PAPERS IN PHYSICAL OCEANOGRAPHY AND METEOROLOGY

PUBLISHED BY

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

AND

WOODS HOLE OCEANOGRAPHIC INSTITUTION

VOL. IX, NO. 1

REPORT OF THE FIVE-DAY FORECASTING PROCEDURE, VERIFICATION AND RESEARCH AS CONDUCTED BETWEEN JULY 1940 AND AUGUST 1941

BY

H. C. WILLETT

WITH CONTRIBUTIONS BY

R. A. ALLEN
J. NAMIAS

CAMBRIDGE AND WOODS HOLE, MASSACHUSETTS

November, 1941

CONTENTS

INTRODUCTION

The present report is intended to cover fully the activities of the long-range forecast project both at the Massachusetts Institute of Technology and at the U. S. Weather Bureau in Washington, between July 1, 1940, and August 1, 1941. It includes all material bearing on the activities of the current fiscal year which has appeared in the three progress reports that were written during the year. The report is in four sections.

Section I outlines the administrative set-up of the project and its transfer from the Massachusetts Institute of Technology to the U. S. Weather Bureau in Washington, indicates the general purpose of the project, outlines the program of routine synoptic and statistical work which is maintained as a necessary part of the five-day forecast service, and lists the personnel which has been available to carry on the project.

Section II covers in some detail the five-day forecast procedure as practiced during the past year, including one illustrative case selected and discussed by Mr. Namias. The discussion of the five-day forecast procedure is concluded with some remarks on the significance of the results obtained by the basic method and a summary by Mr. Allen of the success of the forecasts as shown by the statistical verification of the forecast temperature and precipitation anomalies.

Section III contains a brief discussion of each of the special investigations made during the past year which bear on the five-day forecast problem. For the most part, the results of these investigations were not obtained soon enough to be incorporated in the forecast procedure outlined in Section II.

Section IV sets forth recommendations for further theoretical, synoptic and statistical research which is needed to develop and extend the five-day forecasting technique which has been developed by this project.

SECTION I. ORGANIZATION OF PROJECT

A. Administrative Set-up of the Long-range Forecast Project

The five-day forecasting unit was established at the Massachusetts Institute of Technology at the beginning of the fiscal year, July 1, 1940, as a cooperative project between the Weather Bureau (U. S. Dept. of Commerce), the Agricultural Marketing Service (Bankhead Jones Funds, U. S. Dept. of Agriculture), and the Massachusetts Institute of Technology.

As set up at M.I.T., the project was under the general supervision of Dr. S. Petterssen as head of the Institute's meteorological department, and under the immediate direction of Dr. H. C. Willett.

During the winter it was decided by the Weather Bureau that the best interests of the majority of those interested in the long-range forecast project would be served by transferring the complete five-day forecasting unit to the central office in Washington, D. C. This transfer was effected about May 1 without interruption of the regular issuance of five-day forecasts. Much of the personnel employed on the project was transferred with the project to Washington. However, numerous changes were made at this time among the assistants engaged in the synoptic and statistical work, not to mention changes in the routine itself, as pointed out under C and D of this section.

At the time of this transfer, the project was established as a section of the Scientific Services of the Bureau. The scientific program remained under the immediate direction of Dr. Willett, but with the transfer of the project to Washington its general supervision has, of course, been taken over by the Chief of the Bureau.

When the transfer to Washington of the entire forecasting unit was effected, a small group remained at the Massachusetts Institute of Technology to complete certain statistical research which had been undertaken as supplementary to the development of the five-day forecasting technique, and to perform certain drafting and clerical work required for the preparation of needed base maps and statistical forms, and for the printing of this report.

B. Principal Objectives of the Long-range Forecast Project

The immediate practical purpose for which the long-range forecast project was set up for the fiscal year 1941 was the semi-weekly issuance of five-day forecasts for the entire continental United States. These forecasts were to take the place of the former weekly forecasts issued by the Weather Bureau. This practical service justified the expenditure of government funds to establish the project on the necessary scale. But this practical aim, if it is to be attained with any success whatsoever, implicitly requires the existence of a program of investigation with the following principal objectives:

1. The extension of our knowledge and understanding of the factors which control the state of the general circulation of the earth's atmosphere and regulate its large scale changes. The attack on this problem may be made by statistical, synoptic, or theoretical methods; but in the last analysis, the results obtained by statistical and synoptic methods are useful only for empirical forecasting and to guide the theoretical attack. Such basic research looks toward the eventual extension of the forecasts beyond the present five-day range.

2. The development and extension of the working tools and routine procedure by which the five-day forecasts are prepared. This implies the immediate incorporation into the forecasting technique of any useful results of the basic research referred to under 1 above.

3. The extension of the forecasting technique to the ocean areas adjacent to North America. Obviously, the basic forecast must extend well across the oceans, if the entire continental area is to be correctly forecast. However, the issuance of practical forecasts for the ocean areas is a somewhat different problem than the issuance of similar forecasts for the continental area, involving as it does emphasis on different meteorological elements and the absence of a fixed network of verification stations. It is in this problem that the Navy Department is particularly interested.

4. The development of a system of rigid statistical verification of the five-day forecasts which will express satisfactorily the success of the forecasts in terms of the forecaster's skill as measured against the statistically probable verification percentage. Such verification is impossible to make over the oceans with the present scarcity of verification data, and would be difficult even with a maximum of ship reports.

C. List of Maps, Charts, Diagrams and Indices Prepared as Part of the Routine of the Five-day Forecast Service

The following list of maps, charts, diagrams and indices include all such material prepared regularly as part of the forecasting routine as distinct from such material prepared as part of special research investigations which were conducted as supplementary to the forecasting routine. Such special investigations are discussed in Section III, but where they resulted in the inclusion of additional charts or indices in the regular forecast routine, such additions are listed below. The map routine was changed appreciably from time to time during the year as a result of experience or of changes in available personnel. All such changes and the reasons for the change in each case are included in the following list. However, no reference is made in this list to the interpretation and utilization of these charts in the forecast procedure. That is treated entirely in the discussion of that procedure in Section II.

