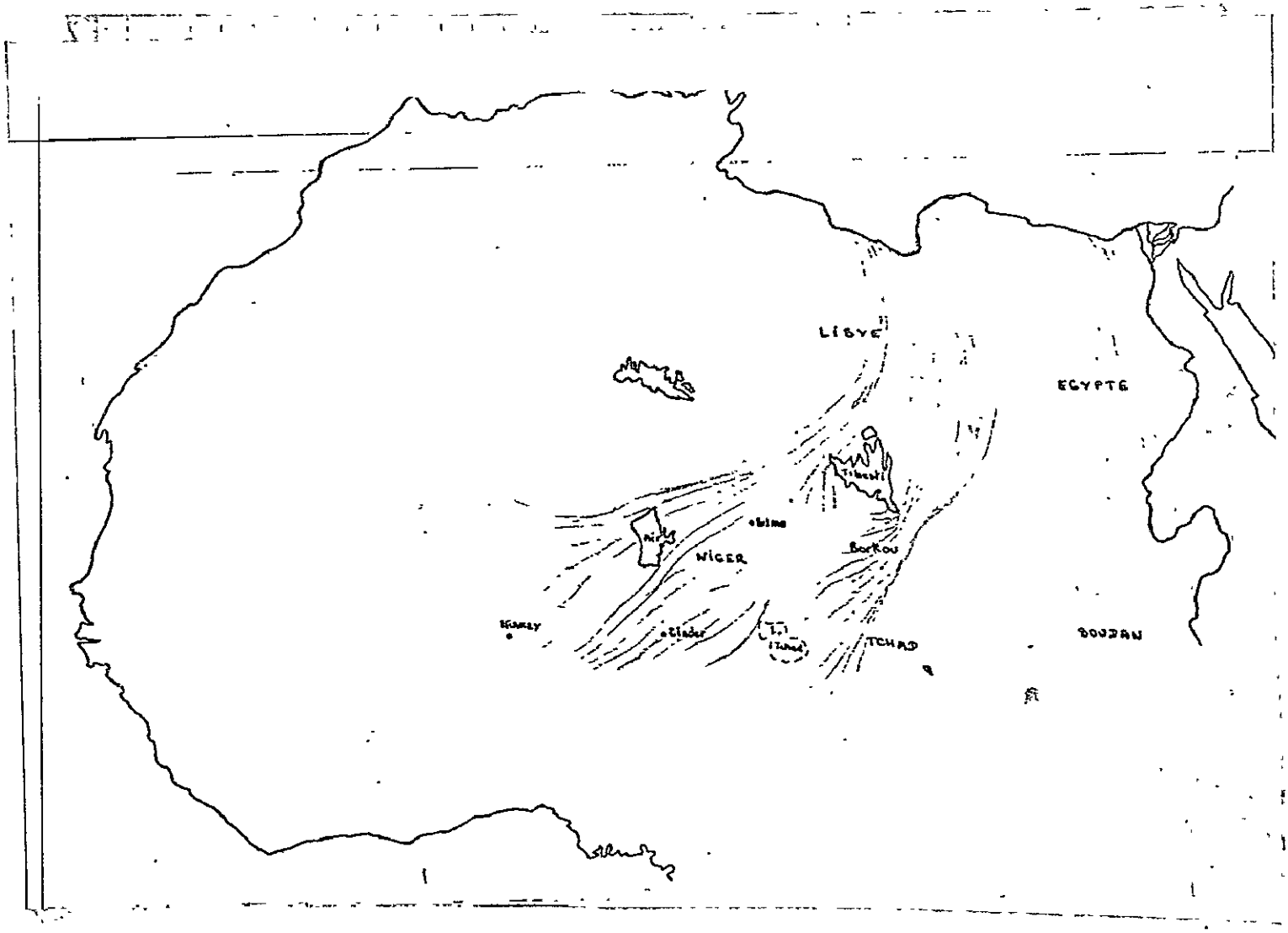


Fig. 3. Eolian transport paths for the wind of the Haussa erg.

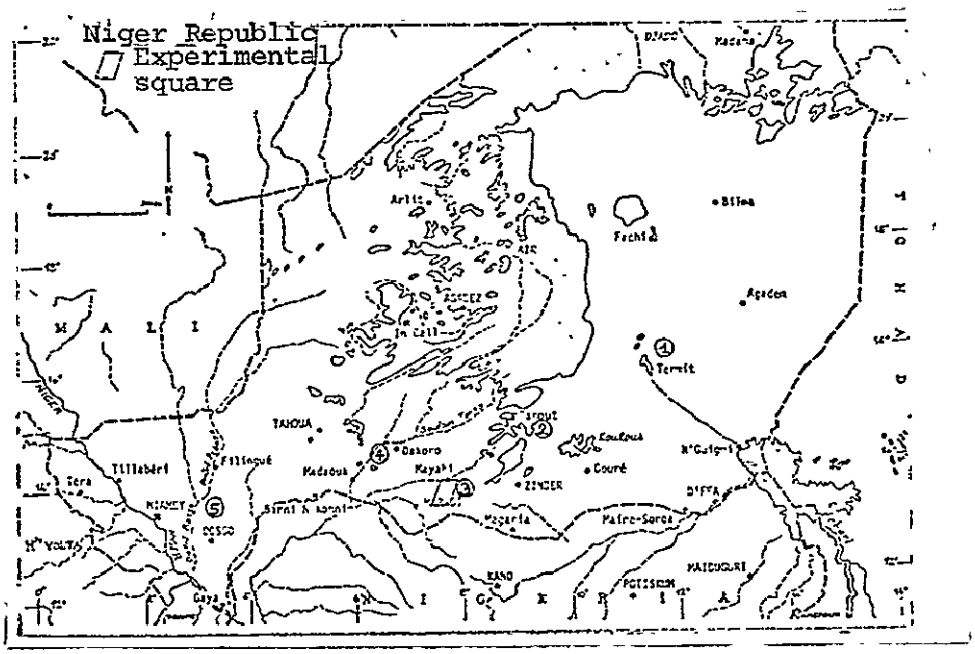


Fig. 4.. Sand reserves of the Haussa erg.
1. Termit sector: coarse allochthonous eolian sandy matter (mode 600 um)
2. Tanout sector: medium and fine (mode = 315 um)
3. allochthonous sandy matter
3. Mayahi sector: mixture of fine (mode = 160 um) eolian sandy matter and coarser fulviatile matter
4. Peri Ader Doutchi sector: fine allochthonous eolian sandy matter ( mode 160 um)
5. Dallols sector: mixture of medium allochthonous eolian sandy matter and coarse fluviatile matter.

nature of silks and ghourds in the accumulation regions where the ergs are born. All of these dunes are characterized by the fact that the sand is completely mobile.

When the ergs are covered with vegetation, like those of the southern region of the sahara which have become sahelian since the last preneolithic dry phase ([illegible]), erosion forms are succeeded by deposit forms in time and space (towards the south). In the mass of sand, which is covered with a more or less dense blanket of vegetation, the wind, armed with sand which it has picked up upstream in the area of active sand and which is the wave carrier, can carve out a system of periodic valleys accentuated by water erosion.

In contrast to mobile dunes, stabilized eolian sandy structures are characteristic of ers in the process of becoming extablished and are therefore forms which correspond to a very transient stage of incipient fixation of a sandy mass: that stage during which the deposited sand can no longer be moved by deflation but can still be attacked by eolian corrasion. The tool, that is to say the sand which is used by the wind to sculpt the landscapes, comes from upstream where it is still arid. Here too the explanation demands a global view of the landscapes. The sectors shown in Figs. 3 and 4 succeed one another from NE to SW along the path of the trade wind.

In many ergs transverse waves are adjacent to large longitudinal waves. There can even be landscapes with a checkered appearance, still perfectly visible in aerial photographs and satellite pictures. The former are due to a direct action of the wind charged with sand and the latter are due to a cutting action which gives the periodic alingments of the closed basins, sometimes covered with lacustrine deposits (Thar Desert, south of the Fachi Bilma erg), or continuous corridors perpendicular to the wind which accentuatesthe transverse dunes resulting from /16
waves which the wind takes charge of when it encounters topographical obstacles. These structures are studied with the dunes covered with vegetation.

## Conclusion

A step forward was made in the study of sandy landscapes by distinguishing between the texture and structure of sandy mantles. The texture defines the parameters which make up the picture and the structure defines the organization of these parameters. Depending on the scale of the documents studied, it is understood that these two factors have differentymeanings.

The spatial arrangement in an erg is not perceptible from the ground. Man here is like an ant on a pile of sand. He sees the sand, the slopes and the primary modules up to the second order provided that the assemblage and the distribution are not too dense nor the size too great. Orders 3, 4 and 5 escape him completely.

In aerial photographs the third order (assemblage of silks and barchans) can be perceived. The same for the fourth order, represented by chains of ghourds and areas covered with draa.

Orders 5 (ergs) and 6 (chains of ergs in a eolian current) are only within the reach of Landsat and Noaa 3 satellite pictures (Table III).

The aim of this work is to propose a classification of all combinations, based on a simple form -- the seif -- and ending up with compound forms which are grouped into two families, i.e. linear families (silks) and multidirectional families (ghourds). With this classification it is possible to assign an order to the dunes, as has been done for rivers.

Mobility, the fundamental parameter for any arrangement, has proved to be one of the effective criteria for classifying dunes. It is decreasing from the barchan to the seif, to the silk and to the ghourd and zero for erosion dunes which are smoothed out waves. It is understood that, on the one hand, even in the barchan the sand is restrained and moves less quickly than in saltation mantles and that, on the other hand, each type of dune has an original function which corresponds to the prevailing context of accumulation or transport for which it is specific.

Finally, in contrast to mobile dunes are stable eolian structures, the second large category in our classification which

is incomplete because we have only analyzed and classified the forms in the areas of active sand or those in the process of fixation. The classification of eolian structures and of all the degradation forms in the Sahel regions remains to be considered.

## Chapter II. Inventory of Sandy Structures on the Arid Borders of the Sahel /17

### The Use of Photographic and Multispectral Aerial Pictures for Studying the Active Erg of Fachi Bilma and Its Extension in the Sahel, the Erg of Haussa.

The transition from an erg with active dunes to an erg whose sandy structures are covered with vegetation was the criterion that we used to define the border between the Sahara and the Sahel. Roughly it follows the southern Sahara (Niger, Chad), isohyet 150 mm.[1] By analyzing Landsat 1 satellite pictures it was possible to determine, in a steppe with shrubs or trees, the extension to the south of the Niger Republic and to Nigeria of a periodic topography in large waves, the origin of which is peculiar to active sandy areas. It was also possible to demarcate the quaternary wavering in the Sahara-Sahel border to the south of the Sahara.

Our reseaches have led us to propose, for the first time, a classification of active eolian sandy structures [ 6 ]. Quite naturally our interestshas been devoted to the study of these same structures blanketed either with steppe or savanna vegetation.

The sandy mantles currently covered by a continuous blanket of vegetation consisting of graminaceous plants or trees were positioned during more intense dry phases than those which we know today. Two of these are known with certainty in the Niger

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1. According to P. Chamard, the limit of active groups in the southwestern Sahara corresponds to isohyet 50 mm.

Republic: one before 2000 BP [expansion unknown] and the other at the Lower Holocene after 7,500 BP [ 2 ]. P. Chamard places the last rainy season of the Sahara between 10,000 and 3,500 BP.

Definitions of Terms used /18

- Covered dunes are sandy structures with a dense or open blanket of vegetation. Fozzilized [sic] by a blanket of vegetation, the sandy structures lose their particular shape, in any case their ridge or peak angle and their specific dynamics.

- Fixed dunes are eolian structures whose surface is paved with coarse sandy particles which are too large to be moved by existing winds. Around Termit in the Niger Republic these fixed dunes, i.e. stable with respect to eolian dynamics, are also covered with vegetation.

- A "transverse" wave is an elongated sandy eolian structure, rectilinear to slightly sinuous, with a convex profile, often dissymmetrical, sometimes with a flat summit, most often organized into a periodic whole and whose direction is roughly perpendicular to the dominant effective wind.

- A "longitudinal" wave is an eolian structure which describes a rectilinear linear path, with a convex profile, most often organized into a periodic whole, likely to have a direction roughly equivalent to the dominant effective wind.

- Reticulated waves are an assemblage resulting from the cris-crossing or superposition of the two above types of waves.

- An eoloian sandy ensemble of periodic structure is a regular alternation of crests and corridors (extended interdune

hollow, sometimes the seat of ponds) following a preferential orientation, sometimes longitudinal, sometimes transverse.

- Monticular refers to a relief of small bulges of sand with a convex profile separated by rounded hollows, arranged in semi-circles often following a regular network inside one and the same region. Wer are still not able to state with certainty that these are eolian structures or if only the cap is eolian.

- Barchans and parabolas are isolated eolian structures, sometimes coalescent, but always clearly individualized, crescent-shaped with the convex side pointing to the wind when they are barchans and with the concave side pointing into the wind when they are parabolas. At the time of their degradation when a humid period is becoming established the barchans can give rise to perfectly conical rounded hills.

- Hilly refers to hills of sand which are slightly separate or coalescent. In the Sahel environment or in any other semi-arid tropical climatic environment involving a cover of vegetation these hills result from the transformation of barchan type dunes.

In a study it is not possible to dissociate the Fachi Bilma /19
erg from the Haussa erg because the latter is continuous with the former in the Sahel region, which, by the way, confirms the granulometric and morphoscopic studies.

At the start of our work we thought of limiting it to the study of the dynamics characterized by the different aspects of the reactivation of the sandy cover and of deflation. But we have been led to study the basis of these phenomena, i.e. the different sandy accumulation relief which make up the local landscape. In fact, two aspects of these accumulations surprised us:

(1) the entire organization of the sandy cover and (2) the discovery of orginal shapes, covered sandy structures which it was necessary to define and then classify.

By examining aerial photogrpahs werwere able to map and localize these different structures, to detect the existence from north to southwest, i.e. from Termit to Maradi, of a transition from structures of an active erg to structures of a covered erg: from the well pronounced longitudinal and transverse structures of Termit to the indistinct monticular structure of Maradi, passing through the transverse monticular structure with the existence of a distinct transverse structure around massifs.

Thus we can state that the Maradi and Tarka regions are almost totally occupied by the slightly differentiated monticular structure and we can note the presence of 4 other structures which occupy only a small percentage of the surface are. Three of them are not very extensive: the hilly structure, the transverse monticular sturcture and the longitudinal monticular structure. The existence of the fourth structure, the longitudinal structure, if it appears surpirsing, can be explained by the channelization of one branch separated from the eolian current of the Fachi Bilma erg between the Damergou massif and the Tegama Plateau.

Each of these families of structures, depending on their topographical appearance, i.e. in particular their slope and the grain size of the material of which they are composed, present various degrees of attraction and repulsion with respect to human occupation.

We also find that the region from Tanout to Zinder is occupied by more differentiated monticular type structures -- almost hilly -- and over smaller surface areas. /20

The families of structures which occupy the largest space in the region studied are the following:

- separate dunes (barchans andéparabolas), ovoid dunes with closed or open caoudeyres which indicateâthe progress of degradation in these structures and which can result in the hilly structure due to coalescence, terminating with a transport current, with barchans blocked in their migration, fixed and then degraded and regressing to the hill stage. This is proof of an abrupt incursion towards the north of a more hûmid climate.

- The transverse monticular structures, which are very widespread on the maps of Gamou and Zinder, indicate the presence -- during the transition from an active erg to a covered erg -- of a region covered by a dune structure very similar to the formation stage of the transverse structure.

- The well pronounced transverse structure around the Koutous Massif and downwind of the Damergou Massif.

The progression which can be detected in the dune relief from Termit to Maradi is supported by a similar progression in grain size and the shaping of grains of eolian origin. In fact, the samples of sand at Termit include grains of all sizesbbetween 160 and 800 µm. At Tanout selection has already taken place and the coarsest sizes tend to disappear. In Maradi the coarsest sizes have disappeared entirely. A selection process continues and only grains ranging in size from 160 to 315 µm exist in a preponderant manner.

The same is true for the surface conditions. The very blunted particles, iee. those which have undergone long eolian transport, are distributed according to different sizes from Termit to Maradi. In Termit they still reach a size of 630 µm, in Tanout they are larger than 315 µm and at Maradi only 250 µm.

This progression in grain sizes caused us to perceive the

the existence of a uniformity tying together these different regions; namely, the wind, the uniformity in the shaping of the paleorelief but even more the dry paleoclimatic periods. This wind is responsibe for transporting and sorting the material and its strength decreases along its dominant path. This weakening of the wind prevented the eolian transport of large particles to Maradi. There is, however, a supply of coarse sand at Maradi which was carried by fluviatile transport.

An eolian current from the Tibesti region, which feeds the /21
active erg of Fachi Bilma and crosses the Termit massif, partially supplies our region with sand, shaping it with decreasing force when our region was active. Simultaneously and in proportion with the deposit of grains of sand, from the coarsesttsto the finest, it effected a load substitution and took up autochthonous grains over the supply of sandstones of the cretaceous period. Thus there is a triple action of the wind: (1) bringing in allochthon sand which is deposited selectively according to its size; (2) load substitution, taking away the local decomposition material; and (3) shaping the topography of the deposited sandy mantle. In the material deposited by this eolian current is found a fraction of particles which can be picked up again by existing winds. The percentage of this fraction has increased due to the effects of soil genesis which the sands have undergone.

The existence of deflation regions shaped like spearheads which can reach lengths of up to 200 km and which are more obvious in satellite pictures reinforces the assumption that an eolian current is connected with the region which is capable of depositing and shaping and also sweeping the deposited material. This deflation action was particularly manifested during the active erg period, but it still continues to operate on a small scale today. The connection between our regions and this old eolian

current, which was very active when the erg was active, can, a priori, facilitate the resumption of eolian erosion in these regions. However, since nowadays our region is covered with a blanket of vegation and fixed by a pavement of coarse material, this resumption is normally not conceiveable without a disruption in the natural equilibrium.

The gradual process described in these dune reliefs and in the morphoscopy of the material making up these reliefs is found again in the different aspects of current reactivation and deflation.

On the maps of Gamou, East Zinder, Tanout and Zinder Magaria there are many varied and distinct deflation and reactivation areas. Even if in places erg reactivation still takes on indistinct appearances, i.e. just beginning or still compensated for by animal evacuations -- for example, around vilages -- we often find more distinct and pronounced reactivation in a linear shape or resembling a micro-crescent. The maximum intensity of the deflation is reached on the Gamou map. There it appears in the form of shading and heavy marks alternating in successive waves.

On the maps of Dakoro, Guidan Roumji and Maradi and Tarka the /22
small spots of deflation and reactivation blend together and in the aerial photographs look like fuzzy areas, "fuzzy features" accompanied by soft scratch marks.

When we discovered these reactivation phenomena in the 1975 aerial photographs we refered back to the corresponding aerial photographs of 1957. Although the difference in scale made it difficult to compare the two sets of photographs, we found thatt in the majority of cases, especially between 6° and 8° of east longitude, reactivation and deflation were practically nonexistent in 1957.

## II. The Sandy Structures in the Sahel Region

### A) General Characteristics

The Niger Republic (13-23°N and 4-6°E) includes an arid fringe in the north, becomes Sahelian in its interior and in the southern section becomes Sudan-like. The Sahel region maybe situated between isohyets 150 mm (current limit of the active dunes) and 550 mm. The current reactivation processes extend to isohyet 625 mm.

In the Sahel region of the Niger Republic the majority of the surface area is covered with sand, an extension of the Fachi Bilma erg. The active part of this erg describes and extensive right hand wake 800 km long and 300 km wide downstream.[1] It begins at the southwestffoot of the Tibesti downwind of the massif, between 19° and 20°N and 17°E, at the confluence of the two branches of the Harmattan which have flowed around it and along which allochthon sand has been brought in in the form of barchans or a saltation mantle. In the first stage of our work we thought that the Fachi Bilma erg ended longitudinally in the west next to Aïr. Studies of satellite pictures and ground studies revealed that it was more extensive, going beyond the existing Sahara-Sahèl border (16°N) up to 12°N and 6°E against the eastern foot of the Ader Doutchi, which brings its total length to 1200 km. But this is not a tight termination, since a small ortion of sand still escapes more towards the west, sweeping across the Ader Doutchi, and towards the north between the Ader Doutchi and the western edge of Aïr.

Granulometric and morphoscopic studies of several hundred samples of sand revealed that, upwind from the topographical

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1. Considering that an erg is an oriented structure having a beginning and an end we speak of upstream and downstream.

north-south barrier formed by the Aïr and Tanout massifs, it is the coarsest grains which have the greatest roundness coefficient. Downwind from the same barrier the coarsest grains, on the other hand, have the smallest roundness coefficients. These are the smallest sandy particles which are the most used. Thus in the Termit region the roundness coefficient increases proportionally with the increase in grain size up to a maximum of 630 µm and then decreases. In the Tanout region the roundness coefficient increase no more than up to 315 µm. Finally, in the Maradi region it increases up to the granulometic threshold of 250 µm.

This means that the supply of coarse grains which appears downwind from the Tanout massif is autochtonous, drawn from the decomposition products of the sandstone substrate shot with quartz, and Cretaceous. And it means that only the small grains are allochtonous since theyeare rounded, the rrounded coarse grains having been deposited upstream.

The dunes of the Sahel region, either fixed or covered, can /24
classified into three categories:

1. Sturctures deposited in periodic systems. These are common to the active erg regions of the arid zone and are covered in the Sahel.

2. Structures organized into monticular or hilly structures. They are found exclusively in the region of covered ergs.

3. Individualized structures. These exist in both areas, but differ in their topography. The individualized structures of the Sahel result from the degradation of those structures of the arid zone.

B) Periodically Arranged Sandy Structures

1. Transverse Waves

When a current of sand-bearing air encounters an

obstacle it begins to oscillate and produce waves. The resulting eolian structures reflect this phenomenon by their periodic arrangement. These structures are called "transverse" with reference to the dominant effective winds. These have been studied in the Niger Republic over a period of 10 years (from 1966 to 1975). These structures also exist in the active ergs. They form the majority of the surface area of the downwind half of the Fachi Bilma erg.[1]

Now the eolian currents which sweep the Sahel from the Niger Republic encountered upwind from this country in Chad, the Tibesti massif, then, leaving the arid zone, ran into the Air. These are the two major obstacles, and in addition there are two smaller ones, those of Tanout and Koutous.

The transverse waves are present in the arid zones and Sahel /25
zones, but in the fomer they are larger. Indeed, we have pointed out that in the active part of the Fachi Bilma erg their period was greater than in the Sahel, although we did not find an explanation for this difference.

The transverse waves are one of the specific forms of the southern part of the Fachi Bilma erg southof 17°45'N. This is why we have been led to speak of it with respect to stabilized dunes. The 1:1,000,000 map (separate from the text) gives the directions of these structures.

a) Transverse Waves of the Fachi Bilma Erg

The transverse waves cover an area of 4,500 $km^2$, from 11°25'E-17°20'N to 12°30'E-17°45'N. They are found in smaller areas around 13°E-17°45'N, around 11°35'E-16°05'N and around 11°E-17°05'N. There is a small isolated area around 10°37'E-

1. As on p. 29

16°07'N. Except in the area of 4,500 $km^2$ where they reach a length of 30-40 km, the transverse waves are shorter than the longitudinal waves, since their lengths vary from 5 to 20 km.

Although the profile and altitude of transverse waves are not as regular as those of longitudinal waves -- the crests too are more sinuous -- their overall directions are distinct and regular. The large area of transverse waves already mentioned has orientations which vary between 153° and 167° with a mean value of 163°, and sort of turns back in the direction of 170° to the north close to longitudinal waves. The range in direction of these waves is more extensive thanthat of longitudinal waves, since it spreads out over 45°. The values far from the mode are thoseeof short waves in small isolated areas, as if there existed a relationship between the length of the waves and the regularity of their direction.

Their profile differs from that of longitudinal waves. It is more often dissymmetric, the slope of the wupwind face being less than the slope of the downwind face. This asymmetry is more or less pronounced. (AO 55-56 NE 33 VII-VIII, no., 623-624, plate XVIII a and no. 740-741, plate XVIII b).

The waves are periodic and separated on an average by a distance of 2,000 m, with small variations (1,500-3,000 m).

b) Transverse Waves of the Haussa Erg /26

In the Haussa erg of the Nigerian Sahel, which today is covered with vegetation, the transverse waves are located downwind from the Tanout massif, from 14°19' to 14°24N and from 8° to 8°12'E, and theyyare arranged like a sash around the Koutous Massif from 13°50' to 14°30'N and from 9°35' to 10°E (Fig. 5). The systematic location of this structure in the

vicinity of massifs is remarkable.

The transverse waves are perpendicular to the direction of the dominant dry season wind and have a north-northwest - south-southeast orientation. Following a sinuous course and varying in length from 5 to 10 km and in width from 500 to 1000 m, they present a dissemmetrical profile, with the steepest slopes downwind, and with interdune hollows which seem to be excessively hollowed out but are nevertheless sandy.

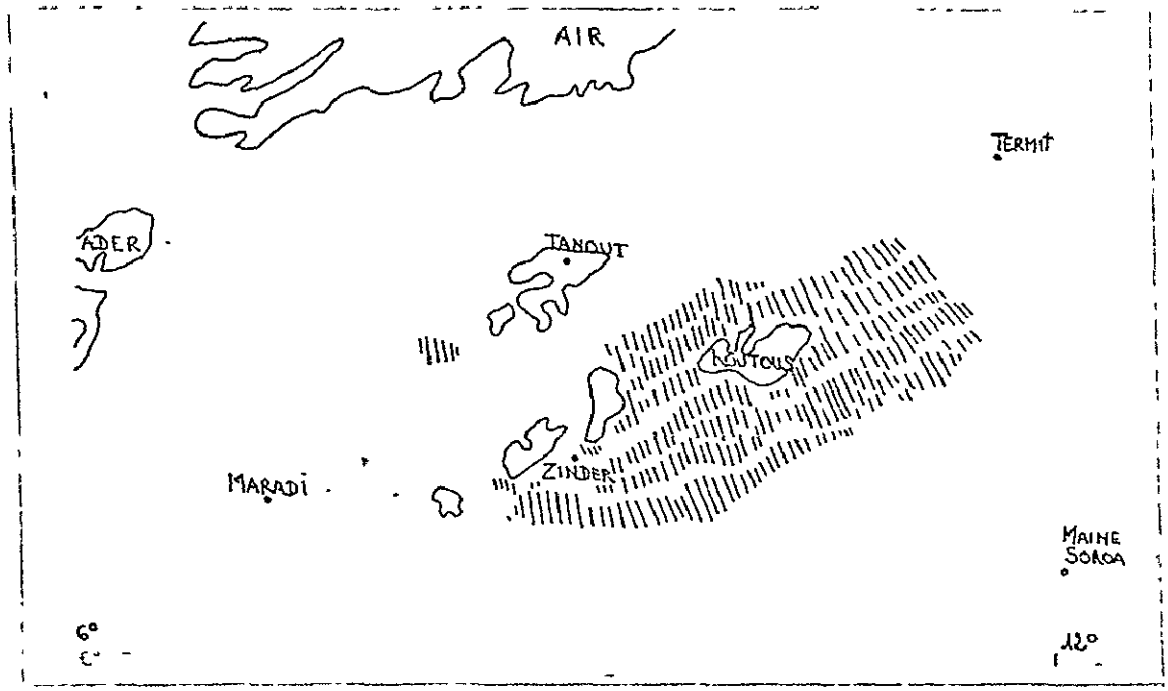


Fig. 5. Location of the transverse dunes of the Haussa erg.

2. Longitudinal Waves /27

a) General Remarks

In the Fachi Bilma erg the longitudinal waves cover 1,700 $km^2$, reaching a length of 180 km and varying in width between 750 and 1,500 m. In the downwind direction they gradually alternate with

chains of ghourds.

In the downwind section of the Fachi Bilma erg the waves are topped with silks with a right hand angular divergence which can reach 15°. In some cases these silks criscross all of the waves and valleys separating them, but when they exist only on a part of the wave they are always on its north-northwest face and not on its south-southeast face (Fig. 6).

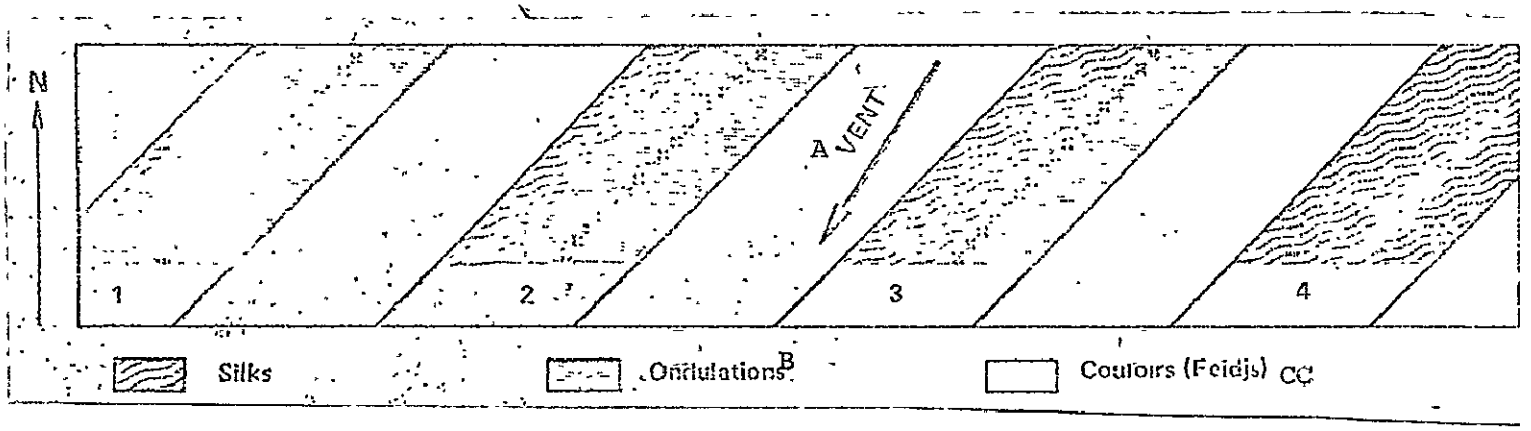


Fig. 6. Relative arrangement of silks on giant waves

Key: A) Wind
B) Waves
C) Valleys

In the case of large waves it is not possible to estimate the migration rate of the sand. The sand remains trapped for a more or less long time in the waves which are fixed by a protective pavement when they are subjected to eolian winnowing.

The silks reflect the dynamics of the moveable sands of the present period. They correspond to a current climatic environment and thus differ from those of the environment which prevailed when the waves were formed.

The most elaborate example of giant longitudinal waves is that of the Chech Erg. Aerial photographs show their north-

northeast - south-southwest orientation and the extent of the gassis which are much wider than the sandy structures which they separate. The sands which feed the erg certainly come from two soruces: (1) some comes from the Erg Raoui erg which is in turn fed by inputs from the Saoura and the Great Eastern Erg; (2) but a large part comes across the Tademaït from barchans which abut obliquely onto the first wave of the erg. From one wave to the next the sands move crosswise along the valleys, as indicated by the light corrasion striations. They also migrate on the large waves, along the peaks and especially along the silks.

b) Location in the Fachi Bilma Erg /28

The longitudinal wave in the Niger Republic begins around 19°20'N and 15°E, i.e. 2° east of the "cliff" of Bilma which cuts through the middle of the erg. Downwind from this escarpment these longitudinal waves form the southern part of the Ténéré erg while continuing up to 11°E. This large area of longitudinal waves which extends over 4° is replaced in the south by a large reason of transverse waves. These appear around 18°N and 13°E, precisely in the region where the Bilma "cliff"[1] obstacle disappears, and extends just to the right of the Termit massif, up to 11°20'E. Another bundle of longitudinal waves to the south replaces the transverse waves. It begins at the same latitude as the transverse waves, follows a constant east-northeast - west-southwest direction, skirts the Termit Massif and gradually dies out a little in front of the Tanout Massif in the Sahel region. South of this second major longitudinal bundle of waves and in all of the southern portion of the Niger Republic the longitudinal wave disapperared. Curiously it reappears in the Niger Republic downwind from Lake Chad in a

1. The effect of the obstacle was described in M. Mainguet, 1976, "Geodynamic Study of the Effect of a Topographic Obstacle in Eolian Transport. Results Obtained Using Aerial and Satellite Pictures of the Sahara," Bulletin de la Société frahcaise de photogrammétric, No. 61, p. 31-38.

latitude between Nguru (12°50'N) and Jamaari (11°40'N) and in a longitude between Gumel (9°30'E) and Maigumeri (12°50'E).

c) Description in the Fachi Bilma Erg.

We think that the giant waves are regularization dunes, which amounts to saying that the valleys separating them result from the effects of deflation in a region of extremely regular wind or have been amplified by the action of water during more humid periods. This explains why one could consider them longitudinal because they are formed not only as a result of accumulation -- which produces oblique or transverse forms -- but also as a result of eolian sweepage or even erosion when the sand reacts like a solid rock with respect to the wind when it is in the process of being fixed by a pavement or covering of vegetation.

d) Covered and Fixed Giant Waves of the Fachi Bilma Erg Upwind from the Termit Massif /29

These waves are covered with ripple marks. The stability of their surface is due both to the vegetation which is found there, but especially to the pavement of homogeneous, coarse particles measuring up to 1,000-1,250 m with a mode of 630-800 µm. These are "round-dull" grains which produce unimodal curves. One could say that the surface state of these dunes has been recorded. The fixation of these waves was modified locally in February, 1976, by reactivation processes giving rise to:

- nebkas behind the clusters of euphorbia,
- craters at the foot of shrubs or small trees,
- very curved silks clinging to rocky obstacles and the reappearance of an active peak on the waves.

The peaks of these giant waves are sprinkled with a large number of tools made of volcanic lava or sandstone highly

impregnated with iron. These tools lie on the surface or are buried to a depth of a few millimeters. Probably from a neolithic age, this specific location on the peaks of eolian structures provides several pieces of information:

- the interdune spaces were spared, probably because they wer flooded. This supports the assumption of a neolighic paleo-climate more humid than the existing climate.

A sample of charcoal taken west of the Berno dispensary gave an age measurement of 3,100 ±100 BP. (The measurements were made by Mrs. G. Delibrias of the Radiocarbon Laboratory of the Atomic Energy Commission and of the National Center for Scientific Research.) This charcoal was found in a hearth pearched on top of a dune. It appeared thanks to the action of deflation and even erosion which in a local area on the top of the dune cleared away the covering of mobile sand which allowed the outcropping from the horizon of the slightly solidified red dune. The hearth was included there, making up part of the solid mass, looking like a round spot (40-50 cm in diameter) browner than the rest of the slightly aggregated mass of the dune. This may indicate that the slight coehsion of the dune is neolithic. The site of the hearth on top of the dunes alos implies flooded interdune spaces, in contrast to the current situation.

- Since the neolithic period the giant waves have evolved only slightly: the tools are actually all on the surface. Perhaps only one winnowing has occured? It all looks as if the entire north-east section was winnowed to the advantage of the southwest section where it is all accumulating.

- The traces of reactivation mentioned above are of the recent period or just before the recent period.

e) Longitudinal Waves in the Haussa Erg /30

In the covered region beginning downwind from the Termit Massif and ending at the foot of the Ader Doutchi the extent of the longitudinal waves is limited.

They are located as follows: downwind from the Termit massif, from 15°30' to 16°N, and from 10°30' to 11°E; downwind from the Damagaram massif, from 13°50' to 14°N and from 8°50' to 9°E; from 15° to 16°N and from 6° to 7°E. Theyeare located in a channel formed by the Tegama Plateau to the north and the Damergou and Ader Doutchi massifs to the south.

Characterized by a ENE-WSW right hand orientation, these large waves are 10-25kkm long and can reach a height of 20 m. Their slopes are less steep than those of the same waves located in an active erg. The side facing to the south east is more abrupt than the northwest face.

f) Formation and Evolution Mechanisms

The dynamics which give these waves their longitudinal character are bounded by the laws of ablation and transport which give rise to longitudinal forms and the laws of accumulation which give rise to oblique to transverse forms.

The two mechanisms, erosion and accumulation, act simultaneously, one and the same wind causing both of them when the degree of fixation of the erg causes this combination, which is also favored by the small angle between the two vectors.

Analysis of photographs of the upwind portion of the Fachi Bilma erg, where different stages in the evolution of the large waves can be observed, suggests the following three kinetic stages:

1. Longitudinal wave systems in the process of being formed: the wind has a tendency to cut into the "—" regions, while the "+" regions are left relatively untouched.

2. Silks deflecting to the right are established preferentially on the right hand slopes of the waves, probably because in the case of right hand deflection the slope promotes their growth on this face. This preferential position of silks then causes an influx of sand into the valley, which causes the wind to sweep into (a) before continuing its cutting action, and at the same time causes a narrowing of the valley which increases the cutting action on face f1 of wave A, while the increase in cutting action on face f2 of wave B is compensated for by additions of sand from the silks on the right (Fig. 7).

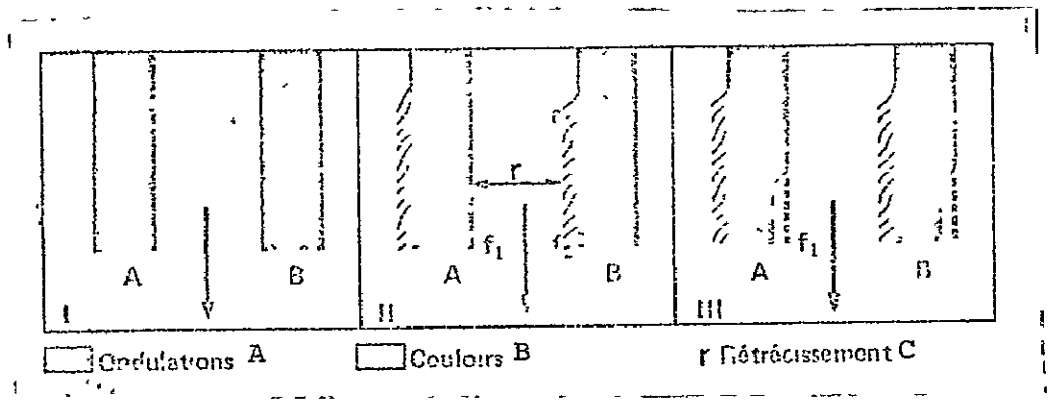


Fig. 7. Changes in the direction of longitudinal waves.

Key: A) Waves
B) Valleys
C) Narrowing

3. Equilibrium between the additions of sand from the silks on the right, thinning due to the wind on side f1 of wave A, and increase in the cutting action due to narrowing of the erosion valley. Starting upstream, this change should, by successive "removals," be able to spread over all of the waves, but it is likely that it became established, at least in certain cases, when scouring began, which allows a general establishement /31

and not a progression from upstream to downstream, and this all the more so as a period of incipient scouring is generally not a period of out and out erosion.

In fact, the wave-silk angle illustrates the evolution of an erg through several successive arid and humid phases, currently reactivated by an arid period. During one and the same period there is no necessary coincidence of surface relief: angles exist between dunes of different types and even of similar types. In general, when such an angle appears this suggests the existence of winds differing in direction from existing winds. However, in the regions studied the development of waves makes us assume to the contrary that the wind directions have been highly stable since the end of the Tertiary period and perhaps even before. This stability is confirmed around the erg by erosion valleys in the sandstones. It is this stability which leads us to look for two different formation processes for the waves and for the silks under the effect of the same annual winds, the former increasing ablation and the latter accumulation. These two mechanisms combine and slightly defelct the waves from their longitudinal direction. This slight deflection made us group the longitudinal waves among the doubtful forms of a fixed erg. Their alignment close to the wind, their lack of active ridges, the amount of sand affected by the phenomenon -- a sign that the wind uses its energy to scour and not to make local changes in the shape always of the same sand --, the scouring of valleys along with depositing on the waves, all of this leads us to think that the longitudinal waves are indeed a form of semi-stabilized erg, stable enough to maintain itself in the reactivated part of thererg.

The active silks on the right tend to cause the waves to deflect towards the north, while erosion tends to keep them in a longitudinal direction. This deflection is fundamental. When it begans to scour the wind was more or less channeled between

clusters and bands of silks which spread out on the corrasion valleys and had deflected such that the wind then found itself more channeled into these slightly deflected forms. There is a combination between the longitudinal corrasion vector and the right hand accumulation vector

| Change in the erg | Following the Path of the Harmattan | | | | /32 |
|---|---|---|---|---|---|
| | | Upstream | | | Downstream |
| Over time | Active Fachi Bilma erg | Transverse<br>Regularization Longitudinal | Transverse<br>Transverse in the process of longitudinal regularization | Transverse | Truncated transverse |
| | Covered Haussa erg | Fixed, paved longitudinal | Transverse in the process of longitudinal regularization<br>Truncated longitudinal (longitudinal Monticular) | Fixed transverse<br>Accentuated transverse | Truncated, fixed transverse<br>Transverse Monticular<br>Semi-circular Monticular |

The original transverse waves can be modified into a relief of regularization longitudinal waves in two contexts: (1) active ergs and (2) covered ergs. /33

1. In a context of active ers the sandy particles in the form of transverse waves are transported from one ripple to another along the shortest path then deposited along a right or left

oblique line. Little by little the transverse waves decompose, while hollows appear lined up from one ripple to another. These hollows, give rise to furrows. Between the furrows sand bridges are established from one ridge to another, giving rise to longitudinal waves. When the transverse ridges are destroyed they supply material which will allow the formation of longitudinal ridges. Thus all of the criss-crossing stages can exist.

2. When a Sahel environment replaces an arid environment the change from transverse ripple to longitudinal ripple can be interupted at different intermediate stages, which can be reflected in the landscape of a covered erg by different types of discontinuous longitudinal ripples.

When the transvers wave is fixed before any degradation takes place it can be subjected to erosion factors peculiar to the Sahel: for example, the combination of primary water phenomena and winds which are still slightly active. The latter, channeled by the transverse valleys, can help over scour the valleys, creating a relief with a more differentiated topography. The trnasverse wave of the Sahel is more sinuous and smaller than in the arid regions which are not covered or only slightly covered. This type of surface relief is not attractive to the farmers of the Nigerian Sahel.

The transition from transverse to longitudinal is to be studied in space and time.

1. In space the currently covered erg of the Sahel region is an extension of the active Fâchi Bilma erg. Four types of periodic relief succeed one another in this region, in the following order going from upstream to downstream:

a longitudinal relief downwind from the Termit Massif;

a discontinuous longitudinal relief upwind from the Tanout massif;

a transverse relief which skirts the Koutous Massif;
a discontinuous transverse relief which characterizes the downstream portion of the covered erg until the current dies out completely at the foot of Ader Doutchi.

2. In time, the reliefs deposited in an active erg then evolved into existing forms when the erg became covered:
covered longitudinal wave resulting from regularization of the transverse wave in the still active erg;
discontinuous longitudinal wave due to regularization of the transverse wave, halted during an intermediate stage and incomplete; /34
fixed continuous transverse wave which only belongs to the transverse wave of the still active erg;
discontinuous transverse wave inheirited from the transverse relief in the process of formation in the still active erg, stopped in its evolution at an intermediate stage and incomplete.

## 2. Sets of Giant Waves with a Reticulate Structure (Fig. 8)

The cris-cross patterns which result from the criss-crossing or superposition of two wave types with dominant longitudinal and transverse components form a landscape of mounds of sand with rather, gradual, convex slope. The mounds are separated by valleys which run in two directions: east-northeast - west-southwest and north-northwest - south-southeast. The asymmetry frequent in transverse waves is rarely found in the slopes of the mounds. The mounds are relatively symmetrical: they are always rounded as are their two original forms.

The traditional checkering forms a three-level relief: mounds, medium levels and valleys, each level representing a type of combination.

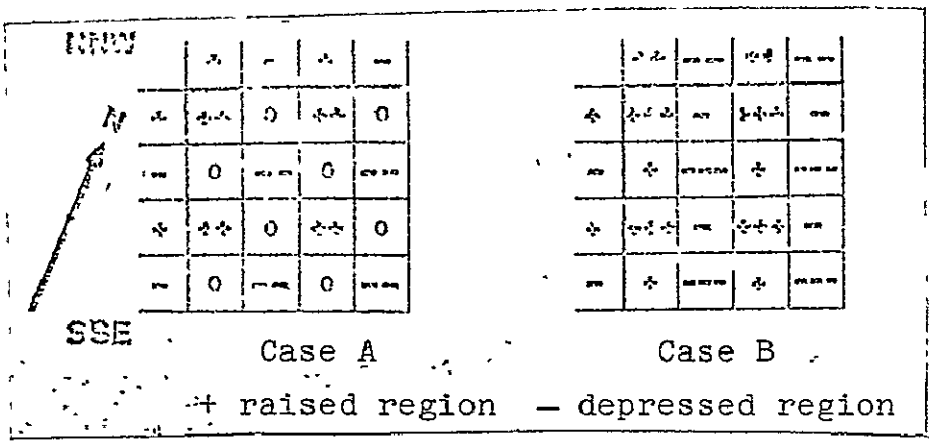


Fig. 8. Arrangement of topographical levels in the sets of giant waves having a reticulate structure: 3 levels of depression and 3 levels of relief can be counted.

A checkered pattern is not necessarily produced in the vicinity of two types of waves. If one of the directions prevails in a region, the areas of opposing waves will be marked by checkered regions without the second type of waves appearing. This situation of an isolated checkered pattern in a section where only one directionsexists is already evident to the east of the Bilma cliff, downstream from the region of longitudinal waves which succeeds the large ghourds, around 17°15'N and 13°30'E, 70 km upstream from the first transverse waves.

The checkered patterns are distinct in a vast region bordered by the following coordinates: 17°20'N - 10°50'E; 18°N - 13°E; 17°20' N - 17°25'E; 16°N -11°30'E; 17°N - 13°E; 16°N - 12°E. This regions does not exclusively involve checkered patterns, but rather is a juxtaposition of sections with transverse and longitudinal waves separated by checkered sections. The sections without waves or checkered patternsaare rare, in particular around 17°10'N - 11°15'E bordered by a band running northeast-southwest, about 10 km wide and 40 km long.

| Type of structure | Map | Location | Distance between 2 crests | Distance between tow 2 valleys |
|---|---|---|---|---|
| Full Monticular | Tanout | 14° 30' – 14° 35' N<br>8° 40' – 8° 45' E | 320 – 480 m | 300 – 400 m |
| | Zinder Magaria | 13°10' – 13° 15' N<br>8° 30' – 8° 35' E | 260 – 380 m | 260 – 320 m |
| | Gamou | 14° 34' – 14°40' N<br>9° 15' – 9° 28' E | 300 – 480 m | 300 – 390 m |
| | East Zinder | 13° – 13° 06' N<br>9° 02' – 9° 14' E | 240 – 360 m | 240 – 300 m |
| | Tarka | 14° 33' N<br>7° 30' E | 420 – 480 m | 360 – 420 m |
| Small Monticular | Gamou | 14° 45' – 14° 52' N<br>9° 40' – 9° 52' E | 90 – 150 m | 60 – 120 m |
| | Tarka | 14° 33' – 14° 12' N<br>7° 30' – 7° 46' E | 300 – 360 m | 60 – 120 m |
| | Dakoro | 14° 21' – 14° 25' N<br>6° 35' – 6° 38' E | 240 – 300 m | 60 – 120 m |
| Longitudinal Monticular | Dakoro | 14° 53' N<br>6° 10' – 6° 25' E | 420 – 540 m | 360 – 480 m |
| | Guidam Roumji | 13° 56' – 13° 42' N<br>6° 11' – 6° 24' E | 420 – 480 m | 360 – 420 m |
| | Maradi | experimental square | 210 – 300 m | 180 – 280 m |

/36

Measures of the Monticular Running from the Covered Erg of Haussa

| Type of structure | Map | Location | Width of valleys | Length of valleys | Distance between valleys |
|---|---|---|---|---|---|
| Small transverse monticular | Tanout | 14° 30' N | 60 m | 300 m | 120 - 180 m |
| | Gamou | 14° 30' N | 60 m | 300 m | 120 - 180 m |
| | East Zinder | 14° 10' - 13° 05' N<br>9° 30' - 8° 40' E | 60 m | 300 m | 120 - 180 m |
| Full transverse monticular | Gamou | 14° 30' N | 120 m | 1200 m | 240 m |
| | East Zinder | 14° 00' - 13° 30' N<br>9° 00' - 10° 00' E | 120 m | 1200 m | 240 m |
| | Zinder Magaria | 13° 20' N | 120 m | 1200 m | 240 m |
| Very large transverse monticular | Zinder Magaria | 13° 12' N<br>8° 40' E | 240 m | 1800 m | 600 m |
| | East Zinder | 13° 40' and 13° 20'N<br>9° 30' E | 240 m | 1800 m | 600 m |

C) Sandy Monticular Relief

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The topography of the sandy mantle in the covered erg of the coungry of Haussa, an extension into the existing Sahel of the Fachi Bilma erg, has already been described by A.T. Grove [ 4 ] and L.P. White [ 7 ]. Between 12° and 14°N the erg, whose width can reach 60 m, becomes discontinuous, cut by an outcropping of bits of Precamberian base or of sandstone plateaus of the late continental period. The edges of the outcropping are hardened. An accidentally functional drainage network flowing from the right bank of the Sokoto there traces out a series of valleys filled with sand. The sand is sculpted into a landscape which we have called monticular as defined above.

It begins northh of Zinder where it assumes the stage of a landscape with large transverse waves. It is organized into three specific structures: in semi-circles, or oriented according to two tendencies, one transverse and the other longitudinal. The existence of a monticular with a longitudinal tendency and a transverse tendency implies that there is a relationship between the period and the Monticular. The monticular has a transverse tendency when, in a hill, sandy landscape, the effects of topographical obstacles makes themselves felt. It has a longitudinal tendency in regions dominated by deposits where deflation has played an increasing role, as is the case downwind from the Koutous Massif or the Termit Massif.

a) The Semi-circular Monticular

This structure of swellings separated by cavities can vary depending on the size and the frequency of the two constituent modules. Thus a distinction is made between:

1. The full monticular which attains its maximum size on the maps of Tanout, where it occupies 3/4 of the map, and of Zinder Magaria, where it occupies 11/12 of the map. It covers all of the southern portion of the map of East Zinder. It is less extensive on the map of Gamou.

2. The small monticular which is the smallest module. It is found on the map of Tanout in 2 small places and on the map of Gamou where it is larger. On the map of Tarka it is located southeast of Guidan Makao and northeast of Labara. On hthe map of Dakoro it is found between Bajani and Guidan Maza. In the experimental square of Tchadwa-Mayahi the size of the alveolar formation is intermediate between the first two types mentioned.

b) The Direction-Oriented Monticular

1. Longitudinal orientation. The two modules (monticule and alveous) are no longer organized in a multidirectional fashion, but rather they run in a west-southwest - east-northeast direction. For the most part we find it in the upper third of the Tarka and Dakaro maps (between Koren Mayata and the Tchaglate Plateau), northwest of Guiday Roumji (south of Takorka and north of Oubandawaki) and along the south bank of the valley of the Goulbi N'Kaba on the map of Maraid /38

2.Transverse Orientation. The two modules are oriented in a constant north-northwest - south-southeast direction.

Using the criterion of size the following distinctions can be made:

1. The small monticular with a transverse tendency is found on the maps of Tanout, Gamou and East Zinder.

2. The full monticular with a transverse tendency is found on the map of Gamou where it is adjacent to the small monticular with a transverse tendency; on the map of East Zinder where it describes a north-south band and a second east-northeast - west-southwest band which becomes thinner and extends to 9°E; on the Zinder Magaria map where a beach terminates the region of the small monticular with a transverse tendency.

3. The very large monticular with a transverse tendency is found on the map of Zinder Magaria in a band 6 km long and 4 km wide, and on the map of East Zinder with an initial section measuring 8 km long and 6 km wide and then a second section measuring 20 km long and 6 km wide.

c) Formation and Evolution of the Monticular Sandy Relief

The perfect similarity between the measurements of the semi-circular monticular and those of the transverse monticular on the one hand and, on the other, the succession "transverse - transverse monticular - monticular" starting at the base of topographical obstacles suggest that there is a relationship between these different structures. In the vicinity of massifs is found the fixed transverse wave, in a second halo the transverse monticular and in a third halo the semi-circular monticular which, during Sahelian degradation of the erg, results from a transverse monticular, the topography of which, however, was not very pronounced and whose modules were not sufficiently differentiated to be able to preserve their original form in the face of Sahelian degradation systems. The large transverse monticular was degraded into a full monticular and the small transverse monticular into a simple small monticular.

D) Separate or Coalescent Sandy Structures of the Hilly Type /40

1. Coalescent Hilly Sandy Forms

We apply the name hilly to landscapes with large eolian structures whose diameter can reach two kilometers. These structures are well separated from one another, sometimes coalescent. In general, this structure was found on a hard or rocky substrate, along an eolian path in a prevailing transport section. It results from the degradation of barchan-like structures in a Sahel environment. On the Tanout map it is located mainly to the west and southwest of the massif; on the Gamou map it covers an area extending from the northeast to the southwest from 14° to 14°30'N and from 9° to 8°50'E, and there are separate spots to the south and southwest of the Koutous Massif. It extends the area on the Gamou map in two small, slender parallel patches, at 13°30' and 13°40'N, which end around 8°05'E on the Zinder Magaria map.

Table of Comparative Measurements between the transverse Monticular and the Semi-circular Monticular

| | | | | |
|---|---|---|---|---|
| Full transverse monticular | A: Length of interdunal valley 1,200 m | L: Width of interdunal valley 120 m | L: Distance between two interdunal valleys 240 m | |
| Semi-circular monticular | A'1: distance between two valleys of the same plane 240 m | A'2: distance between two displaced valleys 300 m | B'1: Distance between two crests of the same plane 360 m | B'2: Distance between two displaced crests 240 m |

$A'1 = L = 240$ m

$A'2 = 2\ (0{,}5 \times A) = 2\ (\frac{1200}{2}) = 1200$ m

$2\ (0.5 \times A) \neq A'2$ since during the time of formation of the monticular the crests are cut off their ends being partially filled with material from the transverse sections of the transverse monticular.

$B'1 = 1 + 2\ (0.5 \times L) = 120 + 2\ (\frac{240}{2}) = 360$ m

$B'2 = 2\ (0.5 \times 1) + 0.5 \times L = 2\ (\frac{120}{2}) + \frac{240}{2} = 240$ m

This structure involves two variables: (1) the periodicity, because the distance separating two hills is not constant (it changes in the presence of other structures); (2) the diameter of the hilly convexities, which can vary from 600 to 1,800 m.

## 2. Separate Hilly Sandy Structures

We know that barchan dunes characterize the marginal regions of ergs and the regions where the sandy mantle of the erg becomes torn and lets the rock break through in places, and we know that barchan dunes are found in regions where deflation, and thus transport, prevail.

In the Sahel these barchan or barchan-type structures have a transformation which can lead to a rounded hill form with a rounded conic profile. These structures have ceased moving for four reasons: (1) their enormous size, (2) the decrease in wind, (3) the appearance of a blanket of vegetation and (4) winnowing, resulting in a pavement of very coarse particles, occuring at the same time as the transformation, afterwards or even before. At the present time, water runoff is degrading these forms.

### a) Barchan Dunes (Fig. 9)

Degraded, these dunes often only remotely recall the characteristic crescent shape, the wings of which point downwind.

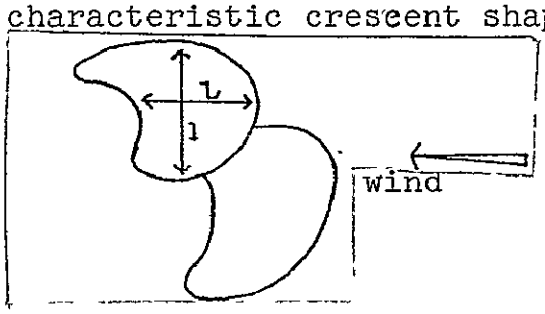


Fig. 9. Barchan southwest of Maysararaka, Tanout map 17°37'N-8°16'E. L = 750 m, l = 750 m

### b) Ovoid Dunes with caoudeyres (Fig. 10) /41

- Ovoid dunes with closed caoudeyres. These are oval-shaped accumulations, about 600-1,200 m long and 360-600 m wide.

They have a oval-shaped central depression.

- Ovoïddunes with open caoudeyres. The body of these dunes is more slender and the wings less distinct than those of barchans and they point into the wind. Neither are the wings parallel as in the case of barchans, but they have a tendency to comettogether, describing a circular arc.

Barchans after R.A. Bagnold

Ovoid structure with open caoudeyre

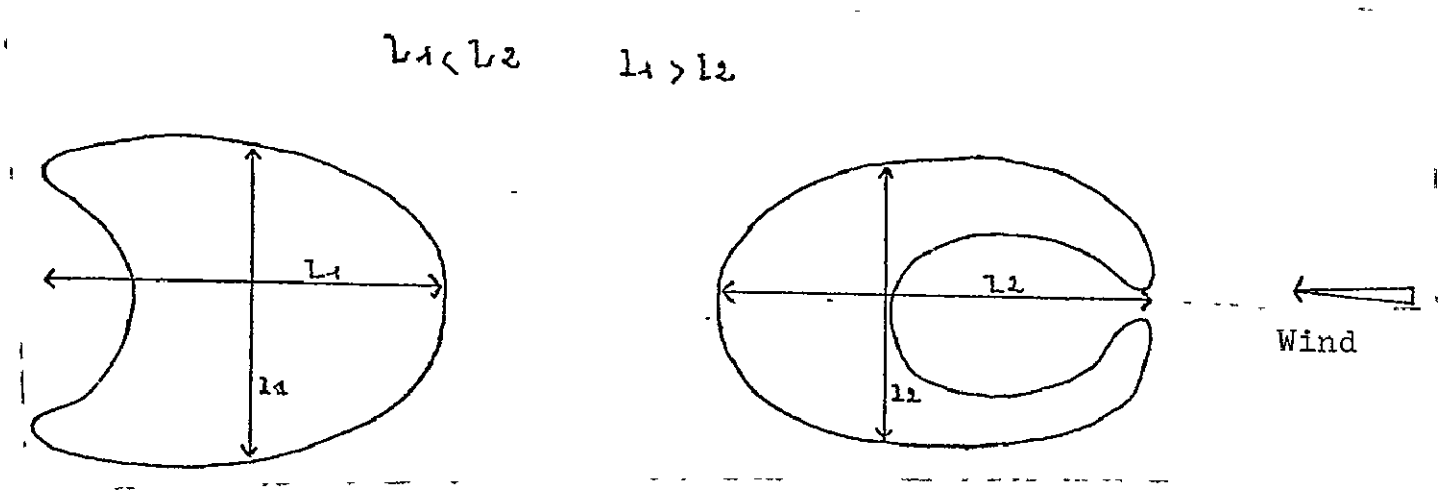


Fig. 10. Barchan and parabolic dune (top view).

The ovoid structures appear in four regions:

1. on the Tanout map in the same regions as the barchan dunes (14°37'N - 8°16'E);

2. on the Tanout and Gamou maps, between 14°06' and 14°13'N - 8°52' and 9°08'E;

3. on the Gamou map, between 14°05' and 14°11'N - 9°42' and 9°50'E, and between 14°1and 14°02'N - 9°23' and 9°25'E;

4. on the Zinder Magaria map, between 13°40' and 13°50'N - 8°02' and 8°24'E.

With all of these dunes reactivation is occuring on the crest

of the wings on the side towards the wind from bottom to top, the face towards the wind is an erosion sector which at the present time assumes the shape of a parabola. It is the removed sand which is migrating at the present time, forming silks or reactivation nebkas.

c) Proposed Explanation for the Appearance of these Dunes /42

In an active erg the shapes of the separated structures are due to deposit for the shield and to deposit and caving in along the downwind face for structures such as the barchan. Thus we can trace the evolution from shield to dihedron, dihedron to barchan dihedron, barchan dihedron to barchan (Fig. 11). In a covered erg theseparated structures are degradation or destruction forms: (1) degradation in an initial stage when the separate dune keeps the characteristics that it had at the time of its formation when the erg was active; (2) destruction in a second stage when the separate dune losses its own characteristics in acquiring others which are specific for covered ergs. Thus we can trace the following degradation process:

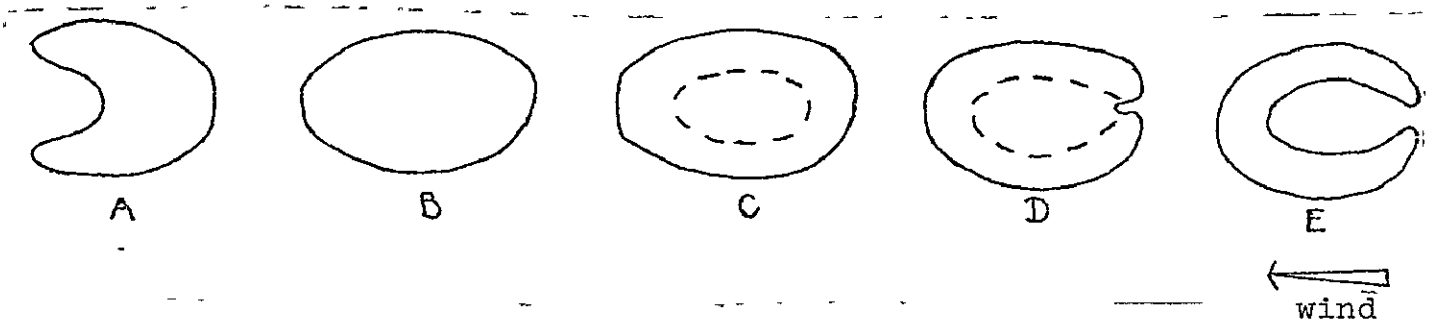


Fig. 11. Various stages of evolution for a barchan in the Sahel region.

A: The barchan structure is still recognizable, but it is more or less degraded.

B: The barchan structure again becomes a shield, looking like a sandy, ovoid hill.

C: Destruction appears with scouring of a central cauldron. This is the ovoid dune with a closed caoudeyre.

D: A notch pointing towards the prevailing wind is formed.

E: The notch enlarges. This is the ovoid dune with a open caoudeyre.

This progression, considered over time, is revealed by examples observed upwind in the experimental square: (1) we find slightly degraded barchans (stage A) on the Tanout map north of the village of Yerima (14°36'6"N and 8°15'4"E), and we find conical ovoid hills (stage B) in the vicinity of the barchans; (2) we find ovoid dunes with caoudeyres (stages C-E) on the Tanout map west-northwest and east-southeast of the village of Maymagaria (14°12'N and 8°9' to 9°E), i.e. upwind of the preceding region, and we also find them on the Gamou map, west-southwest of the village of Dania (14°10'N and 9° to 9°1'E). /43

A few isolated hilly, ovoid dunes are found between these two locations.

These dunes have become the chosen site for the culture of millet or sorghum. This breaks them down. Their peaks are reactivated, however if cultivation does not take place a protective pavement appears. Burrowing animals, which are less numerous than to the north of the Koutous Massif, here too bring to the surface fine sand which can easily be moved by the wind. The interdunal spaces are vast, very gently sloping faces converging towards miniscule temporary ponds where the material, which is dry in summer, is cracked by dessication cracks when it does not bear any hoof marks. The slopes which lead to these ponds are subjected to intense icing. In February, 1976, (the time of our visit) there existed there only a few grassy places

with shrubs or trees. Intense icing and runoff phenomena which can cause gullies jepordize the stability of these forms.

The experimental square consists entirely of monticular sandy structures. This study shows its position to be downwind from all the other sandy structures. The section of monticular structures is found downstream from all other types of dunes.

Book II. Climatic Study of the Niger Republic /44

Chapter I. Study of Principal Climatic Parameters of the Niger Republic

Monthly Rainfall Norms from 1931 to 1960 (Fig. 13) /47

Rainfall norms are the precipatation averages over a period of 30 years. Fig. 13 shows the monthly precipatation levels for 6 stations in the Niger Republic (Maradi is station no. 5). The inset in the upper left hand corner shows the averages of the same stations over the same period of years with the annual number of the days of rain.

The precipitation profilesis comparable for all the stations. In general, the rains last from April to October, the maximum most often coming in August (except for Mainé Soroa).

Maradi and Gaya hold the records for amounts of water falling per day, (259.6 and 282 mm); Bilma holds the record for the smallest amount. Between the two we see a decrease from north to south, which speeds up after 15°N, and from west to east it speeds up after 10°E. Niamey has the greatest number of days of precipitation.

Specifically, there are three groups of graphs:

1. A group of 5 southernmost and westernmost stations (Tillabery, Niamey, Birni N'Konni, Maradi and Zinder). The amount

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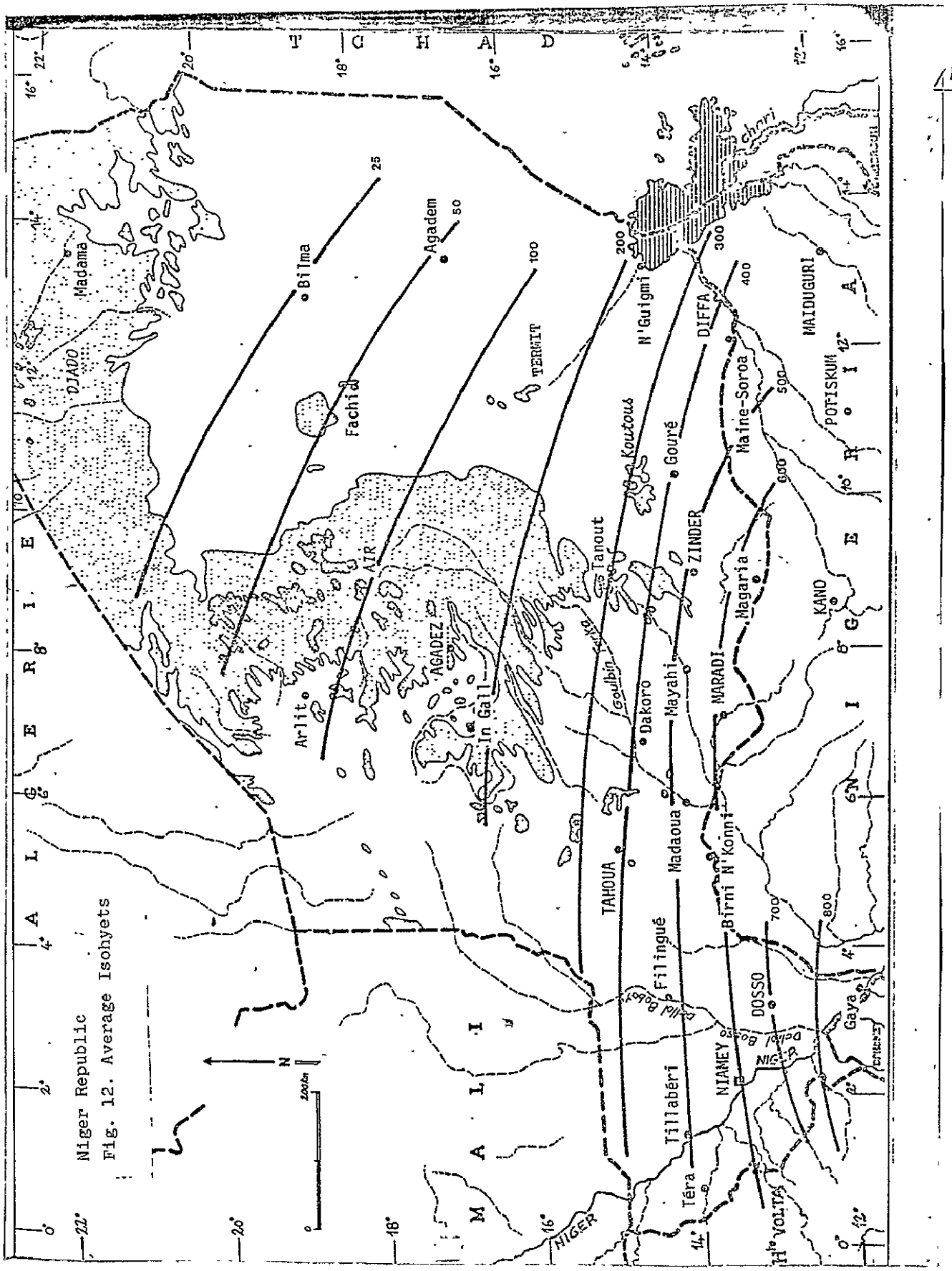

Fig 43. Rainfall Norms
- 1931 - 1960 -
Niger Republic
Annual
Monthly
1mm=4mm of precipitation
Bilma
Agadès
Tahoua
Zinder
Birni N'Konni
Maradi
Niamey
Tillabéri
Maine-Soroa
Nguigmi
Lac Tchad

of water in this area is large and the shape of the diagrams is identical with a maximum in August and a minimum in December. Note that there is a slight decrease for Zinder.

2. A group of 4 stations to the north and to the east (Tahoua, Mainé Soroa, N'Guigmi and Agadès), with a decrease in precipitation when the continentality and the latitude cross, from Tahoua to Mainé Soroa, to N'Guigmi and to Agadès. The length of the rainy season decreases at N'Guigmi and at Agadès (from May to October). At Mainé Soroa the maximum is in July.

3. A station in the northeast (Bilma). The amount of rain here is very small. Therrainy season stretches from April to October, but with insignificant amounts of water. It is in fact a desert station.

## K Rainfall Averages Compared (From 1956 to 1969) in the Maradi Region (Fig. 14) /50

Since we did not have any meteorological data for the experimental square we tried to set up the rainfall picture for the nearest possible region. To do this we calculated the averages of various stations having a minimum of 7 years of data. Thus we obtained the following values, listed in decreasing order: (1) Maraka 740 mm, (2) Maradi 625 mm, (3) Gazaoua 586 mm, (4) (4) Madaroumfa 572.9 mm, (5) Guidam Roumji 510 mm, (6) Mayahi 478 mm, (7) Tessaoua 477 mm, (8) Dakoró 419 mm.

Note that there is a reduction in rainfall from south to north (from 14-14°30'N) and, for the stations of the same latitude, from west to east.

Maraka: 1962 was marked by a drop in rainfall, but it is very regretable not to be able to make comparision with the years 1968 and 1969. The maximum occurred in 1964.

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Ascena
Meteorological Service
Niger Republic

Standard rainfall norms
(1931 - 1960 Average)

| Stations | | Jan. | Feb. | March | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AGADEZ | H | 0.2 | 0.1 | 0 | 1.2 | 6.4 | 8.2 | 49.2 | 78.3 | 20.0 | 0.5 | 0 | 0 | 164.1 |
| | J | 0.1 | 0 | 0 | 0.2 | 1.3 | 2.0 | 7.0 | 10.4 | 2.8 | 0.2 | 0 | 0 | 24.0 |
| BILMA | H | 0.2 | 0.1 | 0 | 0.1 | 0.5 | 0.8 | 2.2 | 11.4 | 3.6 | 1.7 | 0 | 0 | 20.6 |
| | J | 0.1 | 0 | 0 | 0.1 | 0.2 | 0.2 | 0.5 | 1.6 | 0.6 | 0.1 | 0 | 0 | 3.4 |
| BIRNI-N'KONNI | H | 0.5 | 0.1 | 0 | 2.3 | 29.0 | 71.9 | 138.0 | 231.5 | 111.3 | 13.0 | 0 | 0 | 597.4 |
| | J | 0.1 | 0 | 0 | 0.7 | 2.9 | 7.6 | 11.5 | 14.0 | 9.3 | 1.5 | 0 | 0 | 47.6 |
| GAYA | H | 0 | 0 | 3.9 | 14.3 | 70.0 | 112.4 | 205.3 | 282.0 | 156.6 | 24.3 | 2.0 | 0 | 870.8 |
| | J | 0 | 0 | 0.3 | 1.2 | 5.4 | 7.8 | 10.0 | 12.6 | 10.0 | 2.3 | 0.2 | 0 | 49.8 |
| MAINE-SOROA | H | 0 | 0.1 | 0.2 | 2.5 | 12.6 | 32.9 | 105.8 | 87.3 | 59.7 | 11.4 | 0 | 0 | 412.5 |
| | J | 0 | 0.1 | 0.1 | 0.4 | 2.3 | 4.9 | 10.3 | 13.0 | 6.7 | 2.0 | 0 | 0 | 39.8 |
| MARADI | H | 0 | .0 | 0.1 | 3.9 | 32.4 | 60.4 | 103.5 | 259.6 | 110.4 | 12.0 | 0 | 0 | 642.3 |
| | J | 0 | 0 | 0.1 | 0.7 | 3.7 | 6.3 | 11.1 | 14.7 | 9.8 | 1.4 | 0 | 0 | 47.8 |
| N'GUIGMI | H | 0 | 0 | 0 | 0 | 6.7 | 8.3 | 57.3 | 140.8 | 22.4 | 0.3 | 0 | 0 | 235.8 |
| | J | 0 | 0 | 0 | 0 | 1.0 | 0.9 | 5.2 | 9.8 | 2.9 | 0.1 | 0 | 0 | 19.9 |
| NIAMEY - AERO (1946-1970) - (1944-1973) | H | 0 | 0 | 1.0 -1.7 | 5.9 -5.7 | 23.2 | 60.1 | 139.1 | 205.9 | 92.6 | 13.6 | 1.1 | 0 | 543.0 |
| | J | 0 | 0 | 0.4 | 1.0 | 4.1 | 8.5 | 13.0 | 16.6 | 10.6 | 2.4 | 0.8 | 0 | 57.4 |
| TAHOUA | H | 0.5 | 0 | 0.3 | 2.3 | 17.6 | 44.9 | 117.4 | 143.8 | 66.1 | 14.3 | 0 | 0 | 407.2 |
| | J | 0 | 0 | 0.1 | 0.7 | 2.7 | 6.5 | 10.8 | 13.3 | 7.9 | 1.5 | 0 | 0 | 43.5 |
| TILLABERY | H | 10 | 2.0 | 2.0 | 1.4 | 17.9 | 55.4 | 131.9 | 203.3 | 85.6 | 10.8 | 0.2 | 0 | 509.5 |
| | J | 0 | 0.1 | 0.1 | 0.4 | 3.0 | 6.4 | 10.9 | 13.2 | 7.9 | 1.6 | 0.1 | 0 | 40.7 |
| ZINDER | H | 0 | 0 | 0 | 3.1 | 27.3 | 54.7 | 153.1 | 232.4 | 71.4 | 6.7 | 0.4 | 0 | 549.1 |
| | J | 0 | 0 | 0 | 0.3 | 3.5 | 6.3 | 11.3 | 14.0 | 7.8 | 0.9 | 0.1 | 0 | 44.2 |
| NIAMEY-VILLE | H | 0 | 0.2 | 0.8 | 5.7 | 37.7 | 71.0 | 138.6 | 201.3 | 94.1 | 14.3 | 0.8 | 0 | 566.5 |
| | J | 0 | 0.1 | 0.4 | 0.9 | 4.6 | 7.3 | 11.4 | 15.1 | 9.1 | 2.2 | 0.1 | 0 | 51.2 |

H= Amount to the nearest 1/10 of a mm
J= Number of days of rain

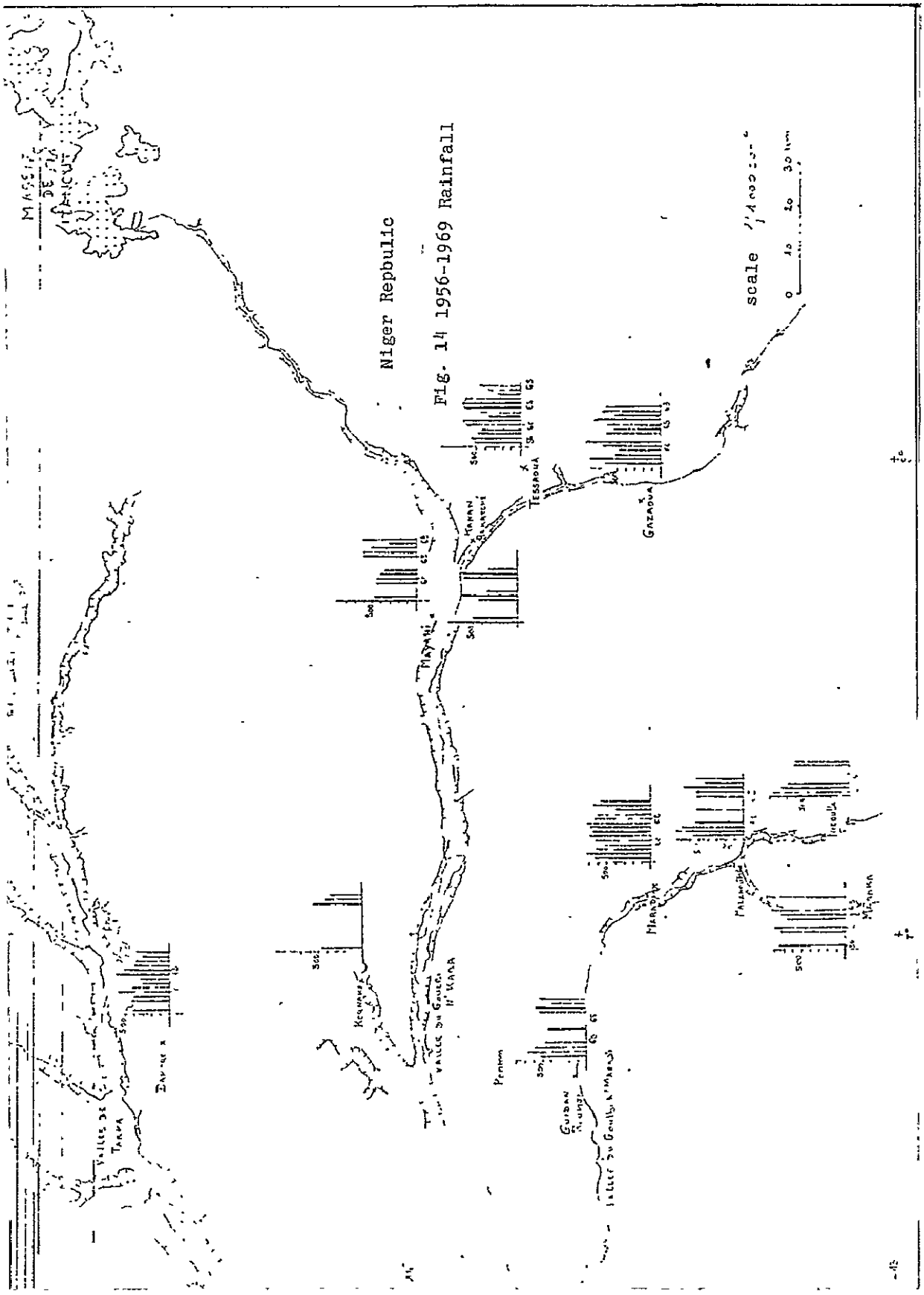


Fig. 14 1956-1969 Rainfall

Maradi: Distinct drop in 1967 (362 mm) while the 30-year average, from 1931 to 1960, is 642.3 mm. The maximum, 730 mm, occured in 1964,

Gazaoua: The minimum occured in 1959 (485 mm), with two additional years of deficient rainfall (1958 and 1967). The maximum (845 mm) was recorded in 1961. One can see a very large difference between the years 1957, 1958 and 1966, 1967.

Madaroumfa: A minimum of 424 mmswas recorded in 1968 and a maximum of 743 mm in 1957.

Guidam Roumji: Two years of light precipitation, one in 1962 (410 mm), and the other, clearly more pronounced, in 1968 (381 mm). In 1957 a maximum of 649 mm was recorded.

Mayahi: An initial minimum of 362 mm was recorded in 1962 and a second one, more pronounced, in 1968 (336mm). Because of the gaps in the data we could not consider the 1965 maximum as meaningful.

Tessaoua: The minimum which marks the year 1967 is remarkable. It occured suddenly after a well watered period (1963-1966) which in turn followed the 19622minimum. The rise in 1968-1969 is very gradual. The maximum (647 mm) was observed in 1961.

Dakoro: Again two minimums, this time very comparable. They are for 1962 (281 mm) and 1968 (294 mm). The maximum occurred in 1964 (605 mm).

Nieoulla and Kanan Bakatché: The small amount of data supplied for these two stations requires us to be cautious in making any sorthof interpretation. For Nieoulla there is no significant minimum, and for Kanan Bakatché there are two important minimums

in 1962 (319 mm) and 1967 (331 mm). The maximums are even more difficult to detect.

As a general rule, for this region we note the existence of two minimum periods: 1962 and 1967-68, and two maximum periods: 1960-61 and 1964.

Niger Republic /51

Comparative Rainfall (1956-1965)

Taken from the annual report of 1969 of the Agricultural Service, Department of Maradi, Ministry of Rural Economy.

| | 1956 | 1957 | 1958 | 1959 | 1960 | 1961 | 1962 | 1963 | 1964 | 1965 | 1966 | 1967 | 1968 | 1969 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TESSAOUA | 503 | 555 | 495 | 415 | 609 | 647 | 346 | 449 | 635 | 643 | 561 | 220 | 350 | 458 |
| GAZAOUA | 636 | 797 | 523 | 485 | 660 | 845 | | 610 | 517 | 590 | 756 | 523 | 665 | 595 |
| MADAROUNFA | 570 | 743 | 696 | 542 | | | 525 | | | 515 | 537 | 665 | 424 | 512 |
| NIEOULLA | 842 | 756 | 581 | | | | 592 | 597 | | | | | | |
| GUIDAN ROUM | 510 | 649 | 568 | 462 | | | 410 | | | | 521 | 570 | 381 | 520 |
| DAKORO | 402 | | 438 | 399 | 574 | 431 | 281 | 339 | 605 | 524 | 392 | 399 | 294 | 378 |
| MARAKA | 740 | | | 719 | 787 | | 653 | 718 | 835 | | | 732 | | |
| MAYAHI | 478 | | | 451 | 446 | 400 | 362 | | | 603 | 594 | 509 | 336 | 601 |
| KANAN BAKATCHE | 495 | | | | 435 | 621 | 319 | | | 609 | 656 | 331 | | |
| KORNAKA | 452 | | | | | | | | | | 547 | 412 | 360 | |
| MARADI | 630 | 736 | 625 | 537 | 616 | 697 | 643 | 667 | 730 | 630 | 595 | 362 | 641 | 641 |

Normal Temperatures from 1951 to 1970 (Fig. 15) /53

Normal temperature is what we call the average of temperatures over a 30-year period.

For all of the stations the maximum temperatures have two minimums, in August (31°-33°) and in January (29°-33°), and two maximums in April or in May-June depending on the stations and in September-October (36°-38°).

The minimum temperatures also have two minimums. The August minimum drops much less than the August maximum, and the December or January minimum is just as pronounced.

The temperature decreases from May to August. It increases in the months of January, February and March and from October to December. The increase is more pronounced for the two most continental stations.(Bilma and N'Guigmi).

Four groups of graphs can be distinguished:

1. A group of two stations (Zinder and Niamey) for which the maximum of the minimum temperatures occurs in October. It is much more pronounced than for the other stations.

2. Aggroup of five stations (Tillaber, Tahoua, Birni N'Konni, Maradi and Mainé Soroa) whose graphs are nearly identical, reflecting the general tendencies mentioned above.

3. A group of two stations (N'Guigmi and Agadès) which have identical graphs, with a maximum temperature maximum in May-June and a second maximum temperature maximum in September. Nevertheless, they differ in the second maximum temperature maximum, which comes in October for N'Guigmi and in September for Agadès. Another difference is found in the maximum temperatures, which are

greater for Agades.

4. The Bilma station is a special case. On the one hand, the maximum temperatures there are greater, and on the other hand the second minimum (that which corresponds to the rainy seaseon) disappeared thus giving only a single maximum occuring in May-September for the maximum temperatures and between June and August for the minimum temperatures.

Average Evaporation from 1961 to 1970 (Fig. 17). /58

General Outline of the Curve:

Two maximums in March or April (Depending on the stations), and two minimums in October or November, one in the rainy season (August) and the other in the dry season (December and January) characterize the Sahel of the Niger Rebpublic.

Three groups of stations can be distinguished:

1. One groupscombines 5 stations (N'Guigmi, Mainé Soroa, Zinder, Tahoua and Birni N'Konni) which, in spite of differences in intensity, have very similar curves with two maximums in March and November and two minimums in August and December-January. The maximum evaporation increases with continentality towards the east (Zinder, Mainé Soroa and N'Guigmi) and towards the arid region in the north (Tahoua).

2. One group combines 3 stations (Maradi, Tillabery and Niamey). Up until August the curves for all 3 stations do not show any unusual features. Then, the November maximum is erased and the December minimum no longer exists because evaporation is greater in December than in October and November.

