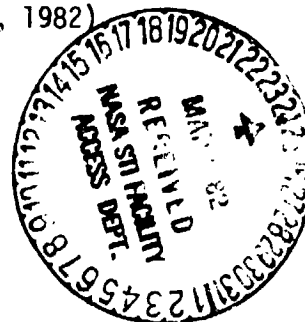# NASA CONTRACTOR
REPORT

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TERRESTRIAL COOLING AND SOLAR VARIABILITY

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16. Abstract

Observational evidence from surface temperature records is presented and discussed which suggests a significant cooling trend over the Northern Hemisphere from 1940 to the present. This cooling, about 0.5°C, has compensated for much of the warming that took place during the first 40 years of this century and has occurred primarily at the middle and high latitudes. The cooling trend for the Northern Hemisphere has been associated with an increase of the latitudinal gradient of temperature and the lapse rate, as predicted by climate models with decreased solar input and feedback mechanisms. Evidence has also been gathered to suggest that four of these 80- to 100-year cycles of global surface temperature fluctuation may have occurred, and in succession, from 1600 to the present.

Observations and interpretation of sunspot activity have been used to infer a direct thermal response of terrestrial temperature to solar variability on the time scale of the Gleissberg cycle (90 years, an amplitude of the 11-year cycles). Measurements at the Greenwich Observatory and the Kitt Peak National Observatory, as well as other supportive information and arguments, are presented to hypothesize a physical link between the sunspot activity and the solar parameter. On the time scale of the Gleissberg cycle, when the mean annual sunspot number exceeds 50, it is proposed that global cooling may be initiated due to the decreased insolation, and conversely for increased luminosity and warming.

Observations of sensible heat flux by stationary planetary waves and transient eddies, as well as general circulation modeling results of these processes, have also been examined from the viewpoint of the hypothesis of cooling due to reduced insolation. The westerlies appear to have shifted southward and to have strengthened during the recent cooling period, which allows for arguments of a preferred wave number for stationary waves due to mountain interaction. This type of interaction may give rise to preferred regions of heat flux as seen observationally, e.g., the warming in the far western regions of the United States and the sharp cooling in central and eastern regions.

17. Key Words (Suggested by Author(s)) Sunspot activity Solar-climatic relationships Solar cycle	18. Distribution Statement Unclassified — Unlimited *(signature)* for J. E. Kingsbury Acting Director, Space Sciences Laboratory

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Hemisphere from 1940 to present. This cooling, about 0.5°C, has compensated
for much of the warming that took place during the first 40 years of this
century, and has occurred primarily at the middle and high latitudes. Some
regions of the middle latitudes have actually warmed while others, such as
the central and eastern United States, have experienced sharp cooling. The
cooling trend for the Northern Hemisphere has been associated with an in-
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activity and the solar parameter. On the time scale of the Gleissberg cycle
when the mean annual sunspot number exceeds 50 it is proposed that global
cooling may be initiated due to the decreased insolation, and conversly for
increased luminosity and warming. This is also supported by umbral-to-
penumbral ratios computed and interpreted by Hoyt (1979a). Further, obser-
vations and results from the Solar Max Mission Satellite program are pre-
sented and discussed, which support the hypothesis that an active Sun is
less luminous. Independent studies of changes of planetary luminosity dur-
ing both quiet and active Sun are also presented and are supportive of this
hypothesis.

Observations of sensible heat flux by stationary planetary waves and
transient eddies, as well as general circulation modeling results of these
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regions of heat flux as seen observationally, e.g., the warming in the far
west regions of the United States and the sharp cooling in central and eastern
regions. Cyclone frequencies have also been observed to shift southward,
with up to 25% reduction in January and July cyclone frequency during the
cooling trend in the western border of the North America continent and in
the Gulf of Alaska. This region corresponds to the location of the large
amplitude ridge in the planetary wave that has been observed, especially
during the winter season when the westerlies are stronger.

Introduction

"Some say the Earth will end in fire, others say ice", as once written
by Robert Frost, but the Earth thus far has been able to maintain itself
fairly well within its 4.0 to 4.5 billion years old Solar System. Looking
back in geologic time the Earth has enjoyed periods, essentially free of
ice, and at other times it has supported a substantial cryosphere (during
periods of continental glaciation). Several Ice Ages have been noted, and
our present Ice Age dates back to at least two million years ago. During
the periods of major extension of ice southward, over the continents (in
particular), estimates are that about 30% of the Earth was covered with ice
and snow, compared to present day estimates of 8 or 9 percent. The most
recent period of significance in the United States was the Wisconsin Glacier
which retreated out of the midwestern states about 15,000 B.P. (before
present) and out of the northern Great Lakes region about 10,000 B.P. The
maximum extent of the ice (southward) with the Wisconsin era was at ~18,000
B.P. Some postglacial advances and retreats were noted; with the period
from 1000 A.D. to 1300 A.D. being particularly warm in the northern hemisphere
(e.g., as noted by the colonization of Greenland), while the period from 1600
to 1800 was particularly cold (the so-called "Little Ice Age"). A period of
the Little Ice Age, during the 17th century, has been noted by Jack Eddy, an
astronomer at the National Center for Atmospheric Research (NCAR), to corre-
spond with a period of solar inactivity known as the Maunder Minimum. How-
ever, a recent study by Landsberg (1980), (to be discussed in more detail
in a later section), suggests that the Maunder Minimum may have had rhythmic
solar cycles, and other periods of the Little Ice Age era were even substan-
tially colder. This is evident in Landsberg's temperature record presented

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in Figure 1, which suggests that the two coldest periods were centered around 1610 and 1810 A.D. The period of the Maunder Minimum is generally regarded as 1645 to 1710, which was not during the coldest era in central and western Europe.

Essentially this brings us up to the most recent 90 to 100 years of time, which generally is warmer than the previous three centuries (as shown in Figure 1). In fact the cold period in the late 19th century has been regarded by some as the fourth epoch of the Little Ice Age, albeit weaker than the three previous minima (1610, 1670, 1810).

During the past 100 years the Earth (or the Northern Hemisphere) has enjoyed a period that began quite cold near the end of the 19th century and then warmed by nearly $1^\circ C$, at around 1940; and has subsequently dropped by about $0.5^\circ C$. Figure 2 shows a temperature profile taken from the National Academy of Science report, "Understanding Climatic Change", which shows the warming trend during the first part of this century, and the unexpected cooling that has taken place during the past 35 to 40 years. CO_2 enthusiasts in particular have been anticipating the beginning of a warming trend capable of melting a substantial amount of the cryosphere by the year of 2025 (see the CEQ report, 1981). In fact the warming in the first half of this century was looked upon by many as a result of increased CO_2 input into the atmosphere (an estimated 290 ppm before the Industrial Revolution, about 1800; and presently at about 335 ppm). Particularly alarming, however, is the 7% increase in concentration (during the past 15 years) accompanied by massive deforestations on a global scale. The CO_2 problem is a real one that merits our full attention, but it is laid aside for the moment in this paper to address the question:

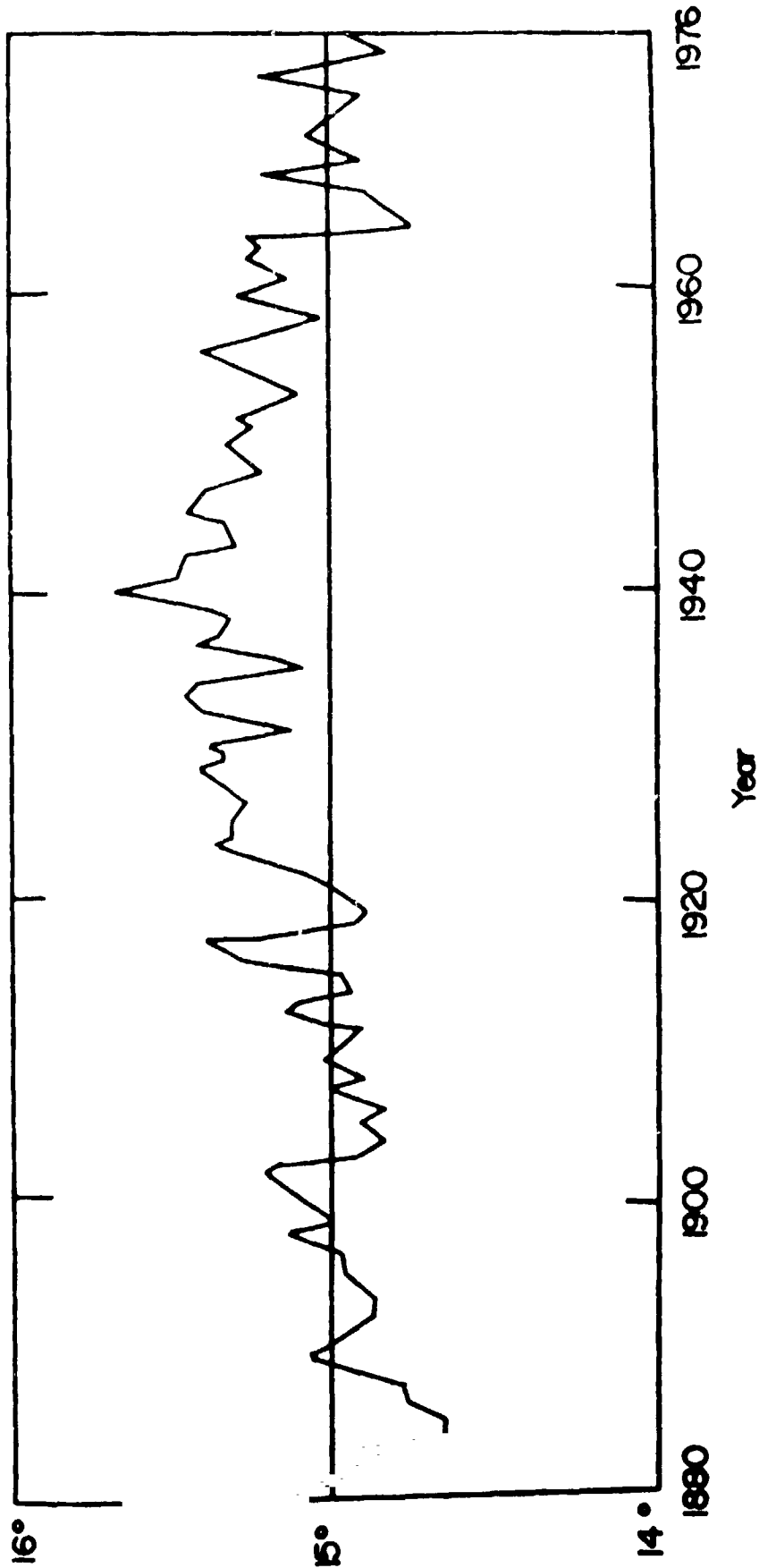"Why cooling during the past 40 years?".
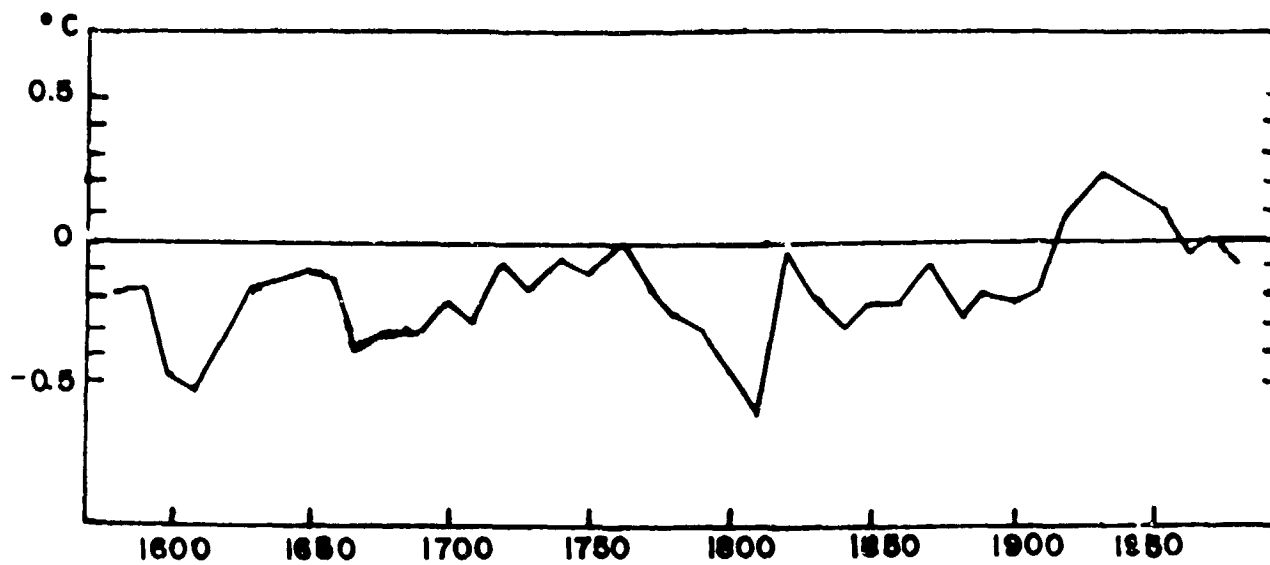
DECADAL TEMPERATURE DEPARTURES FOR THE NORTHERN HEMISPHERE
FROM THE 1881-1975 MEAN, AFTER LANDSBERG (1980)

FIGURE 1

Air temperature (Celsius) over last 100 years (Northern Hemisphere)

from the National Academy of Sciences report "Understanding Climatic Change"