The list follows:

1. *Surface data*

a. Daily northern hemisphere weather maps. These maps are drawn once a day for the observations which are closest to the 7:30 p.m. E.S.T. map in the United States (the 01.00 G.M.T. observations). These maps are carefully analyzed by the Norwegian frontal methods. Unfortunately the spread of war has gradually reduced the network of foreign stations whose reports are obtainable to a point where the Philippines and a little of south eastern Asia is the only portion of the northern hemisphere covered by this map which does not appear on the 7:30 a.m. Atlantic-Pacific maps listed under b.

b. Daily North American surface maps. These maps, covering the North American continent and adjacent ocean areas, were prepared daily and carefully analyzed with a dense network of stations at 7:30 a.m. (E.S.T.), and somewhat less completely at 1:30 p.m. When the project was moved to the Weather Bureau in Washington, with fewer map plotters available, these maps were no longer prepared, but copies of the 7:30 a.m. North American map were supplied by the regular forecast division of the Weather Bureau. However, this arrangement proved unsatisfactory. Since the completion of the new Atlantic-Pacific base map prepared by the five-day project and printed by the Weather

Bureau early in June, an extended North American surface map has been regularly prepared and analyzed by the five-day group. This map is based on the 7:30 a.m. data, to supplement the evening northern hemisphere map. It extends from the west coast of Europe across North America into the western Pacific (140°E). It has proved very useful both as a surface map and for aerological data.

c. Charts of the five-day mean pressure distribution over the northern hemisphere for each five-day period. There are two five-day periods each week, ending with the northern hemisphere maps of Sunday evening and Wednesday evening. These mean pressure maps have come gradually to cover less and less of the northern hemisphere, just as do the daily northern hemisphere maps, until now they cover little more than the western half of the northern hemisphere.

d. Charts of the five-day mean pressure changes over the northern hemisphere from week to week, i.e., between every second five-day period. This corresponds to the time interval over which the five-day forecast extends.

e. Five-day mean pressure profiles (showing the mean meridional distribution of pressure over the northern hemisphere, from lat. 20°N to 75°N). These pressure profiles are based on all the mean pressure data available on each latitude circle, but as the extent of the northern hemisphere maps has decreased, they have come to represent not much more than the pressure profile of the western half of the northern hemisphere.

f. Five-day mean pressure change profiles, taken from the pressure profiles at one week intervals.

g. Charts showing the mean temperature and mean precipitation anomaly patterns over the United States for the five-day period just ended. The anomaly classes of each element are defined in the same terms that are used in the forecast, so that these charts serve to verify the forecast made for the period which has just ended. The temperature anomaly pattern is based on the observed daily max and min temperatures from a network of 140 stations in the United States, the precipitation anomaly pattern on the observed five-day precipitation totals from a network of over 260 stations in the same area.

h. A chart showing the distribution of the temperature departures from normal for the same network of 140 stations over the United States on the last day of the five-day period just ended, or in other words, the temperature anomaly distribution over the country at the moment when the forecast for the coming period is being made. This chart has been prepared regularly only since the early part of last winter, when it was decided that it would contribute information useful to the forecaster.

i. Verification charts showing the overlap patterns of the temperature and precipitation anomalies actually observed for the period just ended against the patterns forecast. The areas of the map where each element was correctly forecast can then be marked off, as well as areas where the forecast was one, two, or more anomaly classes in error. Such verification charts were not originally prepared for much of the past year, due frequently to inadequate assistance, but the missing numbers are now being completed for the final verification of the year's forecasts.

j. Running graphs showing the five-day mean temperatures and five-day totals of precipitation for selected districts (each verified by three selected stations) in the United States. First eight, and later ten, districts were graphed in this manner. These running graphs were in each case plotted over the normal curves of the two elements. With such graphs, it is possible to see at a glance how the weather in different sections of the country has been behaving during the current year with respect to the normal.

2. *Aerological data*

a. Daily ten thousand foot (three kilometer) level charts showing the distribution of pressure, temperature, winds and specific humidity at that level. These charts were first prepared for North America only, in the region where direct aerological observations were available. Since February the maps have been extended over the adjacent ocean areas, at least as far west as 180° and as far east as 50° W, using surface temperature and pressure readings and assuming a saturation adiabatic lapse rate to three kilometers. A few direct raob observations from the Coast Guard patrol vessels and outlying island stations can be used to check the extrapolations. The ten thousand foot pressure maps obtained in this way have been very useful, although open to some question, especially in summer, as will be noted later. At first the northern hemisphere base map was used for these extended three kilometer maps, but since early in June the new Atlantic-Pacific base map has proved to be ideally suited to this purpose. Special effort has been made since the extended three kilometer maps came into use to identify and follow the motion from day to day of the trough lines of the principal low pressure systems aloft.

b. Daily pressure change maps for the extended three kilometer pressure maps. These pressure change maps, which have been drawn only since the extended three kilometer maps were started in February, appear to have become much less consistent and useful this summer than they were in the winter. This may be due in part to the weakness of the summer as against the winter pressure systems, and also to the decreasing number of ship reports and the greater uncertainty in the pressure extrapolation in summer.

c. Daily isentropic charts for at least one selected isentropic surface. These isentropic charts include the pressure, specific humidity, saturation pressure, and value of the stream function at each station. Recently also the shear-stability ratio vectors have been added. Winds are entered wherever observed at the height of the isentropic surface. Height lines, q lines, and stream flow lines are now drawn on the extended Atlantic-Pacific base map.

d. The daily thermodynamic diagrams of all the individual soundings which constitute the aerological network.

e. Daily tropopause contour maps. These maps were started in March as part of an investigation into substratosphere conditions. They were later dropped in favor of ten kilometer pressure maps, which show almost identical characteristics.

f. Daily ten kilometer pressure maps. These maps were also started in March. When the project was moved to Washington, the preparation of high level pressure maps was extended, in support of Dr. Wulf's solar radiation and ozone investigations, to include also thirteen and sixteen kilometer maps each day as far as the radio-sonde network extends. Daily pressure change maps for all three of these high levels are also plotted. It is to be noted that as yet no five-day means are prepared for the high level pressure maps, but it is expected that this will be done for the ten kilometer level as soon as the staff of statistical assistants is brought up to full strength.

g. Charts of the five-day mean pressure distribution at ten thousand feet (three kilometers) over North America for each five-day period. These charts cover the same area and are the same base map as is used for the daily three kilometer charts, which means that since February they have extended at least from 180° to 50° W, and since early June have been plotted on the Atlantic-Pacific base map. They include also the five-day mean values of the temperature observed at the three kilometer level at all the aerological stations, as well as computed values of the mean virtual temperature between sea level and 10,000 ft. as given by the surface and three kilometer mean pressure maps. These mean virtual temperatures are determined at some 22 points of intersection of 5° meridian and 5° latitude circles in the United States. It is to be noted that as yet no weekly mean pressure change maps are prepared for the three kilometer charts, as is done for the surface mean pressure charts. This is another item which may be added when the statistical staff has been completed.

h. Five-day mean isentropic charts over North America. The means, of course, are always averages for the same isentropic surface. The analysis includes the drawing of mean height lines (pressure), q lines, and stream flow lines. These charts are prepared on the same base map as the daily isentropic charts, which is at present the extended Atlantic-Pacific base map.