3. One group of desert-type stations (Bilma and Agadès) where

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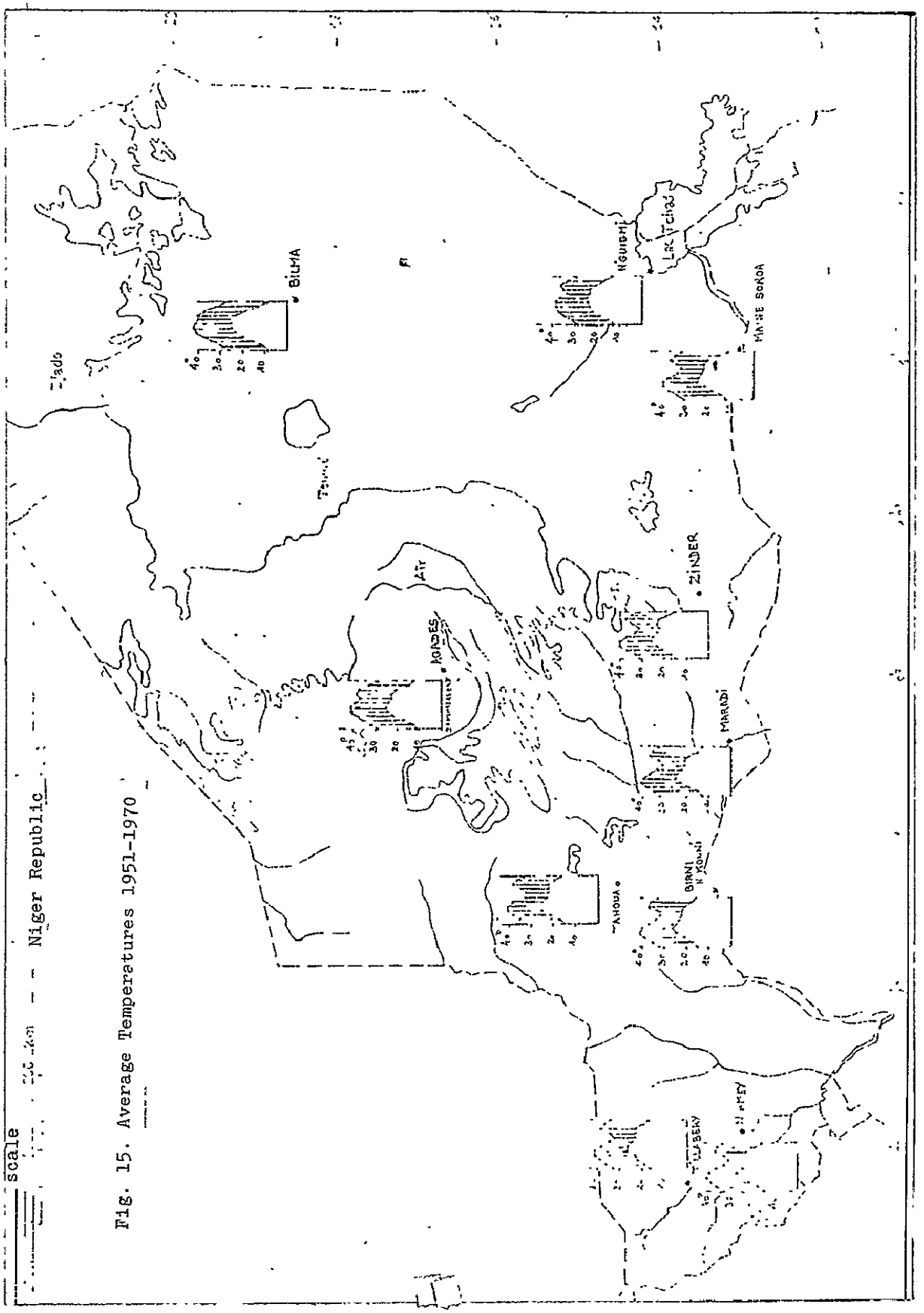


Fig. 15. Average Temperatures 1951-1970

Niger Republic
ASECNA
Meteorological Service

Normal Temperatures
to the nearest 1/10 °C
1951-1970

| STATIONS | | Jan. | Feb. | March | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AGADEZ | Average maximum temperatures | 29.2 | 32.1 | 36.0 | 39.6 | 41.2 | 41.6 | 39.1 | 37.0 | 38.6 | 37.8 | 33.5 | 29.7 |
| BILMA | | 26.3 | 29.8 | 33.9 | 38.4 | 41.1 | 42.2 | 41.0 | 39.9 | 39.9 | 37.2 | 32.0 | 27.9 |
| BIRNI-N'KONNI | | 32.6 | 35.6 | 39.1 | 40.9 | 40.1 | 37.2 | 33.8 | 31.7 | 33.5 | 37.0 | 36.1 | 33.2 |
| MAINE-SOROA | | 31.0 | 33.8 | 37.8 | 40.5 | 40.6 | 38.4 | 34.5 | 32.0 | 34.8 | 37.1 | 34.9 | 31.7 |
| MARADI | | 31.6 | 34.8 | 38.1 | 40.3 | 39.5 | 36.7 | 32.9 | 30.7 | 32.8 | 36.0 | 34.9 | 32.2 |
| N'GUIGMI | | 28.9 | 31.3 | 35.2 | 37.5 | 38.7 | 38.3 | 36.1 | 33.3 | 35.3 | 35.9 | 32.8 | 29.6 |
| NIAMEY-AERO | | 33.5 | 36.3 | 39.4 | 40.9 | 40.0 | 36.7 | 33.6 | 31.5 | 33.3 | 37.3 | 36.8 | 33.9 |
| TAHOUA | | 32.1 | 35.0 | 38.4 | 40.8 | 40.6 | 38.3 | 34.6 | 32.3 | 34.5 | 37.9 | 35.9 | 32.7 |
| TILLABERY | | 33.5 | 36.2 | 39.4 | 41.3 | 41.1 | 38.2 | 34.7 | 32.7 | 34.4 | 38.1 | 37.1 | 33.9 |
| ZINDER | | 30.5 | 33.4 | 37.4 | 40.0 | 39.9 | 37.7 | 33.6 | 31.3 | 34.1 | 37.1 | 34.5 | 31.4 |
| AGADEZ | Average minimum temperatures | 11.3 | 13.3 | 17.4 | 22.1 | 24.5 | 25.5 | 23.9 | 23.0 | 23.0 | 20.6 | 14.9 | 12.6 |
| BILMA | | 8.6 | 10.7 | 15.3 | 20.0 | 23.0 | 24.4 | 25.1 | 25.8 | 23.1 | 18.6 | 13.2 | 9.4 |
| BIRNI-N'KONNI | | 15.5 | 17.6 | 21.3 | 24.7 | 26.2 | 25.1 | 23.3 | 22.3 | 22.3 | 21.0 | 17.9 | 15.9 |
| MAINE-SOROA | | 12.6 | 14.8 | 19.3 | 21.8 | 24.7 | 24.4 | 23.0 | 21.9 | 22.0 | 20.3 | 16.8 | 11.8 |
| MARADI | | 12.7 | 15.0 | 19.0 | 23.2 | 24.9 | 24.1 | 22.3 | 21.5 | 21.6 | 19.2 | 15.6 | 12.8 |
| N'GUIGMI | | 12.7 | 14.7 | 19.1 | 21.9 | 23.8 | 24.4 | 24.2 | 23.3 | 22.9 | 20.5 | 16.6 | 13.0 |
| NIAMEY-AERO | | 15.7 | 18.2 | 22.3 | 26.3 | 27.2 | 25.3 | 23.5 | 22.6 | 23.0 | 23.2 | 19.0 | 16.1 |
| TAHOUA | | 15.3 | 17.5 | 21.7 | 25.3 | 26.7 | 25.4 | 23.4 | 22.6 | 22.8 | 22.4 | 19.0 | 16.1 |
| TILLABERY | | 16.6 | 19.1 | 22.0 | 23.3 | 27.1 | 26.0 | 24.1 | 23.3 | 23.6 | 23.4 | 19.3 | 17.4 |
| ZINDER | | 14.8 | 17.1 | 21.5 | 22.8 | 25.8 | 24.8 | 23.0 | 21.9 | 22.5 | 22.1 | 18.6 | 15.5 |

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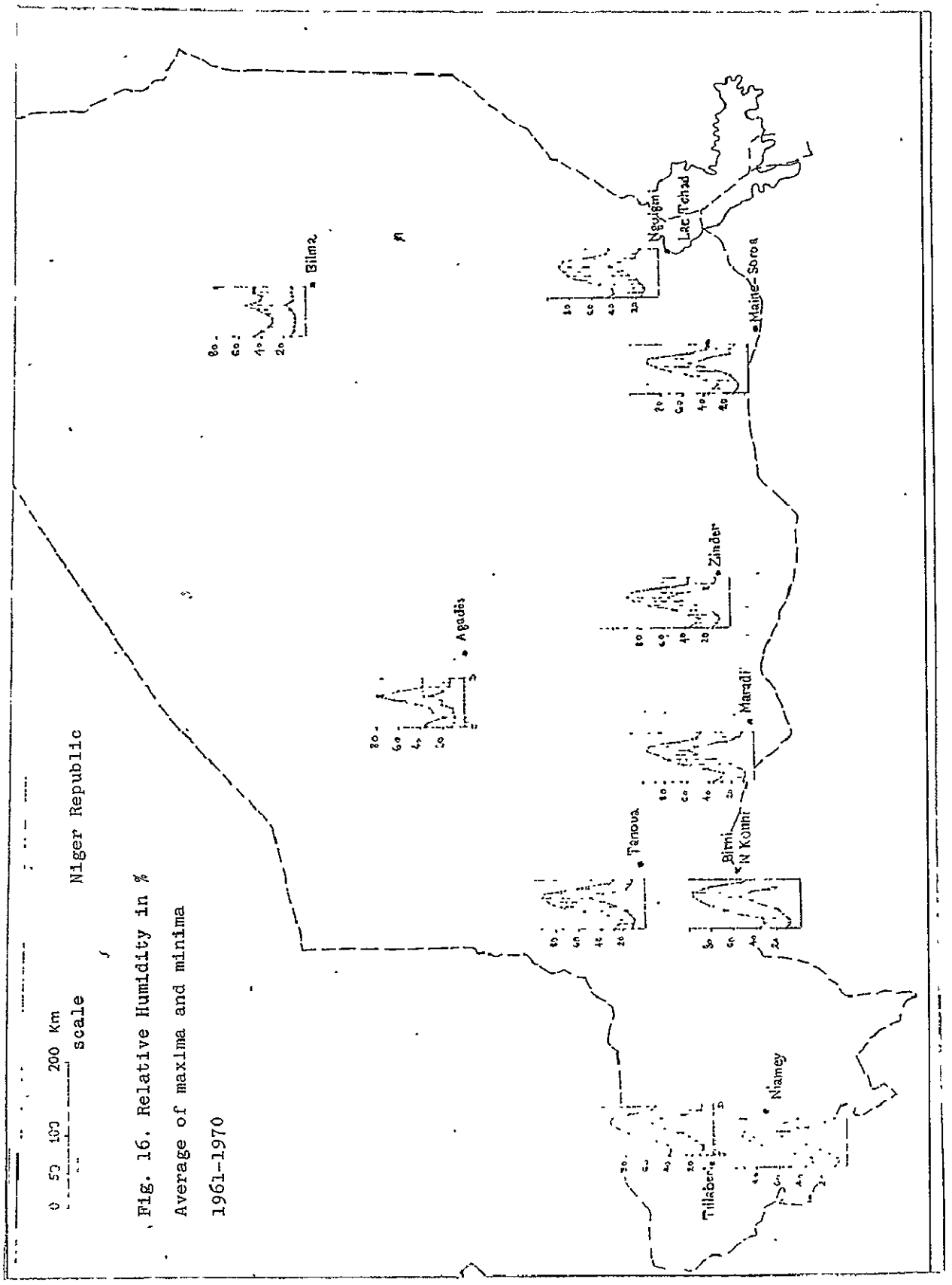


Fig. 16. Relative Humidity in %

Average of maxima and minima

1961-1970

Niger Republic

A.S.E.C.N.A.

Meteorological Service

Relative Humidity in %[1]

Average Maximum and Minimum

1961-1970

| STATIONS | | Jan. | Feb. | March | Apr. | May | June | July | Aug | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AGADEZ | Average maximum humidity in % | 36 | 31 | 19 | 29 | 33 | 45 | 64 | 79 | 60 | 38 | 37 | 37 |
| BILMA | | 46 | 40 | 33 | 29 | 29 | 33 | 42 | 53 | 41 | 39 | 46 | 45 |
| BIRNI N'KONNI | | 36 | 31 | 35 | 51 | 67 | 82 | 89 | 95 | 95 | 82 | 52 | 45 |
| MAINE-SOROA | | 36 | 31 | 27 | 38 | 51 | 70 | 83 | 91 | 90 | 59 | 38 | 37 |
| MARADI | | 36 | 30 | 27 | 45 | 63 | 80 | 86 | 95 | 94 | 82 | 51 | 44 |
| N'GUIGMI | | 45 | 40 | 42 | 53 | 70 | 81 | 85 | 89 | 86 | 64 | 47 | 45 |
| NIAMEY-AERODROME | | 37 | 31 | 32 | 47 | 64 | 76 | 87 | 93 | 91 | 76 | 55 | 44 |
| TAHOUA | | 28 | 24 | 22 | 33 | 54 | 75 | 86 | 92 | 90 | 57 | 32 | 28 |
| TILLABERY | | 41 | 39 | 42 | 52 | 64 | 77 | 86 | 93 | 91 | 76 | 57 | 53 |
| ZINDER | | 36 | 30 | 27 | 37 | 51 | 73 | 86 | 92 | 87 | 56 | 38 | 38 |
| AGADEZ | Average minimum humidity in % | 12 | 10 | 9 | 10 | 11 | 21 | 21 | 30 | 19 | 14 | 13 | 13 |
| BILMA | | 13 | 10 | 9 | 8 | 8 | 9 | 13 | 16 | 11 | 11 | 12 | 12 |
| BIRNI-N'KONNI | | 12 | 9 | 10 | 15 | 19 | 31 | 42 | 53 | 45 | 22 | 14 | 14 |
| MAINE-SOROA | | 13 | 10 | 9 | 12 | 16 | 26 | 40 | 52 | 38 | 17 | 13 | 13 |
| MARADI | | 9 | 7 | 7 | 13 | 20 | 34 | 51 | 58 | 50 | 24 | 12 | 10 |
| N'GUIGMI | | 17 | 15 | 13 | 17 | 19 | 26 | 33 | 44 | 34 | 21 | 19 | 17 |
| NIAMEY-AERODROME | | 11 | 8 | 9 | 15 | 24 | 36 | 48 | 58 | 51 | 30 | 15 | 13 |
| TAHOUA | | 11 | 10 | 9 | 12 | 16 | 26 | 37 | 49 | 38 | 16 | 12 | 11 |
| TILLABERY | | 12 | 10 | 10 | 15 | 22 | 33 | 45 | 55 | 47 | 26 | 15 | 14 |
| ZINDER | | 15 | 11 | 9 | 13 | 17 | 30 | 43 | 55 | 42 | 19 | 14 | 13 |

1. Percentage of saturation of the air or ratio between the actual amount of water vapor in a given volume of air and the possible amount in the same volume at the same temperature.

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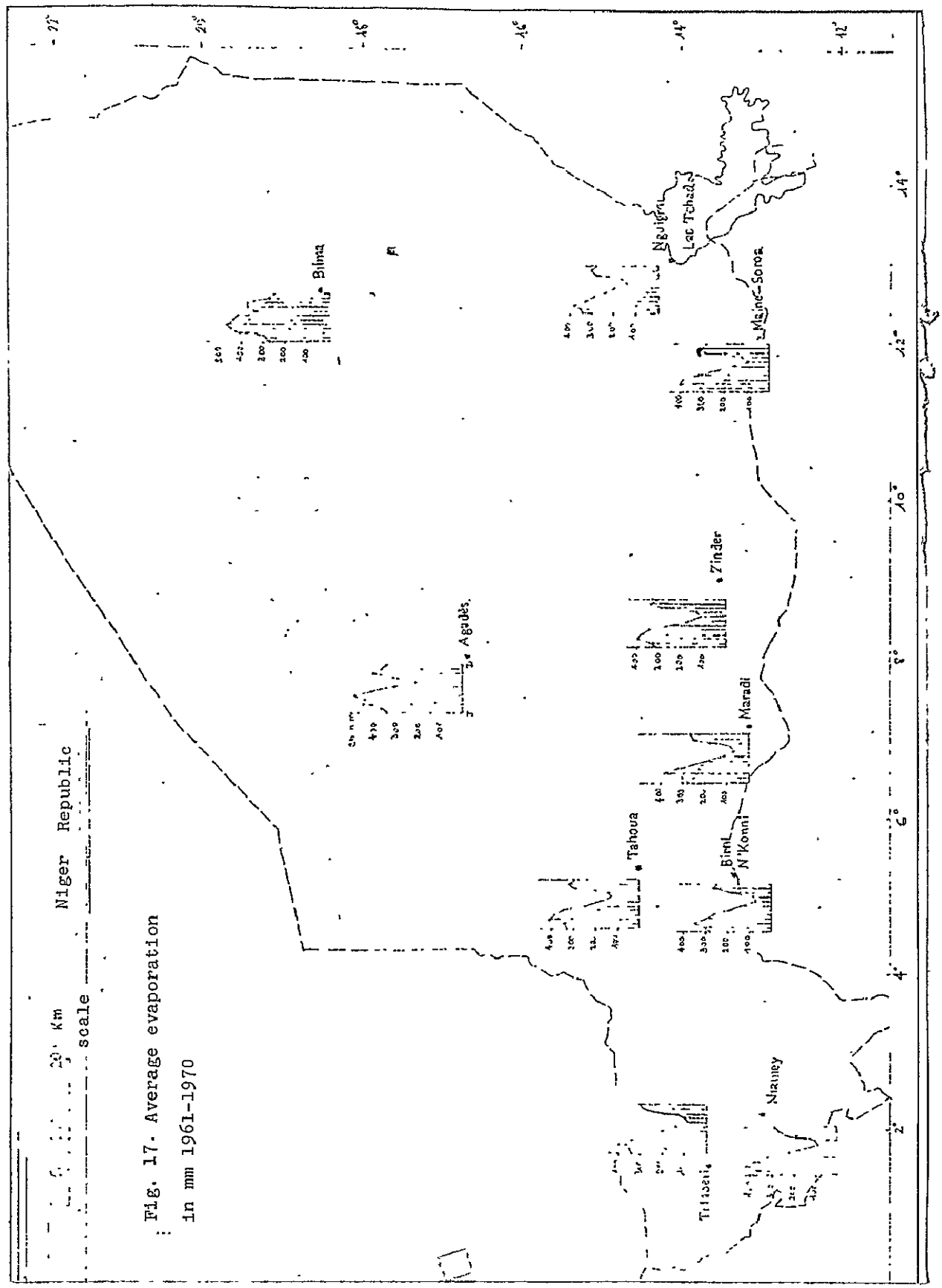


Fig. 17- Average evaporation

in mm 1961-1970

Niger Republic
ASECNA
Meteorological Service

# Evaporation and Insolation Averages

1961-1970

| STATIONS | | Jan. | Feb. | March | April | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AGADEZ | Evaporation in m/m (Piche) | 349 | 374 | 458 | 449 | 492 | 416 | 314 | 212 | 321 | 412 | 372 | 352 |
| BILMA | | 274 | 287 | 409 | 451 | 465 | 440 | 406 | 328 | 373 | 368 | 267 | 253 |
| BIRNI N'KONNI | | 282 | 303 | 349 | 300 | 260 | 186 | 119 | 71 | 83 | 104 | 257 | 254 |
| KAINE-SOROA | | 272 | 311 | 396 | 389 | 313 | 239 | 149 | 87 | 120 | 278 | 299 | 279 |
| MARADI | | 276 | 303 | 377 | 318 | 256 | 174 | 107 | 67 | 79 | 170 | 245 | 254 |
| N'GUIGMI | | 324 | 327 | 374 | 326 | 288 | 241 | 200 | 141 | 160 | 276 | 299 | 287 |
| NIAMEY-AERODROME | | 317 | 363 | 422 | 381 | 317 | 219 | 145 | 87 | 104 | 227 | 264 | 284 |
| TAHOUA | | 329 | 356 | 409 | 392 | 349 | 253 | 180 | 126 | 142 | 291 | 320 | 300 |
| TILLABERY | | 334 | 353 | 401 | 337 | 291 | 201 | 142 | 88 | 99 | 198 | 290 | 294 |
| ZINDER | | 312 | 327 | 402 | 380 | 349 | 235 | 165 | 108 | 134 | 298 | 338 | 314 |
| AGADEZ | Insolation time in hours (Cambell Heliograph) | 293 | 280 | 293 | 266 | 307 | 278 | 303 | 281 | 283 | 273 | 299 | 290 |
| BILMA | | 298 | 280 | 307 | 287 | 335 | 325 | 339 | 328 | 313 | 318 | 306 | 300 |
| BIRNI N'KONNI | | 293 | 277 | 283 | 257 | 297 | 285 | 268 | 224 | 260 | 302 | 297 | 300 |
| KAINE-SOROA | | 286 | 276 | 327 | 390 | 400 | 366 | 313 | 285 | 335 | 362 | 326 | 278 |
| MARADI | | 282 | 265 | 269 | 241 | 294 | 286 | 260 | 222 | 251 | 293 | 280 | 278 |
| N'GUIGMI | | 290 | 283 | 278 | 259 | 299 | 282 | 267 | 238 | 260 | 304 | 295 | 302 |
| NIAMEY-AERODROME | | 318 | 269 | 281 | 243 | 282 | 257 | 260 | 219 | 242 | 288 | 292 | 289 |
| TAHOUA | | 280 | 266 | 256 | 215 | 253 | 259 | 283 | 253 | 251 | 288 | 282 | 285 |
| TILLABERY | | 295 | 262 | 281 | 247 | 294 | 264 | 261 | 239 | 243 | 283 | 282 | 288 |
| ZINDER | | 292 | 279 | 281 | 259 | 302 | 292 | 270 | 236 | 268 | 297 | 292 | 301 |

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the evaporation is greatest with two maximums,=in May and October, and two minimums, in August and January at Agadès and in Decemberrat Bilma. Nevertheless, differences appear. For Bilma the August minimum is less than the December minimum (the reverse is true for Agadès); the Bilma curve is smoother than the Agades curve.

For August the evaporation minimums correspond to the precipitation maximum and the temperature minimum, and for December-Januaryythey correspond to the single temperature minimum.

For November, the evaporations maximums correspond to an initial temperature maximum in the dry season, and for March they correspond to a second temperature increase in the dry season. (The May and October shift for Bilma and Agadès is explained by the temperature curves, which are likewise shifted for these two stations.)

Chpt. II. Study of Winds in the Niger Republic /60

1. Prevailing Annual Directions of Winds in the Niger Repbulic (Fig. 18)

The prevailing winds are divided into 2 regions: (1) a NNE-ENE regionscorresponding to the Harmattan and a SW regions corresponding to the monsoon.

1. The Harmattan

Its frequency is hardly seen to diminish as a function of latitude and longitude. Tahoua receives a harmattan equivalent ot that which is received by Bilma in spite of a difference in longitude of 8°. Bilma, N'Guigmi and Niamey, which differ in latitude by 6°, receive equally frequent amounts of harmattan.

This map reveals three different circulation paths for the harmattan:

a) the Sahara stations of Bilma and Agades receive a harmattan from the NE. This is a barely deflected continental trade wind, or, if there is deflection, it is due to the Tibesti massif.

b) The direction of the harmattan which arrives at Tahoua and N'Guigmi has a much more southerly direction. Its NNE direction results from the trade wind being channeled at Tahoua between north of Aïr and louth of Hoggar and at N'Guigmin between north of Djado and the northwest point of the Tibests.

c) The Sahel stations of Niamey, Birni N'Konni, Maradi and Zinder a harmattan with a much more regional tendency which is accentuated from Niamey to Zinder.

## 2. The Winds of the Rainy Season

The monsoon decreases very distinctly and uniformly from Niamey to N'Guigmi. With the exception of the Zinder station its direction in all places is SW. With respect to the monsoon Tahoua is like Niamey, but with respect to the harmattan it is like Zinder and N'Guigmi. One can thus conclude that between Maradi and Zinder a change in the wind patters occurs.

We think that the Mayahi-Tchadaoua experimental unit has /61 roughly the same wind characteristics as Maradi, which is very important for the installations of wind breaks. If the installation of wind breaks is recommended, these will have a NW direction which fortunately is found to be both perpendicular to the harmattan and perpendicular to the effective wind which is not insignificant at the beginning of the rainy season, since the harmattan and monsoon follow roughly the same line but in opposite directions.

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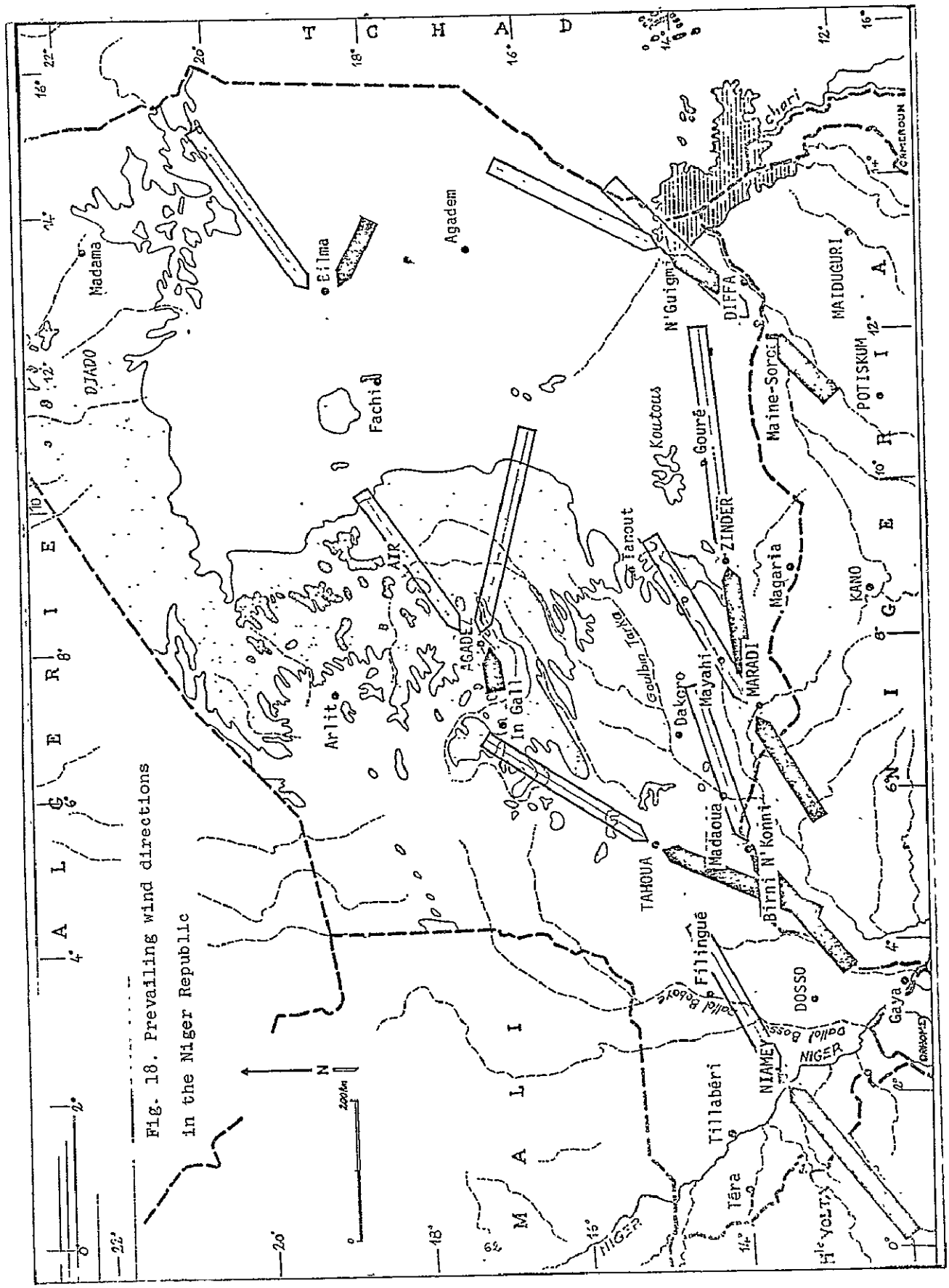
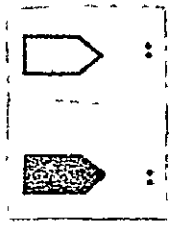



Fig. 18. Prevailing wind directions in the Niger Republic

Legend



: 200 observations for the dry season winds

: 200 observations for the rainy season winds

Average Annual Number of Prevailing Winds in the Niger Republic

| STATION | Years | Prevailing Direction | Average Number of winds |
|---|---|---|---|
| AGADES | 1966 à 1975 | Nord-Est NE | 811 |
| AGADES | 1966 à 1975 | Sud-Est SE | 1167 |
| AGADES | 1966 à 1975 | Sud-Ouest SW | 239 |
| BILMA | 1966 à 1971- 1975 | Nord-Est NE | 932 |
| BILMA | 1966 à 1971- 1975 | Sud-Est SE | 352 |
| BIRNI N'KONNI | 1966 à 1975 | Nord-Est NE | 816 |
| BIRNI N'KONNI | 1966 à 1975 | Sud-Ouest SW | 710 |
| MAINE SOROA | 1966 à 1971- 1975 | Nord-Est NE | 913 |
| MAINE SOROA | 1966 à 1971- 1975 | Sud-Ouest SW | 430 |
| MARADI | 1966 à 1975 | Nord-Est NE | 924 |
| MARADI | 1966 à 1975 | Sud-Ouest SW | 582 |
| N'GUIGMI | 1966 à 1975 | Nord-Est NE | 908 |
| N'GUIGMI | 1966 à 1975 | Sud-Ouest SW | 509 |
| NIAMEY | 1966 à 1975 | Nord-Est NE | 822 |
| NIAMEY | 1966 à 1975 | Sud-Ouest SW | 902 |
| TAHOUA | 1966 à 1975 | Nord-Est NE | 924 |
| TAHOUA | 1966 à 1975 | Sud-Ouest SW | 825 |
| ZINDER | 1966 à 1975 | Nord-Est NE | 1123 |
| ZINDER | 1966 à 1975 | Sud-Ouest SW | 511 |

3. The Winds of the Southeast

Bilma and predominantly Agades receive winds from the SE. We donnot yet have any explanation for these winds.

4. The Regional Tendency of the Harmattan and Monsoon At Maradi

How are we to explain this deflection between N'Guigmi and Maradi? Can it be due to the presence of the line of obstacles formed by the Air and the sedimentary haloes which extended to the south; namely, the Koutous and Tanout massifs?

2. Monthly Prevailing Wind Directions in the Niger Republic (Figs. 19-30) /65

The study of annual prevailing wind directions in the Niger Repbulic was supplemented by a study of monthly winds. The reason for this was to provide a rigorous study for a protection program against wind erosion.

In January, February and March the Niger Repbulic is affected only by winds from the NE, with the exception of Agadès which receives winds from the SE during the entire year with maximums from December to May. In March the westernmost stations (Niamey and Tahoua) receive the first incursion of the monsoon. This tendency asserts itself in April when the winds from the SW then spread out through the entire Sahel region of the Niger Republic. The monsoon still does not reach Agadès. In May the harmattan dies out persisting at a longitude only up to Maradi. Tahoua still receives a little of it because of its latitude. The harmattan finally disappears. In May Agadès receives the first puffs of the monsoon which has been established. In June the above trends assert themselves: the trade wind stops at the latitude of Zinder and the longitude of Agadès. Niamey and Tahoua

receive the strongest monsoon. In July and August the harmattan reaches no further than N'Guigmi. The flow is from the prevailing SW quadrant up until September when the situation reverses itself agains with the monsoon dying out and a trade wind reappearing further south, at Tahoua and further west, at Zinder. In October the situation of April seems to reproduce itself with a weakening monsoon which no longer reaches Agadès and a trade wind which again becomes predominant, reaching Niamey. Zinder presents a special case. There is no longer any monsoon in October, while at N'Guigmi it is still blowing. This is probably due to the direction and the existence of an obstacle. At Zinder the monsoon is nearly east-west which causes it to cross the Ader Doutchi, and its crossing manages to extinguish its lasts puffs earlier than at N'Guigmi which, however is further away. Because of its SW direction it does not encounter any obstacles. From November to February the prevailing trade wind blows, diminishing towards the south and west. At Bilma, in December, winds blow from the SW which are difficult to explain.

In summary, an examination of these monthly winds allows us:

1. To distinguish different stations of the Sahara as a result of the direction of the monsoon current and because of obstacles.

2. To note a progression from east to west, from N'Guigmi to Niamey, with a transition between Zinder and Maradi. In some respects Tahoua is similar to Zinder and N'Guigmi because of its latitude. It receives the trade wind earlier than Niamey, Birni /66
N'Konni and Maradi, but it keeps characteristics of a western station in receiving the monsoon earlier than Birni N'Konni, Mar Maradi, Zinder and N'Guigmi.

3. To point out the transition months: April and October.

4. To see the remarkable separation between two six-month seasons, from January to August and from September to December [sic].

5. To better grasp the importance of the relationship between wind directions and the arrangement of surrounding obstacles.

Monthly Average of the Number of Prevailing Winds in the Niger Republic

| STATION | Years | Sector | Average No. of Monthly Wind Readings | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | J | F | M | A | M | J | J | A | S | O | N | D |
| AGADES | 1966/75 | NE | 77 | 64 | 88 | 78 | 69 | 67 | 38 | 23 | 50 | 89 | 99 | 93 |
| AGADES | 1966/75 | SE | 115 | 109 | 117 | 104 | 117 | 82 | 44 | 51 | 95 | 99 | 128 | 110 |
| AGADES | 1966/75 | SW | 1.6 | 5.2 | 8.1 | 14 | 22 | 33 | 67 | 56 | 28 | 7 | 3 | 2 |
| BILMA | 66/71 -75 | NE | 96 | 85 | 101 | 75 | 62 | 58 | 54 | 53 | 67 | 89 | 83 | 90 |
| BILMA | 66/71 -75 | SE | 11 | 15 | 26 | 35 | 49 | 43 | 34 | 34 | 36 | 26 | 19 | 20 |
| BIRNI N' | 1966/75 | NE | 159 | 133 | 115 | 56 | 17 | 9 | 7 | 9 | 12 | 43 | 115 | 136 |
| BIRNI N' | 1966/75 | SW | 0.2 | 1.7 | 13 | 55 | 107 | 142 | 156 | 121 | 89 | 35 | 1.4 | 1 |
| MAINE SO | 66/71 -75 | NE | 130 | 115 | 120 | 82 | 50 | 27 | 5 | 5 | 18 | 100 | 128 | 127 |
| MAINE SO | 66/71 -75 | SW | 0 | 0 | 3 | 20 | 48 | 69 | 99 | 97 | 74 | 16 | 0.4 | 0.2 |
| MARADI | 1966/75 | NE | 165 | 127 | 118 | 74 | 29 | 10 | 5 | 8 | 8 | 74 | 156 | 155 |
| MARADI | 1966/75 | SW | 1 | 2 | 12 | 43 | 86 | 93 | 120 | 90 | 75 | 27 | 12 | 16 |
| N'GUIGMI | 1966/75 | NE | 123 | 122 | 91 | 67 | 41 | 32 | 29 | 41 | 27 | 61 | 130 | 143 |
| N'GUIGMI | 1966/75 | SW | 5 | 5 | 9 | 21 | 56 | 71 | 97 | 99 | 87 | 31 | 14 | 2 |
| NIAMEY | 1966/75 | NE | 188 | 140 | 110 | 56 | 17 | 8.1 | 7.1 | 9 | 10 | 34 | 109 | 139 |
| NIAMEY | 1966/75 | SW | 1.2 | 3.6 | 20 | 71 | 142 | 154 | 158 | 135 | 113 | 92 | 8.7 | 2.1 |
| TAHOUA | 1966/75 | NE | 185 | 151 | 132 | 90 | 44 | 18 | 7 | 10 | 20 | 84 | 146 | 161 |
| TAHOUA | 1966/75 | SW | 1.8 | 5.5 | 24 | 54 | 104 | 140 | 172 | 153 | 120 | 42 | 5.4 | 4.5 |
| ZINDER | 1966/75 | NE | 174 | 143 | 134 | 97 | 50 | 22 | 8 | 7 | 21 | 112 | 170 | 167 |
| ZINDER | 1966/75 | SW | 0.7 | 1.1 | 7 | 26 | 55 | 95 | 139 | 108 | 63 | 11 | 1.2 | 1 |

Fig. 19. Prevailing wind directions in the Niger Republic in January

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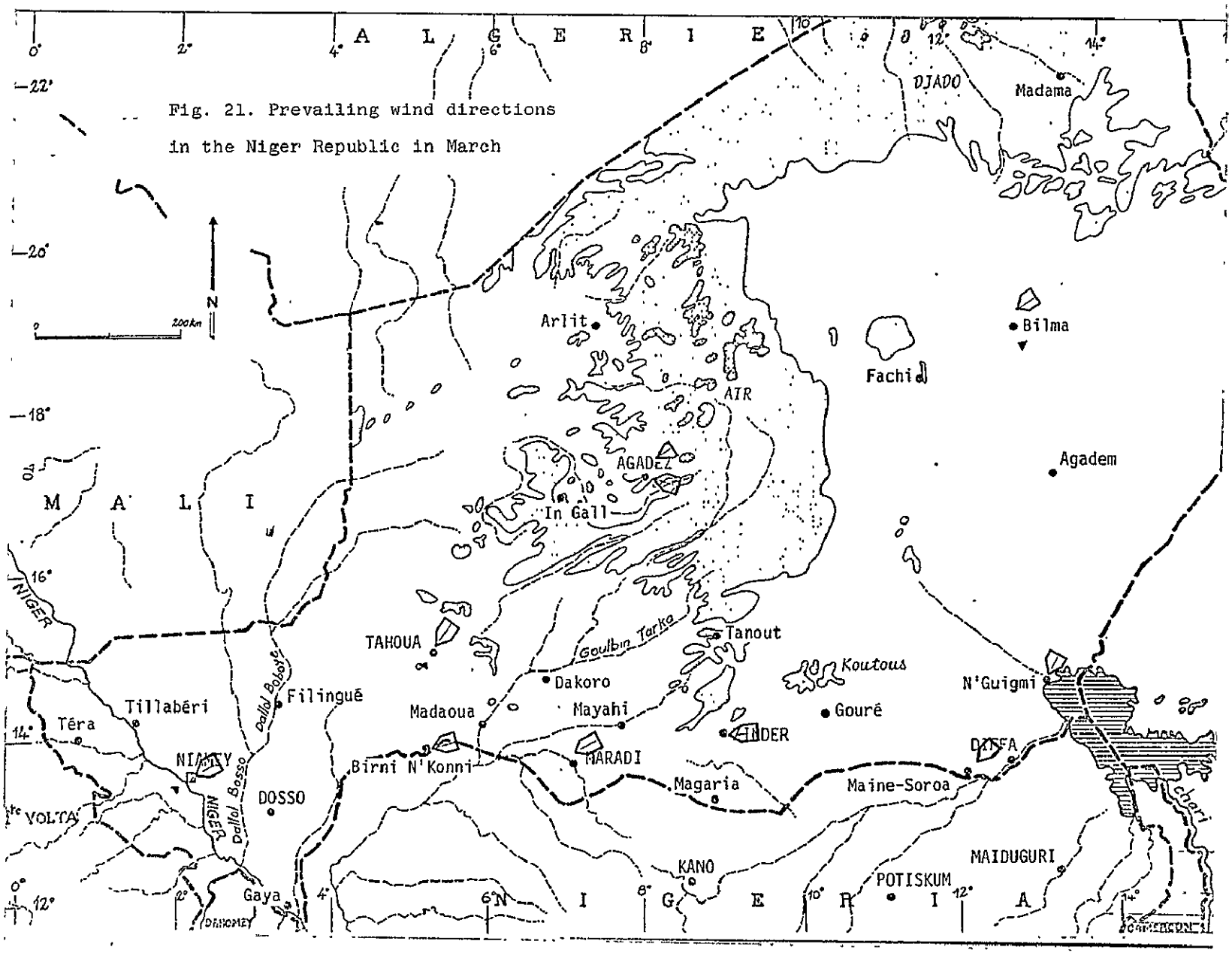


Fig. 21. Prevailing wind directions in the Niger Republic in March

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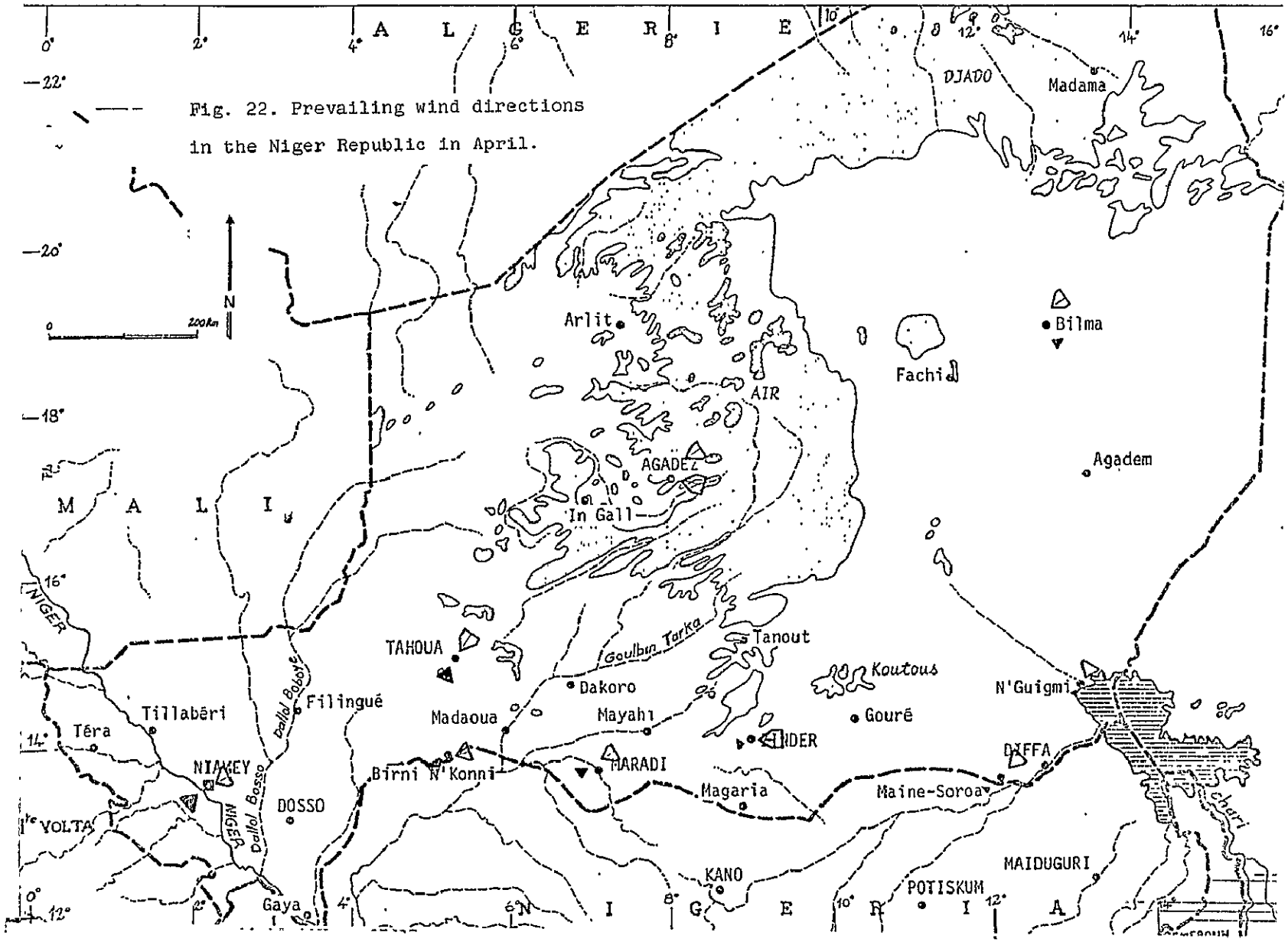


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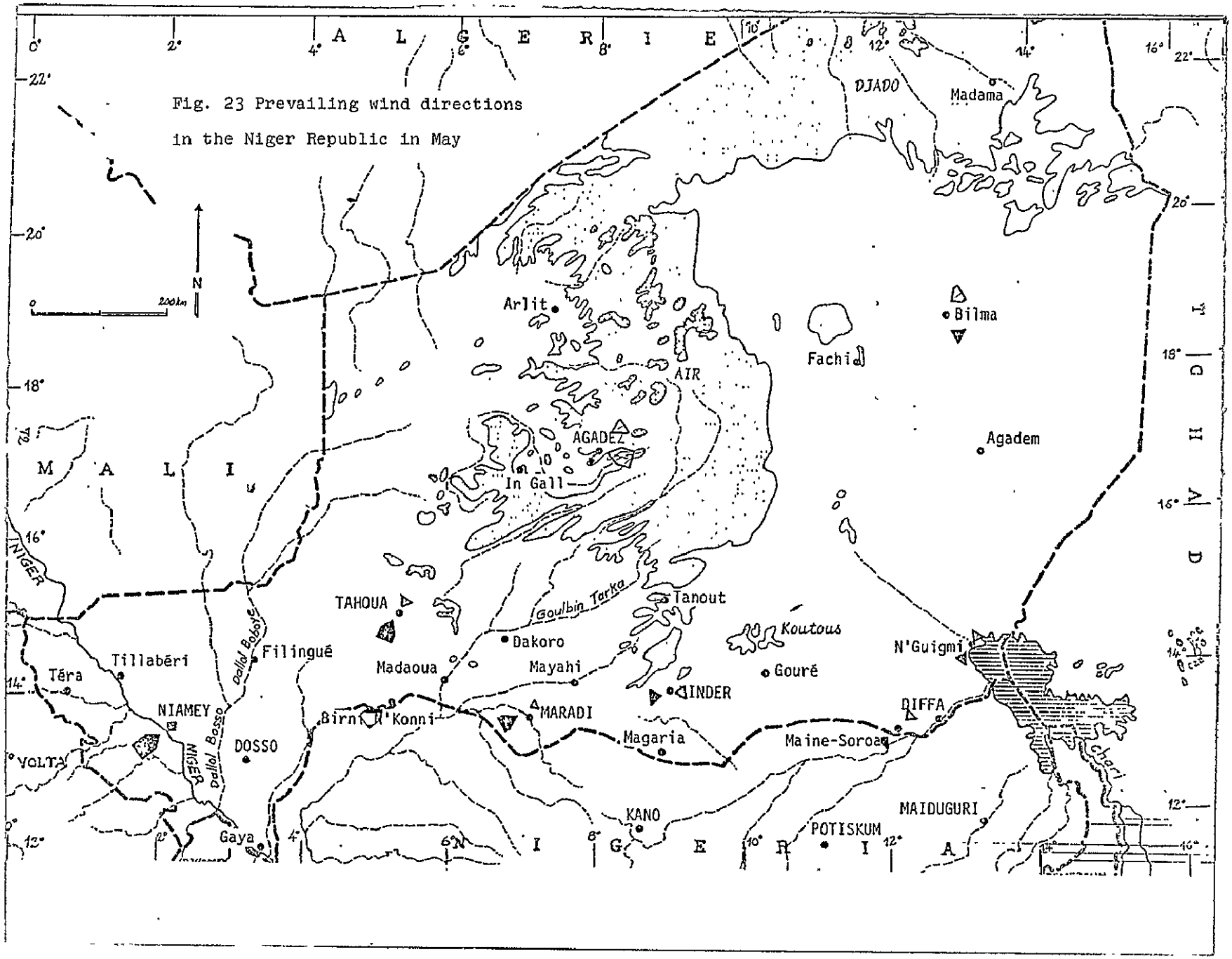


Fig. 23 Prevailing wind directions in the Niger Republic in May

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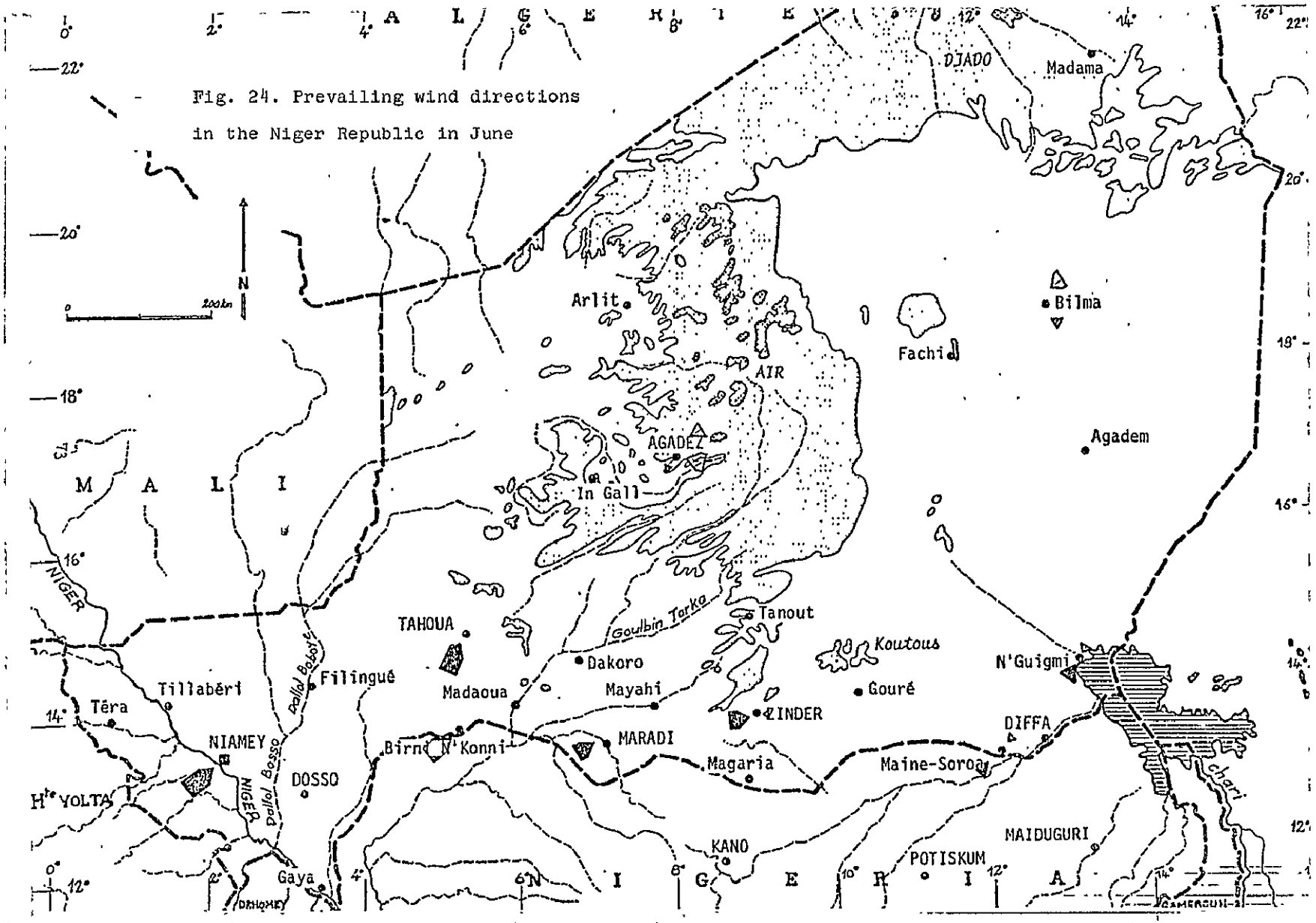


Fig. 24. Prevailing wind directions in the Niger Republic in June

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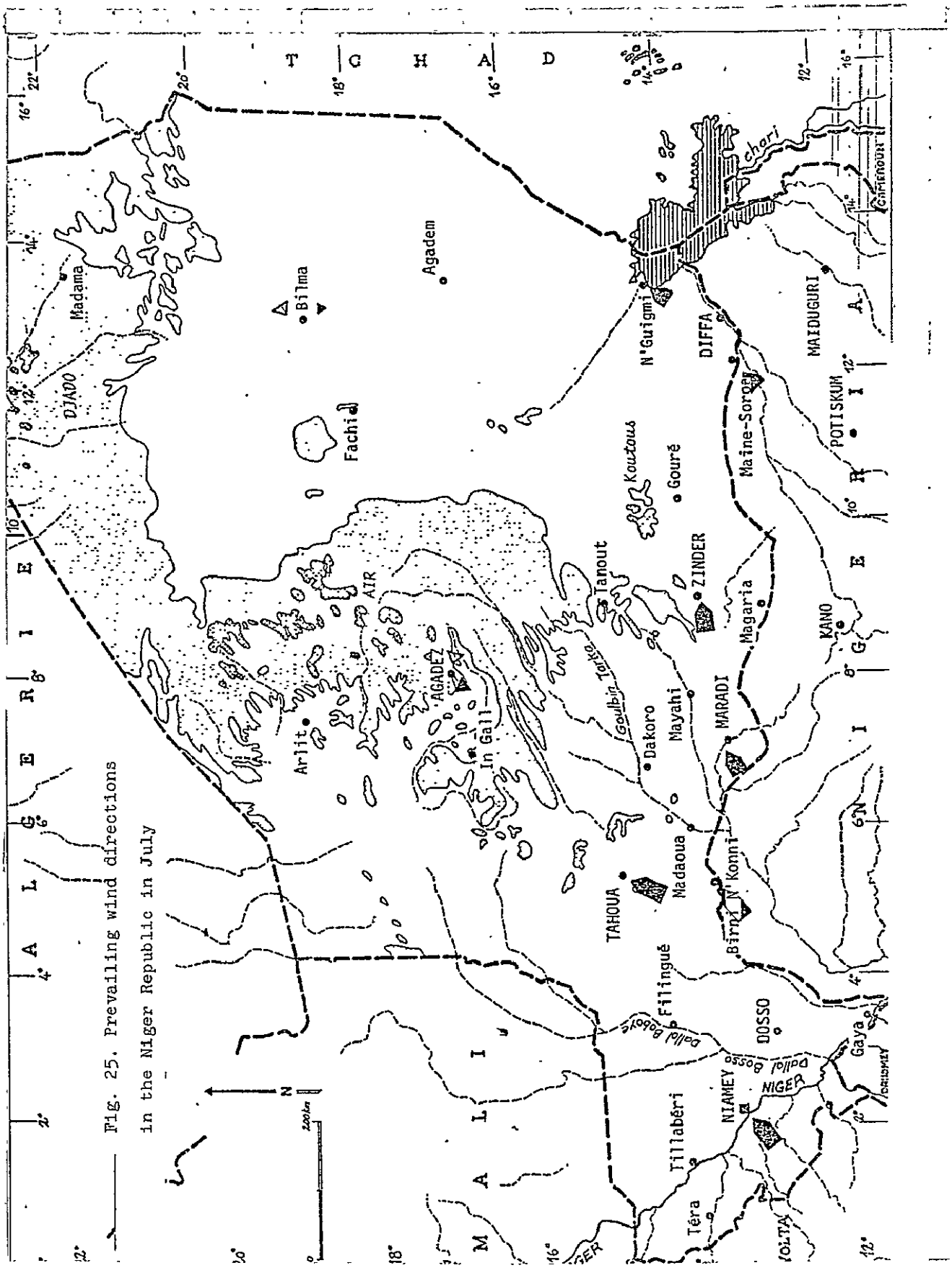


Fig. 25. Prevailing wind directions in the Niger Republic in July

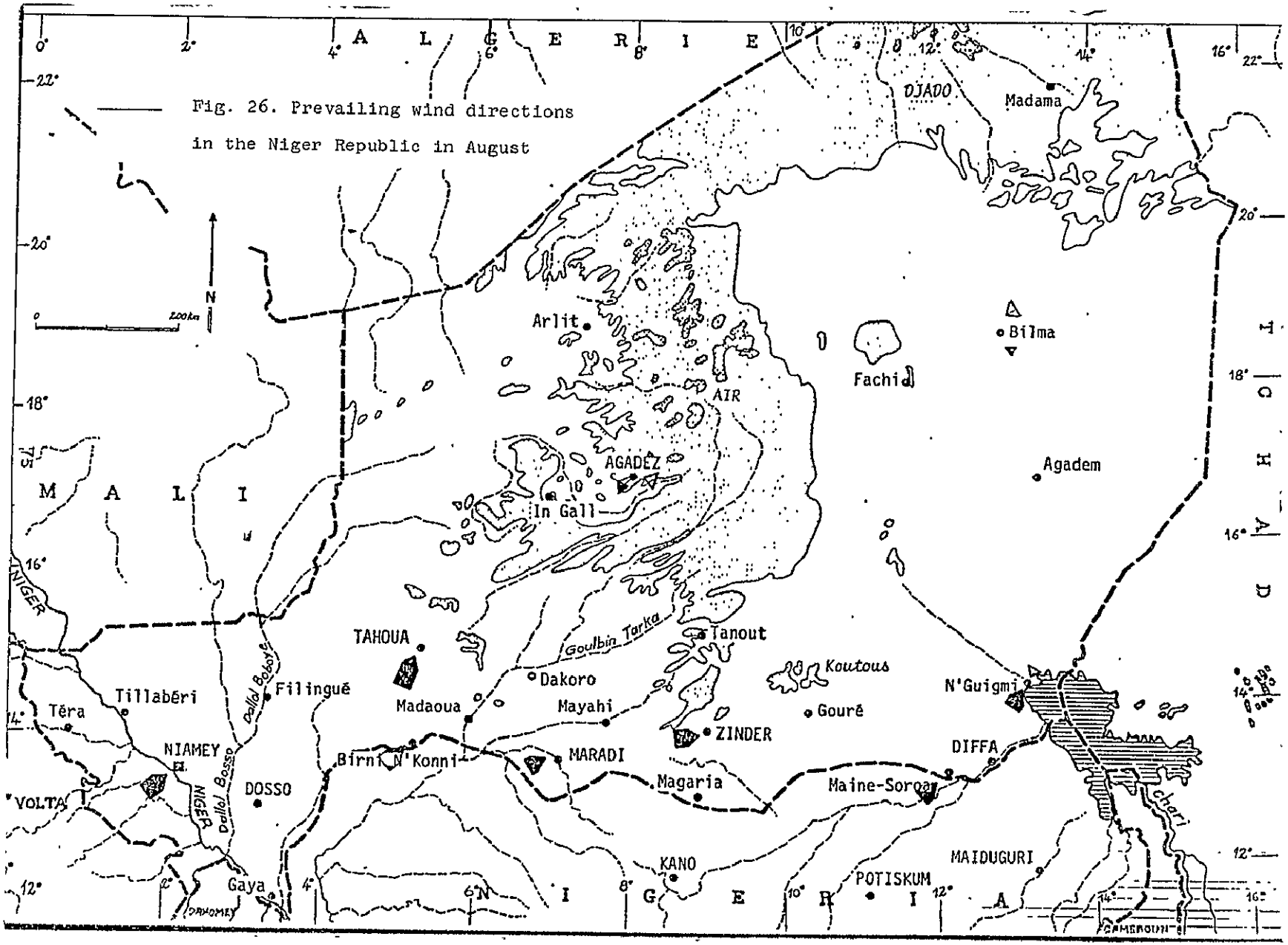


Fig. 26. Prevailing wind directions in the Niger Republic in August

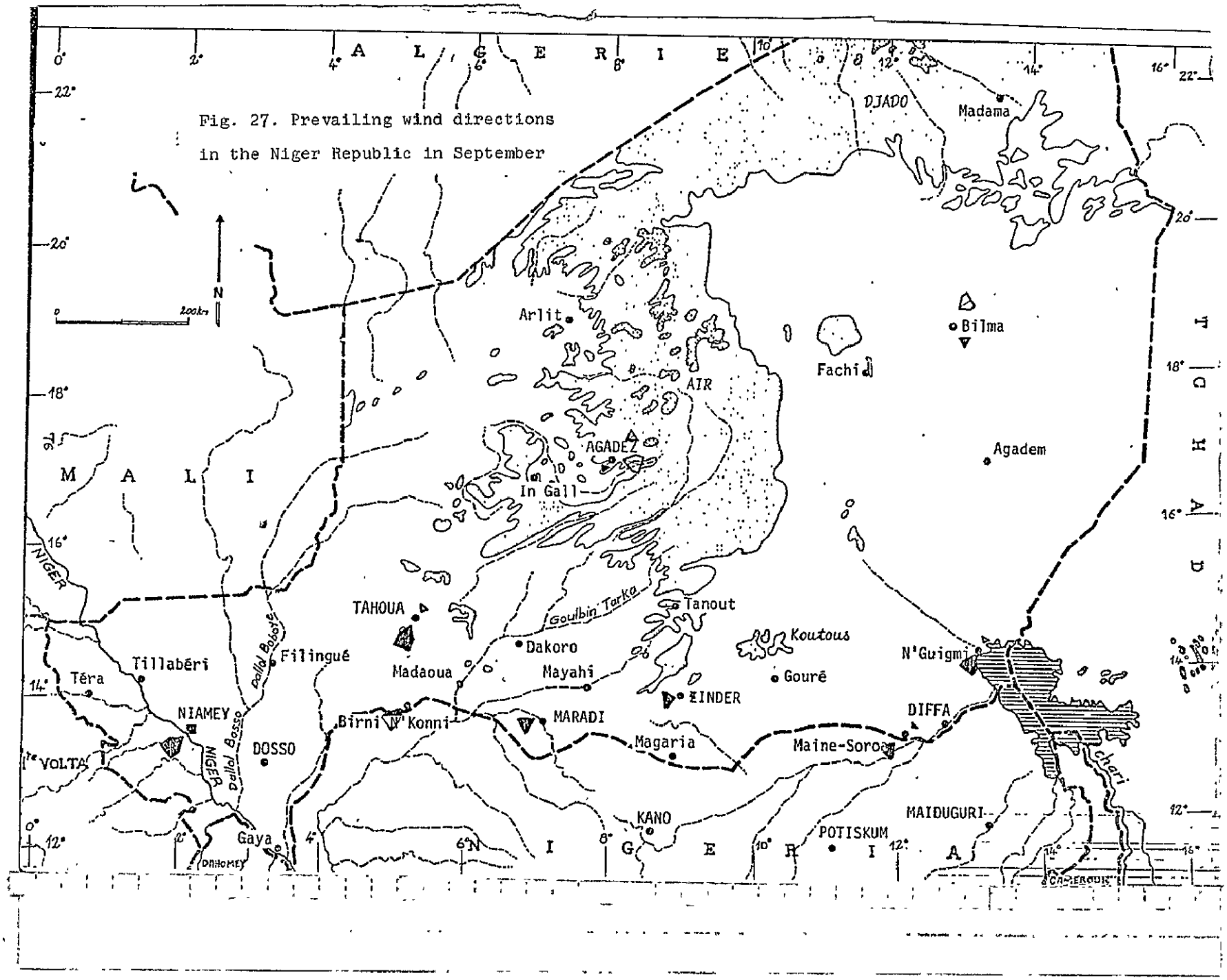


Fig. 27. Prevailing wind directions in the Niger Republic in September

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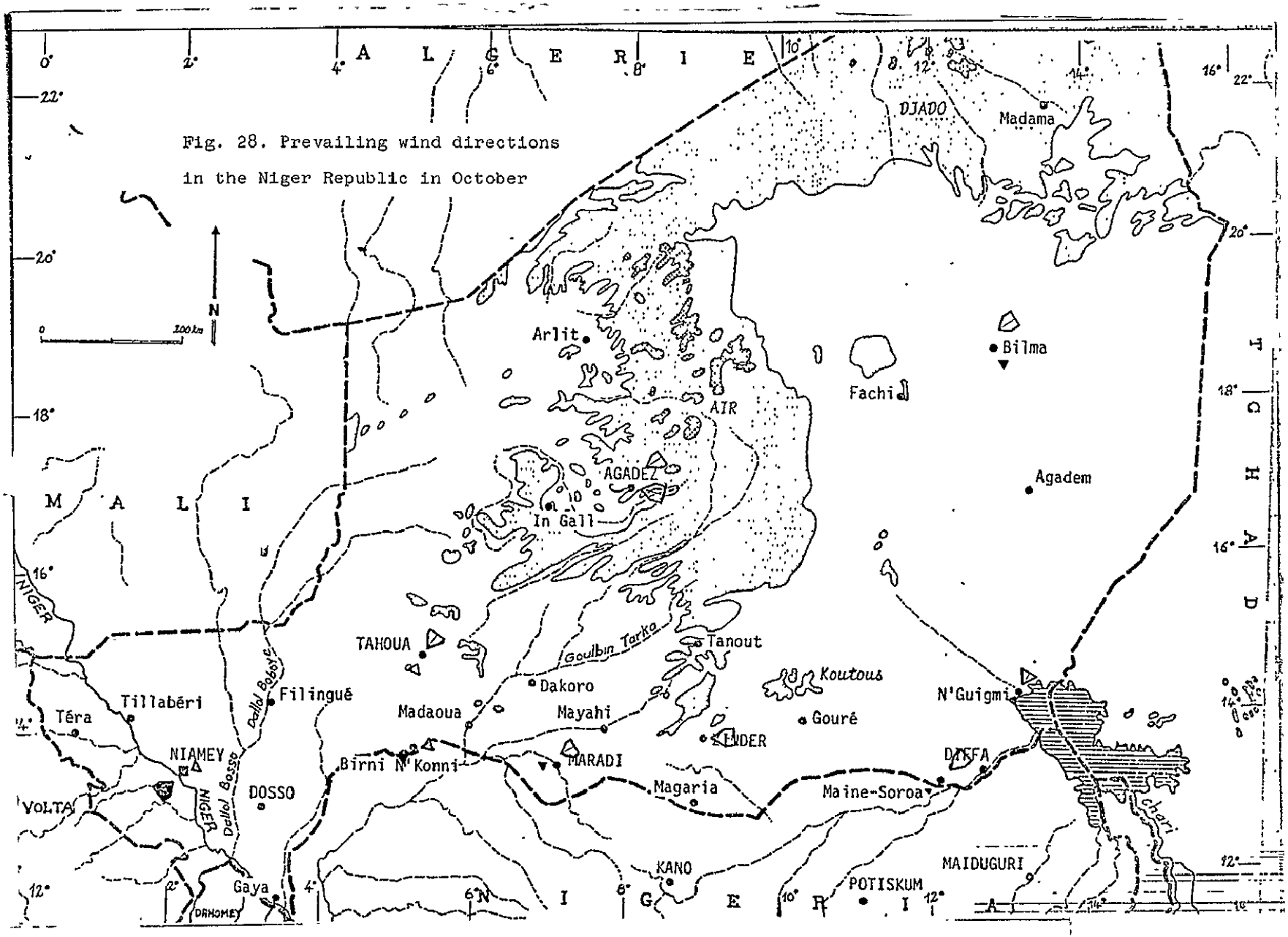


Fig. 28. Prevailing wind directions in the Niger Republic in October

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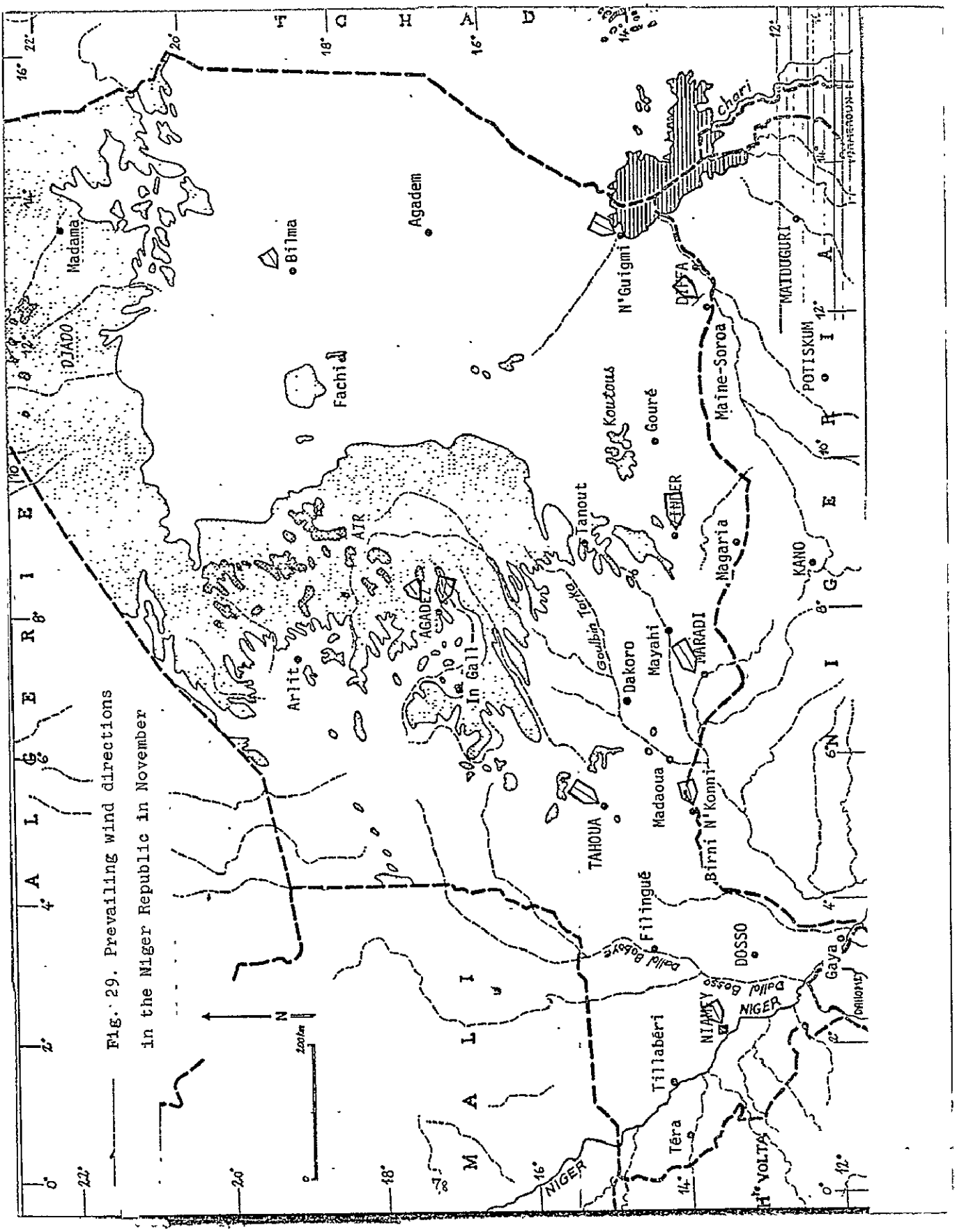


Fig. 29. Prevailing wind directions in the Niger Republic in November

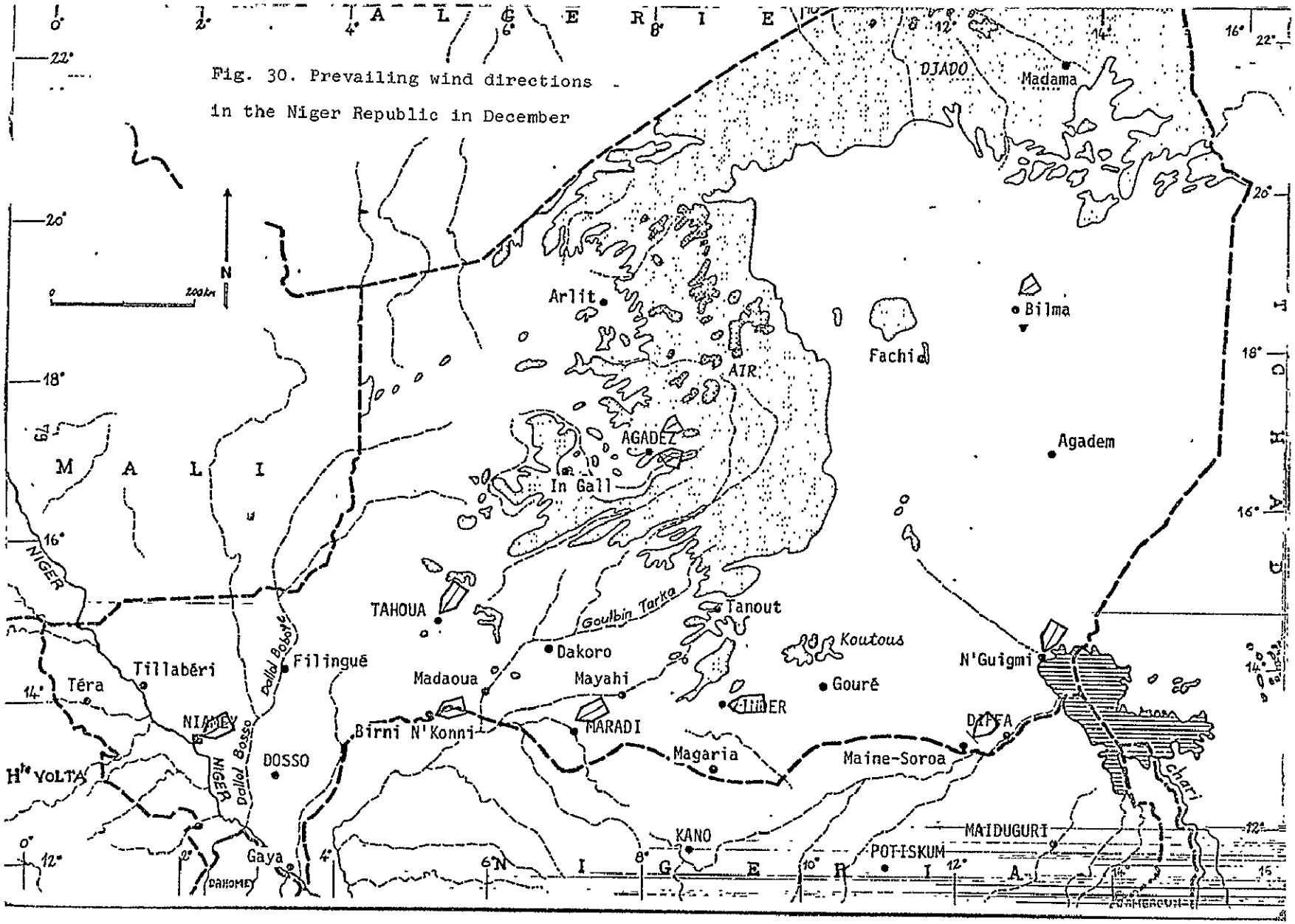


Fig. 30. Prevailing wind directions in the Niger Republic in December

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## 3. Study of the Average of Prevailing Winds (1961-1970) (Figs. 31-35)

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These monthly rose diagrams for the averages of prevailings winds are only sketchy diagrams of the detailed rose diagrams. They were made in connection with the work for 8 stations (5 of which are treated here). This representation actually shows only one of the three factors treated by the detailed rose diagrams, namely the prevailing direction for each month. The speed, which is given as an average, indicated no more than monthly fluctuations and no peaks of efficient wind, which are so significant for the planner, are shown.

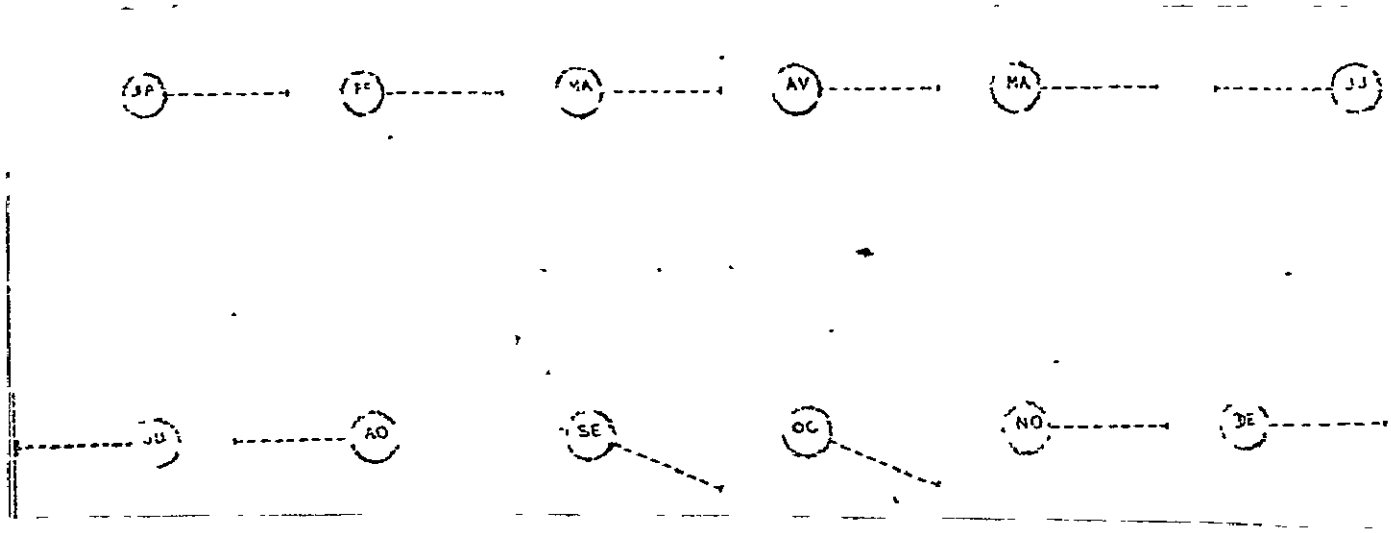


Fig. 31. Agadès: average of prevailing wind (1961-1970). Agadès. The average of the prevailing winds is characterized by two opposing wind directions: (1) from the east from November to May then (2) from the west during the rainy season, with two months of transition characterized by an east-southeast wind. The winds reach their maximum speed in the dry season (Jan., Feb., March). Their average annual speed is 3.6 m/s.

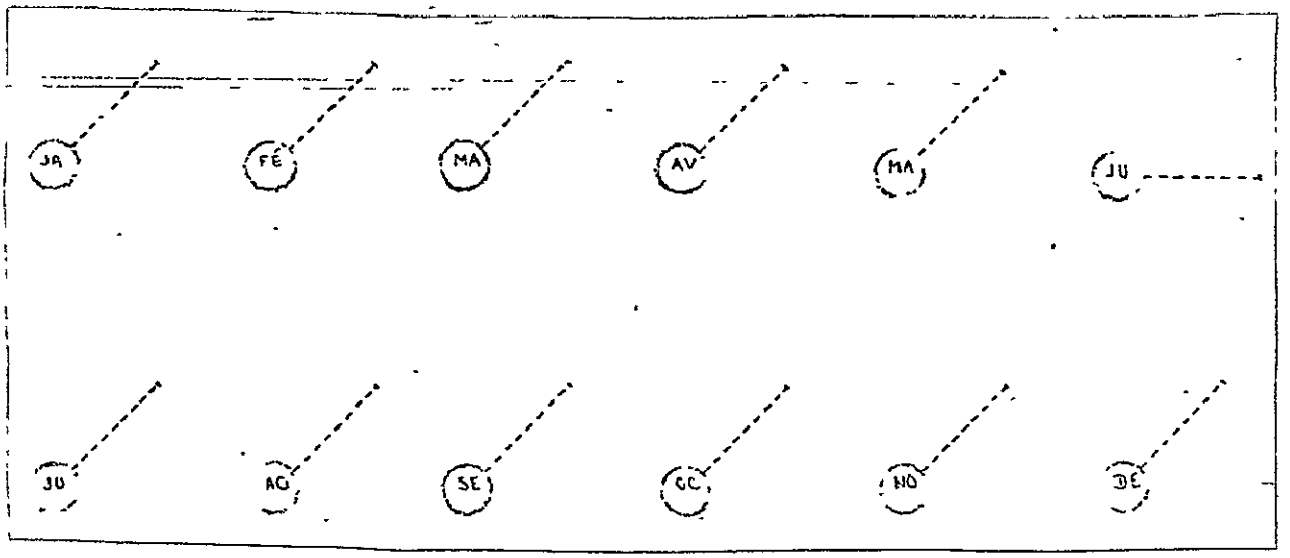


Fig. 32. Bilma: average prevailing wind (1961-1970)
Bilma. The average of the prevailing winds is characterized by a single direction, from the northeast, throughout the year, except for June when it blows from the east. The highest speeds are reached in March and April. The average annual speed is 3.89 m/s.

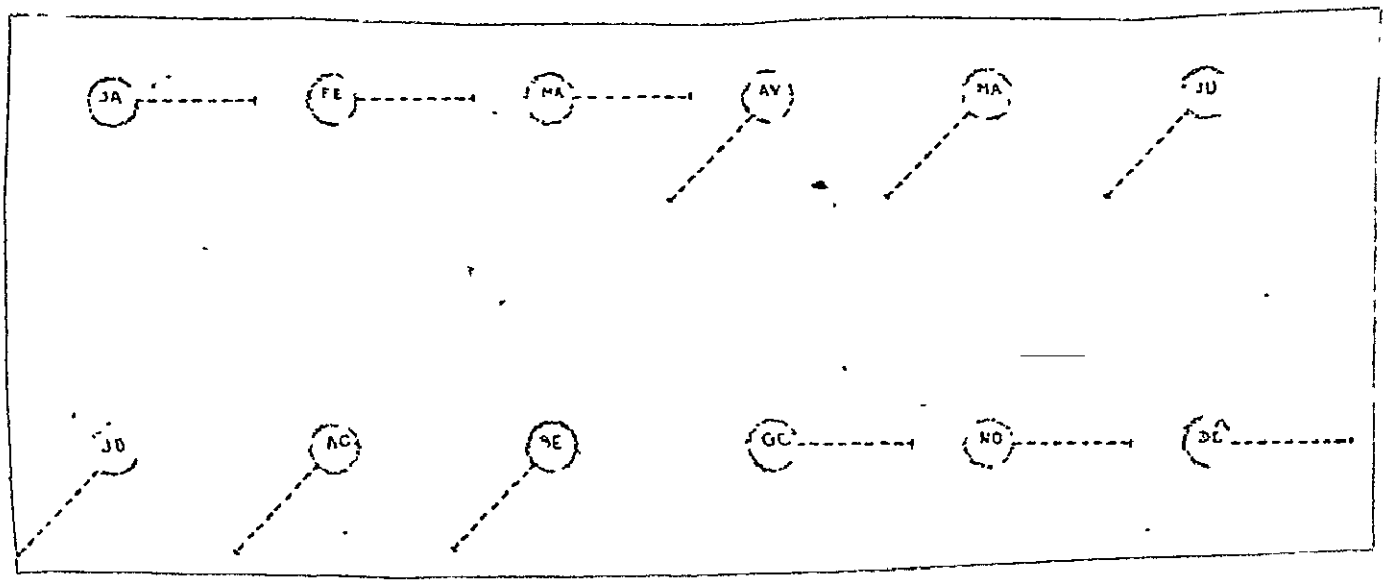


Fig. 33. Birni N'Konni: average of prevailing wind (1961-1970).
Birni N'Konni. The average of prevailing winds is chracterized by two opposite directions which divide the year. This semi-annual separation into two opposing winds is controlled by the dry season and the wet season. An east wind blows from October to March and a southwest wind from April to September. The greatest average velocities occur in 2 different months (February and June), each in one of the two seasons. The average annual velocity is 2.6 m/s with two peak months: February and June.

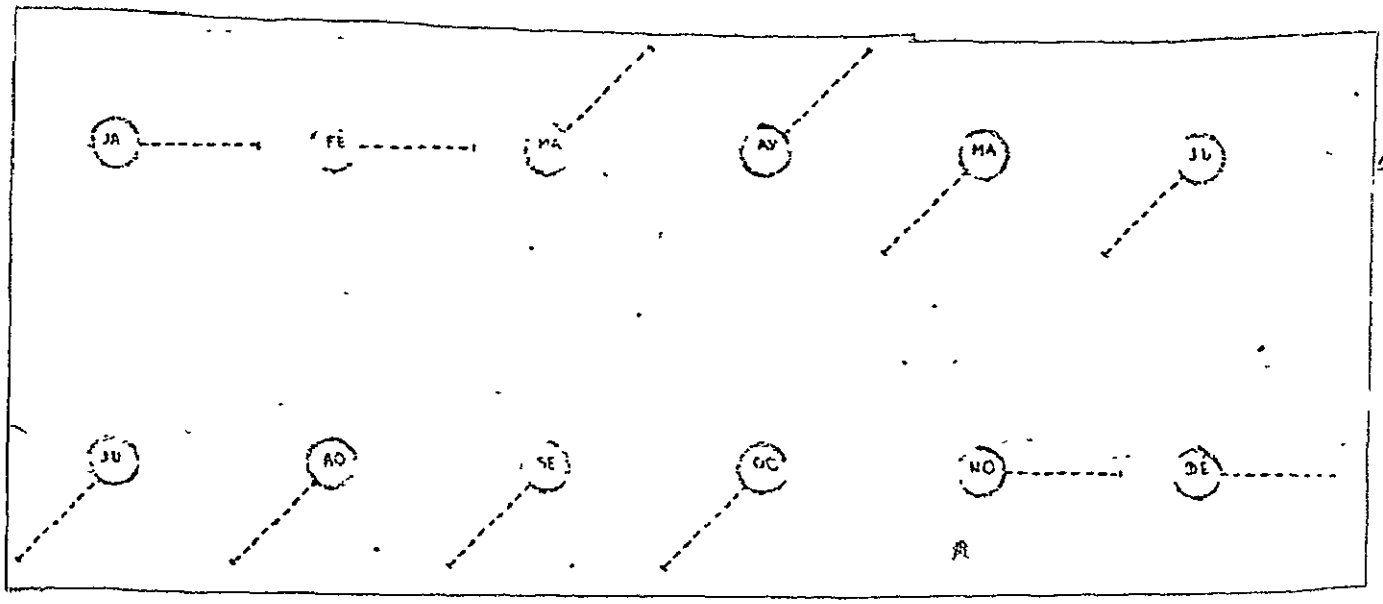


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Fig. 34. Maradi: average of prevailing winds (1961-1970). Maradi: The average of the prevailing winds is again characterized by 2 winds blowing in opposite directions. During the dry season from October to February the winds are from the east, and during the rainy season, from May to September, they are from the southwest. However the transition from the dry season to the rainy season, from March to April, is noteworthy because of its winds from the northeast. The maximum speeds are reached in January and February. The average annual speed is 2.4 m/s.

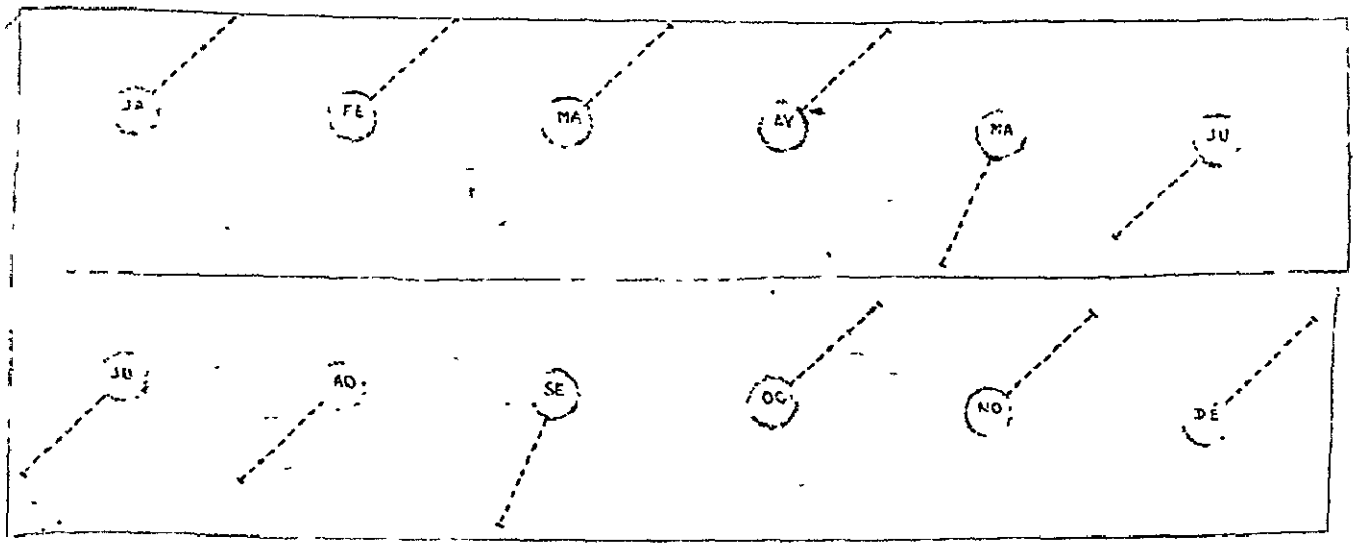


Fig. 35. Tahoua: average prevailing wind (1961-1970). Tahoua. The average of prevailing winds is chracterized by 2 opposite wind directions: from October to April winds from the northeast and from June to August, winds from the southwest. The two transitions in May and September are expressed by winds from the south-southwest. The greatest velocities are seen in January and February. The average annual velocity is 3.9 m/s.

ASECNA
Meteorological Service

Averages of Prevailing Winds 1961-1970

| Station | Period | illegible | Jan | Feb | Mar | Apr | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. | Yearly average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Agadès | 1961/1970 | Dir. | E | E | E | E | E | W | W | W | ESE | E-ESE | E | E | |
| | | Vel. | 4,3 | 4.5 | 4,2 | 3.5 | 3.4 | 3.1 | 3.1 | 2.9 | 2.6 | 3.5 | 4,2 | 4.0 | 3,6 |
| Bilma | -do- | Dir. | NE | NE | NE | NE | NE | E | NE | NE | NE | NE | NE | NE | |
| | | Vel. | 3,9 | 3,3 | 4,8 | 4.4 | 4.0 | 3.7 | 3,6 | 3.0 | 3,5 | 4,5 | 3.7 | 3.8 | 3,89 |
| Bum N'Kon | -do- | Dir. | E | E | E | SW | SW | SW | SW | SW | SW | E | E | E | |
| | | Vel. | 3.2 | 3.4 | 3.0 | 2.5 | 2.9 | 3.4 | 3.1 | 2,2 | 1.6 | 1.6 | 2,4 | 2.7 | 2,6 |
| Moradi | -do- | Dir. | E | E | NE | NE | SW | SW | SW | SW | SW | E | E | E | |
| | | Vel. | 3.1 | 3.1 | 2.9 | 2.5 | 2,5 | 2.7 | 2.4 | 1.7 | 1,2 | 1.6 | 2,9 | 2.7 | 2,4. |
| Tahoua. | -do- | Dir. | NE | NE | NE | NE | S/SW | SW | SW | SW | SSW | NE | NE | NE | |
| | | vel. | 4.3 | 4.6 | 4.1 | 3.9 | 3,9 | 4.2 | 4.4 | 3.8 | 3,1 | 3.2 | 3,5 | 3.8 | 3,9 |

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## 4. Monthly Distribution of Winds According to Prevailing Directions (Figs. 36-44)



Niamey, Tahoua and Zinder are the 3 windiest stations of the Niger Repbulic. N'Guigmi, Maine Soroa and Maradi are the least windy stations. Thus, Bilma and Agades, the two desert stations, receive less wind than the Sahel stations.

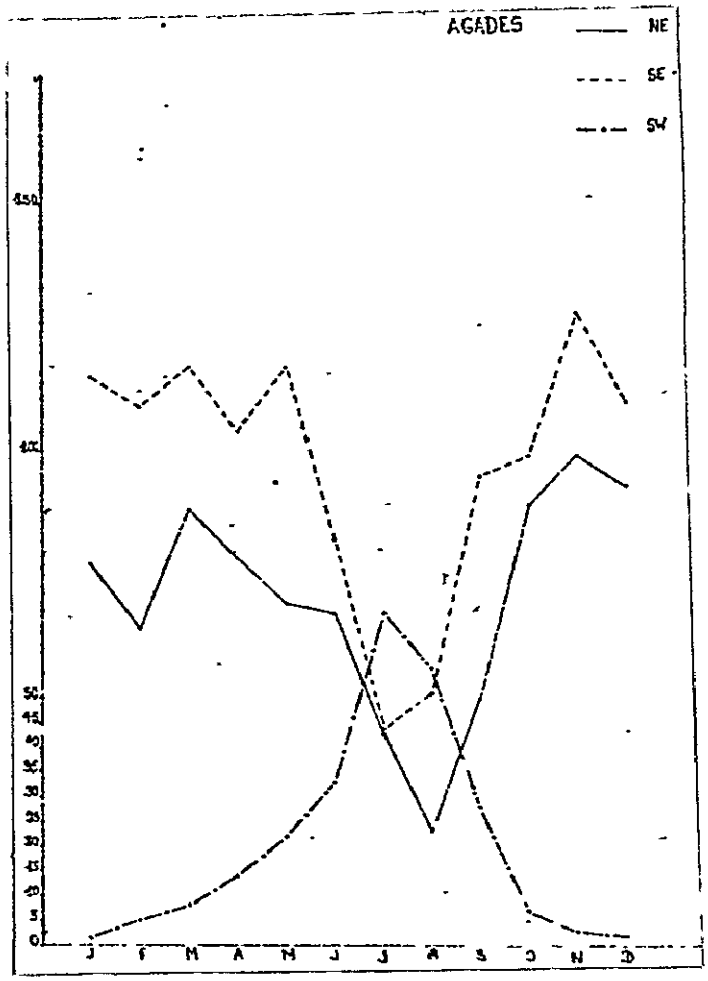



Fig. 36. Agades. Monthly distribution of winds according to the prevailing directions.