FIGURE 2

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Further Evidence of Cooling

Additional data are now examined to further illustrate the cooling trend in the Northern Hemisphere, and to examine in perspective the climate fluctuations within the contiguous United States during this recent 90-100 year cycle of warming and cooling. Waite's (1968) data summaries presented in Figure 3, although not up to date, show the cold period at the end of the 19th century and the warming to about 1930-40 and the subsequent downturn in temperature. The stornger signal in the temperature is evident in the middle to high latitudes and over the continent (or Iowa). A representative station for the region impacted is Lafayette, Indiana. Looking at the mean annual temperature at Lafayette for about the past 100 years (see Figure 4), the Northern Hemisphere trend is dramatically present (as in Iowa). The slight upward trend in the early and mid 70's was again pointed out by CO_2 enthusiasts as the beginning of CO_2 warming, but the down trend has continued. In fact, 1979, not shown, was the coldest year at Lafayette this century (47.5°F), with only 1885 being colder (46.9°F). The warmest was in 1931 at (56.5°F). The plot of decadal means at lafayette show about a 5°F rise and a comparable drop. The trend at Lafayette during this 100 years has been characteristic of all seasons of the year, but was most prominent for the winter season (DJF). The decadal drop for winter ranged from an average of about 32°F in the 1930's to about 24.5°F in the 1970's. The average daily temperature at Lafayette was notoriously cold for the three consecutive winters of 1976-77, 77-78, and 78-79. For example, the month of January 1977 averaged about 17°F below the normal of about 24°F, and the 7°F average broke the ∿100 year record (of 11.1°F) by over 4°F. In fact, one day in January averaged over 40°F below normal. The temperature trace for this winter also showed systematic 2 to 3 week oscillations in average daily temperature, which may be linked to westward propagating planetary waves.
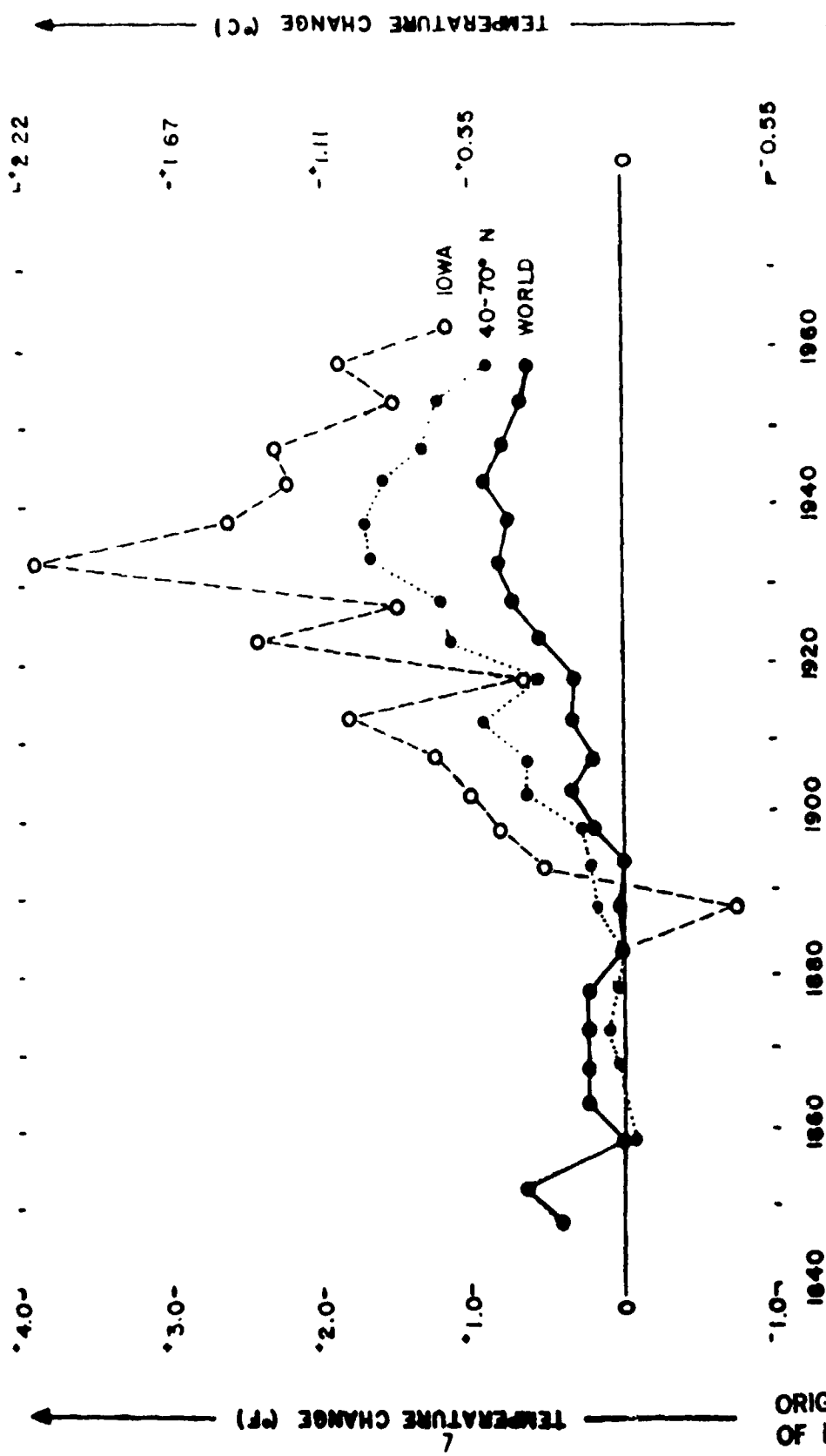
FIGURE 3

WORLD WIDE TREND IN MEAN ANNUAL TEMPERATURE AFTER WAITE (1968)

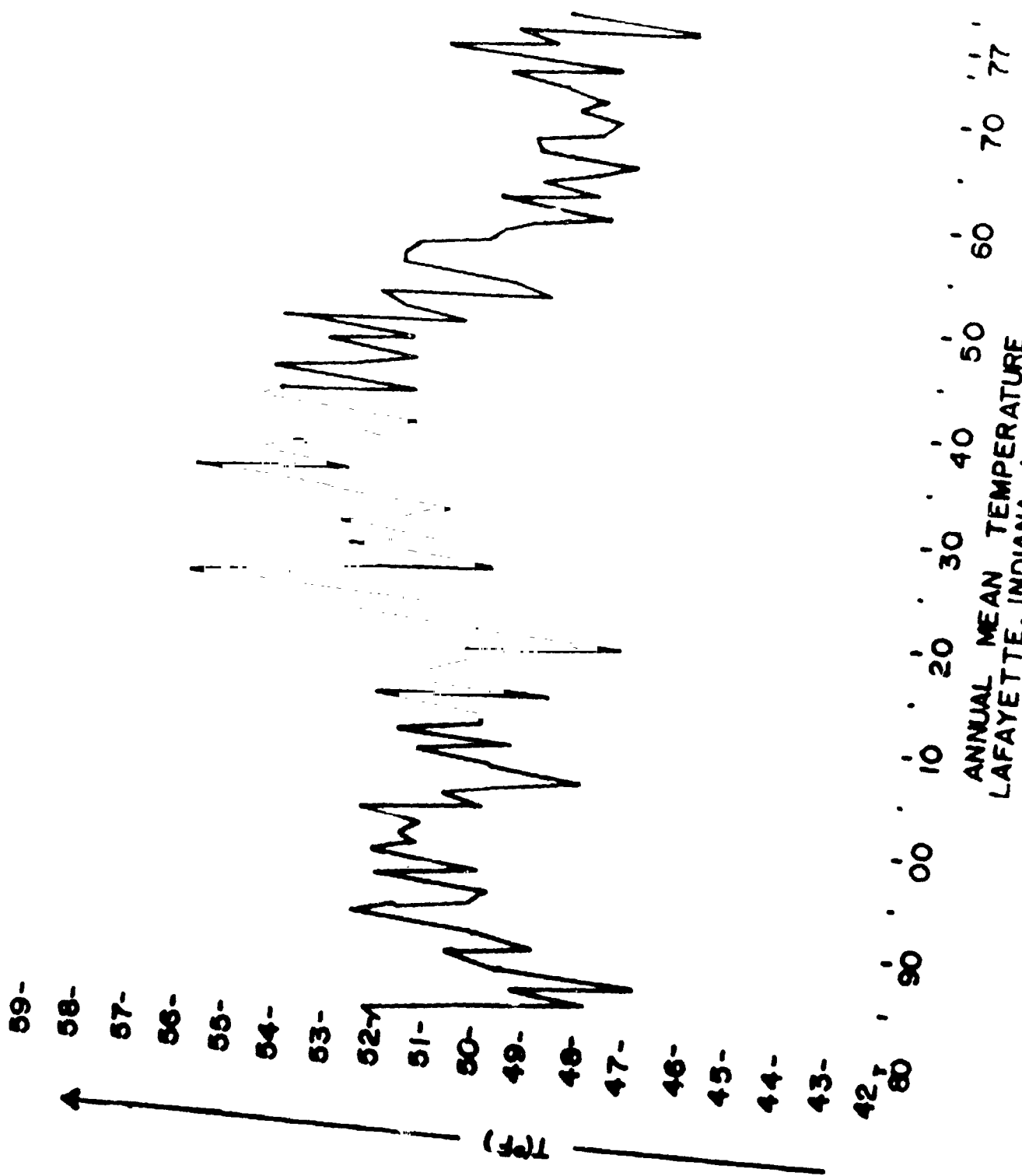ANNUAL MEAN TEMPERATURE
LAFAYETTE, INDIANA (1880-1977)

FIGURE 4

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Temperature departures from the normal for the United States during these recent harsh winters has shown a persistent pattern of cold in the east and warm in the west, as shown for example in Figure 5 for the winter of 1977-78. This was also characteristic of the cold period over the United States during the 19th century as shown in Figure 6, after Wahl and Lawson (1970). Studies by van Loon, Williams, Jenne and others at NCAR (76, 77, 78) have shown the hemispheric trend from 1949 to present (the NCAR data set is regarded by most as the best, most representative data set for identifying hemispheric climatic trends). Actually, their data set is for the region 15°N to 80°N, so most of the tropics and the Southern Hemisphere has not (and cannot) been examined in light of any confirmation as to an established global trend. The work by van Loon and Williams (1977) shows a net hemispheric cooling of about 0.3°C from 1949 to 1972, primarily at middle and high latitudes. As presented in Figure 7, this net cooling occurs while some areas have actually experienced warming. Focusing on the United States, one can see the pattern of cold in the East and warm in the West. During the Winter season, the Midwest and the East have been cooling at a rate of about 0.2°C per year. Another such area of exceptionally strong cooling is found in northern Europe and Asia. The representativeness of Lafayette as an indicator for the global trend at that latitude can be seen in Figure 8, which compares the surface temperature for the Winter season (from 1949 to present) with van Loon's value of the 700 mb-level zonal mean at 40°N. The downward trend in temperature can be noted during the period, including an oscillation during the 1970's (thought to be the start of CO_2 warming as previously noted). A persistent cooling trend in both van Loon's data and the Lafayette record, for the past 30 years is apparent. Van Loon's, et al.,