3. *Running graphs of certain zonal indices of the general circulation*

The intensity of different branches of the general circulation of the northern hemisphere can be indicated by average zonal pressure differences taken between selected latitude circles. Such zonal indices, whose practical significance is discussed in Section II, may be extended completely around the northern hemisphere. They may be determined for sea level pressures or upper level pressures, for daily pressure maps or for five-day or longer period mean pressure maps, and for zonal easterlies or zonal westerlies. The practice now is to reduce the observed mean zonal pressure difference to the mean geostrophic wind velocity in meters per second, which corresponds to the observed mean zonal gradient, using the mid-point of the latitude zone. Running graphs have been plotted of the following zonal circulation indices obtained in this manner:

a. The general circulation index, often called the zonal index. This is the index of the zonal westerlies, between 35°–55° N, taken from each five-day mean northern hemisphere sea level pressure map, for all of the northern hemisphere from which mean pressure data are available. When the normal poleward pressure gradient in this zone is reversed, giving east winds, the index value is taken as negative. During the current year, this index has been variable in its extent, tending to cover less and less of the northern hemisphere as the data has become less extensive. It has therefore undergone irregular fluctuations due to variations in the extent of the data which make it unreliable as a general circulation index. It now includes little more of the northern hemisphere than does the North American index.

b. The North American index. This is the same as the general circulation index, except that it is restricted to the zone from 50°W to 180°, thus indicating the intensity of the zonal westerlies in the North American quadrant. Since the data is always reasonably complete in this quadrant, this index has not suffered this year from the fictitious variations that have affected the zonal index.

c. Daily values of the North American index. A running graph of the daily values of this index has been kept up since last fall.

d. The easterly index. This is the index of the zonal easterlies, from 35°N–20°N., taken from each five-day mean northern hemisphere sea level pressure chart. It has been restricted to the zone 40°W–160°W, due to lack of data in other regions. When the usual equatorward gradient in this zone is reversed, giving rise to prevailing westerlies instead of easterlies, the index becomes negative.

e. The three kilometer index. This is the index of the zonal westerlies at the three kilometer level, from 40°N–50°N, taken from the five-day mean three kilometer maps. For the first half of the year this index was extended only across North America, but since the extension of the three kilometer map started in February the three kilometer index has been computed from 50°W–180°. This makes it coextensive, longitudinally, with the North American surface index. It is restricted to only 10° of latitude because that is the zone in which the aerological data are a maximum.

f. Daily values of the three kilometer index. A running graph of the daily values of this index, taken from the daily three kilometer maps has been kept up since last February when the extension of the three kilometer map was started.

It might be noted that indices of the intensity of the meridional component of the general circulation may be highly significant, but such indices become meaningless without complete circumpolar observational data, which cannot be obtained at present. In Section III a discussion of meridional indices is included in connection with the special investigation of circulation indices based on the use of the Second Polar Year pressure data.

All the material listed above is displayed at the time of preparation of the five-day forecasts so that it can readily be surveyed by all the forecasters. All daily maps for the past eight days, five-day mean maps, anomaly charts and pressure profiles for the last three weeks, and all the running graphs extending back for several months are arranged and by utilizing sufficient wall space, are exhibited in such form that they can be studied with a maximum of convenience by the official and practice forecasters. To facilitate the use by the forecasters of the past five-day mean maps, more than three weeks back, for comparative reference, the entire sequence of these maps for the past year has been photostated, and small photostat copies of the maps are filed in convenient book form.

D. Long-range Forecasting Personnel and Duties

The personnel engaged in the long-range forecasting project is composed of two groups whose duties may be designated essentially as synoptic and as statistical. Both of these groups underwent considerable disruption at the time of the transfer of the project to Washington, and are not yet entirely re-established. Ultimately, however, the project should, as planned, be adequately staffed to function quite efficiently.

As set up at the Massachusetts Institute of Technology, the synoptic staff consisted essentially of the following:

1. Two forecasters (Dr. Willett and Mr. Namias) who prepared all the official forecasts, gave the forecast and the forecast post-mortem discussions, performed the analysis of the mean maps, partook in the analysis of the daily maps, and conducted or supervised the various special supplementary research investigations.

2. One full-time and one part-time synoptic assistant who took care of a large part of the analysis of the daily surface and upper air charts, and contributed to the special research investigations. It should be noted further that part of the routine analysis of the daily maps was performed by the teaching staff at M.I.T. who were not technically a part of the project.

3. One full-time radio operator with one part-time assistant to take and plot the international northern hemisphere synoptic weather broadcasts.

4. Three full-time and two part-time map plotters for the plotting and duplication of the various daily synoptic surface and upper air charts. It should be noted here also that part of this duplication of daily synoptic charts was for the use of the teaching staff at M.I.T. as well as for the five-day project.

Following the transfer of the project to Washington, the proposed synoptic staff was set up as follows:

1. Two forecasters and two assistant forecasters in training. The assistant forecasters are to acquire training and experience in all of the forecasters' duties to a point where they can take the full forecasting responsibility. The assistant forecasters have been tentatively selected, but neither was available for duty until six weeks after the transfer. Dr. Willett and Mr. Namias continue, at least temporarily, as the chief forecasters.

2. Three full-time synoptic assistants or analysts, for the regular analysis of the daily synoptic charts, both surface and aerological, and for assistance on research investigations. These men are all new to the project. Two of them have been on the job acquiring experience since the end of June, the third has not yet been appointed. Mr. Boucher was brought to Washington from M.I.T. for the months of May and June to help tide over the period of extreme shortage of assistance for map analysis.

3. The radio reception of the foreign synoptic broadcasts continues unchanged at Boston until such time as the lack of data may force its cancellation.

4. Three full-time and one part-time map plotters for the plotting of the daily synoptic charts, both surface and aerological. Three of these men were new to the project, and quite inexperienced, but the amount of such work is somewhat less than it was at M.I.T. Major Moorman has had two assistants detailed to the Weather Bureau who assisted with some of the routine and some special plotting at a time when the plotting staff was inadequate. One of the map plotters takes the dictation of forecasts. Recording of the forecast discussions is handled mechanically.

As set up at M.I.T., the statistical unit of the long-range forecasting staff consisted of one statistician (Mr. Allen), with one part-time and four full-time assistants. Of these assistants, only one was a comptometer operator. The others did tabulation, drafting, and clerical work. As set up at the Weather Bureau, Mr. Allen will have four assistants, three of whom will be qualified to operate comptometers. This qualification will serve to facilitate the work of the statistical unit. But two of the comptometer operators are not yet on the job. This has left the statistical unit so short-handed since the transfer to Washington that Mr. Allen has had to take over much of the routine work, and in general both the routine statistical work on forecast days and the special statistical program has been considerably retarded.