The monthly distribution of winds is very similar for the two directions NE and SE, but the winds from the southeast are more numerous and their maximum in July precedes by one month the maximum for the winds from the northeast, which occurs in August.

This shift could be explained by the effect of an obstacle produced by the Aïr along a current of the harmattan which is thus slowed down and attentuated. A positive peak, in May, for the SE direction does not exist for the NE direction.

The monsoon winds from the SW reach a maximum in July at Agades. They are not very frequent and their direction tends to be subject to regional variations due to the topographical arrangements of the mass.

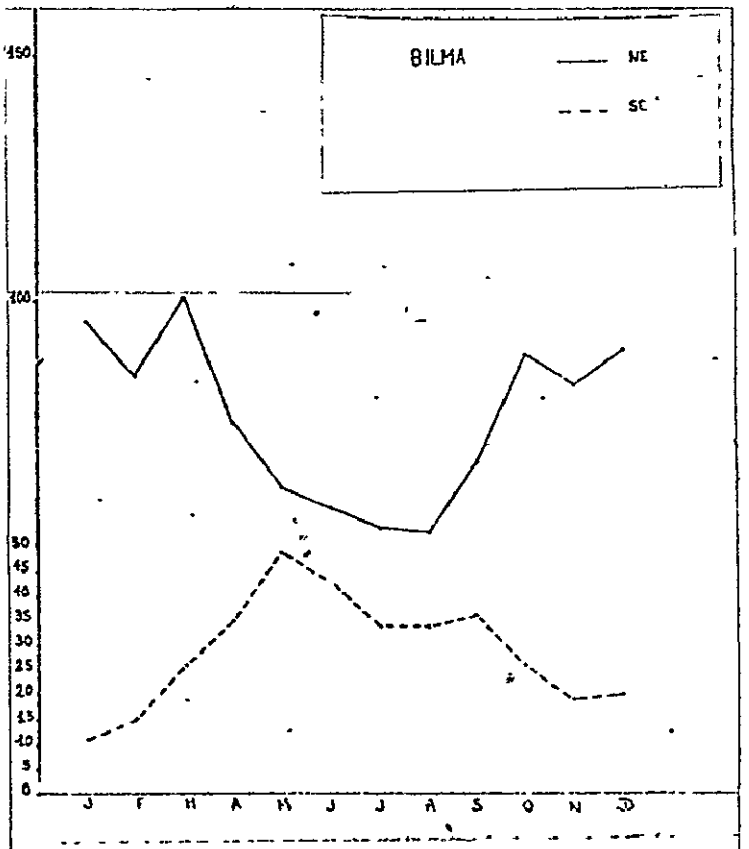



Fig. 37. Bilma. Monthly distribution of winds according to the prevailind directions. /85

Bilam is not a very windy station. The winds of the dry season from the northeast are more numerous than the monsoon winds from the southeast whose maximum in May is early, but on the whole their frequency remains low. The harmattan of the dry season also has a very early maximum in March, and a minimum in September.

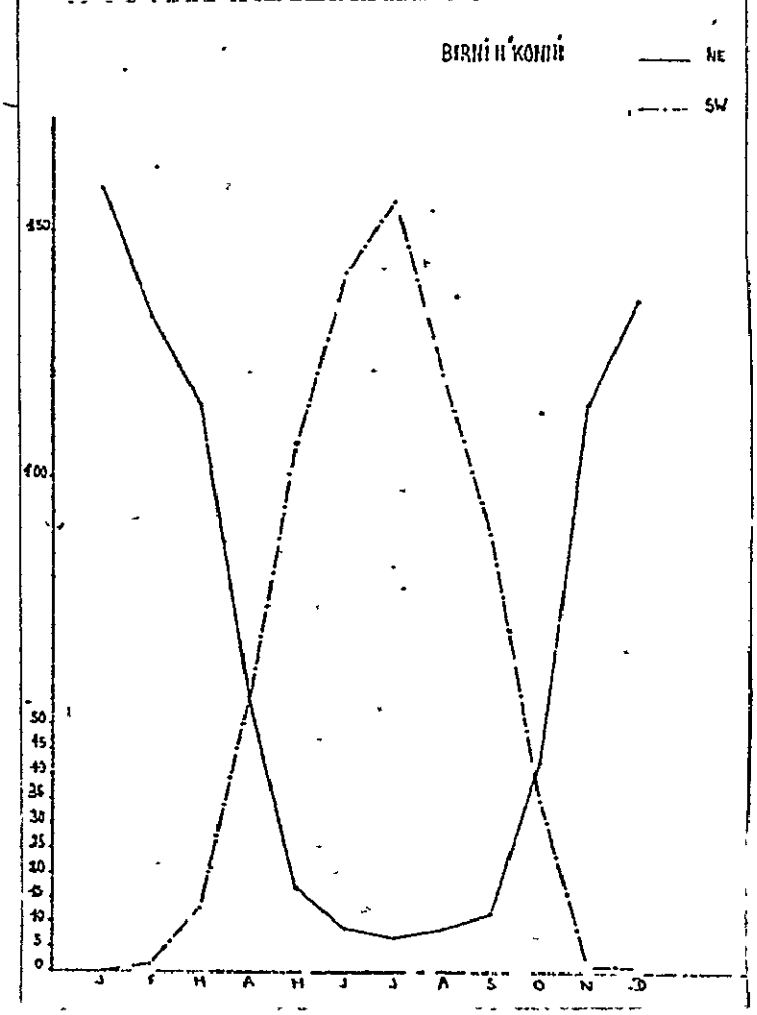



Fig. 38. Birni N'Konni. Monthly distribution of the winds a according to the prevailing wind directions.

This station frequently receives winds. The winds of the dry season (harmattan) reach their maximum here in January, and their minimum from June to September. In July, by contrast, the monsoon reaches its maximum. The July peak is extremely distinct.

Along with Maine Soroa, Maradi, Niamey and Zinder this station forms a family which has a very similar monthly distribution of winds: these are typical Sahel Stations between 13° and 14° N.

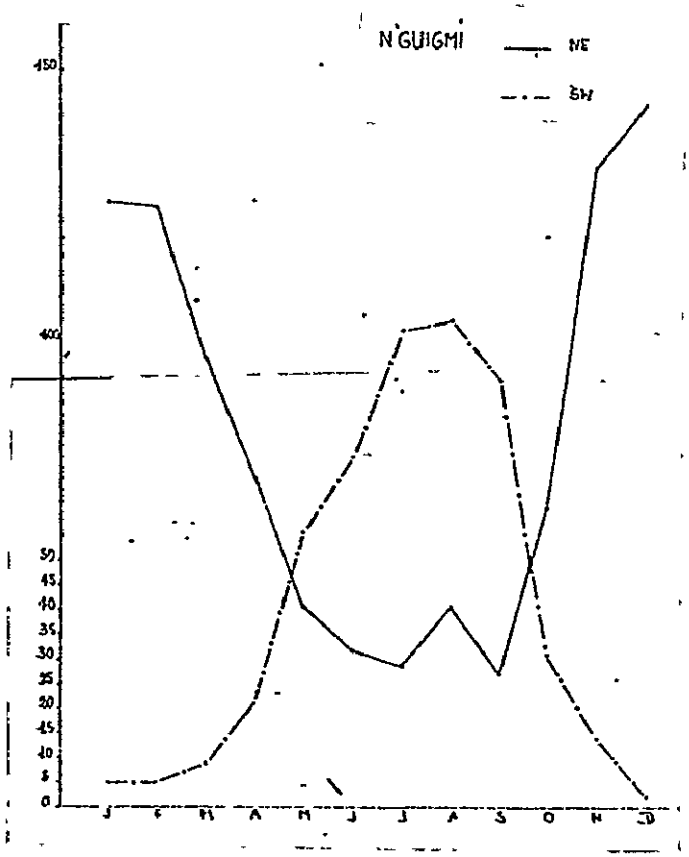



Fig. 39. N'Guigmi. Monthly distribution of the winds according to the prevailing wind directions. /86

At N'Guigmi the maximum for the southwest winds corresponds to the minimum for the northeast winds. The winds from the north east diminish slowly from February to July, then increase rapidly from September to December. The maximum for harmattan-type winds occurs in December.

The rise and fall of the winds from the southwest are symmetrical. The maximum occurs in August.

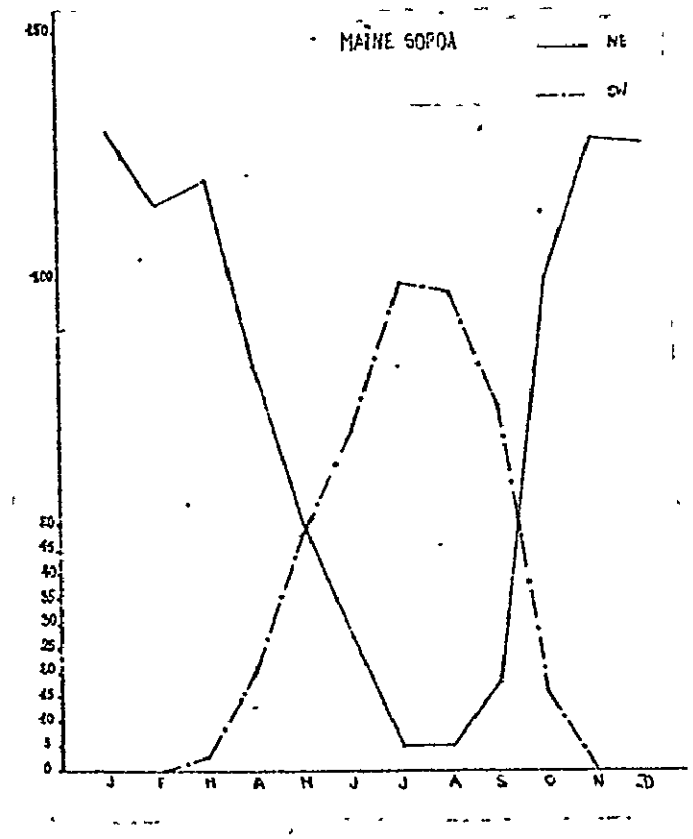



Fig. 40. Maine Soroa. Monthly distribution of the winds according to the prevailing wind directions.

The two directions complement one another. The winds from the northeast (harmattan) are more numerous than those from the southwest. Their increase in frequency, with a maximum in December, is more rapid than the decrease, with a brief but clearly defined minimum in July-August.

The winds from the southwest have a maximum in July-August.

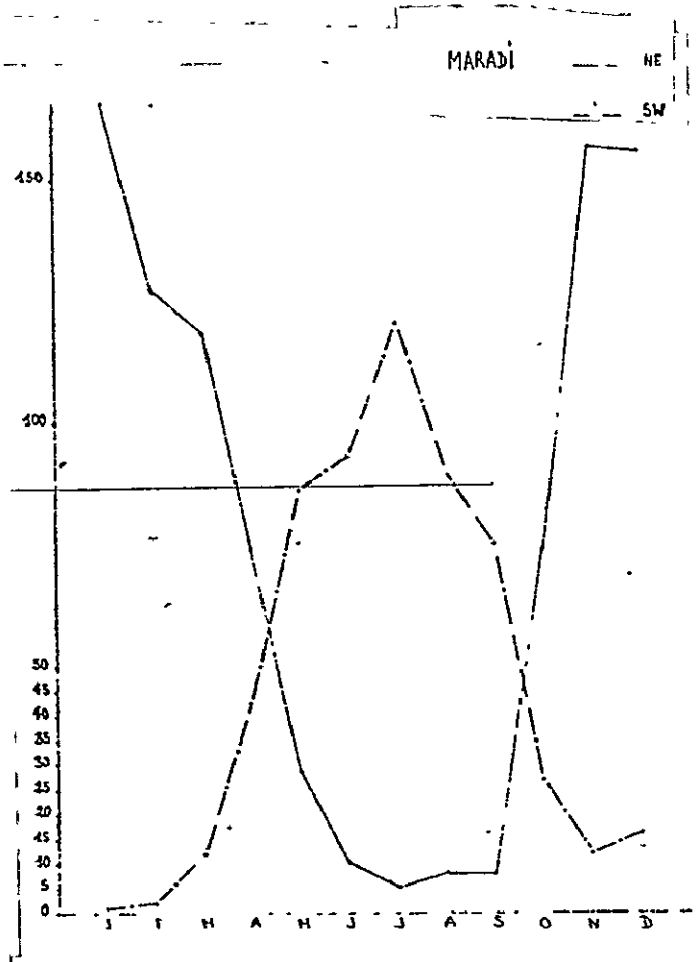



Fig. 41. Maradi. Monthly distribution of the winds according to the prevailing wind directions. /87

Maradi is a station with a high frequency of harmattan-type winds. The general curve for Maradi is similar to those for Birni N'Konni, Tahoua and Zinder. The winds from the northeast at Maradi are numerous, with a very distinct maximum from November to January. It has a well defined minimum period from June to September.

The winds from the southwest (monsoon) have a maximum in July. The winds of the wet season are less numerous at Maradi than the winds of the dry season.

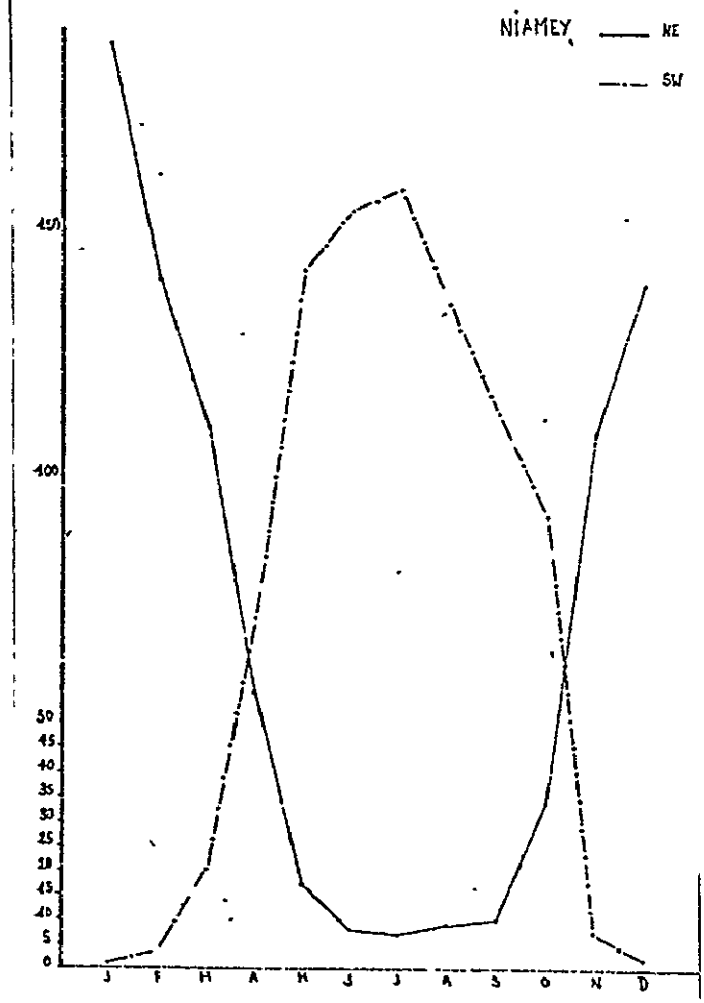


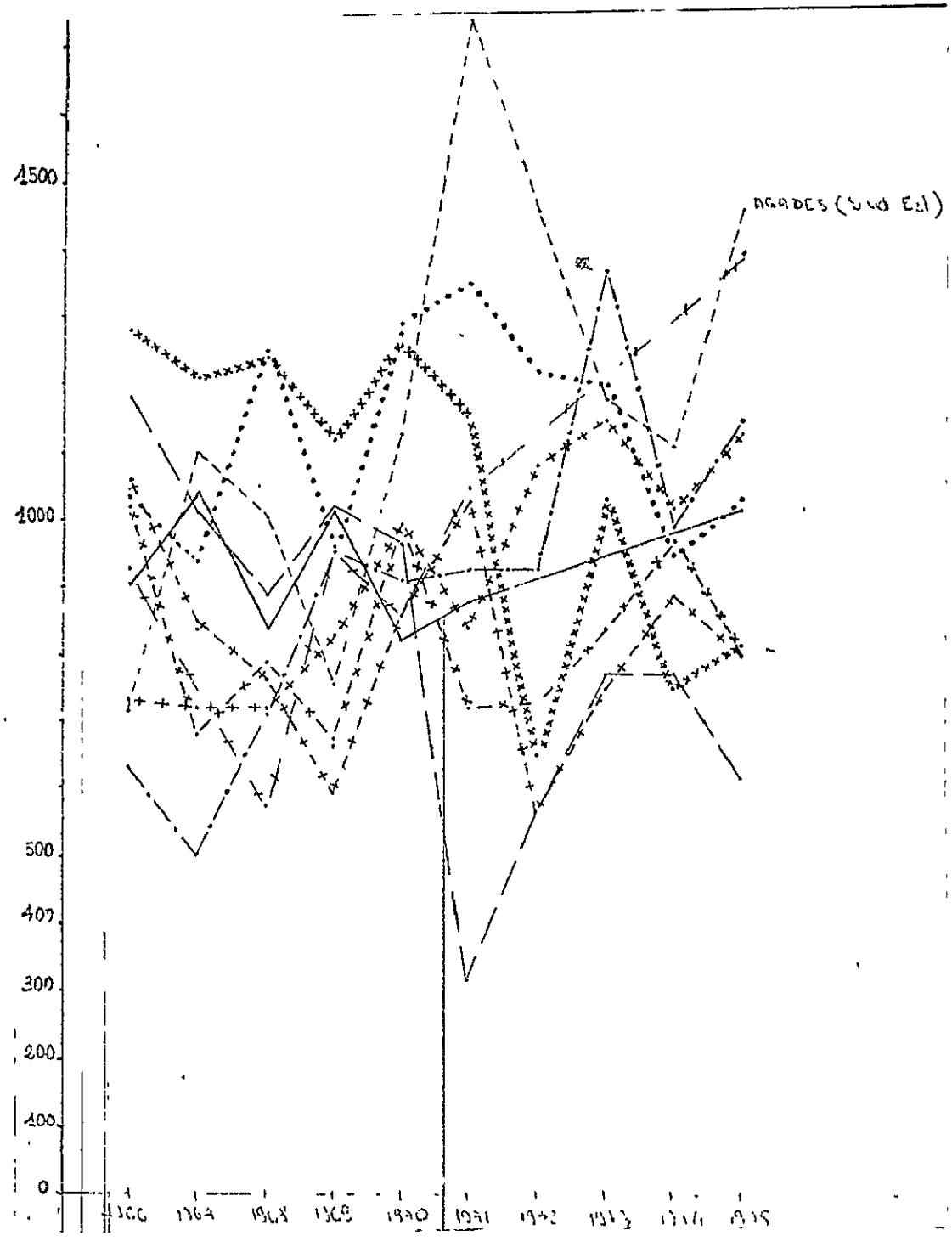

Fig. 42. Niamey. Monthly distribution of the winds according to the prevailing wind directions.

Niamey is a very windy station whose wind curves for the dry season and rainy season are characterized by maximums and minimums spread out over several months. In spite of its longitude, Niamey is very frequently reached by harmattan-type winds, whose maximum is in Jan. and whose minimum spreads out from May to Sept.. Along with Tahoua and Zinder, Niamey is one of the stations which receives the most winds from the NE. The season of NE winds is particularly long, since it begins in Sept. It does not end until April-May. The incursion period for monsoon winds (from March-April to Nov.) corresponds to the dead season of winds from the east which extends from May to Sept. The transition months, March-April-May and Sept.-Oct., receives simultaneously winds from the NE and from the SW.

Niamey receives fewer winds from the SW than from the NE. The winds from the SW become established rather rapidly between April and May.

There is striking resemblence between Tahoua and Zinder. The two wind curves for the dry season are almost identical, with a maximum in January. This situation is all the more surpising as the postions of the 2 stations differe considerably in longitude and latitude. The maximum period always extends from June to Sept. The pattern of monsoon winds is also similar, but Tahoua, of the stations of the Niger Republic studied, is the one which is most frequently affected by the monsoon.

Fig. 43. Tahoua and Zinder. Monthly distriubtion of the winds according to the prevailing wind directions.



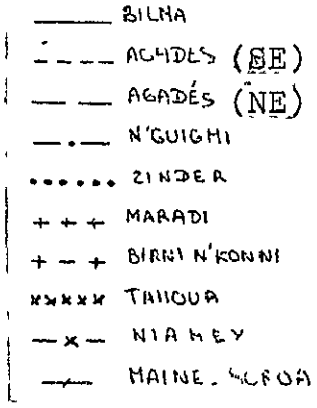




Fig. 46. Changes in the number of winds of the dry season in the Niger Republic (1966-1975). [Translators note: this should probably be numbered 44].

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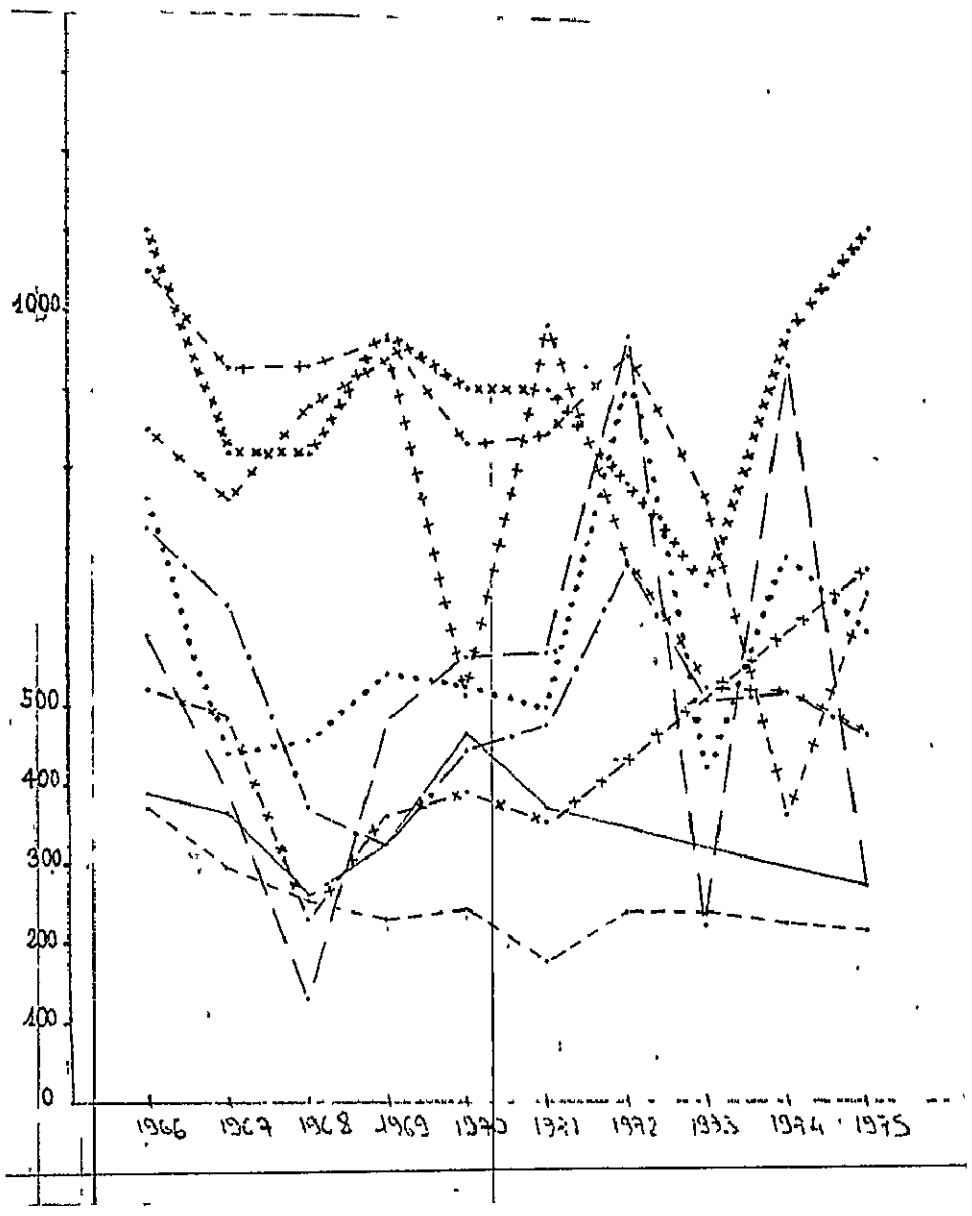
## 5. Changes in the Number of Dry Season and Wet Season Winds in the Niger Republic from 1966 to 1975 (Figs. 45 and 46) /90

These graphs were made in order to reveal the effect of the climate crisis which occured between 1969 and 1973 on the frequency of wind.

### 1. Dry Season Winds

From 1970 onwardswe see that the number of dry season winds varies much more considerably from one station to another than vefore. It seems that between 1973 and 1975 the situation prior to 1969 becomes reestablished. But in 1975 new discrepancies appear which suggest athat the climatic crisis is not over. Prior to 1969 peaks of minimum and maximum frequency appear simultaneously at several stations.

- Minimum points common to several stations:
  - 1967 for Tahoua, Zinder, Niamey and N'Guigmi,
  - 1968 for Agadès (NE), Bilma, Mainé Soroa and Maradi,
  - 1969 for Tahoua, Zinder, Agadès (SE), Niamey and Birni N'Konni,
  - 1971 for Maradi, Niamey and Agadès (NE),
  - 1972 for Tahoua and Birni N'Konni,
  - 1974 for Agadès (SE), N'Guigmi, Maradi, Zinder and Tahoua.
- Maximum points common to several stations:
  - 1967 for Agadès (SE), and Bilma,
  - 1968 for Tahoua, Zinder and Niamey,
  - 1969 for Agadès (NE), Bilma, N'Guigmi and Mainé Soroa,
  - 1970 for Tahoua, Maradi and Niamey,
  - 1971 for Agadès (SE), Zinder, and Birni N'Konni,
  - 1973 for N'Guigmi, Maradi, Tahoua and Agadès (NE),
  - 1974 for Niamey and Birni N'Konni,
  - 1975 for Agadès (SE), Mainé Soroa, N'Guigmi, Maradi, Zinder, Bilma and Tahoua.




BILMA (SE)
AGADÉS
N'GUIGMI
ZINDER
MARADI
BIRNI N'KONNI
TAHOUA
NIAMEY
MAINE SOROA

Fig. 45. Changes in the number of Wet season winds in the Niger Republic (1966-1975). /91

By contrast, except for the minimums of 1969 and 1974 and the maximum of 1975 which a large number of stations each collected, there is no agreement between the stations with respect to peaks and valleys for winds of the harmattan. This tends to prove that differences in location, even small ones, are reflected in the winds. /92

2. 2. Wet Season Winds

From 1973 to 1974 the number of wet season winds was more homogeneous from one stationsto another and, on average, smaller than before 1971.

Three groups can be distinguished according to the number of winds:

1. a small number of winds for Agadès (239) and Bilma(352);
2. an average number of winds for N'Guigmi (509), Mainé Soroa (430), Zinder (511) and Maradi (582);
3. many winds for Birni N'Konni (710), Tahoua (825) and Niamey (902).

Minimum points common to several stations:

- in 1967 for Niamey, Birni N'Konni, Tahoua, Maradi,
- in 1968 for Mainé Soroa, Bilma and N'Guigmi,
- in 1969 for Zinder and Agadès,
- in 1970 for Niamey, Birni N'Konni and Tahoua,
- in 1971 for Maradi, Maine Soroa and Agadès,
- in 1973 for Niamey, Birni N'Konni, Zinder, Maradi and N'Guigmi,
- in 1975 for Maradi, Birni N'Konni, Zinder, N'Guigmi, Bilma and Agadès.

Maximum: points common to several stations:

- in 1966 for all the stations,
- in 1969 for Tahoua, Niamey, Birni N'Konni and Maradi,
- in 1970 for N'Guigmi, Bilma, Mainé Soroa and Agadès,
- in 1972 for N'Guigmi, Tahoua, Maradi, Zinder and Agadès,
- in 1974 for N'Guigmi and Maradi,
- in 1975 for Niamey, Mainé Soroa and Tahoua.

In summary, The period of dryness from 1969 to 1972 is reflected by increases in harmattan-type winds at Adagès, Zinder and Tahoua, and to a lesser degree at Maradi, Birni N'Konni and Niamey. The monsoon-type winds clearly diminished during the same period of dryness from 1967 to 1970. The three stations of N'Guigmi, Mainé Soroa and Zinder experienced the greatest decrease in 1968. Bilma and Agadès, the two desert stations, have a place apart because of the small number of wet season winds.

## 6. Study of Monthly Rose Diagrams of 11 Stations in the Niger Repbulic (1966-1975).

/93

| STATION | LATITUDE | LONGITUDE | 65 | 66 | 67 | 68 | 69 | 70 | 71 | 72 | 73 | 74 | 75 | 76 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AGADES | 17° 00' N | 7° 59' E | | x | x | x | x | x | x | x | x | x | x | |
| BILMA | 18° 41' N | 12° 55' E | | x | x | x | x | x | x | | | | x | |
| BIRNI N'KONNI | 13° 48' N | 5° 15' E | | x | x | x | x | x | x | x | x | x | x | |
| GAYA | 11° 20' N | 3° 20' E | | | | | | | x | | | | x | |
| MAINE SOROA | 13° 13' N | 12° 02' E | x | x | x | x | x | x | x | | | | x | |
| MARADI | 13° 28' N | 7° 04' E | | x | x | x | x | x | x | x | x | x | x | x |
| N'GUIGMI | 14° 15' N | 13° 07' E | | x | x | x | x | x | x | x | x | x | x | |
| NIAMEY | 13° 28' N | 2° 07' E | | x | x | x | x | x | x | x | x | x | x | |
| TAHOUA | 14° 53' N | 5° 15' E | | x | x | x | x | x | x | x | x | x | x | |
| TILLABERY | 14°12' N | 1° 27' E | | | | | | | x | | | | x | |
| ZINDER | 13° 48' N | 9° 00' E | | x | x | x | x | x | x | x | x | x | x | |

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For the region of the experimental square we have basically taken meteorological data. But we realized that, isolated from their Sahelian context, these figures could not be interpreted. This is why we have tried to draw up a balance sheet of anemometric data for the years 1966 to 1975 for all of the stations of the Nigerian Sahel which have continuous measurements. By studying monthly rose diagrams and various climate graphs based on tables of data supplied by the stations of the National Meteoro-

logical Service and by ASECNA[1] we have tried to find out in what way the drought from 1969 to 1973 manifests itself in the climate of the Sahel. In particular, we looked at (1) changes in rainfall patterns -- shortening of the rainy season or decrease in the overall annual amount -- (2) changes in wind patterns by an increase in dry season winds, a decrease in monsoon winds or an intrusion of new winds.

It is difficult to come up with indisputable conclusions. With respect to the climate in Africa, isn't it said that each year is exceptional?

Presentation of Rose Diagrams

The rose diagrams from 1972 to 1974 were made by a computer at the University Institute of Technology of the University of Reims from magnetic tapes supplied by ASECNA using a program written by A. Jarlaud of the UIT. The rose diagrams for 1966 to 1971 were done by hand. Nevertheless, the presentation is pretty much the same. Each rose illustrates the data for the month which is indicated in abbreviated form in the center of the circle. Each sheet caries either the first 6 months or the last 6 months of the year indicated.

The monthly rose diagrams include 3 types of data:

1. The direction of the wind is indicated from Jan. 1966 to Aug. 1968 by the letters of the rose (i.e. 16 directions) and from Aug. 1968 to Dec. 1974 by every 20° (i.e. 18 directions).

2. The velocity V of the wind in meters per second, measured about 11 meters above the ground, is indicated in 3 ways:

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1. ASECNA = agence pour la sécurité de la navigation aérienne en Afrique [Agency for Aerial Navigation Safety in Africa].

V<4 m/s: small dashes
5<V<7 m/s: long dashes
V≥7 m/s: solid line.

3. The frequency of winds per direction and velocity category is indicated for each of the three velocity categories shown by a dash measuring 0.5 mm. A frequency set apart because of its direction and velocity is shown by a cross.

For the entire 10 years all wind directions exist for all of /95 the stations with a more prevailing wind from the northeast in the dry season which is easy to recognize. It is the harmattan. During the rainy season winds blow from the southwest-- south-southwest. Here again they are easy to recognize. These are the monsoon winds which carry water. During the summer months the monsoon winds are accompanied by blasts of wind from the east. During the two intermediate seasons, which can be defined as April and October, winds blow from all directions.

The winds from the north-northwest affect all stations during all months, with a maximum in the winter season from November to February. We are unable to explain what causes these winds. Likewise, we do not know the origin of the winds from the southeast which sometimes become dominant, as in February, 1971. Is it the trade wind from the Southern Hemisphere which crosses the equator without being deflected, or which indeed, according to the scheme of G. Dhonneur, is deflected when it crosses the equator and becomes a monsoon, then in the most continental regions of Africa is deflected again so that it resumes its initial direction?

Study of the Arithmetic Average of Prevailing Winds, Covering the Period of 1961 to 1970 for the Stations of Agadès, Bilma, Birni N'Konni, Maradi and Tahoua

This study reveals winds which are not very effective for transporting sand. In fact, only those of the months of January, February (and March for Tahoua) have average speeds over a period of 10 years greater than 4 meters per second, i.e. winds suitable for transport by saltation of sand when the sand is fine. The most striking fact is, for Maradi and Birni N'Konni, the extraordinary similarity of direction for the average of the prevailing winds except during the interseasonal periods of March-April and October. At Maradi the monsoon winds last a month longer than at Birni N'Konni. Thus one witnesses the triumph of latitude (the difference is small, however) over the criterion of continentality. At Maradi the interseasonal period of March-April is expressed in the wind pattern by harmattan-type winds giving way to winds from the east. The interseasonal period disappears completely at Birni N'Konni, which is characterized by having only two clearly divided seasons -- one receiving winds from the east (thus a harmattan with a regional direction) from October to March and a monsoon coming from the southwest from April to September.

This same well pronounced contrast is found at Tahoua. The months from October to April receive winds from the northeast, typical harmattan, while the months from May to September are characterized by winds whose direction is specifically that of the monsoon, however with two small shifts towards the south-southwest during the interseasonal period: May and September.

Bilma is a typical Saharian station, especially subject to /96
the harmattan 11 months out of 12. Agadès, although it lies in the latitude of the Sahara, receives winds whose direction is controlled by the arrangement of obstacles surrounding it.

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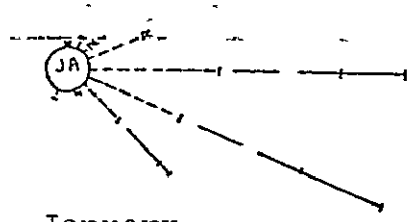


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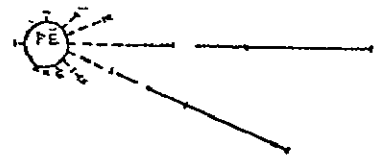


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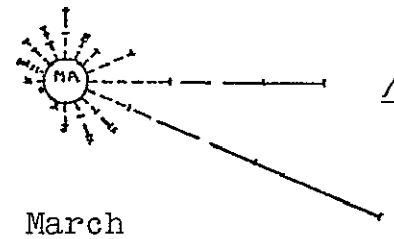


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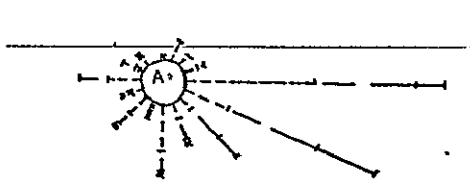


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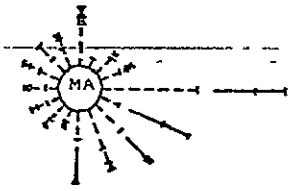


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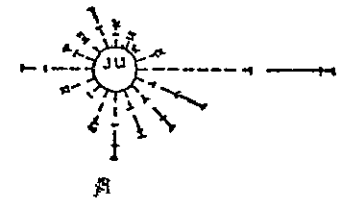


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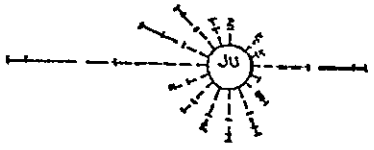


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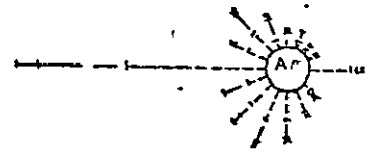


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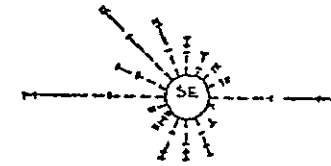


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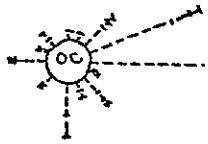


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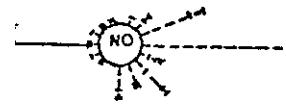


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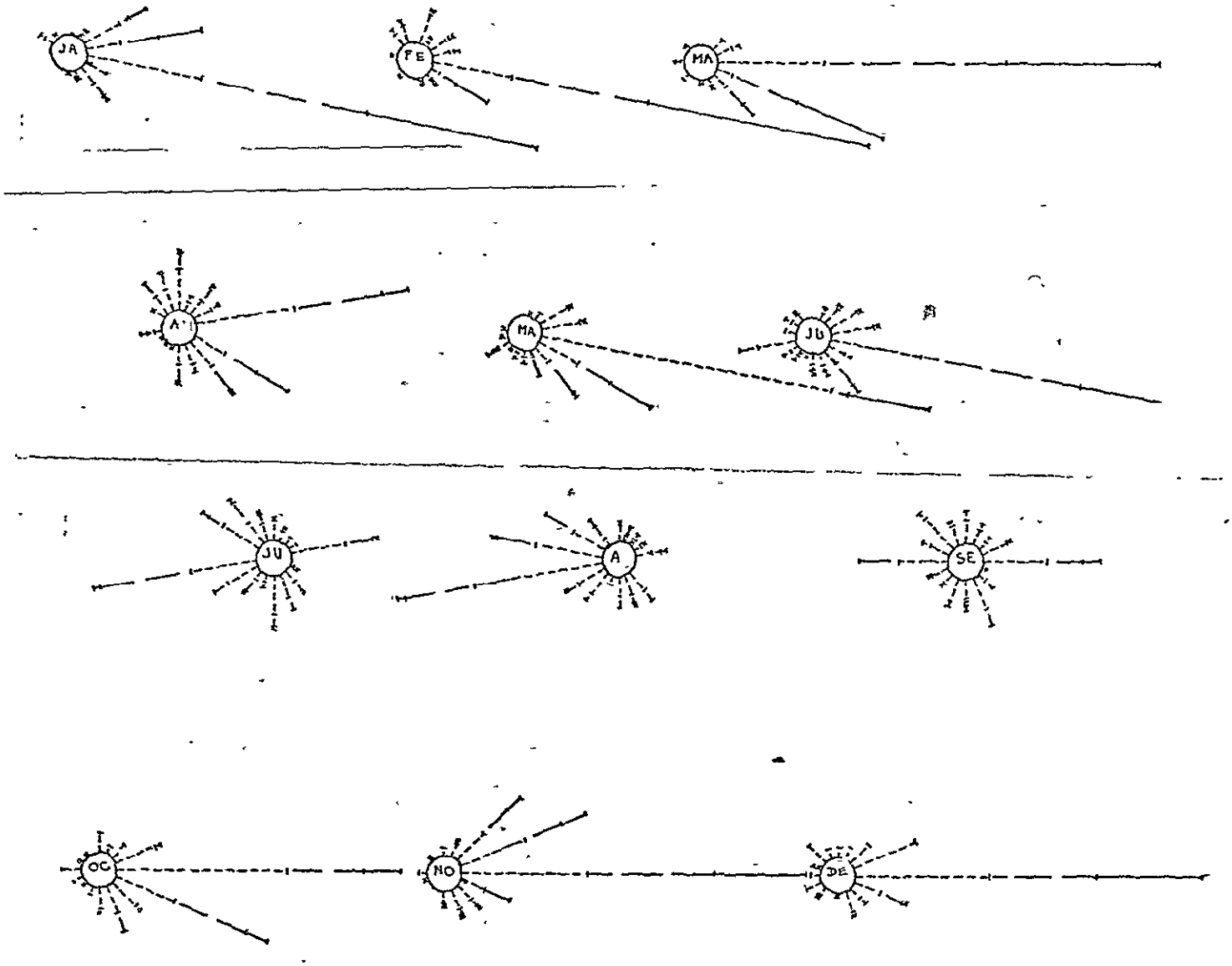
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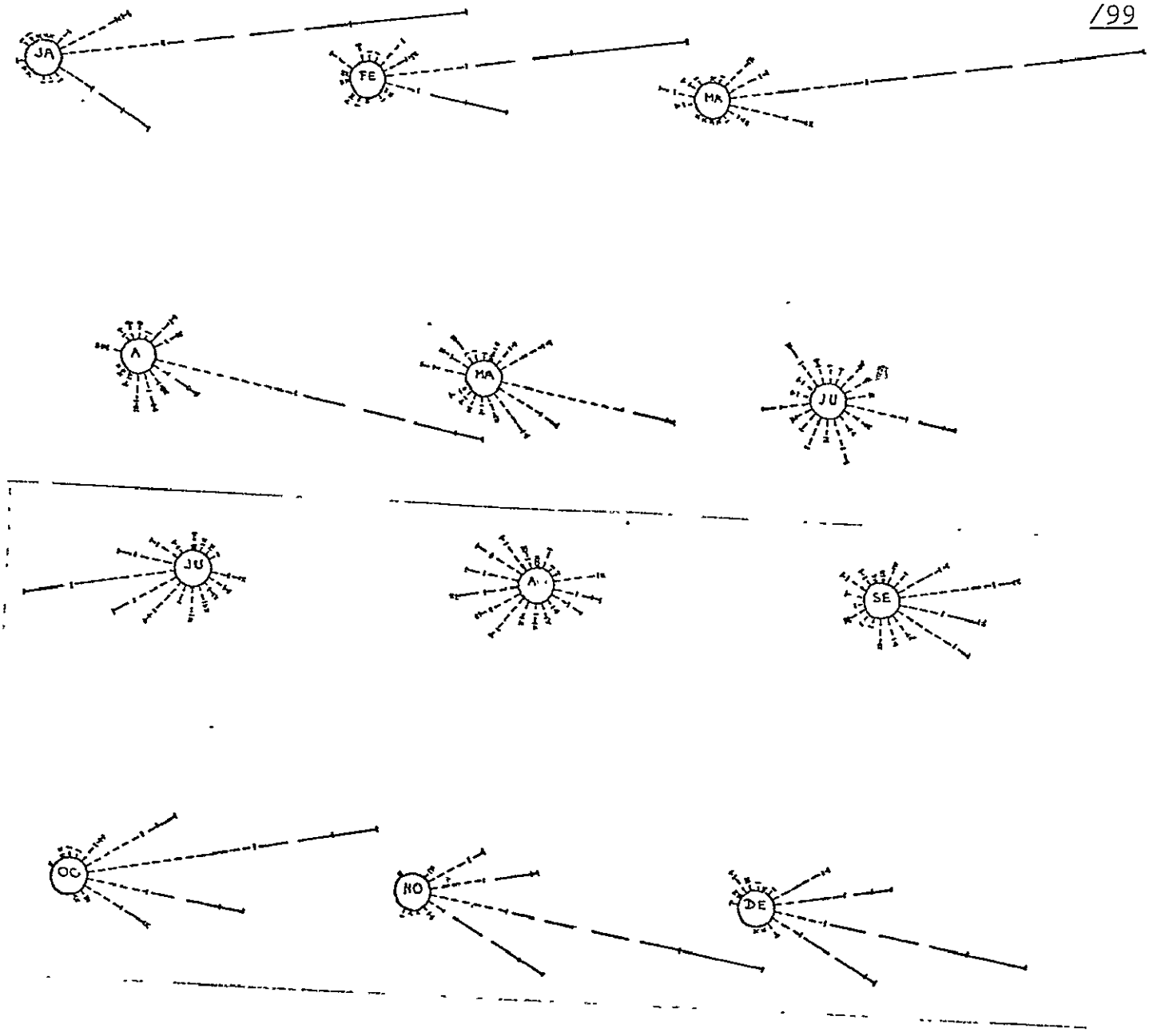
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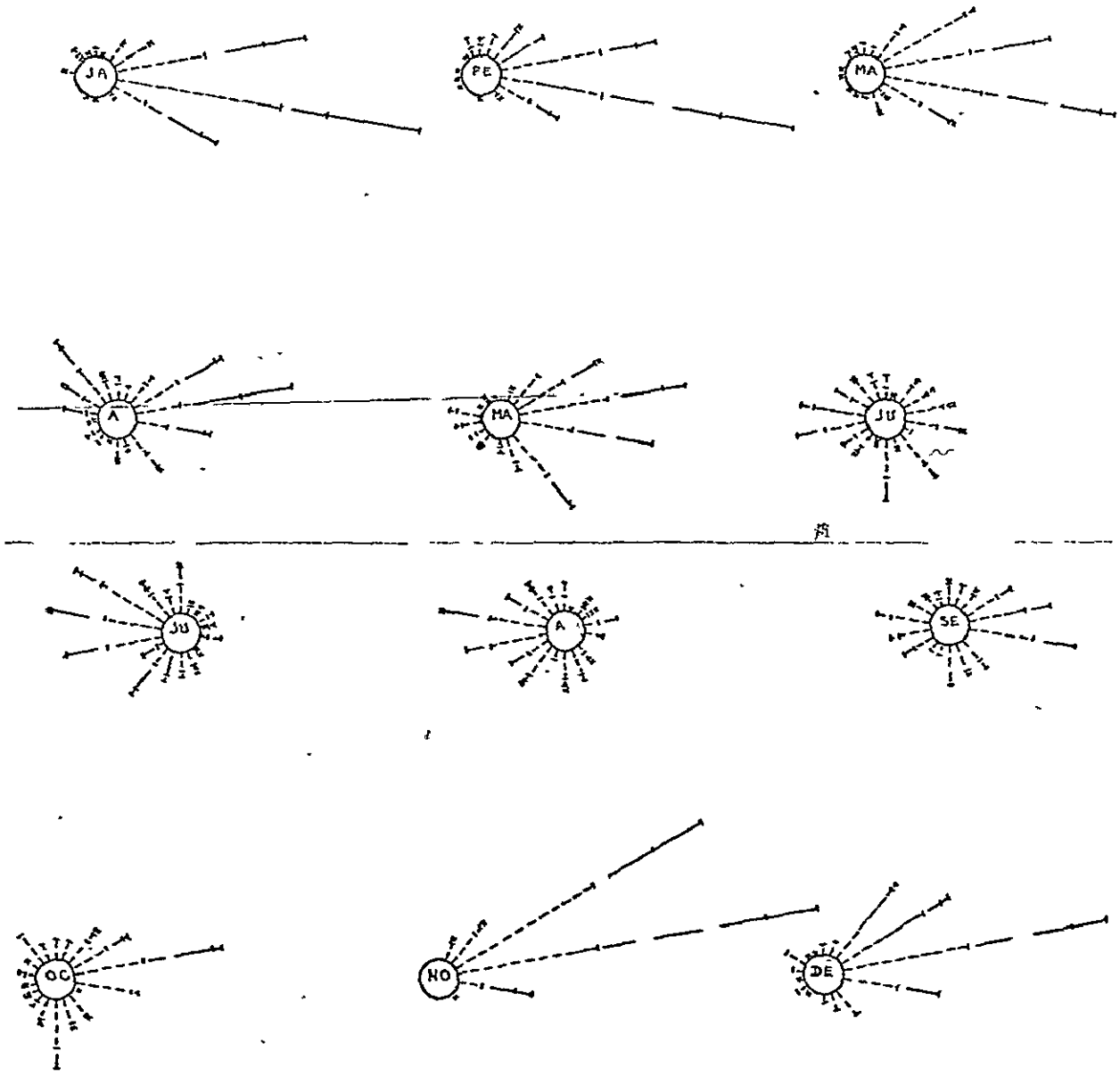
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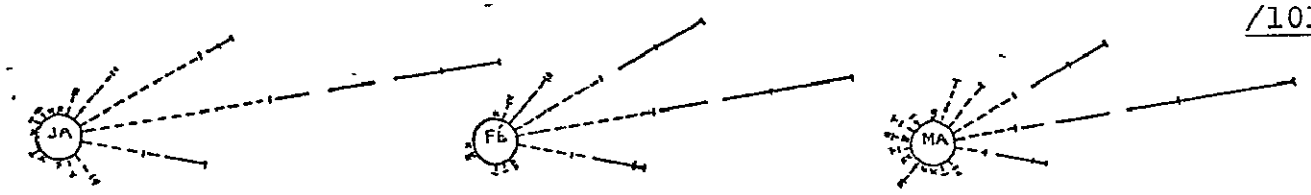


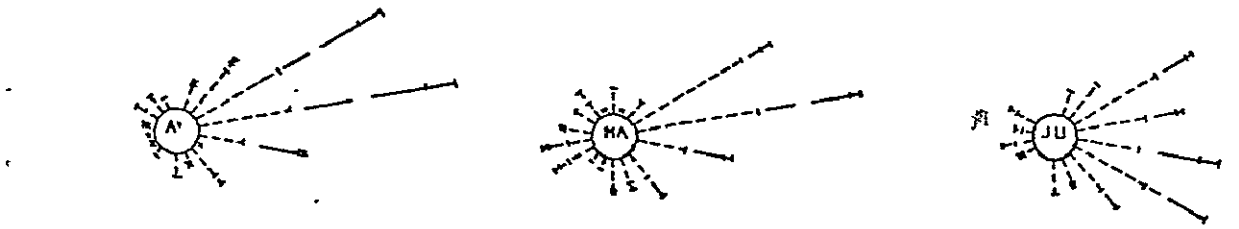


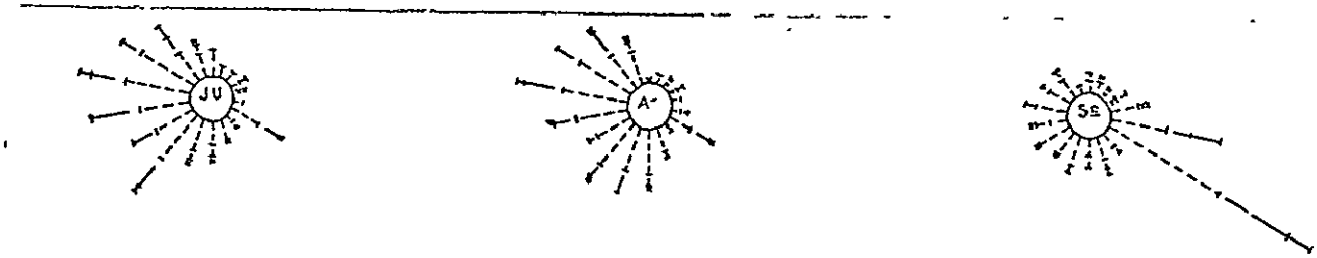


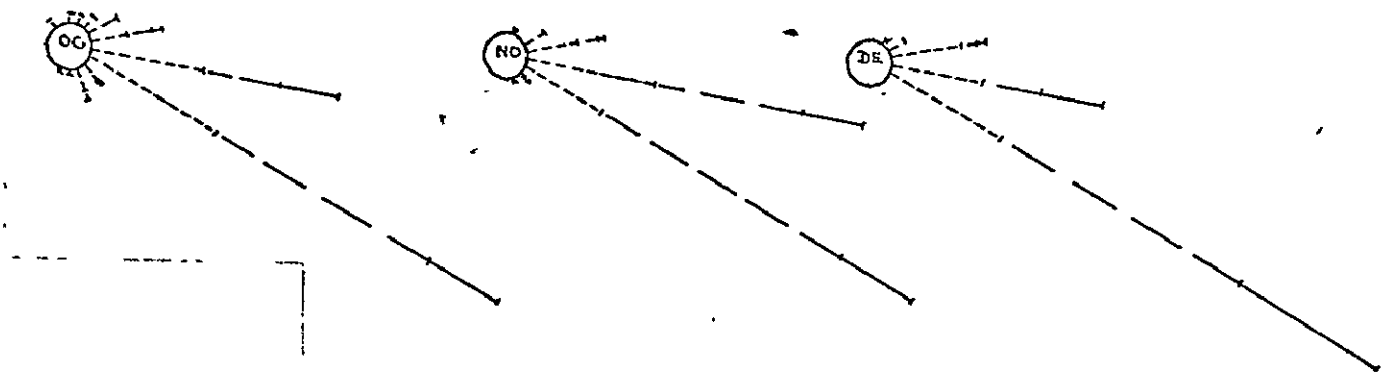

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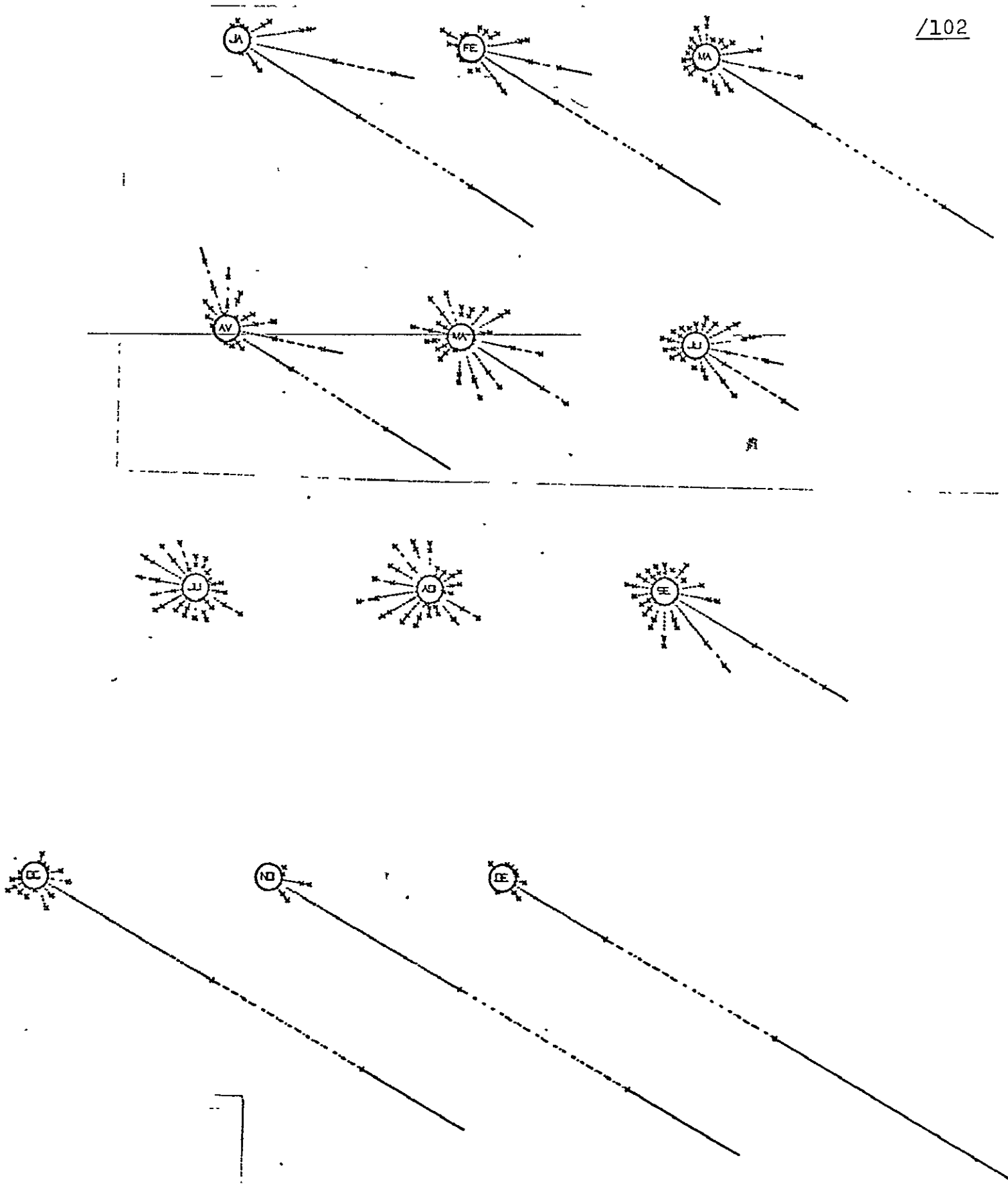

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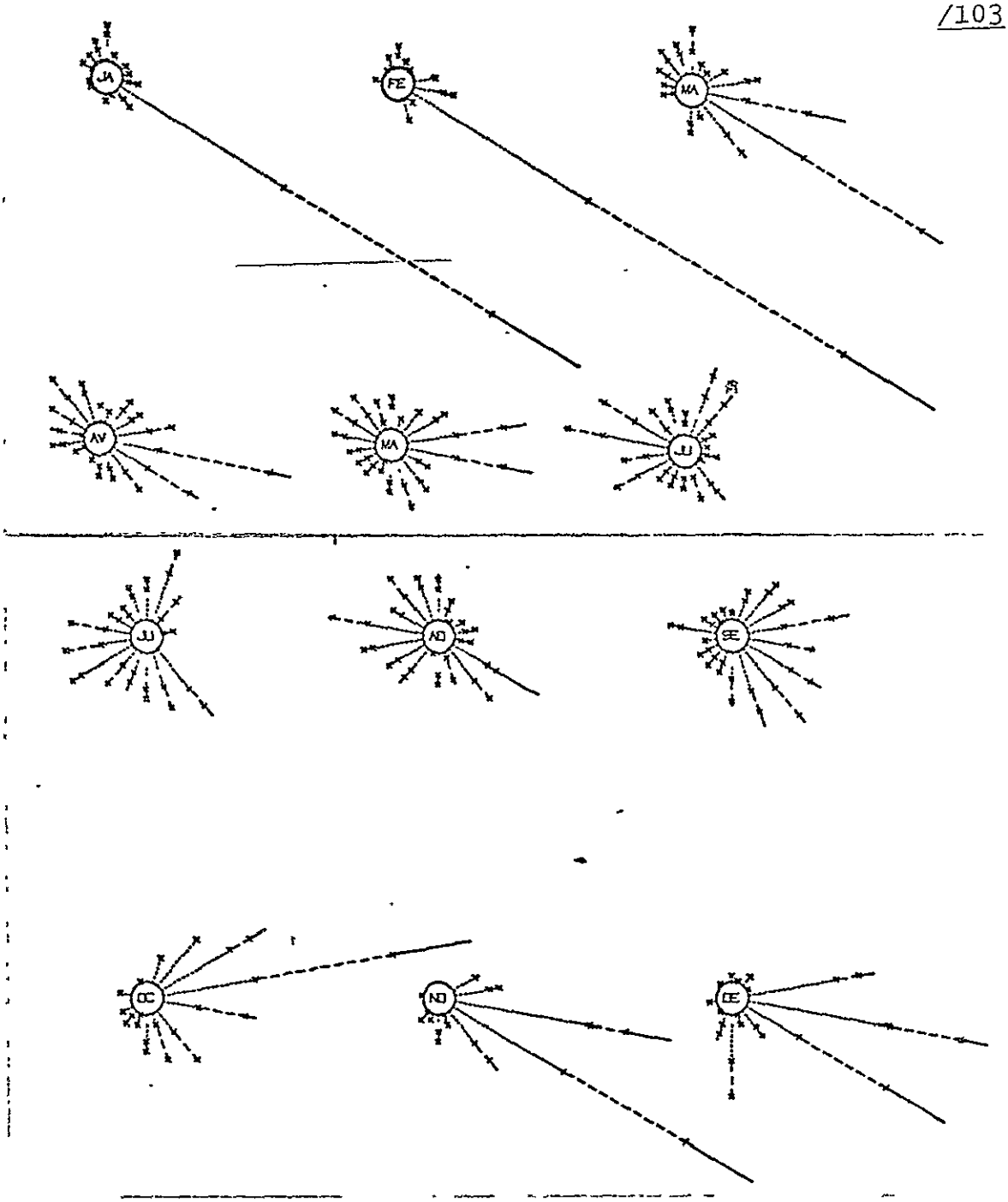
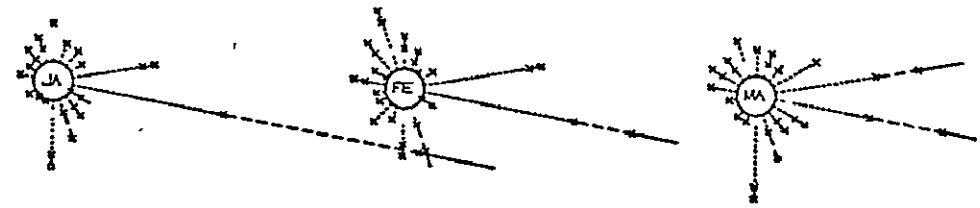



AGADES 1972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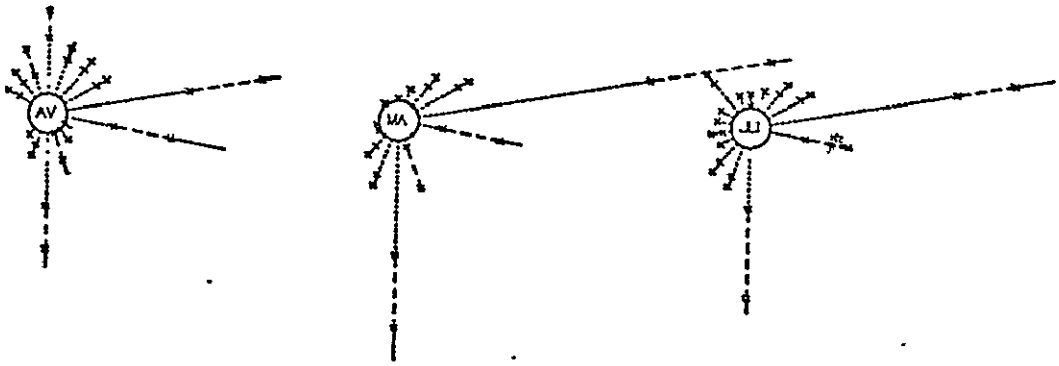
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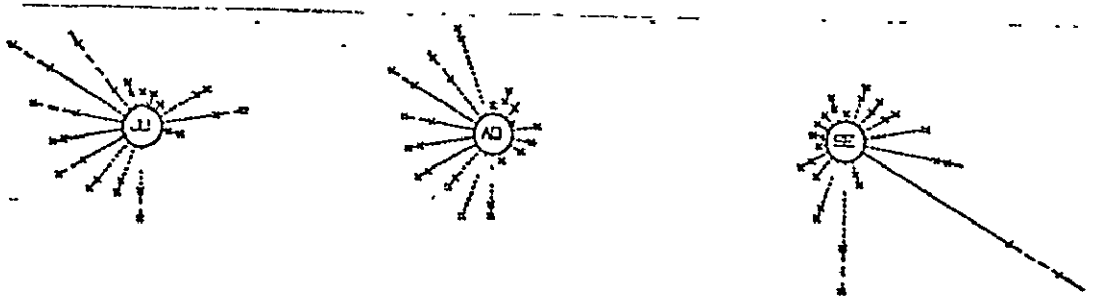
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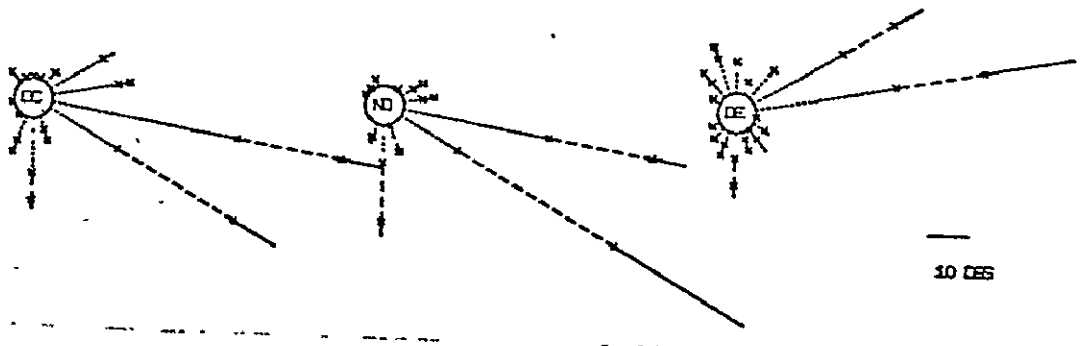
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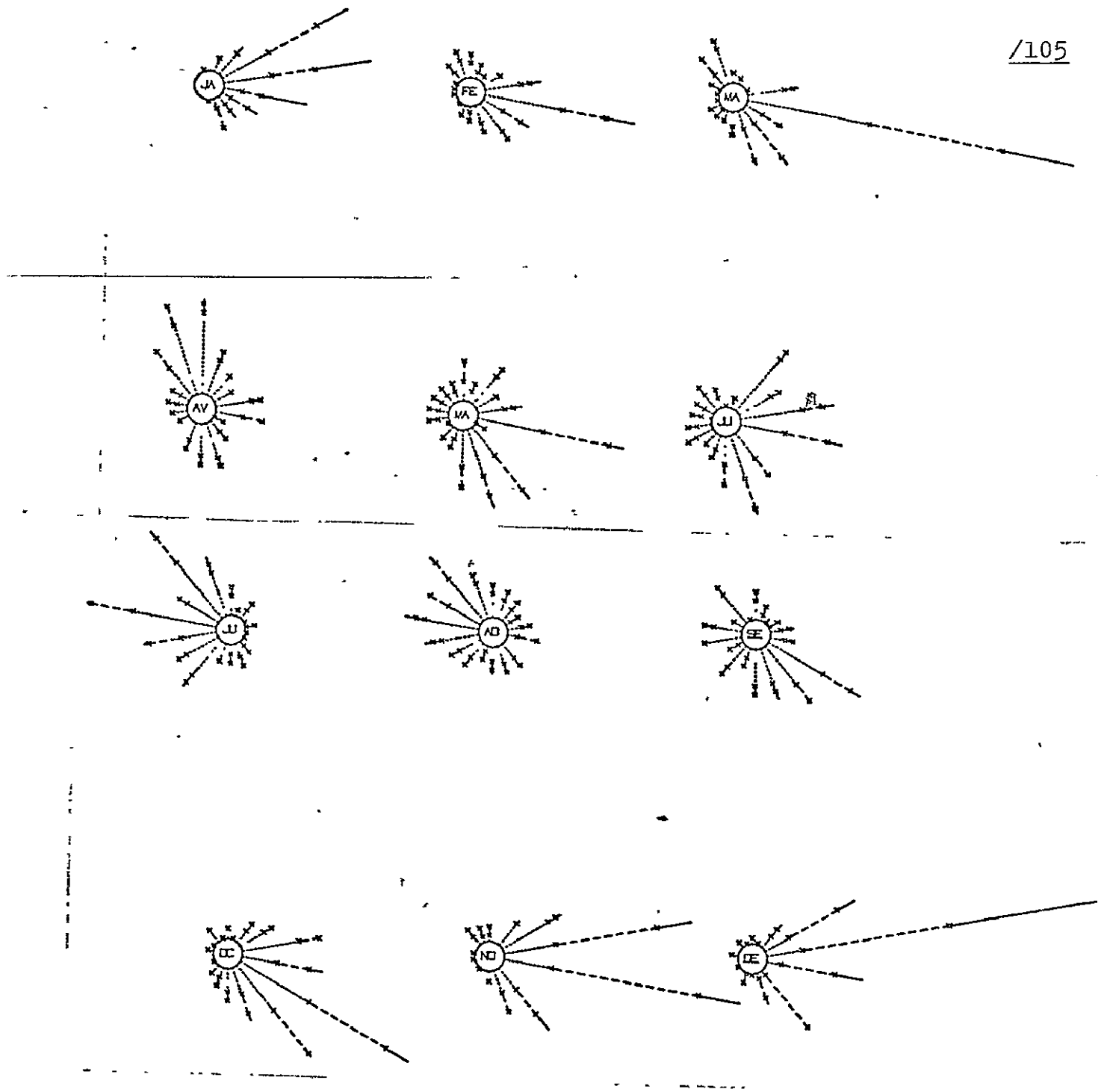

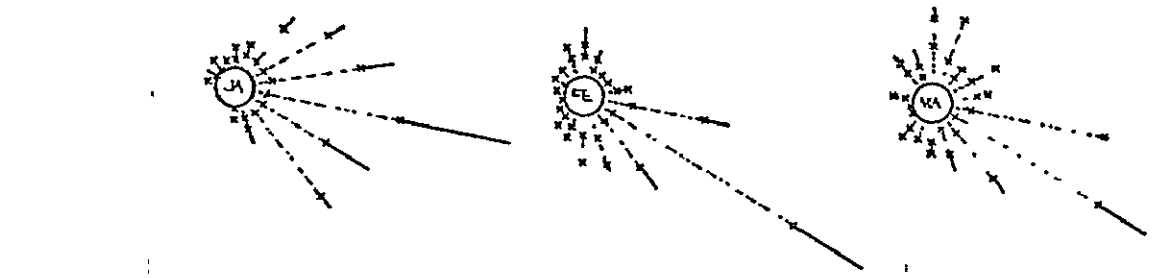

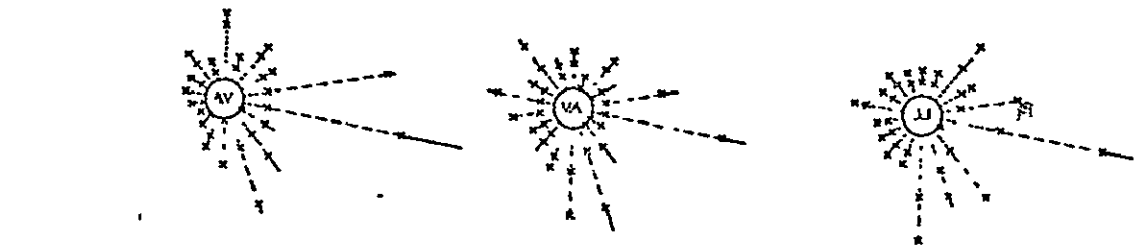

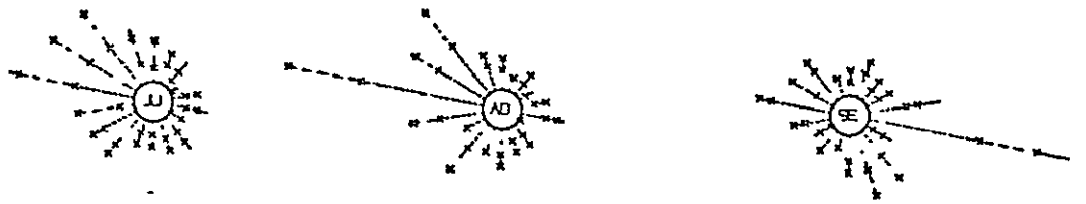

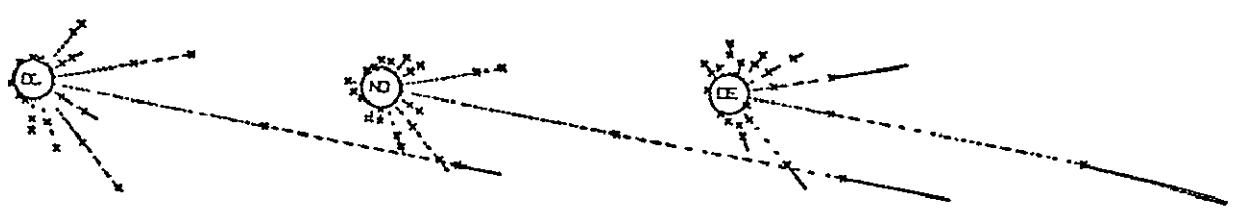

Monthly Rose Diagrams for the Period 1966 to 1975 /107

Agadès (latitude: 17°N Longitude: 7°59'E)

Agadès could be refered to as a station of obstacles. Its position, hemmed in by the southwest overhang of the Aïr, explains the three prevailing wind directions: winds from east-southeast (i.e. regional direction) from October to June; winds from the west from July to September, the latter being the transition month; very violent, effective and frequent winds blew from the southeast from September, 1970 to May, 1971. They stopped in July and August, 1971 and resummed again until May, 1972. We still do not have an explanation for these winds from the southeast.

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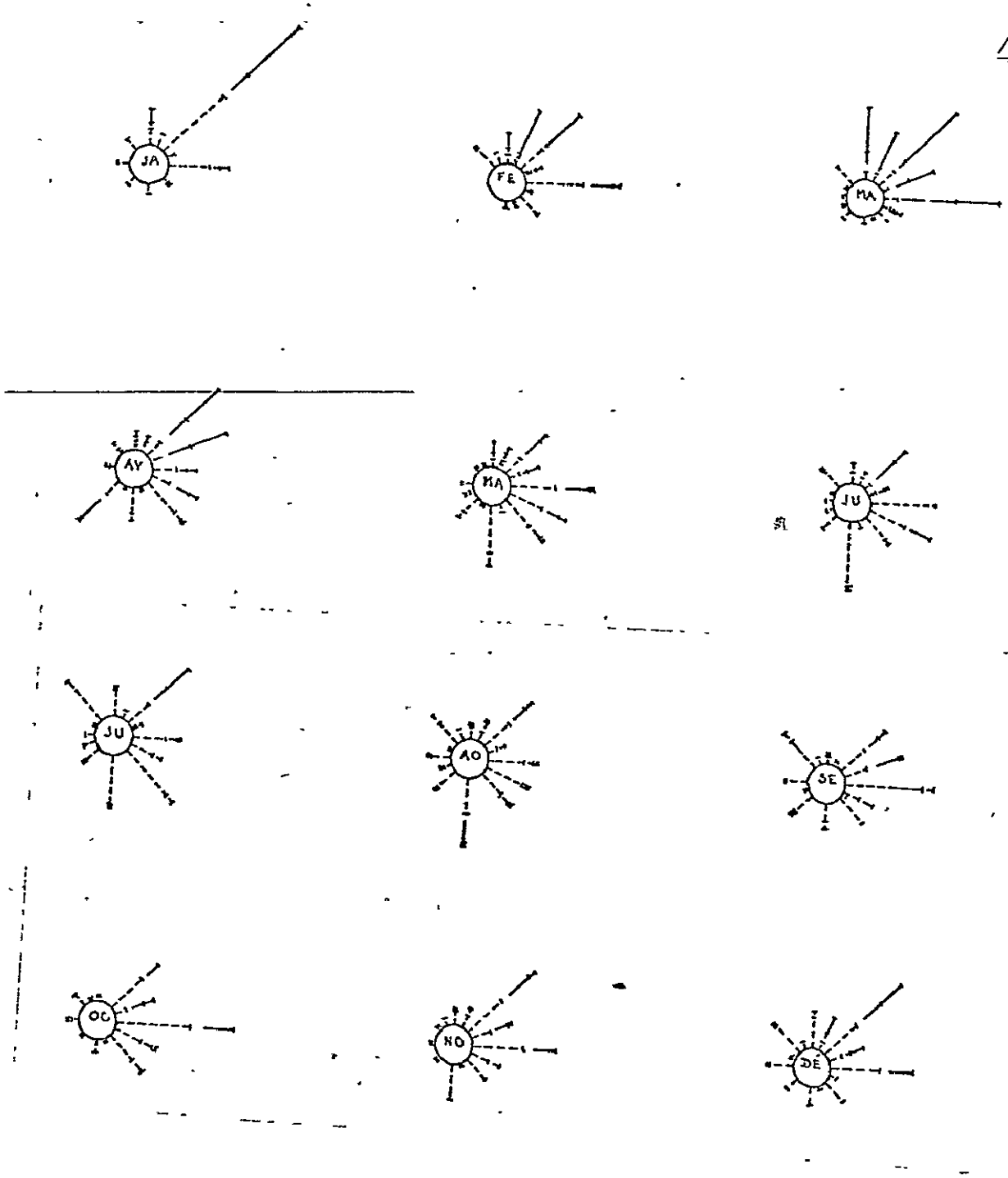


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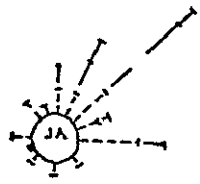
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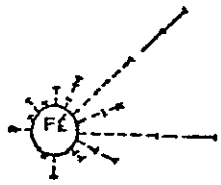
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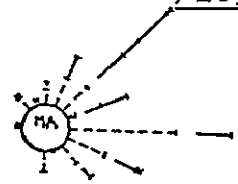
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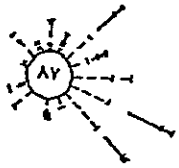
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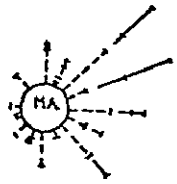
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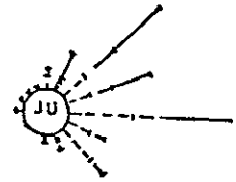
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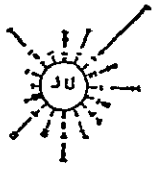
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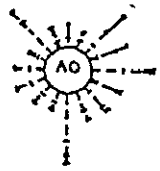
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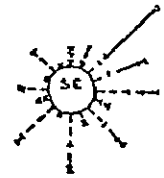
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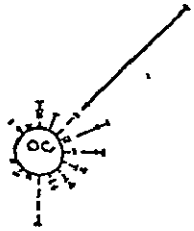
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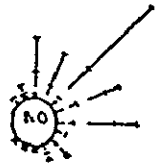
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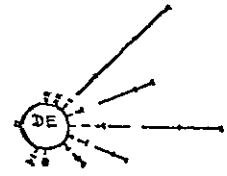
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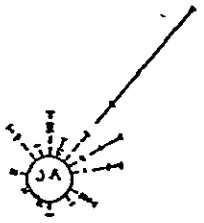


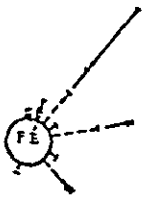


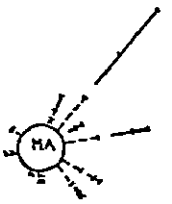


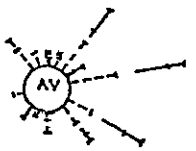


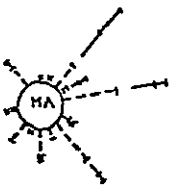


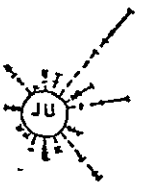


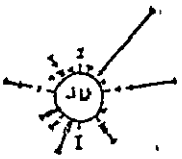


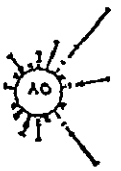


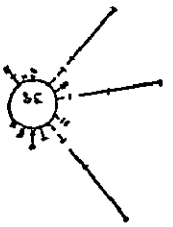


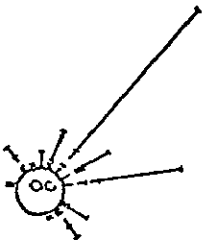


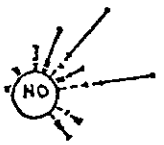


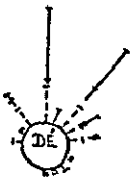

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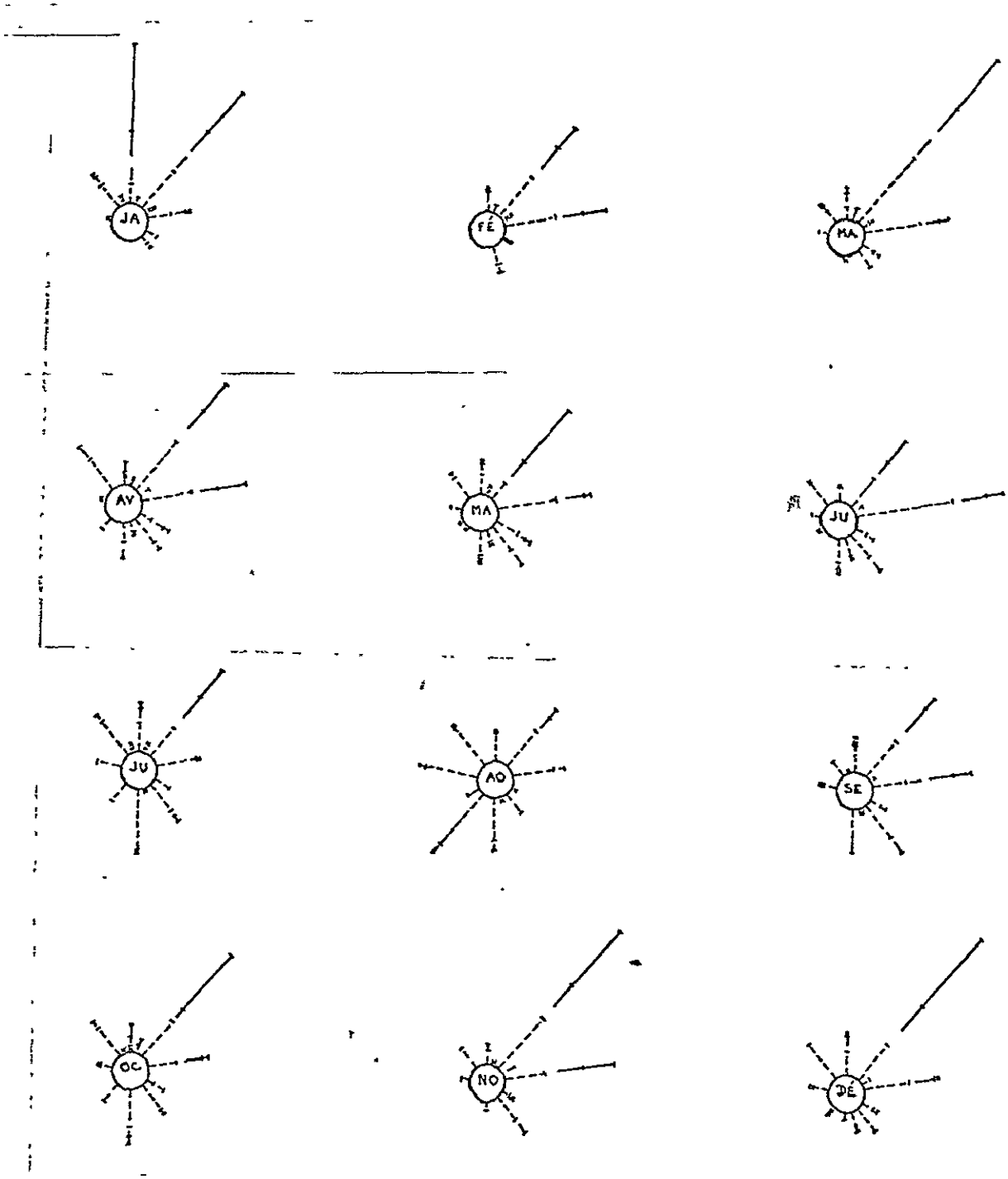
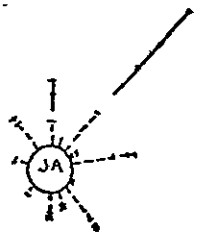
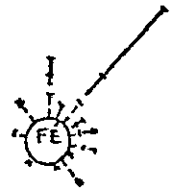
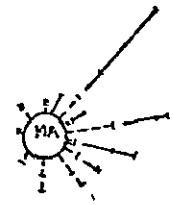
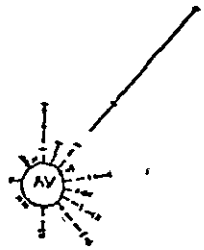


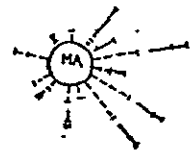

BILMA 1969

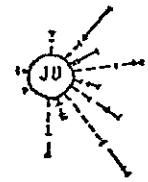


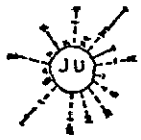



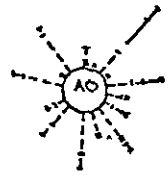



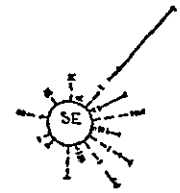



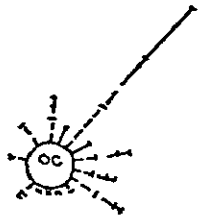



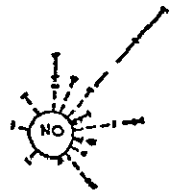



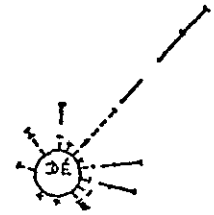



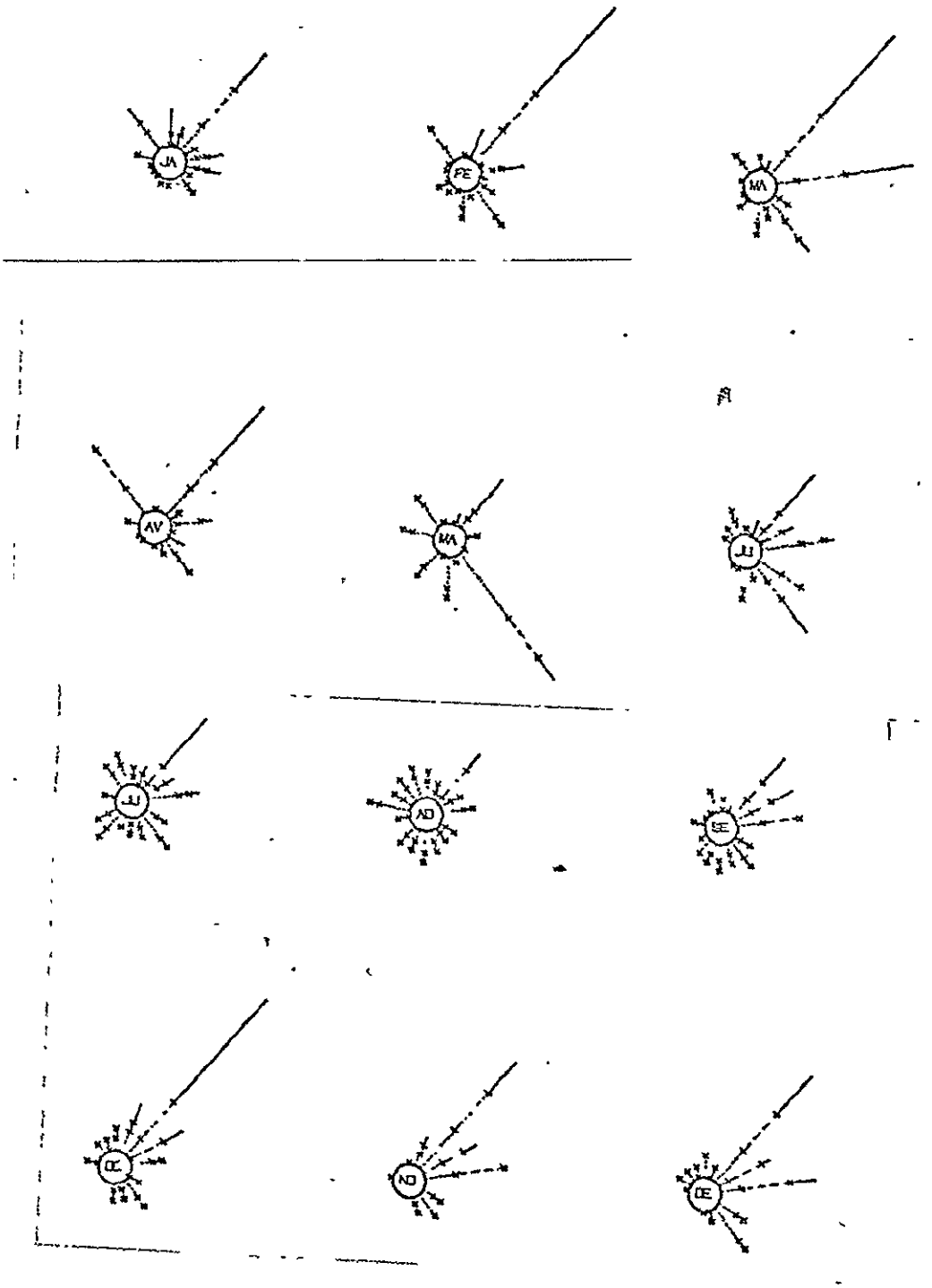



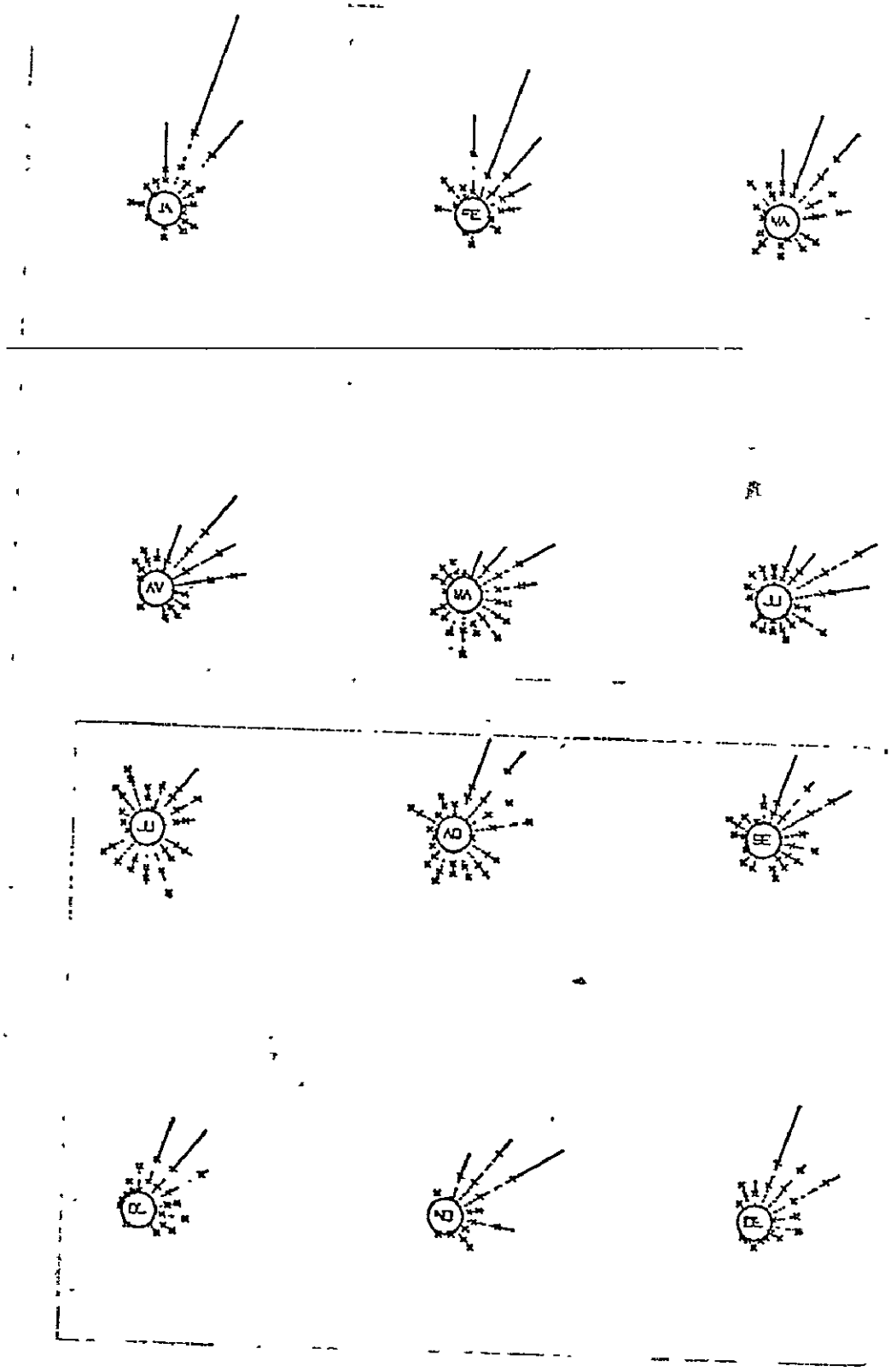



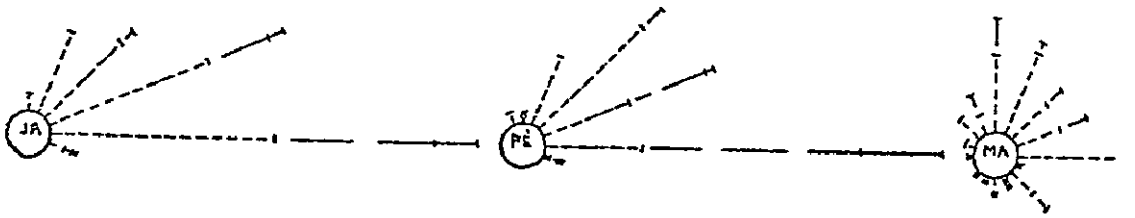

BILMA 1970

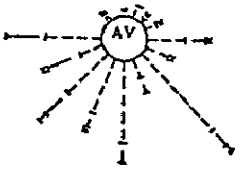


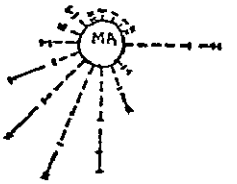


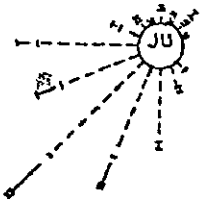
Monthly Rose Diagram for the Period 1966 to 1975 /115
Bilma (Latitude 18°41'N Longitude 12°55'E)

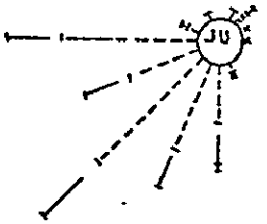
Bilma is an example of a Saharian station for which the majority of prevailing winds are recorded from the north-east quadrant. There are some exceptions: April, 1966, when the prevailing wind is from the southwest, and May, 1972, with the prevailing wind from the southeast.