TEMPERATURE DEPARTURES FROM NORMAL
DEC, JAN & FEB 1977-78
NOAA NATIONAL WEATHER SERVICE
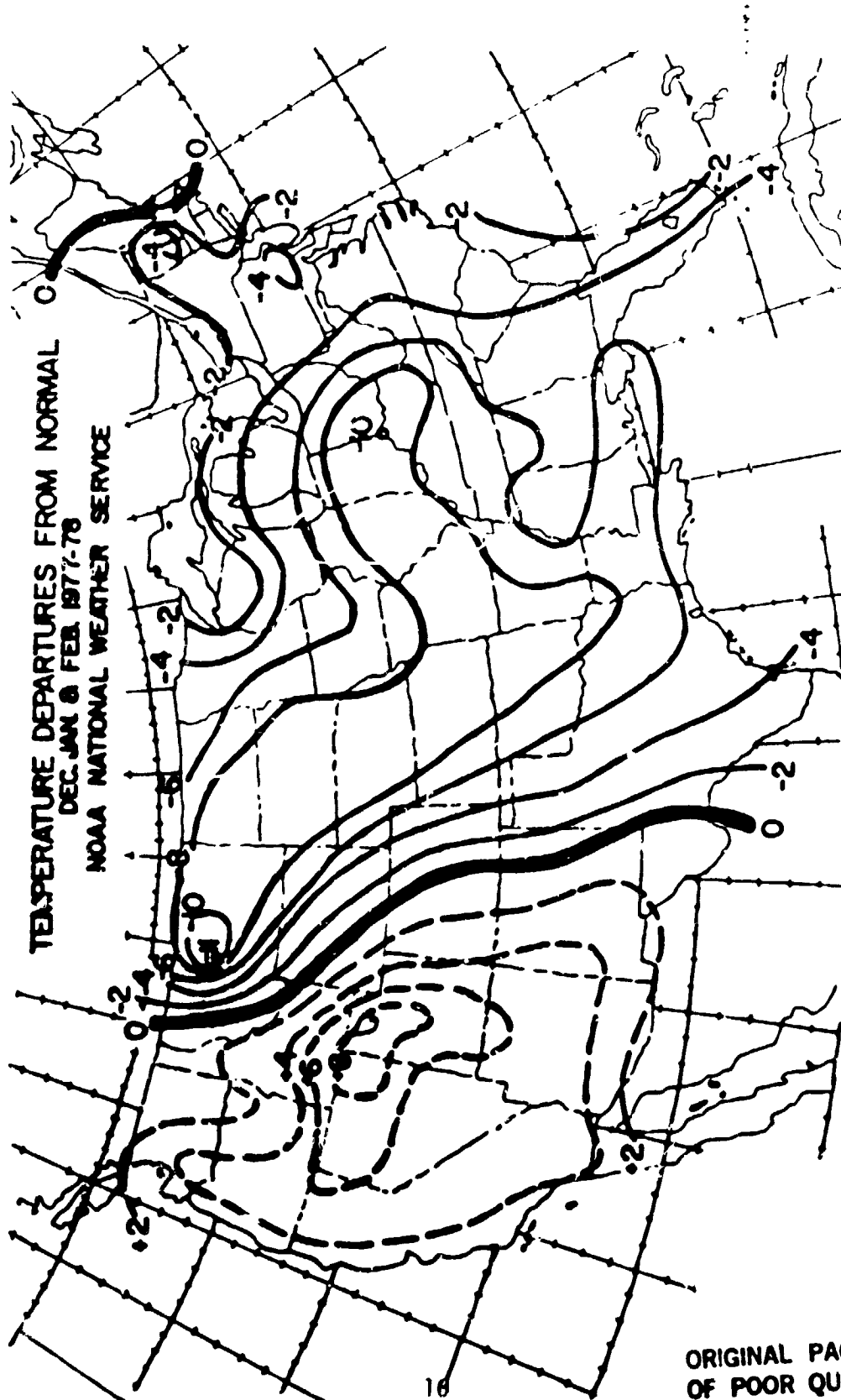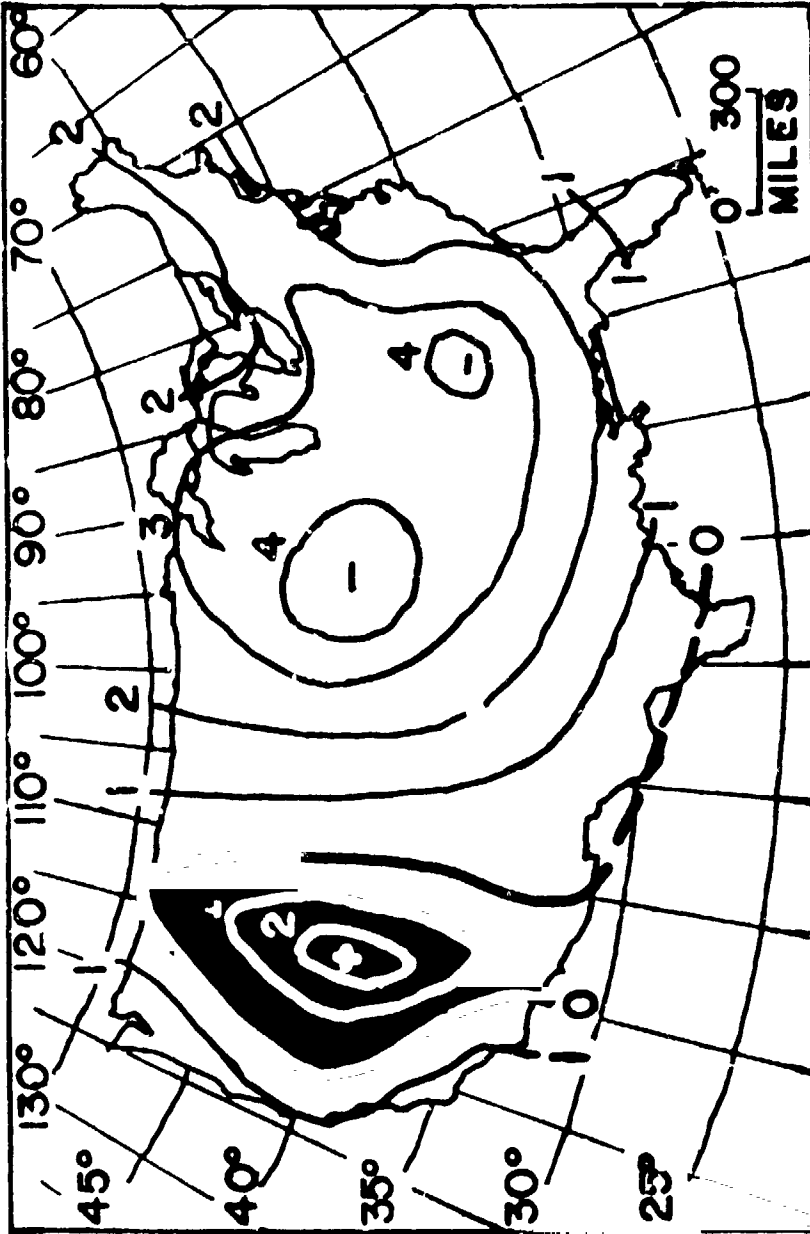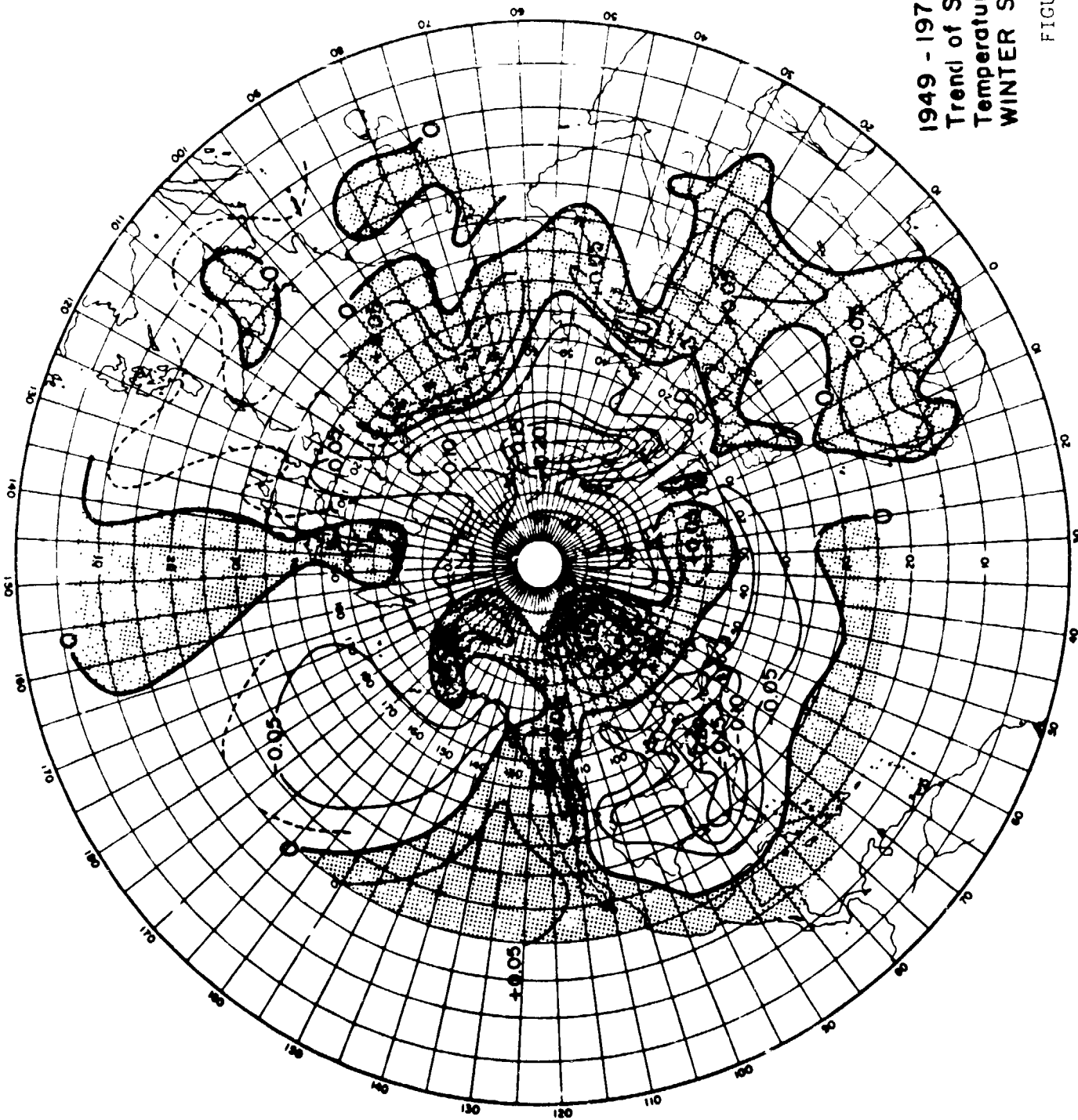
FIGURE 5

TEMPERATURE DEVIATIONS (IN °F) OF THE
1950'S AND 1860'S FROM THE 1931-1960
CLIMATIC NORMALS.

FIGURE 6

1949 - 1972
Trend of Surface Air
Temperature (°C yr⁻¹)
WINTER SEASON
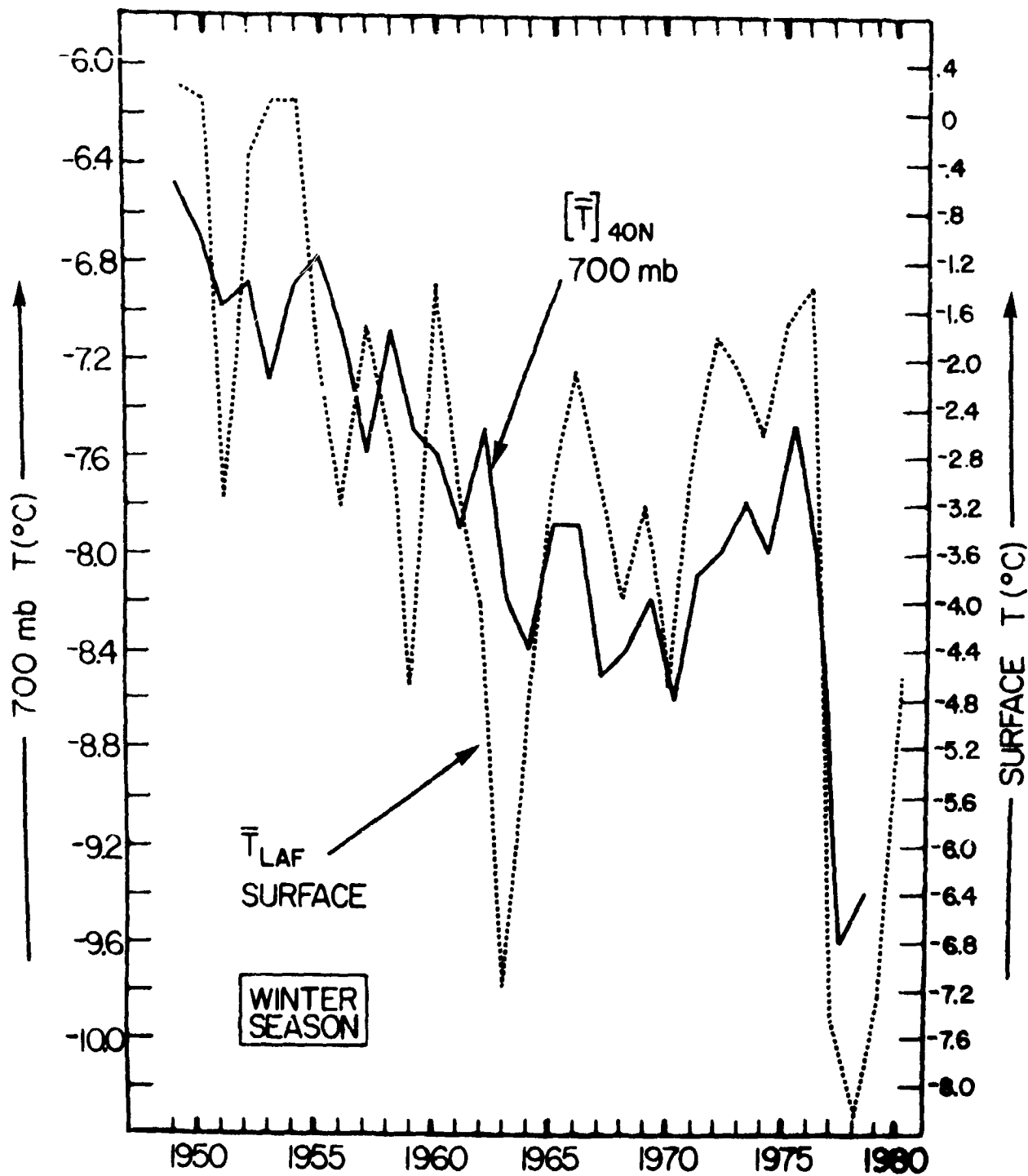
FIGURE 7

FIGURE 8

analyses have more specifically shown, for both winter and summer, the following:

    (1)   net cooling, primarily at middle and high latitudes, implying an increase in the latitudinal gradient of temperature and

    (2)   even stronger cooling at the 700 mb level, primarily at middle and higher latitudes, implying a trend of decreasing hydrostatic stability.

Causes of Climatic Change

Climate is defined as the collection of all "longterm" statistical properties of the state of the atmosphere. The elements of the climate system are the atmosphere, oceans, land surfaces, cryosphere and biosphere. The transitive or intransitive nature of the climate system is viewed by many as the key to whether or not the equations that govern the climate system will admit a deterministic or non-deterministic prediction of our future climate. Causes of climatic change are generally regarded to be in any one of three categories:

    1)   External forcing mechanisms, regarded as deterministic, which represent processes external to and independent of the climate system,

    2)   Internal stochastic mechanisms, that are probabilistic, which represent internal interactions and feedbacks between the components of the system that are mathematical in nature (due largely to nonlinearities of the system), and

    3)   Resonance between the internal modes of the system and external forcing.

A good review on the deterministic and probabilistic nature of climate change is given in the collection of papers by Lorenz (1968, 1970, 1976, 1979) and also by Hasselmann (1976). Examples of forced and free oscillations in the weather and climate system might be regarded, respectively, as the onset of continental glaciation and the day-to-day weather variations.

The study of climatic change can be done through observational or theoretical studies, both of which are rather controversal in nature. The observational task is trivial by no means and it is very difficult to be totally convincing or definitive. Likewise, a theoretical explanation of an observed or expected climatic change is subject to tremendous scrutiny, because the climate system and the interpretation of its behavior involves the net effect of several processes.

Causes of climatic change are generally regarded to be attributed to the following: changes in the Earth's orbital parameters (or Milankovitch theory), solar variability, volcano activity, input of CO_2, other gaseous inputs and depletion of the ozone layer, ocean circulations, other human influences, and mathematical nonlinearities.

Views concerning the possible effect on climate of the Earth's orbital variations were initiated by Wegener (the architect of continental drift theory, but better known to meteorologists for his work in cloud and precipitation physics); but were formally postulated by Milankovitch (of Yugoslavia) in 1941. The specific features of this theory are stated below, and illustrated in Figu. 9:

1 - the precession of the equinoxes (wobble of the axis) can produce a 22,000 year cycle of temperature fluctuation, and

2 - the cbliguity (the changing tilt of the earth's axis) can produce a 41,000 year cycle, as a result of critical changes in seasonal insolation at the right time and latitude.