The function of the statistical unit of the five-day forecast section is to perform all computations of a routine nature in connection with the preparation and verification of the five-day forecasts, and to conduct all statistical investigations which bear on the formulation and checking of relationships in the atmosphere which may be suspected to be of value in the preparation of the forecasts. Broadly speaking, there are thus two types of work carried on by the statistical group; first the routine preparation of mean data, circulation indices, verification charts, etc. for the week-to-week forecasting operations, and second, the preparation and statistical analysis of special data for research purposes. The distinction between these types is not always clear, however, for the reason that new material of an initially research character is often incorporated into the routine forecasting and prepared regularly thenceforth. Other data, such as temperature and precipitation normals, have been computed month by month during this first year, but will be available for use without revision in future years.

The material prepared as a regular routine is discussed under sub-headings below. It is used for the preparation of the mean charts, circulation indices, pressure profiles and running graphs listed under C of this section.

a. *Tabulation and averaging of data for the mean charts.* The mean charts prepared consist of mean sea level pressure for the Northern Hemisphere, mean temperature and pressure at 10,000 feet above sea level and mean pressure, specific humidity and stream function on a given isentropic surface. For the pressure charts, daily pressures as interpolated from isobars are tabulated for the intersections of 5° latitude circles with 5° meridians, then on forecast days averages obtained for the preceding five-day periods. For the mean isentropic chart the three elements are entered on tabulation forms for each of the stations reporting isentropic data, then averaged on the forecast day as soon as that day's data has been entered. The work of tabulating and averaging for these three charts totals about 30 man-hours per week. This efficiency can be obtained only by having the tabulation done by persons with some training in meteorology and the averaging done by comptometer operators.

b. Tabulation and averaging of data for verification—preparation of the five-day mean temperature and precipitation anomaly charts. The verification of the temperature and precipitation forecasts is carried on in a nearly complete manner as discussed in the last part of Section II. As soon as possible after the end of each forecast period, however, charts are prepared for the post-mortem discussion showing the distribution over the United States of five-day mean temperature departure from normal and five-day total precipitation. The temperature departure charts are based on 140 stations and the precipitation charts on over 260 stations. Mean temperatures are derived from the average of the five daily maxima and five night minima. Normals for the stations are based on records for all available years. For many stations normals for five-day periods must be interpolated from monthly normals. This involves considerable labor of comparison between stations to evolve a proper interpolation curve. Much of the work of preparing verification charts during this first year has been devoted to obtaining normals.

The max and min temperatures for the current departure charts are obtained from the teletype reports, tabulated in a form convenient for averaging, and on forecast days averaged for the preceding five-day period. The precipitation amounts are tabulated in similar fashion and totaled for the five-day period. The total labor of tabulation and averaging is about 30 man-hours per week. After plotting the temperature departures and precipitation totals, lines are drawn to indicate the extent of the areas classed as much below normal, below normal, near normal temperature, etc. and as heavy, moderate and light precipitation. This analysis requires careful comparison of the observed values as plotted on the chart, with the numerical limits which define the classes, together with a knowledge of the representativeness of the station observation.

c. Computation of class limits of the anomaly charts. The methods of computing the numerical limits of the class intervals much below normal, below normal, near normal, above normal, and much above normal for temperature, and heavy, moderate and light for precipitation as used in forecasting temperature and precipitation, are explained in the last part of Section II. The work has been done month by month throughout this first year, and has taken nearly all of the time of the comptometer operator aside from the averaging of data as discussed above. Most of this time has been put on the precipitation limits, which also are the most reliable as explained later. Once these limits have been obtained in a satisfactory fashion, however, they may be used year after year.

d. Computation of indices, profiles, etc. On each forecast day there are prepared the daily and five-day mean indices of the velocity of the westerlies at sea level and at 10,000 feet and the five-day mean index of the velocity of the subtropical easterlies, for the preceding five-day period. Computation of these indices requires tabulation of the observed pressures along the latitude circles involved, averaging and obtaining the pressure difference. This routine is assigned to the statistical clerk, who also plots the values on a running graph.

e. Running graph of temperature and precipitation at selected stations. The five-day values of mean temperature and total precipitation averaged for three representative stations in each section are plotted on a time scale for each of ten sections of the United States. These running graphs enable the forecaster to see at a glance trends of longer period than five days which may exist for a part of the country.

Averages for these graphs are obtained by the comptometer operator at the same time as values for the verification charts of temperature and precipitation.

f. Miscellaneous items listed under C. Several other charts and means are prepared regularly on forecast days. A chart is prepared showing the distribution of mean temperature departure from normal for the United States for the 24 hours preceding the time of making the forecast. Mean virtual temperatures of the air column between sea level and 10,000 feet are computed and plotted at 22 points on the five-day mean 10,000 foot chart. Zonal pressure profiles are computed and plotted both for sea level and for the 10,000 foot level.

The time and man-power available for non-routine computations has been much limited during the past year. The statistical verification of forecasts has accounted for most of that available. The only major project of a research nature was that relating precipitation to various characteristics of the mean charts, such as curvature of isobars, available moisture, etc., but this project was carried on with a limited amount of statistical assistance. (See Section III, Smith's investigation of precipitation anomalies.)

The statistical verification of the forecasts is discussed in detail in Section II and will not be amplified here except to point out the way in which the work fits into the other duties of the statistical unit. The temperature and precipitation verification charts (see b above) form the principal basis of verification. Overlap charts showing both the forecast class and observed class are prepared by the statistical staff during spare moments between other duties, and are measured with a planimeter to determine the proportion of the area of the United States in each of the 25 possible temperature and 9 possible precipitation groups. Further computation shows the proportions to be expected by chance, and the final score for the forecast.

Forecasts of latitude, longitude and intensity of the principal semi-permanent pressure centers were checked by various statistical tests. Much of this testing of forecasts is still in process of computation, and it is not yet possible to draw definite conclusions.

SECTION II. PREPARATION OF THE OFFICIAL FIVE-DAY FORECASTS

A. Description of Forecast Service and Forecasting Routine

The five-day forecasts are prepared by the forecast group twice each week, on Mondays and Thursdays. They are formulated to cover the period from 7:30 p.m. of the following day (Tuesday or Friday) for five full days, up to 7:30 p.m. Sunday or Wednesday. The information is sent directly to each of the eleven weather bureau district forecast centers, as well as to a few other weather bureau centers.