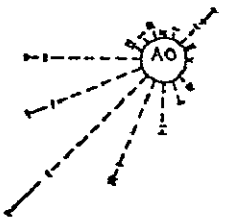


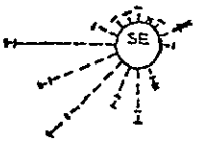



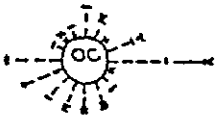



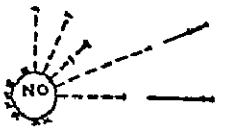



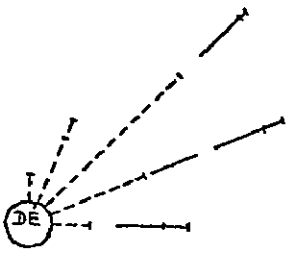



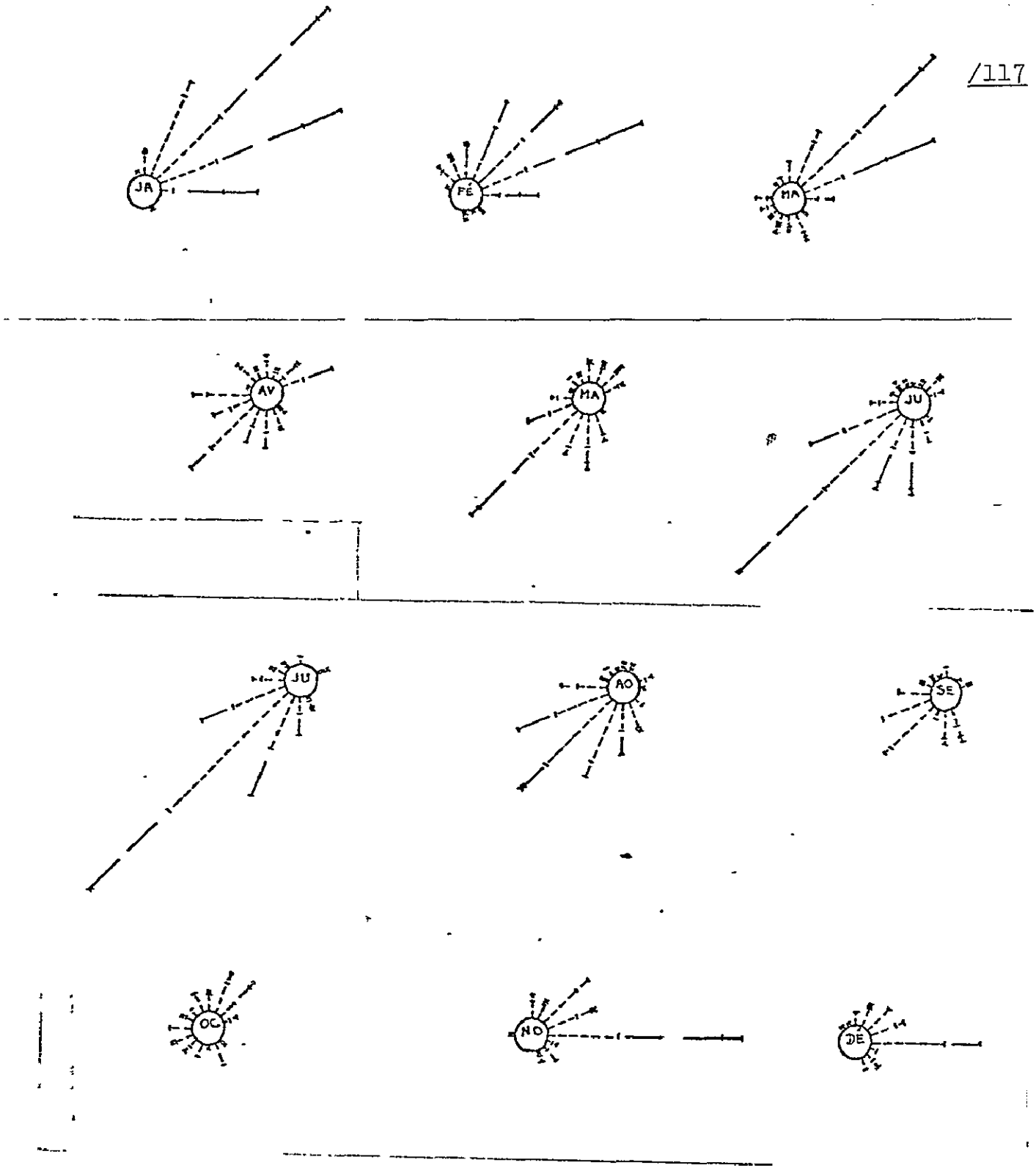




BIRNI N'KONNI 1966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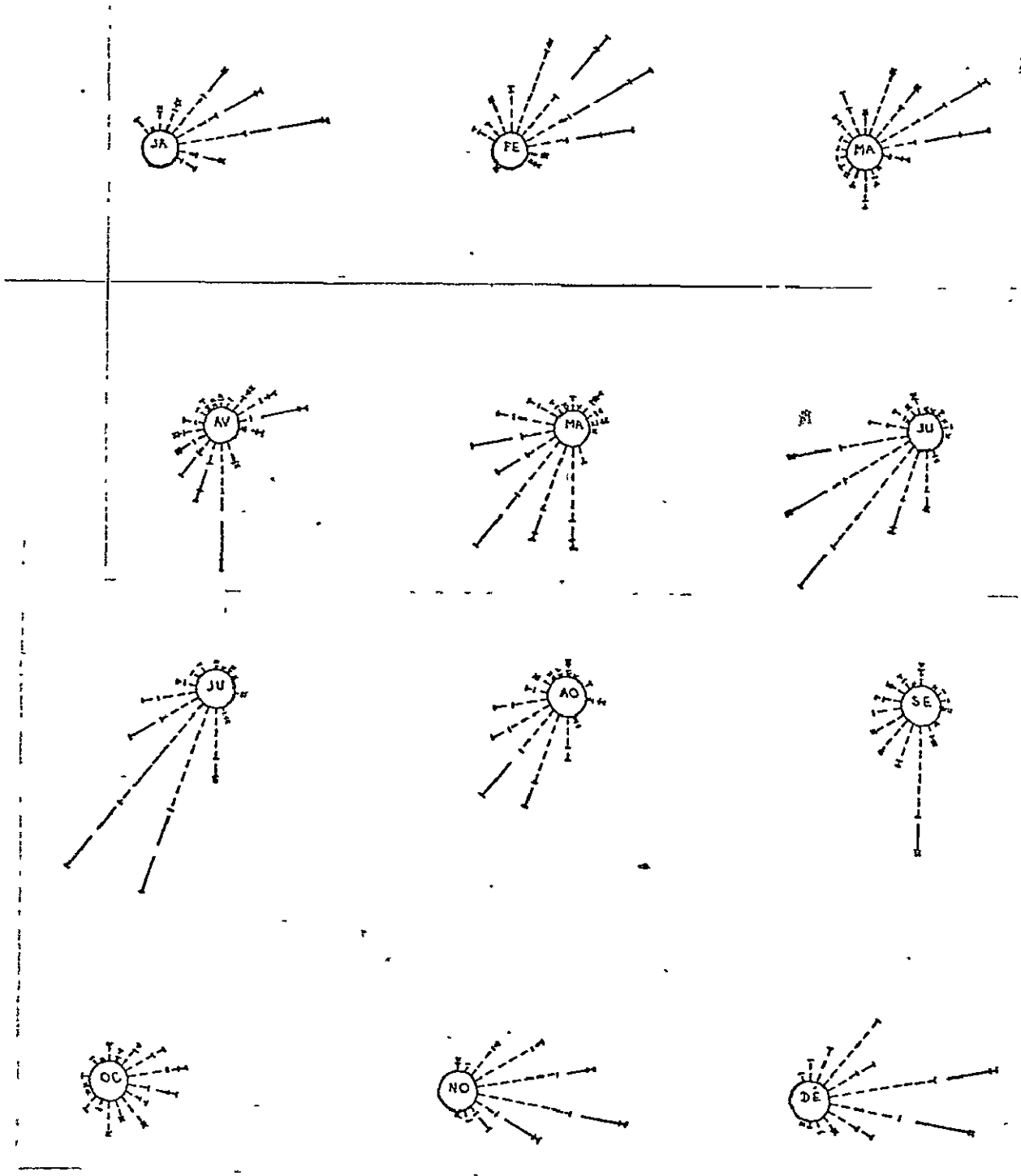
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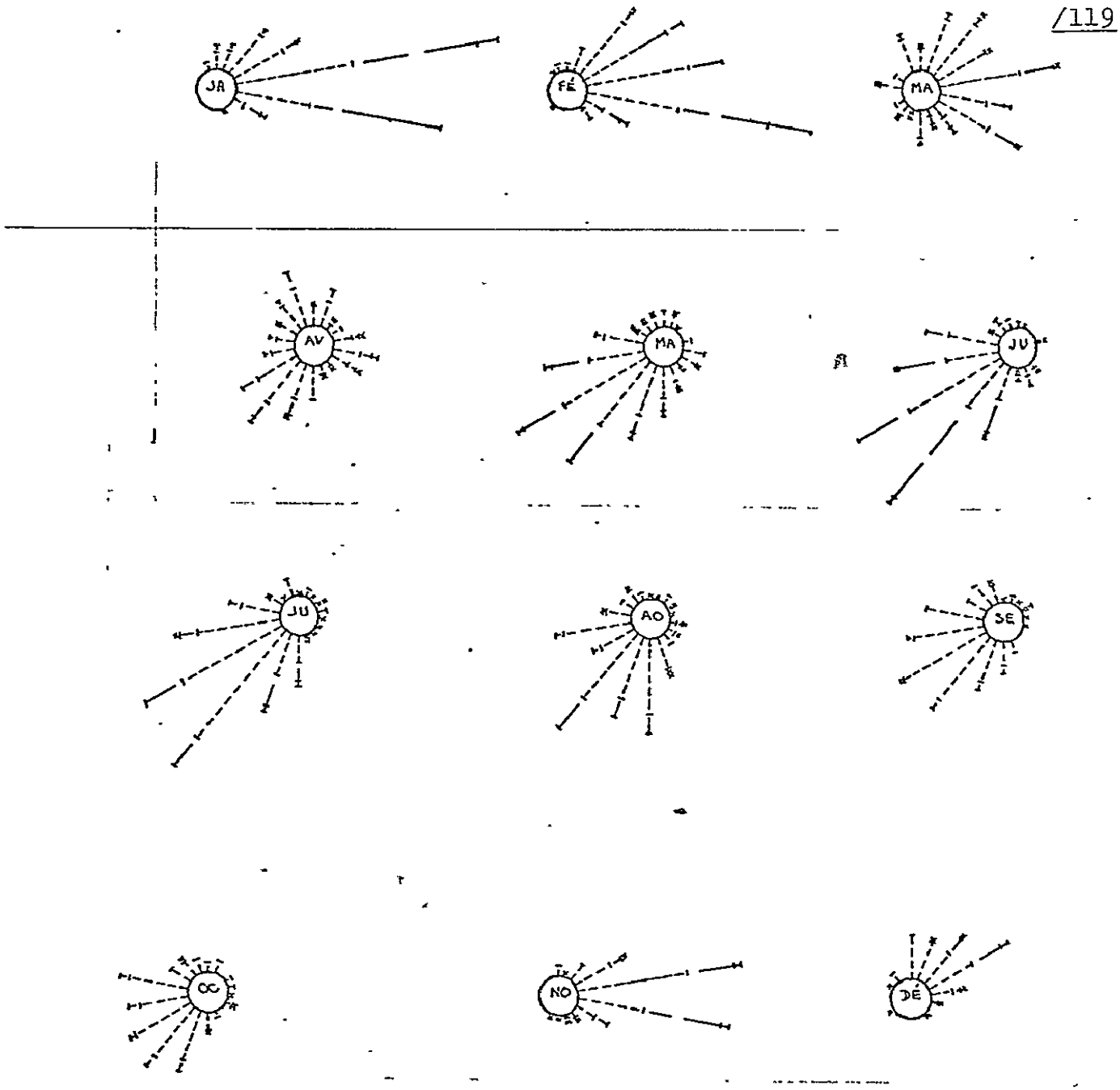




BIRNI N'KONNI 1969

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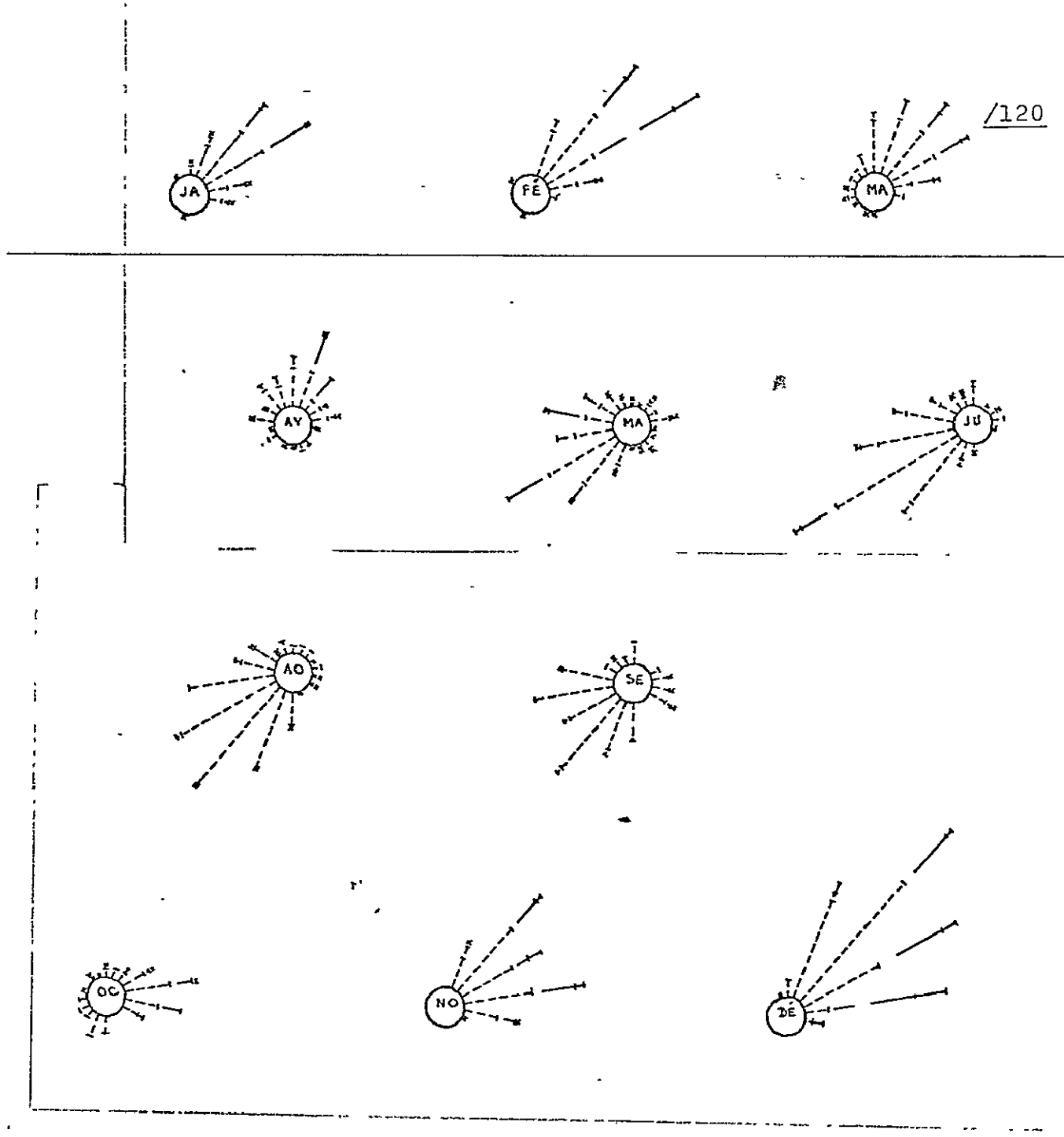

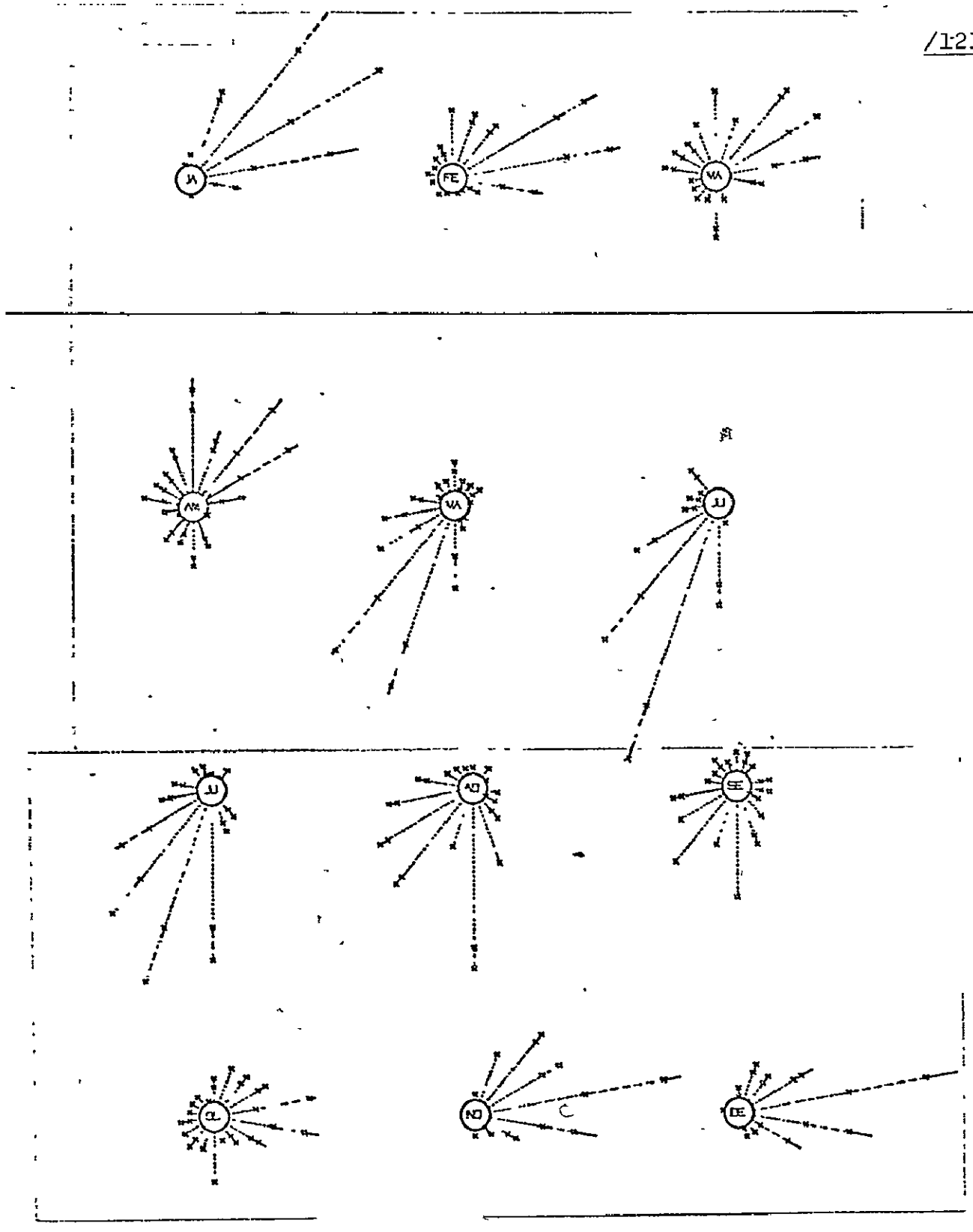

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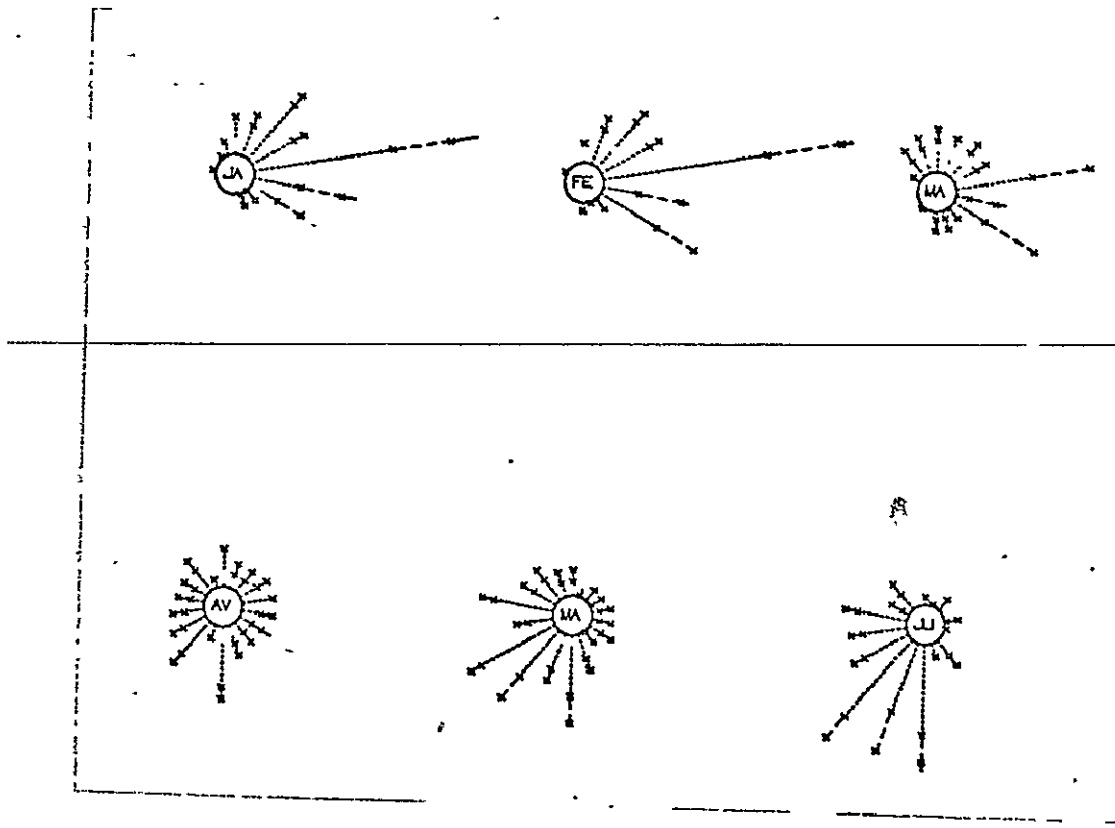


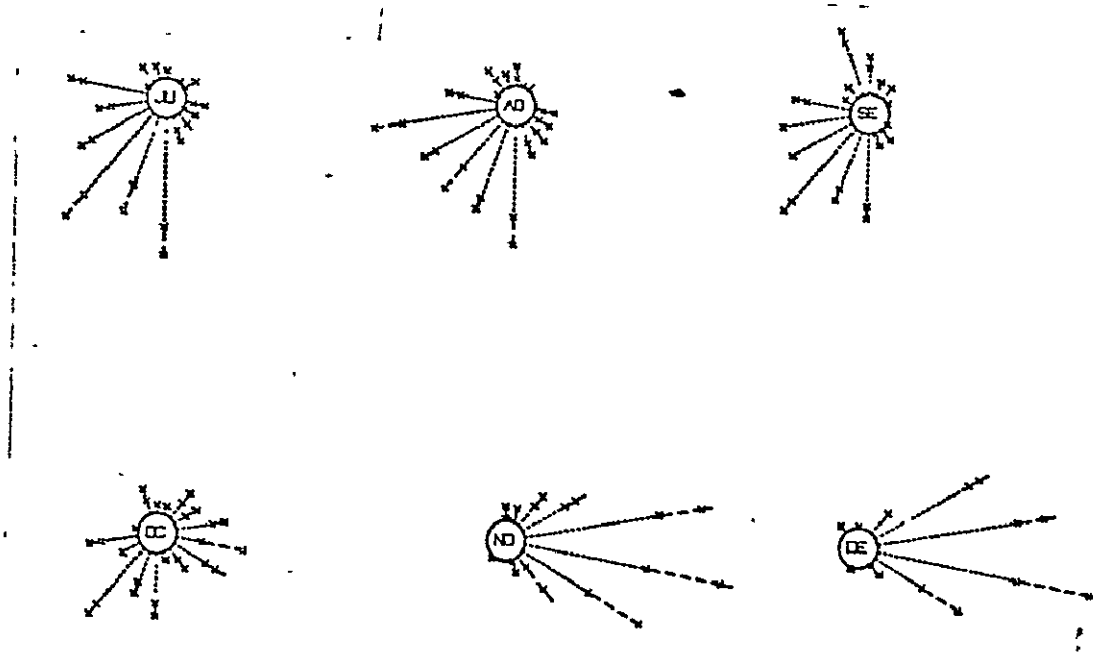

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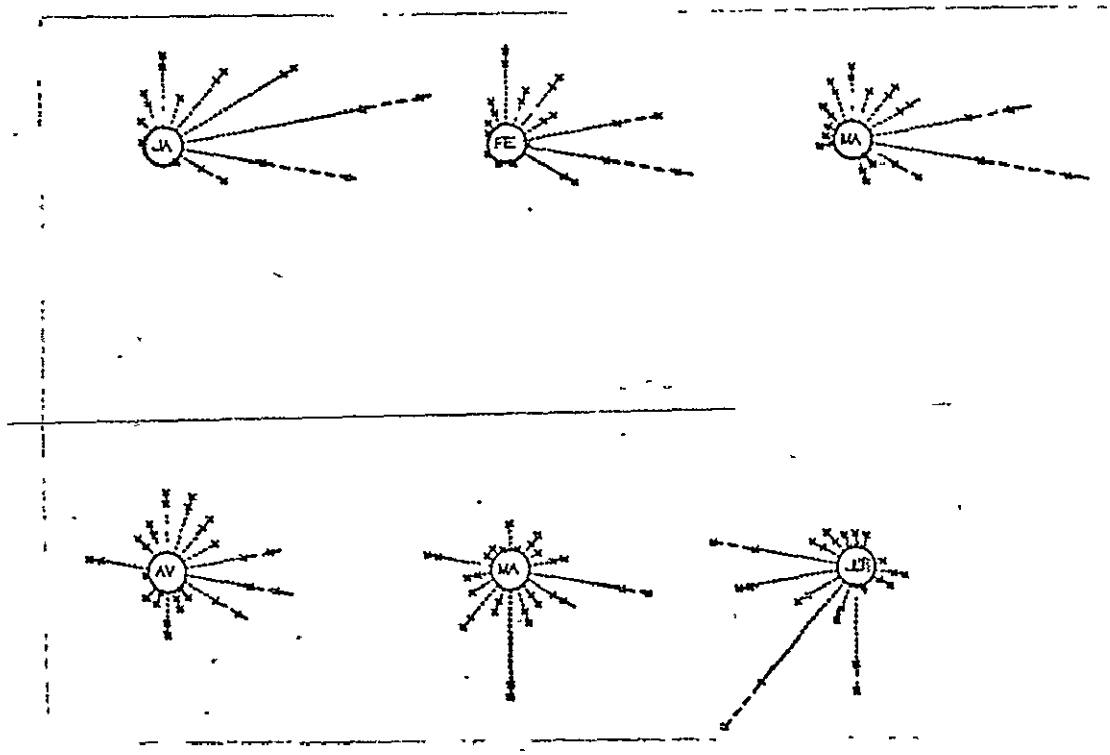
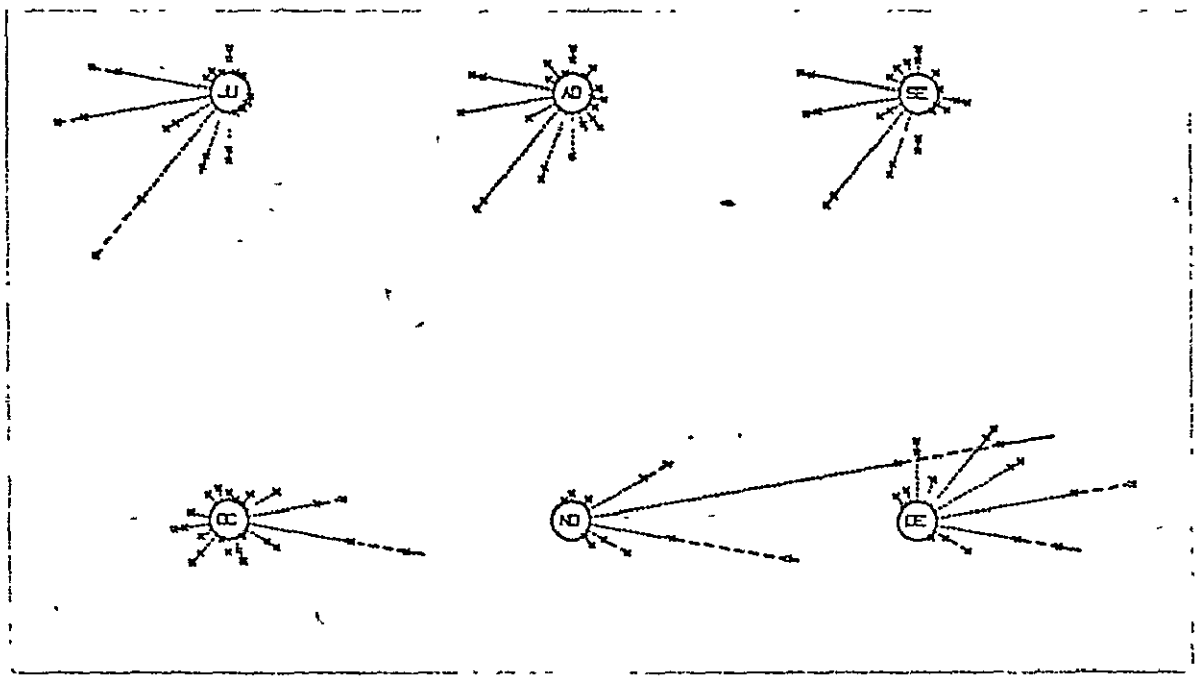
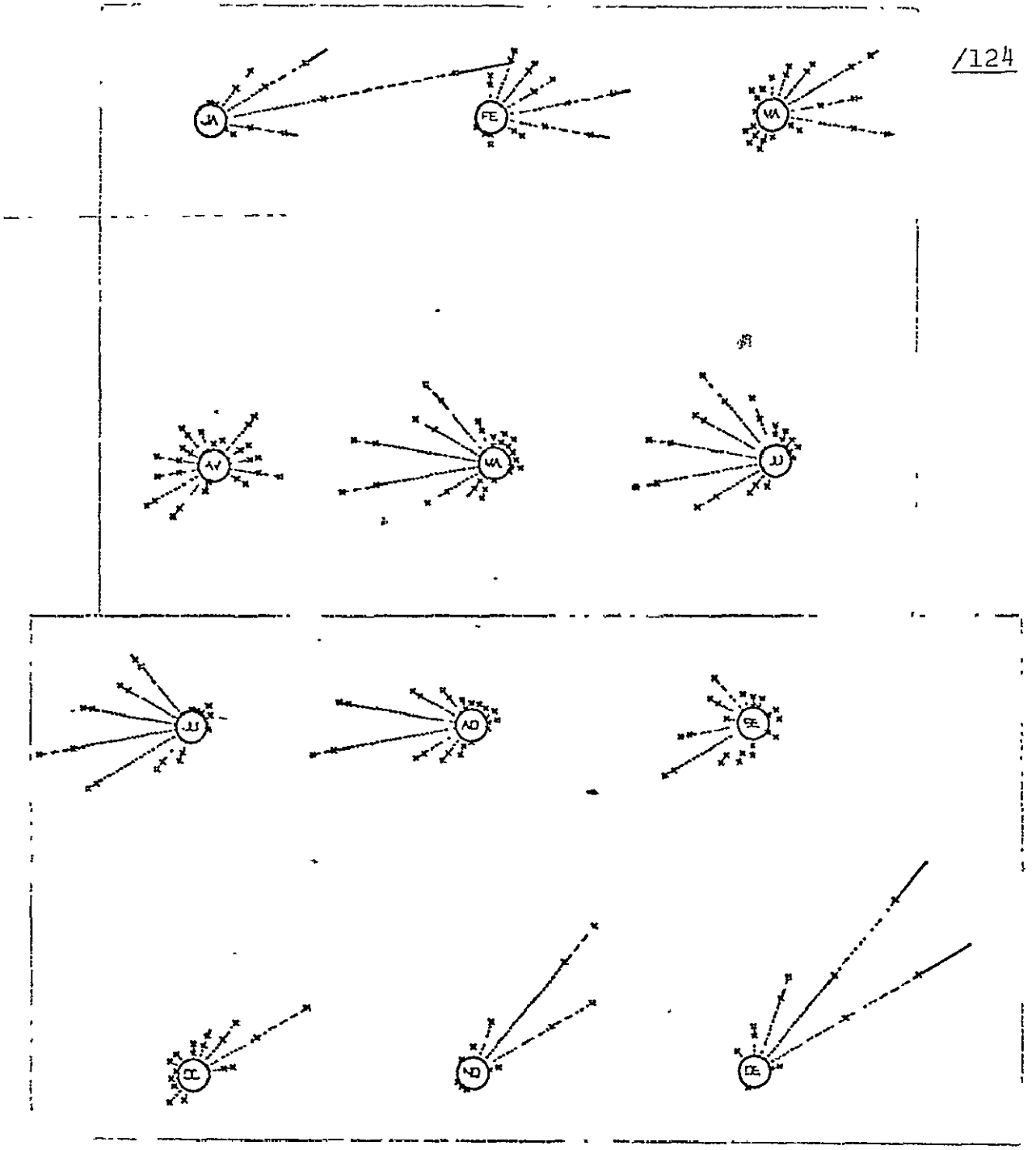
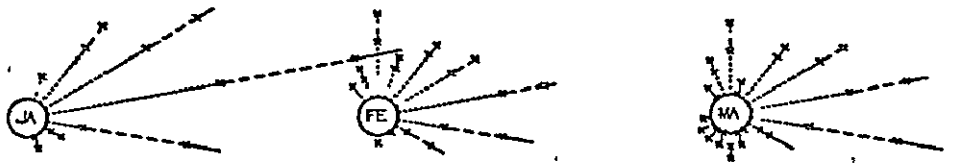




BIRNI N'KONNI 1973

/124

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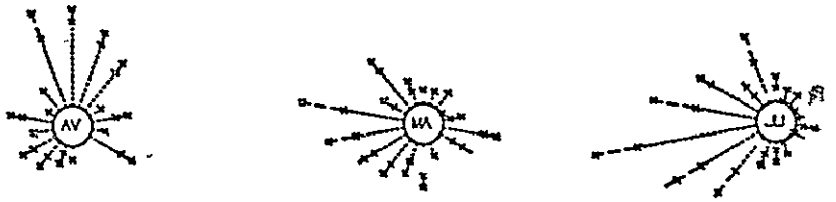
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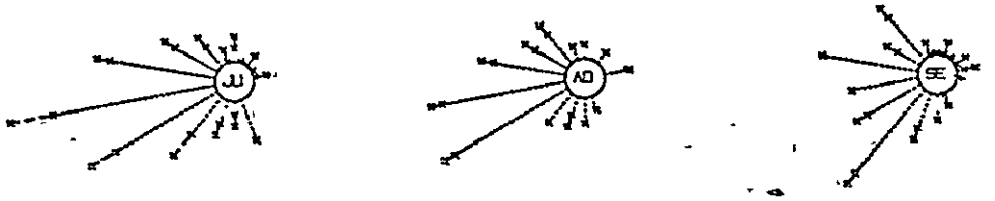
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Monthly Rose Diagrams for the Period 1966 to 1975 /126
Birni N'Konni (Latitude: 13°48'N Longidute: 5°15'E)

1 - Dry Season (November to March).

The dry season is clearly marked, with winds from the north-northeast - east quadrant (1966-67-68), sometimes spreading to east-southeast.

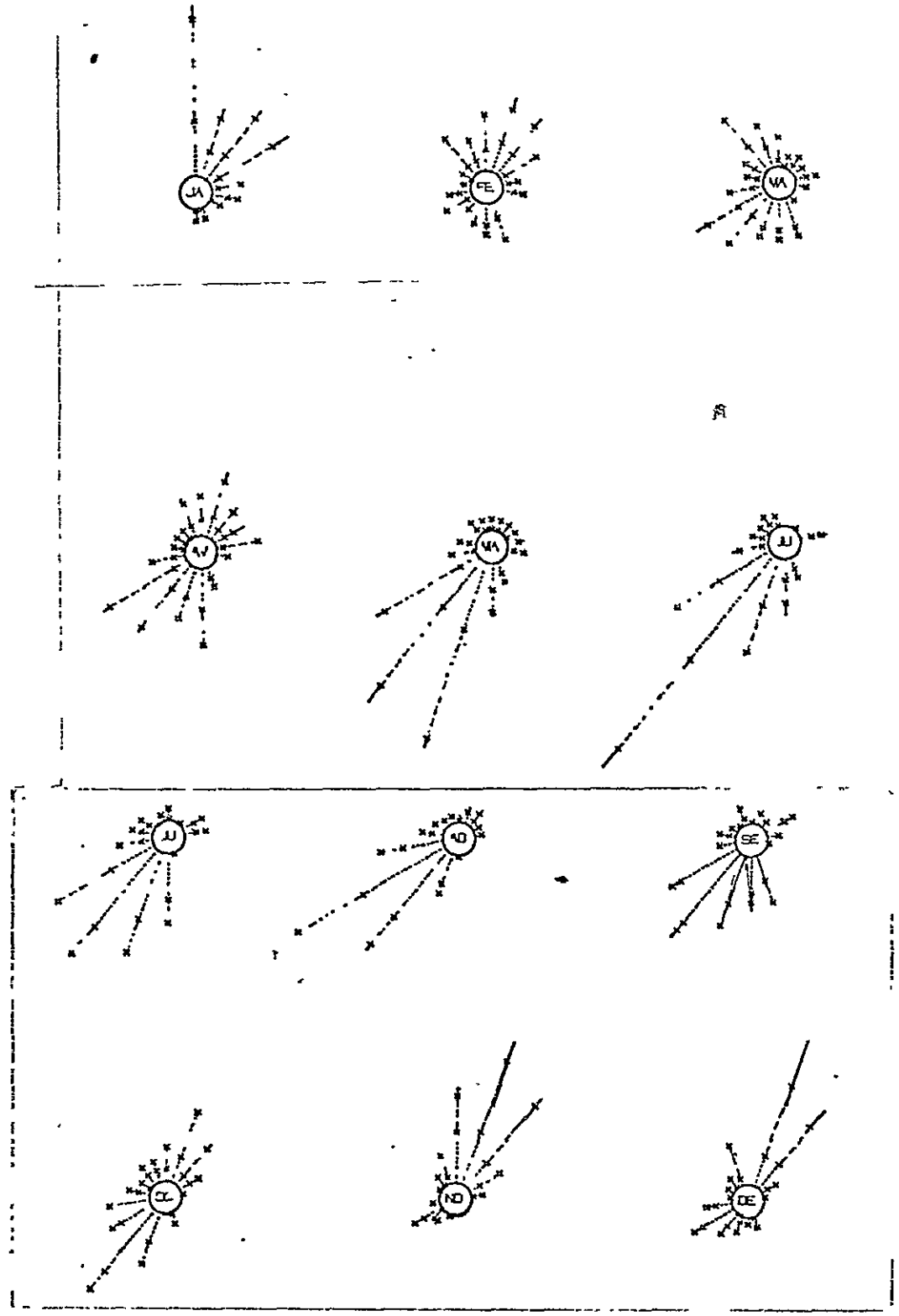
2.- Interseasonal Periods

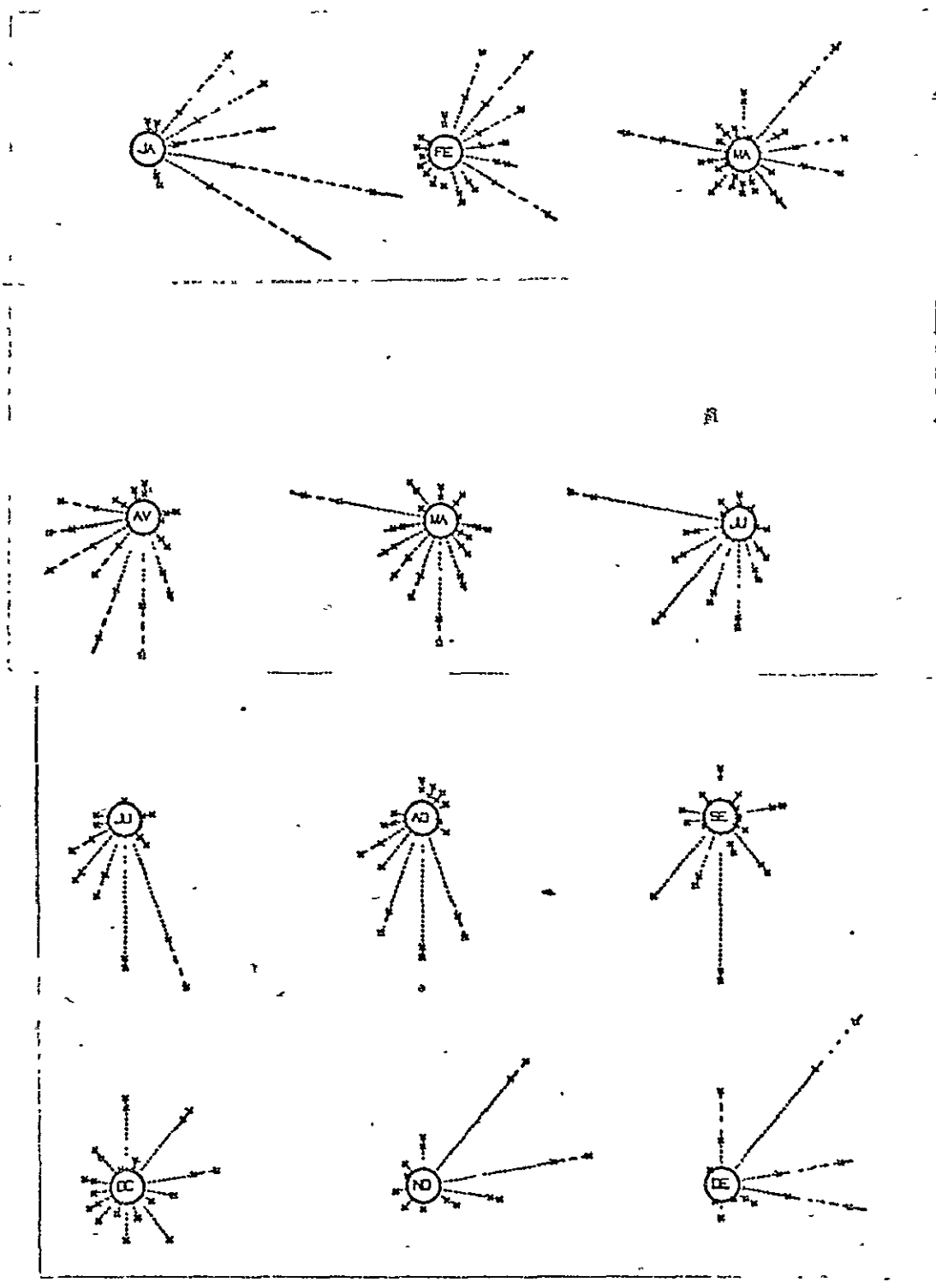
April. During the entire month of April the winds have no prevailing direction. This a typical transition month. Effective winds at this time are rare.

October. This month can already herald dry season winds. It then presents a prevailing direction from the east. This is the case for 1966, 1971, 1973 and 1975. It can also still receive winds of the rainy season type, but this is rare.(1969). On the whole, October, like April, is devoid of effective wind.

3 - Rainy Season (May to September).

From May to September Birni N'Konni is under the influence of the monsoon. The effective winds can be nearly as frequent as during the dry season. The wet season months with the greatest amount of effective windsaare July and August. In general, the monsoon winds are concentrated in the south=southwest directions, with a prevailing wind from the southwest - west-southwest. From 1973 to 1975 the direction of the rainy season winds was more southerly with the prevailing direction spreading from west-southwest to northwest.

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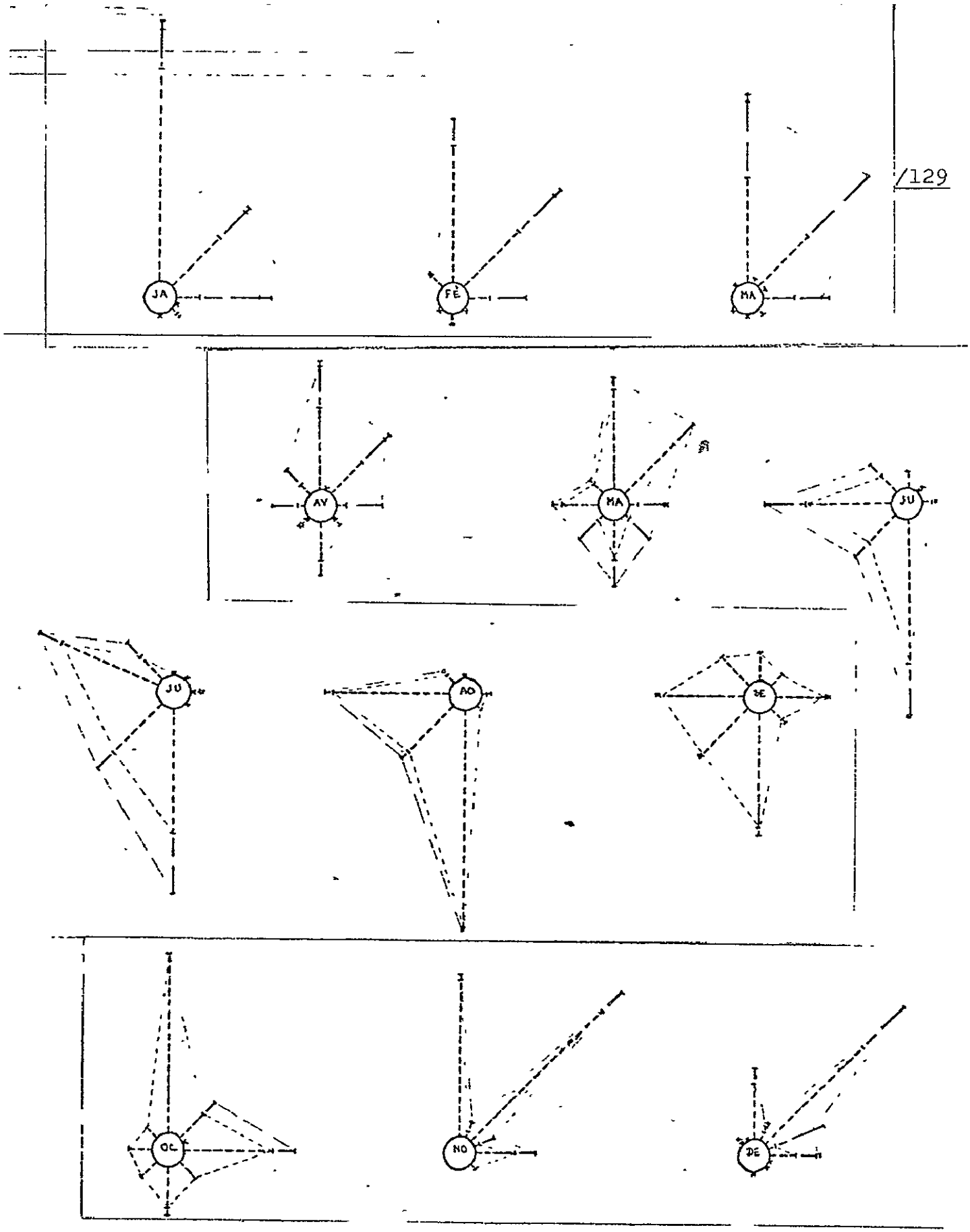
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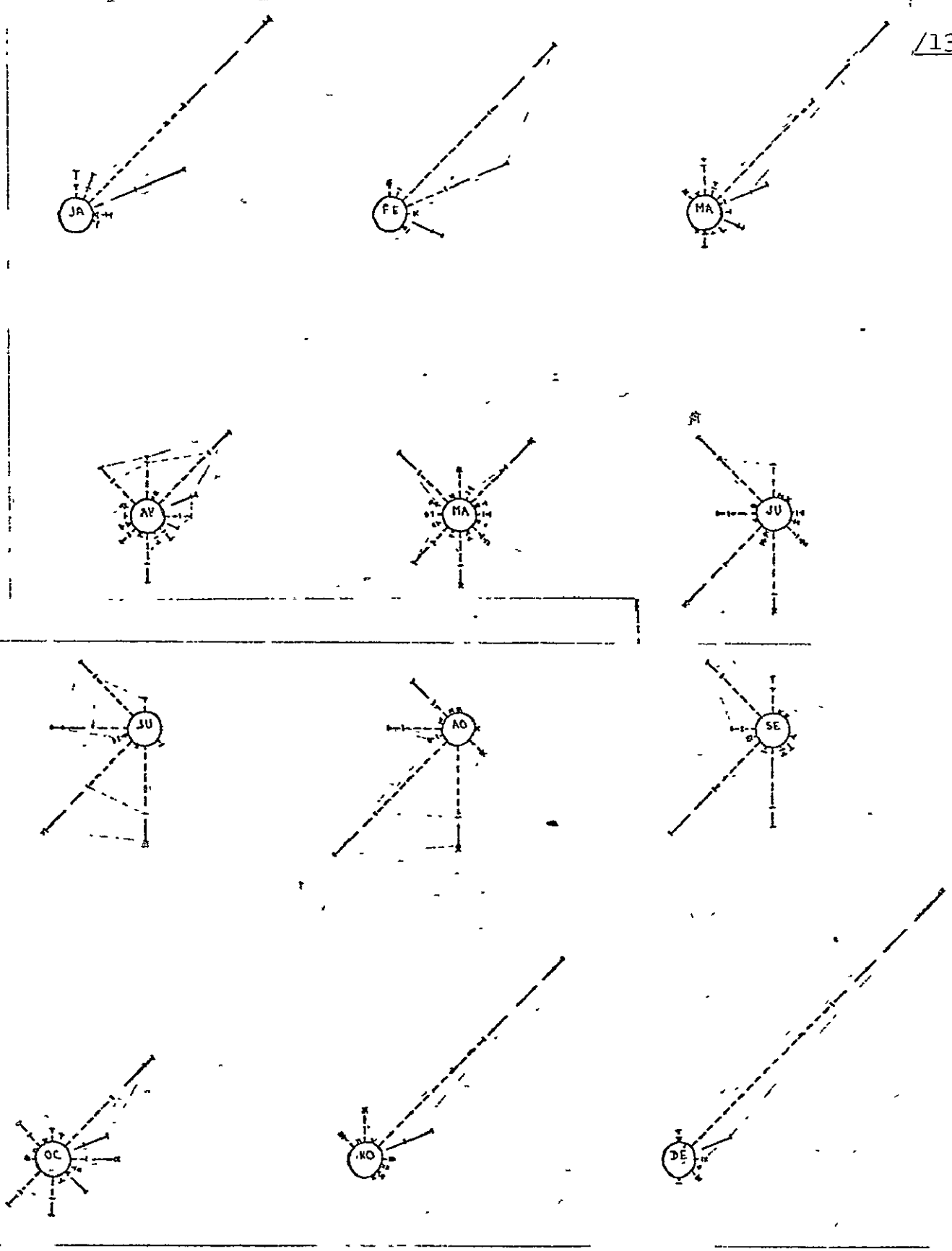
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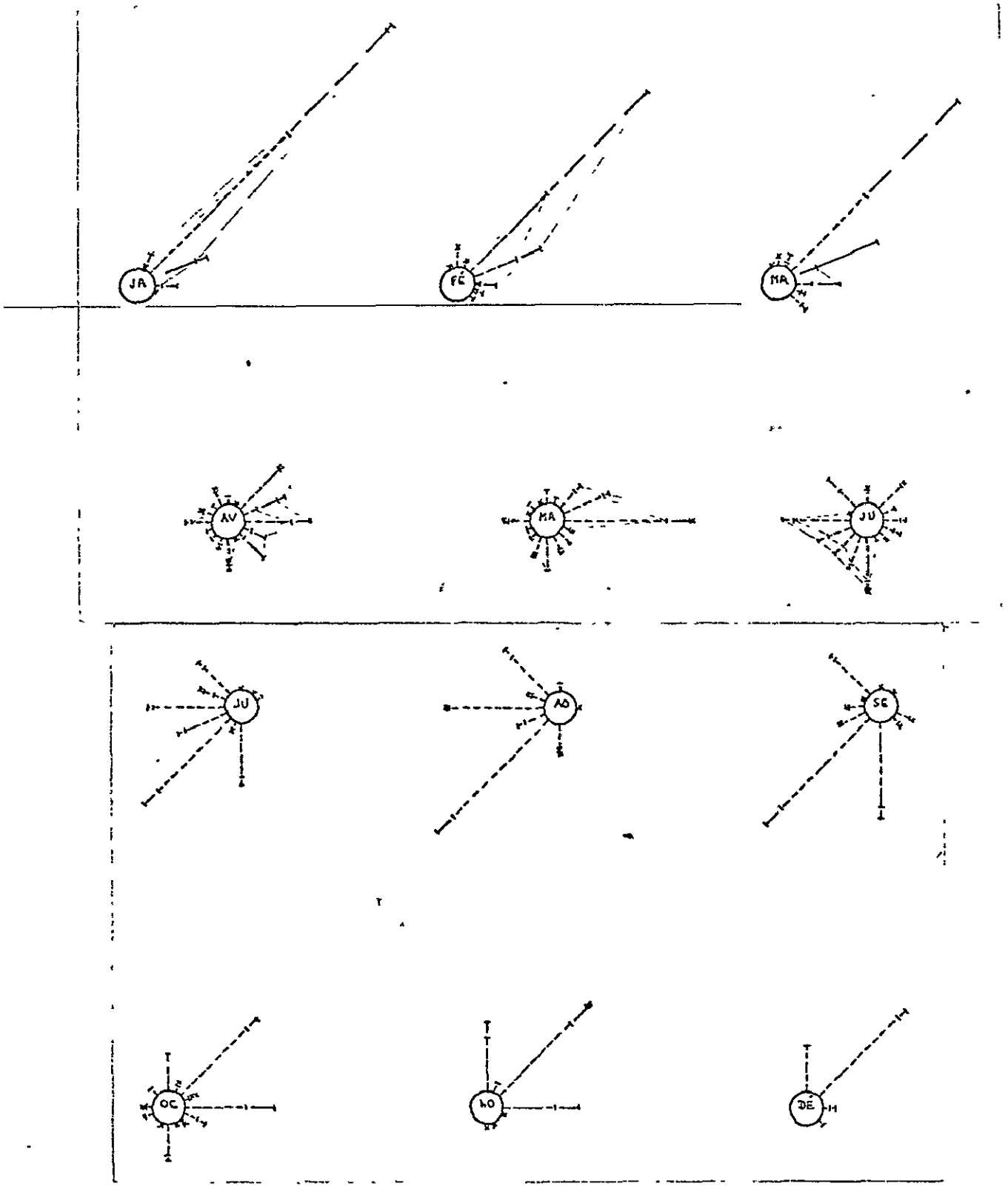
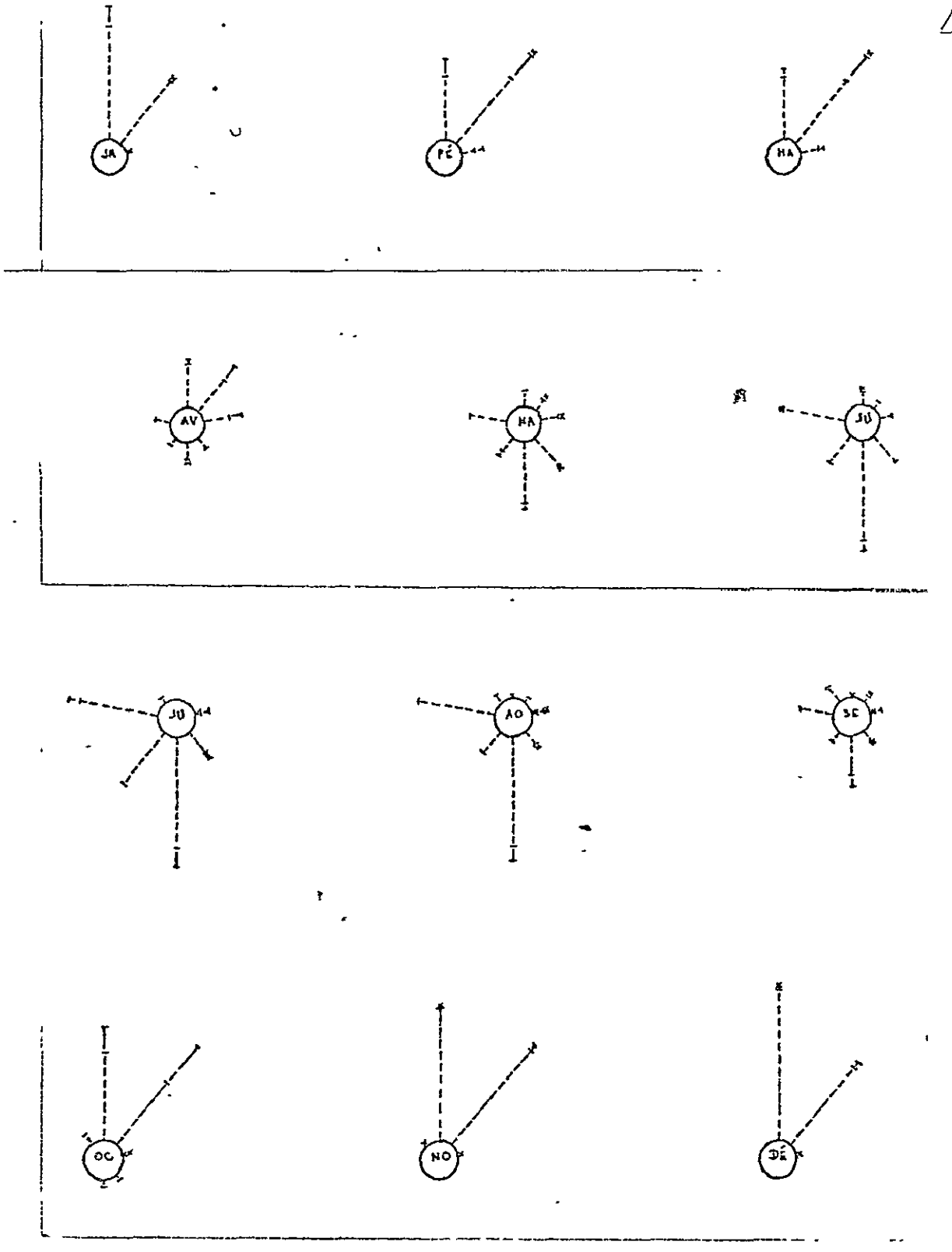



MAINE SOROA 1967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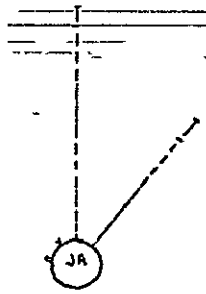


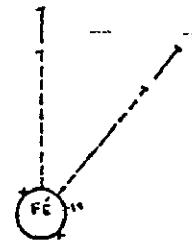


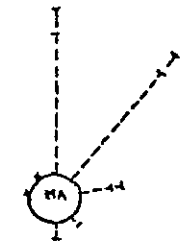


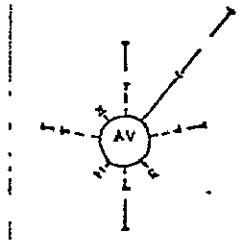


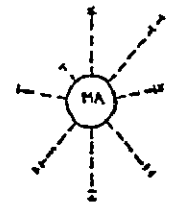


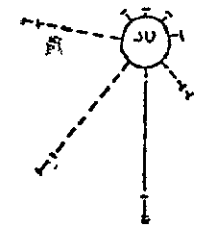


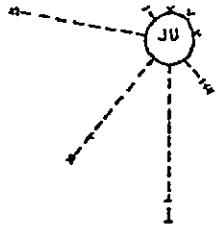


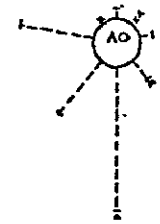


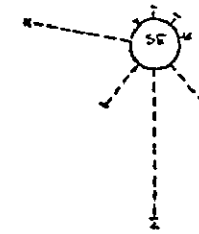


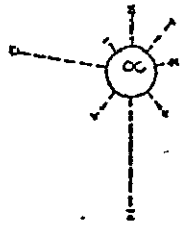


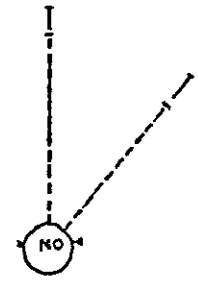


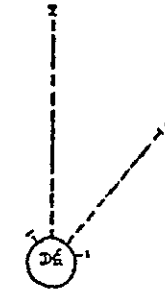

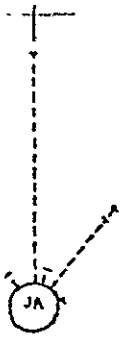
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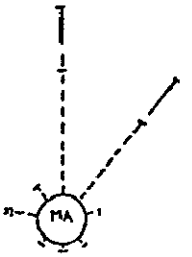
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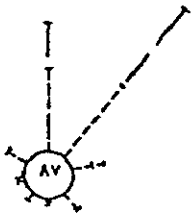
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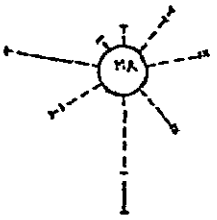
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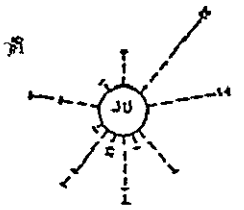
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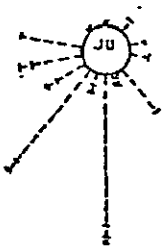
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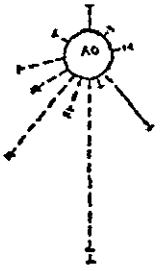
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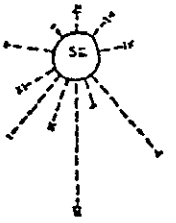
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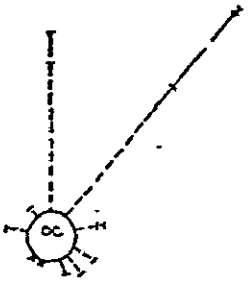
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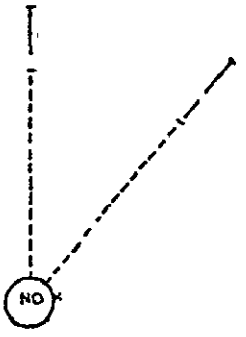
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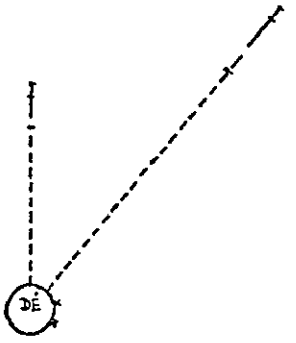
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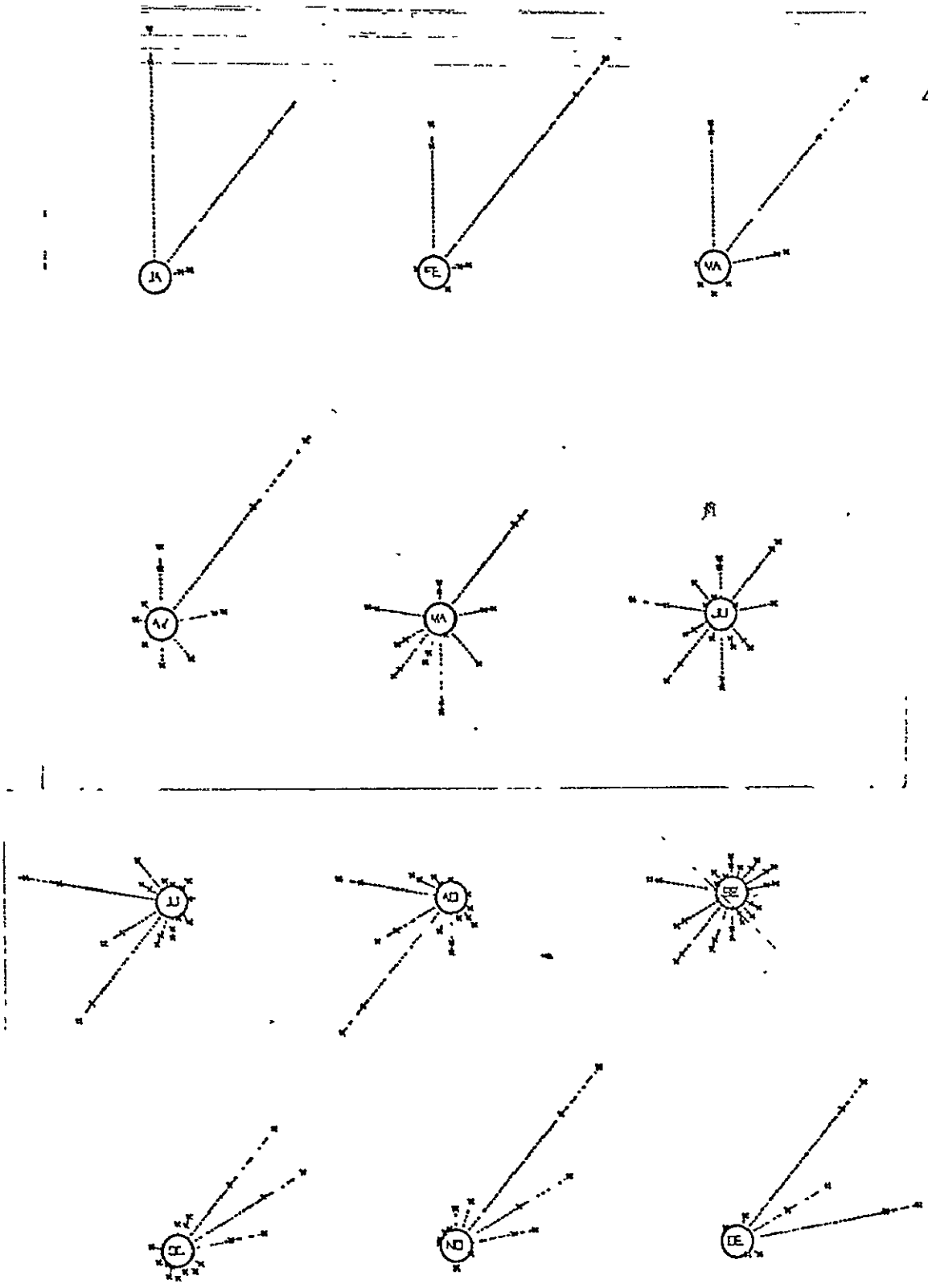
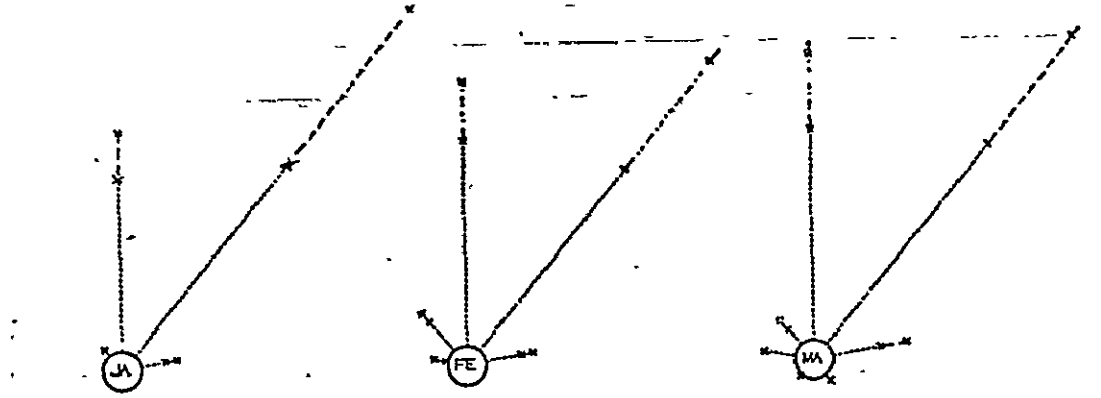
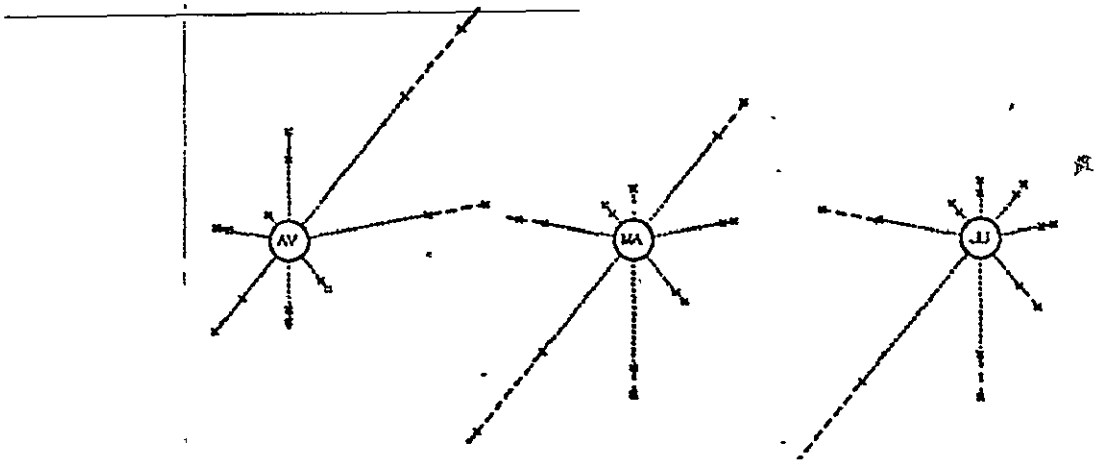
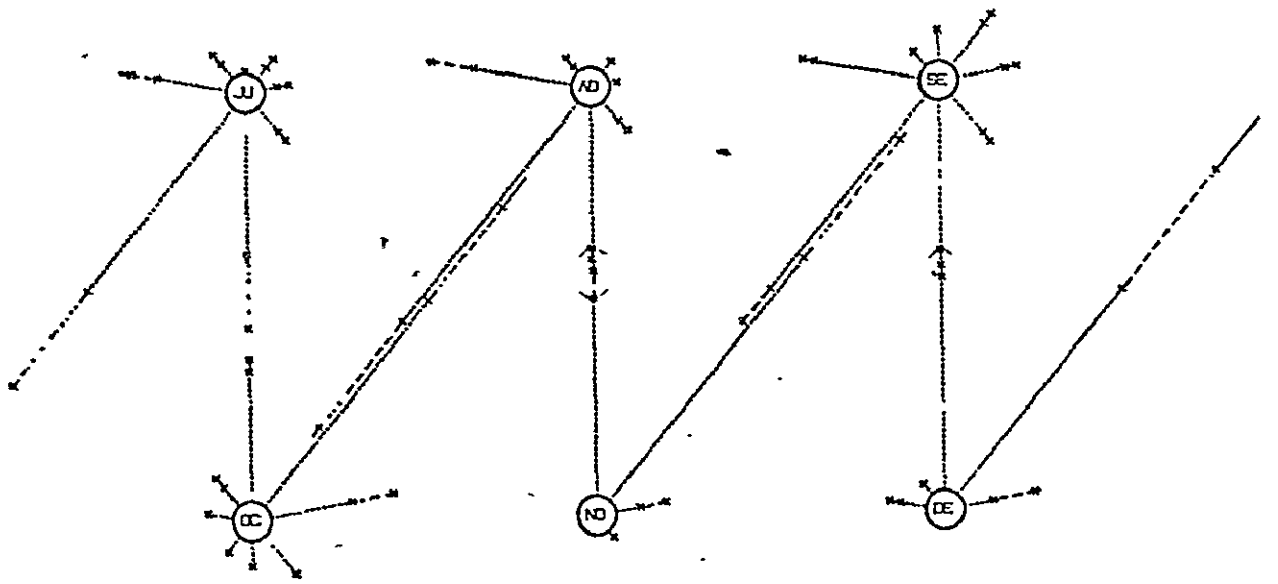








Monthly Rose Diagrams During the Period 1966 to 1975 /137
Mainé Soroa (Latitude: 13°13'N Longitude: 12°02'E)

For this station we lacked data for the years 1972, 1973 and 1974, but we have it for 1965.

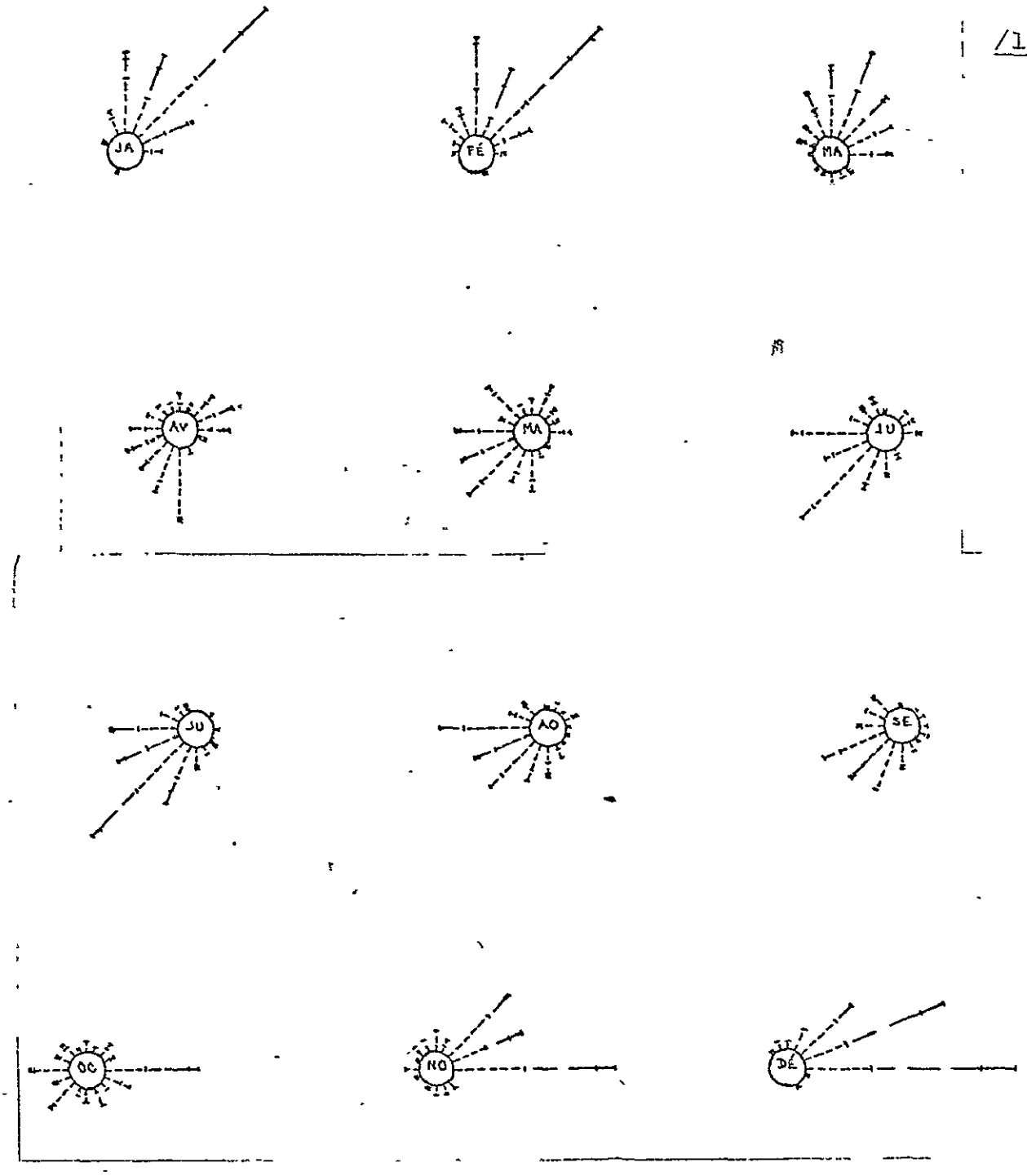
1. Dry Season (October to May).

The winds of the harmattan blow for 8 months, withaa maximum frequency and force most often in January. In October, November and December 1975 the winds were especially frequent and strong. The prevailing dry season winds are strictly from the north-northeast. The transition of winds from the dry season to the rainy season is abrupt. It takes place in October.

2. Rainy Season (June to September).

The monsoon-type winds blow only for 4 months at Mainé Soroa, which is surprising in view of the latitude of this station. The same situation occurs at Zinder, but at Mainé Soroa the monsoon winds do not have a regional direction as at Zinder. They spread out over a section which varies from west-northwest to south. One is surpirsed by the similar line followed by the harmattan and the monsoon (which blow in opposite directions). This situation can be particularly noted on the Rose diagrams from July to September 1975.