EARTH'S ORBITAL PARAMETERS AND CLIMATIC CHANGE
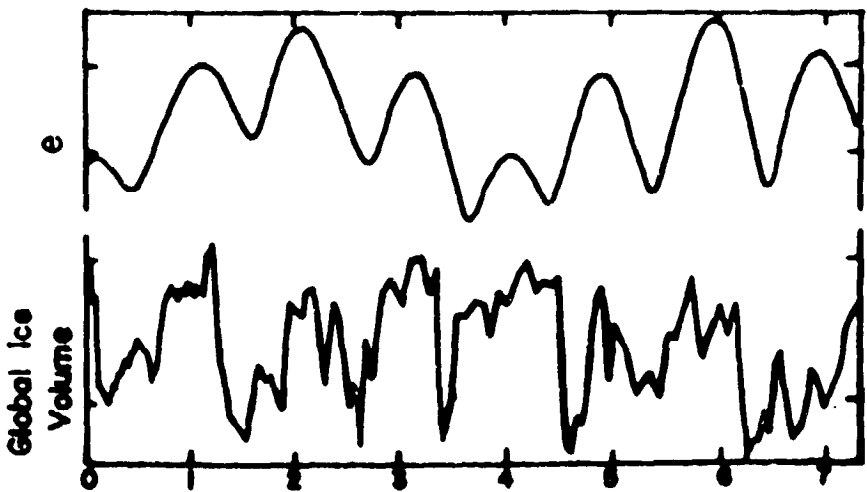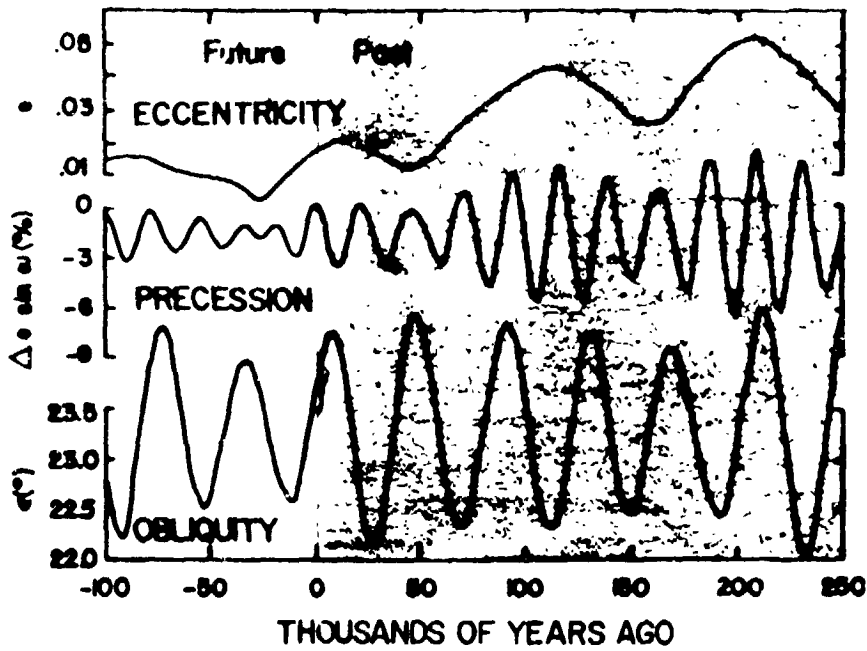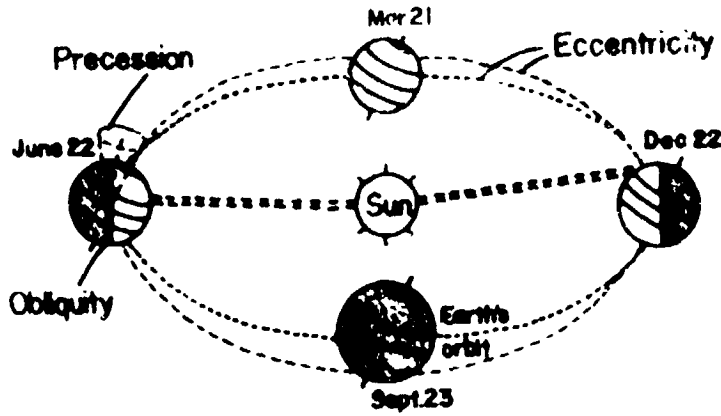
FIGURE 9

Also it has been proposed and supported in recent work at the Lamont-Doherty Geological Observatory that,

　　3 - a 90,000 - 100,000 year cycle of climatic change can occur due to the changes of the eccentricity (e) in the Earth's orbit. This has been supported by the observed systematic variations in the volume of global ice (for seven periods of severe glaciation - based on radioisotope techniques and analysis of ocean-bottom sediments).

The Milankovitch theory is regarded by many as adequate for explaining "Quaternary ice ages", but of no significance in examining smaller time scales such as the Little Ice Age or the temperature fluctuation in the past 100 years (although the onset of glaciation could be more sudden than realized).

　　Next, it can be pointed out that substantial evidence exists to suggest that volcano activity can be a mechanism for climatic change. This is suggested by the results shown in Figure 10, where both instantaneous responses and cumulative effects of volcano activity on temperature change can be noted. The eruption of Krakatoa in 1883, or better yet Mt. Tambora (in Indonesia) in 1815 and 1816 are examples of sudden response. Tambora is the largest known volcano eruption, which produced an incredible global dust veil in 1816. That summer, no crops were grown in the midwest and New England, with snow cover in July and August and frequent freezes reported (see Stommel's (1979) paper, and the notes kept by Yale President, Timothy Dwight). Also in Figure 10, it can be noted that the absence of any major volcano activity from 1920 to the 1940's interestingly corresponded to a warm period. Also, it was generally cooler when major volcano activity was present.

　　Surface measurements of solar radiation shown in Figure 11, after Budyko (1969), are also consistent with the view of a cooling trend, although not
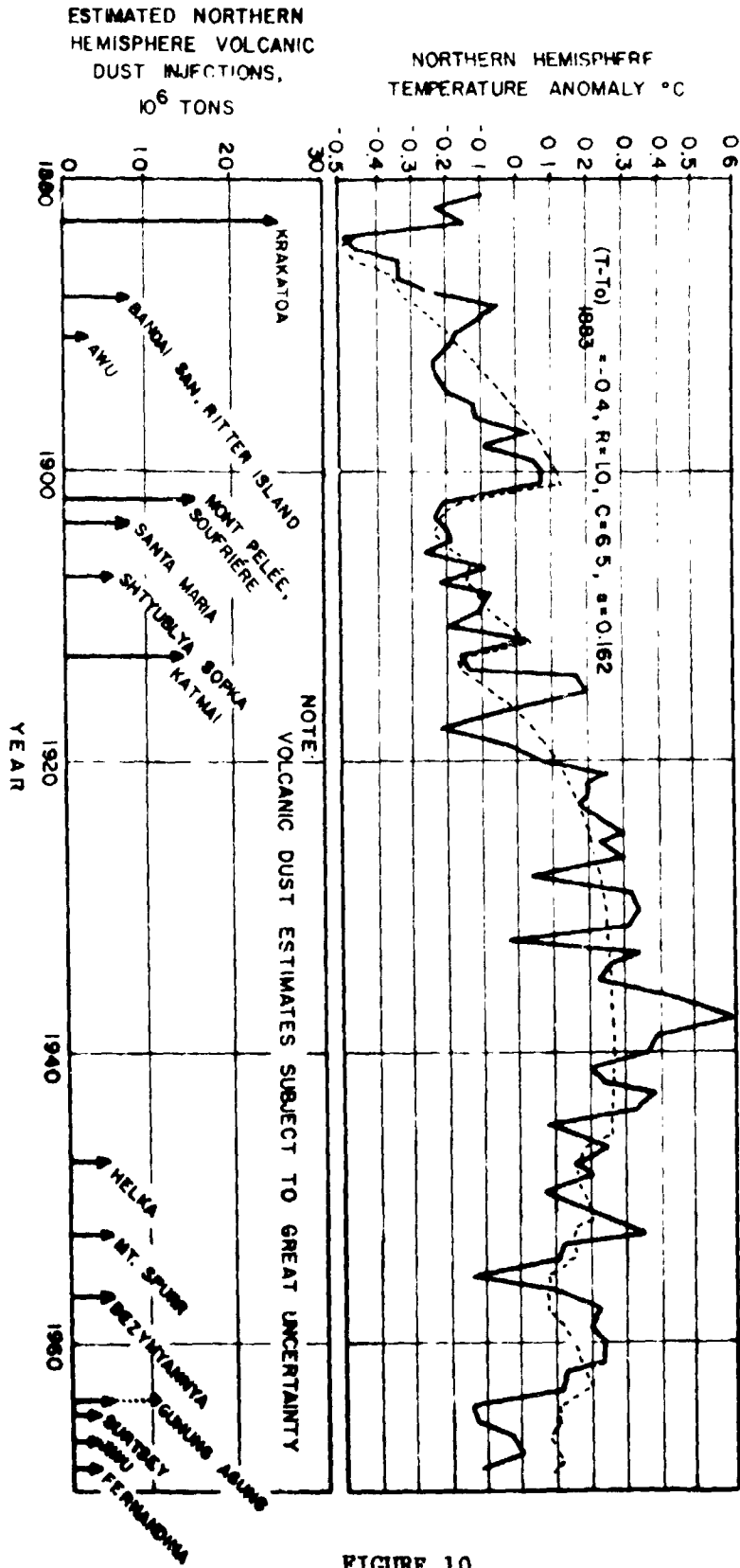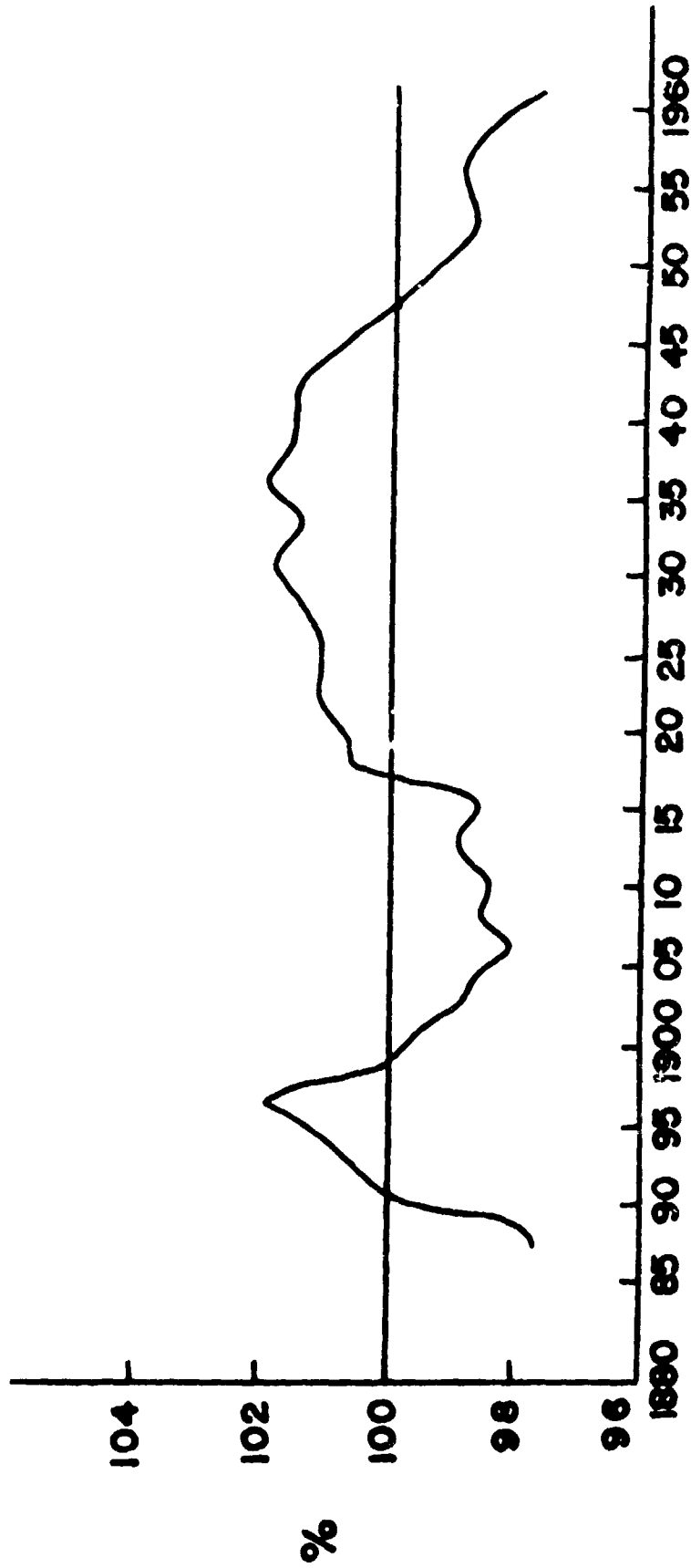
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FIGURE 10