The information which is transmitted to each district forecast center in the afternoon or evening of each forecast day includes the following:

1. The five-day mean pressure data from the latest northern hemisphere mean map.

2. In winter the five-day mean pressure data from the latest three kilometer mean map.

3. In summer the five day mean values of the pressure (height) and mixing ratio (w) from the latest mean isentropic chart.

4. The general outlook, which includes

(a) The forecast value of the zonal index and a brief description of the principal features of the mean pressure distribution (general circulation pattern) over the northern hemisphere as forecast for the coming period. This can now include only the western half of the northern hemisphere.

(b) A brief description of the corresponding mean pressure distribution as forecast for the three kilometer level for the coming period.

(c) A brief description of the mean moisture pattern as forecast for the mean isentropic chart for the coming period. All of these descriptions of mean circulation patterns as forecast for the coming period are taken from the mean prognostic charts whose preparation is discussed at length in B of this section.

5. The general forecast, in which are transmitted the boundaries of the forecast temperature and precipitation anomaly patterns over the entire United States for the coming five-day period, as well as a brief explanation of the reason for expecting the principal anomaly areas. The anomaly patterns are taken from the prognostic anomaly charts, the preparation of which is discussed at length in B of this section.

6. The complete district forecast as prepared for the particular district served by that forecast center.

The wording and elaboration of the five-day forecasts for public consumption, as well as the handling of their distribution, is left entirely to the district forecaster. This is usually taken care of on Tuesday and Friday mornings, after the completion of the daily forecasts. Furthermore, the district forecaster is at liberty to change even the basic forecast as prepared by the five-day group if it seems to him to be warranted. He may decide to do this either on the basis of the latest daily maps which are a full day later than those which are available when the forecasts are first prepared, or he may do it on the basis of his more extended local experience. But whether the basic forecast is changed or not, some elaboration of the forecast is necessary if the public is to make full use of it. This follows from the statistical nature of these five-day forecasts, as will appear in the explanation of the forecasting technique which is outlined under B of this section.

Unfortunately a large part of the synoptic and statistical work which goes into the preparation of a set of five-day forecasts has to be performed on the forecast day. On the other days the routine analysis of all the daily maps is performed regularly, and the daily values tabulated in readiness to take the five-day means. But since the last set of daily maps to be included in the five-day means is the set analyzed on the morning of the forecast day, the tabulation cannot be completed nor the averaging performed until the analysis of the charts of the current day is completed. Consequently the plotting and subsequent analysis of the current maps must be started on forecast days about five hours before the official five-day forecaster can expect to get any of the five-day mean maps plotted and ready for analysis. At present the earliest time at which the official forecaster can expect to get to work on the analysis of the mean maps is about ten o'clock in the morning.

The analysis of the five-day mean maps (northern hemisphere pressure, northern hemisphere pressure change, three kilometer, and isentropic) takes the official forecaster a full two hours, perhaps a little more in winter.

The man who presents the post-mortem discussion of the official forecast prepared one week previously, which is verified by the five-day mean maps just completed on the current forecast day, should be allowed one and one half hours after the completion of the analysis of the current mean maps, and preferably one hour after the completion of the temperature and precipitation anomaly charts for the period just ended, in order properly to prepare the post-mortem discussion. At present the completion of both the mean maps and the anomaly charts for the period just ended is likely to be so delayed, due to the short-handed condition of the statistical staff, that the post-mortem man is given entirely too little opportunity to consult them before giving his discussion. The post-mortem discussion is intended to evaluate every aspect of the forecast which has just been verified, including the constructive criticism of the forecast offered during the discussion at the time the forecast was made, and to suggest possible reasons for the failure of any part of the forecast. It is therefore considered an important step in the preparation of the current forecast for the coming five-day period. The discussion is not expected to run beyond an hour's time. A record is kept of all the post-mortem discussions either by complete mechanical recording or in the form of a written summary prepared by the man giving the discussion.

Upon completing the analysis of the current mean maps, the official forecaster starts immediately on the preparation of the current five-day forecast, while the forecaster who prepares the post-mortem puts his discussion in final form. Following this discussion, the official forecaster requires a minimum of two and a half hours, making a total of about four hours altogether, to complete the official five-day forecast and to prepare the forecast discussion. The complete official forecast includes the circulation index forecasts, the prognostic mean charts, the prognostic anomaly charts, the general outlook and forecast and the complete district forecasts for the entire country, as explained in detail under B of this section.

During the two and one half hours between the post-mortem and the forecast discussions, while the official forecaster completes the current forecast, the assistant forecasters and synoptic assistants prepare their own practice forecasts in the form of independent prognostic mean charts and prognostic anomaly charts. Under the present procedure, however, one of these men, instead of making his own practice five-day forecast, assists the official forecaster by analyzing carefully the latest (7:30 a.m.) complete Atlantic-

Pacific surface map, by drawing daily prognostic charts to fit the official forecaster's prognostic mean charts, and by taking over the formulation of the detailed district forecasts. This preparation of daily prognostic charts and division of the official forecaster's responsibility is a recent innovation the purpose of which is indicated under B below. The formulation of the district forecasts may be delayed until after the forecast discussion, to facilitate the incorporation of suggested changes.

When the official forecast has been completed, the forecaster gives the forecast discussion, in which he outlines his reasons for each step by which he has arrived at his final forecast as expressed by the prognostic anomaly patterns, and indicates how the daily prognostic charts fit into the mean prognostic patterns. This forecast discussion is not expected to exceed an hour and a half in time. The last part of it is devoted to constructive criticism from the various forecasters present, which may result in some modification of the official forecasts. The forecasts are not transmitted until the discussion is completed and any desired changes incorporated. Records of all the forecast discussions have been kept either by mechanical recording or in the form of a written summary prepared by the forecaster. After the close of the forecast discussion, there remains only the final formulation of the district forecasts and their transmission to the forecast centers to complete the forecasting routine.