/138




— MARADI 1966

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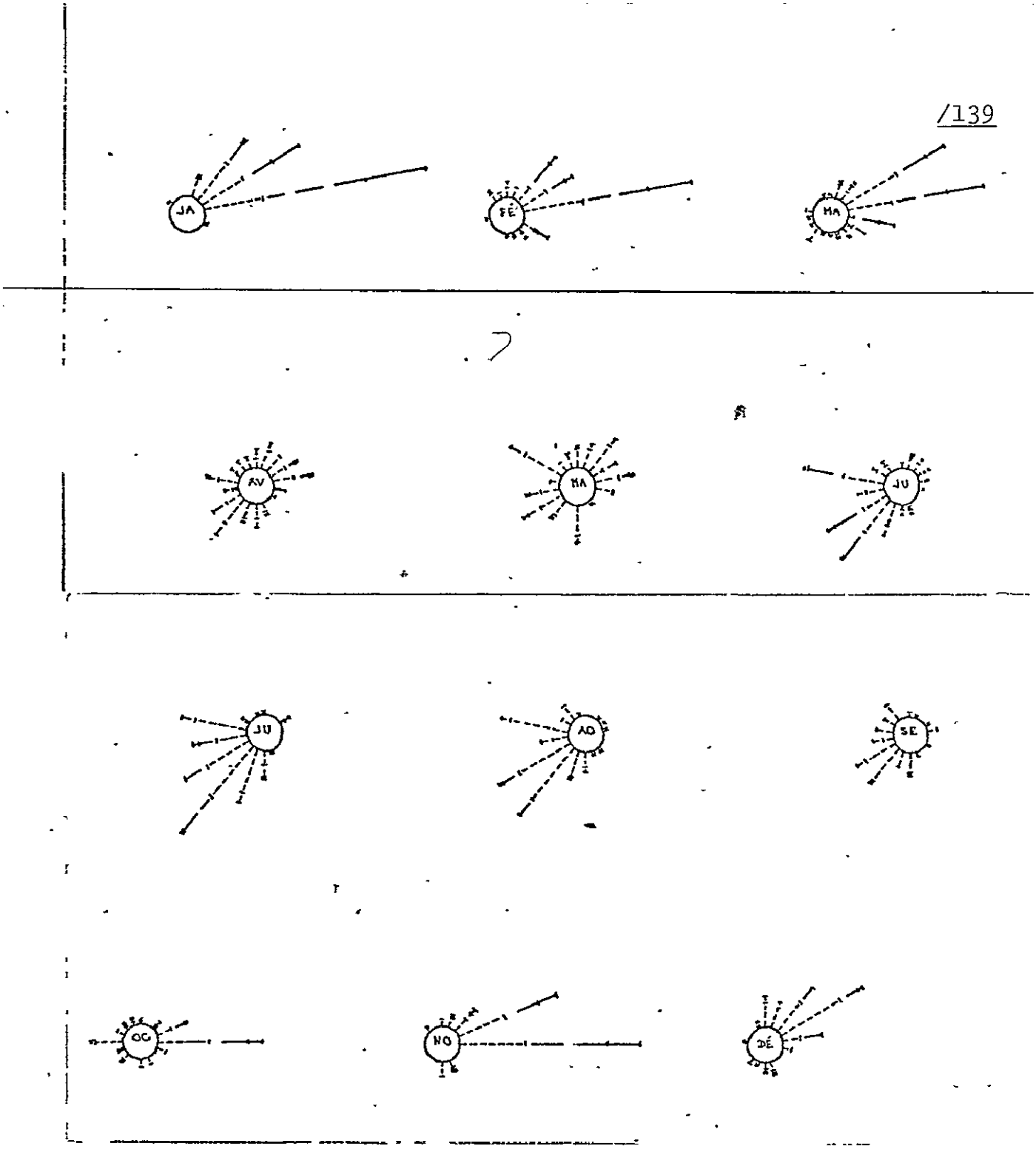
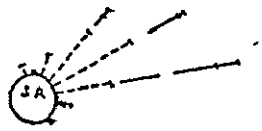



MARADI 1967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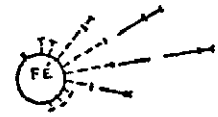
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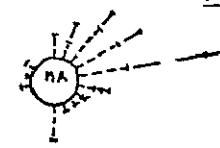
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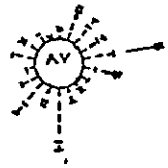
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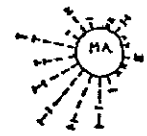
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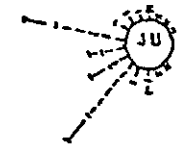
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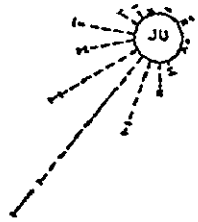
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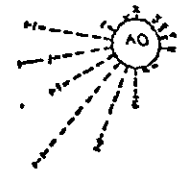
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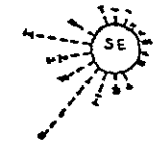
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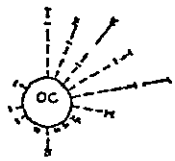
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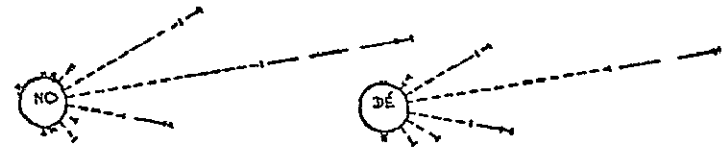
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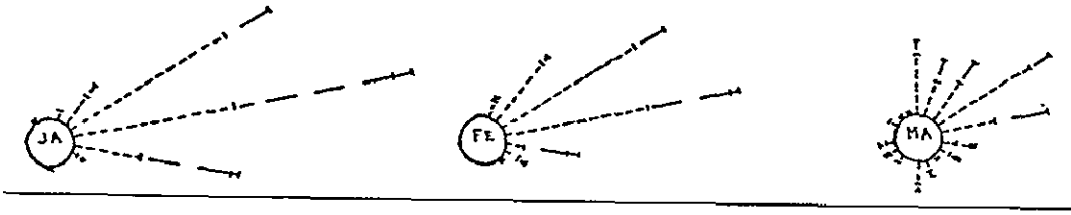
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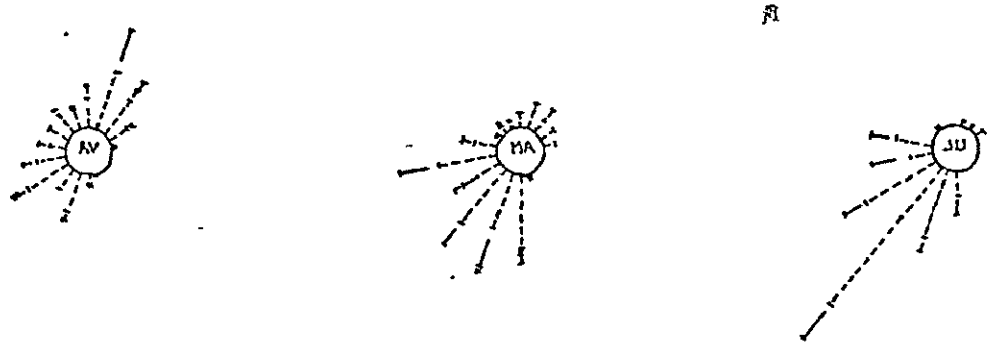
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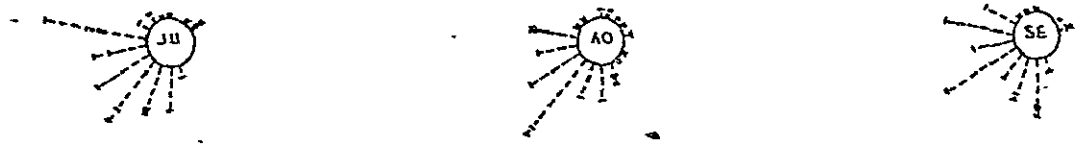
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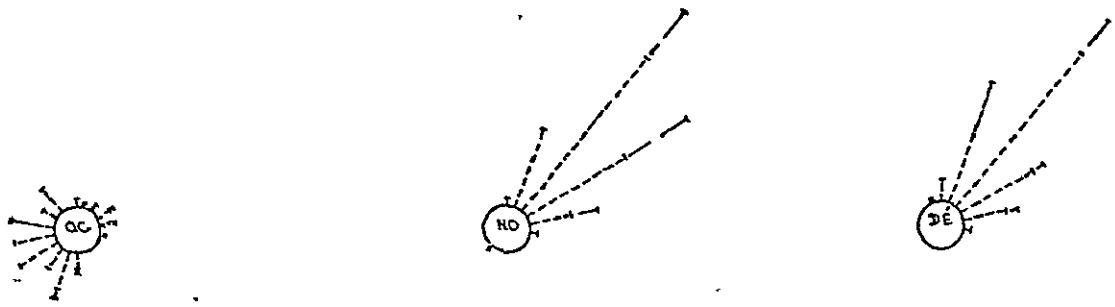
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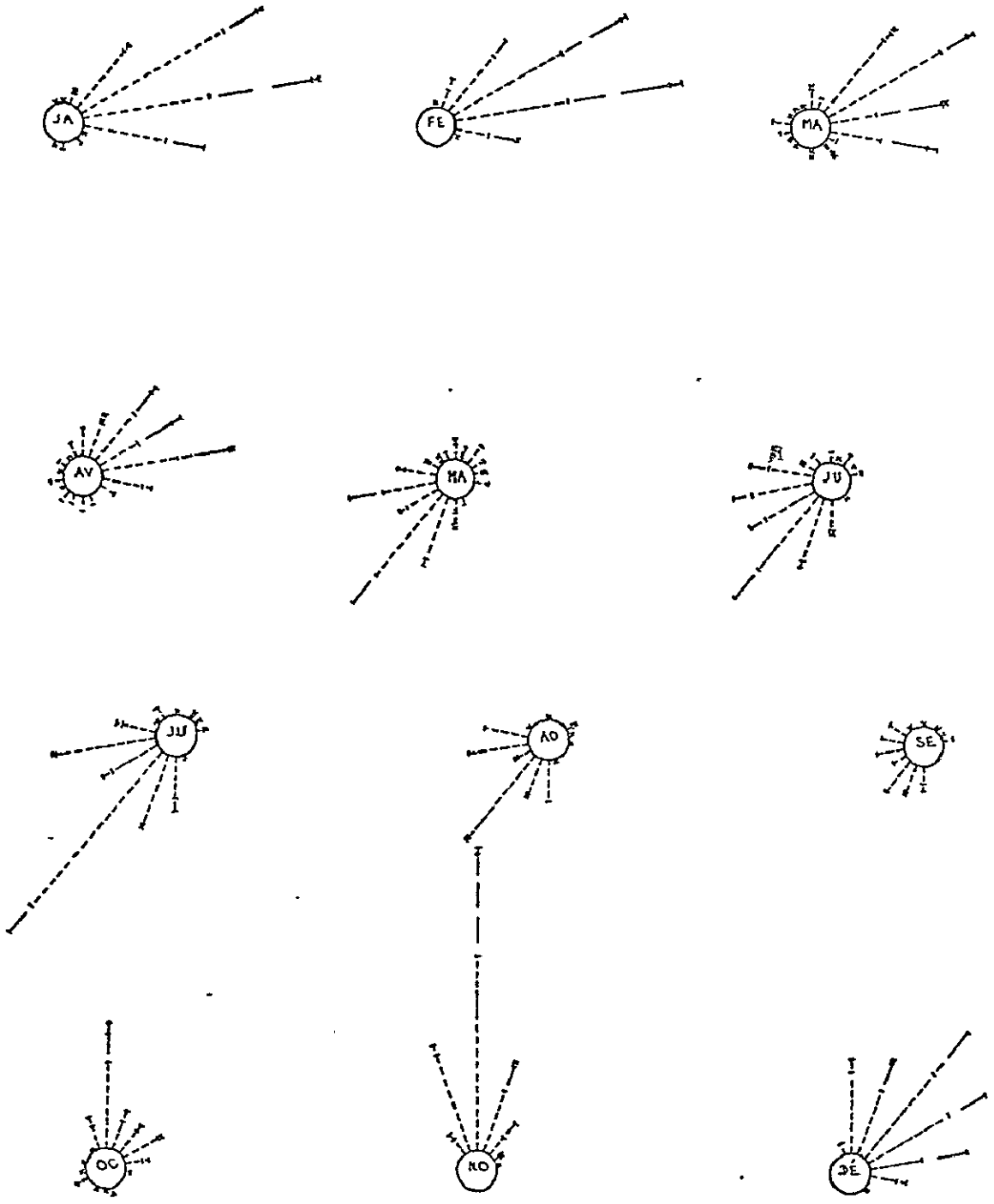
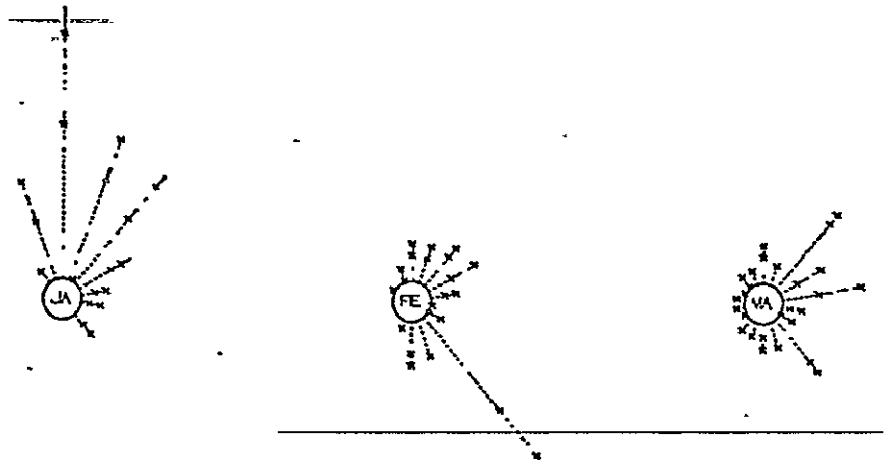



MARADI 1970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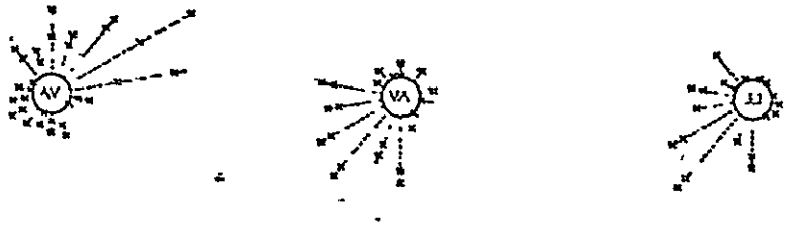
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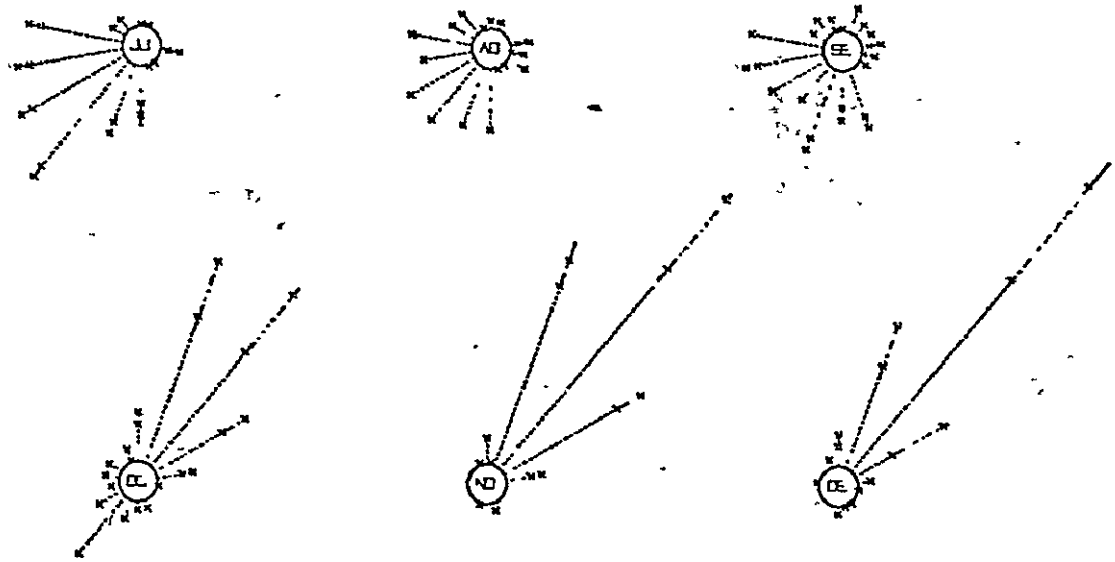
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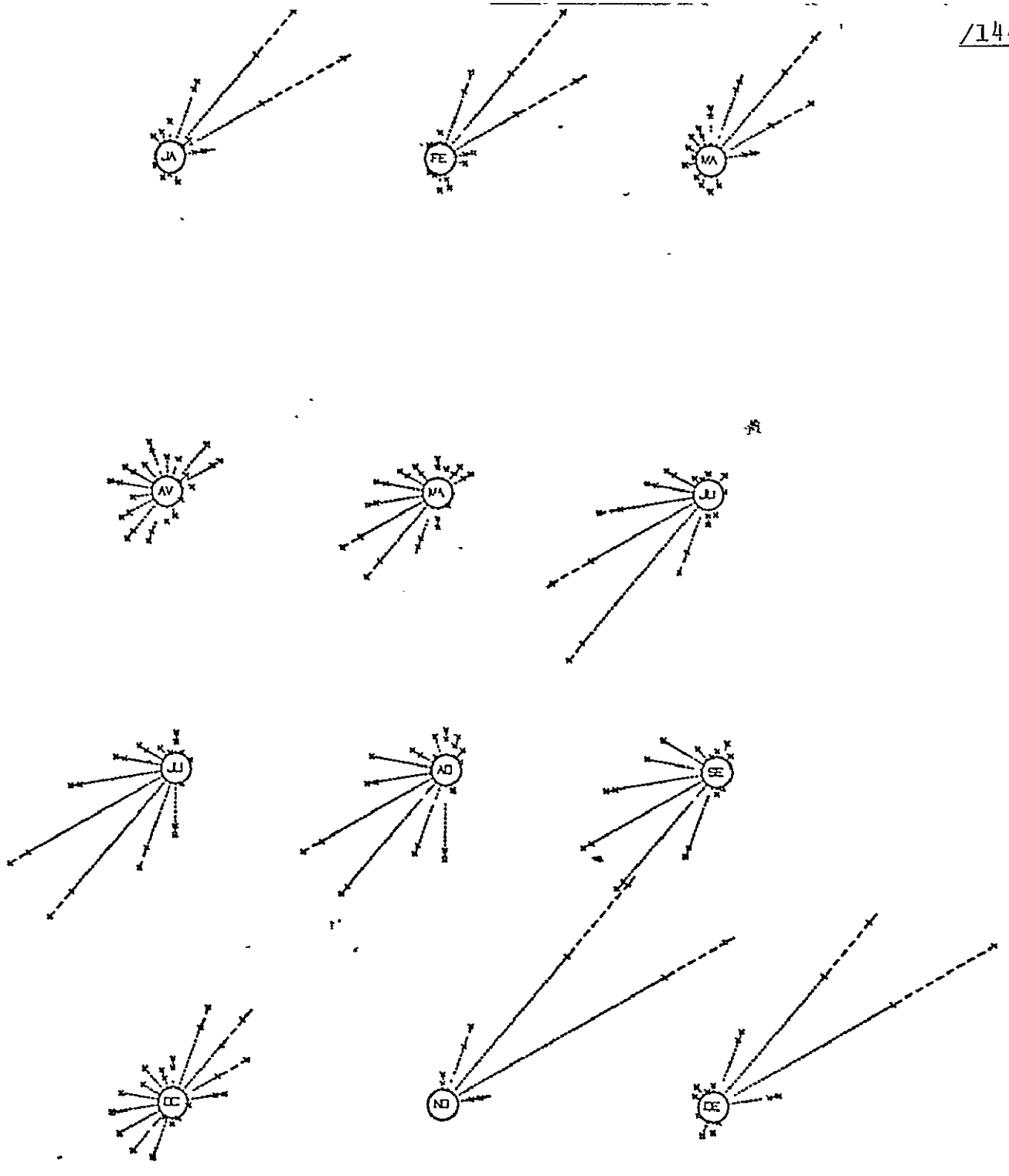

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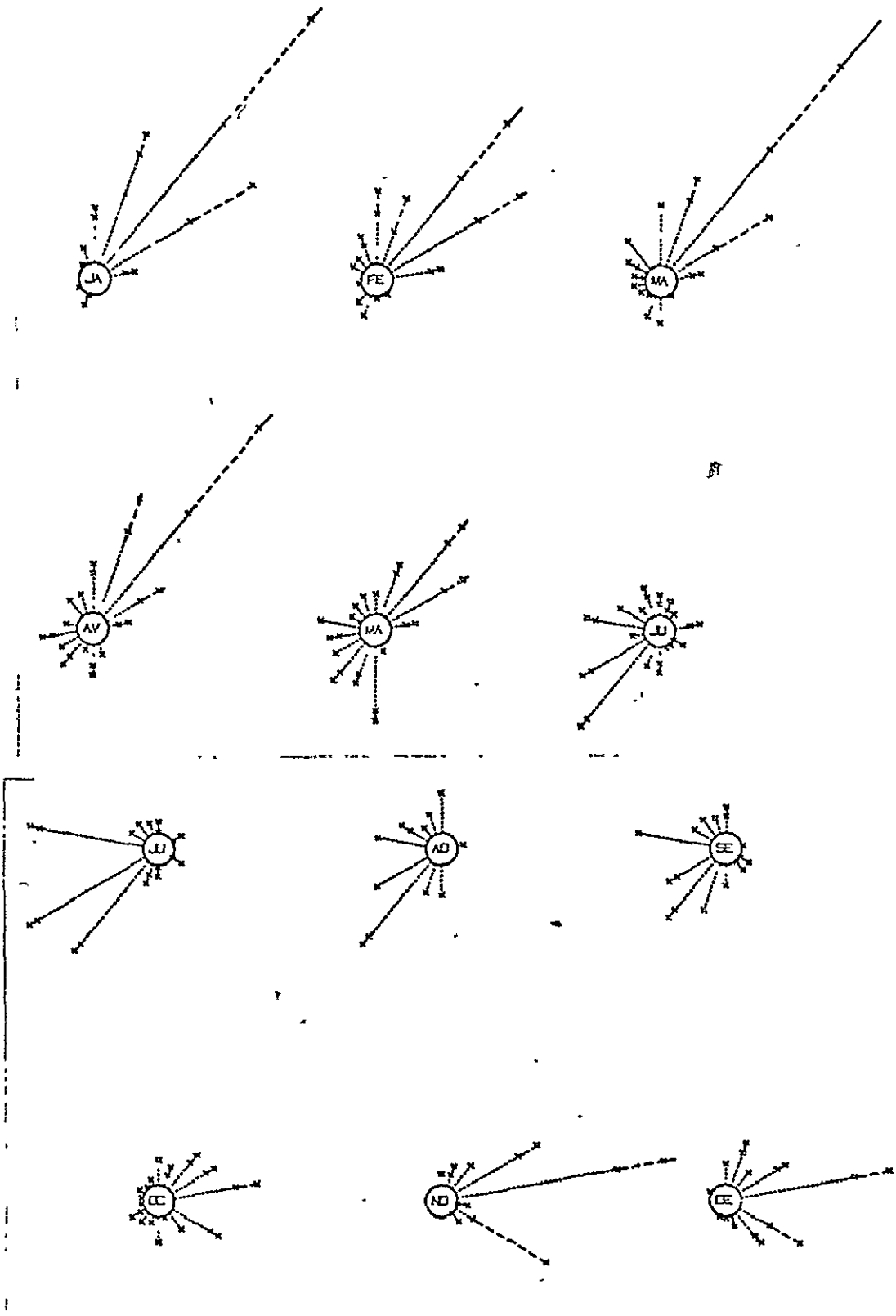

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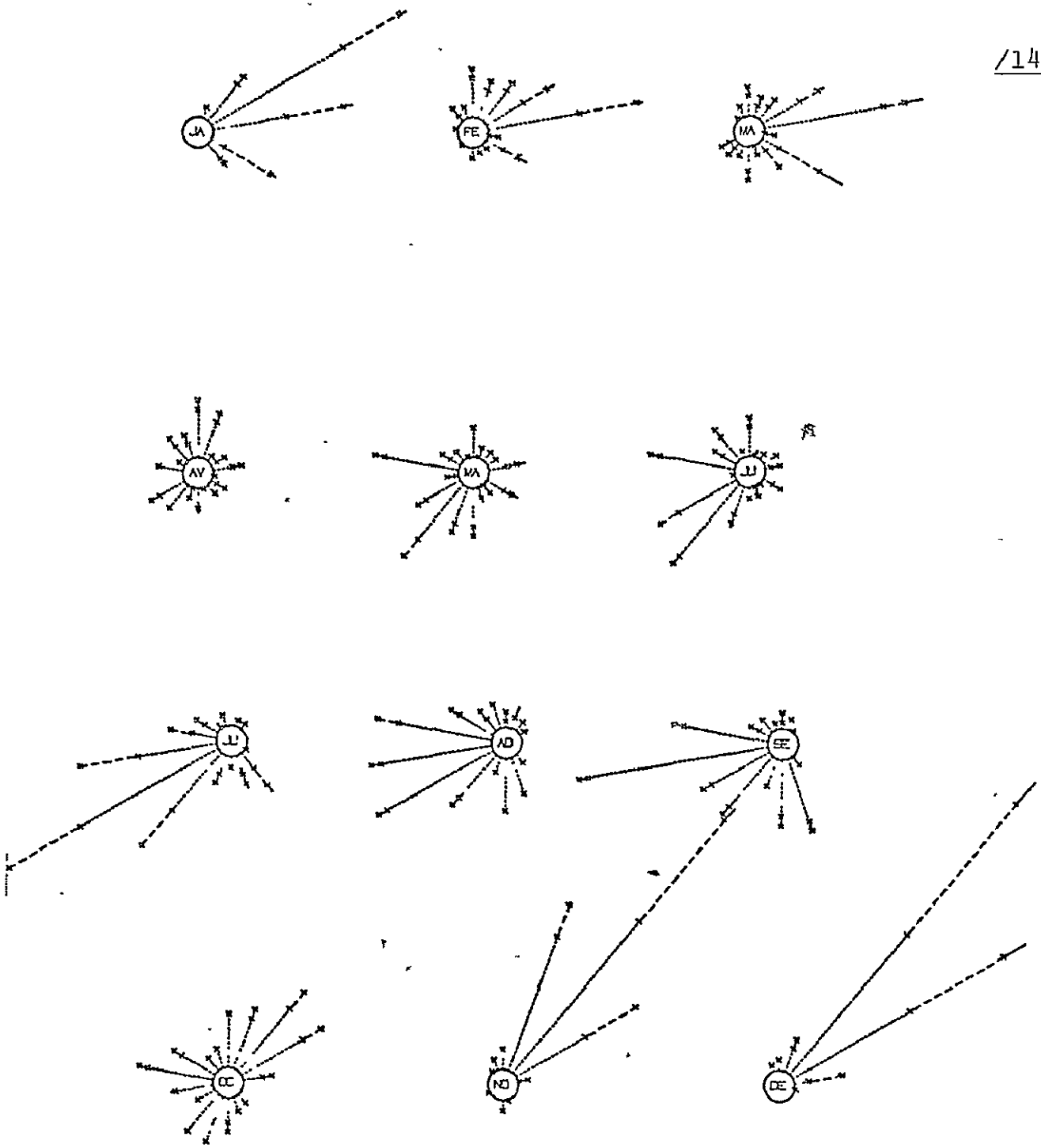

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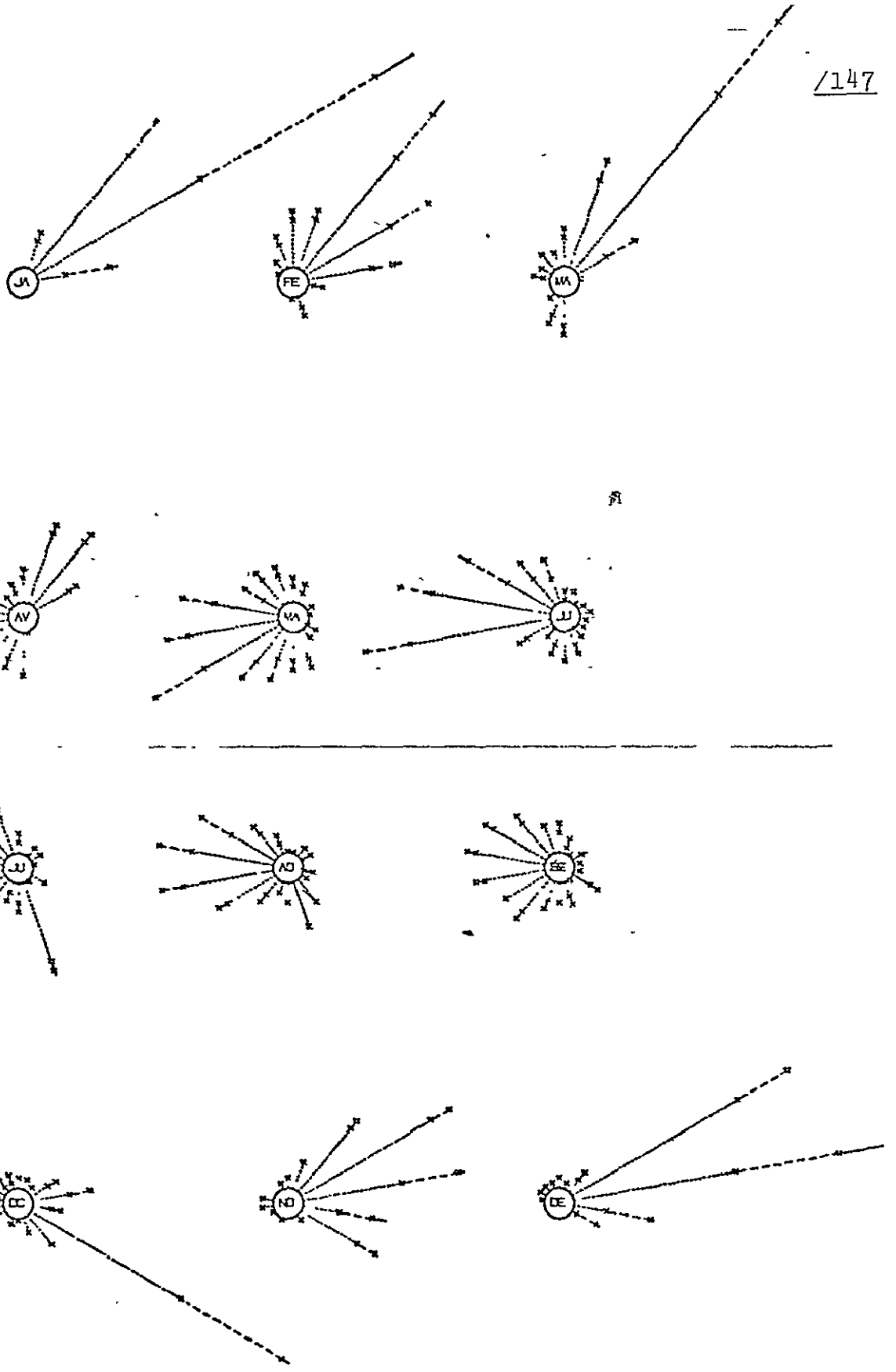

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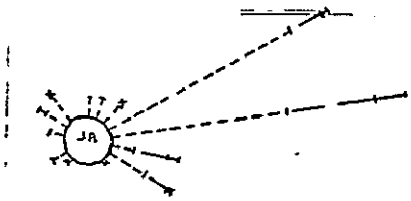
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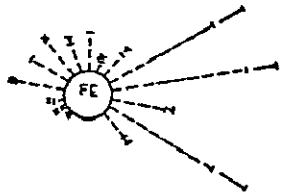
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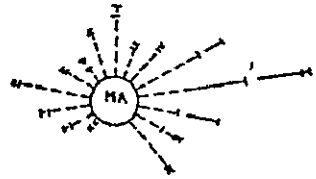
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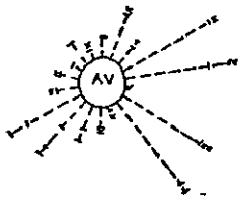
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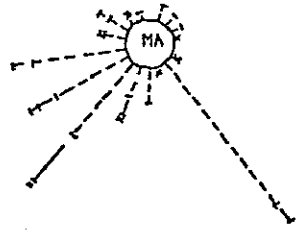
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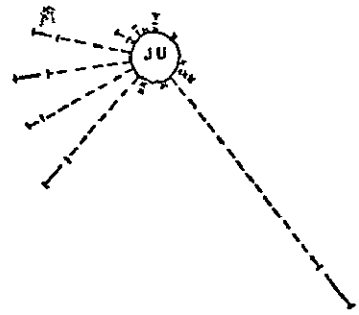
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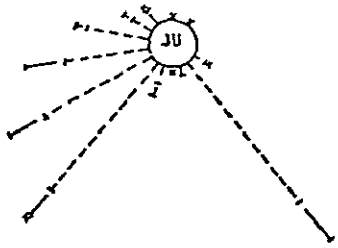
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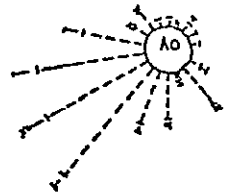
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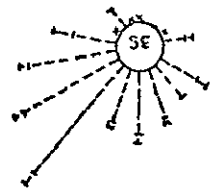
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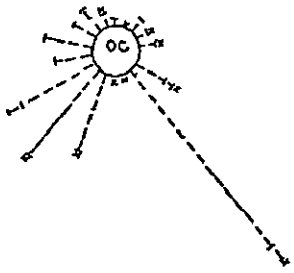
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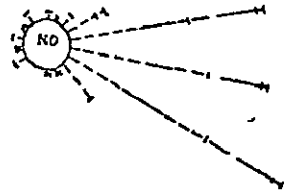
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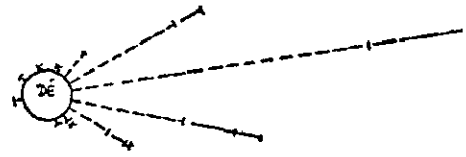
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Monthly Rose Diagrams for the Period 1966 to 1975 /149
Maradi (latitude: 13°28'N Longitude: 7°04'E)

1 - Dry Season (November to March).

From 1966 to 1970 the winds are distributed through a prevailing arc from 40° to 80°. A shift towards the north, i.e. a range of wind direction from 20° to 80°, is observed from 1972 to 1975. 1971 is an exceptional year between the two models.

The efficient winds (with speeds greaterrthan 4 m/s), which are sand-carrying winds capable of causing reactivation, are most frequent in the dry season. During the period 1966 to 1970 they are concentrated in a prevailing arc from 20° to 40°, and between 1972 and 1975 they are concentrated between 40° and 60°. The same exceptional situation is observed in 1971 when the direction of efficient winds of maximum frequency is 140°.

The efficient winds are most frequent in November and December.

2 - Interseasonal periods

April: there is no prevailing wind, except if there is an extension of the three preceding months. This was the case in 1970-71 and 1973 when the dry season was extended up until May. Also at this time there are the most effective winds: their frequency always increases in proportion with the frequency of winds in general.

May: First barely perceptible signs of a prevailing wind sector becoming established between 180° and 260°.

October: transition month between the rainy season and dry

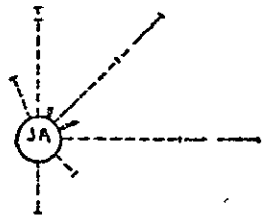
season, can already be either already under the influence of prevailing winds of the rainy season or maybbe without any prevailing wind. But the winds of October can also extend the dry season and thus still receive winds coming from an arc ranging between east and northeast.

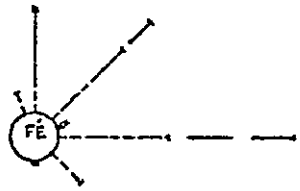
3 - Rainy Season (June to September, October for 1969).

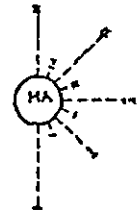
The winds are concentrated in a clearly dominant sector from the south, from 200° to 260°, and 280° maximum. There are very few efficient winds, and these always come from between 220° and 240°.

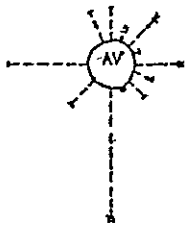
The winds from the southeast, which are still unexplained, exist in all seasons (February 1971, October 1975, May-June 1976). However, they are interesting since when they do exist they are efficinet and dominant.

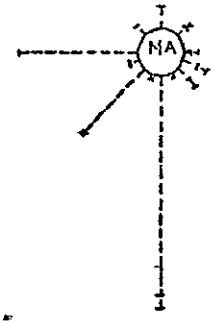
/150

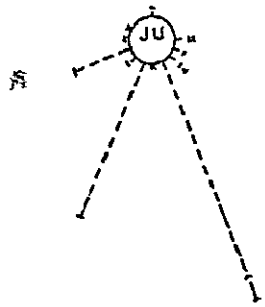


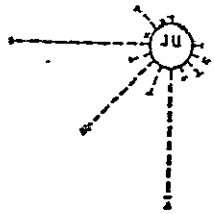



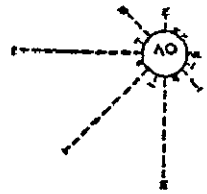



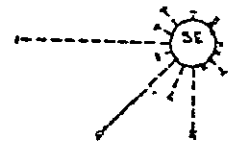



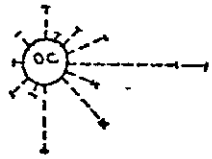



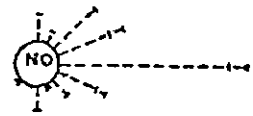



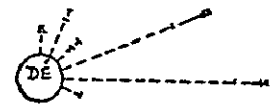




N'GUIGMI 1966

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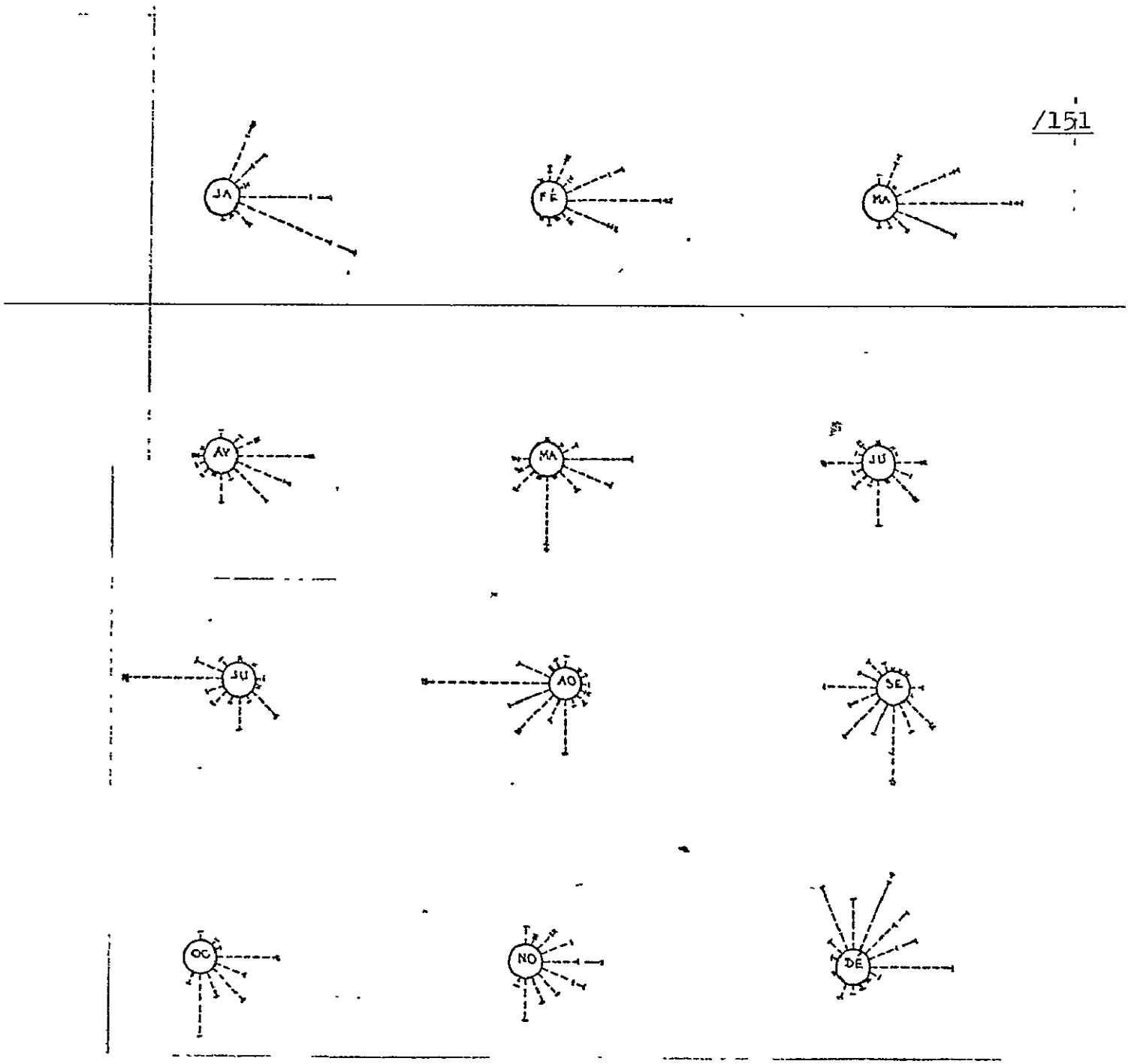


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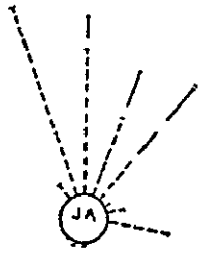


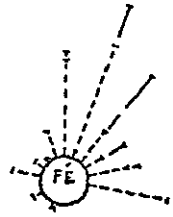


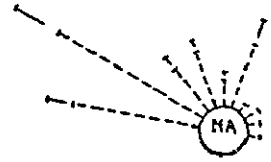


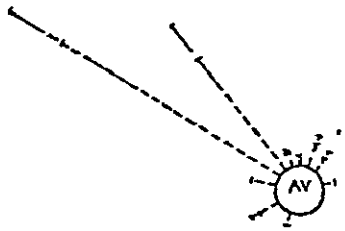


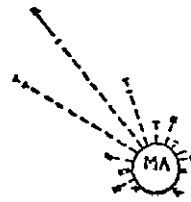


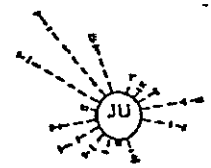


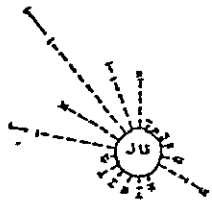


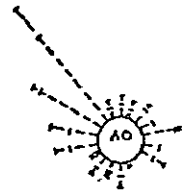


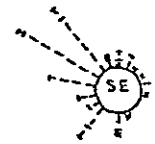


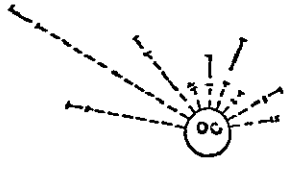


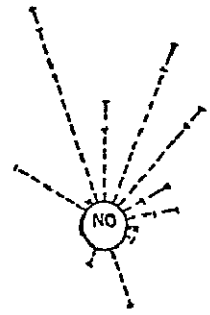


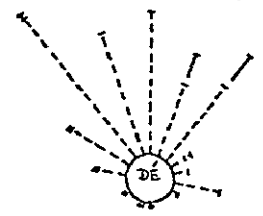


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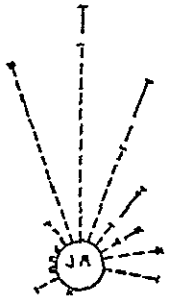
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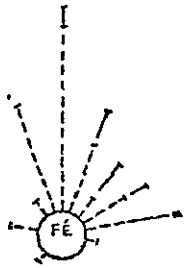
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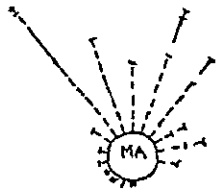
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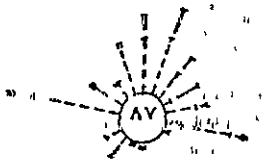
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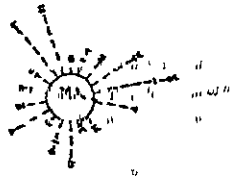
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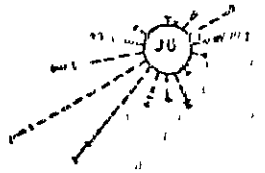
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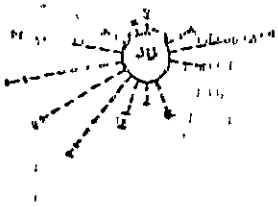
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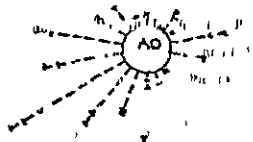
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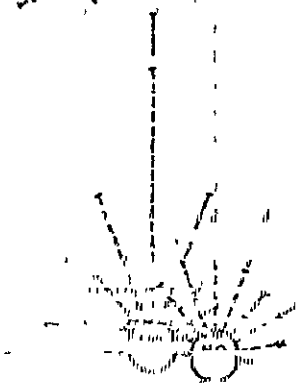

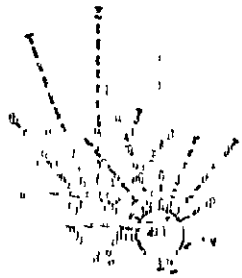

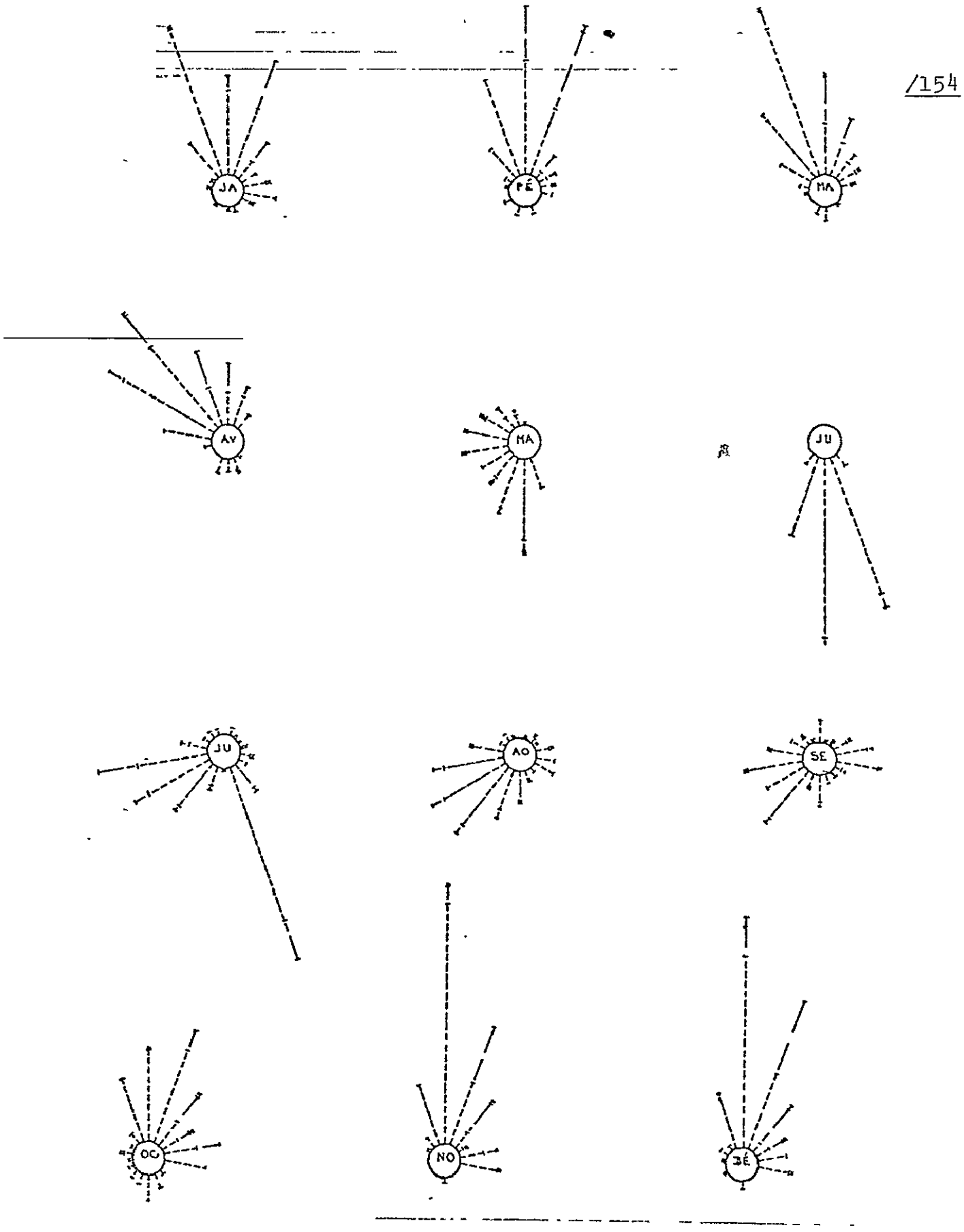


N'GUIGMI 1970

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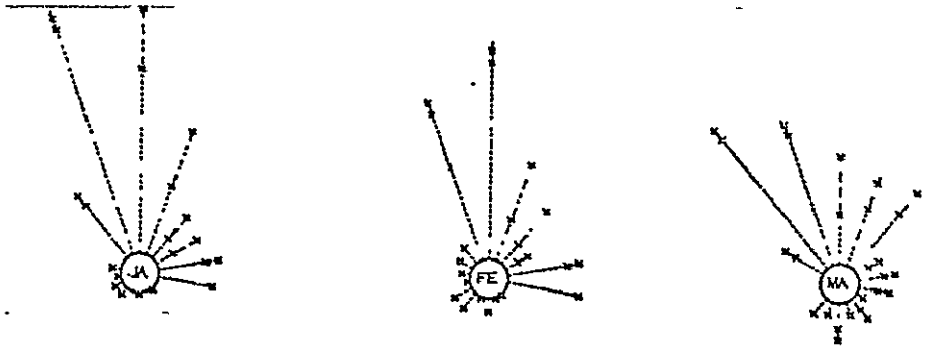


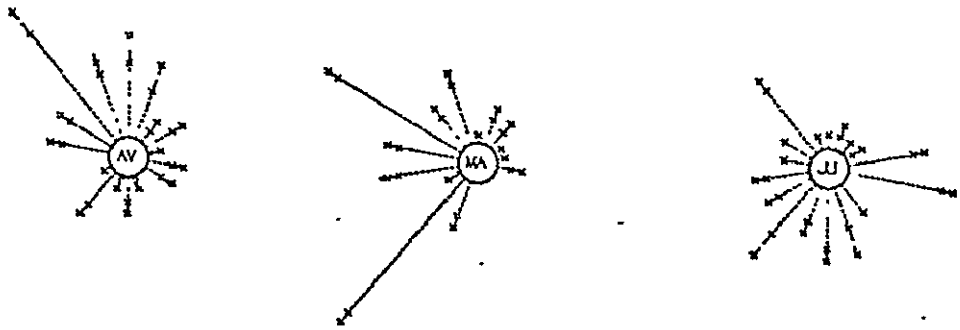


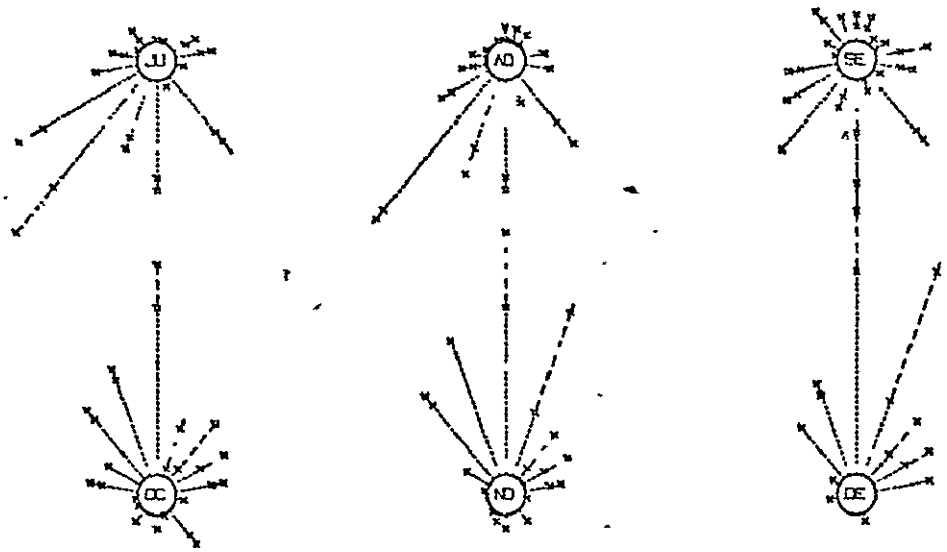


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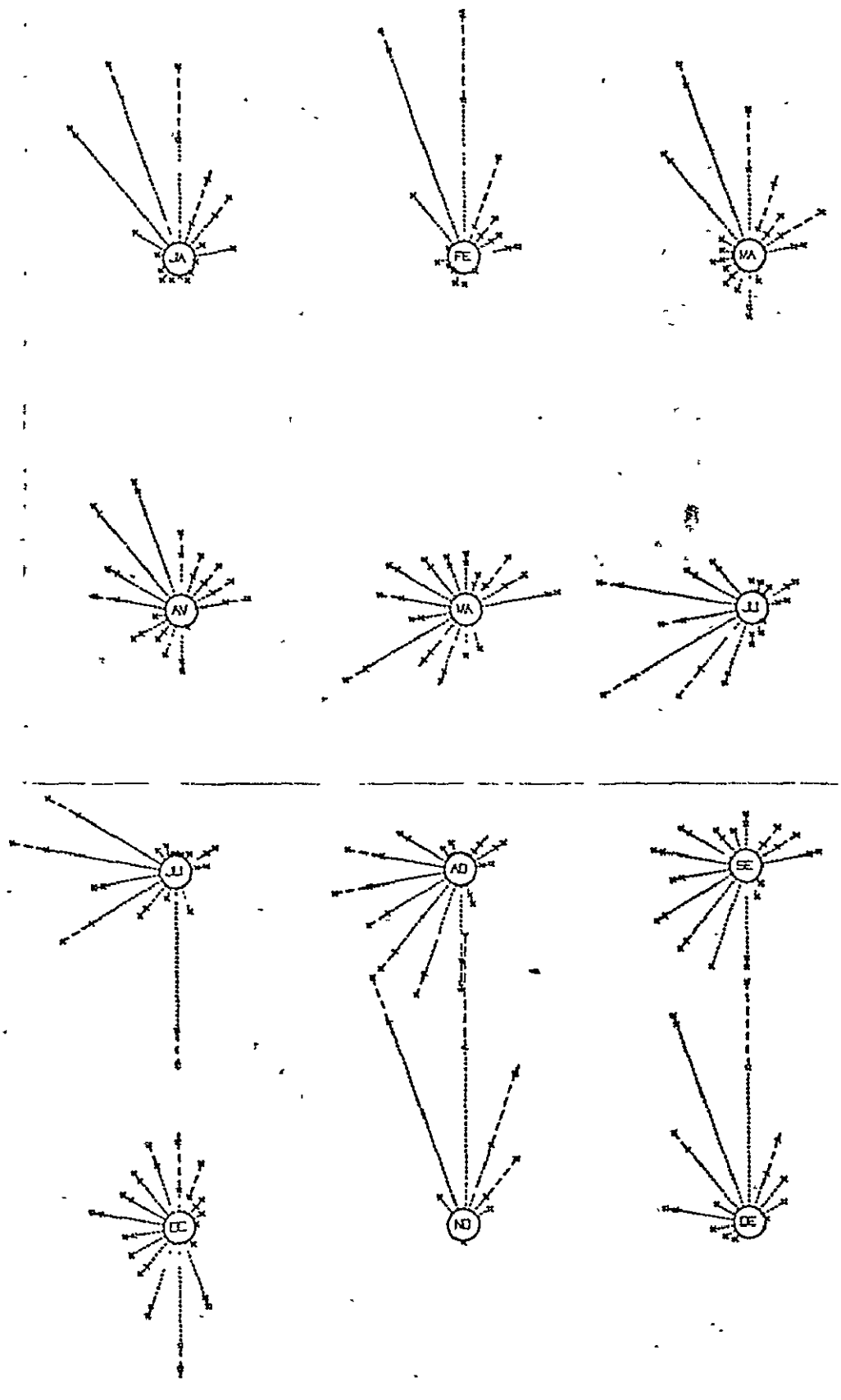

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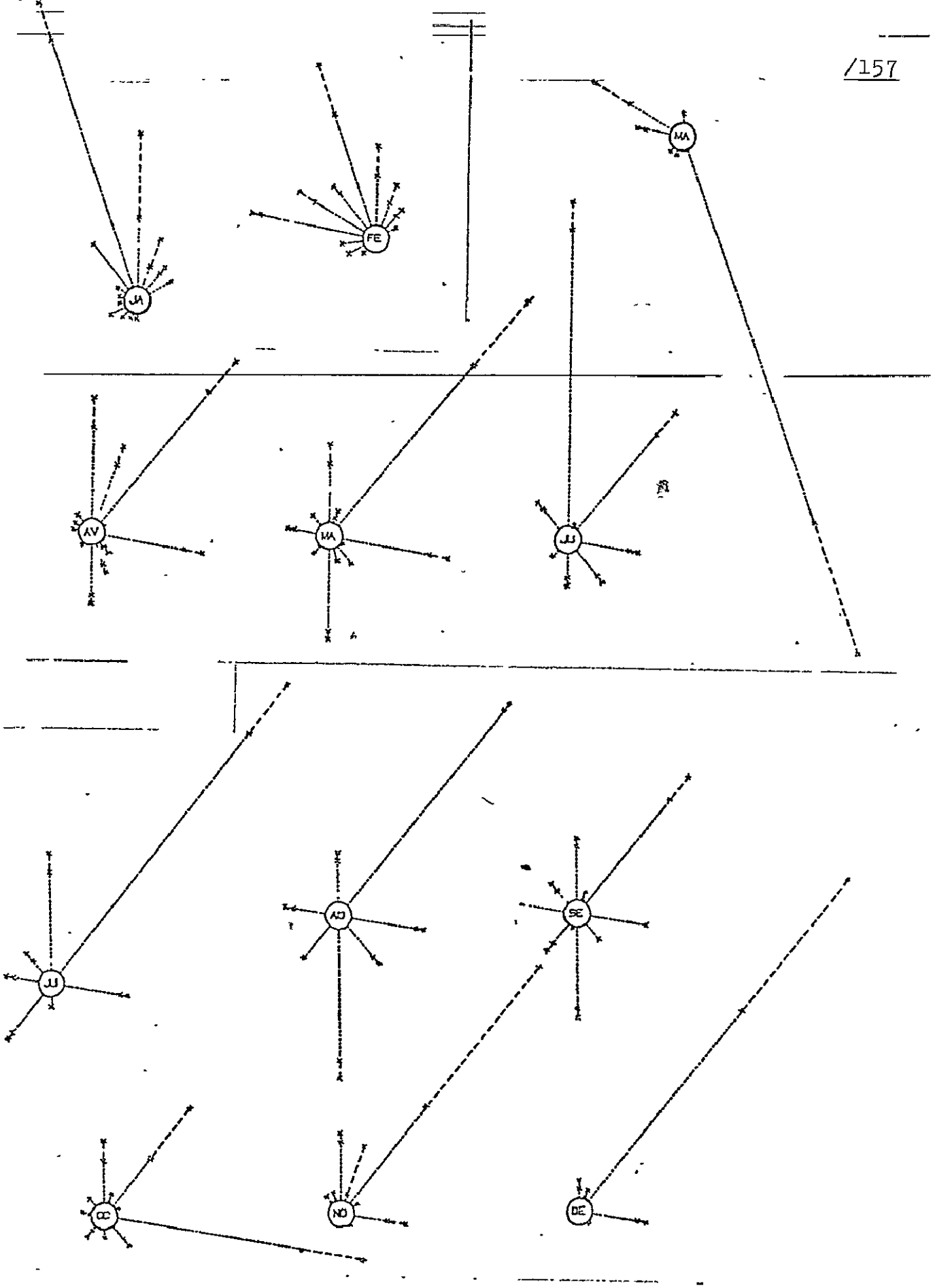
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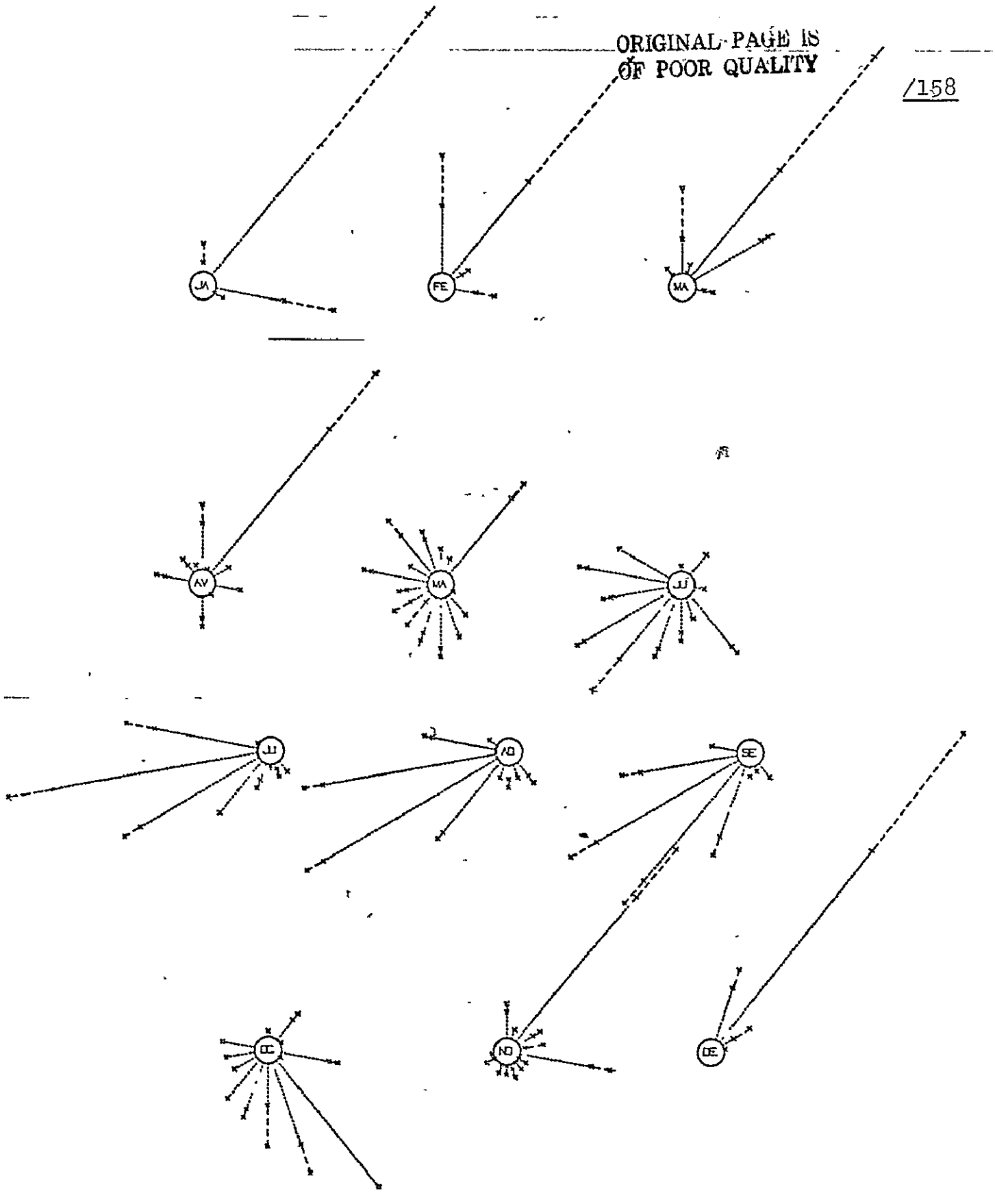


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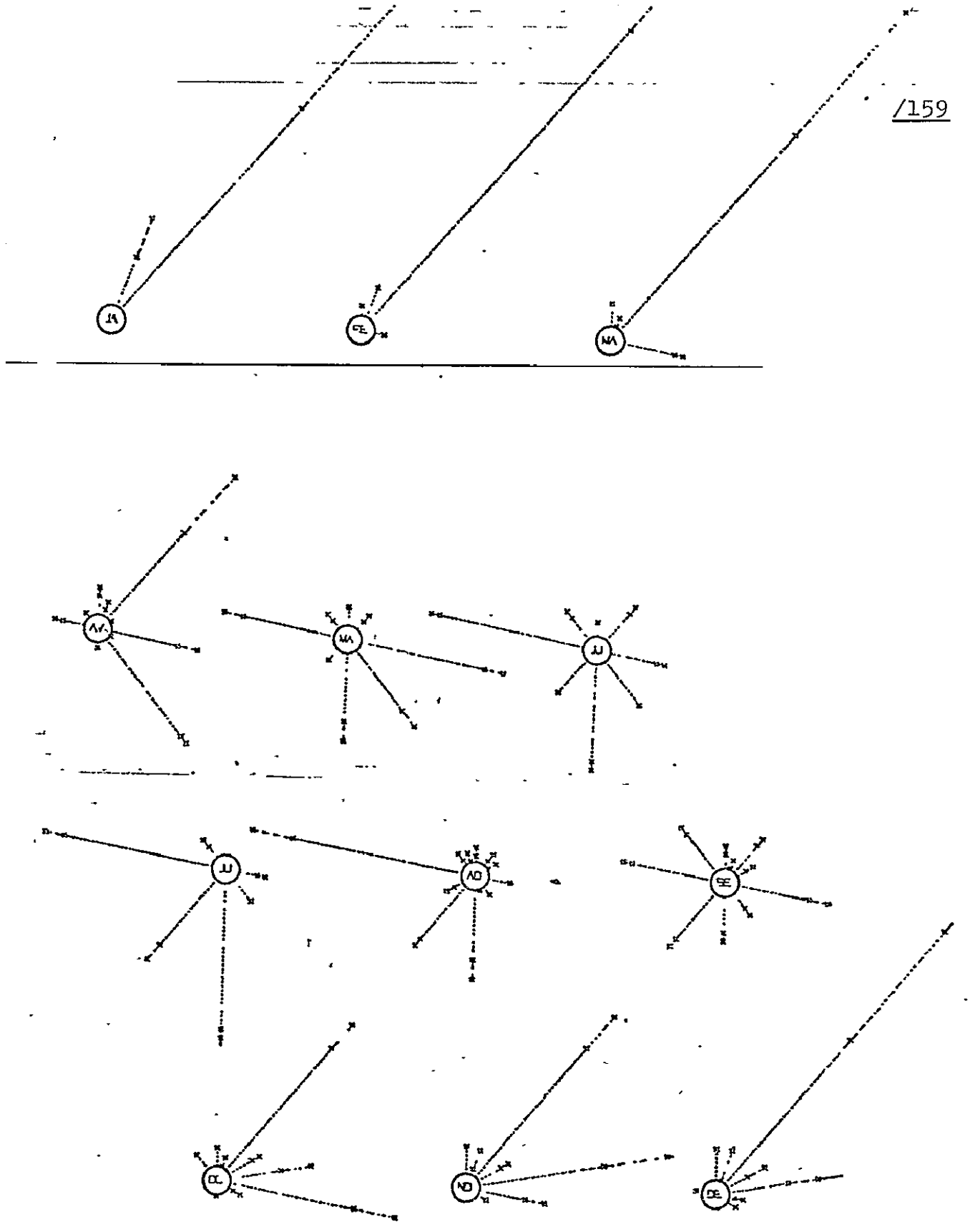

Monthly Rose Diagrams for the period 1966 to 1975 /160
N'Guigmi (Latitude: 14°15'N Longitude: 13°07'N)

N'Guigmi is the most continental station of the Niger Republic.

1 - Dry Season (October - November to March - April).

The prevailing winds are concentrated in a distinct arc ranging from north to east. In the course of the 10 years studied 3 prevailing directions appear: (1) winds with a zonal direction from 1966 to 1968, (2) winds from the north in 1969-1972 and (3) from the northeast between 1973 and 1975.

2 - Transition months.

April. The winds sometimes extend the tendency of the dry season, i.e. ranging in an arc between north and east-northeast (1970-72), or else they come from all directions possible, with a greater frequency from an arc ranging between northwest to north.

October. No direction dominates, except when October is already under the influence of dry season winds, which is frequently the case (1970 to 1973 and 1975).

3 - Rainy Season (May to September).

It will be seen that at N'Guigmi there is no clear cut establishment of winds from the sector corresponding to the monsoon. In 1973 the monsoon does not appear. The entire year was subject to the effect of winds from the northeast. From May to September the winds are not effective winds because their velocity is less than 4 m/s. Their direction varies depending on the year,

from south to northwest in 1966-69, 1972, 1974-75, sometimes southeast to south.

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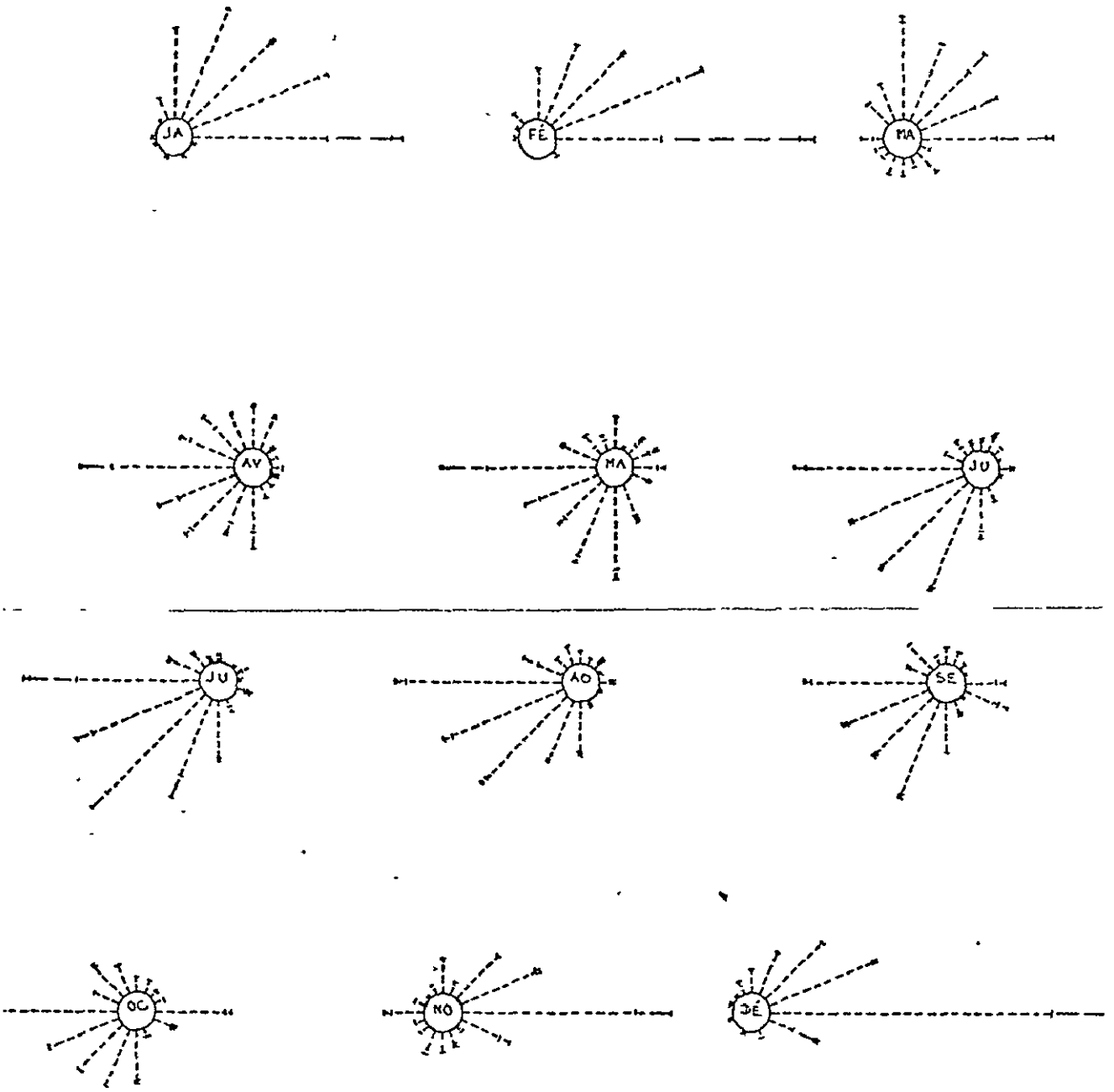


NIAMEY 1966

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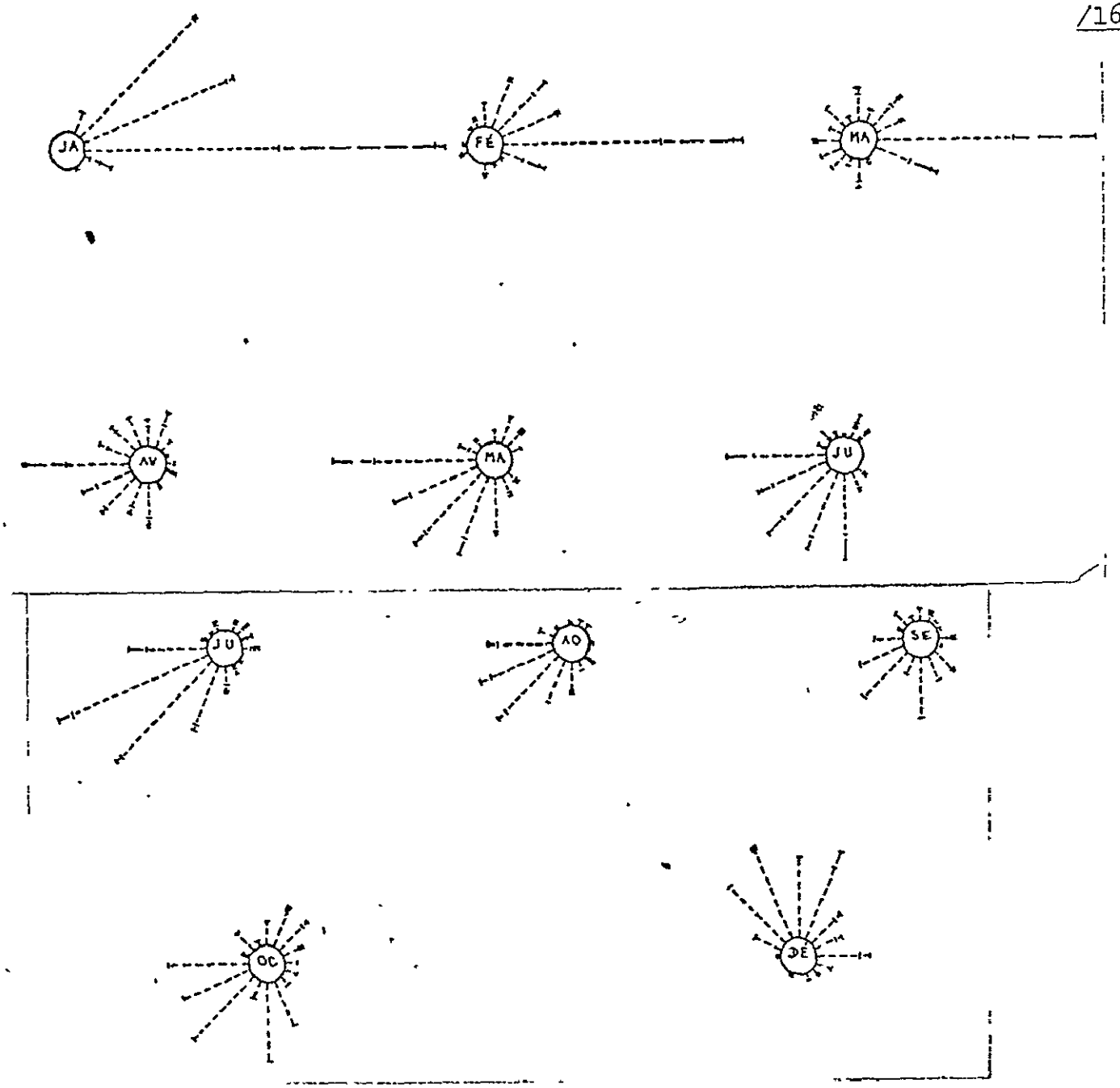


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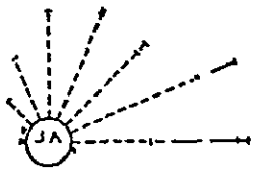


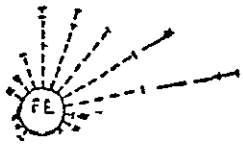


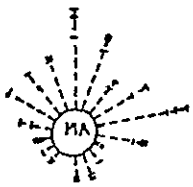


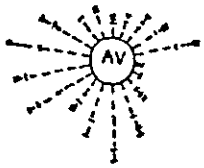


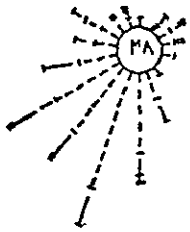


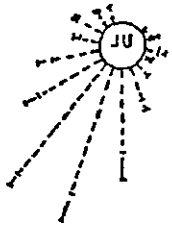


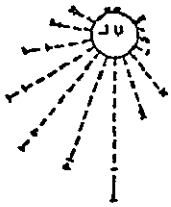


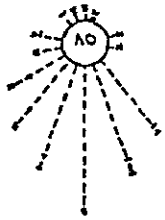


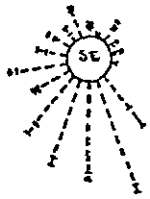


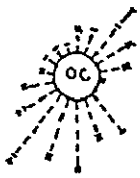


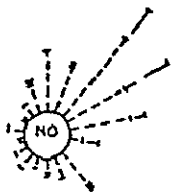


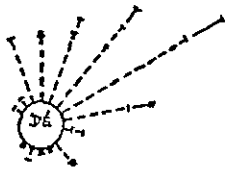


NIAMEY 1968



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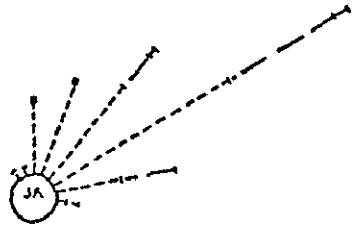


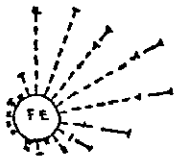


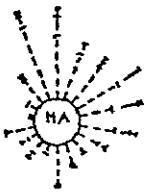


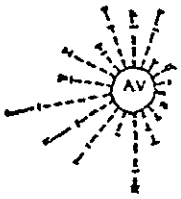


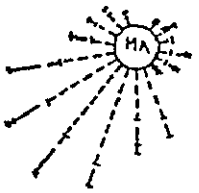


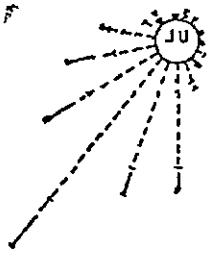


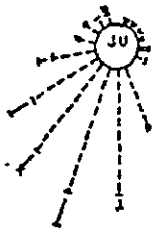


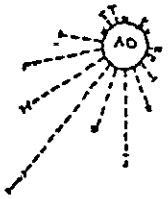

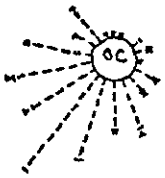

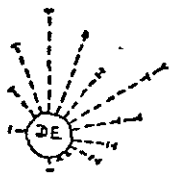


NIAMEY 1969

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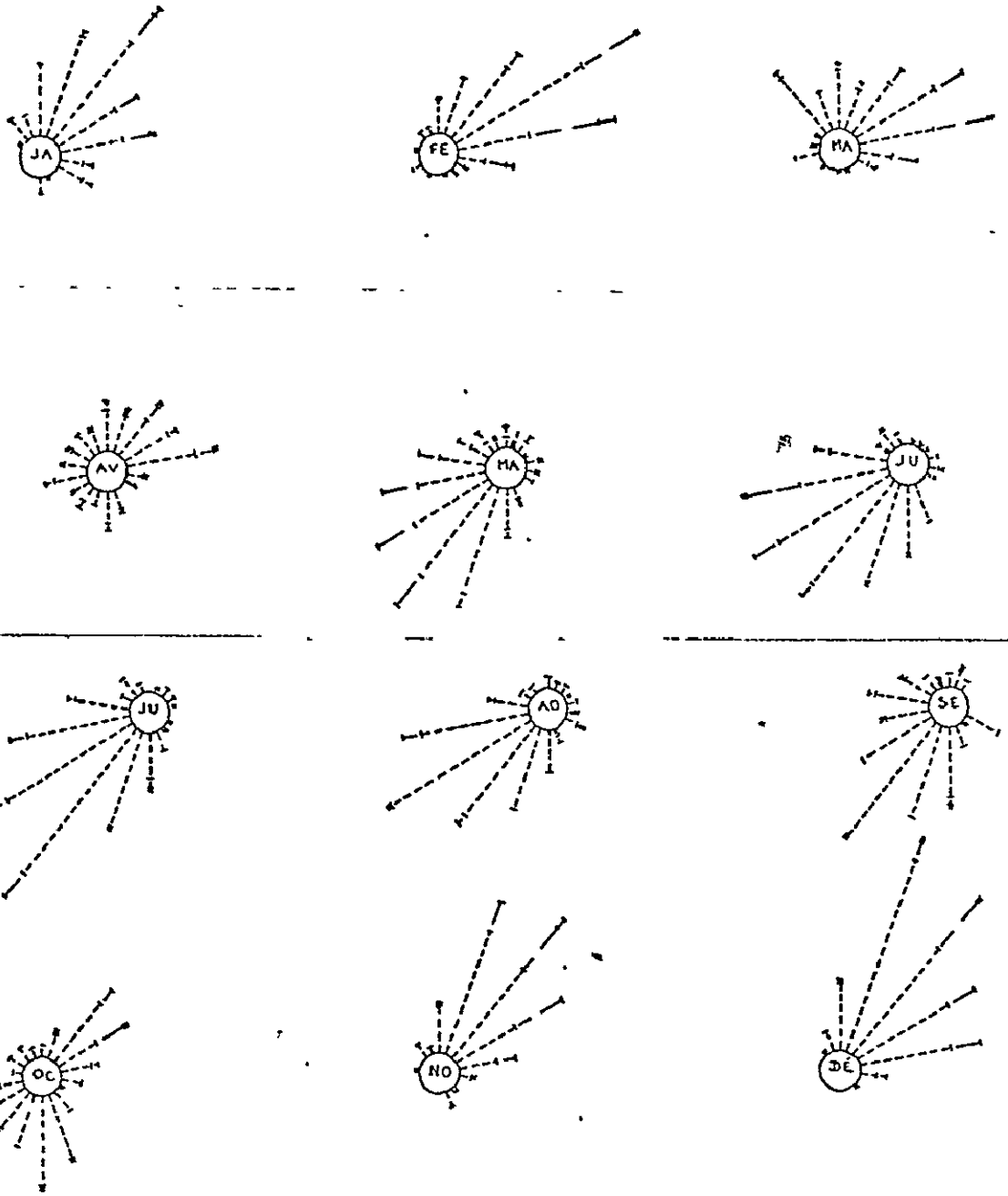


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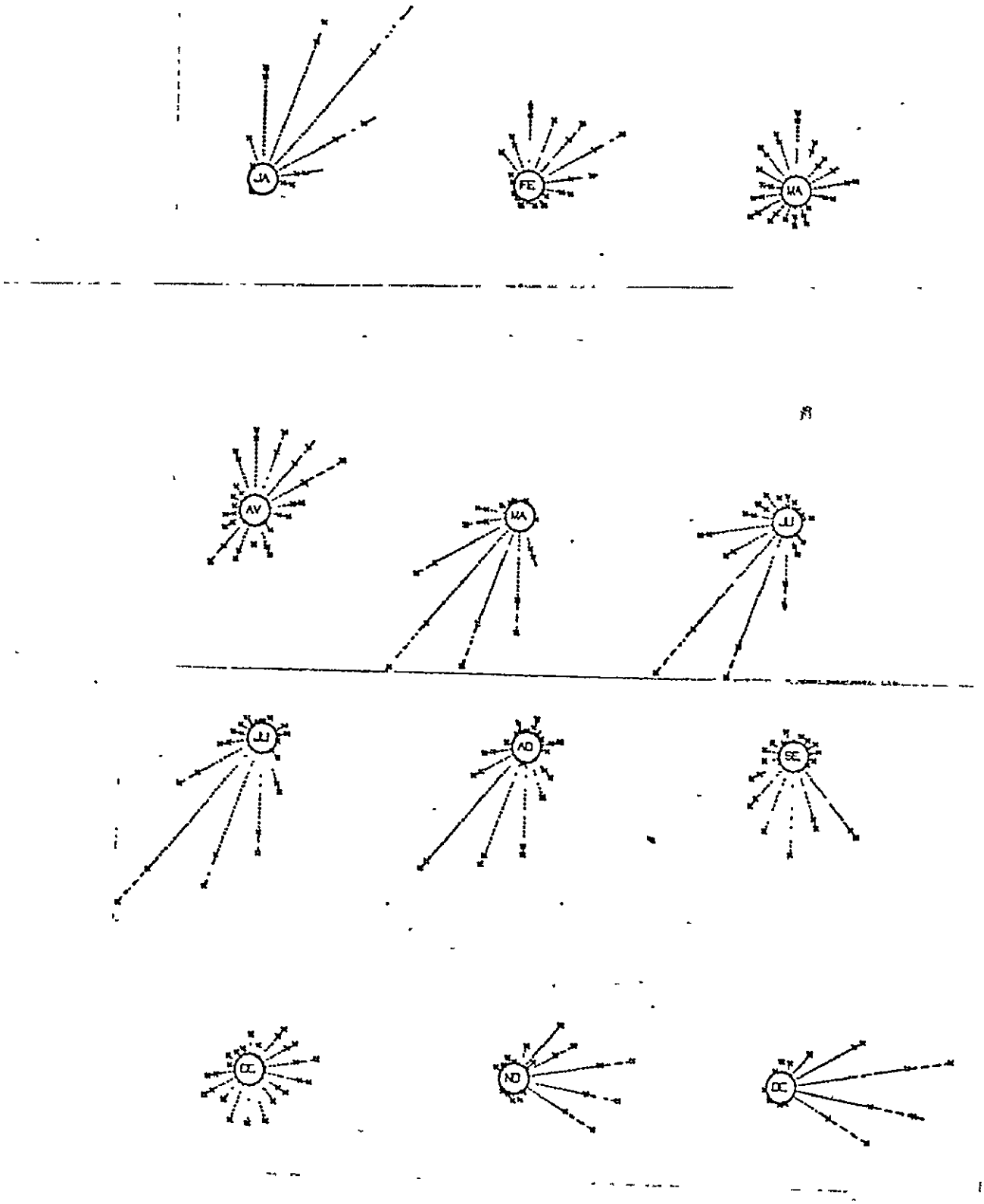

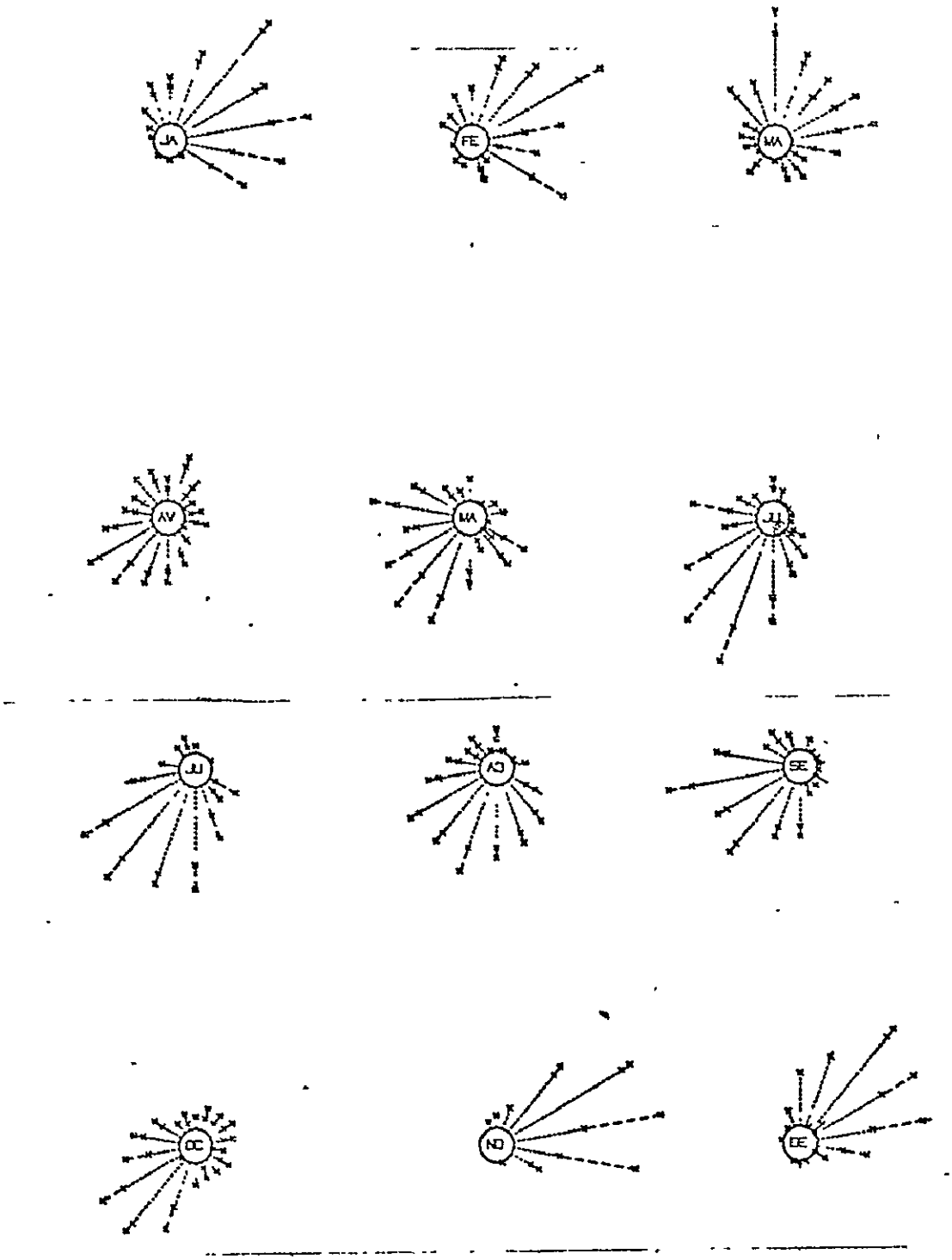

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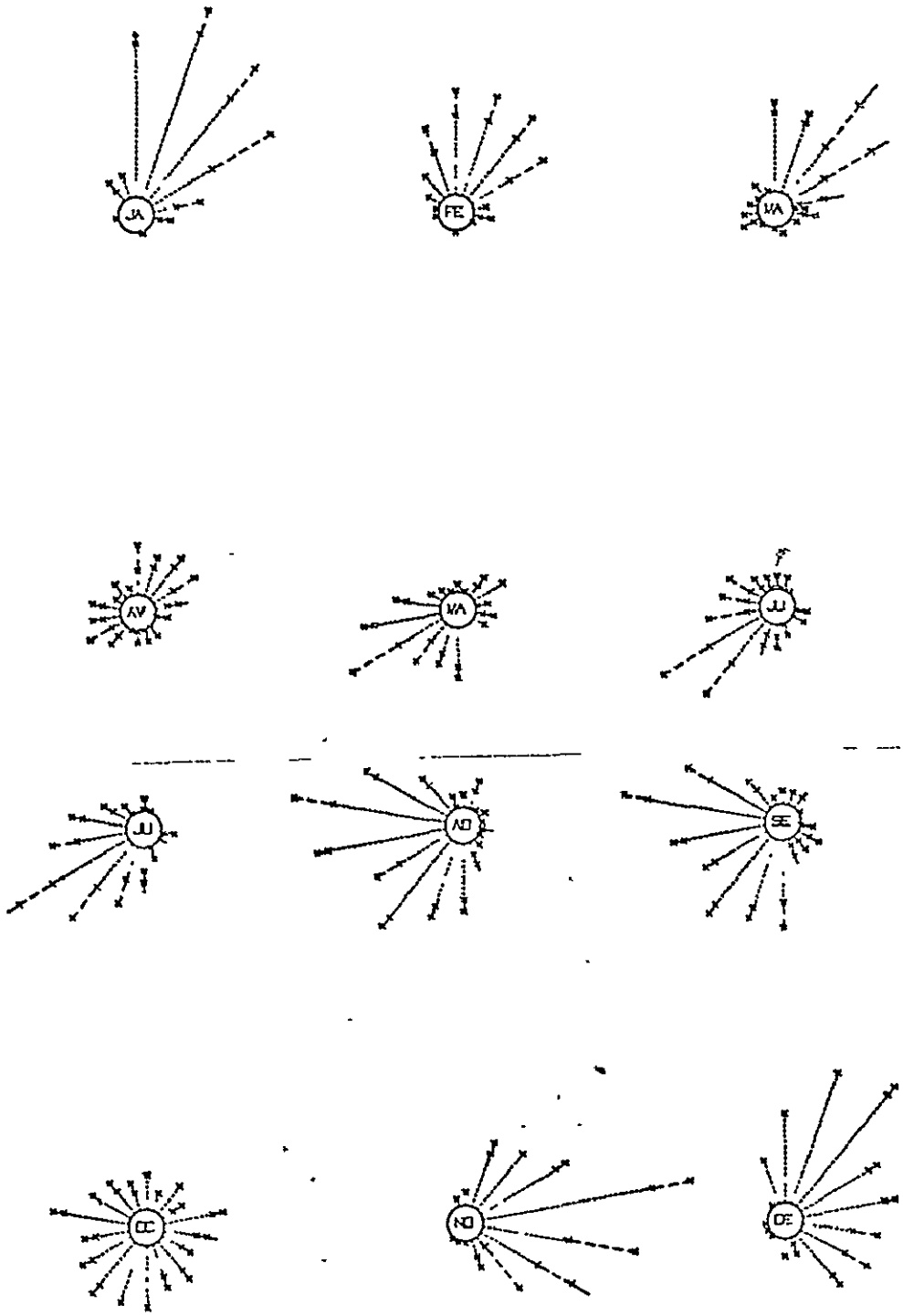

NIAMEY 1973

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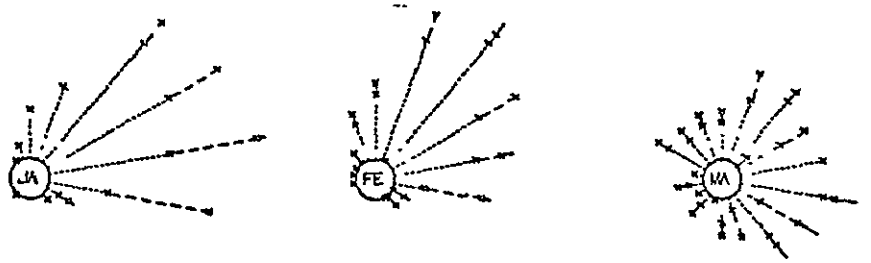
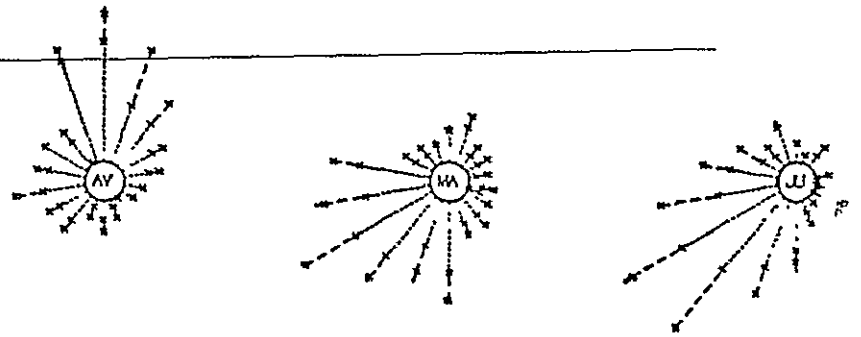
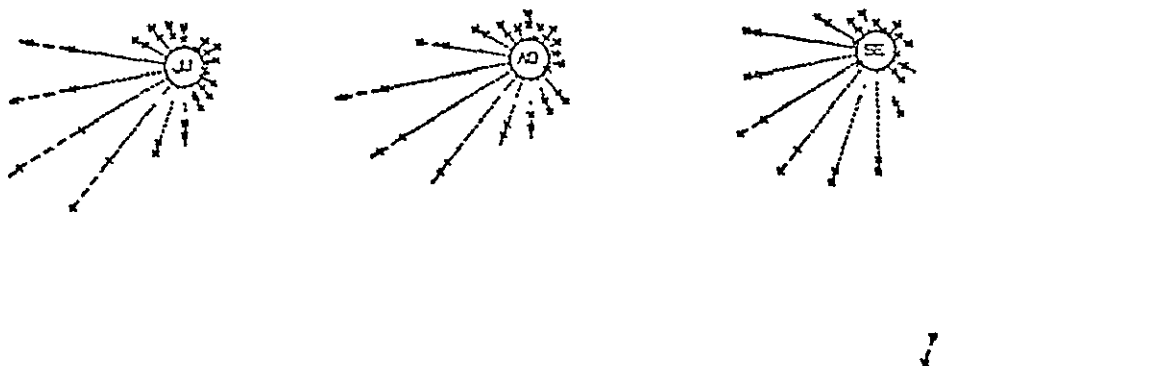
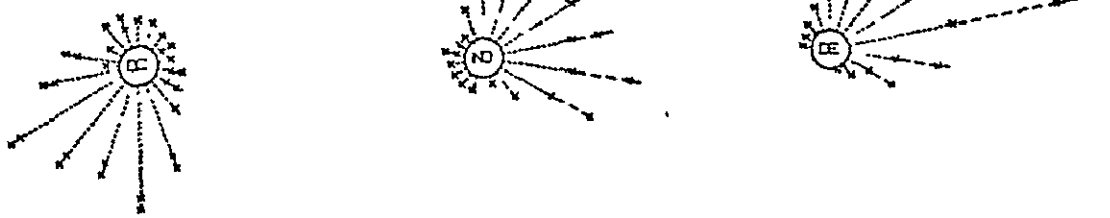
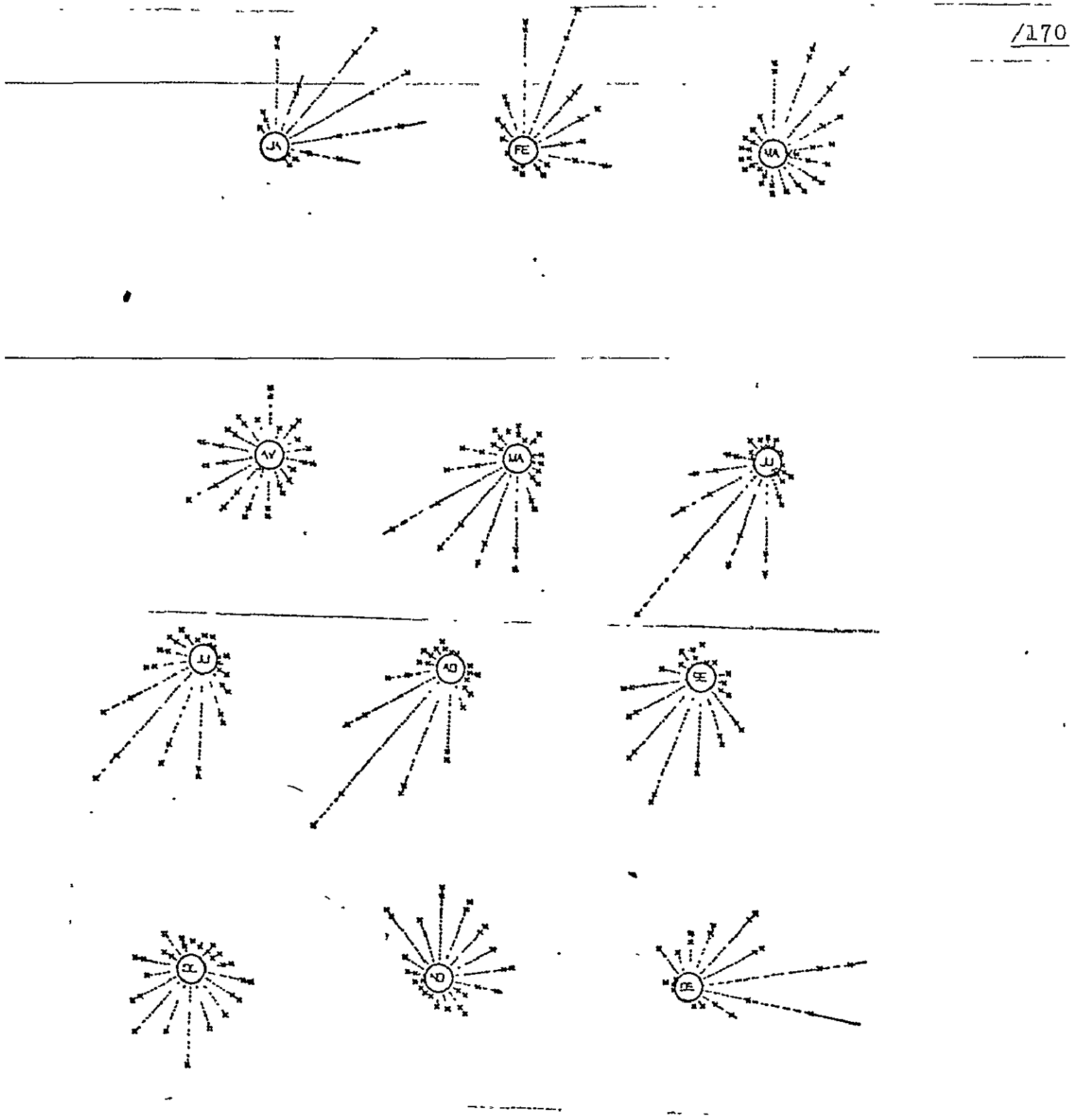








NIAMEY 1974




NIAMEY 1975

Monthly Rose Diagrams During the Period 1966 to 1975 /171
Niamey (Latitude: 13°28'N Longitude: 2°07'E)

1 - Dry Season (November to March)

During the dry season Niamey is still affected by the harmattan. The most effective winds are very clearly those of December and January, soemtimes those of November and February, but less consistently. On the whole, the winds come from a sector ranging between north-northeast to east, sometimes, however, spreading towards the north. But the winds are strongest when they come from between northeast and east.