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Secular Variation of Surface Solar Radiation (Cloudless Sky)
for Europe and North America—after Budyko, 1969.
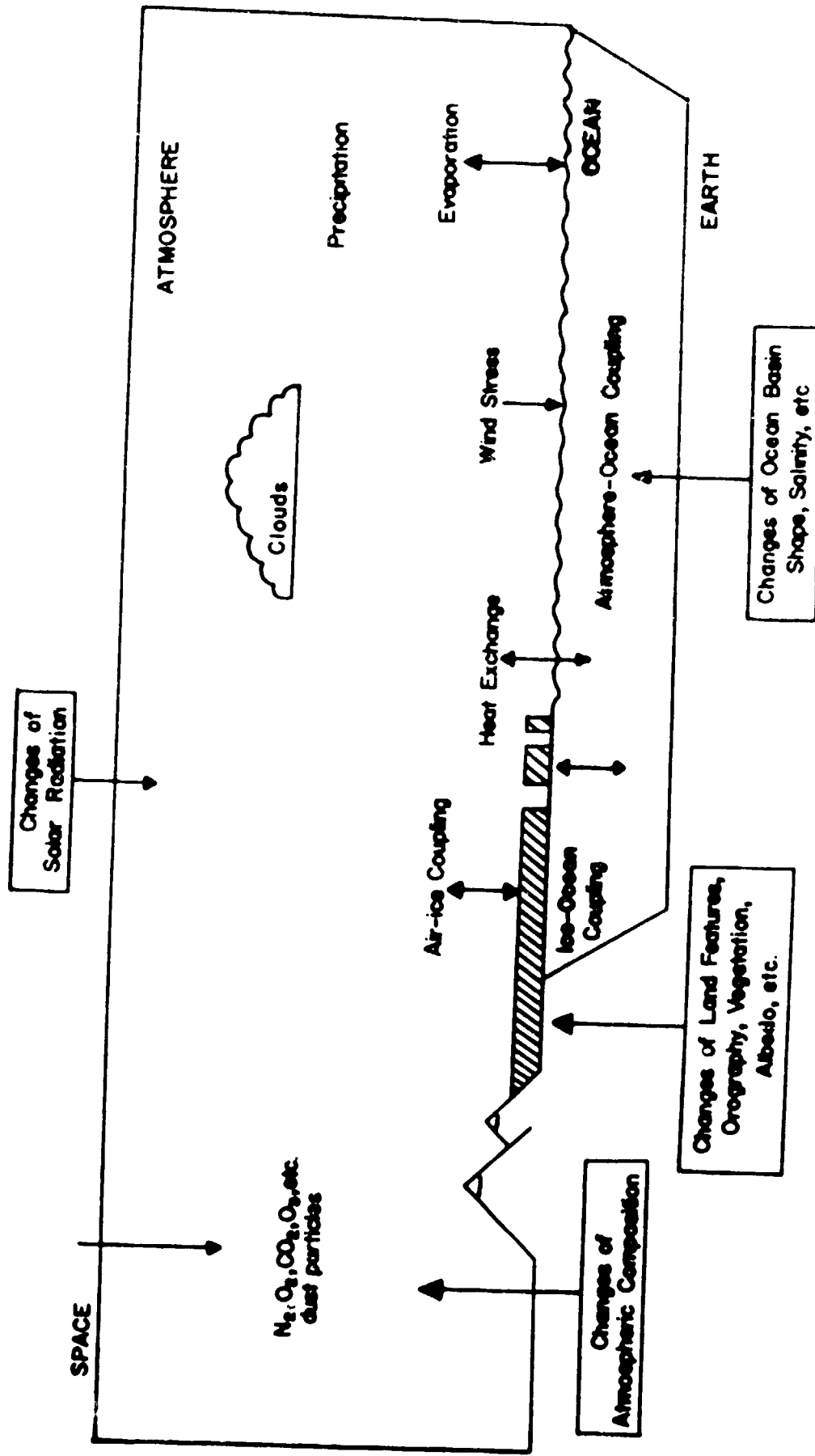
FIGURE 11

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conclusive as to a cause. Other studies for various region also support

the downward trend of solar radiation during the period of cooling frrm

1940 to present.

An illustration of a coupled atmosphere-ocean-ice-earth system is pre-

sented in Figure 12. If one takes the most simple approach possible by

neglecting the effects of an intervening atmosphere, assume heat balance,

and assign a value of 0.30 for the planetary albedo, the corresponding sur-

face temperature of the Earth is computed to be 254°K (too cold). It one

moves forward from this zero-order model and calculates the intervening

effects of a typical atmosphere the surface temperature is about 330°K for

radiative equilibrium (too warm). By making a convective adjustment to the

radiative equilibrium temperature profile, a representative value of surface

temperature can be obtained, about 288°K. If north-south variations are also

considered then the atmospheric heat engine is set into motion to produce

a general circulation pattern of highly transient baroclinic waves to quasi-

steady ultralong planetary waves, with the topics acting as the boiler and

the polar latitudes as the condenser. The dynamical heat exchange and its

response to possible mechanisms believed to produce climatic change are next

to impossible to assess, however general circulation models of the climate

system do offer considerable promise. It is also intriguing to note that

energy balance models of the climate system are suggestive that relatively

small changes of the mean global surface temperature can be associated with

major climatic changes, as evident in past periods of cooling (such as during

the Little Ice Age) or even the warming and cooling trend during the century.

Solar Variability

The remaining possible cause of climatic change to be discussed in this

paper is that attributable to solar variability. In fact it will be

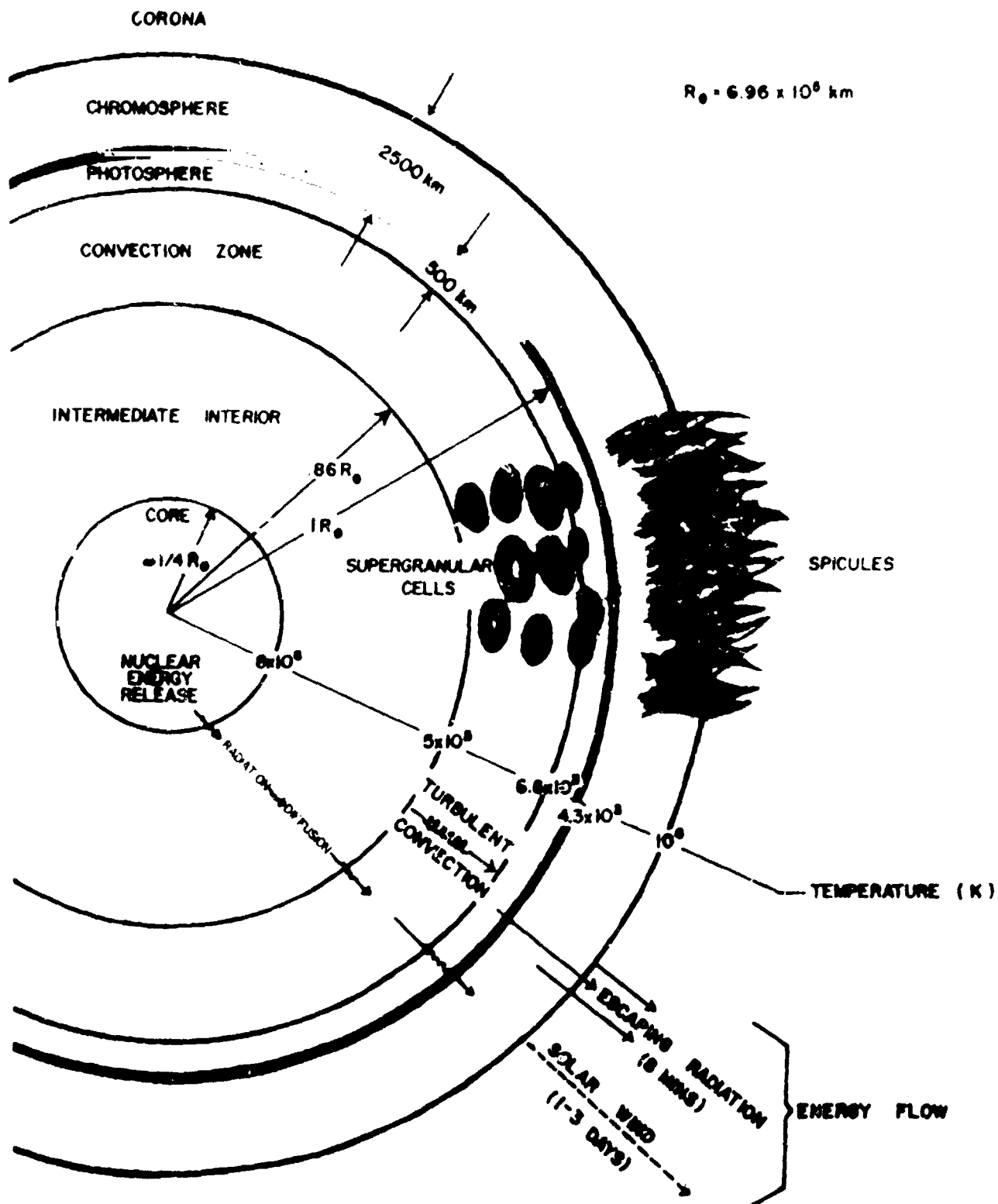MODEL OF A COUPLED ATMOSPHERE–OCEAN–ICE–EARTH CLIMATE SYSTEM

FIGURE 12

2;

hypothesized and supportive evidence presented to show that the present

cooling trend is due primarily to the effect of solar variability. Prior

to the introduction and treatment of the central thesis of this compilation,

some general properties and behavior of the sun are now discussed.

Figure 13 shows an idealized cross-section of the sun with its nuclear

core and primary energy source. The outer most zone of the sun is the con-

vection layer, which is recognized to play a very important role in the amount

of thermal radiation that is emitted from the sun's surface or photosphere.

The top of the convection zone is manifest with its granulation, super granu-

lation and the sunspots that periodically come and go with regular intervals.

The behavior of the convective zone and its relationship to solar activity

(particularly, sunspot activity), and the occurrences of this activity (or

inactivity) may be related to the output of thermal radiation from the sun.

More specifically it could be linked to variations in the solar Parameter

F_0 (i.e. the radiant flux density at the top of the Earth's atmosphere -

assuming no interplanetary attenuation).

Granulation is a manifestation of Benard-Rayleigh convection cells in

the presence of a magnetic field. Supergranulation is about 18 times larger

than granulation cells (or about 2½ earth diameters) and can persist 120

times longer. Convective motion is given by monitoring the doppler effect.

The flow of ionized gas from the center to the edges of the cell enhances

the magnetic field, which helps induce the "spicule" or flame out into the

chromosphere.

A grouping of sunspots is presented in Figure 14, as photographed by

Project Stratoscope on 17 August 1959, at the time of the largest sunspot-

number events this century. The large sunspots are about equivalent to one

earth diameter. The dark region is the umbra and the gray periphery is called

CORONA

CHROMOSPHERE

PHOTOSPHERE

CONVECTION ZONE

INTERMEDIATE INTERIOR

CORE

≈1/4 R₀

.86 R₀

1 R₀

NUCLEAR
ENERGY
RELEASE

RADIATION AND/OR FUSION

$R_0 = 6.96 \times 10^6$ km

2500 km

500 km

SUPERGRANULAR
CELLS

SPICULES

6×10⁶

5×10⁵

6.0×10³

4.3×10³

10⁶

TURBULENT
CONVECTION

TEMPERATURE (K)

ESCAPING RADIATION
(8 MINS)

SOLAR WIND
(1-3 DAYS)

ENERGY FLOW

IDEALIZED GENERAL SOLAR PROPERTIES, STRUCTURE, AND MODES OF OUTWARD
ENERGY FLOW.

FIGURE 13

A portion of the surface of the photosphere at 10:01 CST 17 August 1959 taken by Project Stratoscope. The radii of the large sunspots are roughly equivalent to the diameter of the earth.

FIGURE 14

the penumbra. Results discussed later suggest that the ratio of the umbral/ penumbral region may be indicative of changes in the convective heat flux at the top of the convective zone, i.e. the penumbral region becomes proportionally smaller because it is eroded by more intensive granulation. Granulation is noted at the top of the photo in Figure 14.

Solar Cycles. Solar activity occurs with an approximate 11-year ($\pm$ 3 years) regularity and an active sun displays not only sunspots, but also plages, prominences, flares and heterogeneities or holes in the solar corona. There is still some disagreement as to the cause of sunspots, but the dynamo concept may be the most meritous (dynamo = a pattern of motion that amplifies the magnetic field lines). The combined effects of differential solar rotation and convection can amplify magnetic field lines, through both stretching and tilting processes. Field lines may be amplified and brought near the surface, where some type of convective perturbation or buoyancy pushes the field lines through the surface to form a pair of sunspots of opposite polarity (one in the Northern Hemisphere, and one in the Southern Hemisphere). Sunspots originate in the middle latitudes and form with time at the lower latitudes until they appear near the equator in about 11 years, producing the typical "butterfly" pattern.

Sunspots were observed and reported by the Chinese with the naked eye (some observers also went blind), and then Galileo invented the telescope in 1610 and first observed and reported the sunspot phenomena in 1611. It was not until the middle of the 19th century that the 11 year cycle in sunspot incidence was noted, associated with improved technology (e.g. better telescopes), better techniques such as the solar spectograph, and the statistical evidence of about 10 consecutive 11-year cycles (from 1760 to 1870). From the period in the 1700's to the present, the 11-year cycle has occurred

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with regularity and with varying intensity as shown in Figure 15. We are presently in the middle of the Modern Cycle No. 21. Jack Eddy (1977), using the data provided by Walter Maunder's records at the Royal Greenwich Observatory in London concluded that the period from 1645 to 1710 was void of any 11-year sunspot cycles and labeled this period of quiet/inactive sun as the Maunder Minimum (see Figure 15). Eddy further postulated that this period of Quiet Sun was responsible for the most severe epoch of the little Ice Age, and this was because a quiet sun was a cold sun (and also implied that an active sun is a warm sun). It is an objective of this paper to show that Eddy's view is interesting but not correct, and in fact that a Quiet Sun is a Warm Sun and that an Active Sun is a Cold Sun (just the opposite to Eddy's hypothesis). This has also be n rectified to some extent in the study by Landsberg (1980), examining additional evidence of sunspots and corresponding temperature trends.

Besides the 11-year solar cycle, there is a 22-year solar cycle that corresponds to a reversal in the polarity of the magnetic field of the sun as a whole and that of individual sunspots as well. This cycle does not effect the value of the sunspot number (the Zurich Relative Sunspot Number R is plotted in Figure 15 and is defined as $K(10g + f)$, where K efficiency factor of the telescope, $f \equiv$ number of individual spots, and g number of sunspot groups).

Thirdly, the Gleissberg cycle has been proposed (initially by Wolf in 1862, later by Gleisberg in 1944, and more recently by Hurd Willett at MIT) as a (80 to 100 year) cycle that represents the envelope of maxima associa'ed with eight 11-year cycles. Since the age of the telescope only about four Gleissberg cycles (at the very best) have resulted, and thus the persistence or track record of this cycle has not been substantiated (statistically).