B. Explanation of the Five-day Forecast Technique

1. *Basic facts concerning the general circulation*

Basically the five-day forecasting technique is built up entirely on the conception of the general circulation of the earth's atmosphere which has been developed in recent years by C.-G. Rossby and his collaborators, and which Rossby (1) has recently summarized. Rossby's complete discussion cannot be incorporated into this report (see enclosure I), but it is necessary at this point to summarize a few of the fundamental concepts of his theory of the general circulation to make the following discussion intelligible. These concepts are stated here simply as hypothetical facts, their justification, including all illustrative charts and diagrams must be looked for in Rossby's writings (Rossby, 1, 2, 3).

a. The general circulation of the earth's atmosphere is maintained by the unequal supply of heat to the atmosphere in equatorial and polar latitudes. The intensity of this circulation is proportional to the inequality of the heat supply. The principal direct (insolational heating) heat source in the atmosphere is located at the earth's surface and lower atmosphere in tropical and subtropical latitudes. Important secondary heat sources are found wherever there occurs systematic large scale condensation of the water vapor which is supplied to the atmosphere by surface evaporation in the primary heat source region. Principal cold sources in the atmosphere (direct radiational loss of heat to space or by conduction to the earth's surface) occur quite generally throughout the troposphere in polar and north temperate regions (except where large scale condensation occurs) and quite generally in the upper troposphere in south temperate and subtropical latitudes, except in the very cold uppermost part of the troposphere in the tropics. Thus the general circulation must effect a poleward transport of heat at all latitudes, and an upward transport in middle and lower latitudes. Much of this heat may be transported in the latent form as water vapor, being released by condensation.

b. The effect of the earth's rotation prevents the existence of the single thermally direct cell of the general circulation which would otherwise prevail on either hemisphere between equatorial and polar regions. Instead, the effect of the earth's rotation together with the operation of surface and internal friction in the atmosphere leads to a breakdown of the single thermally direct circulation cell of either hemisphere into three distinct cells which may be characterized as follows:

(1) The subtropical cell, a thermally direct cell extending roughly from the equator to the middle of either subtropical high pressure belt. This cell is characterized by zonal easterly winds at the surface which progress equatorward as they slowly rise to high levels. At high levels they begin to spread poleward, with slowly diminishing westward velocity, such that in the subtropics, above the surface high pressure belts, they appear as west winds which are slowly sinking to lower levels, where part of the air returns again toward the equator, and part mingles with the westerlies of middle latitudes. The principal heat source in this cell is found near the ground in the rising surface easterlies, and in the heavy condensation of water vapor which occurs in the tropical convection in this rising easterly current. The principal cold source is found at upper levels, especially at the northern edge of the cell, where the sinking of the westerlies aloft is a maximum.

(2) The polar cell, a thermally direct cell extending roughly from the pole to the circumpolar belt of low pressure in sub-polar latitudes which marks the northern limit of the westerlies of middle latitudes. This cell is characterized by a shallow layer of sinking and southward moving circumpolar easterlies at the ground, and a strong circumpolar westerly current moving slowly poleward aloft. At its southern edge the easterlies are in part drawn into the westerlies of middle latitudes, and in part may be sufficiently warmed to rise and join the poleward moving westerlies aloft. At this southern boundary of the polar cell there is a systematic ascent by the warm moist air of the westerlies from lower latitudes over the cold polar easterlies, as the warm air progresses northward into the circumpolar cell aloft. This zone of interaction is the polar front. This air mass interaction leads to systematic heavy condensation of water vapor along the southern edge of the circumpolar cell, which presumably constitutes the principal heat source by which its circulation is maintained. Most of the remainder of the cell probably constitutes the cold source.

(3) The zonal westerlies of middle latitudes, a thermally indirect cell or forced circulation extending roughly from the subtropical belt of high pressure to the subpolar belt of low pressure (polar front). This cell consists of westerly winds which tend to increase from lower to higher latitudes, and from the ground upward to the upper troposphere. The surface layer of these westerly winds has a northward component of motion on the average. At upper levels the westerlies of middle latitudes have on the average a southward component of motion which brings this air to the zone of descending motion in the subtropical high pressure belt, whence part of it returns northward in the surface westerlies, and part continues southward in the surface easterlies of the subtropical cell. At the northern edge of the zonal westerlies along the polar front a large part of the northward moving surface air ascends and continues poleward in the upper branch of the polar cell, as noted above, while part of it returns southward in the upper branch of the zonal westerlies.

This middle thermally indirect cell is driven principally by the polar cell, which imparts some of its strong eastward momentum aloft to the upper level westerlies at lower latitudes by means of internal friction (large scale horizontal eddy turbulence). There may also be some similar drive exerted by the subtropical cell, but it is doubtless much weaker. This driving of the upper level westerlies in middle latitudes from the northern cell tends to produce supergradient west winds aloft, and thus to maintain the mean southward motion aloft against the pressure gradient. The establishment of an equilibrium poleward pressure gradient aloft is prevented by the continuous sinking of air at the southern edge of the zonal westerlies. Surface friction permits poleward progress of the surface air in the zonal westerlies. It also appears that the strong cyclogenesis along the polar front which necessarily follows the southward deflection of the surface cold polar easterlies into the zonal westerlies (see p. 21) must help to intensify the circulation of the zonal westerlies, or to drive the middle cell.

c. The intensity of the general circulation as a whole evidently depends upon the intensities of the three cells which constitute it. But it is not to be expected that the circulation of each of these cells will vary its intensity in exact correspondence one with another. Rather it is to be expected that the two direct cells would be affected first, and that the indirect cell would adjust itself with some lag. Furthermore the two direct cells should not react together. The tropical cell should react more directly to changes in solar heating, the polar cell more directly to changes in the general circulation pattern affecting the transport of warm moist air to higher latitudes. The indirect cell of the zonal westerlies can be expected to follow more closely the intensity variations of the polar than of the tropical cell. But in any case, since the middle cell is driven by the other two, an index of its intensity is probably the best index of the intensity of the general circulation. This is especially true insofar as this index is to be used to forecast the general circulation pattern in middle latitudes.

Zonal indices may be used to express the circulation intensity of each of the three cells of the general circulation. Zonal indices expressing either the mean latitudinal pressure gradient, or better, the mean geostrophic zonal wind velocity in each cell of the general circulation may be computed wherever the pressure field is known. If observational data were available, six such zonal indices would be very useful to have, one for each of the following:

(a) The subtropical easterlies at sea level

(b) The subtropical westerlies (anti-trades), at some upper level in the northern portion of the tropical cell

(c) The zonal westerlies of middle latitudes at sea level

(d) The zonal westerlies of middle latitudes at some upper level, perhaps at three kilometers

(e) The polar easterlies at sea level

(f) The circumpolar westerlies at some upper level, the same as that chosen for the zonal westerlies of middle latitudes.