2 - Interseasonal Periods.

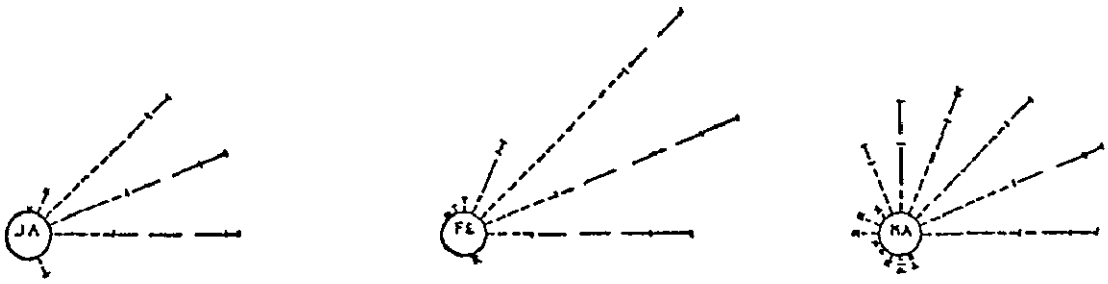
April. The transition from the dry season to the rainy season is often abrupt, in particular when the dry season and the dry season winds extend beyond the month of March up to April. Then, however, these winds are not very effective. From 1972 to 1975 the month of April did not receive any winds from a dominant direction, or else the direction was scarcely pronounced. What we see here is the dying out of the harmattan, extended slightly beyond the month of March, or harbingers of the monsoon.

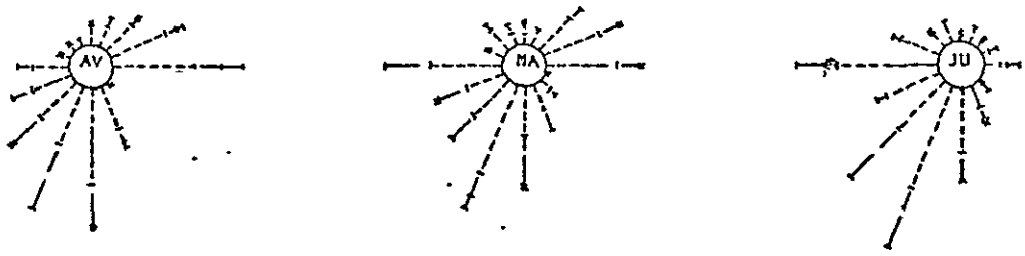
October. October is a month which can still be affected by the monsoon (1966-69, 1972, 1974-75), or else it can receive the harmattan, which then is not very effective (1970), or tit can be a month without any wind of a preferential direction (1971 and 1973).

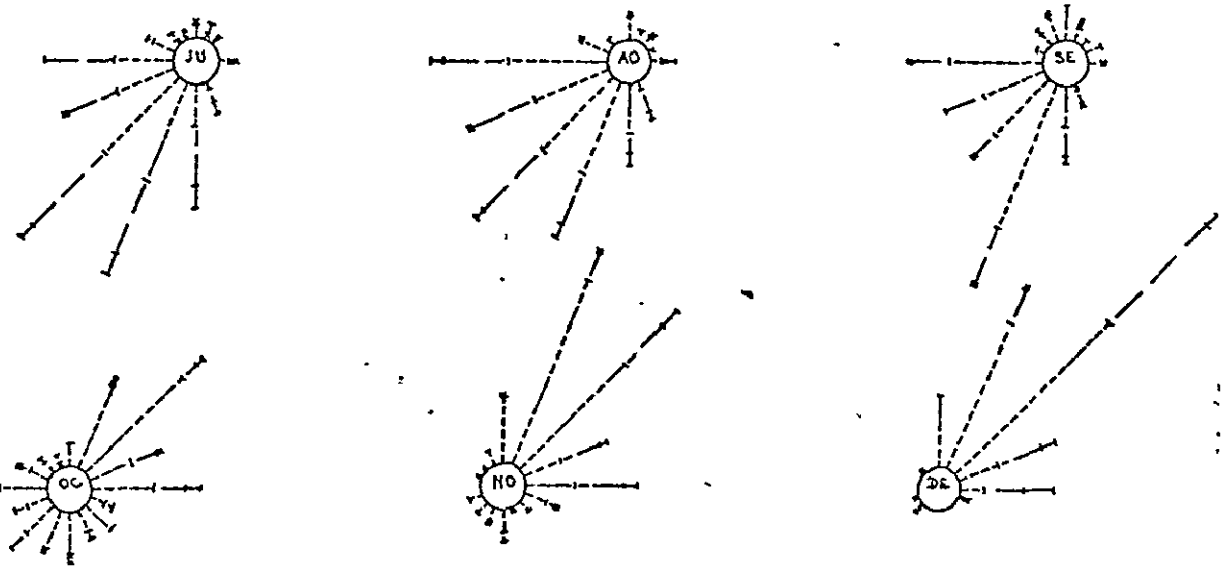
3 --Rainy Season (May to September).

This season stands out clearly. The shortage years, 1972 and 1973, are manifested by an attentuated or delayed incursion of the

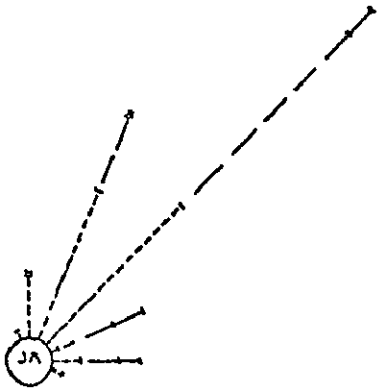
monsoon or an early arrest of the same (September 1967). In July, August and September 1968 it is replaced by a southeast wind.




TAHOUA 1966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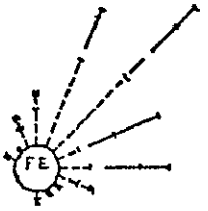
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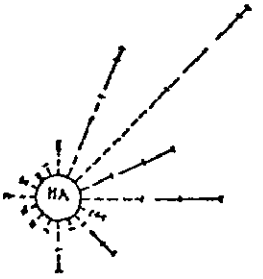
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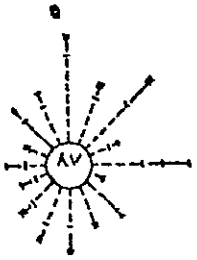
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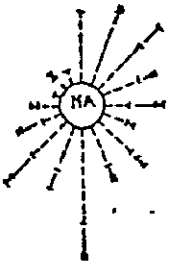
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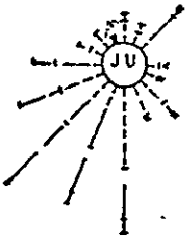
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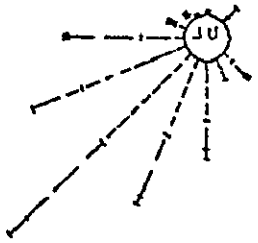
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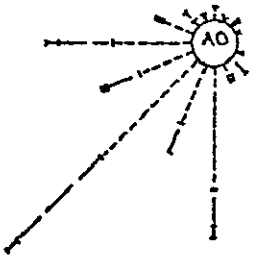
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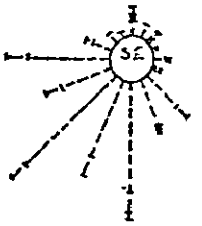
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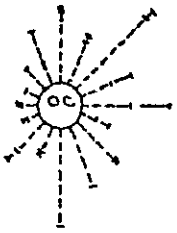
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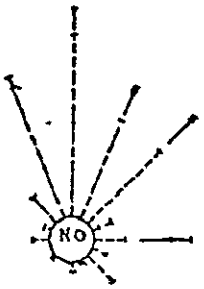
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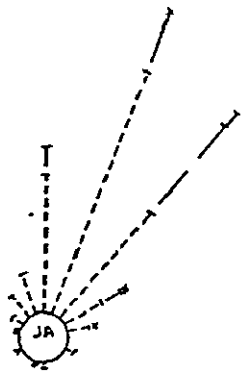
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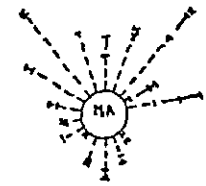
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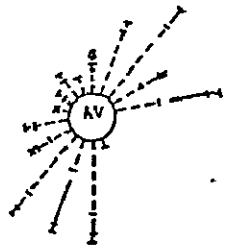
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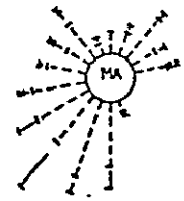
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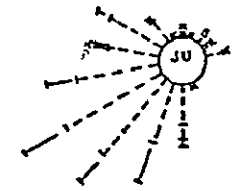
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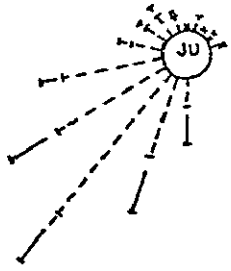
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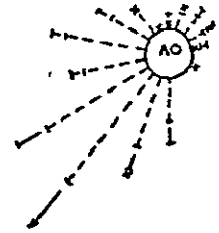
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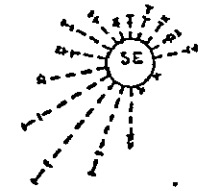
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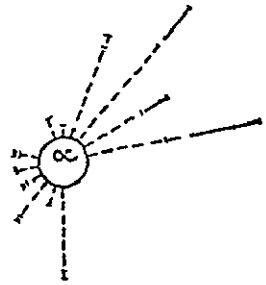
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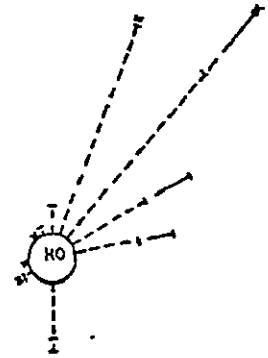
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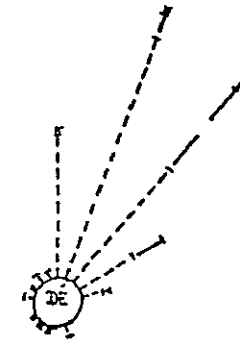
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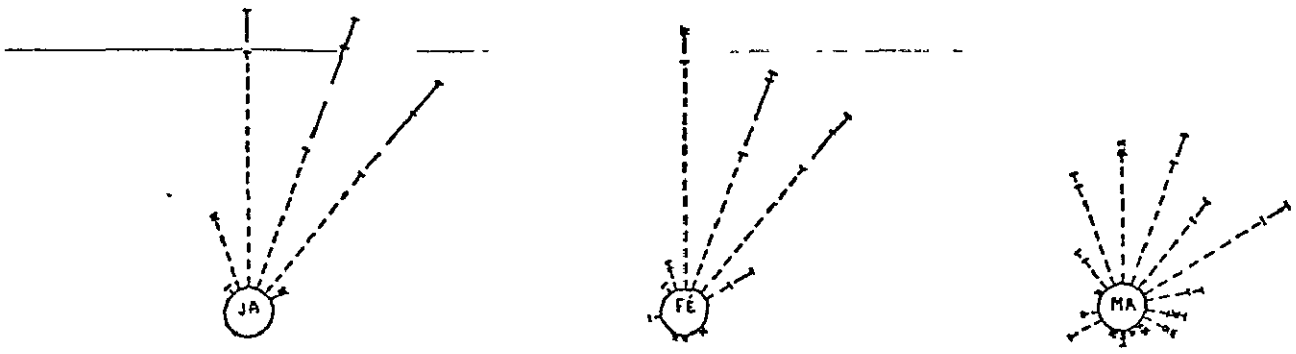
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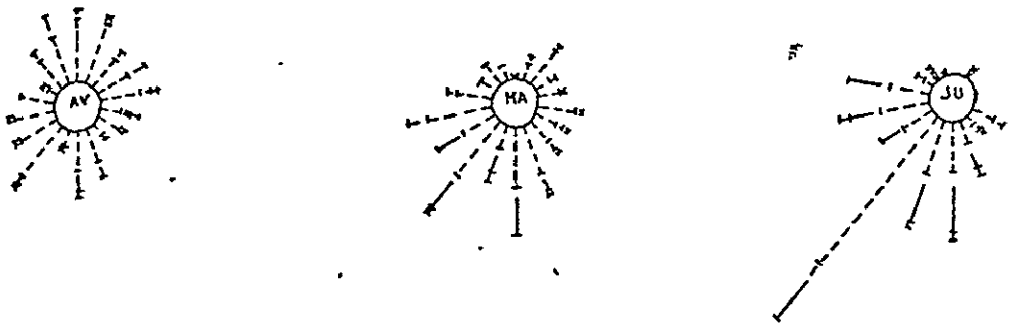
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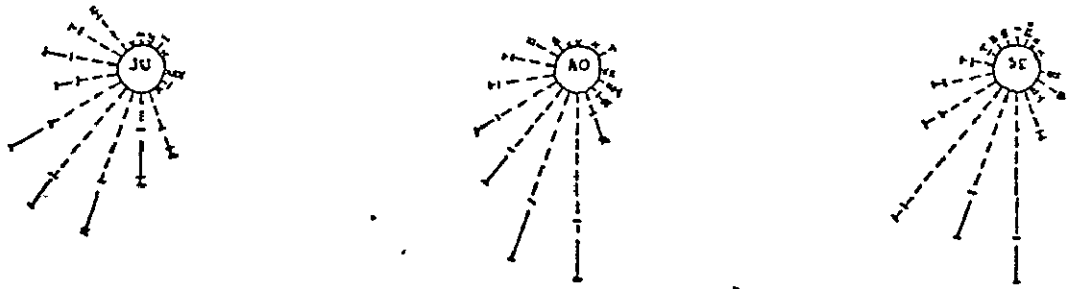
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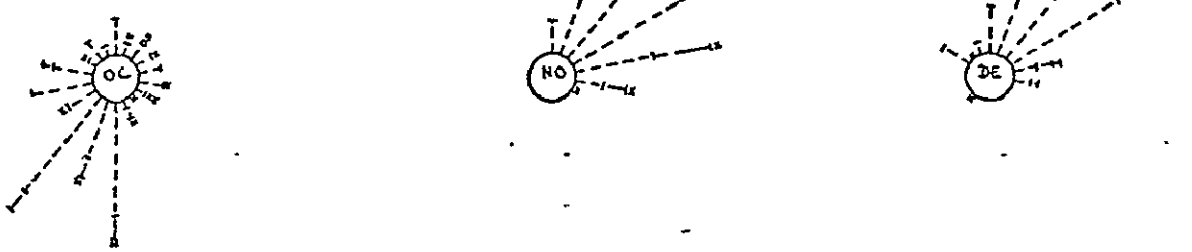
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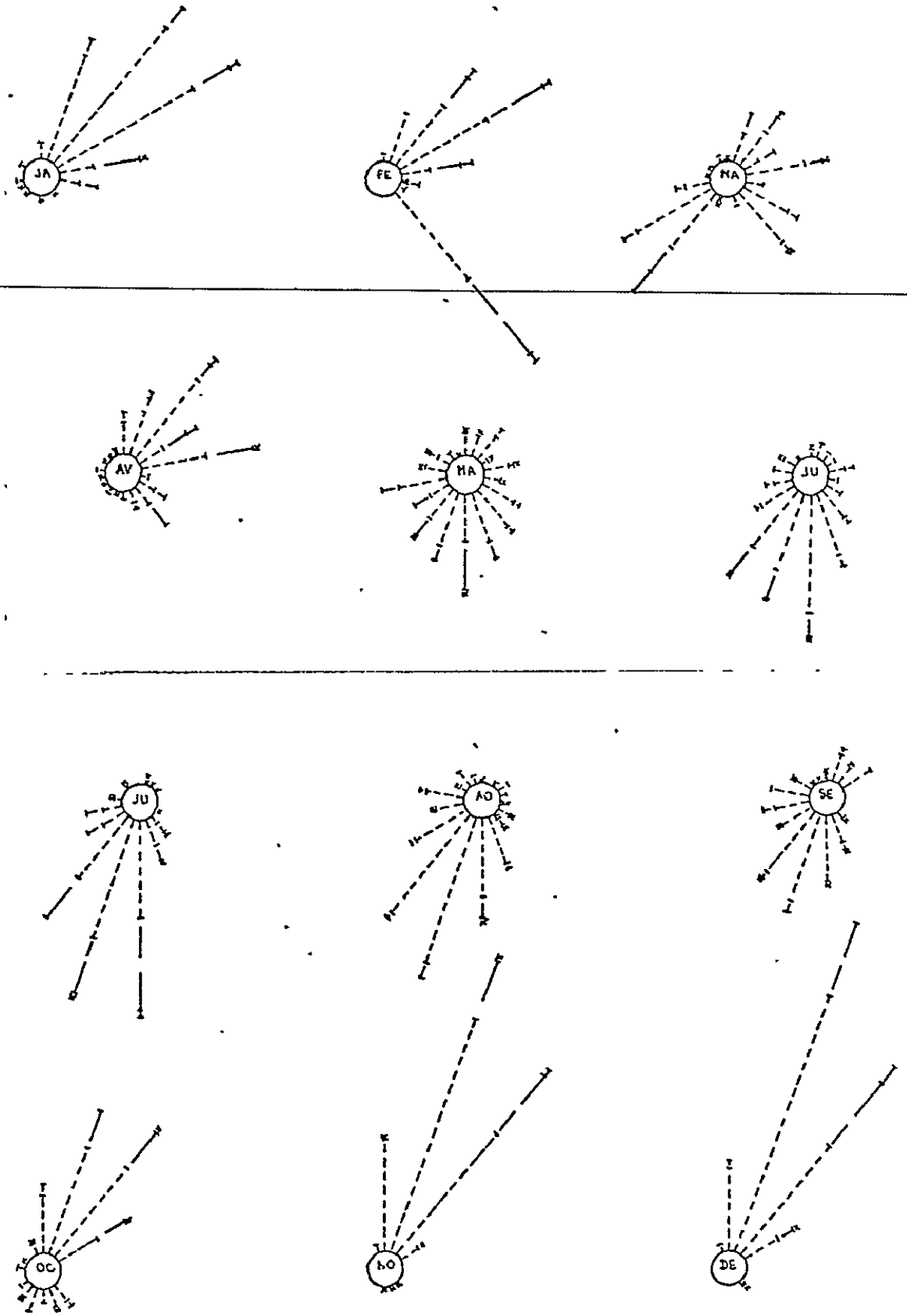

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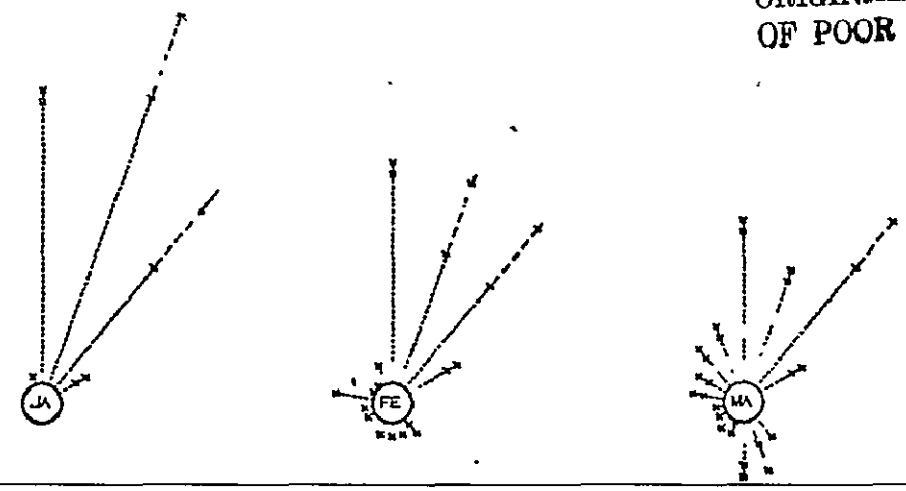

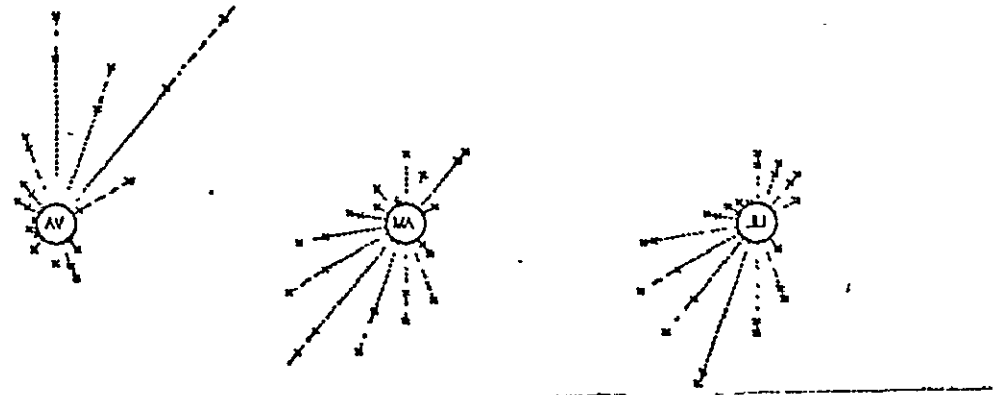

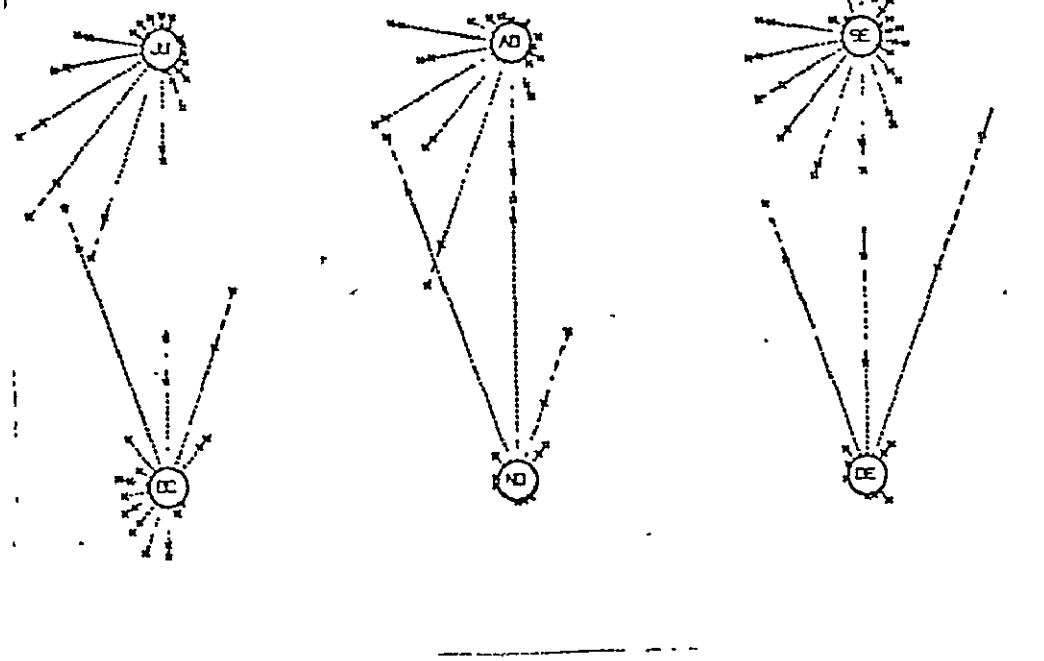

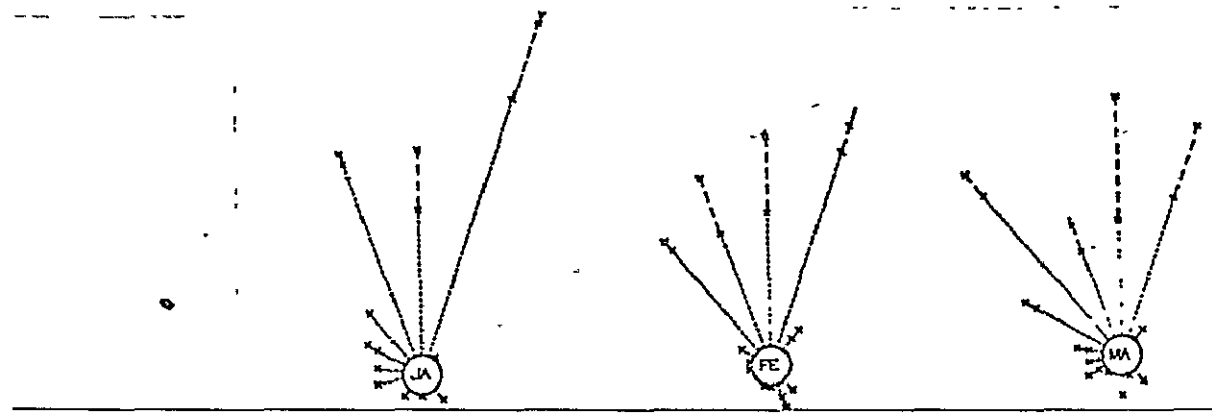

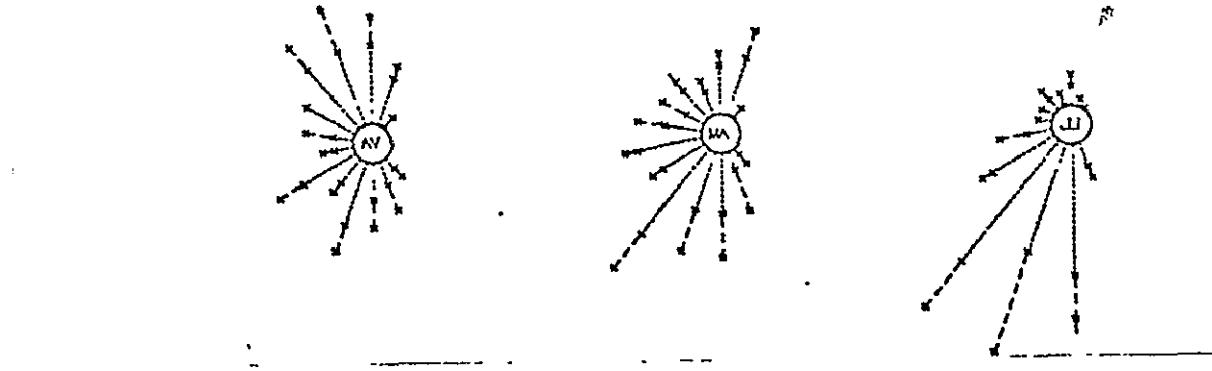

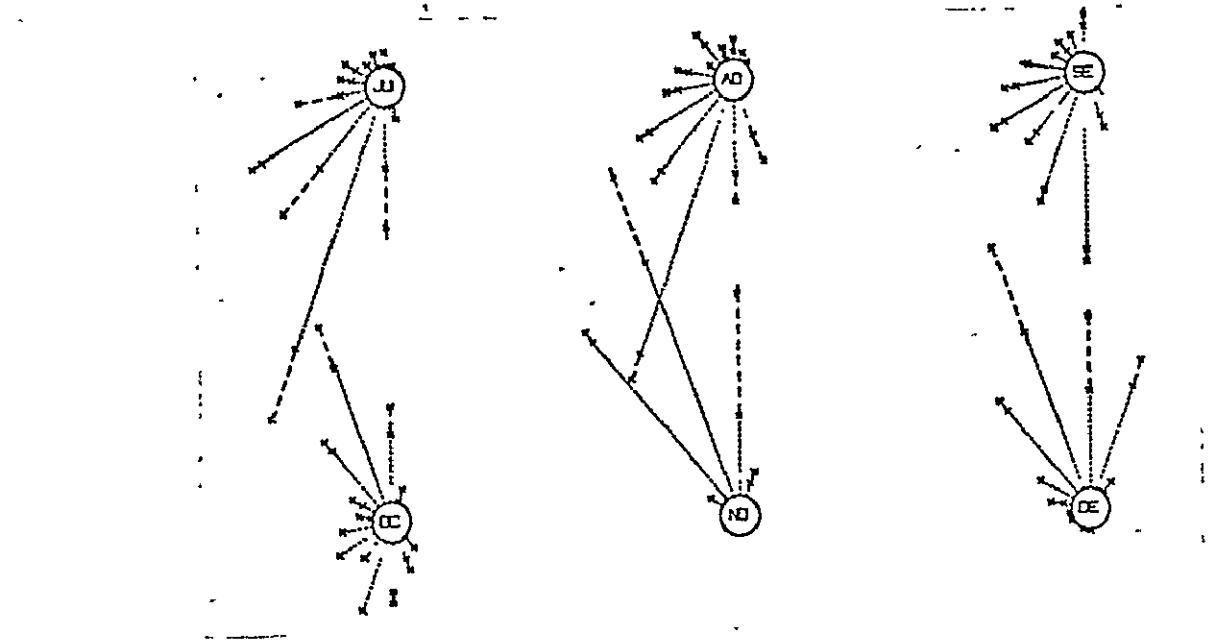

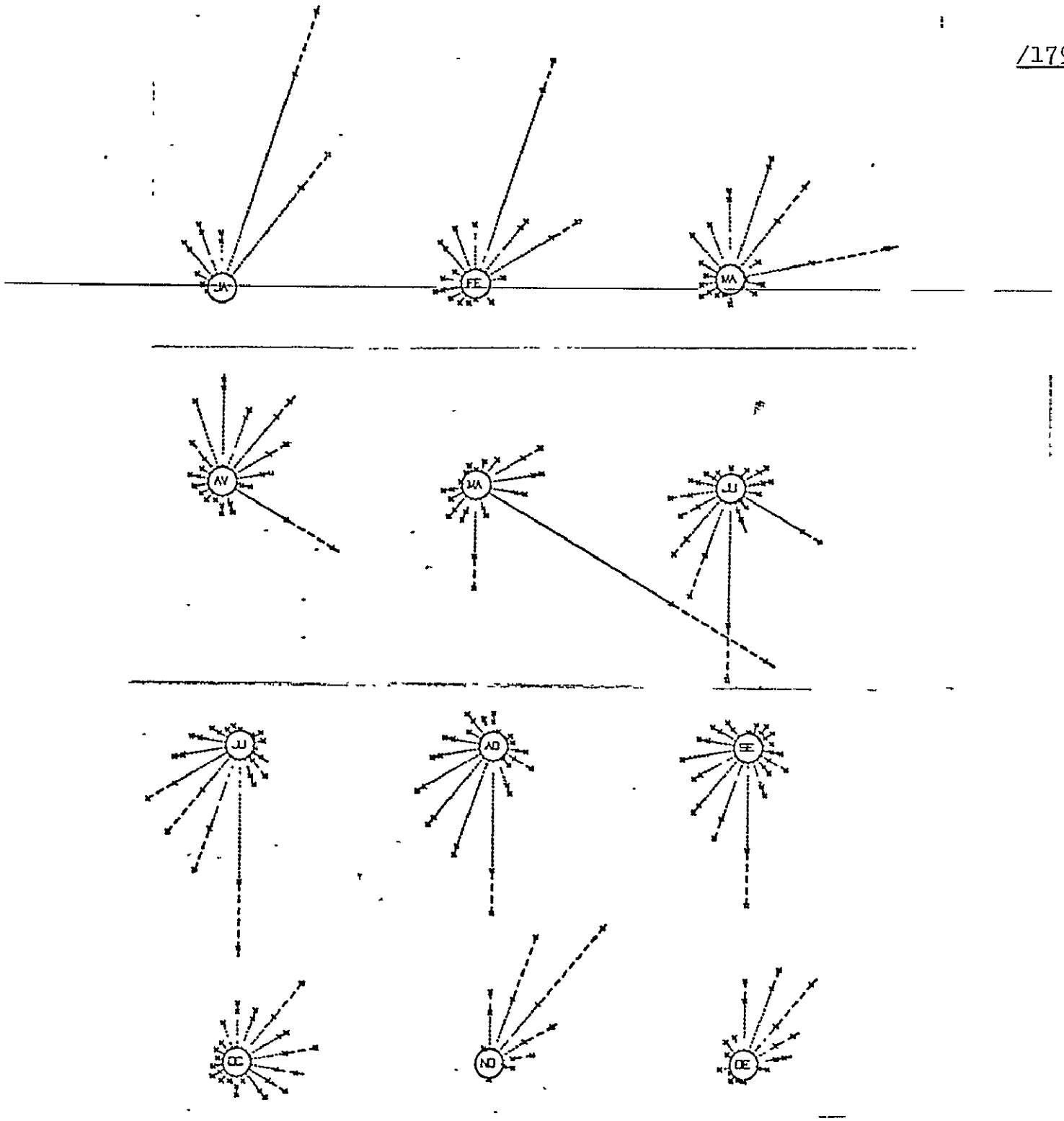

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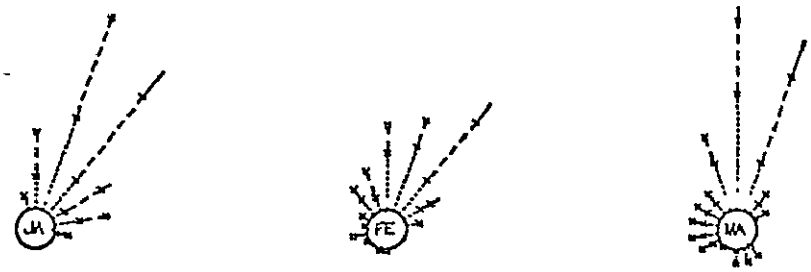
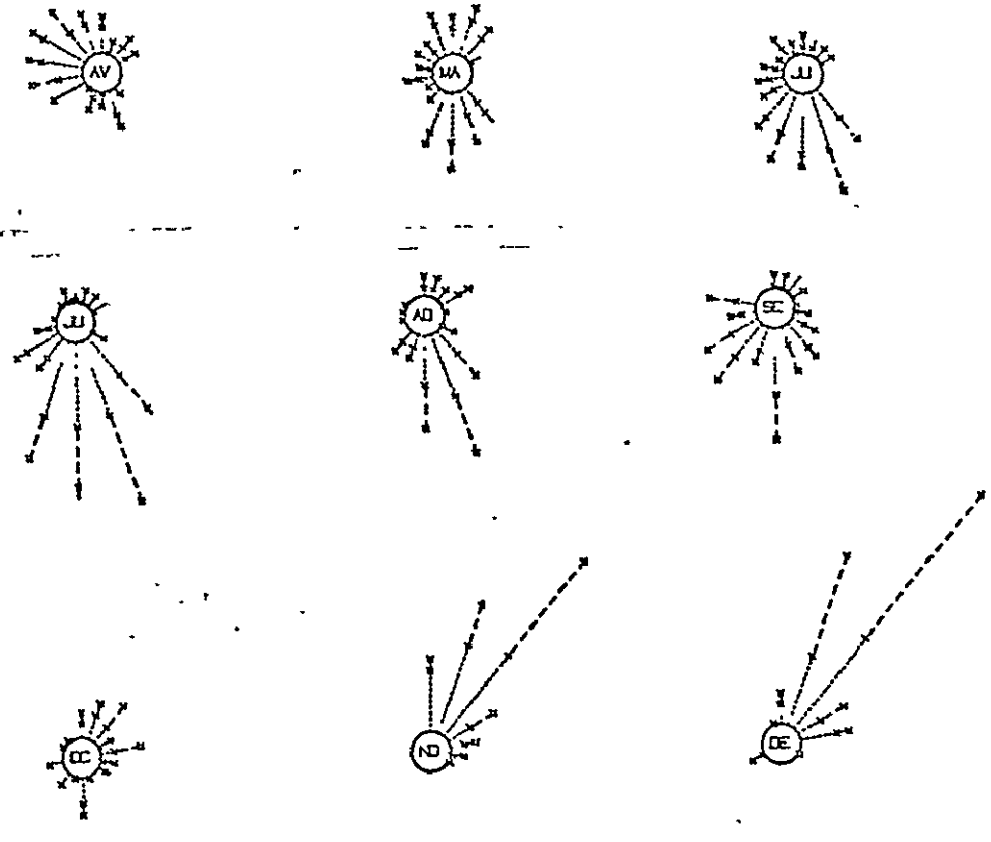
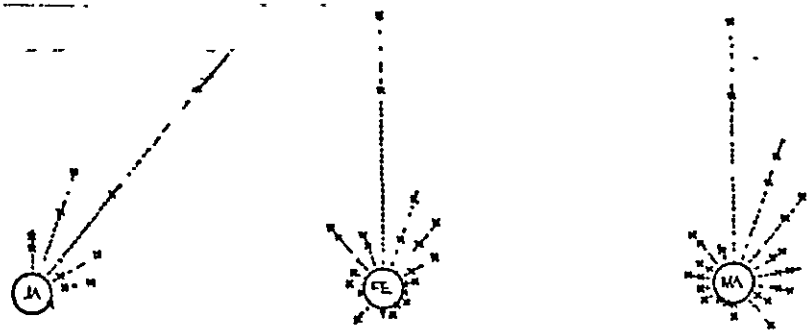
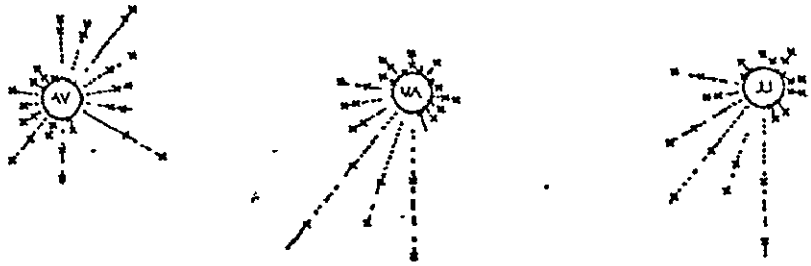
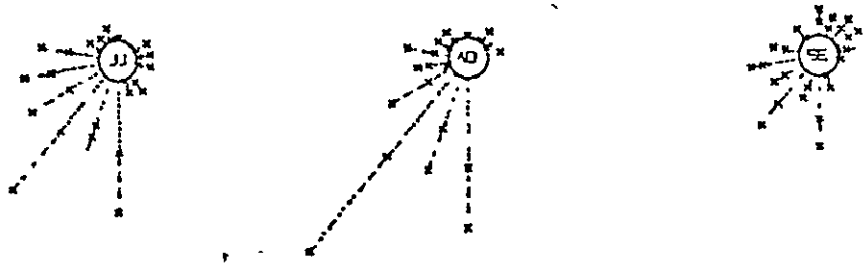


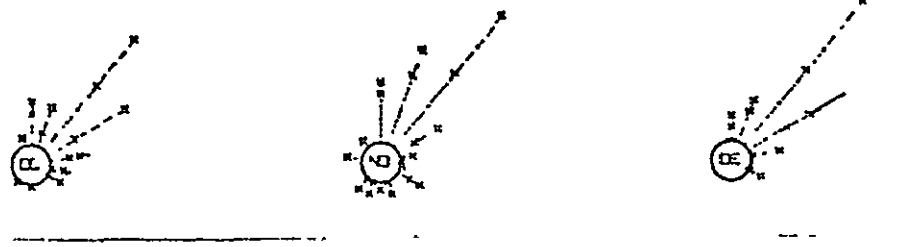


TAHOUA 1974









Monthly Rose Diagrams for the Period 1966 to 1975 /182
Tahoua (Latitude: 14°53'N Longitude: 5°15'E)

1 - Dry Season (October to March).

During the dry season Tahoua is a station typically under the influence of the harmattan from the northeast, except in February 1968 and 1969 when the prevailing winds blow from the north. In February 1970 the prevailing winds blew from the southeast, and from the northwest at the beginning of hthe dry season in 1971. This prevailing northwest-north wind persists during the entire dry season and is found again during the same season in 1972. It is only 1973 that a more traditional situation is reestablished with winds from the northeast. Thus the shortage years from 1969 to 1972 are very evident in the rose diagrams. The winds are the most frequent and strongest in January, in particular when they blow from the NNE or from the northeast.

2 - Interseasonal Periods.

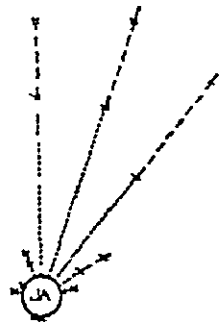
The transitionsfrom the dry season to the wet season generally occurs in April. But in 1968 and 1970 it occured in March, and in May in 1971. Thus the years 1968, 1970 and 1971 are characterized by an advanced or late arrival of the monsoon.

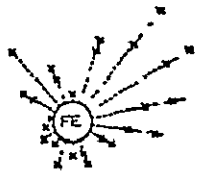
From 1966 to 1973 there is no interseasonal period at the time of transition from the rainy season to the dry season. In September Tahoua is still under the influence of the monsoon and from October onward it is under the influence of the harmattan. There is a brief interseasonal period only in 1974 and 1975.

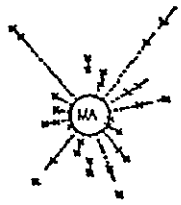
The interseasonal periods are very short at Tahoua.

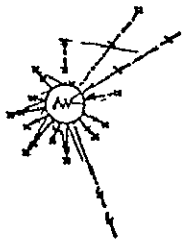
3 - Rainy Season (May to September).

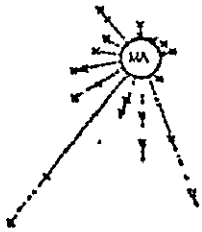
If one observes the wind parameter, one is stuck by the abruptness of the incursion of the monsoon which replaces the harmattan without transition. The direction of the rainy season winds, which make themselves felt for 6 months, coincides with the southwest-northeast path of the monsoon, except in 1973 when the prevailing winds from May to August come from southeast to south. The dry period from 1968 to 1971 is not reflected, or only slightly so, in the pattern of rainy season winds. /183

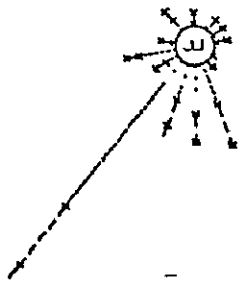


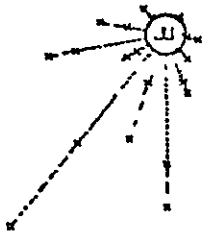


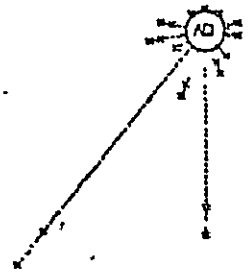


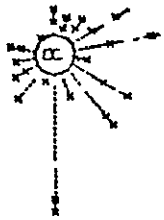


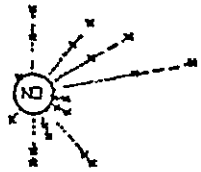


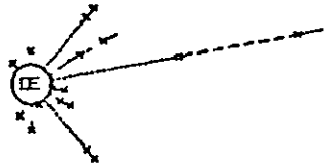


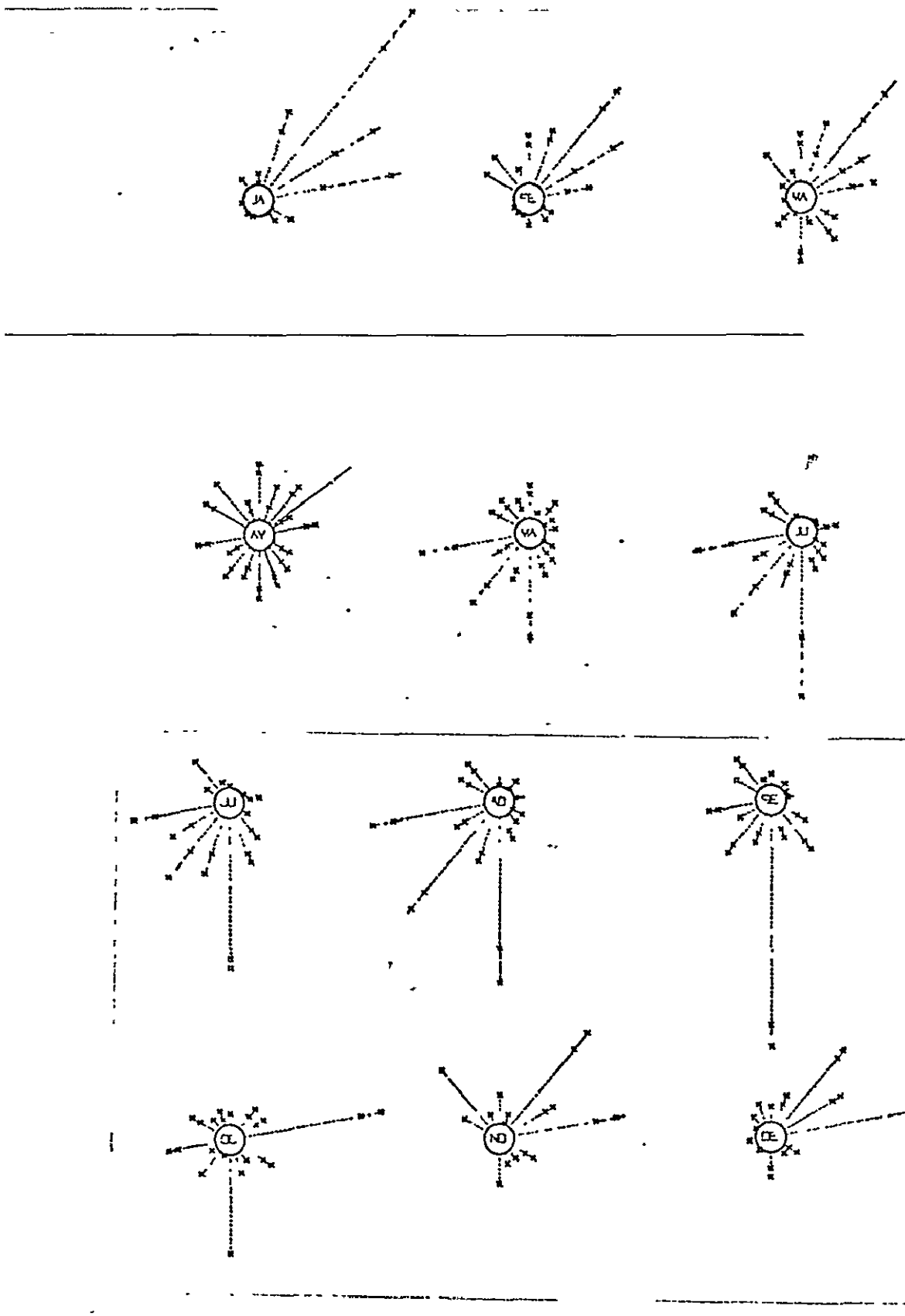












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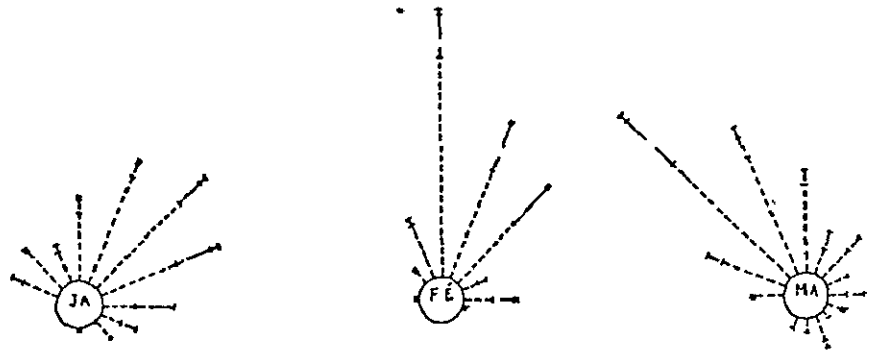


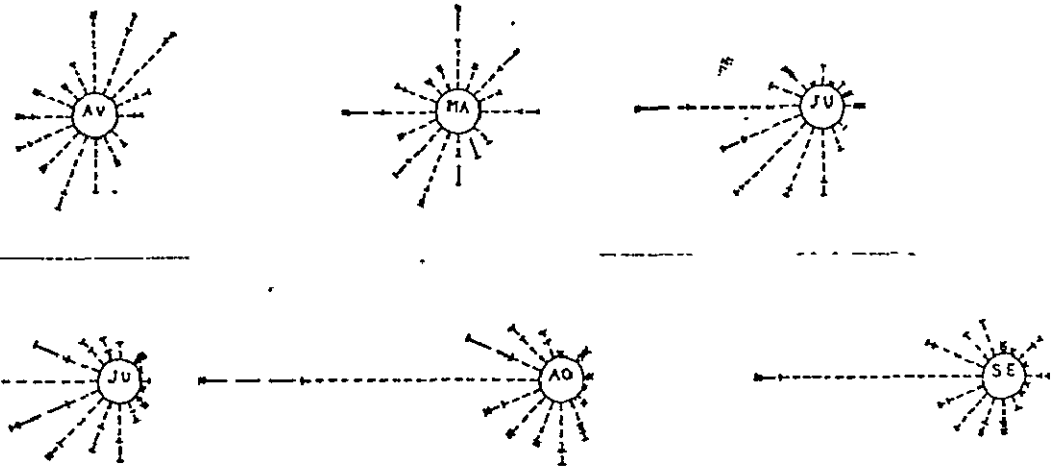


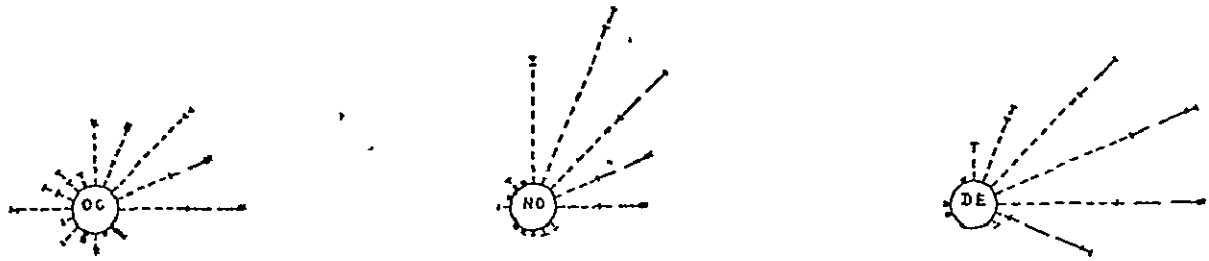


ZINDER 1966

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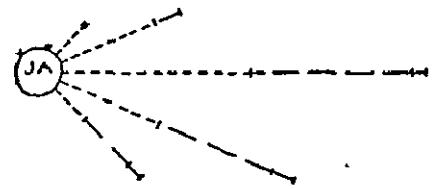


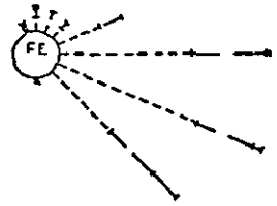


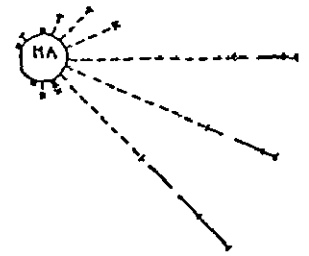


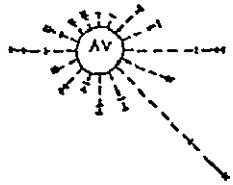


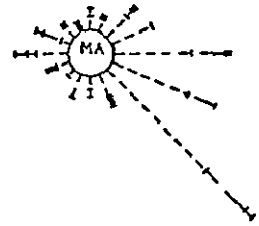


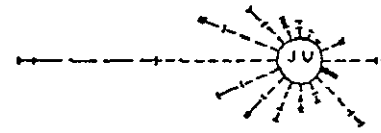


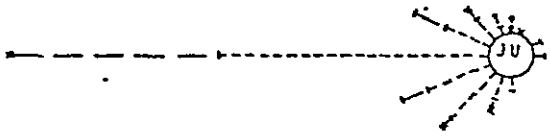


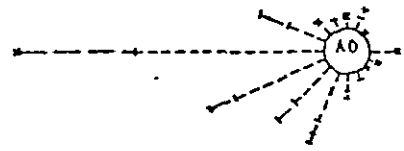


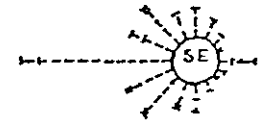


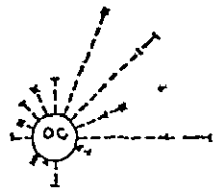


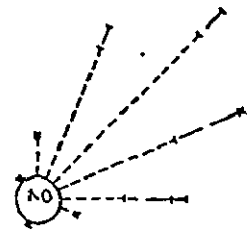


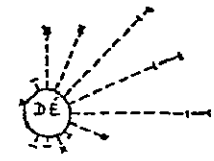


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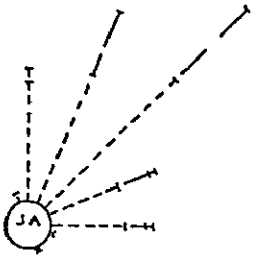


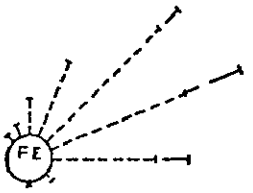


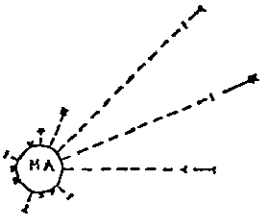


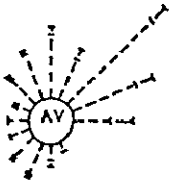


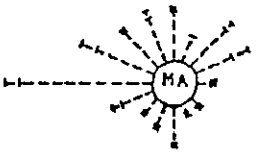


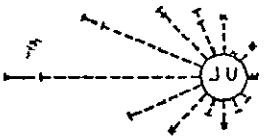


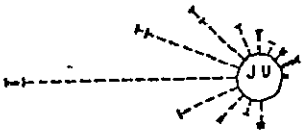


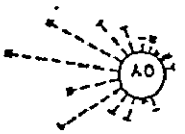


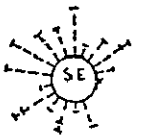


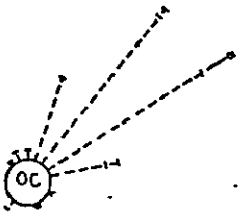


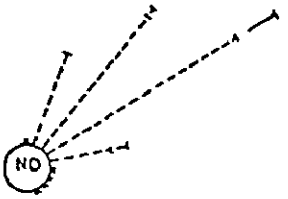


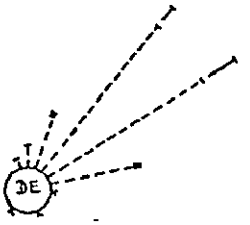


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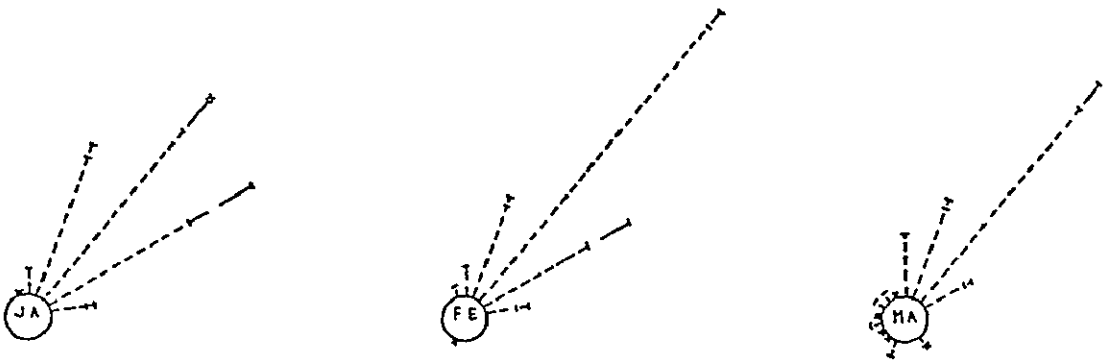


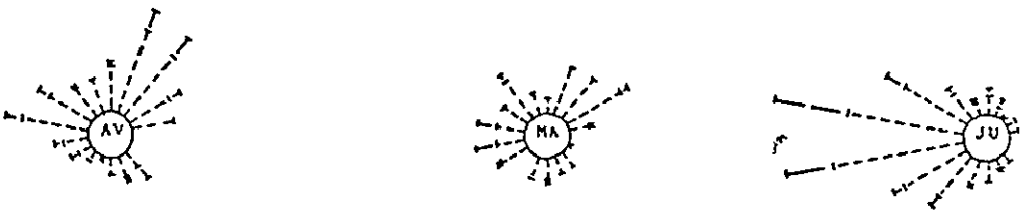


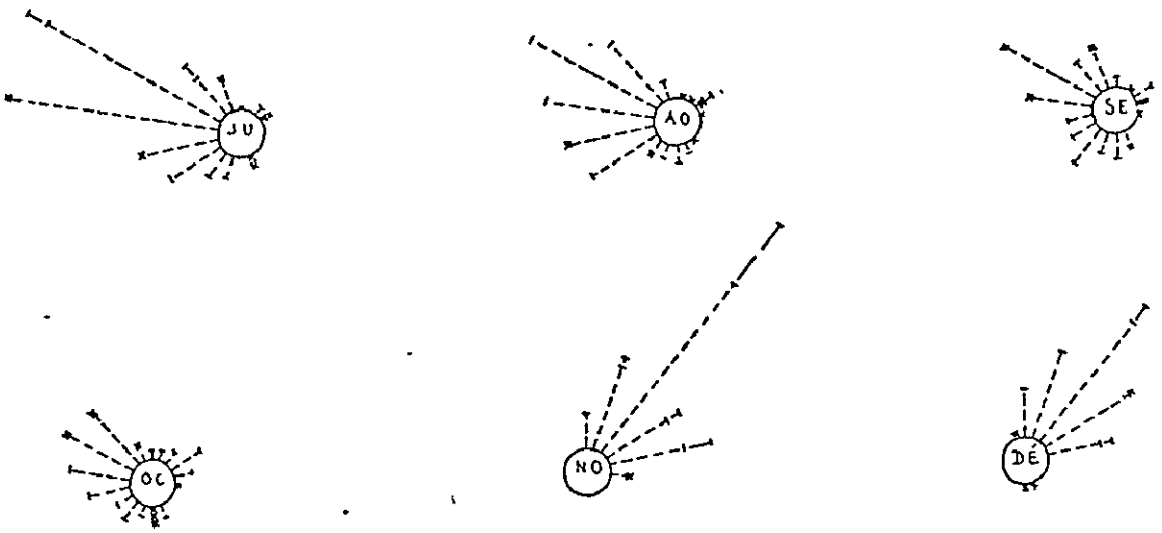


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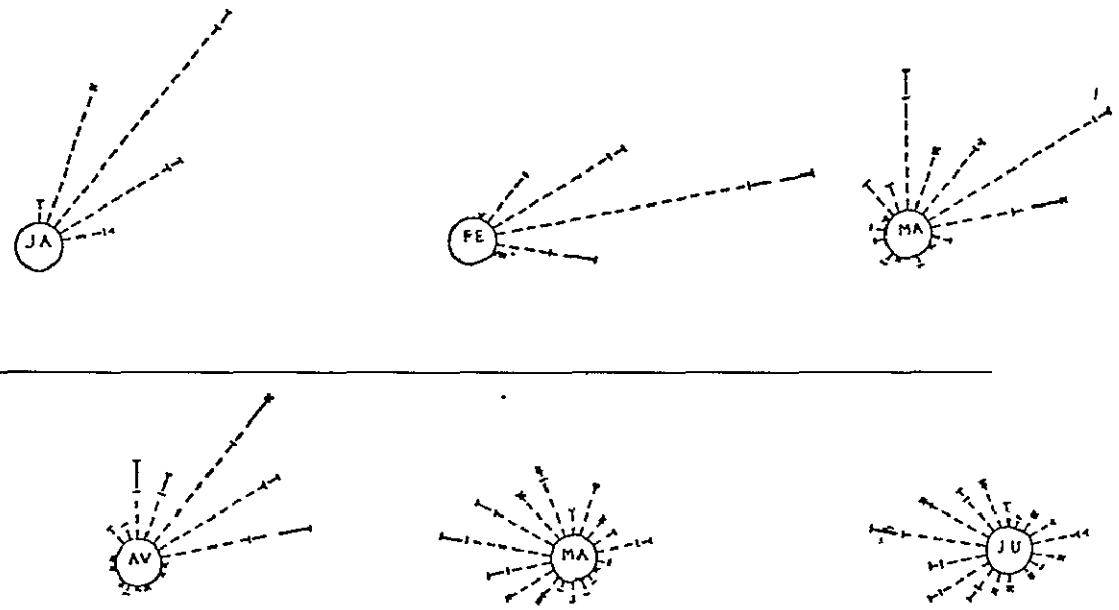


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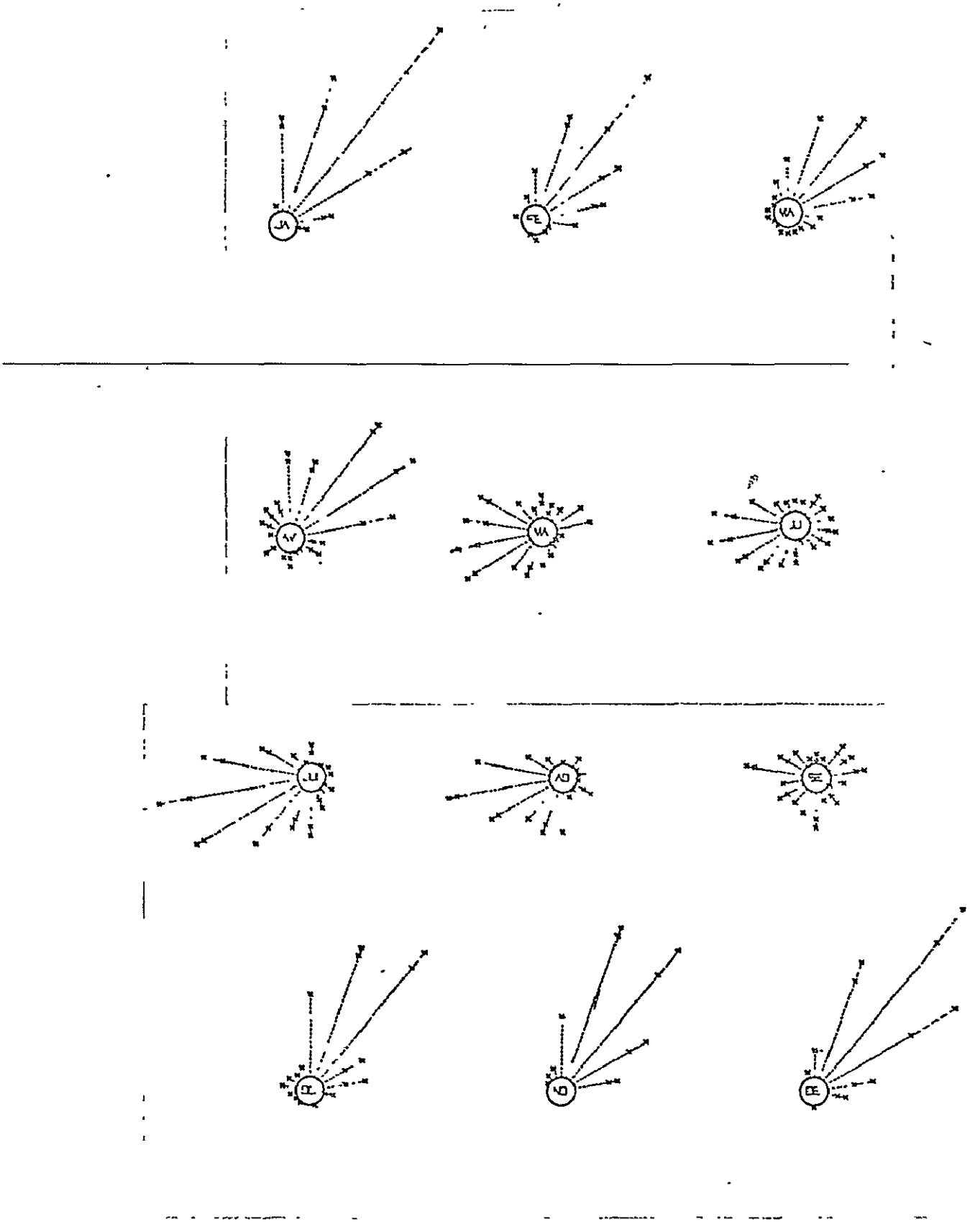

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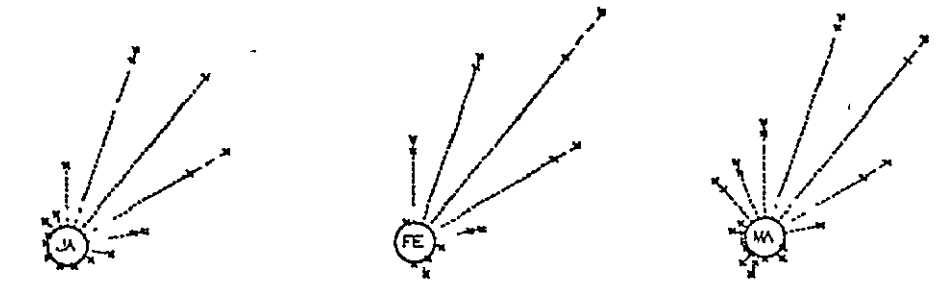

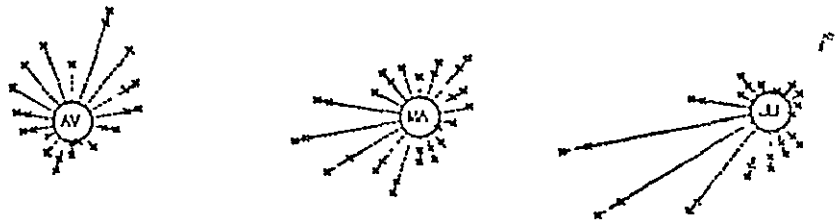

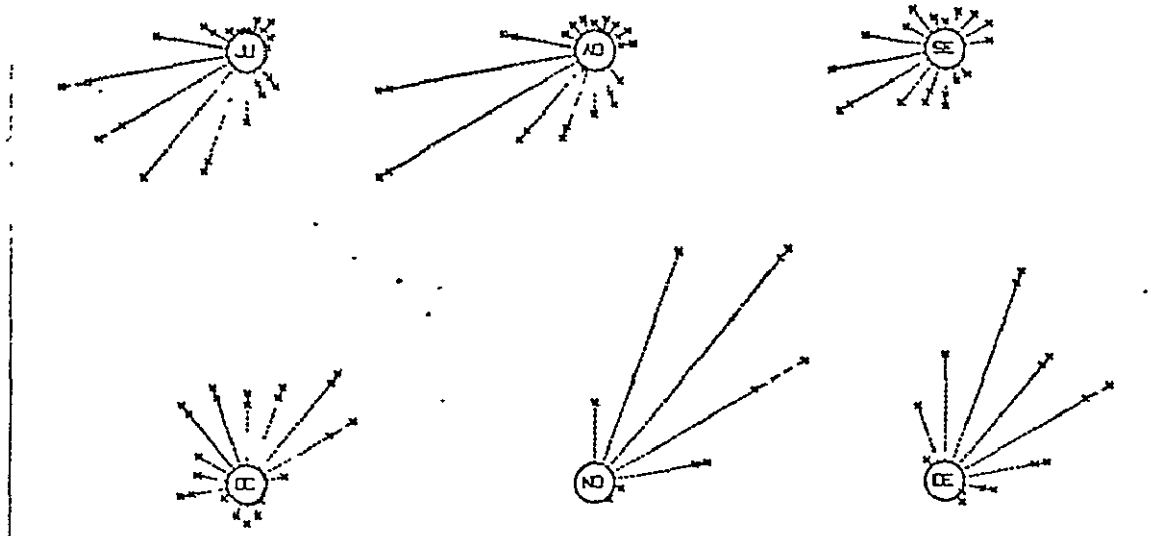

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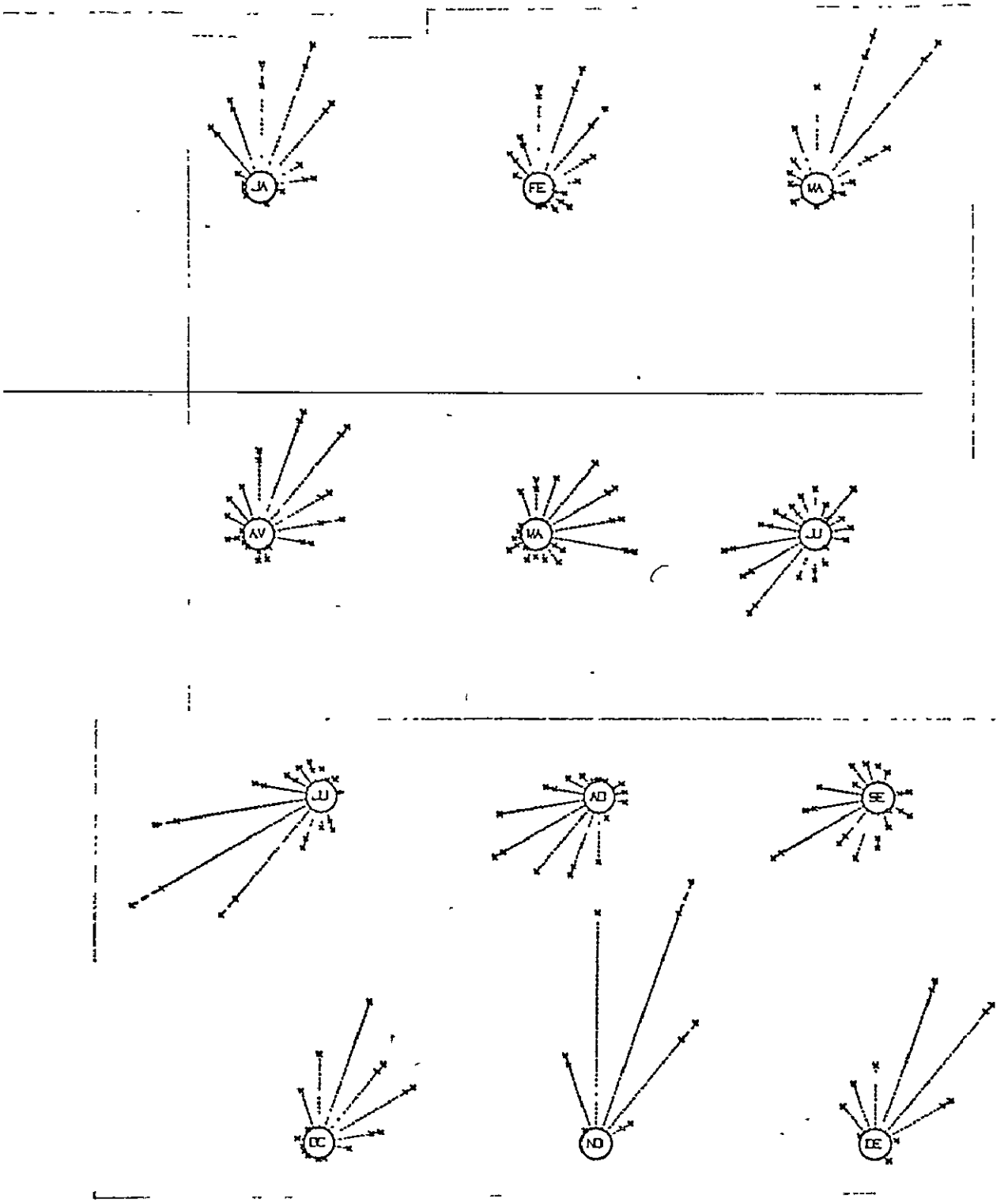

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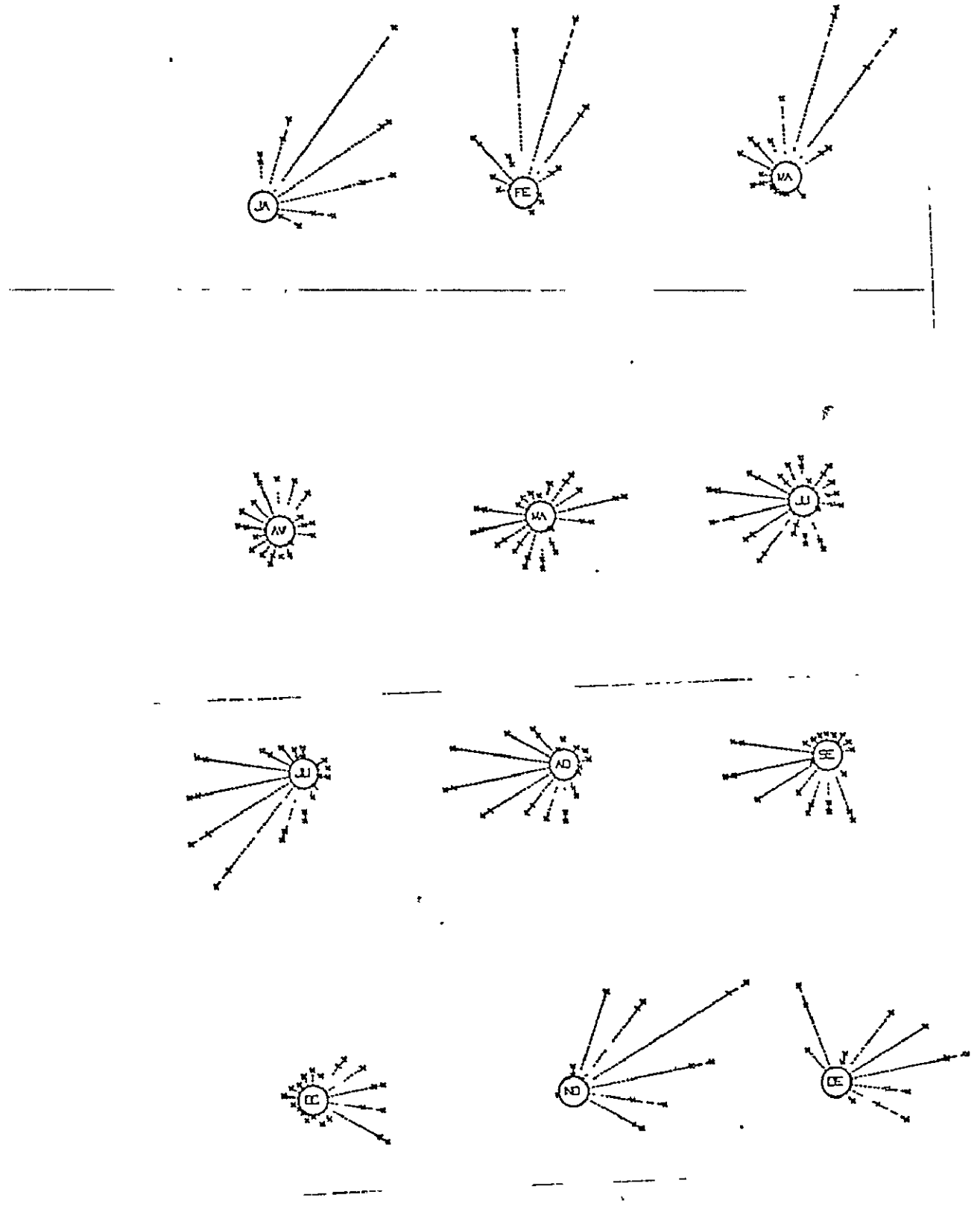

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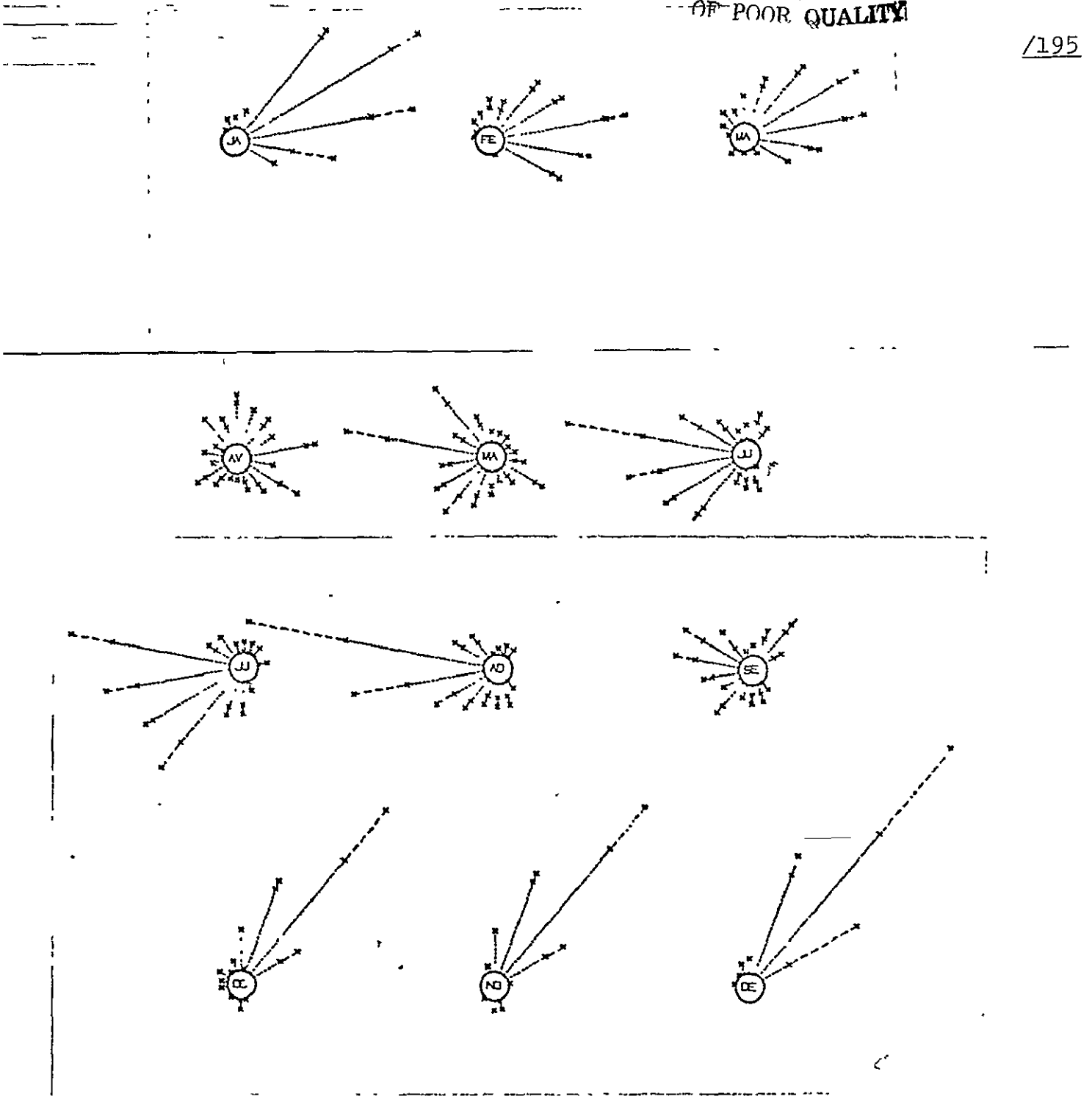


ZINDER 1975

Monthly Rose Diagrams for the Period 1966 to 1975 /196
Zinder (Latitude: 13°48'N Longitude: 9°00'E)

1 - Dry Season (November to April).

This season extends from November to April from 1968 to 1973 inclusive. In 1966, during March and April, prevailing winds blew from the northwest. In 1973 the dry season winds continued up until May. The dry season begins in October, except in 1969 when it begins in November. On the whole the winds come from the north-northeast, sometimes from the east-southeast. The dry season is perfectly marked at Zinder with frequent and effective prevailing winds of the harmattan type, especially during January and February.

2 - Interseasonal Periods

April-May. April can no longer be considered as the only transition month. Both April and May constitute the transition season. The incursion of the monsoon made itself felt only in Man and only in 1968, 1970-72 and 1975.

October. October is clearly the first month of the dry season, with winds already of the harmattan type, except in October, 1969, when winds from the northwest were dominant.

3 - Rainy Season (June to September).

In June, on the whole, the direction of the monsoon is remarkably zonal and persists in July, August and September during the years 1966 to 1971. Starting in 1972 the direction is the usual one from the southwest, but it resumes a zonal direction in 1975. These observations are particular for Zinder.

## 7. Analysis of the Direction and Average Frequency of Monthly Average Prevailing Winds. Comparative Study of Interannual Instability Indicies of the Winds. /197

Each station is studied with respect to two specific wind variables: frequency and direction.

The study is based on: (1) meteorological data supplied for each station (8 readings per day) for the years 1966 to 1975 and (2) on rose diagrams obtained by processing this data statistically.

The frequency is defined by the number of readings for a prevailing direction for one month, and the frequency percentage is defined by the number of readings for a dominant direction for one month with respect to 240 readings (= 30 x 8 per day).

By using a graphical representation of the average frequencies of average prevailing winds and by means of a composite representation of the monthly average variations of the period of years considered, the intended aim is to establish the main prevailing direction of the winds and for each of these directions to isolate both their direction and frequency components.