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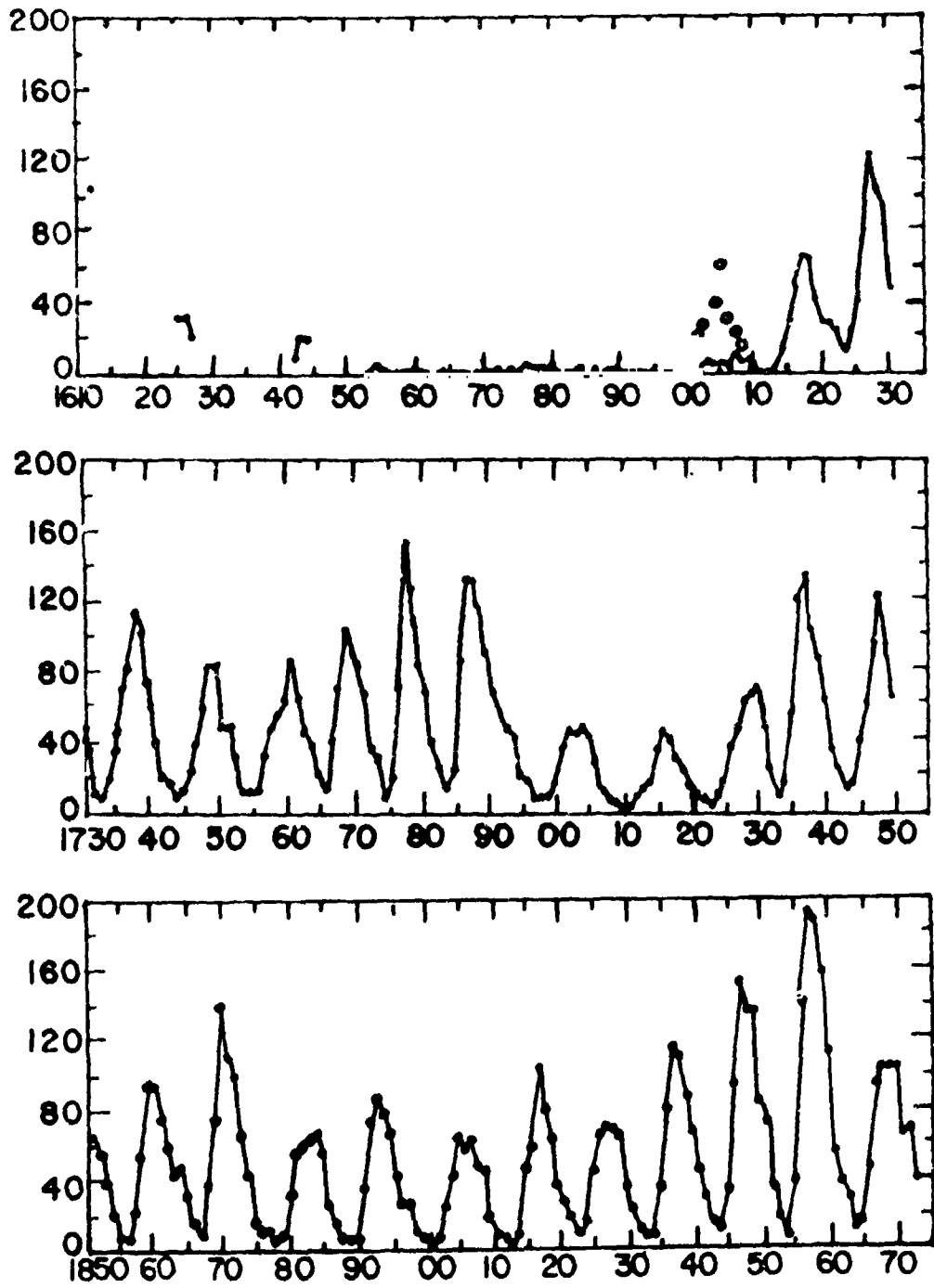
TIME SERIES OF ANNUAL AVERAGE
SUNSPOT NUMBER. THE LACK OF
SUNSPOT ACTIVITY DURING THE 17TH
CENTURY IS BELIEVED TO BE REAL.

FIGURE 15

The most recent Gleissberg cycle, shown in Figure 16, should be in the process of ending. The precise beginning and ending of the 90-year cycle is somewhat vague.

Hypothesis of Solar Variability and Terrestrial Response

It is now proposed explicitly that the apparent observed behavior of global surface temperature during this century is directly related to the Gleissberg cycle of solar activity. The central elements of the hypothesis are as follows:

- A Quiet Sun is a Warm Sun, and an Active Sun is a Cold Sun (contrary to Eddy's earlier hypothesis)[1].

- The Sunspot Number is an adequate indicator for measuring Solar activity.

- On the time scale of the Gleissberg Cycle ($\sim$90 years) there is a corresponding response in terrestrial temperature: Warmest Sun during the weak 11-year cycles, and Coldest Sun during the strongest 11-year cycles ($50 \leq R_{max} \leq 200$ for annual means, or $25 \leq R_{max} \leq 100$ for 11-year running means).

- Response of Terrestrial temperature lags the occurrences of Warmest Sun and Coldest Sun, such that the strongest rate of cooling occurs during the maximum 11-year cycles (e.g. 1957-58-59 for the current Gleissberg cycle) and conversely. (Note: output of thermal radiation or the Solar Parameter F_0 is proposed to be essentially constant, unless the solar activity exceeds some critical value ($\sim$50), and then the value of F_0 can drop).

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[1] In a seminar presented by Jack Eddy at NCAR, on 12 October 1981, his view was reversed (i.e. now consistent with the hypothesis presented here), based largely on preliminary data analysis from the Solar Max Mission program.

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ANNUAL MEAN ZURICH SUNSPOT NUMBER
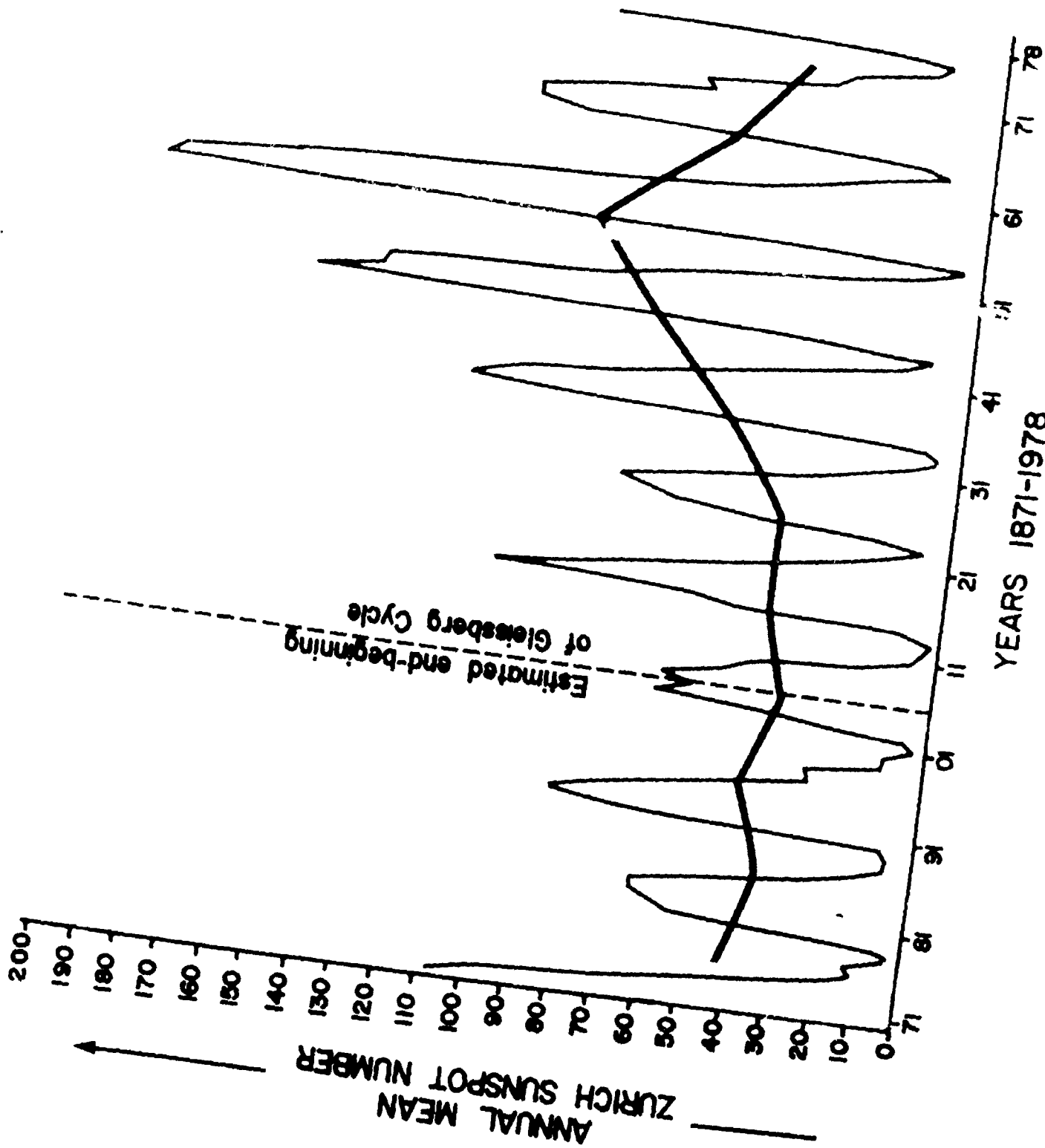
YEARS 1871–1978

FIGURE 16

Estimated end-beginning of Gleissberg Cycle

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The present Gleissberg Cycle works okay from the viewpoint of this hypothesis as shown in Figure 17. The warm period existed when the sunspot # was low, and cooling began when R exceeded 50. The strongest cooling rate corresponded to the largest sunspot number in late 1950's, when F_0 was lowest. The relationship of the Gleissberg cycle and the temperature cycle is illustrated in Figure 18.

Landsberg's Studies. Using the diaries of the Kirches, a well-known astronomy family in Germany, (from 1639-1774); Winkelmann, Klemm, Arnold, Liebknecht and others, Landsberg concluded that the basic solar rythms (although weak) were maintained through the period of the "Maunder Minimum" and that Eddy's conclusion is not substantiated. It is further argued by Landsberg that Eddy was wrong on a second point: namely that the coldest epoch of the Little Ice Age was from 1645-1710. Landsberg shows that the periods (1600-1619) and (1800-1819) were in fact the coldest periods in the Northern Hemisphere (refer back to Figure 1). Finally, Landsberg did a spectral analysis of the 400 years of estimated annual temperature departures for the northern hemisphere, and found peaks (significant at the 99% confidence level) only for 99 years and the quasi-biennial oscillation (~2.2 years). This 100 year signal is an important finding, and is most likely attributable to an external forcing function rather than some internal behavior of the terrestrial system.

Measurement of the Solar Parameter F_0

Excellent review papers by Willson (1977), Eddy (1977), Mitchell (1975), Kondratyev and Nikolsky (1970) all support the view that a trend in F_0 based on conventional data this century is not possible, since the accuracy of measurements is no better than 0.5% to 1.0%. Is this kind of accuracy good
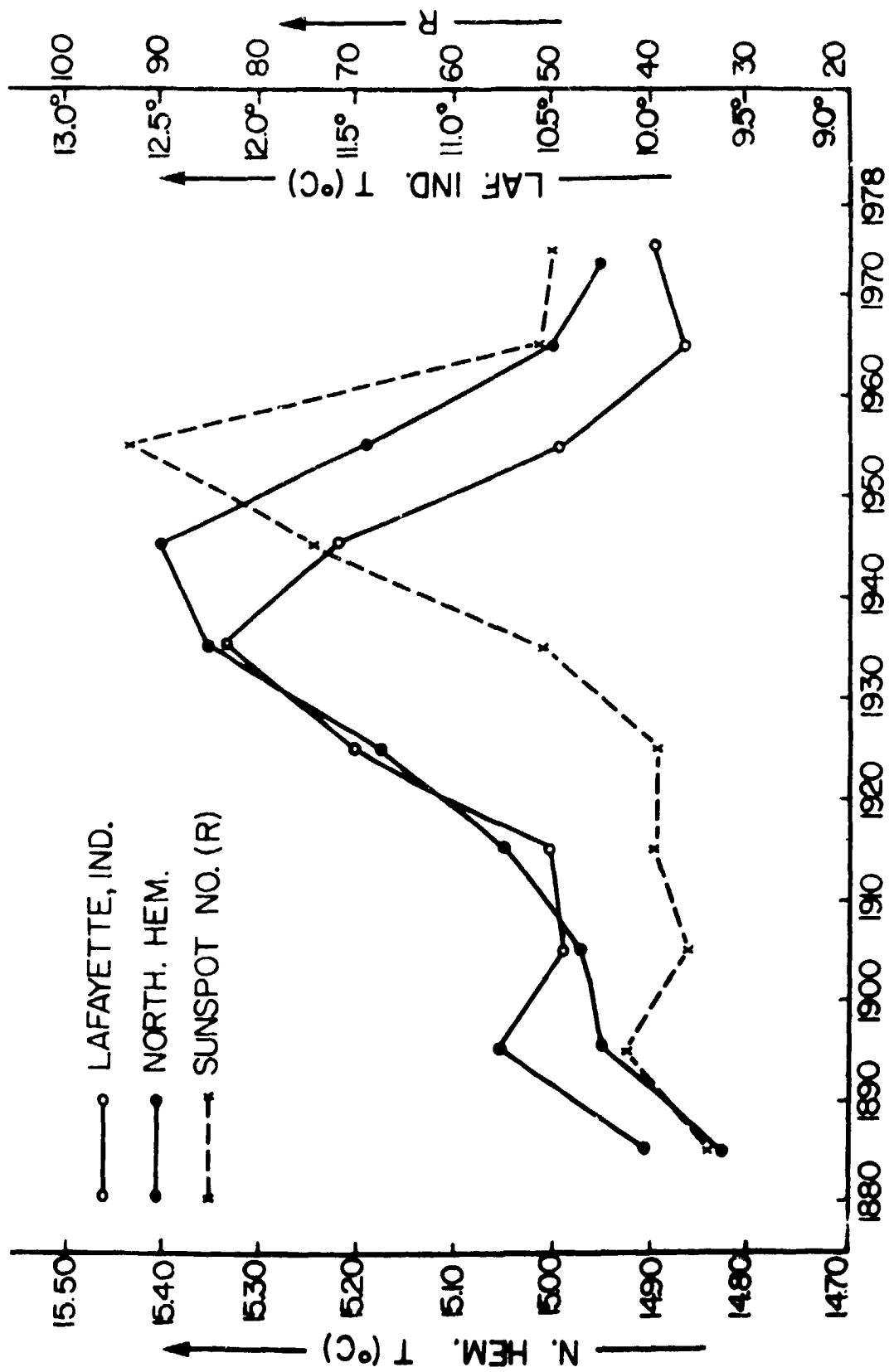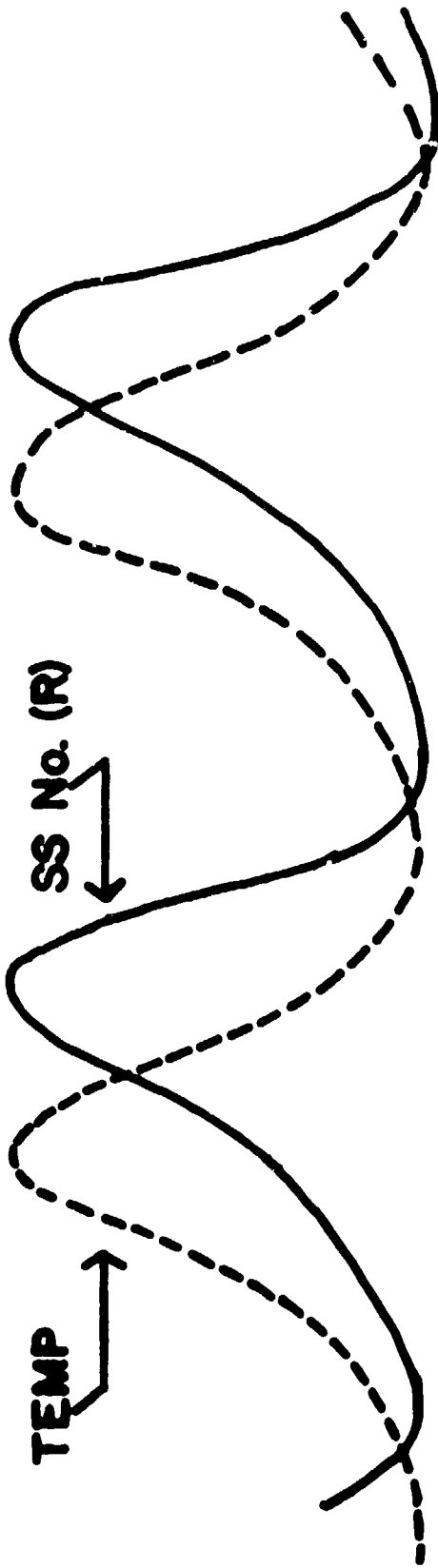
30