If such indices were available, then according to the picture of cellular interaction suggested above, index changes in the circumpolar westerlies aloft should precede similar changes of the zonal westerlies aloft and of the zonal westerlies at sea level in middle latitudes. Other lag relationships might be expected. Up to the present, however, the available data have permitted the computation only of the sea level zonal indices. A three kilometer index of the zonal westerlies in middle latitudes is now available for the western half of the northern hemisphere.

d. It is a fact of observation that the three cells of the general circulation do not show an unbroken zonal structure, but are broken longitudinally into smaller cells. These cells are the semipermanent centers of action, such as the Atlantic and Pacific anticyclonic centers in the subtropical belt of high pressure, and the Aleutian and Icelandic cyclonic centers in the circumpolar belt of low pressure. As shown by five-day mean pressure maps, these centers of action change their intensity from week to week, shift westward or eastward from their normal positions, and not infrequently break into two separate centers of less intensity, one east and the other west of the normal central position. Such variations in the general circulation pattern control the longer period weather anomalies with which weather forecasts extending a week or more into the future are concerned.

At upper levels in the zonal westerlies the closed isobars of the surface cyclonic and anti-cyclonic centers of action tend to open out into the normal poleward pressure gradient aloft. Thus over the surface cyclonic centers are found troughs of low pressure, where the westerlies dip strongly southward, and over the surface anticyclonic centers ridges of high pressure, where the westerlies dip strongly northward. Thus there is seen to be a set of more or less stationary waves in the westerly flow aloft corresponding to the large surface pressure centers. This wave pattern undergoes changes of wave length, frequency, amplitude and position corresponding to the changes shown by the surface pressure pattern.

The semi-stationary character of this wave system, tied as it is to the semi-permanent surface centers of action, indicates beyond doubt that it is produced by the arrangement of continents and oceans. The oscillations in the westerlies aloft are produced principally by the thermal and perhaps to some extent by the frictional influences of the land and water surfaces on the overlying atmosphere. This is conclusively shown by the differences between the circulation patterns of the northern and southern hemispheres. Rossby (1) has shown, on the basis of the conservation of absolute vorticity, that such oscillations set up in the zonal westerlies will be stable, in that a southward moving flow of air in the westerlies will be deflected cyclonically northward again, whence as a northward flow it will be deflected anti-cyclonically southward to repeat the oscillation. On the other hand, when an easterly current is deflected southward it tends to describe a cyclonic loop, when deflected northward, an anti-cyclonic loop.

Since air from the polar easterlies tends to be deflected southward into the region where the westerlies dip southward (upper level trough of low pressure), this southward flow of polar air tends to accelerate strongly the surface cyclonic circulation, or center of action, in that region. In the same manner, where the westerlies dip northward (ridge of high pressure aloft) the subtropical easterlies tend to be deflected northward and consequently to accelerate the surface anti-cyclonic circulation, or center of action, in that region. Thus each of these major waves appearing at upper levels in the zonal westerlies corresponds to the establishment of a strong polar cyclone on one side, a strong subtropical anti-cyclone on the other, with the establishment of a section of the polar front between the two. They represent injection points of cold polar air into the westerlies on one side and of warm moist air into the polar cell on the other side.

When the zonal westerlies are strong, the wave pattern established on the northern hemisphere is one of long wave length. The upper level trough tends to be established off the eastern edge of either continent, with a single strong cyclonic cell at sea level in a north central location over either ocean. A single strong anticyclonic cell covers the entire central and eastern portion of either ocean in middle latitudes, extending inland over the western portion of the continent.

When the zonal westerlies are weak, the wave pattern established is one of short wave length, so that the single long wave formation covering each ocean breaks into two shorter waves. In this case the subtropical highs break into two cells, and likewise each cyclonic center of action tends to break into two centers, one center being displaced eastward, the other westward, from the normal position of the single cell. Thus over each ocean there exists two frontal zones, one along the eastern edge of either continent, and one over the central or eastern side of either ocean, between the two cells of each subtropical anticyclone. Under these conditions there is a tendency for strong polar anticyclonic centers to become established over the north central portion of either continent.

When the zonal westerlies are undergoing rapid changes of intensity, or the upper level wave pattern of the zonal westerlies is changing wave length, the adjustment of the wave length to the strength of the westerlies may not be maintained. In that case the wave system is set in motion. Increase of the westerlies, or decrease of the wave length, establishes an eastward movement of the wave system. Decrease of the westerlies, or increase of the wave length, establishes a westward movement (Rossby 2, 3; Haurwitz 5, 6). Such movement of the upper level wave system leads to a corresponding displacement of the centers of action and frontal zones. Thus it is seen that important changes in the general circulation pattern may result either from the breakdown of a pattern of the single strong center of action type (high index) to one of the divided center of action type (low index) and vice versa, or merely from a longitudinal shift of any or all of the centers of an established circulation pattern. Changes of both kinds must be closely related to corresponding changes of the different zonal indices of the general circulation.

The intensity of the meridional exchange of atmosphere in the general circulation may be just as important a characteristic of the circulation as is the intensity of the different zonal cells. It determines, for instance, that transfer of water vapor from lower latitudes into the polar cell of the general circulation, the latent heat which Rossby has assumed to be the principal heat source that drives this cell, which in turn drives the zonal westerlies. It is easy to compute, for any latitude circle, on the basis of the total west-east pressure differences summed around the circle regardless of sign, a meridional index which indicates the average north-south wind velocity across that circle. Such meridional indices need not necessarily show any correspondence to the contemporary zonal indices, but they should show some correlation with the subsequent development of the circumpolar westerlies aloft, and with the still later development of the zonal westerlies, if Rossby's hypothesis is correct.

It should be noted that considerations of the state of the general circulation become much less satisfactory as a basis of long-range forecasting in summer than in winter. This happens in part because the intensity of the general circulation becomes much weaker in summer, due to the disappearance of much of the latitudinal inequality of heating of the atmosphere. Changes in the intensity of the general circulation are correspondingly reduced. Consequently the general circulation patterns lose their strong characteristics and decisive changes of character. Not only is the general circulation weakened, thereby removing much of the significance of the general circulation pattern, but it tends to be shifted poleward in all its branches. The effect of this is to bring most of the area of the United States somewhat out of the principal west wind zone, or even into the zone of the stagnant anticyclonic circulations of the subtropical high pressure belt, between the tropical and middle latitude cells of the general circulation. Furthermore, the continents and oceans in middle and higher latitudes reverse their winter thermal roles, the continents becoming relatively warm, the oceans relatively cold. Consequently the winter circulation patterns are largely obliterated, and the general circulation is too weak to establish significant patterns other than that of the relatively stationary monsoon systems which are for the most part mutually independent. Thus the forecasting technique has to be considerably modified in summer.

2. *Outline and brief explanation of the procedure followed in preparing the official five-day weather forecasts*

The following outline of the forecast procedure applies essentially to this procedure as actually practiced during the year just ended. At a few points suggestions are made as to how it may well be extended, eventually. But, in general, investigations of the past year directed to that end are not discussed, except insofar as the results have already been incorporated in the forecast procedure. All such investigations are outlined in Section III of this report. One important modification in the procedure, which was introduced at the very close of the year, is explained in full at the end of this discussion, since it was at no time the object of a special investigation, and since it has been made a permanent part of the procedure. This refers to the introduction of the use of prognostic daily maps for the five-day period.