A second more refined study will be made using the same methods on the effective winds.

We define our terms as follows:

- monthly average prevailing wind: the average angle -- obtained from data for the years 1966 to 1975 -- of directions whose frequency is the greatest for the month considered.
- dispersion index: the ratio

$$\frac{\text{absolute deviation from the mean}}{\text{arithmetic mean}} \times 100.$$

The absolute deviation from the mean is the sum of deviations from

the mean in absolute value of each term of the series divided by the number of terms.

- instability index: the product of frequency dispersion indicies and direction dispersion indicies divided by the monthly average frequency of the station considered.

## Comparative Study of Interannual Instability Indicies of the Winds of the Stations in the Niger Repbulic Studied /198

From a comparative study of instability indicies of the winds we can distinguish two groups of stations: (1) those having a single instability maximum (Niamey and N'Guigmi) and (2) those having two instability maximums (Tahoua, Zinder, Maradi and Birni N'Konni).

### 1) The Group of Stations with One Instability Maximum

This group is made up of two stations whose interannual variations for the series of 10 years under consideration are not homogeneous. This reflects the fact that they are located at the two ends of the Sahel region of the Niger Republic. N'Guigmi has very Saharian features, such as a large variation in rainfall and one year in the series without any south or southwest wind. (wet season wind). On the contrary, Niamey shows a high degree of uniformity from year to year. The month of march, whose index is the highest, has all the characteristics of a transition month, hence a beginning of the wet season as early as march, a month which already receives periodic rainfall.

### 2) The Group of Stations with Two Instability Maximums

This group is divided into two subgroups:

a) one subgroup consists of the stations whose instability maximum is situated at the end of the wet season (October): Birni N'Konni and Maradi.

These two stations thus have a wet season whose instability tends to prolong the potential period of precipitation.

b) This group consists of the stations whose instability maximum is situated at the beginning of the wet season (April): Tahoua and Zinder.

This type of instability characterizes stations whose wet season ends during the month of October and begins some time in April.

These two stations therefore have a wet season whose instability tends to reduce the potential period of precipitation

The study of this instability index is supported by the analysis of Joël Charre, who states that "one can, however, deduce that the duration of the wet season has all chances of being as much longer as the beginning was early." /199

In addition, it should be noted that the presence of dry years (1969 to 1972) in the series does not play a particularly significant role in the distribution of the types of months (with winds prevailing from the east or from the south-southwest) over all of the months of the year, i.e. not for the directions but for the wind intensities.

This comparative study reveals the break in the rainfall pattern between Maradi and Zinder. Maradi represents the eastern most Sahel type, which is characterized most homogeneously by Niamey. Zinder represents the westernmost station of the Sahara type, which is characterized by N'Guigmi and Bilma. Tahoua is found in this region because of its latitude and the obstacle effect

of the Aïr. The break is also manifested by the relative values of the instability index maximums. Maradi has the highest values of the Sahel type.

This leads to the following fundamental conclusion: the means of the instability indicies of the wind decrease from N'Guigmi to Zinder then, after a break region, they undergo a similar decrease from Maradi to Niamey.

Agadés. Analysis of the Prevailing Winds and Their Frequency /201
1966-1975 (Fig. 46).

Prevailing Winds

The prevailing winds are characterized by the absence of a monthly dominance of winds from the sector ranging from south to southwest. Only 2 months (July and August) give, on average, a dominant west direction (260°-265°).

The winter months (from October to May)aare characterized by an average of winds from the east between 90° and 120°. The difference between the averages is 30° (from 90° to 120°).

Two months can be considered transition months -- June and September -- with alternations between winds from the east and winds from the west. For two years the month of June had winds from the west, and for 1 year September had winds from the west (1966).

These winds are characterized by a small interannual dispersion index, with the exception of the transition months.

Frequencies

Three groups stand out:

Fig. 46. Average frequency of monthly average prevailing winds from 1966-1975. Agades

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1. October to March, with a high frequency, representing 43% to 52% of the data for the averages.

2. April to May, with an average frequency with rather large differences (from 109 to 31 readings for April, from 127 to 40 readings for May). The frequencies for the dominant directions are smaller, which implies a greater distribution for the other directions, in particular the SSW sector which brings periodic precipitation.

3. From June to September the frequency is low, approximately 1/2 of the average monthly frequencies of the months of October to March, but with lower dispersion indicies.

Instability Index /202

The indicies obtained allow us to characterize the series as stable. The transition months clearly reappear (April, May and September). They represent the months in which the directions of the prevailing winds can change very broadly from east to west without any intermediate position.

The summer or winter months are characterized by an extreme interannual stability.

In comparison with Tahoua, the following points should be considered:

1. The complete disappearance of winds from the south.

2. The keeping of transition months, but shifted in this case April and May instead of October. The transitory nature of these winds is especially manifested by their deviation from the frequency average.

3. The extreme stability of the summer and winter months when the zonal direction appears very clearly. To characterize the latter it would perhaps be useful to consider the location of Agades, in particular the presence of the Tiguedi escarpment which may deflect the prevailing directions of the large current flowing along the Bilma-Termit-Maradi path.

Monthly Coefficient of Instability

| January | February | March | April | May | June | July | August |
|---|---|---|---|---|---|---|---|
| 3.96 | 4.08 | 3.86 | 9.71 | 7.00 | 13.9 | 3.13 | 5.43 |

| September | October | November | December |
|---|---|---|---|
| 7.17 | 4.75 | 2.57 | 3.51 |

Birni N'Konni: Analysis of the Prevailing Winds and Their Frequency. (Fig. 47) /204

Prevailing Winds

Three groups of months stand out:

1. The months of the wet season, from May to September. They are chracterized by a rather high degree of interannual stability. The angular variation reaches 40° in June.

2. The months of the dry season with winds from the east or the months of November and March. The averages for these months are very similar, from 69° to 77°E. In the middle of this series it should be noted that the winds of a zonal direction are rather frequent in January and February for the years 1972 to 1975.

3. The transition months, April and October. The inter-annual variations are much more distinct in April than in October. Thus the previaling directions allow one to state that the wet

Fig. 47. Average frequency of monthly average prevailing winds from 1966-1975. Birni N'Konni

season has a tendency to have more variations in the beginning, and while the end of the season is more constant in the years under consideration.

Frequencies

Anaanalysis of frequencies reveals the following groups:

1. A group of months in which the average of the frequencies is very stable. From May to August, these are the months of the wet season.

2. The months of high frequency: November, December and January. These are the months whose dominant winds are directional and not sectorial. They reflect the stability of the dry season winds.

3. The months of low frequency. These represent the months of April and October. They are the transition months. This confirms the fact that the transition for a station is characterized more by a dominant range of winds than by a dominant direction.

Instability Index

Three periods of the year can be differentiated on the basis of the instability index:

1. The months with a very low instability index from 2.43 to 3.54, from June to September.

2. The months with a high index, April and October. /205
These are the transition months. It should be noted that April is bounded by two months with a rather high degree of variability (March and May), which suggests that the transition period is

longer than the frequencies and directions at first seem to indicate.

3. The months with an average index. These are the months of the dry season. It should be noted that the instability index is smaller in January and February. From this it is possible to conclude that January and February are two months whose dominant winds are the most stable of the dry season.

Conclusion

Birni N'Konni is a station which corresponds to a region with a low instability index for the rainy season months, a high instability index for the transition months and an average index for the months of the dry season. The maximum instability is found at the end of the rainy season.

Maradi. Analysis of Prevailing winds and Their Frequency. /207
1966-1975 (Fig. 48).

Prevailing Winds

Three groups can be distinguished:

1. The months with a dominant SW direction (from May to September). They break down into two main average directions whose angular distance is very small (27°). The different months are characterized by a small, interannual angular difference of a maximum of 40°. On the month of May has large differences and can also be considered as intermediate or transition month.

2. The month with a dominant NE direction (November to March). These dominant winds come from the Bilma current, whose

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Fig. 48. Average frequency of monthly average prevailing winds from 1966-1975. Maradi

direction is approximately 60°.

3. 3. The monthswwith a dominant eastern direction (April and October). These are the transition months.

Frequencies

Two groups can be distinguished:

1. The high frequencies, the months of the dry season (November to February).

2. The average frequencies, which do not allow the months of the wet season to differentiated. The transition months cannot be distinguished. The dominant directions are well pronounced.

Instability Index

On the basis of this index three groups can be defined:

1. The months of high instability (October and April), which are the transition months.

2. The months of low instability (June, July and August) which are the three months of the wet season.

3. The months of average instability (from November to February), the dry season months.

Conclusion

At Maradi three periods can be distinguished: (1) a very pronounced wet season (June, July and August); (2) a rather pro-

nounced dry season (from November to February); and (3) a period of transition in March-April and October.

From a few surveys carried out in February, 1977, among farmers of the villages of Azazala, Guidan Ango and Serkin Haussa we learned that the people of Haussa distinguish several winds: /208

- Eskandari: wind form the NE.

The natives say that "this wind picks up the sand." In February, 1977, it had been blowing for two months. It is said that "it causes illnesses" and the winds responsible for dry fog in particular cause bronchitis.

- Eskanbazara: "This is the wind which brings the rainy season."

As soon as it blows from the west-southwest to the west clouds appear. "It will begin in two to four months." This wind is considered bad because it can bury the young shoots of millet under the sand. It lasts for two months and brings the rain.

- Eskandamana: "This is the wind which comes from the same direction as the clouds when the rain has begun." And here the direction indicated to us was east.

"When the millet is green there is never a sand wind, but a wind from the NE-SE sector which can break the young shoots."

We also heard the following revealing statements:

"The wind which brings the sand is good for the millet, the wind which picks it us us bad because one gets harder sand."

"Where there is soft sand, even with little water, the millet grows. Where the sand is hard, if there is not much rain, the millet will die." This shows that millet requires a mobile sandy covering, the hydrodynamic behavior of which is more favorable to the conservation of water.

"The surface sand is coarse when it is always cultivated." This sentence describes the mechanism of deflation and wind winnowing.

Niamey: Analysis of the Prevailing Winds and Their Frequency /210 (Fig. 49)

Prevailing Winds

Two large groups of months appear in the year:

1. The winds from the southwest sector characterize the months of the rainy season, from May to October. The dominant winds are rather stable for the entire series of months, the difference in direction varying from 70° (200° to 270° in May) to 90° (180° to 270° in August). September and October have slightly more variations, indicated by a higher dispersion index. (the 1971 rainy season was shorter than in the other years).

2. The winds from the eastern sector have the same characteristics as the winds of the rainy season. January is the most stable month of the tentire group with 50° of angular variation. The direction in March has a northern tendency (5 years out of 10). The direction in April is intermediate, and this month shows the most variations in direction from year to year. It is a transition month between a north-northeast direction and a south-southwest direction. It has its equivalent at the end of the rainy season (October), but this month shows few variations in wind direction and it cannot be distinguished from the group

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Fig. 49. Average frequency of monthly average prevailing winds from 1966-1975. Niamey.

of months with a dominant southwest direction on the basis of the averages alone.

Frequencies

In general, these are small for the dominant directions, never greater than 22% of the readings, ranging between 11% and 22%.

Two types of months appear:

1. The months of low frequency -- 11% of the readings -- April and October. These are the intermediate months. The frequencies clearly support the variations in direction.

2. The dry season or wet season months, on the other hand, have average frequencies pretty much equal to 15% to 22%.

In conclusion, the frequencies are very uniform. The prevailing winds of the station come from dominant sectors and not form dominant directions.

Instability Index

The instability index confirms the observations made with regard to frequencies and prevailing directions.

Three groups of months appear: /211

1. The dry season months with a very low instability index from 3 to 7.19, thus a very high degree of uniformity from year to year.

2. The months of average instability -- the winter months from October to February. The index varies by 3 points between

October and February.

3. The months of high instability, March and April, which are the transition months.

Conclusion

On the basis of the instability index the station is characterized by a high degree of interannual stability and three groups of months can be distinguished: (1) the rainy season from May to October, (2) the dry season from October to February and (3) the transition months of March and April.

The Niamey station, of all the stations studied, is most characteristic of the annual reversal of prevailing winds.

N'Guigmi. Analysis of Prevailing Winds and Their Frequency. 1966-1975 (Fig. 50). /213

Prevailing Winds

The prevailing winds of N'Guigmi are characterized by a high degree of heterogeneity. For all of the months the dispersion index is very high (never less than 14.67 for August). This large variation is characterized by the presence of an easterly orientation for all of the months of the year with respect to average winds (1973 does not have any prevailing winds from the south or southwest).

Three groups of months stand out:

1. The months with a dominant north-east wind (November to February). For the series of years studied these four months have two preferential directions, either north (0°) for November, December and February 1969, 1970, 1971, 1972, or east (40°) for

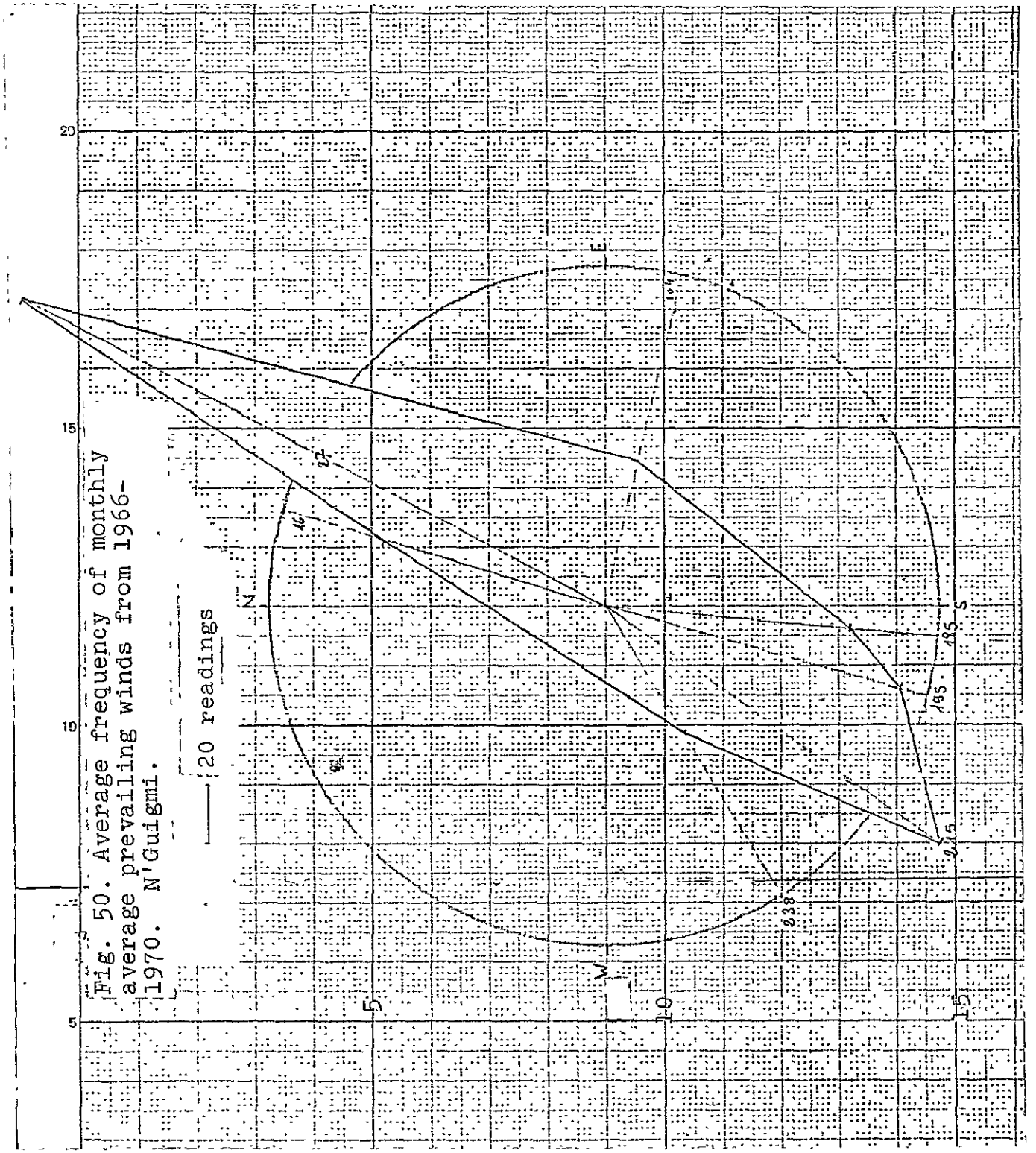


Fig. 50. Average frequency of monthly average prevailing winds from 1966-1970. N'Guigmi.

the 4 months of 1974-1975.

2. The months with a dominant south-west wind (March to September). This direction appears as an average, but each of the these months has at least one wind from the east during this series of years, and for April 4 out of 10 directions are from the east.

3. An intermediate month (October). This is similar to the last category, but it differssby the presence of a full south direction (180° in 1972).

Frequencies

In contrast to the prevailing directions, the frequencies show a certain homogeneity. On average, they are very high. Considering the series as a whole, the frequencies were very high for the last three years of 1973, 1974 and 1975. For all of the months they were never less than 40% of the readings and they can reach 80%. These variations indicate that during the first years there is a donimant sector, whereas during the last three years a specific monthly direction is clearly characterized.

Instability Index

On the whole the instability index is very high, with a maximum for the dry season, but no transition month before the rainy season.

Conclusion /214

The N'Guigmi station is very different from the six other stations studied. It is characterized by a high level of instability from year to year as well as from month to month, so that the station cannot be considered Sahelian, but in fact Saharian.

The existence of an entire year without any prevailing winds from the SSW is compeltely characteristic.

Tahoua. Analysis of Prevailing Winds and Their Frequency. 1966-1975 (Fig. 51)

Prevailing Winds

The average monthly dominant winds of Tahoua break down into three groups:

1. The dry season months (November to March). The winds never have a zonal direction, their average orientation ranges between 17° and 57°E, and only one month of the series gives a direction of 80°E (March, 1973). There is a large variation in direction, from 40°W to 80°E, with the average rainging from 14° to 33°.

2. The transition months (April and October). April is a transition month with three dominant winds: (1) the monsoon, a wind from the south (180°); (2) a dry season type wind (40°W to 0°N); and (3) a temporary wind from 120°. October is a month of unstable predominant winds, the direction of which approaches that of the dry season group (variation from 40°W to 45°E). In no case did October have any wind from the south.

3. The rainy season months (May to September). The dominant winds are very constant for the entire period, the average wind blowing from 192° to 204°.

Frequencies

The frequency is defined by the number of readings for a dominant direction in one month, and the frequency percentage is defined by the number of readings for a dominant direction in one

Fig. 51. Average frequency of monthly average prevailing winds from 1966-1975. Tahoua.

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month with respect to 240 readings (= 30 x 8 per day).

In the dry period the variations from month to month and year to year are high. Between the different months the dominant direction varies from 16% to 34% of the theoretical readings. The frequency reaches a maximum in January. The distributions are very irregular.

In the rainy period the direction never represents more than 24% of the total theoretical readings and the frequencies remain very uniform during the period under consideration (except for May, 1973). As a result, the dominant direction is always bounded by subdominant directions with high frequencies (cf. rose diagrams). Thus the notion of a dominant direction losses its significance compared to the notion of a dominant sector.

In the transition period the frequencies are very heterogeneous which can be attributed to the alternation in direction.

Instability Index /217

The dispersion indicies of the frequencies and dominant directions studied, expressed in the form of this index, enable us to refine the study of the individual months.

There appears a group of months with a low instability index, hence with little dispersion in frequency and direction for the series of years under consideration. These are the months of January and from June to September. There is also a group of months with an average instability index (February, March, May and December), and a group with a very high index (April, October and November). This last group corresponds to the transition months and to the months when the dry season becomes established, with large variation differences in direction and especially in frequency.

The group with an average instability index is formed by the dry season months in addition to May (distortion due to 1973, an aberrant year in the series). The group with a low instability index corresponds to all of the rainy season months plus January.

The dry season is characterized by a high level of over all instability which gradually reduces up to the month of January, the month with a dominant NE wind. As January is one of the months in which the percentage of effective winds issgreatest, it is to be thought that eolian reactivation phenomena of a certain strength should be operative during this period, and also during the month of March. In the latter month, however, the average effectiveness is less.

At the monthly level the wet season is characterized by a very high level of stability both in average directions and in frequencies.

The oppostion between dry season and rainy season is reflected in the main directions of the winds of the two seasons as well as in the pattern and "character" of the two periods.

Obtaining a Monthly Instability Index

This index is obtained by multiplying the dispersion indices of frequencies and dominant directions and then dividing this product by the average frequency of the month for the years under consideration. This makes it possible to reduce the differences of the two dispersion indicies, while maintaining a proportionality which highlights the differences (in absolute value).

Tahoua. Monthly Stability Index /218

| | January | February | March | April | May | June |
|---|---|---|---|---|---|---|
| IS | 4.07 | 21.21 | 10.56 | 105.76 | 17.83 | 4.60 |
| Category | 10 | 5 | 7 | 1 | 6 | 9 |

| | July | Augustu | September | October | November | December |
|---|---|---|---|---|---|---|
| IS | 3.79 | 3.03 | 5.10 | 91.18 | 36.43 | 21.30 |
| Category | 11 | 12 | 8 | 2 | 3 | 4 |

IS = Stability index
IdF = Study of dispersion, frequency
IdD = Study of dispersion, dominant direction
Dm = Average dominant direction

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Zinder. Analysis of Prevailing Winds and Their Frequency. /220
1966-1975 (Fig. 52)

Prevailing Winds

On the basis of dominant directions from year to year two groups of months can be distinguished:

1. The months with winds from the SW (May to September), with interannual variations of two types. Strong variations, May and September. May can be considered a transition month, since for 4 years out of 10 it has winds from the east and southeast. For 2 years September has winds from the north. July and August have rather stable winds for all of the years considered.

Thus there is a short rainy season of three stable months and from three to five months for the period covered.

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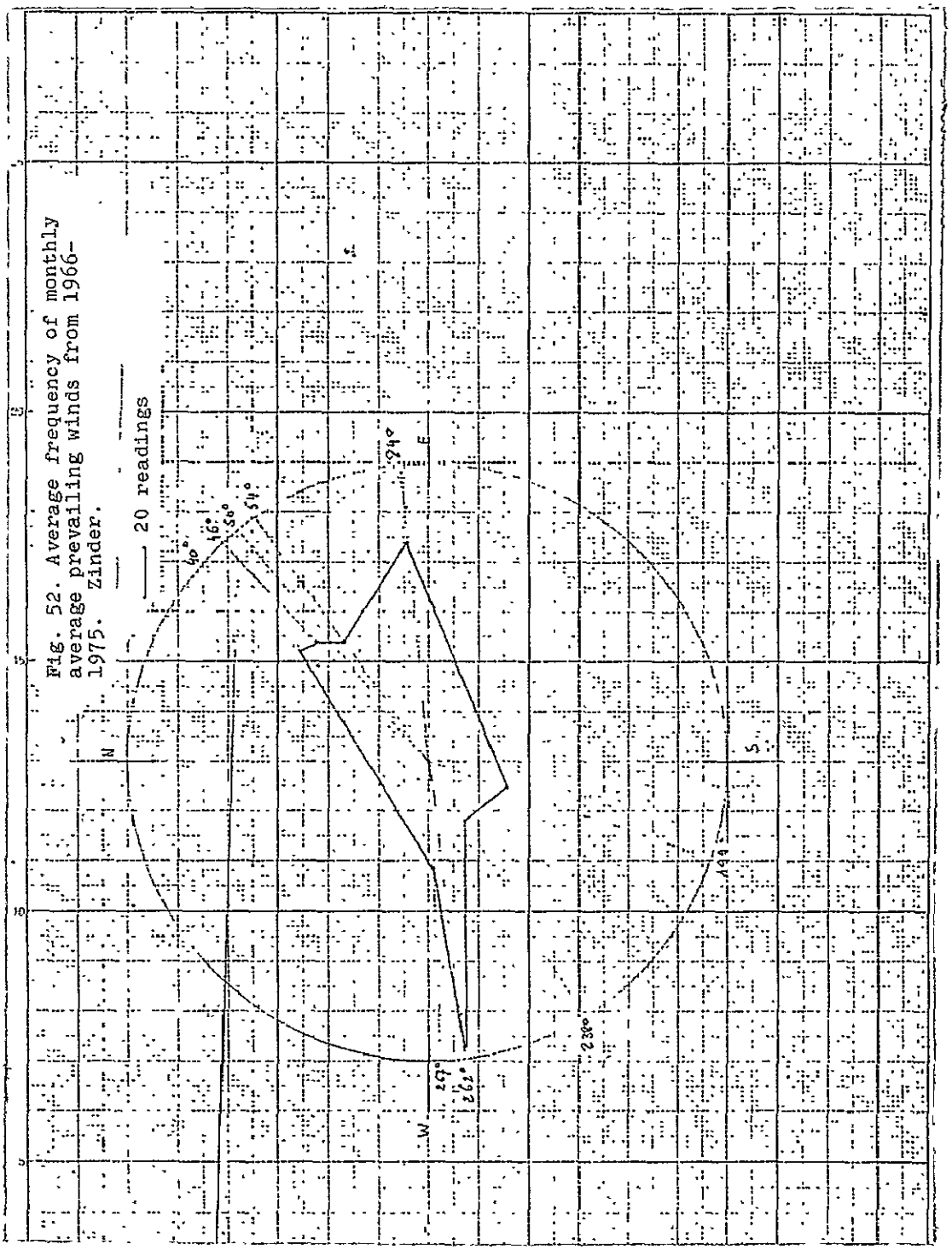


Fig. 52. Average frequency of monthly average prevailing winds from 1966-1975. Zinder.

2. The months with winds from the east (from October to April). These months with winds from the east can be separated into two groups: (1) the months with wind from the east (March, April and October) and (2) the months with wind from the northeast (November, December, January and February).

This breakdown into two easterly winds reveals the convergence of two currents at Zinder: (1) the zonal current coming from N'Guigmi, deflected by passing over Lake Chad, and (2) the Bilma current.

Characteristic transition months cannot be distinguished on the basis of dominant wind directions.

Frequencies

In this regard the situation at Zinder approaches that of N'Guigmi because the average frequencies are rather high. On average, the dry season months have higher frequencies than the summer months (July is higher than the other months). The frequency of winds from the northeast is higher. Thus, on the whole, the current from Bilma is more stable than the current from N'Guigmi. On the basis of the frequencies the following distinction can be made: the current from Bilma is characterized by one specific direction, while the current from N'Guigmi is characterized by a dominant sector.

Instability Index /221

The interannual instability index at Zinder characterizes the year in the following way: the rainy season months have a very low index; the transition months are reflected by the instability index (these are the months of April, May and October whose indicies are very high); and the dry season months have an

average instability index.

On average, the wind directions at Zinder have a higher instability index than those of the Bilma current alone, which confirms the distinction between dominant direction and dominant sector.

Conclusion

On average, Zinder is a station with a short rainy season for the period of years considered. The dry season is affected by two currents with adjacent directions, but they always remain quite distinct.

Chapter III. Climatic Parameters of Maradi /222

Rainfall at Tarna and Maradi from 1932 to 1975 (Fig. 53) /224

The period from 1932 to 1949 is characterized by an extremely accentuated saw tooth pattern with minimums for 1934, 1942 and 1949. The minimum of 1934 (436 mm at Maradi, 435 mm at Tarna) is followed by a sharp rise in 1939 (985 mm at Maradi) and in 1940 (725 mm at Tarna). In 1942 another drop in precipitation (365 mm at Tarna and 455 mm at Maradi) is not followed by such a spectacular rise as that of 1939. In 1945 the total amount of of precipitation at Tarna is 806 mm, and 749 mm at Maradi in 1946. In 1949 Maradi received only 367 mm of precipitation and Tarna 357 mm.

From 1949 to 1967 the saw teeth are much smaller but constant. The amplitude of variations is 200 mm (550 to 750 mm). In 1967 the total precipitation is again less than 600 mm and in 1968 falls to 362 mm at Maradi and 414 mm at Tarna.

Even if the total precipitation minima are pronounced from

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Fig. 53. Annual rainfall from 1932-1975
Maradi —— and Tarna ----

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Normal rainfall total at Maradi from 1930 to 1960

Fig. 54. Monthly rainfall and number of days of rain per month at Maradi from 1960 to 1975.

No. of days of rain per month.
0 - 4 ----
5 - 9 -.-.-
10 - 15 ---
16 - 21 ——

1960 April 1975 | 1960 May 1975 | 1960 June 1975 | 1960 July 1975 | 1960 Aug. 1975 | 1960 Sept. 1975 | 1960 Oct. 1975

1967 to 1976, they are no longer compensated for by high peaks as during the 1932-1949 period. They reach only the average of the preceding years in 1969.

The minimum amount of precipitation during these 45 years occured in 1972, with 288 mm for Maradi and 273 mm for Tarna.

The maximums for the same period occured in 1939, with 981 mm for Maradi.

Although 6 km apart, these two stations show notable differences in the amount of annual precipitation. The general trends are the same, but the shortage years are lower on the graph and the excess years higher at Tarna.

From this graph we obtain the following averages:

- general average from 1932 to 1976: 595 mm for Maradi and 563 mm for Tarna
- average from 1932 to 1949: 609 mm for Maradi and 557 for Tarna
- average for 1949 to 1967: 653 mm for Maradi and 639 mm for Tarna
- average for 1967 to 1976: 434 mm for Maradi and 405 mm for Tarna.

Using these averages we can take into account the following:

1. The difference of the periodic averages from the overall average. This difference is zero or nearly zero for the period 1932 to 1949. The difference is moderate for the period 1949 to 1967 (1.1 for Maradi and 1.6 for Tarna.) The difference is great for the period 1967 to 1976 (3.3 for Maradi and 3.1 for Tarna). It should be noted that from 1949 to 1967 the difference is positive and for 1967 to 1976 it is negative.

2. The difference for the various years from the overall /225

average. The different years differ strongly from the overall average during the periods from 1932 to 1949 and from 1967 to 1976. But they differ in different ways. In the first period the differences are strong in two directions (they cancel each other out). In the second period the differences are strong in one direction (negative).

3. The difference from the periodic average of the years making up this average. In the first period the years 1939 and 1949 differ the most from the average, by +7.7 and −5 respectively. In the second period 1950 and 1959 differ the most from the average, by +4.5 and −2.5 respectively. In the third period the years which differethe most are 1969-1972, with a peak in 1969 of +4 and a minimum in 1972 of −3.

Monthly Rainfall at Maradi from 1960 to1975 (Fig. 54). /228

The maximum rainfall occurs the months of July and August, however there are very large differences from year to year, with more than two fold differences for July and more than three fold differences for August.

In general, April receives only traces of precipitation. When the April precipitation amounts to more than 30 mm they do not necessarily indicate the beginning of a rainy year. For example, in 1966 37.8 mm of rain fell in 15 days in April out of an annual total of 631.7 mm, and in 1968 36.9 mm fell in 4 days out of an annual total of 362.2 mm.

October ends the rainy season. When the rainy season extends through this month, the year is a rainy one. However there are rainy years without any rain in October.

There is no direct relationship between high precipitation

levels and the number of days of rain recorded. For example, 729.7 729.7 mm fell in 54 days in 1964 and 630.5 mm in 62 days in 1965.

Rainfall: Maradi Station, 1960 to 1975

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| Year | A | M | J | J | A | S | O | Average |
|---|---|---|---|---|---|---|---|---|
| 1960 | TR | 152 | 827 | 2215 | 2350 | 557 | NT | 6100 |
| | 1 | 2 | 11 | 14 | 17 | 7 | | 51 |
| 1961 | TR | 78 | 1219 | 1013 | 2871 | 999 | NT | 6911 |
| | 2 | 2 | 12 | 14 | 20 | 7 | | 55 |
| 1962 | 93 | 95 | 784 | 2436 | 1839 | 1165 | 64 | 6436 |
| | 1 | 3 | 11 | 14 | 15 | 9 | 3 | 56 |
| 1963 | TR | 624 | 628 | 1562 | 1360 | 752 | 739 | 5665 |
| | 1 | 6 | 8 | 13 | 18 | 8 | 4 | 57 |
| 1964 | TR | 47 | 588 | 2601 | 3308 | 753 | NT | 7297 |
| | 1 | 4 | 9 | 14 | 20 | 7 | | 54 |
| 1965 | 26 | 326 | 1131 | 1083 | 2350 | 1389 | NT | 6305 |
| | 1 | 4 | 13 | 12 | 18 | 14 | | 62 |
| 1966 | 378 | 171 | 643 | 1025 | 2070 | 1573 | 571 | 6317 |
| | 15 | 4 | 8 | 11 | 14 | 15 | 1 | 58 |
| 1967 | 92 | NT | 656 | 1363 | 2169 | 1141 | NT | 5551 |
| | 1 | | 4 | 10 | 18 | 13 | | 48 |
| 1968 | 369 | 328 | 709 | 1109 | 186 | 289 | 32 | 3622 |
| | 4 | 4 | 7 | 11 | 13 | 3 | 1 | 43 |
| 1969 | 55 | 449 | 804 | 2637 | 1201 | 658 | 361 | 6406 |
| | 1 | 2 | 9 | 13 | 13 | 8 | 4 | 50 |
| 1970 | NT | 35 | 435 | 2260 | 2141 | 979 | 94 | 5844 |
| | | 4 | 6 | 11 | 13 | 8 | 1 | 43 |
| 1971 | NT | 292 | 229 | 1053 | 1783 | 639 | NT | 3995 |
| | | 2 | 4 | 11 | 21 | 8 | | 46 |
| 1972 | 44 | 158 | 238 | 872 | 1381 | 190 | 02 | 2885 |
| | 1 | 5 | 8 | 9 | 8 | 3 | 1 | 35 |
| 1973 | NT | TR | 280 | 1163 | 1212 | 845 | NT | 3590 |
| | | 1 | 3 | 12 | 12 | 4 | | 31 |
| 1974 | NT | 151 | 461 | 1165 | 2155 | 1178 | 33 | 4599 |
| | | 2 | 5 | 12 | 15 | 11 | 1 | 47 |
| 1975 | TR | 411 | 296 | 869 | 1574 | 319 | NT | 3599 |
| | | 7 | 7 | 14 | 17 | 6 | | 45 |

TR = Trace
NT = No Rain
Key: A) years, months
B) No. of days

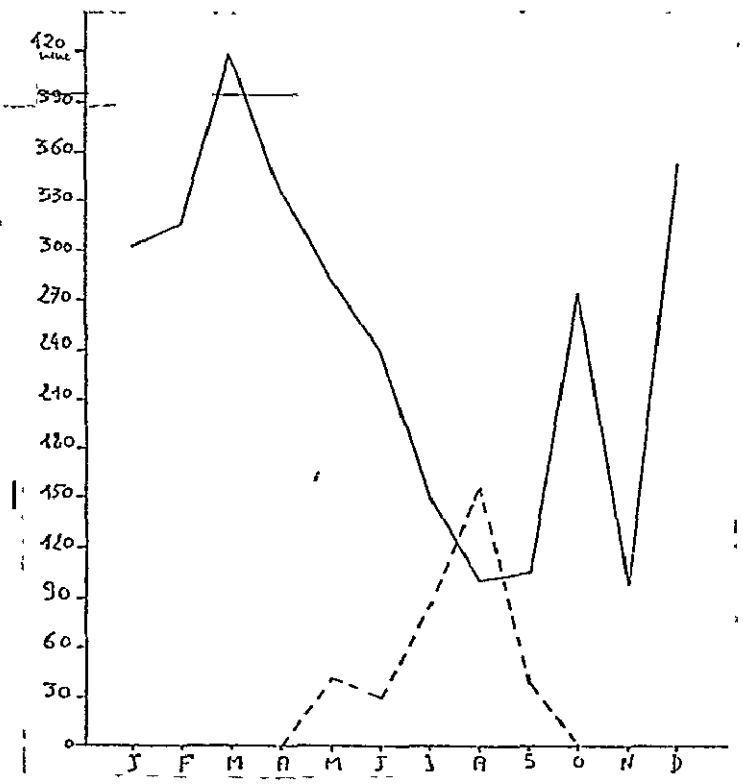


Fig. 55. Evaporation and precipitation at Maradi in 1975.
——— Evaporation in mm
--- Precipitation in mm

Evaportation at Maradi was studied only for 1975. From this we can obtain orders of Magnitude. The total potential evaporation per year is 2.97 m. Maximum evaporation occurs in March (420 mm) and minimum evaporation in November (97.9 mm). While the rainfall is maximum in August (154.4 mm), evaporation (101.4 mm))then is hardly greater than the november minimum. Only August experiences a greater amount of rainfall than evaporation.

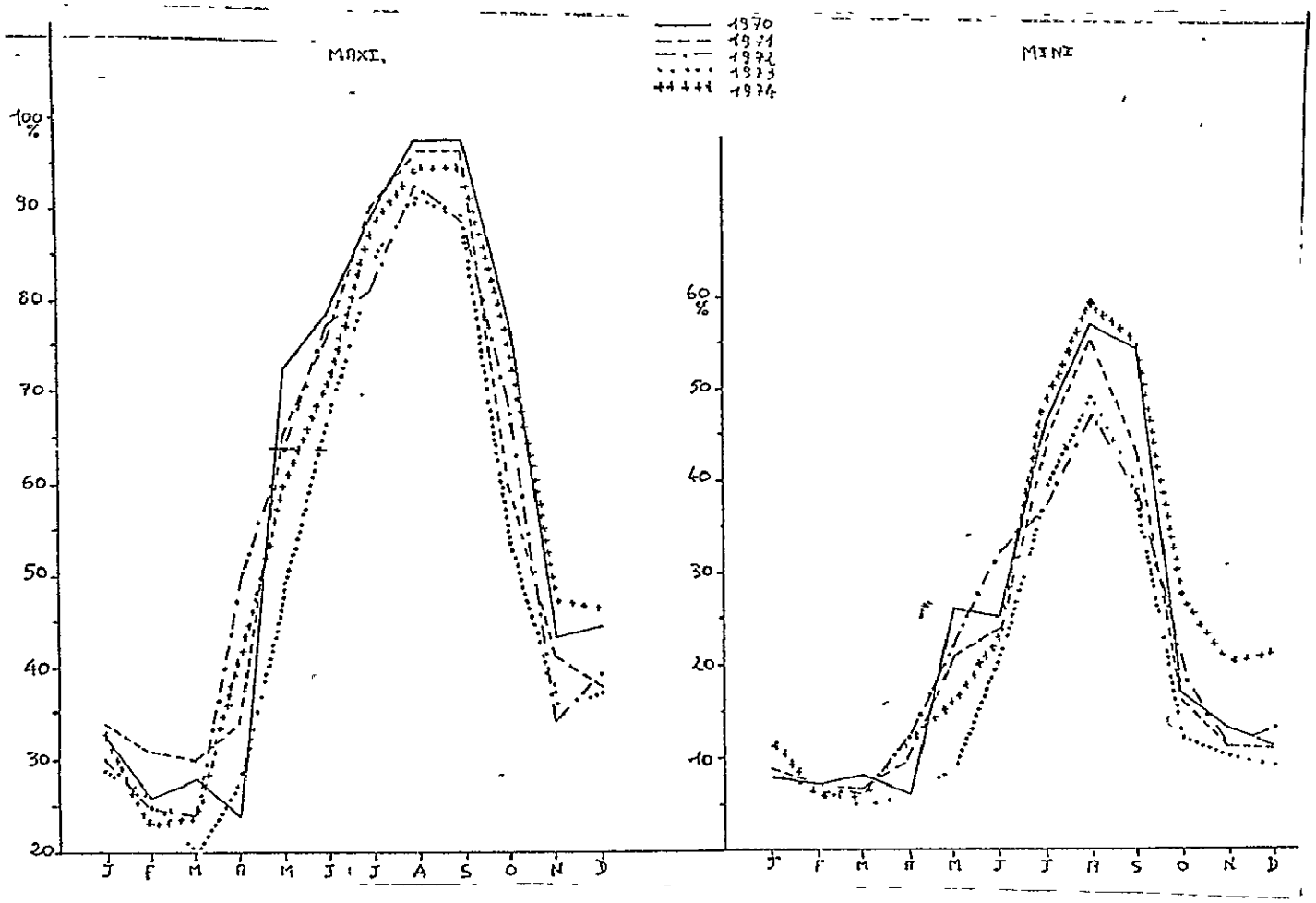


Fig. 56. Monthly humidity of the air at Maradi from 1970-74.

Air humidity is maximum during the rainy season, in August-September. The minimum is more spread out, from November to March (5%).

Maximums

| Annee | J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | 33 | 26 | 28 | 24 | 72 | 78 | 89 | 97 | 97 | 77 | 43 | 44 |
| 1971 | 34 | 32 | 30 | 34 | 65 | 76 | 90 | 96 | 96 | 60 | 41 | 38 |
| 1972 | 30 | 25 | 24 | 50 | 66 | 77 | 81 | 92 | 88 | 68 | 34 | 38 |
| 1973 | 29 | 26 | 20 | 28 | 49 | 67 | 84 | 91 | 89 | 54 | 36 | 31 |
| 1974 | 33 | 23 | 24 | 42 | 60 | 72 | 88 | 94 | 94 | 76 | 47 | 46 |
| Total | 159 | 132 | 126 | 178 | 312 | 372 | 432 | 470 | 464 | 335 | 201 | 203 |
| Moy. | 318 | 264 | 252 | 356 | 624 | 744 | 864 | 940 | 928 | 670 | 402 | 406 |
| Minimums | | | | | | | | | | | | |
| 1970 | 8 | 7 | 8 | 6 | 26 | 25 | 46 | 57 | 54 | 17 | 13 | 11 |
| 1971 | 9 | 7 | 7 | 10 | 21 | 24 | 44 | 55 | 43 | 16 | 11 | 11 |
| 1972 | 8 | 7 | 6 | 12 | 22 | 32 | 37 | 47 | 38 | 19 | 11 | 23 |
| 1973 | 8 | 7 | 5 | 6 | 9 | 21 | 39 | 49 | 39 | 12 | 10 | 9 |
| 1974 | 12 | 6 | 6 | 12 | 16 | 23 | 48 | 59 | 55 | 27 | 20 | 22 |
| Total | 45 | 34 | 32 | 46 | 94 | 125 | 214 | 267 | 229 | 91 | 65 | 66 |
| Moy. | 9 | 68 | 64 | 92 | 188 | 250 | 428 | 534 | 458 | 182 | 130 | 132 |

Humidity of the air in % at Maradi from 1970 to 1974.

Rainfall at Maradi and Tarna from 1932-1975

| Year | MARADI mm/year | MARADI # of days per year | TARNA mm/year |
|---|---|---|---|
| 1932 | 719 | 44 | 718 |
| 1933 | 730 | 45 | 730 |
| 1934 | 436 | 37 | 435 |
| 1935 | 567 | 41 | 565 |
| 1936 | 640 | 59 | 626 |
| 1937 | 502 | 39 | 500 |
| 1938 | 573 | 41 | 589 |
| 1939 | 981 | 52 | |
| 1940 | 657 | 43 | 725 |
| 1941 | 521 | 37 | 527 |
| 1942 | 455 | 30 | 365 |
| 1943 | 528 | 38 | 607 |
| 1944 | 537 | 39 | 639 |
| 1945 | 670 | 59 | 806 |
| 1946 | 749 | 48 | 713 |
| 1947 | 654 | 50 | 653 |
| 1948 | 677 | 55 | 481 |
| 1949 | 367 | 37 | 357 |
| 1950 | 8[illegible] | 47 | 840 |
| 1951 | 541 | 41 | 548 |
| 1952 | 758 | 57 | 760 |
| 1953 | 675 | 51 | 714 |
| 1954 | 610 | 55 | 654 |
| 1955 | 555 | 45 | 532 |
| 1956 | 723 | 49 | 617 |
| 1957 | 736 | 60 | 704 |
| 1958 | 625 | 51 | 582 |
| 1959 | 537 | 58 | 513 |
| 1960 | 616 | 51 | 527 |
| 1961 | 697 | 55 | 735 |
| 1962 | 643 | 56 | 743 |
| 1963 | 567 | 57 | 520 |
| 1964 | 730 | 54 | 748 |
| 1965 | 630 | 61 | 661 |
| 1966 | 632 | 58 | 503 |
| 1967 | 595 | 47 | 617 |
| 1968 | 362 | 42 | 414 |
| 1969 | 641 | 50 | 571 |
| 1970 | 595 | 43 | 510 |
| 1971 | 398 | 46 | 339 |
| 1972 | 288 | 36 | 273 |
| 1973 | 350 | 31 | 296 |
| 1974 | 490 | 47 | 497 |
| 1975 | 351 | 45 | 343 |

Rainfall Averages

| | MARADI | TARNA |
|---|---|---|
| 1932 - 1975 | 595 | 563 |
| 1932 - 1949 | 609 | 557 |
| 1949 - 1967 | 653 | 639 |
| 1967 - 1975 | 434 | 405 |

Average Monthly Temperatures at Maradi from 1970 to 1975 (Fig. 57) /231

This graphsshows maximum temperatures in April and May and the highest maximum of 41.2°

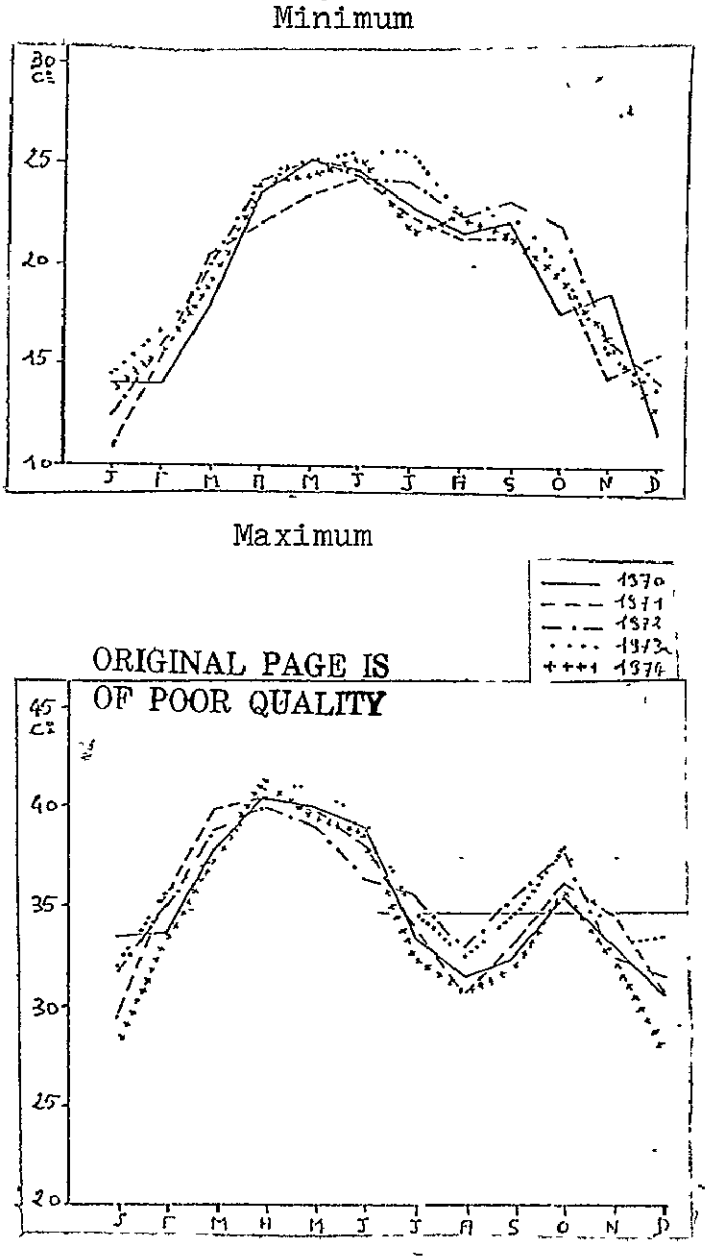


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Fig. 57. Maximum and minimum monthly average temperatures at Maradi from 1970 to 1974

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in April, 1974. The minimum temperatures are in December and January, with the lowest minimum of 11.1° in January, 1971.

The August minimum, whihc is always greater than 20°, falls in the time of maximum precipitation.

ASECNA Maradi /232

Meteorological Service

Maximum and Minimum Monthly Temperature Averages from 1970 to 1974

Maximum Temperature

| | Jan. | Feb. | March | April | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | 33,5 | 33,8 | 38,2 | 40,6 | 40,1 | 38,9 | 33,6 | 31,5 | 32,7 | 35,6 | 33,1 | 30,5 |
| 1971 | 29,5 | 35,3 | 39,8 | 40,5 | 39,9 | 38,0 | 33,7 | 30,7 | 33,2 | 36,2 | 34,6 | 30,7 |
| 1972 | 31,8 | 35,0 | 38,9 | 40,0 | 39,0 | 36,5 | 35,5 | 33,1 | 35,5 | 37,8 | 32,6 | 31,6 |
| 1973 | 32,0 | 35,5 | 37,6 | 41,1 | 41,0 | 39,4 | 34,9 | 32.8 | 34,8 | 38,0 | 33,3 | 33,5 |
| 1974 | 28,2 | 33,4 | 37,8 | 41,2 | 39,6 | 38,8 | 33,4 | 30,9 | 32,0 | 35,7 | 32,3 | 27,8 |
| Total | 1550 | 1730 | 1923 | 2034 | 1996 | 1916 | 1701 | 1590 | 1682 | 1833 | 1659 | 1541 |
| Average | 31,0 | 34,6 | 38,5 | 40,7 | 399 | 38,3 | 34,0 | 31,8 | 33,6 | 36,7 | 33,2 | 30,8 |

Minimum Temperature

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | 14,1 | 14,1 | 18,1 | 23,7 | 25,2 | 24,8 | 23,1 | 21,7 | 22,2 | 17,7 | 18,8 | 11,7 |
| 1971 | 11,1 | 15,3 | 20,5 | 22,1 | 23,5 | 24,6 | 22,7 | 21,4 | 21,4 | 19,4 | 14,6 | 15,8 |
| 1972 | 12,4 | 15,7 | 20,0 | 24,2 | 25,2 | 24,5 | 24,2 | 22,5 | 23,2 | 22,1 | 16,3 | 14,3 |
| 1973 | 14,6 | 16,7 | 19,6 | 24,6 | 25,2 | 25,7 | 25,9 | 22,5 | 22,9 | 20,3 | 15,9 | 14,0 |
| 1974 | 13,8 | 15,6 | 19,4 | 24,2 | 24,5 | 23,5 | 22,9 | 22,3 | 21,6 | 19,5 | 16,2 | 12,8 |
| Total | 660 | 774 | 976 | 1188 | 1236 | 1251 | 1168 | 1104 | 1113 | 990 | 818 | 686 |
| Average | 13,2 | 15,5 | 19,5 | 23,8 | 24,7 | 25,0 | 23,8 | 22,1 | 22,3 | 19,8 | 16,4 | 13,7 |

Average Pressure.

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | 970,5 | 969,9 | 967,5 | 966,7 | 966,4 | 968,5 | 969,1 | 968,6 | 968,2 | 968,1 | 969,8 | 970,7 |
| 1971 | 970,4 | 967,7 | 965,4 | 966,2 | 966,1 | 968,1 | 968,8 | 969,4 | 969,4 | 969,7 | 970,2 | 971,4 |
| 1972 | 969,4 | 969,1 | 967,1 | 966,0 | 966,8 | 968,7 | 969,0 | 968,7 | 968,7 | 968,2 | 971,0 | 970,7 |
| 1973 | 971,3 | 969,2 | 968,3 | 966,3 | 967,2 | 967,5 | 968,7 | 969,1 | 968,9 | 967,3 | 971,1 | 969,6 |
| 1974 | 970,8 | 968,2 | 966,6 | 965,5 | 967,0 | 967,3 | 968,7 | 968,2 | 968,2 | 967,5 | 969,3 | 971,0 |
| Total | 48499 | 48441 | 43349 | 43307 | 48335 | 48401 | 48443 | 48440 | 48434 | 48408 | 48515 | 48554 |
| Average | 970,0 | 968,8 | 967,0 | 966,1 | 966,7 | 968,0 | 968,9 | 968,8 | 968,7 | 968,2 | 970,3 | 970,7 |

[Note: read commas as decimal points.]

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Monthly Climate Table, Maradi -- 1975 /233

| | J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tn | 11 | 15,1 | 19,8 | 24,0 | 25,3 | 25,0 | 23,0 | 22,1 | 22,1 | 19,6 | 17,3 | 14,4 |
| Tx | 26,5 | 32,5 | 36,7 | 39,7 | 37,6 | 37,0 | 33 | 30,9 | 32,4 | 35,8 | 34,2 | 30,3 |
| $\frac{Tn+Tx}{2}$ | 18,7 | 23,8 | 28,3 | 31,9 | 31,4 | 31 | 28 | 26,5 | 27,3 | 27,8 | 25,7 | 22,4 |
| E | 303,6 | 315,8 | 419,3 | 337,2 | 282,9 | 239,6 | 151,4 | 101,4 | 105,8 | 271,1 | 97,9 | 350,3 |
| I | 290,0 | 281,3 | 275,2 | 291,7 | 279,5 | 307,3 | 245,0 | 238,0 | 256,0 | 294,0 | 275,1 | 286,2 |
| P | 0 | 0 | TR | TR | 41,1 | 29,6 | 84,9 | 157,4 | 37,9 | 0 | TR | 0 |

Tn: Monthly average of minimum temperatures in C°

Tx: Monthly average of maximum temperatures in C°

$\frac{Tn+Tx}{2}$: Monthly average of temperatures

E: Total evaporation in mm

I: Number of hours of insolation

P: Precipitation in mm

Surface Wind at Maradi from 1951 to 1960 (Fig. 58). /235

1. Dry Season

Out of a total of 100 observations 56 observations of wind were made and 44 of calm. The wind from the east is largely dominant, with 35 observations, followed by the wind from the northeast with 13 observations, and finally the wind from the southeast with nearly 5 observations. The winds from the north, northwest, west and southwest altogether represent only 3 observations.

/234

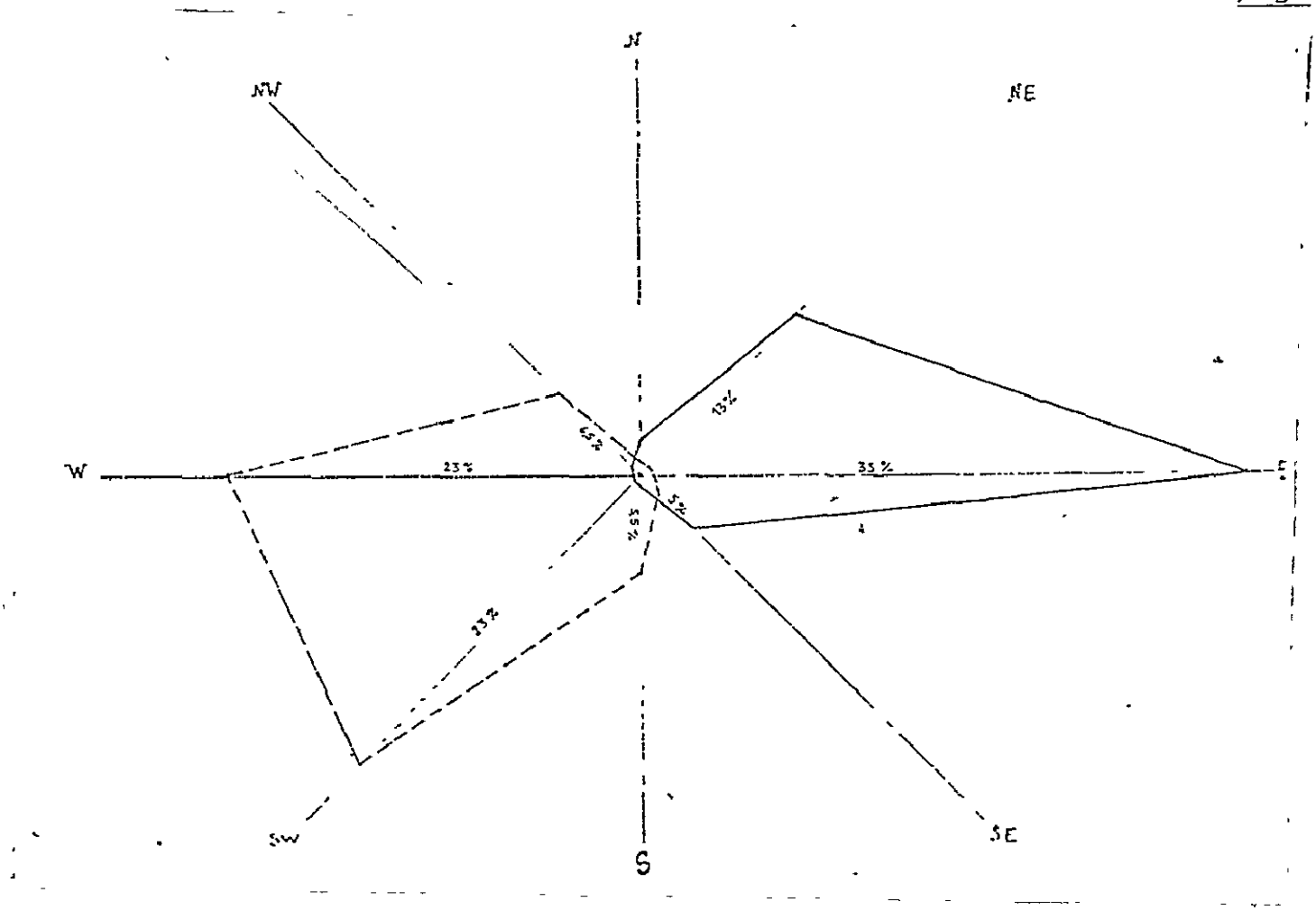


Fig. 58. Surface wind at Maradi (1951-1960)
_____ Dry season (calm = 44%)
------- Rainy season (calm = 30%)
2cm = 5%

2. Rainy Season /235

Out of a total of 100 observations, 62 observations of wind were made and 38 of calm. The winds from the west and southwest dominate, with 23 observations apiece, followed by the winds from the northwest with 6.5 observations, and finally the winds from the south with 5.5 observations. The winds from the

southeast, east, north and northeast all together represent only 4 observations.

This graph has the advantage of showing the directions of the dominant wind per season. Nevertheless, this representation wipes out the directions of secondary wind, the importance of which is recognized however, as this graph gives the impression that the number of days of wind is greater in the dry season than in the rainy season, whereas in reality the reverse is true. Moreover, it is regretable that the speed of the winds is not indicated. Finally, does the calm signify an absolute calm of winds or winds of low velocity which are thus ineffective?

The dry season winds from the northeast-east sector clearly match the harmattan and reflect the zonal bending that the harmattan undergoes in the Nigerian Sahel. The rainy season winds from the southwest-west sector result from the incursion of the monsoon and conform to the familiar plan.

Book III. The Experimental Unit of Serkin Haussa /236

Chpt. 3. Analysis of the Serkin Haussa Experimental Unit Based /238 on Landsat 1 Satellite Pictures (Fig. 59)

1. Analysis using the Method of Textures and Structures of Channels 7 and 4 of the Landsat 1 Picture Corresponding to the Experimental Square.

On channel 7 one can distinguish:

1. the clearest texture, nearly white.
2. Clear gray texture.
3. Medium gray texture.
4. Dark gray texture.
5. Diffuse dots, light gray.
6. Gray stripes, curved lines crossing the various above textures.

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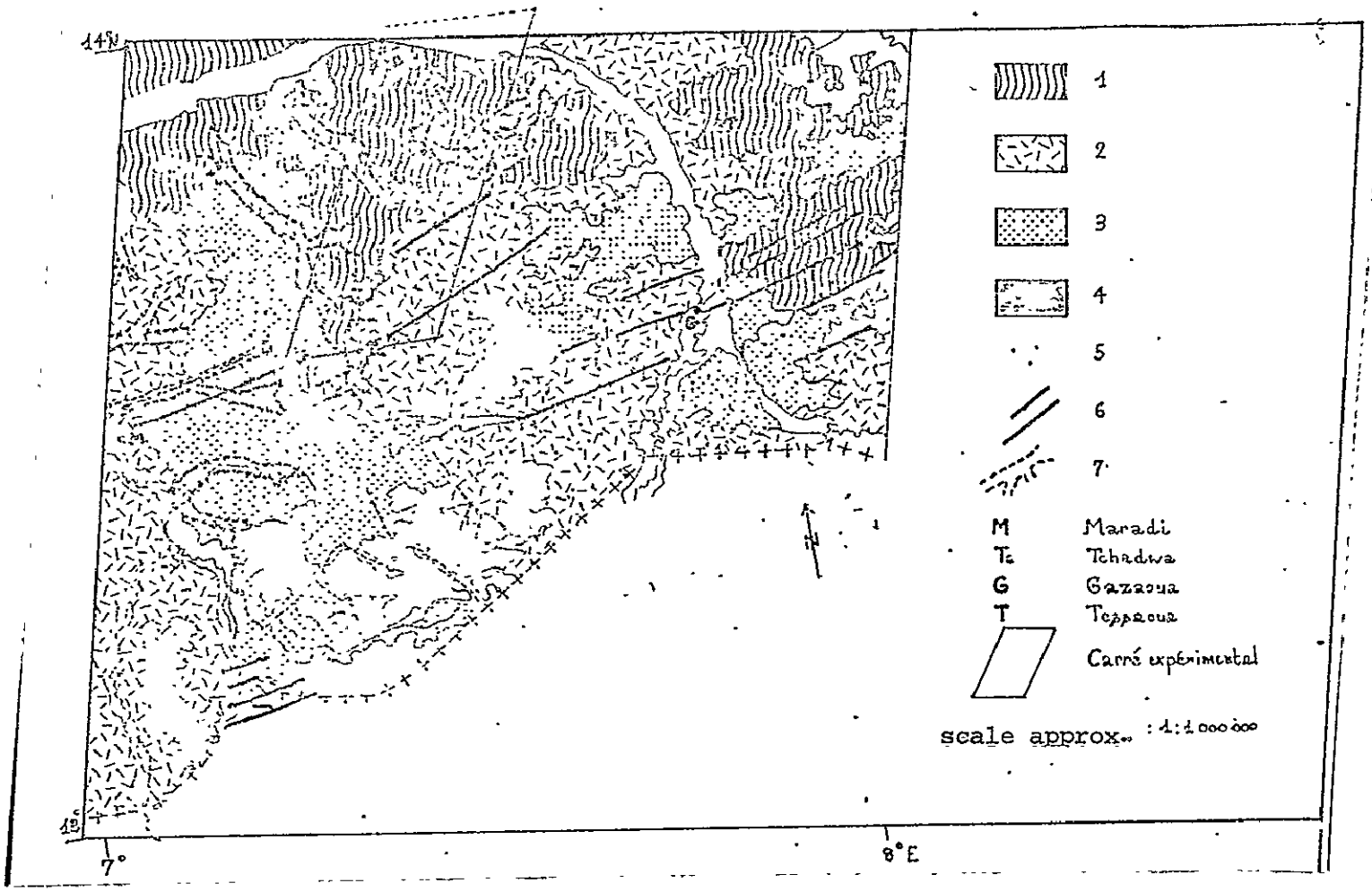


Fig. 59. Satellite picture #1160 09 200, channels 4 and 7, Dec. 30, 1972. Niger Republic.

7. Texture of broken lines, more discernible on channel 4, of a grayness analogous to texture 2 of channel 7.

2. Comparison with the Topographical Map of the National Geographic Institute at a Scale of 1:200,000.

There are no notable differentiations for gray areas 1, 2 and 3, unless, for grayness 3, a slightly less population density.

Grayness 4 corresponds to the valleys of the large Maradi and N'Kaba goulbi and the classified forests, such as Dankada Dodo.

However, these two interpretations of texture 4 do not explain it entirely.

The light gray diffuse points of texture 5 correspond to the villages on topographical maps.

Texture 6 of gray stripes cannot be explained.

On channel 4 texture 7 corresponds to valleys.

3. Comparison with Aerial Photographs.

The overall dunal structure of this region is made up of monticular-type sandy structures. Locally, however, this structure is replaced either by a transverse monticular structure or by transverse dunes, or by hilly structures dispersed over the rocky, outcropping base of the southern Niger Republic, or again, south of Tchadaoua, by longitudinal dunes (local regularization of the monticular structure). Now texture 4, dark gray, which could be likened to forests classified on the basis of the topographical at a scale of 1:200,000, on aerial photographs corresponds to dunal structures, which are not monticular, drawn on a map at a scale of 1:1,000,000 entitled "Natural Wind and Water Erosion Mechanisms and Their Evaluataion With Respect to the Degradation of Sandy Landscapes."

4. Combining the Three Preceding Steps and Ground Analysis, Enabling Us to Define Interpretation Keys /239

Texture 1: it can be interpreted as resulting from the high density of human occupation in regions with a monticular arrangement and from the various degrees of modification in the behavior of the sandy covering. These changes were detailed, in particular, on the basis of ground observations and work with

aerial photographs. Within the context of a map of the effects of dryness for the entire Sahel, this texture would belong to a category entitled: "Danger of Serious Breakdown of the Monticular Structure by Water and Wind Erosion as a Result of Overuse."

Texture 2: The density of human occupation in these regions of monticular dunes does not cause any dangerous immediate degradation of the sandy covering.

Texture 3: the population density in these areas is lower than in the two preceding cases, for no apparent reason.

Texture 4: The population density is practically zero, either because of the establishment of restrictions (classified forests) or because of the unattractive environment created by dunal structures such as the transverse monticular, for example, between the Maradi goulbi and the Nielwa goulbi, or the hilly dunes east of Dan Isa.

Texture 5: the clear gray area with diffuse dots corresponds to villages, as we have seen under heading "2." The size of the dot, however, does not correspond to the actual size of the villages. Actually, the separate gray spot on the satellite picture corresponds to the actual village and the fertilized area surrounding it.(see 1:20,000 map).

Texture 6: the curved lines crossing the other textures were interpreted by broadening the study (limited initially to the experimental square) to the east as far as Termit and to the west as far as Niamey. These are deflation stria due to winds sweeping sandy surfaces arranged in a monticular structure. The stria end to the east of the figure of eolian erosion bands.

Texture 7: this corresponds to a network of dry valleys stuck

in their topography, probably after they ceased to function and after the halt of eolian activities. These are the tributaries of the left bank of the N'Kaba goulbi. They are difficult, if not impossible, to perceive on the ground and difficult to follow in the aerial photographs. It is likely that they can be seen in the satellite pictures because they are drier than the dunes whose sand is more structured. We propose this hypothesis of drier sand because, in addition, these valleys appear clear, almost white, on channel 4. On the other hand, they cannot be seen on channel 7.

## Chapter II. Description and Problems of Reactivation in the Experimental Unit /240

### 1. Monticular Sandy Structures

The experimental unit is a region of monticular dunes. This type of structure begins upwind from the unit, south of a latitude of 15°20'N, i.e. with a current annual rainfall of 250 mm, and west of a diagonal running from NNW to SSE which passes between the two massifs of Koutous and Tanout.

#### a) Specific Location of the Monticular

South of about 15°20'N, going from east to west, it shifts from small trnasverse structures, to thick, undifferentiated sandy tables, to a region of parabolic dunes and large fluviatile spreads of the souther base of the Air, and finally in the west, around 6°E, we arrive at a hilly coalescent area. In latitude, it extends beyond the border of Nigeria. In longitude, west of 10°, itssurrounds the Tanout massif and extends 100 km upwind from it where it shifts to barely differentiated sandy tables, apart from triangular depressions pointing towards the wind and lined up along the line of the harmattan. Proceding southward to the latitude of the Koutous massif the eastern limit of the area with monticular structures extends a further 100 km.

downwind from the Koutous massif.

b) Formation of the Monticular

We have not yet succeeded in solving this problem and for the time being we will only state some observed facts. A north-south cut, running from the N'Kaba goulbi to the experimental unit shows that there is not a true sandy pad south of the N'Kaba goulbi, but, dominating the major bed of the goulbi, there is a sandy bank with a slope of 6-8°. This rises towards a sandy surface shaped into a monticular landscape. The experimental unit is found on this sandy surface. The monticules which border the bank are topographically a little more differentiated than those of the experimental unit because their reactivation -- in the form of a buildup of an eolian cap -- is more advanced.

This fall is discontinuous, made up of a juxtaposition of /241
sandy monticules separated by interdunal valleys, the bottom of which is sometimes at the level of the major bed of the goulbi, sometimes slightly higher. These interdunal valleys and the upwind slopes halfway up their sides have undergone eolian winnowing which has concentrated subangular quartz particles there, reaching a size of 2-3 mm. We even found a pebble here, (brought in by humans?) measuring 2 cm in a depression at the level of the goulbi, but outside of the major bed. Because of the coarseness of the material, in particular of the subangular grains measuring 2-3 mm, based only on ground observation, we rejected the notion of an eolian origin. Unfortunately, ground observation alone, although supported by pedological analysis (different pedogenesis in this bank than in the rest of the unit), does not allow us to propose a hypothesis for the origin of this material.

What does one see on the ground?

1. A winnowed surface on the interdunal valleys and on the

upwind slope.

2. Immediately below this winnowed surface, in the material which is slightly solidified (not red but rather ochre) there is a much finer material with larger fragments. But examination of the terrain does not reveal any 2-3 mm fragments which, however, should exist, even if in small quantities.

3. The dunes are topped with homometric sand, well sifted and typically eolian. Probably the fraction removed by eolian winnowing to the base of the slopes and in the interdunal valleys is brought to the top of the slopes during reactivation. This forms a very general mechanism of desertification.

Problem: Monticules Formed by the Cutting Action of Water or Purely by the Wind

The Batéké Plateau in the Congo, which is also sandy, is cut into similar monticules which are sometimes more differentiated. However, and this has never been doubted, it looks like a landscape cut by the action of water in a sandy mass.

Can there be in these bank monticules interstratification of alternating fluviatile and eolian phases, both of them sandy?

Note: the only pebble layers encountered are those of the Maradi quarries and the Tchadwa goulbi.

In summary, based on our present knowledge it is not possible to know whether or not water is involved in shaping the monticular. If it is involved, what share does it play, what share is played by the wind?

Only two points are certain: not all of the material making /242

up the monticular is carried by the wind. There is reshaping of a decomposition material of the Cretaceous substrate, probably by water, and additions of much finer material brought in by the wind -- allochthon or of local winnowing -- which form the cap of the monticule. At Maradi, alongtthe Maradi goulbi, the monticular constitutes only a surface state on a system of terraces.

## The Supply of Fluviatile Material in the Experimental Unit

At present the experimental unit is very deficient in surface runoff forms. However, several indicies suggest a past which had a more extensive drainage system:

### a) Grain Size of the Material

Many samples contain grains measuring > 2mm, i.e. too coarse to have been deposited by the wind. This is the case, in particular for the monticules in the experimental unit on which the village of Azazala was built (NIG samples 77, 54 and 64). This was also the case with the sandy pad south of the N'Kaba goulbi (NIG samples 77 and 133-137). It is likely that these coarse grains came directly from the local substrate of coarse sandstone of the Cretaceous period and are thus subautochthone or were deposited by fluviatile means.

The existence of a few grains of potassium feldspar suggest that material from the Precambrian stock south of the Niger Republic has been brought in by rivers on both sides of the Niger Republic - Nigeria border.

### b) Morphoscopy of the Sandy Materials

Study of the surface condition of the grains of sand reveals a mixture of two supplies of sand, one with rounded to

perfectly round, pitted-dull, not very large grains, and the other supply of coarser sand with subangular grains with rounded corners.

c) Analysis of Landsat 1 Satellite Pictures

Study of the Landsat 1 pictures, in particular those of channel 7, reveals a dense network of low order valleys, tributaries of the left bank of the N'Kaba goulbi.

2. Discussion of the 1:20,000 Map of the Serkin Haussa Experimental Unit (Separate sheet) /243

Reactivation Mechanisms for the Sandy Mantle by Wind and Water Erosion and the Effects of Human Occupation

The 1:20,000 map of the experimental unit of Serkin Haussa (Niger Republic) was basically done to evaluate the reactivation mechanisms of the sandy mantle due to wind and water erosion and to evaluate the effects of human occupation.

It was made from the special coverage of aerial photographs (1:10,000) taken by the French National Geographic Institute in 1976. On this map it was attempted to make an inventory of the organization of different elements of the physical environment and of the main parameters responsible for the breakdown of landscapes. These parameters are grouped into two categories: (1) morphological processes, among which we can distinguish eolian reactivation either by an overloading of sand or by deflation and water erosion, (2) human factors leading to a change in surface behavior.

I. Surface State of the Physical Environment

The sandy monticules and interdunal valleys were care-

fully mapped. It was our hope, by using a mapping format, to be able to discern an organization which we could not find by simply observing aerial photographs and by making ground observations. But the few rare tendencies which we were able to find are areas where the monticules are more numerous and, on average, separated by distances of from 80 to 120 meters, and other areas where the monticules are almost nonexistent, as is the case east of the village of Azazala in an extended region whereall of the runoff seems to converge. The same is true south and northeast of Serkin Haussa.

It seems that outside of these three bands thermonticular has densities roughly equivalent to the rest of the map. The greatest density is located east of the village of Guidan Angō, following a north-south line.

The interdunal valleys were differentiated from more or less temporarily flooded depressions. We indexed 9 tabkis, which are natural ponds often managed by man. They constitute the best water reservoirs for 5 or 6 months after the end of the rainy season. We thought that these tabkis, in connection with the valleys, had a subsoil of fine lateritic gravel. This turned out to be practically never the case.

We were also struck by the rarity of such areas with a subsoil of lateritic gravel. Studies of the terrain revealed only four such areas: (1) 700 meters southeast of Guidan Lali Bākané; (2) 400 meters north of Dan Diba; (3) 200 meters SSW from the village of Nafoutyé; and (4) 800 meters WSW from Maya Darojia. These four sites correspond to regions where surface runoff is densest, and it goes from the diffuse to concentrated state. For sites 3 and 4, as also noted for the lateritic gravel quarry of May Sokoni, outside the diagram one notes the existence of a detectable underflow in the surface by means of denser lines of vegetation. /244

Ponds flooded for a shorter period of time and wetter inter-dunal valleys were also discerned. One notes that their existence is very often due to surface runoff. By mapping them we were able to mark two preferential regions, one to the west of the map following a NNE-SSW diagonal, in the north passing east of Guidan Lali Bakané, and in the south passing close to May Sokoni; the second region is on the east of the map.

## II. Biological Elements of the Environment

Only those elements were retained which affect wind or water reactivation, such as roughness due to vegetation (trees and shrubs) and termite nests, among which we tried to differentiate between clearly individualized termite nests and more or less spread out well-established termite nests.

## III. Human Environment

The study of aerial photographs reveals the distribution of the habitat into concentrated villages separated by distances which vary considerably. Around these villages the agricultural soil is divided into several surrounding rings:

1. The ring in which man-made degradation of the sandy soils is compensated for by the addition of animal manure.

2. The ring divided up between agricultural soil occupied mainly by millet (the stands can be discerned on aerial photographs as structure of aligned dotted lines) and fallow ground. One is struck by the large proportion of cultivated area with respect to areas left fallow. In general, these regions show forms of water erosion which have been left fallow.

3. Among the other human factors represented are: hedges, cattle trails, roadsand main highways.

## IV. Morphological Processes for Breaking Up the Landscape /245

### 1. Reactivation Due to an Overload of Sand

Among the eolian reactivation processes we have distinguished reactivation due to an overload of sand. Many regions with shrubs surrounded by a trapping ring of active sand were able to be distinguished. Their abundance tends to prove that there is transport and deposit of sand in the experimental unit.

The hedges are subjected to mechanisms of sand-build-up by the combing effect. This sand build up can cause the hedge to be raised with accumulations reaching 40 cm. In exceptional cases werwere also able to discern avalanche effects, i.e.ethe spreading out of sand beyond the hedge, perhaps at the expense of sand trapped by the hedge. When trying to improve the evaluation system it would be dangerous to remove the existing hedges, even when degraded or broken down hedges are involved, because this could lead to the releaserof large quantities of sand which could easily be moved by the wind.

The uprooting is probably local, since it exists around certain large trees in deflation pits with excessive, asymmetrical wind scouring which can expose the roots of the tree (this was found in the terrain).

This same transport of sand, the dangers of which are not insignificant since it can exert an abrasive effect on the young shoots, and these same avalanche effects can be detected around the hedges.

### 2. Reactivation by Eolian Deflation Processes

We have distinguished several types of deflation: (1) area deflation, i.e. in more or less extensive irregular areas; (2) cra-

ter deflation, i.e. describing a dented topography when looked at in detail (dents or craters on the order of decimeters); and finally (3) curious periodic or spot reactivation tendencies.

There is a distinct contrast between regions where water erosion predominates and regions where wind erosion predominates. Why this contrast? What does it indicate?

The regions where runoff is intense and which are less favorable for the cultivation of millet are probably less overused. In these regions one also notes a larger amount of fallow ground. Elsewhere the areas most distant from the villages also seem the most protected. It is around villages like Serkin Haussa and Azazala where wind erosion seems most advanced.

It is certain that there exists a very clear relationship between eolian reactivation and the growing of grain crops and an inverse relationship between water erosion and wind erosion.

### 3. Runoff Effects and Other Forms of Water Erosion /246

We have just seen that runoff does not add to the mechanisms of wind erosion unless -- but this cannot be revealed by examining aerial photographs -- the sand carried by the runoff was of a size such that it could be taken up by the wind. This we will discover by granulometic studies.

There are two regions where more intense runoff is becoming concentrated: (1) east of Serkin Haussa and (2) north of a line extending from Azazala to Dieza Magajiya.

Another mechanism in connection with water occurs in certain areas abundant with extensive termite nests. This process we have called "glazing." It results from a spreading out of muddy or fine

sandy substances making up the termite nests in rather flat regions and where rain waters and diffuse runoff give rise to areas bearing a film which is not conducive to vegetation.

## V. Man-Made Factors and the Vulnerability of Landscapes

Two series of human factors responsible for degradation of the landscape have been distinguished:

1. Those factors connected with the day to day activities and agriculture of the villagers, i.e. around wells, markets, schools and millet granaries. These areas of man-made denudation are generally located in the ring of fertilized ground surrounding the village.

2. Those connected with the raising of livestock: the stamping of hoofs is such that it produces several types of denudation, linearly along the cattle paths and more spread out in certain fallow areas in which threatening reactivation areas are appearing.

## Conclusion

At the time of our first trip in January-February 1976 the experimental unit looked to us like a region threatend by eolian reactivation. Subsequently, the rainy season which followed our first trip had particularly heavy rains, with the rains not stopping until October. Our second trip in February 1977 which followed this season of abundant rains lead us to think that the reactivation mechanisms of the dunes observed in 1976 were reversible and that a good rainy season was sufficient to wipe out the bad effects of a series of dry years.

Study of the 1:10,000 aerial photographs, even though done

after a good rainy season, and the reactivation map of dunes covered by natural or man-made mechanisms have led us to a more pessimistic conclusion: in the context of demography measurements and current evaluation, any attempts at improving the evaluation methods cannot be made without paying constant attention to the mechanisms of wind erosion, the effects of which are shown in the experimental unit.

## 3. Experimental Unit: The Village and Its Surrounding Rings of Agriculture; the Means of Cultivation; the Notion of a Mobile Sandy Covering /247

Around the villages the agricultural soil is laid out in two or three rings. The first, immediately around the village, is generally cultivated in sorghum and corn, which, because they are more demanding than millet, benefit from manure. The addition to the soil of cattle manure makes an excellent protection against wind erosion. The natives are very conscious of the fact that the manure compensates for deflation when the latter reaches too high a level close to the villages. In the aerial photographs there appears a form of visible deflation south of the village of Guidan Gougé like a small leprosy of slightly depressed round areas in which the covering of vegetation is destroyed. At Guidan Gougé this degradation was compensated for by a manure of camel dung and a covering of twigs.

The second ring, further out, is planted with millet which is generally harvested in October, the beginning of the dry season when the harmattan begins to blow. At Maradi, where the harmattan blows, on average, from October to February inclusive, the winds from the east are strong and the millet, once harvested, no longer provides a protective covering. In general, it is in this second ring cultivated in millet, sometimes also planted with "niébé," that the dangers of wind erosion are greatest. These are

increased by an impoverishment of the soils around certain villages due to 20 consecutive years of cultivation without ever letting the land lie fallow, which seems surprising in an especially quartzy sandy material.

Several inquiries among the peasants made us aware of a notion which had escaped us during the first year of our work: the notion of a mobile sandy covering. In fact, good ground planted with millet is a very mobile sandy ground. The red clastic dunes and the interdunal spaces richer in muddy material are considered by the natives to be much less favorable to the cultivation of millet.

When the cultivation of crops extends for too many years the mobile sandy covering can be completely carried away by eolian deflation and the B horizons crop out. Then, in order to avoid a catastrophic drop in production, the natives have recourse to letting the land lie fallow, allowing the mobile sandy cover to reform. Thus, southwest of Guidan Lali Bakané, a very hard region, where the B horizon crops out, was left fallow for three years while waiting for the sand carried by the wind and trapped by the /248 graminaceous covering to become thickneneough to again allow profitable cultivation of millet. The peasants appreciate the sand brought in by the wind ("good for theecultivation of millet"), but, on the other hand, they fear deflation which causes the clastic sandy substrate to crop out.

The mobile sandy covering favors keeping things moist. It is under this mobile sandy covering that the chances of finding moisture at a shallow depth are maximum during the dry season. When there is no covering of mobile sand the cultivation of millet is only profitable in years of heavy precipitation.

The thickness of the mobile sandy covering varies: 5 cm near the Serkin Haussa Gakoudi trail; on the top of dunes it can reach

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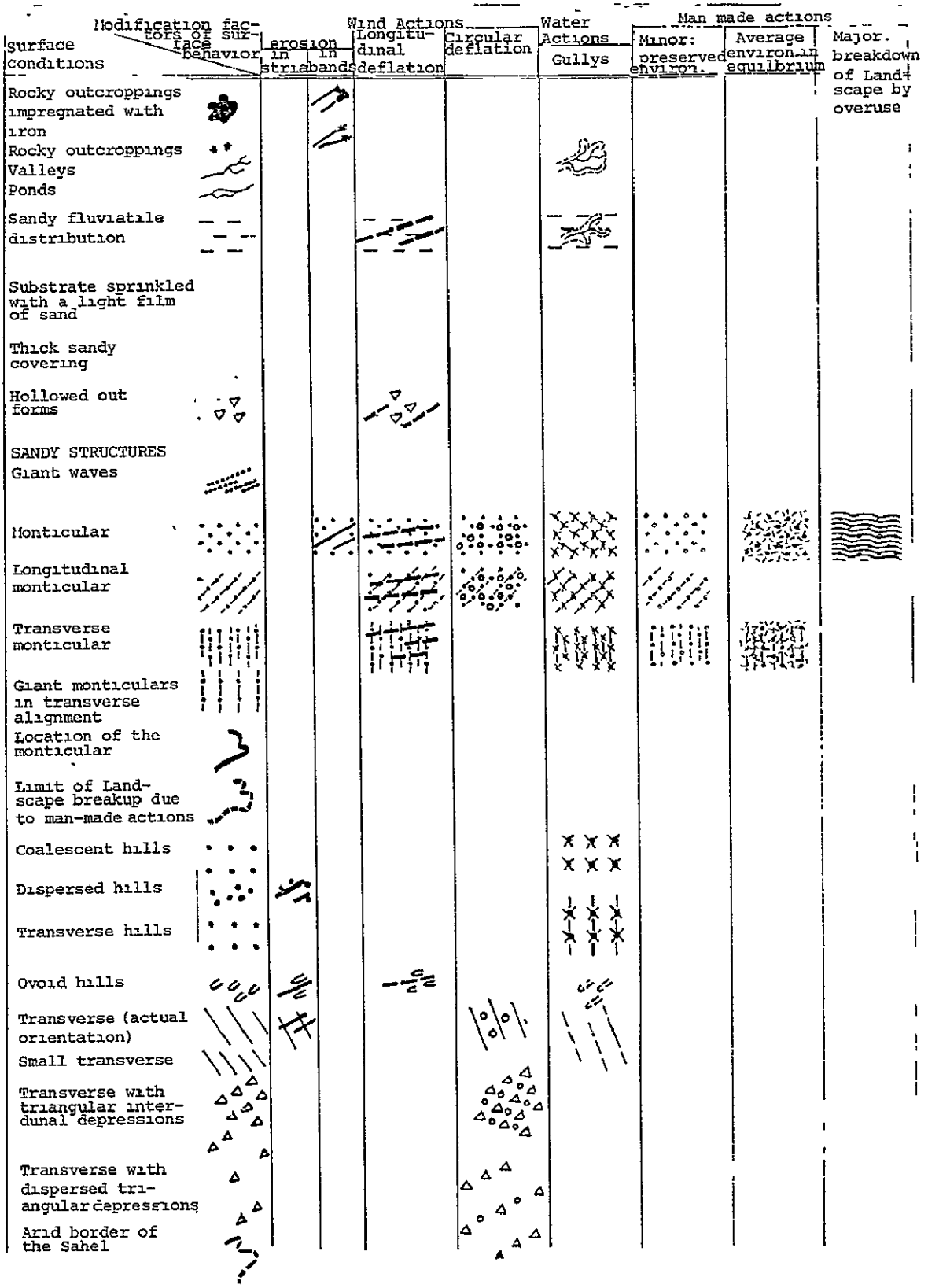
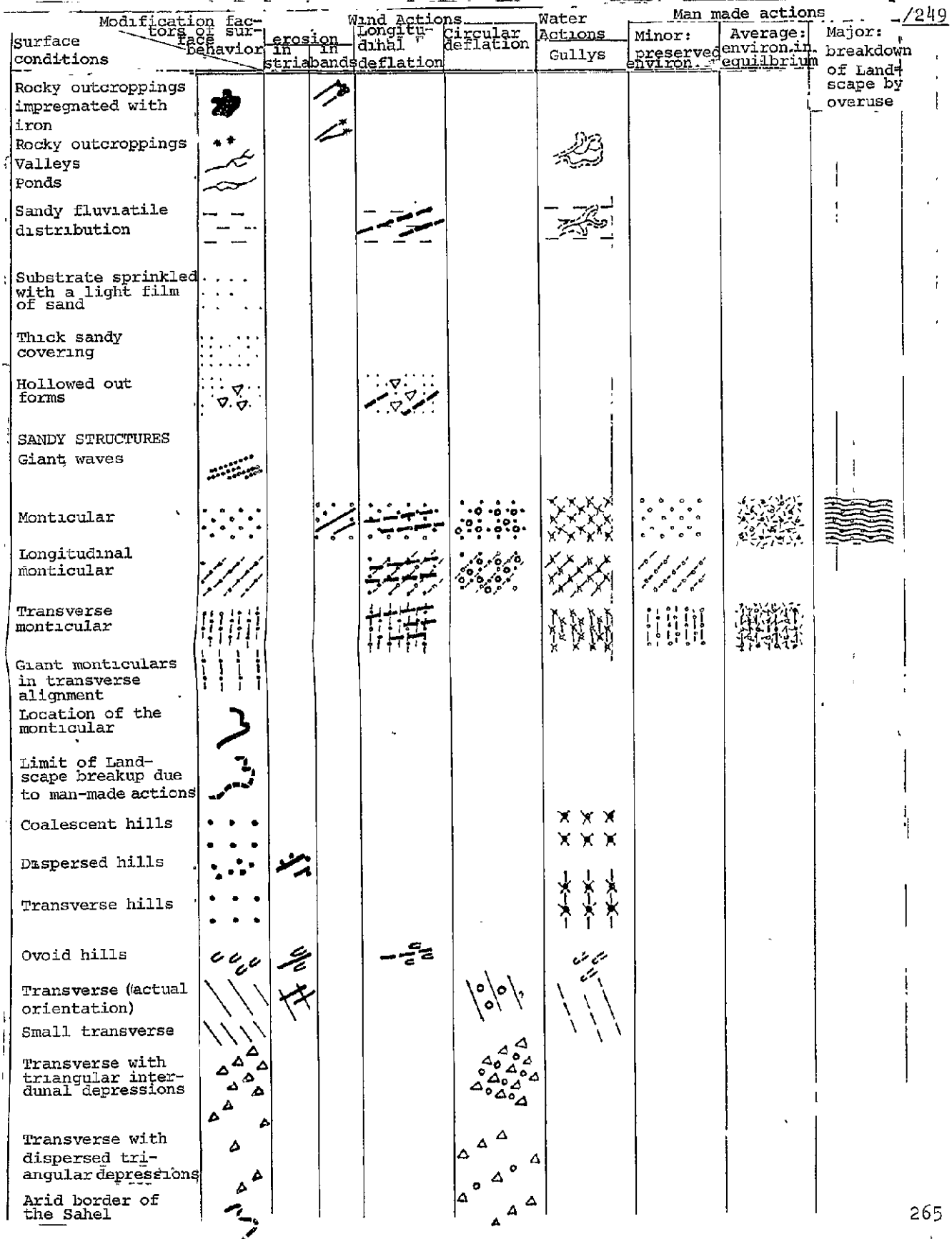
Natural Wind and Water Erosion Mechanisms and Their Evaluation
With Respect to the Degradation of Sandy Landscapes
Niger Republic



# Natural Wind and Water Erosion Mechanisms and Their Evaluation With Respect to the Degradation of Sandy Landscapes

Niger Republic





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In Collaboration with Lydie Canon, Anne-Marie Chapelle
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10±20 cm thick; and 25-30 cm at Tchakye Magaria. The millet seems to appear as soon as the mobile sandy covering exists.