FIGURE 17

31

FIGURE 18

enough to detect climatic change due to solar variability? Sensitivity studies in climate models, with feedback mechanisms generally show the following for variable solar input:

1) 0.1. decrease in F_0 · changes of socio-economic importance, such as the warming and cooling cycle observed this century.

2) 1% decrease in F_0 → T_{earth} lowers about 1-2°C, as in the "Little Ice Age",

3) 10% decrease in F_0 → continental glaciation, and Earth possibly ices over.

Also, it is worth noting that these same sensitivity studies show the need for a 50% increase in F_0 to thaw out a frozen earth.

Solar Max Mission Satellite Program. Richard Willson of the Jet Propulsion Laboratory was able to place his radiometers on board the solar max mission satellite, which was launched on 14 February 1980. The measurement of F_0 from a space platform with 0.1% accuracy offered the hope of more reliably determining the response of thermal radiation emission from the sun with the passage of large groups of sunspots. Preliminary data from this important mission are given in Figure 19, which have substantiated the hypothesis presented in this paper. Figure 19 shows that an active sun is a colder sun, as R = 260 corresponds to about 0.2% drop in F_0. More recent data, not presented, show up to 0.5% drop for passage of big sunspot groups. These results not only support the hypothesis, but discount the statement that nearby luminous plages can more than compensate for the cooler sunspot effects. Longer records of such data are essential to substantiate the effects of quiet sun and active sun on the emission of thermal radiation and changes in F_0.

Kitt Peak Observations. Livingston's (1978, 1979) efforts at Kitt Peak have shown approximately a 5°K cooling of photospheric temperature, from 1976-78.

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SOLAR MAXIMUM MISSION SATELLITE OBSERVATIONS OF SOLAR FLUX VARIATIONS (14 FEBRUARY 1980 – 19 JULY 1980)
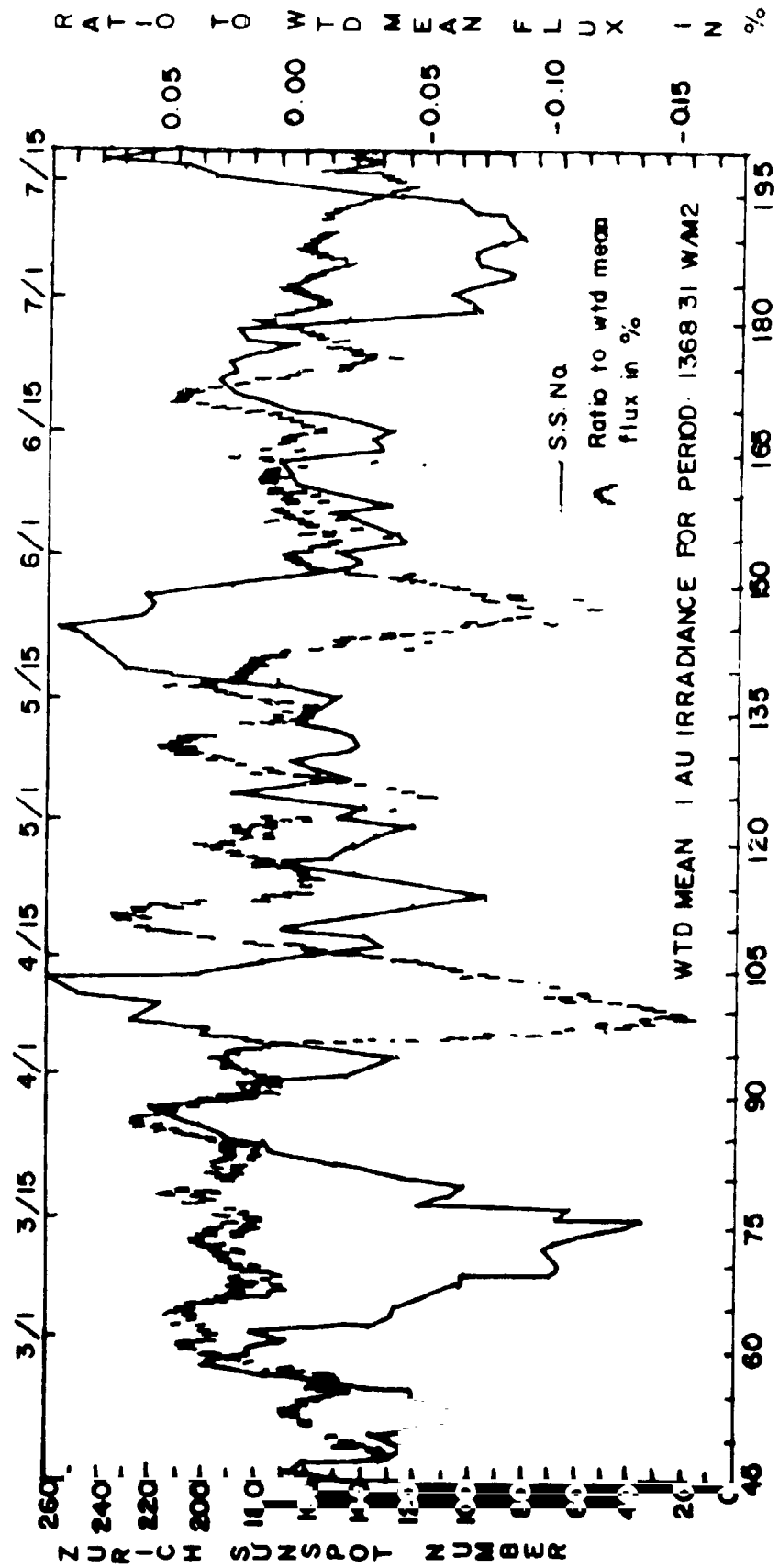
FIGURE 19

WTD MEAN I AU IRRADIANCE FOR PERIOD: 1368.31 W/M2

S.S.No.

Ratio to wtd mean flux in %

1980 DAY:

34

This corresponds to an 0.35% decrease in solar output during the time that the sunspot number increased from about 15 to over 100. Briefly, Livingston's technique is based on changes in the strength or equivalent width of selected Fraunhofer lines, which serve as excellent indicators of changes in photospheric temp of the Sun. For lower temperatures the equivalent width (or line strength) becomes larger and the luminosity decreases. An 0.1% increase in line width corresponds to about a 1K decrease in photospheric temperature. The Carbon line (5380$\overset{o}{A}$) and other nearby Iron lines were monitored in detecting the cooling trend.

Umbral to Penumbral Ratio and Solar Luminosity

The hypothesis for variability in the solar parameter presented here relates in a very consistent way to a similar hypothesis and correlation of sunspot activity to terrestrial surface temperature given by Hoyt (197). He proposes an index, defined as the ratio of umbral areas to penumbral areas of sunspots, which serves as a measure of solar convective flux and luminosity (and thus the solar parameter). Hoyt's umbral-to-penumbral ratios from 1874 to 1970, based on Greenwich data, are presented in Figure 20. Dotted segments in this profile represent quiet sun years and the results are probably questionable, especially around 1900, since the penumbral areas are too small (< one 100 millionths of the solar hemisphere). As can be seen, the profile in Figure 20 coincides very nicely with the cycle in surface temperature during the past 90 years. This oscillation in the umbral/penumbral ratio is offered as additional support for the author's hypothesis, which is now discussed.

One can argue that on the time scale of the Gleissberg cycle, the energy flux from the interior of the sun to the bottom of the convective zone is constant. If the convective zone is in steady state, then the flow of
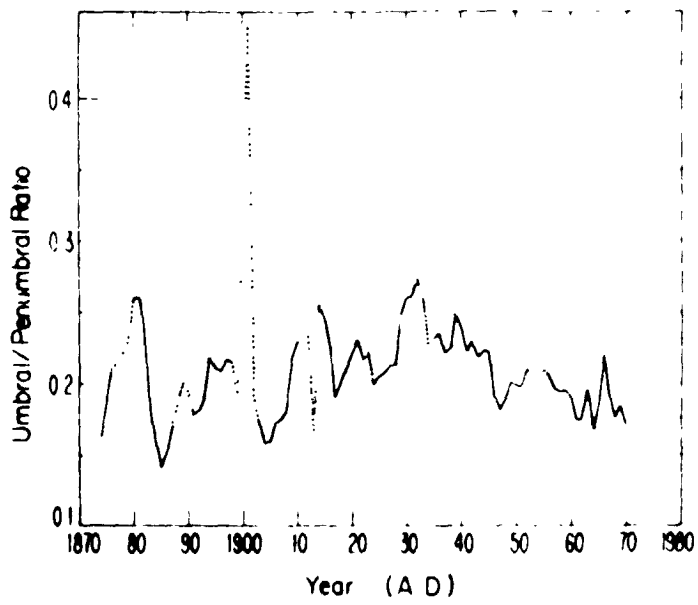
35

FIGURE 20

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energy from the top of the photosphere would balance this inflow of energy. Consider now that the energy flowing into the convective zone is partitioned into several reservoirs, namely rotational, convective, radiational, thermal, and magnetic energies. If the energy content in any of these reservoirs changes with time, then the flow of energy (electromagnetic radiation and/or solar wind) to space would be altered, providing there is no energy transfer between reservoirs. This means that an energy increase (or decrease) in any one reservoir would result in a corresponding decrease (or increase) in solar luminosity. Although plausible, this argument has definite caveats and other opposing views just as plausible could be made.

Hoyt notes that during periods of increasing solar rotation, the umbral/penumbral ratio is decreasing and the climate of the Earth is cooling or cool (e.g., the late 19th century and the middle of the 20th century). As the rotational energy reservoir increases, the convective heat flux at the top of the photosphere relaxes, allowing the penumbral region to be larger. This results in smaller ratios of the index at times of less luminosity and smaller values of the solar parameter. During periods when the solar rotation is decreasing, the umbral/penumbral ratio is increasing and the climate of the Earth is warming or warm. This was the case for the beginning of the 20th century up until the 1930's. The greater convective heat flux during this period decreased the penumbral regions, with granulation overtaking the gray areas around the dark sunspots. Thus Hoyt's index increases during periods of slower rotation and greater luminosity. This tendency turned around in the 1930's when the sun began to rotate faster and the umbral/penumbral ratio began to drop (see Figure 20). Correspondingly the drop in solar luminosity (and therefore the solar parameter) initiated the onset of cooling. Increased rotation and cooling have continued until the present, with umbral/penumbral ratios now reduced to values comparable to those at the end of the 19th century.

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Lowell Observatory Studies by Lockwood   Since 1971 G. W. Lockwood, at the

Lowell observatory in Arizona, has been measuring the relationship between

the luminosity of planets (Saturn, Uranus, Neptune, and Titan) and solar

activity. By 1974 all planets were crower, brighter at time of solar

inactivity, Sunspot Minimum), with Titan's more luminous. The relation

ship continued through 1977 during the period of Quiet Sun. Lockwood's

technique compares the luminosity of planet with 2 control stars in the nearby

sky. From 1978 to 1980, however, with increased solar activity, planetary

albedos have shown a dramatic decrease! Again, another independent yet re-

lated study substantiates the hypothesis concerning the relationship between

solar activity and solar luminosity.

Diagnostic Studies of Planetary Circulation and GCM Models

As reported and discussed at some length by Agee (1980) the following

results have been obtained (largely by van Loon and associates at NCAR) based

on diagnostic studies of the planetary circulation:

1) Net Cooling ($15°N-80°N$, from 1949 to present),

2) Increase in the latitudinal gradient of temperature,

3) An increase in lapse rate between the surface and
    700 mb level,

4) Westerlies moved south and intensified and

5) Largest meridional heat fluxes associated with planetary wavenumber 2.

This coupling between heat flux and planetary waves is apparently locked into

orographic features and land-sea contrast. The positive heat flux regions

are due to both, northward transport of abnormally warm air and southward

transport of abnormally cold air. The strongest cooling is in the eastern

two-thirds of the United States and southeast Canada, and in the northern

regions of Europe and Asia.

Climate (GCM) Model and Comparative Results. In addition to the evidence
presented thus far in support of the hypothesis for cooling, one can use
energy balance climate model results and corresponding GCM simulations to
make some interesting comparisons with global observations. It should be
noted that these models also have inherent weaknesses, as well as the data
sets used in diagnostic studies. Of specific interest in this paper are those
model results that have been obtained by varying the solar parameter. Stone
(1973) increased the solar input into an energy balance model and found an
increase in both temperature and the latitudinal gradient of temperature,
as well as the lapse rate. Stone's result was unrealistic, however, in the
sense that he had no ice albedo-temperature coupling. Sellers (1973) in-
cluded this important feedback mechanism in his energy balance model and
found that for a decreased solar input there was 1) an increase in the lati-
tudinal gradient of temperature, which was due to greater cooling rates at
the higher latitudes, and 2) an increase in the lapse rate (i.e., decreased
hydrostatic stability). These results, just opposite to Stone's, were re-
confirmed by Manabe and colleagues using the Geophysical Fluid Dynamics Lab-
oratory's (GFDL) GCM (see Smagorinsky, 1974) and were subsequently reported
by Wetherald and Manabe (1975). Even more importantly, these results are
consistent with both van Loon's observational findings and the hypothesis
presented here for climatic cooling. It follows that the more realistic
climate models should not only have the proper physical response to climate
mechanisms (e.g., solar variability), but they should respond (in concert
with all other influential mechanisms) according to the proper time scale
(in this case the 90-year Gleissberg cycle). Conceptually, one can envision
the accumulative effect of reduced solar radiation, particularly at the
higher latitudes during the summer months where daily insolation amounts

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are largest (but reduced by a decreased Γ_{ℓ}) As a consequence, the annual accretion of the ice and snow over a period of several years of cooling could result in a net increase in the cryosphere and thus contribute to a stronger cooling in the polar latitudes. The accretion of snow and ice in the Northern Hemisphere has been shown in a recent study by Matson and Wiesnet (1981), based on rather precise satellite obsevations, which suggests about a 10% increase in the cryosphere during the past decade.

Another very important aspect of the climatic cooling mechanism proposed here pertains to the manner in which the dynamics of the general circulation responds to a reduced input of solar radiation. It is recognized that the meridional sensible heat flux can be due to both standing waves and transient waves (or eddies), with obvious differences in their origin and structure. Van Loon and Williams (1977) have examined the sensible heat flux by these waves and van Loon (personal communication) has found a strong coupling between the anomalous distribution of Northern Hemispheric temperatures and an apparent planetary wave number (~ 2) associated with the stationary wave heat transport. Specifically, the regions of mountain ranges eastward to warm ocean currents (e.g., from the Himalayas to the Kuroshio, and the Gulf Stream) seem to have the strongest effect on the occurrence of standing planetary waves and the associated heat flux. Large positive values of meridional heat flux are observed over eastern Asia and North America due to north-to-south eddy transport of negative anomalies in temperature, while the positive regions over the North Atlantic and North Pacific are due to the south-to-north transport of positive anomalies. Van Loon has shown a particularly strong correlation in this kind of coupling between the North Atlantic and eastern Asia. GCM model results by Manabe and Terpstra (1974)

have also shown that the contribution of standing eddies to heat flux is very important with mountains in the model, whereas transient eddies dominate in the mountainless model. It can be further argued that a possible strengthening and southward shift of the westerlies during the current cooling trend (see van Loon and Williams, 1977) could more effectively interact with the topography of eastern Asia and North America to yield a more prominent role by the standing planetary waves in meridional heat transport, resulting in cooling in the interior of continents at mid- and high latitudes. This may account for the type of "isobaric geometry" (a term coined by Rossby) that has been observed to produce the three successively harsh winters in the central and eastern United States. Referring to Figure 7 one can also note the warming in the western part of the North American continent and the eastern Pacific, which is consistent with the location of the large amplitude stationary planetary wave over North America. The pattern that has been depicted here would support the continuation of a strongly baroclinic zone along the east coast of North America (with frequent cyclone development), but perhaps a suppression of cyclone frequency along the western border of North America and in the Gulf of Alaska (particularly during the winter season).

Van Loon and Williams (1977) have compiled the tracks of January cyclones crossing $70^{O}W$ between 30° and $55^{O}N$ during 1949-72. Their statistics showed that the total cyclone frequency remained essentially constant during the period but the highest frequency shifted to the south. This was consistent with the findings that the westerlies tended to shift southward during this period. Furthermore, as discussed previously, from the context of favored positions for stationary planetary waves the region off the east coast of the United States might be expected to remain baroclinically active with no

significant change in total cyclone events (but shift to the south as noted).

These results on the climatology of cyclones during the current period of climatic cooling have also been independently derived by Zishka and Smith (1980). Their work for both January and July cyclones was actually carried out for a much larger region (approximately 20-70°N, and 30-170°W) that encompasses North America and large regions of the adjacent oceans. For the period from 1950 to 1977, they observed approximately a 25% decrease in cyclone frequency. Most of the decrease was associated with decreased activity in the storm tracks in the far west regions of North America and particularly in the Gulf of Alaska. This is a very important result, in view of the discussions in the previous section, which is very consistent with the warming that occurred in the region (while strong cooling was observed in the central and eastern part of the North American continent). Zishka and Smith's results not only show the continuation of active storm tracks in the central United States and along the East Coast and Gulf Coast throughout the period, but also some evidence for deeper storm systems as seen in the lowering of the mean minimum pressure in storms. The mean minimum pressure in January cyclones dropped from 990 mb at the beginning of the period to 985 mb at the end (based on a linear regression least-squares fit), and July cyclones dropped from 1002 to 1000 mb.

Summary and conclusions

Considerable evidence has been presented to show that the mean annual temperature over the Northern Hemisphere has been declining from around 1940 to the present. This cooling trend has amounted to over 0.5°C, which compensates for much of the warming that took place earlier this century. This cooling has occurred primarily in the middle and high latitudes. Interestingly, at the middle latitudes (e.g., 40°N) some regions have experienced warming.

while others (e.g., the central and eastern United States) have experienced very strong cooling. Temperature data for a station (Lafayette, IN) within the region of strongest cooling have been presented and discussed, which show a drop in the mean annual temperature of $2.2^{o}C$ from the 1930's to the present. The cooling trend for the Northern Hemisphere has been shown by observations to have 1) increased the latitudinal gradient of temperature, and 2) decreased the degree of hydrostatic stability.

Observations of the Northern Hemisphere cooling trend have been coupled with corresponding observations of sunspot activity to infer a direct response of terrestrial temperature to solar variability on the time scale of the Gleissberg sunspot cycle ($\sim$90 years). Central to this inference is that the solar parameter decreases during an active Sun and increases during a quiet Sun, which has been supported by recent data from the Solar Max Mission satellite observations. This view is also supported indirectly by solar observations at the Kitt Peak National Observatory and the Greenwich Observatory, and the interpretation of these data by the author and by Hoyt (1979a) as well as independent study of the variation of planetary luminosities. The hypothesis presented states that the recent 90-year trend in surface temperature (warming and then cooling) has been externally forced, largely by the Gleissberg cycle and its associated change in the solar parameter (higher for small R or inactive sun, and lower for large R or active sun).

Additional supportive data for the solar variability mechanism have been discussed, using the results from climate models under the condition of decreased solar input. Net cooling at the surface, an increased latitudinal gradient of temperature, and an increased lapse rate have been simulated in model predictions, which is consistent with observations reported in this paper. Also, the sensible heat flux by the standing and transient eddies

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has been considered, which again shows consistency between observations and model predictions (although there are recognized weaknesses in both observational findings and model results). Of particular interest is the apparent southward shift of the westerlies and its associated cyclone storm track. Interaction between mountain ranges and an adjusted stronger westerly flow may contribute to larger amplitude stationary waves, which correspond approximately to a wave number of 2. This is consistent with temperature changes that have been monitored in the North American and Asian continents, as well as independent studies of cyclone frequency. About a 25% decrease in January and July cyclone frequency has been observed in the ridge of the planetary wave over the western sections of the North American continent. The cyclone events in the frequent baroclinic regions of the central United States, East Coast, and Gulf Coast, however, have shown no decline. Evidence has also been presented to indicate that these storms may be increasing in their intensity through the current cooling period. The changes of the mean annual temperature across the United States during the cooling trend have resulted in exceptionally strong cooling in the central and eastern regions, but above normal temperatures in the far west. This kind of temperature change may represent a deterministic dynamic response of the planetary circulation to a decreased solar parameter.

Finally, some comments are offered about the prospects for continued cooling and its possible impact. Based on the hypothesis presented, the current 35-40 years of cooling due to solar variability should be approaching the minimum level. However, this cooler period could be sustained through the remainder of this century, especially if aided by unusually strong volcano activity. Empirical results by Hoyt (1979b) suggest that the present cooling due to solar variability has been reduced somewhat by the onset of CO_2 warming.

The views, expressed by Hoyt are similar to those of the author, which are portrayed schematically in Figure 21. By the turn of the century the anticipated weaker 11-year cycles (and thus an increased solar parameter), associated with the end of the current Gleissberg cycle and the beginning of a new one, should effect an upward trend in the temperature and produce climatic warming like that during the first half of this century. This warming could be even more dramatic, considering the likely prospects for CO_2 warming. Obviously, the author cannot be sure of this projection, especially when so many factors are seen to influence our weather and climate. If the proposed physical link between sunspot activity and the solar parameter is substantiated, it becomes even more imperative to be able to model and predict solar activity and variability. The occurrence of another 90-year Gleissberg type of oscillation is somewhat uncertain, especially in view of the unexpected large magnitude of the current 11-year cycle. There are also past accounts of unusual behavior of the Sun, such as the Sporer and Maunder Minima as well as the Grand Maximum. Also, a view could be expressed that if and when the onset of cooling begins, corresponding to the next epoch of continental glaciation, the addition of CO_2 to the atmosphere could be a means of opposing this cooling.

Finally, attention should continue to focus on the results from the Solar Max Mission satellite measurements of F_0. Additional measurements from a space platform should be planned and continued so that an adequate period of F_0 data can be compiled (at least through one 11-year solar cycle). Also, other independent efforts related to solar activity, as reported here, should be continued and supported. Precise determination of the thermal radiation emitted by the sun is essential and necessary to adequately address the problem of climatic change, especially since we have the technological capability to do so.

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Warming due to CO₂

cooling due to volcanoes

— — — Solar

⋯⋯⋯⋯ Solar & Volcano

———— Solar & Volcano & CO₂

Temp →

1890   1935   1980
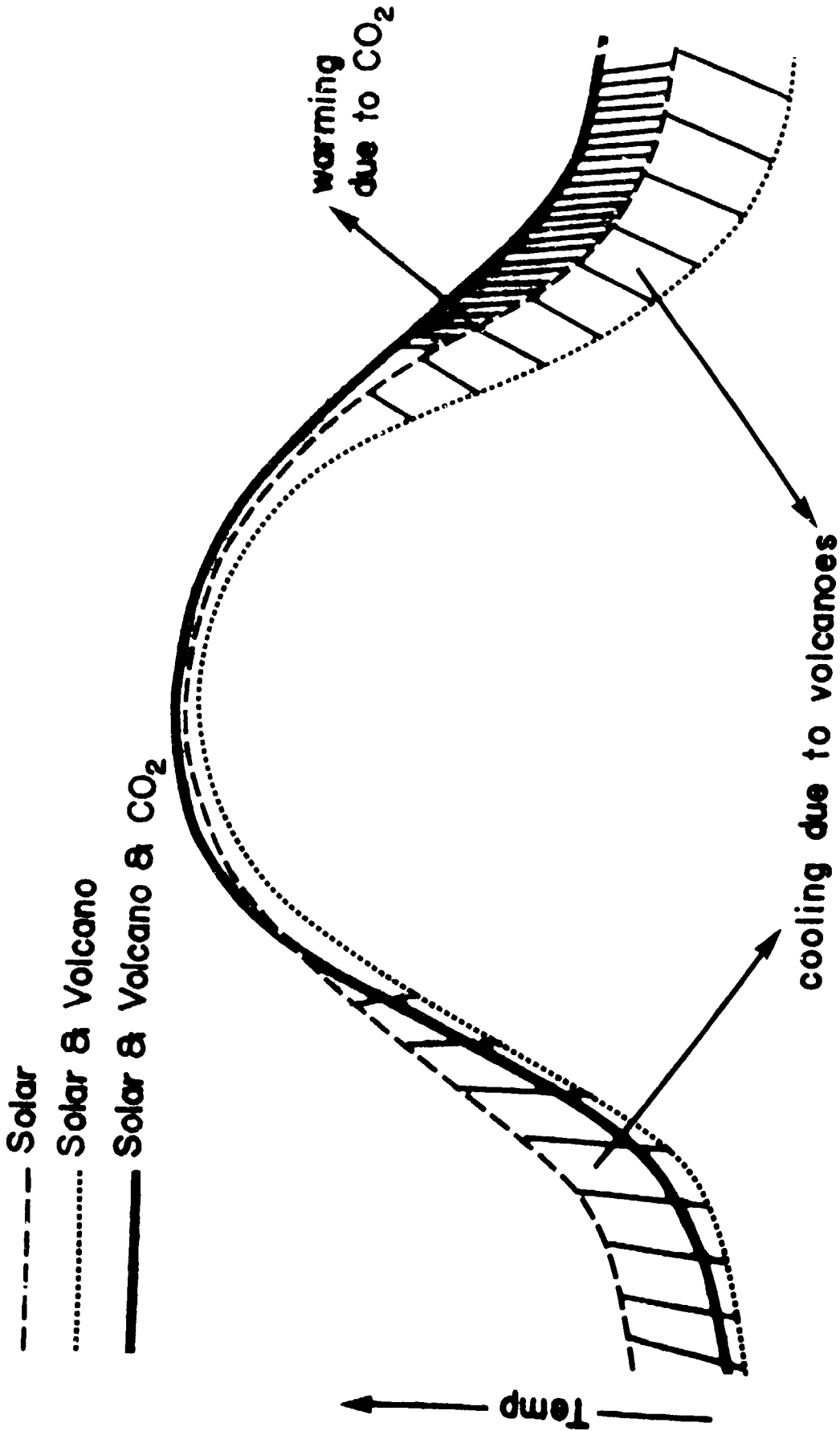
Proposed Schematic of Northern Hemisphere Surface Temperature

FIGURE 21

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