4. Reactivation Agents of the Haussa Erg. Study Based on Satellite Pictures and Aerial Photographs. 1:1,000,000 Map: "Natural Wind and Water Erosion Mechanisms and Their Evaluation with Respect to the Degradation of Sandy Landscapes. Niger Republic." (Map on Separate Sheet) /250

1. The Dangers of Reactivation by Water Erosion in the Experimental Unit and the Area Upwind of the Unit

The index of runoff erosion (ratio between the length of rill marks in km and the surface area in $km^2$) is very low in the experimental unit. Thus the dangers of reactivation by water mechanisms there are negligible, in contrast to what is occuring around 15°50'N, i.e. approximately at the latitude of the southern tip of the Termit Massif where a band of gullied dunes is observed which stops around 14°10'N.

On the basis of a combined study of wind and water actions east and south of the Termit Massif made it possible to locate a border between a sandy landscape with typical arid forms and a landscape of sandy structures degraded by Sahelian mechanisms, such as the effacing of dunes and gullying. The band of gullied dunes forms a true transition between the two landscapes. In this region the precipitation levels (from 250 mm to 400mmm in the south) are sufficient to cause runoff and the covering of vegetation is insufficient to counteract it.

The gullies in this area are of two sorts: old rounded gullies and more distinct gullies, probably more recent. These gullies affect two kinds of covered eolian structures: hilly and transverse structures. The map of this band (1:1,000,000 scale map) and

its comparison with the isohyet map show that water erosion on the sandy mantle is less effective with precipitation levels of 600 mm than with from 250 to 400 mm of precipitation.

In the experimental unit water erosion takes place only in preferential locations governed by pedological factors of differentiation. In fact, the gullies only appear in areas, or on the periphery of areas, with a subsoil of lateritic gravel or incipient hardpan, and on reddened dunes, thus with a slightly clastic mass, when they are subject to "glazing" as a result of overuse which has caused deflation of their mobile sandy mantle. This glazing promotes the start of intense runoff. Thus on the basis of the postion of areas with lateritic gravel or of red dunes it is possible to easily predict water erosion dangers in different regions of the experimental unit. However, the danger of water erosion is still not very high.

2. 2. Wind Reactivation /251

There are four wind reactivation mechanisms: (1) uprooting, (2) erosion, (3) sprinkling with sand and avalanche effects, and (4) buildup of small structures such as nebkas or silks.

The reactivation signs observed differ according to the scale of the documents referred to.

A. Diagnosis of Reactivation Using Satellite Pictures

The following can be detected on the 1:1,000,000 scale ERTS pictures:

1. Circular deflation: areas of reactivation on monticular, longitudinal monticular and transverse structures. A structure

of central white areas, 2-4 km in diameter, sometimes coalescent, shows up particularly clearly on channel 7. The black central point corresponds to the village and the surrounding ring of fertilized ground. The white ring surrounding the village corresponds to cultivated agricultrual ground. Thus the reactivation connected with the villages and agricultural soils can be detected on satellite pictures.

2. Longitudinal deflation: reactivation occurs along the streaks, but in a discontinuous way which makes it difficult to detect on 1:50,000 scale aerial photographs and easier to detect on satellite pictures.

3. Two types of erosion: (1) in stria on the dunal structures, sometimes arising downwind from an obstacle, or (2) in sweeping bands downwind from the Koutous and Tanout massifs. The sweeping bands often describe an arc of a circle, while the erosion stria are rectilinear. Their edges, which are always sharply defined on the northside and wavy on the southside, are dissymmetrical. The small sweeping bands are shaped (in top view) like a spearhead tapering downwind, whereas the large bands taper without reaching a perfect spearhead shape. On the Tessaoua-Zinder road which crosses the eolian sweeping bands can be seen hilly dunes at the edge of the bands and monticular dunes in the center. The substrate is rocky with hardpan phenomena. The bands are located downwind from the Tanout and Koutous massifs. Downwind from the Koutous Massif which blocks the passage of sand the longer erosion band reaches a length of 230 km with a width of 25 km. Shorter erosion bands form below the Tanout Massif, tapering downwind.

Deflation streaks extend the erosion bands of the Koutous and Tanout massifs, north and south of the Koutous Massif and at the northern beginning of the alveolar. We still donnot understand the rules governing their location. Human occupation begins where

these deflation streaks stop, hence the site of the experimental square was well chosen.

While the erosion bands are unattractive regions for farmers because the rocky substrate crops out in these areas without any sandy covering, the deflation streaks are not unattractive areas as is shown by the region south of Tarka valley west of Dakoro.

B. Wind Reactivation: Study of Aerial Photographs /252

No region, no matter what the dunal relief characterizing it, seems to be sheltered from current reactivation phenomena. However, the highest frequency of these phenomena is found on the transverse structure which skirts the Koutous Massif. This may explain the concentration of reactivation phenomena in this region.

1. Wind Reactivation and Topographical Factors

Wind reactivation often arises downwind from a talus, from a trail and from wadi beds. We found it in these places on the 1:60,000 scale aerial photographs of 1975 in 2 forms: (1) in streaks running ENE-WSW obliquely to the wadi beds, always located west of the beds, i.e. downwind from the beds; or (2) extending the end section of the bed of the wadis, broadening the area affected, which seems to have a tendency to move towards the west in ring-like or finger-like progressions.

a) Reactivation seems to be promoted by the presence of valleys:

1. for the region extending from 41°30' to 15°N and from 6°30' to 7°50'E there is a correspondence with the Koren Adwa, the Afagag, the Eliki and the Goulbi N'Tarka.

2. Three small very localized spots to the south at 13°45',

13°55' and 14°05'N and 6°40'E seem related to the presence of the Goulbi N'Kaba valley and the Goulbi N'Maradi valley.

3. A reactivation area located at 14°40'N and 8°50'E is related to the valleys of Dagazaram and Dan Gagara (sources of the N'Kaba Goulbi).

4. An area at 13°15'N and from 8°30' to 9°20'E is related to the course of the Korama.

b) Reactivation is related to the presence of massifs:

1. an area extending from 14°40'N and from 8°30' to 9°E is related to the southern part of the Damergou.

2. An area extending from 14°10' to 14°30'N and from 9°20' to 9°45'E, located between the Koutous and Damagaram massifs.

## 2. Eolian Reactivation Phenomena of the Sandy Mantle: Different Aspects in Aerial Photographs

A

a) Reactivation:

1. Incipient reactivation shows up in aerial photographs in 2 forms. One is a hazy appearance which can be attributed to the areas around the villages trampled by animal hoofs. It tends to efface the borders of the fields and forms a kind of light film, lighter than the neighboring areas. Incipient reactivation also appears as flaky areas in the form of white flakes with fuzzy outlines.

2. Established reactivation appears as follows in aerial photographs: (1) very white, distinctly outlined plots of various sizes and shapes; (2) spots whose linear shape is governed by the slopes of transverse dunes; and (3) spots whose micro-crescent shape is traced on the benches of slopes. /253

b) Deflation:

1. Incipient deflation: fuzzy streaks, with not very clear outlines, resulting from sand being carried away by the wind.

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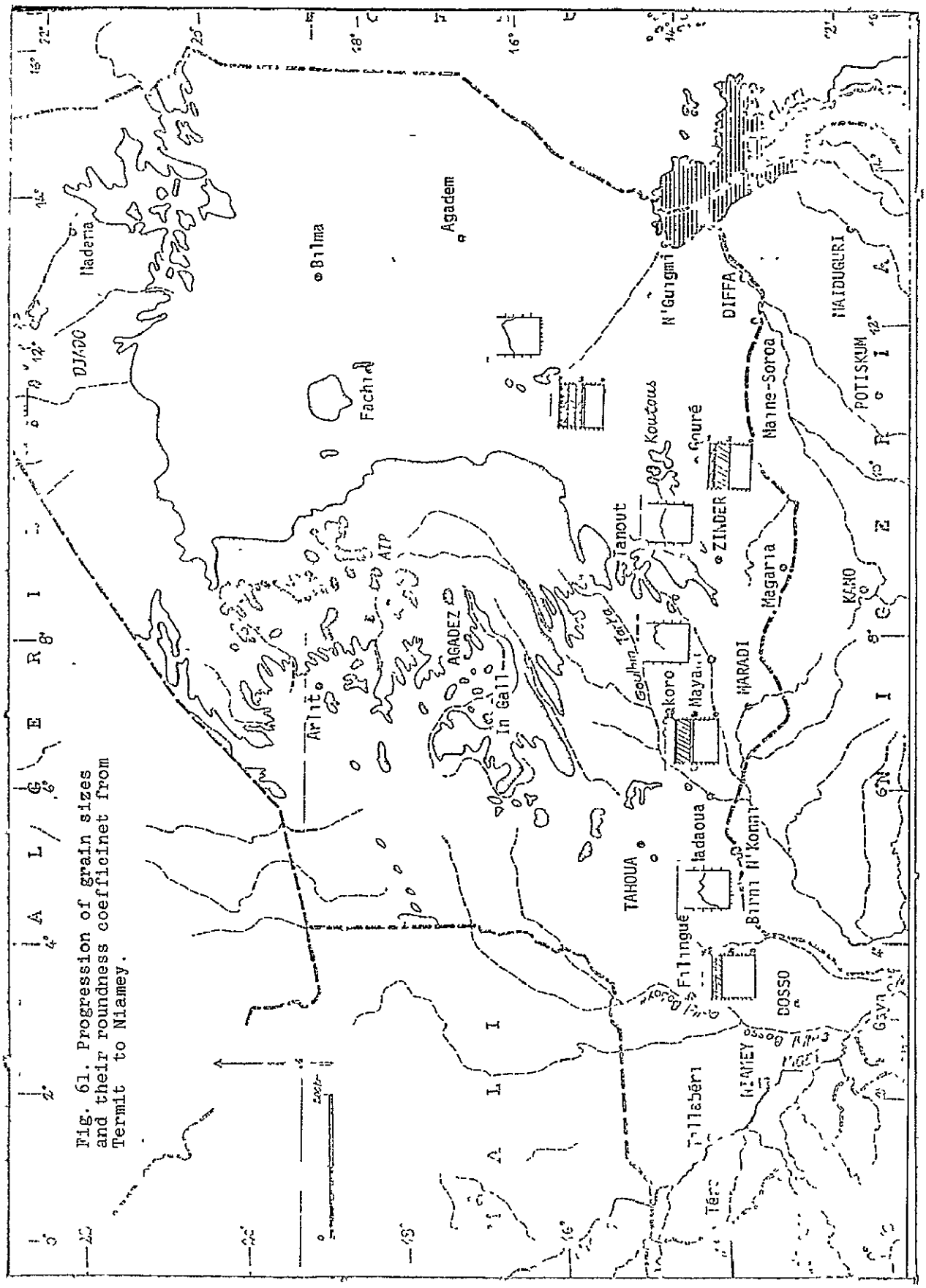



Fig. 61. Progression of grain sizes and their roundness coefficient from Termit to Niamey.

Legend on next page.

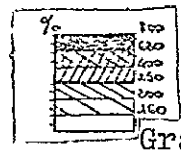
2. Established deflation breaks down into the following: (1) deflation smudges. The outlines of the spot look like a used paint brush. The deflation spot which contains a bundle of streaks expands in various ways depending on the streaks. (2) Deflation in waves of scratch marks. These seem to be the most elaborate form of present deflation. The deflation extends in successive waves of scratch marks. The scratch marks are arranged in bundles. In the first stages these areas have a hazy appearance and then the bundles develop into periodic waves. Each wave, which is fuzzy on the upwind side, has a distinct edge on the downwind side and then is succeeded by a following wave. The last wave often ends in the shape of a crow's foot.

## Book IV. The Sandy Material of the Haussa Erg from Termit to Niamey, Granulometric and Morphoscopic Study[1] /254

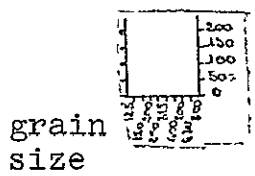
### Progression of Grain Sizes and Their Roundness Coefficient from Termit to Niamey (Fig. 61) /257

Legend

Percentage of Modes per granulometric category




Roundness coefficient values for the granulometric categories of 125, 160, 200, 250, 315, 400, 500, 530 and 800 µm.




1. Since all of the sand samples have not yet reached us we can only give partial results in this report. However, we do not believe that the subsequent analyses will invalidate the results obtained.

In the course of two ground trips sand samples were collected for the following reasons: /258

1. To verify the existence of the large transport current transporting particles from Bilma to Ader Doutchi, by showing the decrease in grain size in the direction in which the sand is moved, by showing the existence of load substitution phenomena and by showing the degrees of wear on the sandy particles.

2. To locate the material in the experimental unit along this current.

3. To specify the degrees of allochthony and/or autochthony or the mixtures of distanty and local supplies of sand in the sandy material.

4. To study the existence of a single current or several adjacent currents as apparently indicated by the satellite pictures.

5. To specify the range of particle sizes of particles subjected to deflation and saltation transport during dunal reactivation.

6. To specify the size of particles according to the type of sandy structure which they form.

7. To investigate differences in grain sizes of the material according to its depth in order to determine variations in placement processes, for example superposition of a stratum formed by dominant water actions by a stratum formed by dominant wind actions

Three kinds of laboratory analyses were done on the samples: /259

1. Study of grain sizes.

2. Optical study of surface shapes and conditions.

3. Attempt to compare different indices:
   a) the Qdphi (of Krumbein) which allows the sorting of particles according to the shape of the semi-logarithmic cumulative frequency curve. The greater the Qdphi, the more poorly sorted is the sediment, i.e. heterometric.
   b) the mode, which corresponds to the size of particles of maximum frequency.
   c) the median, which is the size of particles such that 50% of the particles are smaller and 50% are larger.

Three groups of samples were distinguished: one group in the Termit region, another in the Maradi region and a third between Madaoua and Niamey.

Granulometric Study of Sands from the Termit Region /261

A) Comparative Study of Krumbein Qdphi Indices (Fig. 62).

According to the value of the Qdphi index three groups can be distinguished:

1. Qdphi > 0.40. At Termit Kaoboul this value corresponds to the foot of the downwind face of the ripple mark (NIG 76 41c), and in the Fachi Bilma Erg, upwind from Termit, it corresponds to sand taken from a depth of 10 cm. (NIG 76 49). These formations are therefore very heterometric.

2. 0.25 < Qdphi < 0.40 for the sands of the depressions, substrate and sandy substrate at a depth of 10 cm of a ripple mark at Termit Kaoboul (NIG 76 39c, d, e), and sands of the Fachi Bilma

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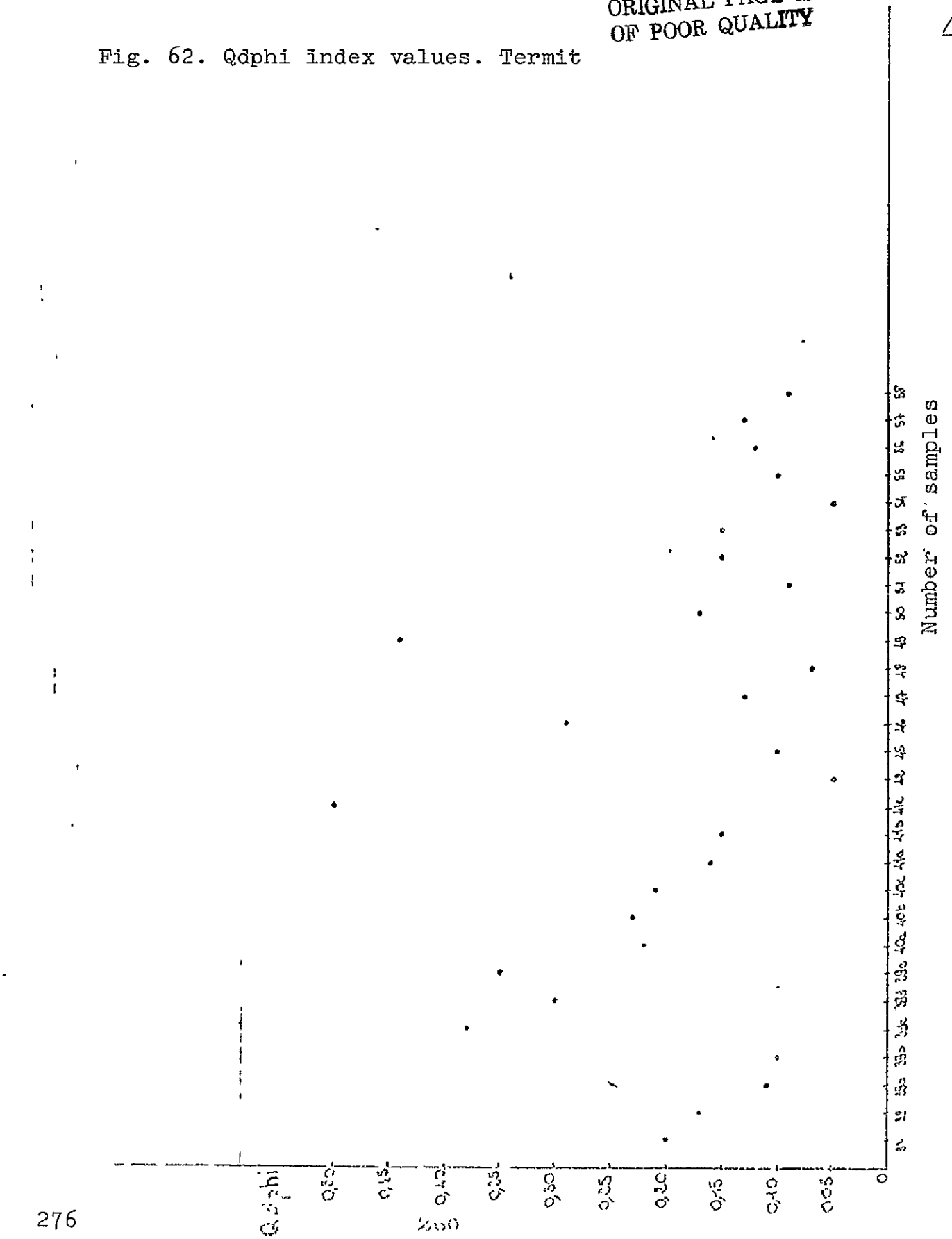
Fig. 62. Qdphi index values. Termit



erg taken from a depth of 20 cm (NIG 76 46). Again these formations are rather poorly sorted.

3. 0 < Qdphi < 0.25. Since we were not able to keep in a single group formations with Qdphi numbers as different as 0.05 and 0.25, we subdivided this last group. Since no limit shows up on the graph, we preferred to make an arbitrary separation based on a calculation of the arithmetic mean of this last group. The calculated mean being 0.13, we thus have:

a) a Qdphi group > 0.13 for the very red and movable sands of the top of the Termit knoll (NIG 76 37) and the sands falling downwind from the same knoll (NIG 76 38); the sands of the top, slope and train of a Termit Kaoboul nebka (NIG 76 40 a, b, c); those of a front side and convex back side of a Termit Kaoboul ripple mark (NIG 76 41 a and b); the red sands at the foot of the slope of a cave-in at Termit Dole (NIG 76 50); the sands of the levee on the western bank of Lake Chad (NIG 76 52); and finally the sands of an existing nebka of N'Guigmi (NIG 76 53). This material can be considered to be moderately sorted.

b) A group with a Qdphi number less than or equal to 0.13. This pertains to the front and back side of a Termit Kaoboul ripple mark (NIG 76 39 a and b), the reactivation silks of Termit (NIG 76 42 and 47) which reveal the infrequency of effective winds, whence excellent sorting or a very limited range of efficiency. This group also includes the paving of large waves (NIG 76 45 and 48), the dunes in the vicinity of N'Guigmi (pedogenic sands) (NIG 76 51, 57 and 58); existing redeposition sand at N'Guigmi (NIG 76 56); and finally the Tall dunes (NIG 76 54). In this last area the wind has lost some of its energy and after crossing the low-lying obstacle represented by Lake Chad it immediately deposits its sand. The material of these samples can be considered homometric and well sorted.

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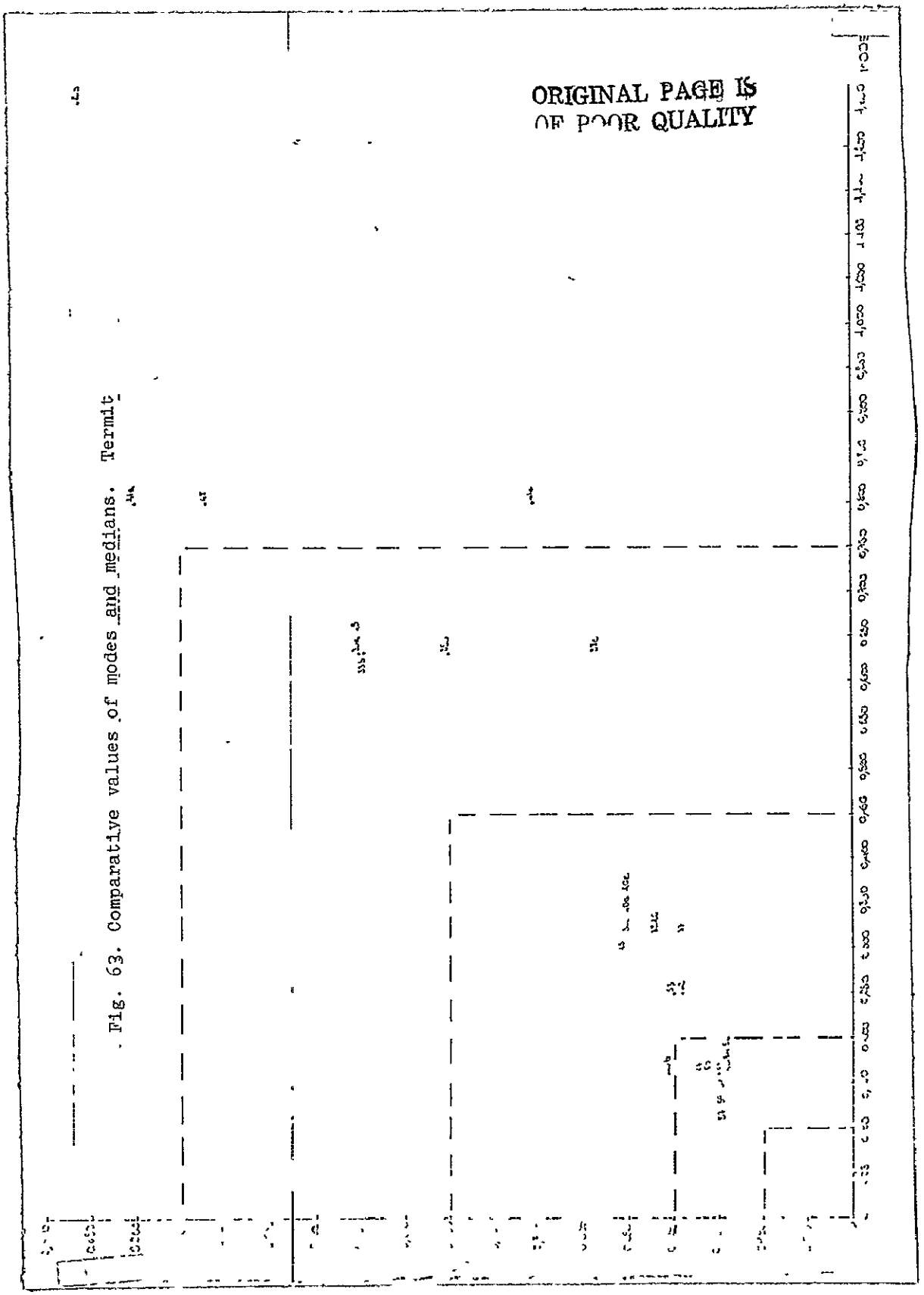

. Fig. 63. Comparative values of modes and medians. Termit

This first granulometric study reveals the following: /263

1. Surface winnowing of the Fachi Bilma erg, since the particles which remain by forming a paving are better sorted than the particles at a depth of 20 cm. Among the most well sorted particles are those of the reactivation silks of the Fachi Bilma erg which show a narrower rangesof effectiveness for existing winds than for the winds which deposited all of the material of the Fachi Bilma erg.

2. The obstacle effect caused by Lake Chad, downwind from which only well sorted material is deposited.

3. The granulometric composition of existing structures (nebkas, sand which has fallen downwind from the Termit knoll) which are relatively well sorted but less than the reactivation silks of the Fachi Bilma erg.

B. Comparative Values of the Mode and Median (Fig. 63)

We know that the difference between the mode and the median reveals the degree of homometry of a mobile formation. The larger this difference, the more poorly sorted, i.e. heterometric, is the formation and vice versa.

Fig. 63 enables us to rather quickly evaluate this difference. Let us draw a bisecting line which connects the angles of the squares drawn in: the more distant the points, the greater the mode-median difference. Nevertheless, this distance must be evaluated in relative terms. In the range of high values a moderate difference will correspond to a large difference for the low values.

By using this method -- which is imperfect because it would be necessary to precisely define the relativeness described above --

we can distinguish several groups:

1. A group with little or no difference.

Among the samples of fine sand this includes the sands of reactivation silks (NIG 76 42 and 47), the red sands at the foot of a caved in slope at Termit Dolé (NIG 76 50), the sands of dunes close to N'Guigmi (NIG 76 51, 55, 57 and 58), existing redeposition sand N'Guigmi (NIG 76 56) and finally the sand of the active dunes of the Tal (NIG 76 54). All of these samples have a mode of 160 µm ándaa median of 150 µm.

Among the samples of coarse sand this groups includes the sand of the front side of a ripple mark at Termit Kaoboul (NIG 76 41 a) with a mode and median of 800 µm.

2. A group with a moderate difference. /264

Among the samples of fine sand the following sands can be distinguished:

a) sometimes nebka sands, the nebka slope at Termit Kaoboul (NIG 76 40 b) whose mode and median are 160 µm and 205 µm; the top and train of the Termit Kaoboul nebka (NIG 76 40 a and c) whose mode and median are 315 µm and 250 µm; and finally the N'Guigmi nebka (NIG 76 53) whose mode and median are 250 µm and 200 µm.

b) Sometimes ripple markssands, like that of Termit Kaoboul, taken from a depth of 10 cm (NIG 76 39 e), or agains like that taken from the giant waves of the Fâchi Bilma erg at a depth of 10 cm (NIG 76 49) whose mmode and median are 315 and 250 µm.

c) And finally sometimes sands from the levee which borders the western bank of Lake Chad (NIG 76 52) hwhose mode and median are 250 µm and 200 µm.

Among the samples of medium sand the following sands can be distinguished: ripple mark sands, front and back side of a Termit Kaoboul ripple mark (NIG 76 39 a and b) and that of a ripple mark on the giant wave of the Fachi Bilma erg (NIG 76 45) whose mode and median are 630 µm and 550 µm.

Among the samples of coarse sand the following sands can be distinguished: surface pavement sands of a ripple mark on a giant wave of the Fachi Bilma erg (NIG 76 48) whose mode and median are 800 µm and 720 µm.

3. A group with a large difference.

Among the samples of fine sand the following can be distinguished:

a) Sometimes ripple mark sands at a depth of 20cm in the Fachi Bilma erg (NIG 76 46).

b) Sometimes sands from the top part of the eolian pass at the foot of the Termit knoll (NIG 76 37).

c) Sometimes sands from the base of an eolian fall at the foot of a slope (NIG 76 38). All of these samples ahave a mode and median of 315 µm and 200 µm respectively.

Among the samples of medium sand the following can be distinguished: sands from the hollow and substrate of a Termit Kaoboul ripple mark (NIG 76 39 c and d) whose mode and median are 630 µm and 450-285 µm respectively.

Among the samples of coarse sand the following can be distinguished: sands of the back convex side of a Termit Kaoboul ripple mark (NIG 76 41 b) whose mode and median are 1,250 µm and 850 µm; also sands from the base of the front side of the same ripple mark (NIG 76 41 c) whose mode and median are 800 and 350 µm.

This graph yields two results:

1. A classification of material according to its grain size and its degree of heterometry. Particularly coarse (with a mode and median $\geq$ 7000µm) are the pavements either arranged or not arranged in ripple marks, and particularly fine (mode and median 350and 400 µm) is the material which is currently being moved (nebkas and silks).

2. As for homometry, the most homogeneous material is that of the pavement of the erg which is a residue of winnowing and the southernmost material taken at Maine Soroa. The redeposition sand is also relatively homogeneous.

C. Comparison of Figs. 62 and 63 /266

By comparing the groups distinguished in the two cases and the formation to which these groups belong we will be able to verify and confirm the more or less large degree of homometry of the material.

- The best sorting is attained by samples from group "d" of Fig. 62 and group "a" of Fig. 63. These are the reactivation silks downwind from the Eachi Bilma erg (NIG 76 42 and 47) the dunes in the Chillia Dillia north of N'Guigmi (NIG 76 51), the active dunes of the Tal (NIG 76 54) and finally the material deposited downwind from Lake Chad in a very southern branch of the harmattan (NIG 76 55, 56, 57 and 58).

Then, in decreasing order of sorting, come the following:

- The formations belonging either to group "c" of Fig. 62 and group "a" of Fig. 63, or to group "d" of Fig. 62 and group "b" of Fig. 63. These are the front and back sides of Termit

Kaoboul ripple marks (NIG 76 39 a and b and 41 a), a red formation at the foot of a Termit Dolé cave-in slope (NIG 76 50) and the ripple marks on the large waves of the Fachi Bilma erg (NIG 76 45 and 48).

- The formations belonging to group "c" of Fig. 62 and group "b" of Fig. 63. These are the nebkas of Termit Kaoboul and N'Guigmi (NIG 76 40 a, b, c and 53) and the sand of the levee bordering Lake Chad (NIG 76 52).

- The formation belonging to group "c" of Fig. 62 and group "c" of Fig. 63. These are the sands of the top of the fall of the Termit knoll (NIG 76 37 and 38) and the convex back side of a Termit Kaoboul ripple mark (NIG 76 41 b).

- The formations belonging to groups "a" and "b" of Fig. 62 and group "b" of Fig. 63. These are the substrate at a depth of 10 cm of a Termit Kaoboul ripple mark (NIG 76 39 e) and a ripple mark on a large wave of the Fachi Bilma erg at a depth of 10 cm (NIG 76 49).

- Finally, the formations belonging to groups "a" and "b" of Fig. 62 and group "c" of Fig. 63. These are the hollows, substrate and front side base of Termit Kaoboul ripple marks (NIG 76 39 c and d and 41 c) and a sample taken at a depth of 20 cm in a wave of the Fachi Bilma erg.

In summary, the best sorted material is that which results /267
from current deposits: the reactivation silks of the Fachi Bilma erg and the material deposited along the southern most current which crosses Lake Chad. In both cases the effectiveness of the winds is small, on the one hand because effective winds are rare since the region is now experiencing a wet period, and on the other hand because on the path of the harmattan Lake Chad acts a

as an obstacle or brake and reduces the effectiveness of the wind.

The fineness of the material and the fact that it is well sorted downwind from Lake Chad makes this region particularly vulnerable to reactivation, and thus the area is to be worked with caution.

The most heterogeneous material is that of the Fachi Bilma erg. Despite winnowing by the wind which it is subject to, the pavement of the erg remains rather poorly sorted.

Granulometric Studies of the Sand of Silks (NIG 76 42 and 47) and of Waves (NIG 76 45 and 48). Silks are the Reactivation Dunes of the fixed Fachi Bilma Erg in the Termit Region. /268

We find the following:

1. Very similar shapes of frequency curves and cumulative frequency curves. The frequency curves are unimodal and very straight, especially those for NIG samples 76 42 and 48. The first part of the NIG 76 45 curve is less straight and the end section of NIG 76 47 curve is less straight. This is reflected by the Qdphi values: NIG 76 42 = 0.04 (silk), NIG 76 45 = 0.07 (wave), NIG 76 47 = 0.09 (silk), NIG 76 48 = 0.05 (wave). Nevertheless, these four Qdphi values reflect good sorting of the material.

2. Basic differences concerning the size of the material. The mode of the silks is 160 µm and the mode of the waves is 630 and 800 µm.

3. Differences between the two silks and the two waves. The sand of silk NIG 76 42 is certainly a perfect example of material

which can be easily moved by the wind -- more than 60% of the material has a size $\leq$ 160 µm and no grains are greater than 250 µm. The sand of silk NIG 76 47 is less characteristic. Even if 30% of the material is $\leq$ 160 µm, 8% of the material ranges in size between 160 and 315 µm.

The wave NIG 76 45 consists 46% of sand with a grain size $\leq$ 630 µm, and 6% of this material is finer: $\leq$ 250 µm. Thus there exists a supply of predominantly coarse sand mixed with a supply of fine sand, less abundant but still there. By contrast, the sand of wave NIG 76 48 is exemplary: 58% of the material is $\geq$ 800 µm and there is no material < 4000µm. It is a pavement which is perfectly winnowed by the wind. Only the coarse material remains in place; the fine material is carried awaysby the eolian current downstream from the functional eolian unit.

Comparative Values of the Mode and Qdphi (Fig. 64) /270

In Fig. 64 we have assembled all of the samples taken from around Termit, Tanout and Maradi.

This graph has two advantages: (1) it enables a comparision of grain sizes and brings to light a progression in sizesfrom Termit to Maradi by considering the mode and Qdphi and (2) it quantifies the susceptibility of each sample to wind corrosion.

1. The General Decrease in Grain Size from Termit to Maradi

In the Termit region the material is distributed into six major modes, thus all the sizes are well represented. The batch represented the maximum range of particle sizes.

In the Tanout region the material is distributed into only three major modes, the coarsest sizes tending to disappear,

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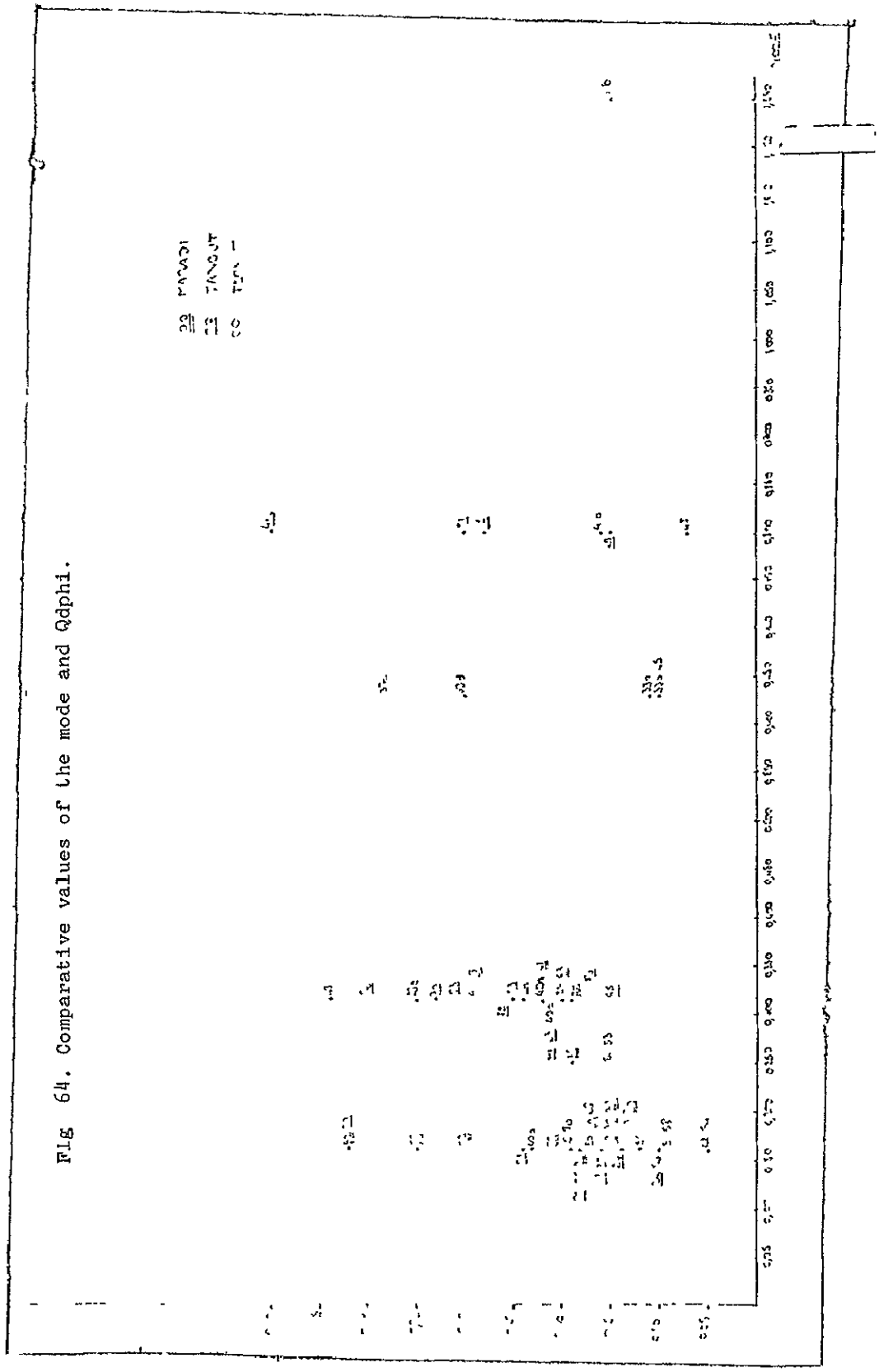

Fig 64. Comparative values of the mode and Qdphi.

| Mode in m | Termit region in % | Tanout region in % | Maradi region in % |
|---|---|---|---|
| 160 | 44,74 | 50,63 | 59,13 |
| 250 | 5,57 | not represented | 4,42 |
| 315 | 16,51 | 35,35 | 36,43 |
| 630 | 19,58 | not represented | not represented |
| 800 | 11,64 | 14,01 | not represented |
| 1250 | 2,96 | not represented | not represented |

except for a few ripple marks. A selection process has already taken place.

In the Maradi region the material again breaks down into three modes, but smaller than at Tanout. The coarse sizes have completely disappeared and the selection process is continuing.

The smaples with a mode greater than 315 m, whether from Tanout or Termit, come from ripple marks and thus correspond to grains forming a pavement, organized into wind ripples after being displaced by rolling.

Maximum sorting of the sand is found in the following places:

1. In the Termit region the reactivation silks (NIG 76 42 and 47) the dunes in the Chillia Dillia (NIG 76 51) and the sands downwind from Lake Chad (NIG 76 55, 56, 57, 58). /271

2. In the Tanout region, the nebkas (NIG 76 78 and 80), the currently mobile sands (NIG 76 26, 27, 28 and 76) and from material sampled at at depth of 10 cm in a megaripple planted with millet (NIG 76 75).

3. In the Maradi region, the reactivation sand (NIG 76 65),

a nebka (NIG 76 72) and sandy knolls (NIG 76 69, 70 and 73).

## 2. Quantification of Susceptibility to Wind Erosion

The samples with a small mode (160 µm) and small Qdphi (homometric) are the most moveable by the wind. They can easily be inventoried:

1. In the Têrmit region, the reactivation silks (NIG 76 42 and 47), a formation at the base of a cave-in slope (NIG 76 50), a dune in the Chillia Dillia (NIG 76 51), andactive dune of the Tal (NIG 76 52), the sands deposited downwind from Lake Chad (NIG 76 55, 56, 57 and 58) and the slope of a nebka (NIH 76 40 b).

2. In the Tanout region, the currently mobile sands (NIG 76 26, 27, 28 and 76), the nebkas (NIG 76 78 and 80), the samples taken at the top (NIG 76 86), at a depth of 10 cm (NIG 76 91) and at a depth of 20 cm (NIG 76 25) in the separate dunes.

3. In the Maradi region, the material at the bottom of a well (NIG 76 20), a sample taken from a depth of 1mm 20 cm in a dune of the Maradi goulbi (NIG 76 66), sandy knolls,(NIG 76 69, 70, 71 and 73) and a nebka (NIG 76 72).

Adding up the weights of the grains measuring 160 µm of the samples listed above we obtain the following:

| | Absolute weight in grams | Relative weight with respect to the total weight of material sampled, in % |
|---|---|---|
| Termit region | 430.78 | 15.38 |
| Tanout region | 310.55 | 13.50 |
| Maradi region | 214.80 | 13.42 |

Roundness Coefficient Plotted Against Grain Size (Fig. 65, 66 and 67) /272

In the Termit sector the roundness coefficient increases in proportion with the increase in grain size up to a limit of 630 μm and then it decreases. However there is one exception: the pavement of the giant waves of the Fachi Bilma erg (NIG 76 48) whose roundness coefficient at a grain size of 800 μm is 248.

In the Tanout sector the roundness coefficient increases in proportion with the increase in the size of the grains. But the threshold has dropped to 315 μm. Thus, this indicates that the grains transported by the wind up to Tānoût are smaller than those at Tērmit.

In the Maradi sector it seems that the roundness coefficient increases up to a threshold size of 250 μm. But the large drop which occurs at a size of 200 μm and the small number of data for the 250 m size may allow the threshold to be located at 1 160 μm.

Thus the decrease in the size of the grains transported by the wind as the distance covered increases is confirmed. Termit, Tanout and Maradi are located along the same current of eolian sand transport. Upstream, at Tērmit, just at the start of the Sahel, large allochthonous grains have been carried in. At Tanout, in the interior of the existing Sahel, there are no coarse allochthonous grains. Only medium-sized grains have been carried in. At Maradi, in the southern portion of the existing Sahel, large and medium-sized allochthonous grains are rare; only small grains which could be transported by the wind up to that point have a high roundness coefficient.

All of this data is represented quantitatively in the following table:

| Size of particles in μm | Mean of roundness coefficients | | | |
|---|---|---|---|---|
| | Termit | Tanout | Karadi | Niamey |
| 125 | 146,6 | | 148 | 59 |
| 160 | 151,6 | 159,3 | 188,4 | 139,9 |
| 200 | 163,1 | 170 | 175 | 155,2 |
| 250 | 169,5 | 168 | 192 | 159 |
| 315 | 178,5 | 186,5 | 184,4 | 174,5 |
| 400 | | 185,5 | | 153 |
| 500 | 224,5 | 176 | 159 | 171,6 |
| 630 | 238,6 | | | 163 |
| 800 | 191,? | 157 | | 157 |
| 1250 | 117 | | | |

Laboratory analysis of the sandy material collected in 1977 /273 in the experimental unit explicitly confirms the results provided by the sample collected at the time of the first trip: the curves are trimodal. The main mode is situated at 315 μm and the two other secondary modes are at 160 μm and 630 μm. This makes explicit the dual origin of this material: eolian and fluviatile, with autochtonous pick-up of the decomposition material of the Cretaceous sandstone substrate, or the bringing in of fluviatile material by rivers originating in the southern Niger Republic.

Morphoscopic examination of the fine material (160 μm) reveals the following:

1. Subangular, sometimes angular or, in rare cases rounded, shiny, pitted grains probably resulting from eolian transport no longer in action at the present time.

2. A medium-sized material (135 μm) which consists of two different supplies of sand: one of angular, shiny-pitted or pitted

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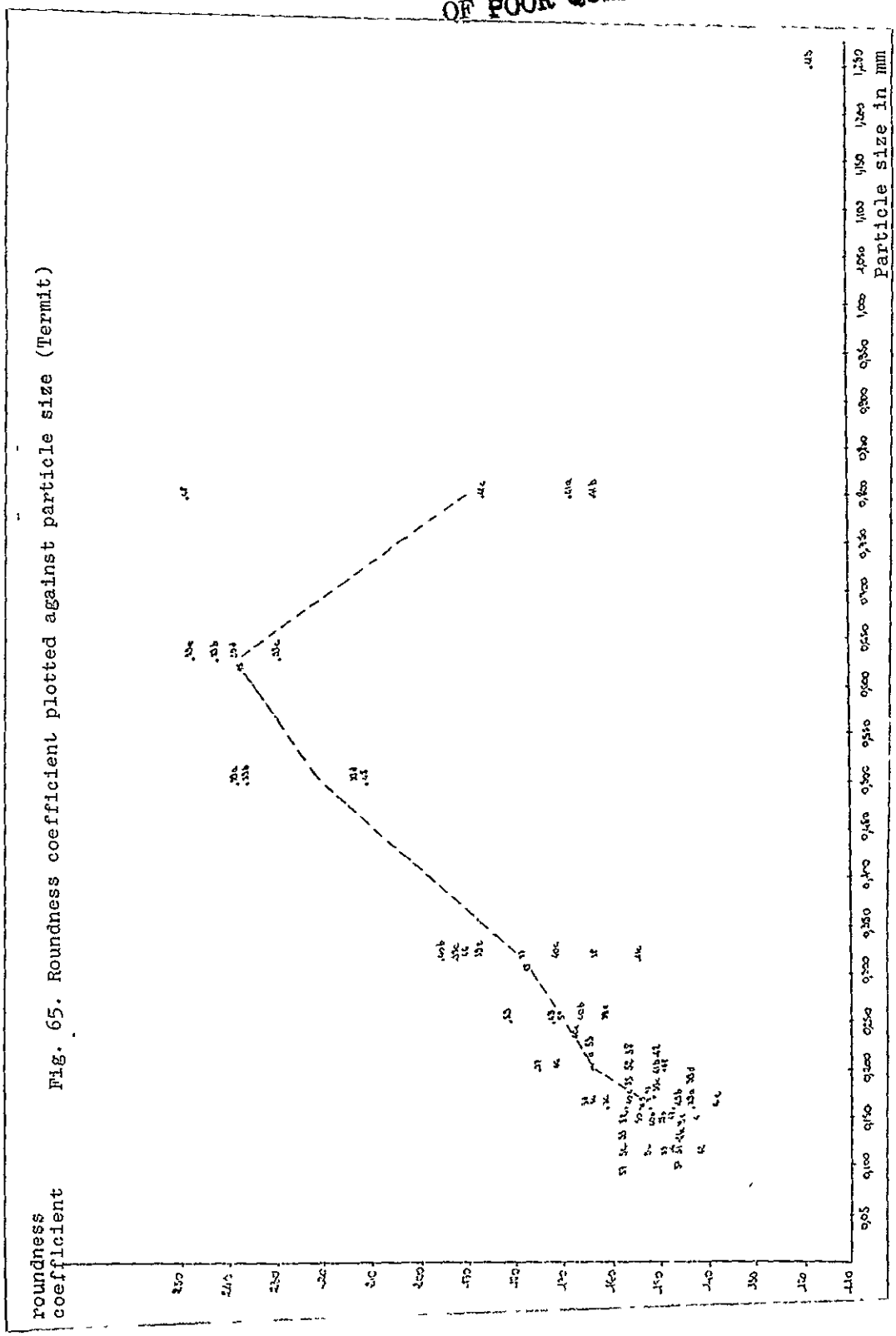



Fig. 65. Roundness coefficient plotted against particle size (Termit)

Fig. 66. Roundness coefficient plotted against particle size (Tanout).

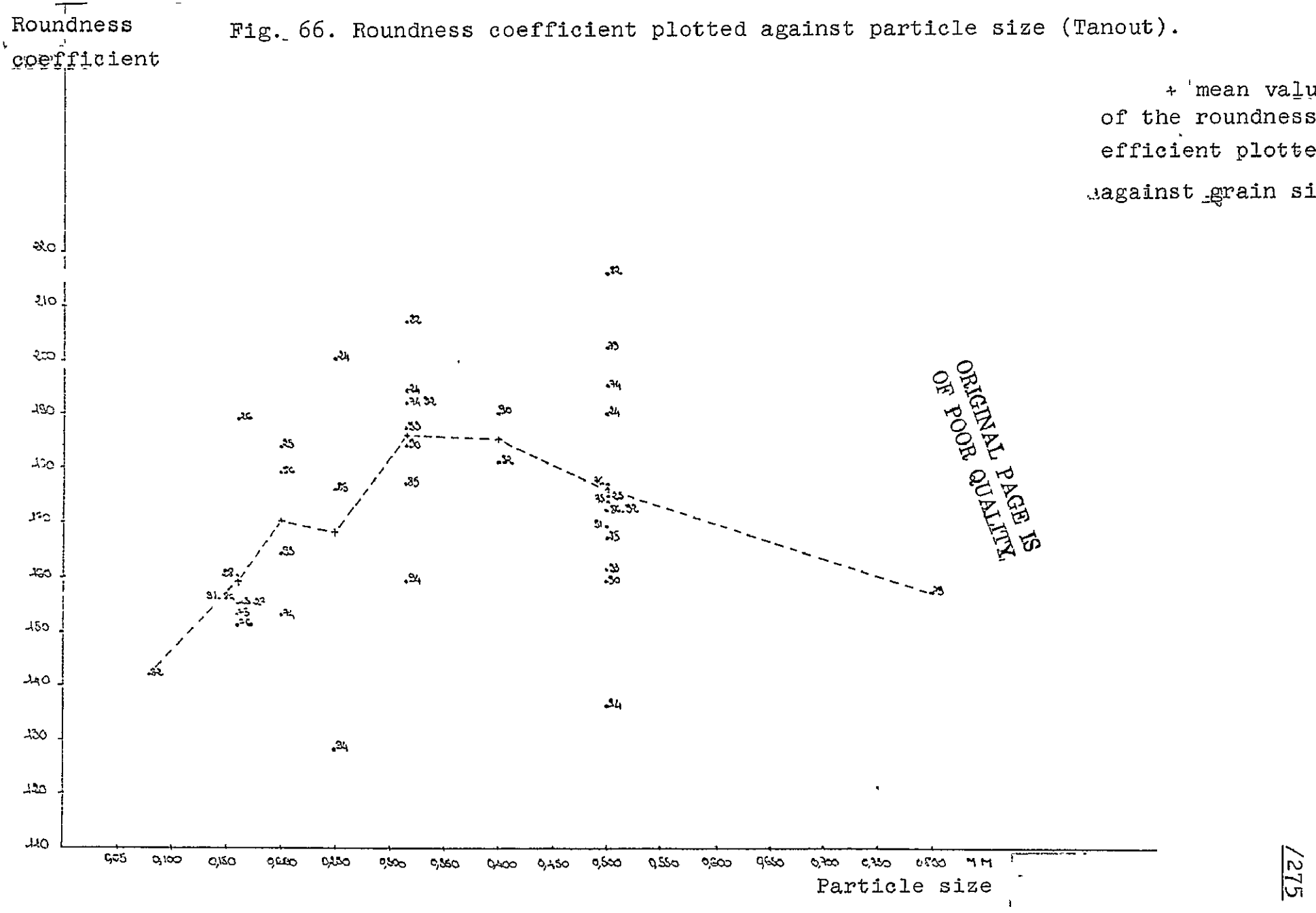
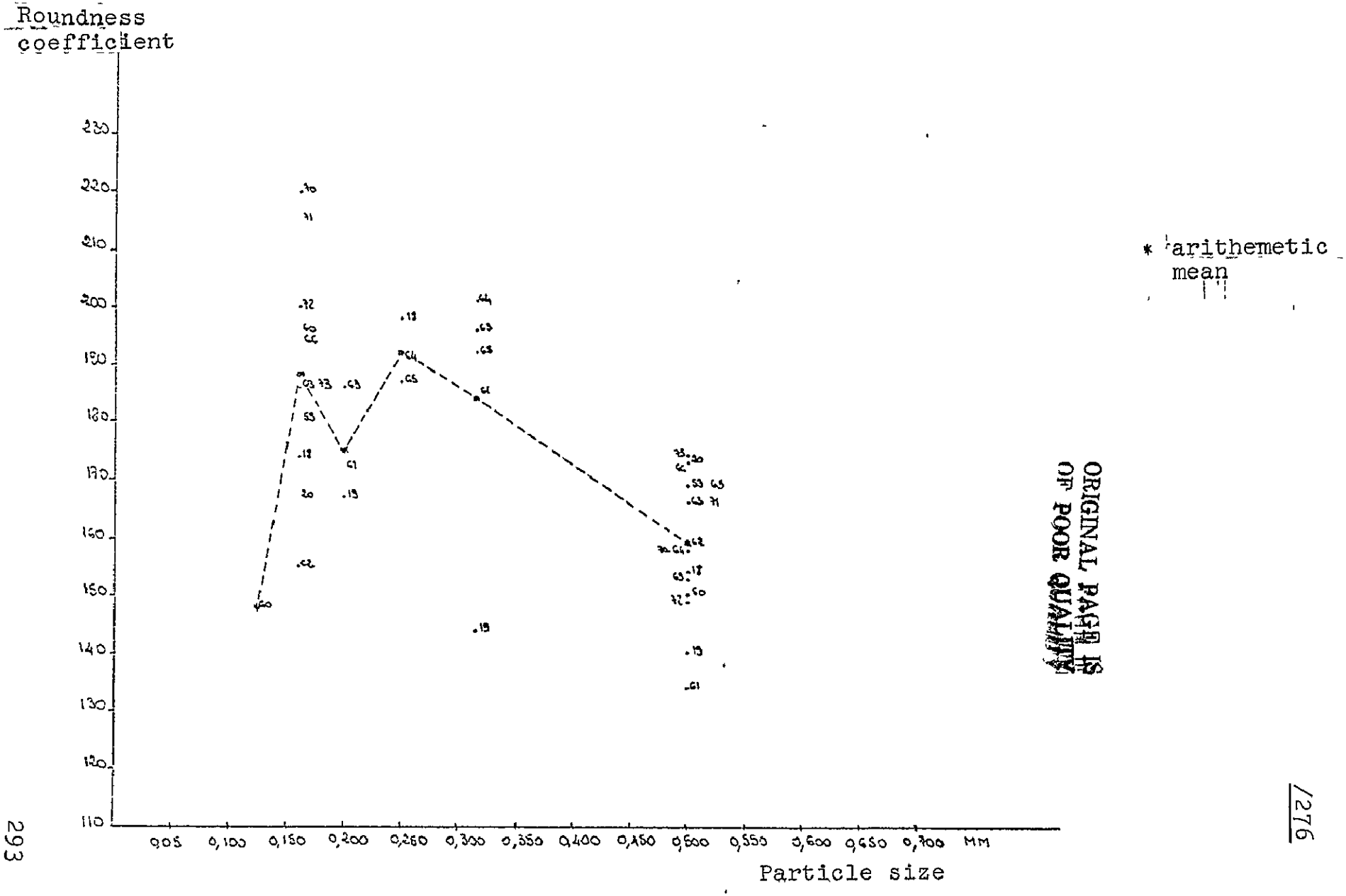


Fig. 67. Roundness coefficient plotted against particle size (Maradi).

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grains, the other of rounded to non-shiny round grains. The latter, undoubtedly eolian, predominates.

3. Coarse material (> 500 µm) which also includes two supplies of sand: one of angular, shiny grains, the other of attractive round, non-shiny grains. But at this size the angular grains are predominate.

Samples Taken between Niamey and Mâdaoua /278

From the Qdphi value graph an initial overall impression emerges, in comparison with the samples taken further to the east, that the average of the Qdphi values is greater, hence the samples are not as well sorted (Fig. 68).

Three groups stand out:

1. Qdphi < 0.15 for existing redeposition sands and coarse ripple mark sands (NIG 776 09 and 15).

2. 0.15 < Qdphi < 0.25 for sands from clastic dunes (NIG 76 02, 04, 10, 11, 12, 13, and 16), for sands taken from these dunes at a depth of 10 cm (NIG 76 08) and ataa depth of 50 cm (NIG 76 03), for existing redeposition sands (NIG 76 06 and 07) and for nebka sands (NIG 76 14 and 17). In the middle of this group one can distinguish Qdphi values < 0.19 which, above all, are for sands from clastic dunes and Qdphi values > 0.19 which, above all, are for existing redeposition sands or nebka sands.

3. Qdphi values > 0.25 for sands from slope bases resulting from washing during the late continental period (NIG 76 05).

Paradoxically, the second graph, which plots the median against the mode, does not show any large differences between the

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Fig. 68. Qdphi Values
(Niamey to Madaoua)

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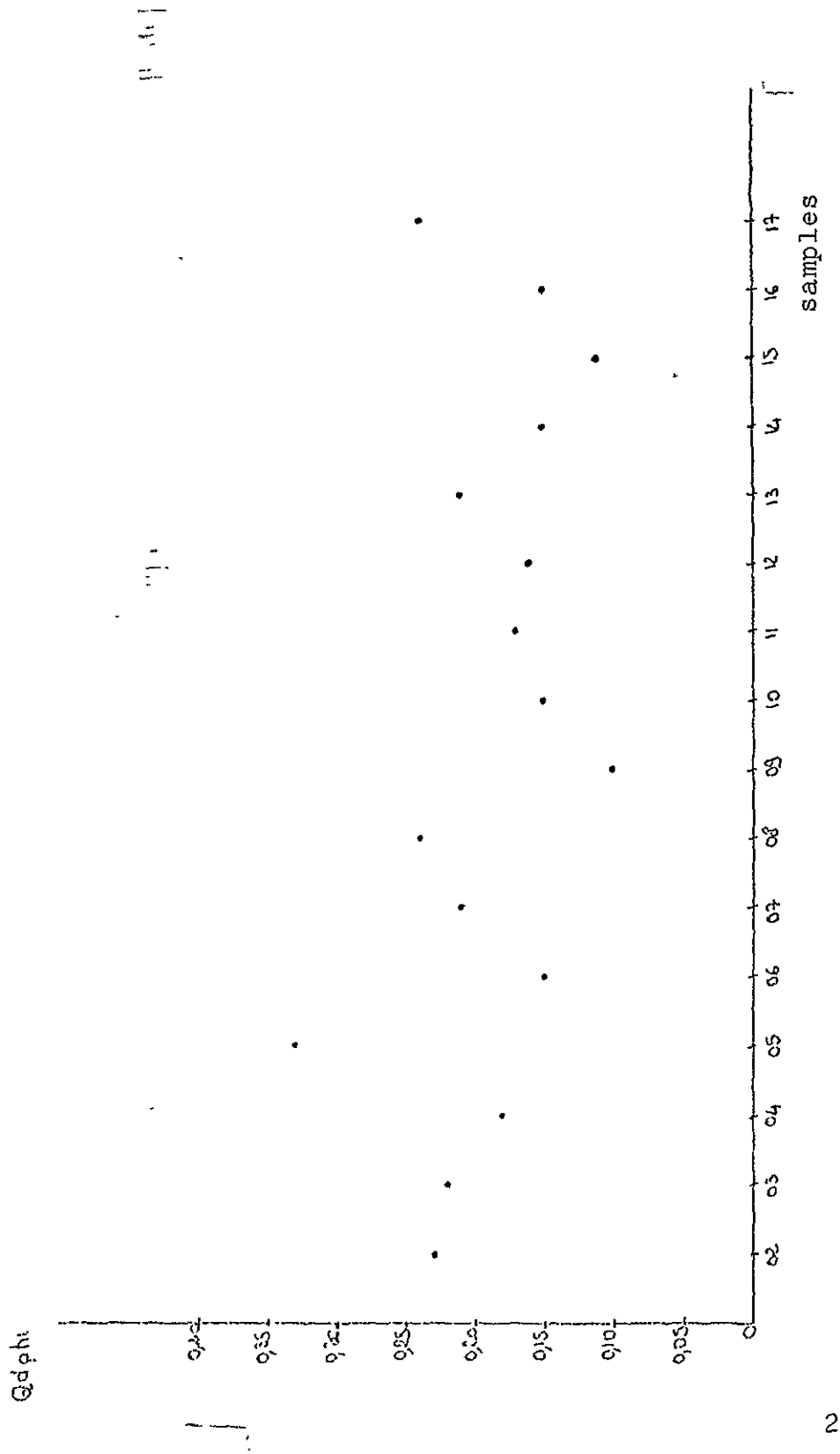

Fig. 69. Median vs. Mode (Niamey to Madaoua). /280

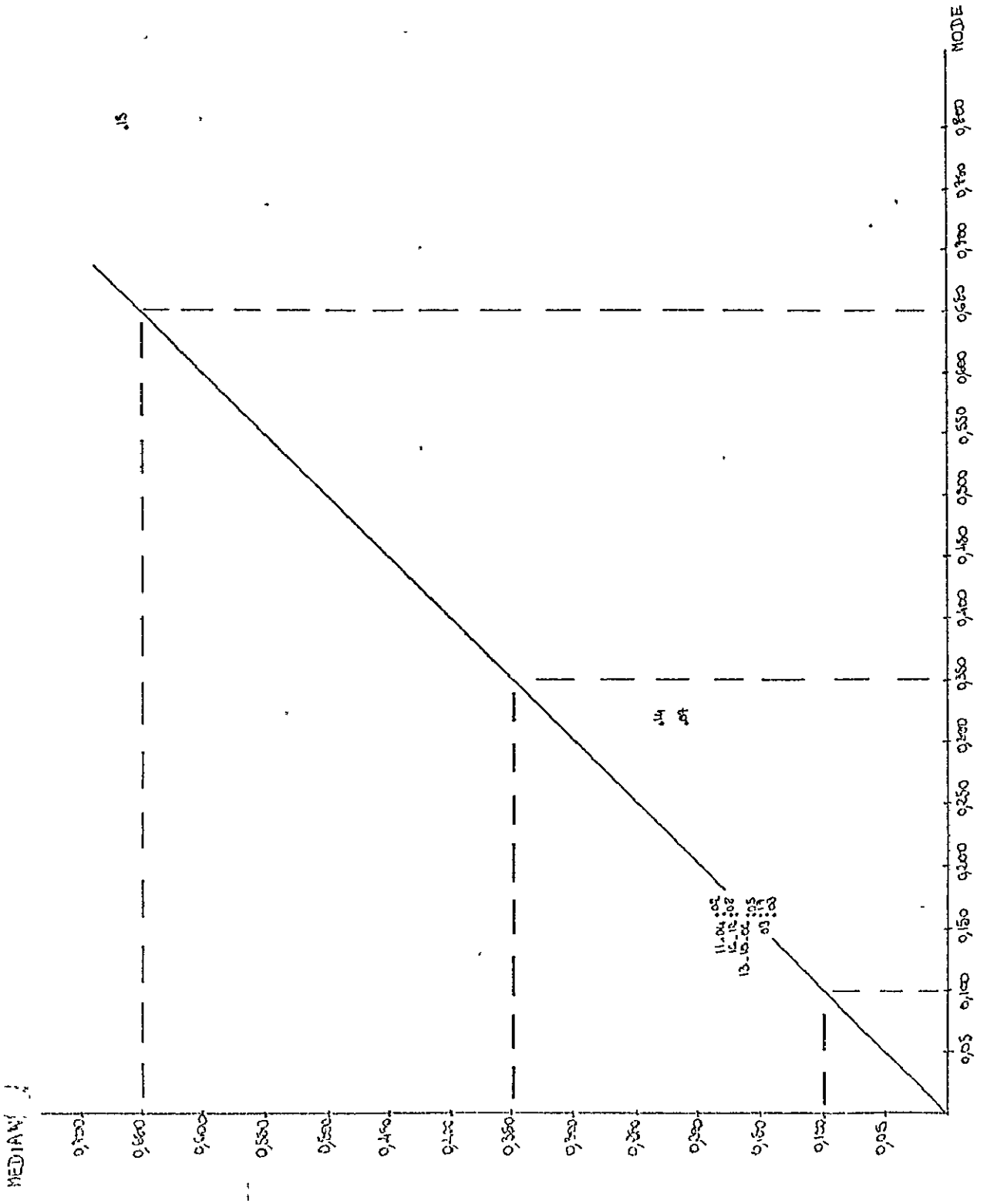

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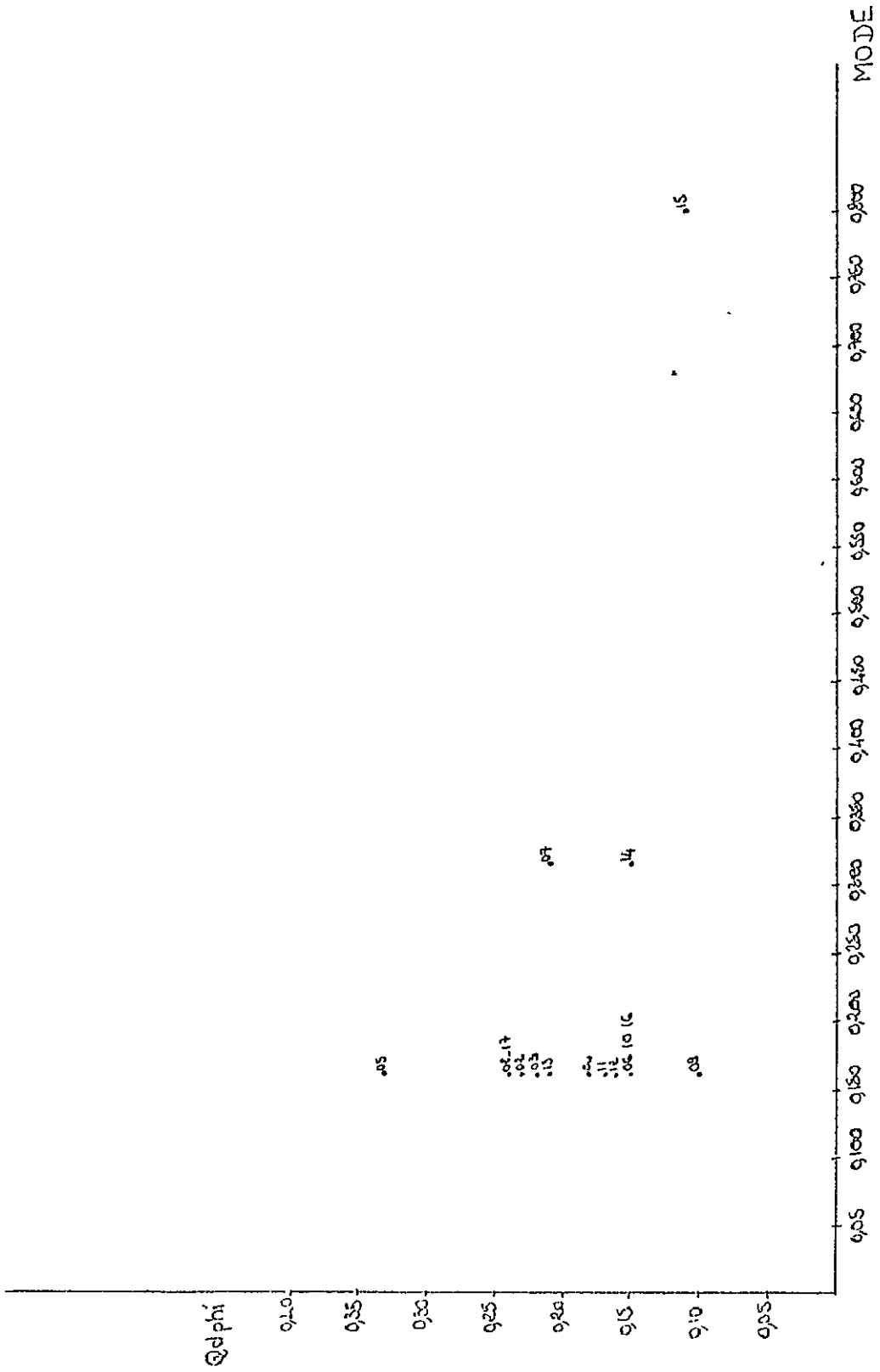
Fig. 70. Qdphi vs. Mode (Niamey tocMadaoua). /281



two values (Fig. 69). This is explained by the frequency of the 160 µm mode, for it is known that small modes have a small mode-median difference; also by the shape of the granulometric curves with gently sloping plateaus bounded by straighter segments, which is reflected by large differences between the Qdphi and Hé [expansion unknown] values.

The third graphs in which the Qdphi is plotted against the mode enables us to evaluate the stability of the sands in this region (Fig. 70). We have the following:

| Mode in µm | Percentage |
|---|---|
| 160 | 77.6 |
| 315 | 13.5 |
| 800 | 9.2 |

Four different Qdphi groups correspond to the 160 µm mode:

1. The existing redeposition sand on a covered dune (NIG 76 09) is very unstable with its low Qdphi value.

2. The sands of hardened dunes (NIG 76 02 and 13), of samples taken at depths of 10 and 50 cm (NIH 76 03 and 08) and the sands of nebkas (NIG 76 17) are less well sorted and thus more stable than the sands of clastic dunes (NIG 76 04, 10, 11, 12 and 16). /279

3. The sands of slope bases resulting from washing during the late continental period are more stable because theyeare more heterogeneous.

4. Adding the weights of the 160 µm grains of existing redeposition sands and of clastic dunes which can be most easily moved by eolian transport (NIG 76 04, 06, 09, 10, 11, 12 and 16) we obtain the following:

| Absolute weight in grams | Relative weight with respect to the total weight of the material sampled, in % |
|---|---|
| 210.58 | 13.01 |

Roundness Coefficient Vs. Grain Size for Samples Collected between Niamey and Madaoua /283

The first general tendency is the large difference of different coefficinets with respect to the mean, i.e. the diversity of coefficients. Because of this one can no longer distinguish an increase in the roundness coefficient proportional to the grain size as was done in the case of the eastern current. However, an increase is observed for the means up to the grain size threshold of 315 µm.

| Particle size | 160 µm | 200 µm | 315 µm | 500 µm |
|---|---|---|---|---|
| Roundness coefficient | 139.9 | 155.2 | 174.5 | 171.6 |

These observations are reinforced by isolated samples whose coefficients follow the same tendencies, but only one of which has this mode.

| Particle size | 125 µm | 250 µm | 400 µm | 630 µm | 800 µm |
|---|---|---|---|---|---|
| Roundness coefficient | 59 | 159 | 153 | 163 | 157 |

The second general tendency is the small roundness coefficient for all of the grain sizes relative to the roundness coefficient of samples for the eastern current.

These two observations combine and could be explained by the same cause: these samples do not pertain to a broad eolian current like that we encountered in the east. The latter extends

Fig. 71. Roundness Coefficient vs. Particle Size (Niamey to Madaoua)

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to the eastern foot of the Ader Doutchi. In this western region the origin of the sand is different. Its low roundness coefficient indicates that it has not experienced eolian transport over long distances but only over local distances.

This explains the first observation: the differences between the samples stems from the fact that since all of the initial material is not very rounded, a simple shift or change in location (change is surface position or depth) can cause a change in the surface state of the particles, even a small change, which will allow it to be easily differentiated from another sample which has remained non-rounded.

But what is the origin of the sand in the region from Niamey to Madaoua? Some of the material could have been brought by the Niger River. This river builds up material from the Gourma region and the interior delta where we are acquainted with the existence of organized sandy accumulations and of paleodeflated regions -- proof of the existence of an eolian current. Another part of the material could have been transported by the Dallol Bosso, an extension of the Azaouak, which, when it was functional, could have deposited here material from the Talak region where we also found organized accumulations of sand (cf. wind current map). /284

What are the proportions of these two inputs? wWe cannot yet say, but this dual origin is the most likely. The sand could then have been redeposited locally by the winds.

Supplemental Note /286

The map entitled "Direction of the Annual Average Resultant Wind Based on Traces of Erosion and the Axis of Nebkas," shows the direction of erosion (eolian wear) and of the axis of nebkas

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(sandy arrows behind an obstacle), measured at random during our trips over the terrain. We believed that they might be a good indicator of the annual resultant wind.

Comparing this map, which was obtained by a process equivalent to "randomization," with the map of prevailing wind directions for the Niger Republic based on the period from 1965 to 1975 (Fig. 18) confirms our hypothesis and the reliability of the method. There is a completely reassuring similarity between the two processes, one being pure geomorphological and the other based on climate. Thus erosion stria and the axis of nebkas can indeed be used as wind direction indicators.

This is an important result because in the absence of anemometric data it allows planners to position all types of protection against wind erosion thanks to easy to use geomorphic criteria, and moreover this can be done on the basis of ground observations.

The map which we have drawn up on the basis of these criteria also shows the obstacle effect, skirting effect and spreading out effect of eolian currents south of the Air.

Conclusion /287

The experimental ecological unit includes the following:

1. Monticular dunes with:

a) a mobile sandy covering which is essential to the variety of millet currently being planted within the boundaries of the unit.

b) sandy material with a large variety of grain sizes below the mobile sandy covering. This material is more or less clastic or solidified. When it crops out as a result of deflation it is not conducive to the cultivation of millet.

2. Regions of tabkis or temporary ponds, more abundant in fine particles, in particular muds, an often supported by a layer of lateritic gravels.

a) The monticular structures are, above all, the site of small-scale eolian shifts.

b) The tabkis are the site of water activity: light to moderate runoff.

c) Along with "a" and "b" there is a third mechanism: glazing phenomena in connection with termites. The role of termites is important since they help in the assimilation of millet and sorghum straw, but they concentrate the organic residues and the finest materials by taking them from the soil as a whole.

The slight changes introduced in the relatively simple morphology have to do with soil formation, which in turn is governed by the topography. The hydromorphic pseudogley soils pertain to the interdunal valleys, and the soils which have been slightly solidified as a result of a type of tropical, ferruginous soil formation -- impoverished or leeched soils -- pertain to the tops and slopes of knolls.

Because of their defficiency in organic matter,[1] their relative lack of structure with respect to monticular dunes and the poor water dynamics with respect to certain tabkis and interdunal valleys, all of these soils are unstable: some with respect to wind dynamics, and others with respect to water dynamics.

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1. In the chalky Champagne region Renard has shown that the percentage of organic matter had to be maintained at 4%. Below this level wind and water erosion occur. In Champagne, nearly all of the beetroot greens and straw and corn stalks, after they have been ground up are burried in the ground.

Two facts should be noted: /288

1. Because of the increasing density of population the occupation of ground in the experimental unit is nearly at its maximum. Most of the surface area is being used for growing cereal grains, especially millet and sorghum, and to a slightly lesser extent corn and "hiebe." The only areas not being cultivated are those which have undergone "glazing," and the temporary ponds and endoreic basins like tabkis which are richer in muds and perhaps in clay (examined in the laboratory). These last areas are reserved for pasturing; the population density no longer allows ground to be left fallow. Thus if one wants to continue breeding animals the remaining pasture land cannot be converted into cultivated ground.

2. In spite of the impossibility of increasing the cultivated areas and in spite of the decrease in yields experienced by the farmers, nevertheless it is necessary to nourish an ever increasing population. One way to ease the situation would be to use plowing. In particular, the fertilizers should be organic in order to help bind the soil. Millet tolèrates poor soils.

The selection of natural fertilizer sites is based on the degree of structural defficinecy of the soils around the villages.

The problem of working the soil when using plows:

Deep working of the soil is preferable as soon as possible after the harvest because:

1. Dirt clods can thus harden, allowing them to remain intact and making them less sensitive to deflation. This is not the case in a situation where the ground is sorked dry.

2. The turning under of stubble is also done before the

termites can get to it who concentrate organic matter and fine mineral salts in their nests. On this point, however, opinions are divided because it has not been shown that the burying of stubble protects it from the termites.

3 33 Trampling of the ground by animals eating stubble is avoided.

Difficulties encountered after the stubble has been turned under:

1. In Muslim countries the stubble is the primary material used in the construction of the walls and roofs of huts and field enclosures. There are no quarries or rocks to supply material for construction and cement is rare and costly.

2. During the dry season the stuble helps fill the gap to /289
feed the animals. When the natives find that the land around their villages is breaking down too much, i.e. that eolian reactivation is becoming too intense, they call in the herds. There are manure contracts between animal raisers and farmers, the latter allowing the herds to eat the stubble. The peasant, faced with the trampling-plus-natural-manure option, chooses the natural manure.

N.B.: In 1976 the rainy season had abundant rains which lasted into October and broke the record set in 1932. This was followed by a distinct decrease in eolian phenomena such as "pick-up, transport and deposit in the form of nebkas." Only saltation seems to persist.

The Mobile Sandy Covering

The mobile sandy covering is extremely important for the millet. Actually the seeds are placed at the base of this

covering. In addition, because of its lack of structure it helps to better preserve the moisture.

If the branches of the wind reach the solidified horizon the soil becomes less favorable for millet and the natives are forced to let the ground lie fallow while waiting for the mobile sandy covering to form again.

The samples taken by us from the surface and at low depth in the experimental square and those taken by the soil scientist C. Feau from holes are in perfect agreement. On the whole they all show two principal modes modes: 160 µm and 315 µm. Sometimes a third mode appears, 100 µm, but it is much less pronounced. Analysis of these samples leads to the following fundamental conclusion: if one compares the sample taken from the surface to that taken from a low depth, one finds either an increase in the mode to 315 µm or a gradual increase from the 315 µm mode to a 400 µm mode. This indicates a relative enrichment of the surface with material $\geq$ 315 µm and proves irrefutably that the finest material $\leq$ 315 µm has been carried away. Thus the 315 µm mode is a threshold with respect to existing eolian transport, i.e. the reactivation of the sandy mantle. The granulometric curves show that the material $\leq$ 315 µm can reach and exceed 80%. Examination of material from nebkas -- small sandy arrows which are formed at certain seasons downwind from an obstacle (a stalk of millet, for example) -- produces the same findings.

The existence in sandy sediments of a supply of coarse grains $\geq$ 500 µm consisting in part of round, dull grains of eolian origin is evidence of paleoclimatic winds, which were stronger than existing winds and carried in some of the sandy mantle in the experimental unit. (With respect to this preceding period we are now in a wet phase.) /290

However, the abundance of fine particles ($\leq$ 315 µm), in this material means that the experimental unit is everywhere vulnerable to eolian mechanisms. Swept by the wind, the sand can be deposited on the top of the highest monticular dunes, trapped by the hedges which rise up or yet again by the villages which create obstable effects. (This explains the striking fact of the freshness, homometry and the quality of sand in the villages; during each dry season it is actually renewed by eolian transport.)

As we have already said, vulnerability to water erosion represents a relatively small, non-threatening danger. The only regions affected by runoff are located around endorheic basins and ponds.

The 1:20,000 scale map of the experimental unit that we have drawn up shows how much the entire experimental unit has become unstable. This is still very difficult to estimate at the present time, however, it is a real phenomenon. This map also shows the overwhelming extent of grounds occupied by crops and the small amount of area left fallow. The farmers are drawing attention to a drop in production which they attribute to the lack of fallow ground.

Nearly everywhere there are signs of reactivation of the sandy mantle, as is especially brought to light by the study of the aerial photographs obtianed during the special mission. These signs are less prominent in the rings of ground fertilized with animal manure around the villages. These areas are still holding firm, but their existnce constitutes a warning bell for future planners, since improper management could cause irreversible traumas.

Ablation: Removal of material. Ablation especially effects loose rocks. It is due to various erosion agents.

Agregate: Basic element of the structure of a soil.

Trade winds: Regular winds from the east, sometimes several thousand meters across, blowing from northeast to southwest in the northern hemisphere and from southeast to northwest in the southern hemisphere on the equatorial flank of subtropical cells of high pressure. These winds affect the intertropical zones on both sides of the equator.

Allochthonous (sand): Originating from a region other than that in which it is found.

Alluviums: Erosion products of soils and rocks sorted by water and redeposited in preferential locations (e.g. alluvial plane).

Clay: Particle whose diameter is between zero and 2 microns.

Autochtonous (sand): Originating in the region in which it is found.

Badlands: Residual form of a slope which has been eroded into very dense gulleys allowing only divides to exist which are very narrow or reduced to a single line.

Barchan: Crescent-shaped sandy eolian structure, with a convex side pointing towards the wind, an active crest, an asymmetric transverse profile, a gentle slope towards the wind and s steep downwind slope.

River basin: All of the rain receiving basins of tributary valleys contributing to the formation of a river at a given point.

Equilibrium amount: Number of heads of livestock which can be fed on a pasture in balance with the actual potentiality of the environment without damaging the environment.

Colluviums: Erosion products of rocks and soils transported without sorting towards the base of slopes.

Corrasion: Effect of eolian sculpturing.

Covering of vegetation: Percentage of the surface of the ground covered by the vertical growth of the above ground portions of plants.

Mobile sandy covering: Layer of surface sand subjected to /293
eolian shifts without any pedological structure.

Crust: Glazing film.

Deflation: Eolian sweeping. Eolian form of ablation.

Eolian deposit: Particles deposited by the wind.

Desert: Continental region whose landscape reflects the dominance of mineral matter over vegetal matter.

Desertification: "Extension of desert landscapes to zones where they should not exist under natural conditions and resulting from the increased agressiveness of erosion phenomena, in particular eolian erosion" (H.N. le Houérou, 1968), or extension in space or intensification of desert conditions or conditions acknowledged as such.

Barchan Dihedron: Bulge of sand with a downwind gap convex to the wind.

Djebel: Arabic term for mountains and hills.

Draa: Complex chain of dunes separated from neighboring chains by valleys called "gassi" when the floor is rocky and "feidj" when it is covered with sand.

Dunes: Sandy structures with an active crest.

Structures

- monticular: a relief of small bulges of sand with a convex shape separated by rounded valleys arranged in "semis" often laid out in a regular network within the same region.

- hilly: slightly separate or coalescent hills of sand. In a Sahelian environment or any other climatic environment with a covering of vegation these result ofrom the degradation of barchan type dunes. When they are degraded barchans often produce perfectly rounded conical hills.

- barchans and parabolas: isolated sandy structures, sometimes coalescent but always clearly individualized, crescent-shaped with the convex side pointing to the wind when they are barchans and with the concave side pointing upwind when they are parabolas.

- set of periodic eolian sandy structures: regular alternation of ripples and valleys (extended interdunal depression, sometimes the site of ponds) following a preferential direction, sometimes longitudinal, sometimes transverse.

- transverse wave: elongated sandy eolian structure, /294
rectilinear to slightly sinuous, with a convex profile, sometimes flat on top, most often arranged in a periodic whole and with a direction roughly perpendicular to the prevailing effective wind.

- longitudinal wave: eolian structure describing a straight line, with a convex profile, most often arranged in a periodic whole, with a direction roughly in line with that of the prevailing effective wind.

- checkered wave: a pattern resulting from the intersection or superposition of the two above types of waves.

Covered dune: Sandy structure with an open or dense blanket of vegetation.

Fixed dune: Eolian structure covered with a pavement of coarse sandy particles which are sufficiently large so as not to be carried away by existing winds.

Ecosystem: "Unit of biological organization consisting of allthe organisms present in a given area and interacting with the physical environment," (Odum, 1969).

Elb: Variety of silks issuing from barchans.

Endoreic/endorheism: This is said of a river which does not have or no longer has an outlet into the sea or into a larger river.

Distribution (area of): Area of alluviation resulting from a drop in the flow of water or an upset in the hydrographic system.

Eradication: Natural or human action consiting of uprooting a plant or cutting it off below the ground.

Erg: (Arabic term): synonomous with edeyen in Libya, goz in thessouthern Sahara, koum in cnetral Asia, nafud in Arabia. On a sandy substrate, whether or not ocovered with a deflation pavement, it signifies an extensive concentration of sandy structures which may or may not be homogeneous in shape, joined or juxtaposed, depending on the various degrees of organization at the limit without any apparent organization.

Potential evapotranspiration (PET): Amount of water taken by evaporation from the soil and transpiration of a covering of vegetation, the latter not being limited by the availability of water in the soil. This is expressed in mm per unit time.

Real evaporation:(RET): Loss of water from the soil and /295
from a covering of vegetation under natural conditions. It is less than or equal to the PET.

Instability of the Sahel environment: Potential vulnerability of the natural environment with respect to reactivation of the sandy mantles. It may be due to the potential vulnerability of the natural environment, to the vulnerability caused by an increase in external dynamic mechanisms due to climatic fluctuations and to the instability brought on by man made pressures.

Ghourd: Predominant pyramidal dune from which silks radiate in any direction whatsoever. The ghourds can be lined up and when they coalesce they can form a chain of ghourds. When the pyramids change or wear down they become draa-type chains.

Glazing: A bright surface film consisting of sand, mud and clay or mud or clay alone formed by the impact of rain drops of the effect of light runoff. Glazing increases the surface

impermeability of the formation.

Harmattan: Continental trade wind, dry winter wind.

Impluvium: Area receiving the precipitation drained towards á given point.(drainage basin).

Underflow: Flow from a wadi within its alluviums. This follows after the surface flow has run dry.

Isohyet: Theoretical line connecting the meteorological stations with equal precipitation readings (expressed in mm).

Fallow: Resting state of a previously cultivated pièce of ground.

Fine Limon: Particle with a diameter ranging between 2 and 20 microns.

Coarse limon or very fine sand: Particle with a diameter ranging between 20 and 50 microns.

Sandy mantle: Layer of sand which "fossilizes" a loose or coherent rocky substrate.

Saltation mantle: Layer of sand moved by an effective wind.

Protected area: Area in which all human activity is prohibited or at least controled for a certain period.

Surface relief: Result of the evolution of the forms of a /296
landscape the relief of which expresses the structure. The two are a momentaneous expression of a dynamic situation: external for the surface relief and internal for the relief. The surface

relief is a temporary state of equilibrium due to the action on the internal relief by the climate and mechanisms which derive from it.

Morphogenesis or glyptogenesis: Sequence of phenomena which form the landscapes.

Morphology: Science which studies morphogenetic mechanisms.

Morphoscopy: Study of the shape and surface conditions of grains of sand.

Monsoon: Change in the direction of the zonal flow of trade winds when they cross the equator.

Sandy "tablecloth": Thin, continuous sandy covering.

Nebka, micronebka: Accumulation of sand downwind from a plant. The plant can rise up when the accumulation increases. Nebkas can reach several meters in height and can be 10-20 meters in diameter.

Stationary waves: Produced by the superposition of processions of infrasonic waves such that a periodic phenomenon results involving an alternation of nodes where the oscillations are in opposite pahse and the movement minimum, and involving bulges, when the waves are in phase, with maximum displacement.

Giant uniform wave: Linear sandy structure, with a convex transverse profile, sometimes covered with a pavement, and made uniform by eolian deflation and winnowing.

Eolian pavement: Coarse particles left behind by deflation which covereeolian sandy structures. These particles are too large to be moved by the force of existing effective winds.

Pedogenesis: All the biological and physicochemical transformations undergone by a rock during its conversion into soil.

Impact film: Highly impermeable film formed on the surface of a loose soil by the impact of water drops.

Solidification: Slight aggregation caused by an abundance of oxide and/or clay.

Gullying: Rain erosion due to concentrated runoff.

Reg: Eolian deflation pavement. /297

Reactivation: Phenomenon of moving a moveable material, formerly fixed by a blanket of vegetation or by a horizon enriched by organic matter or by a deflation pavement.

Ripple marks: Surface state of a sandy mantle with asymmetric ripples without an active crest. They have a gentle slope facing the wind and a steeper slope facing downwind. In the case of a ripple the main transport mechanism is creep or rolling.

Rose diagrams: Graphic representation of the frequency and velocity of winds according to their direction.

Diffuse runoff: Trickles of rain runoff which do not leave any linear traces of erosion on the ground.

Concentrated runoff: Rain runoff which causes ditches and gulleys.

Fine sand: Particle wiht a diameter ranging between 50 and 200 microns.

Coarse sand: Particle with a diameter ranging between 200 and 2000 microns.

Medium sand: PParticle with a diameter ranging between 200 and 630 microns.

Sahel (from the Arabic Sahil: border, bank, literal): In the southern Sahara forms the transition between the arid and sudanian zones.

Saltation: Displacement of sandy particles by leaps.

Vulnerability of the environment: Characterizes the degree of resistance of an environment to the degradation produced by human and animal activities. It is a function of biological and physiochemical factors of the environment as well as the intensity of human activities carried on in the environment.

Sif (saber in Arabic): Elongated dune, tapered towards its downstream end, with a triangular frontal section, the crest of which is sharp and in general describes an arc.

Silk: Overall a straight sandy range of dunes, more or less wavy in detail, due to the homogeneous juxtaposition of sifs along a single direction.

Soil structure: Arrangement of soil aggregates.

Over pasturing: Extensive use of a pasture resulting in its deterioration and sometimes the deterioration of the soil as a result of excessive reduction of the covering of vegetation.

Tabki: Temporary pond. /298

Soil texture: Proportion of soil particles classified according to size after destruction of the aggregates.

Impact slab: Surface slab of a soil hardened by the impact of water drops.

Truncation (truncated): Set of a soil which has been ablated.

Winnowing: Eolian action of sorting.

Wind: Movement of a body of air. Upwind: the face of a relief receiving the wind. Downwind: the face opposite that which receives the wind.

Prevailing wind: Direction of the most frequent and strongest windss

Efficient wind: Wind with a speed greater than 4 or 6 meters per second which can move sandy particles.

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