The procedure outlined below refers essentially to forecasting under winter conditions, which the method is basically best suited to handle, as pointed out above (p. 22). At the same time reference is made at numerous points to modifications which may be entailed by summer conditions. Furthermore, the following outline is one of principles only, without reference to illustrative material. By way of illustration there follows an example of one complete forecast, with illustrative maps and charts, as originally prepared and discussed by Mr. Namias.

The preparation of the five-day forecast may be considered in four principal steps, as follows:

(a) The forecast of the intensity of the general circulation in each of its major branches, as expressed by the different zonal indices. It is with the intensity of the zonal westerlies that the forecast is most directly concerned.

(b) The forecast of the general circulation pattern as expressed by the basic prognostic charts.

(c) The preparation of the prognostic temperature and precipitation anomaly patterns for the continental United States.

(d) The formulation of the final forecasts for distribution, including the general outlook and forecast and the district forecasts.

a. Circulation index forecasts

The problem of forecasting the intensity of the general circulation in each of its principal branches, by forecasting numerical values of each of the circulation indices for the coming five-day period, may be attacked from three different angles, the physical, the statistical, and the synoptic. The physical attack is concerned with conditions affecting the heat and cold sources in the atmosphere (see pp. 18–19). Such conditions may be variations in the solar constant, variations of ozone or other substances in the upper atmosphere which affect the absorption or scattering of solar radiation, and most particularly variations in the state of the general circulation which affect the transport of water vapor (latent heat) northward into the polar cell. However, the physical basis of forecasting changes of the general circulation has not, as yet, been developed to a point where it has found any application in the regular forecast procedure. But the possibility of using some index of the northward transport of water vapor is under investigation (Section III, p. 73). Further investigation of the physical controls of the general circulation is urgently needed.

Up to the present time, the statistical attack is the only independent method applied to the forecasting of the mean state of the general circulation for the coming five-day period. The forecast is expressed in terms of numerical values of the different zonal indices of the general circulation. Up to the present, forecasts have included only surface index of the zonal westerlies (referred to usually as the northern hemisphere zonal index), the three kilometer index of the zonal westerlies (available only from 180°–50°W) and the surface zonal easterly index. However, statistical investigations have been under way looking to the use of more and better indices (Section III, p. 71).

The statistical method of forecasting these indices depends on the use of the following:

(a) Time-graphs of the five-day mean values of the three indices for several months past. These can frequently be extrapolated on the basis of recent regular periodic changes. This method is much more successful in winter than in summer.

(b) Time-graphs of the daily values of the three kilometer index and surface index of the westerlies in the same longitude zone (called the North American index). These daily graphs are used to show whether the latest daily variations of the indices are in line with or indicate a departure from the proposed extrapolation of the five-day mean curves.

(c) Correlation showing persistence of index trends, or lag relationships between indices, or lag relationships between partial (quadrant) indices and total or other quadrant indices. Such correlations have proved of very little use during the past year. Aerological data is so restricted that almost nothing is available in the way of reliable upper level indices. Correlations of surface indices based on the polar year data have just been completed (Section III). The best lag relationships have been found between index changes in the Asiatic quadrant and subsequently in other quadrants or over the hemisphere as a whole (Section III, p. 72; also Willett 1, p. 52). But during the past year data from the Asiatic quadrant has been so incomplete that the determination of Asiatic quadrant indices has been quite impossible.

(d) Northern hemisphere mean pressure and pressure change profiles. These pressure profiles, and pressure change profiles, frequently show circumpolar waves of positive and negative pressure change which progress in sequence, sometimes for several weeks at a time, from pole to equator and less frequently from equator to pole. The regular progress of these pressure waves, coupled with the tendency of poleward moving waves to increase in amplitude, and equatorward moving waves to decrease in amplitude, is very useful in forecasting numerical values of the zonal indices. Circumpolar pressure waves of this type usually go with rather large and regular oscillations of the northern hemisphere zonal index. When these oscillations run in a short period of two weeks, as occurred at times last winter and spring, then the five-day mean pressure change maps at weekly intervals show a striking reversal or oscillation of the isallobaric pattern between high and low latitudes. A particularly useful aspect of these weekly oscillations of the isallobaric pattern, once they are established, is that it applies not only to the zonal arrangement of the isallobaric pattern, but to the individual isallobaric centers which frequently reverse their signs from week to week almost without change of position, or with only small progressive displacements. The difficult problem is to decide when such an oscillation is going to break down.

It is obvious from the character of all these statistical indications which are used to forecast the state of the general circulation as expressed by the circulation indices, that they are useful only as long as the circulation is undergoing fairly pronounced and definite changes with some degree of regular continuity. The period and amplitude of the changes need not be too regular, as long as the progress through an accepted cycle of change is continuous. This is much more likely to be the case in winter than in summer, when, for reasons already pointed out (p. 22) the general circulation becomes relatively weak and local (monsoonal) in character, with a tendency to small and irregular changes. Consequently the statistical method of forecasting the index changes becomes comparatively useless in summer.

The synoptic method of forecasting the zonal indices is not an independent method, in that it depends on the second step of the forecast procedure, that of forecasting the general circulation pattern. It has been pointed out that the intensity of the general circulation, especially the zonal westerlies, determines to a considerable extent the general circulation pattern of the centers of action. But it is also possible to forecast the general circulation pattern from the synoptic indications of all the latest five-day mean maps and daily maps as to the probable development and movement of each of the centers of action. Actually the general circulation pattern, as is explained below, is forecast in part on the basis of the statistical forecast of the zonal indices, and in part on the above-mentioned synoptic indications. If the synoptic indications lead to a pattern which is not consistent with the values of the zonal indices forecast statistically, then either the forecast of the zonal indices may be changed (the synoptic method), or the synoptic indications may be disregarded, or a compromise value of the zonal indices and a corresponding compromise general circulation pattern may be accepted for the forecast. But in any case, the circulation pattern as finally represented on the basic prognostic charts, must agree with the index forecasts. This can be given a quick quantitative check simply by computing the values of the indices from the prognostic charts as drawn, and comparing them with the values forecast. This is the first of a number of checks which have been devised to assure that the complete five-day forecast shall be internally consistent in all its parts.

b. The basic prognostic charts

The basic prognostic charts, the drawing of which constitutes the second step in the five-day forecast procedure, consist of the five-day mean sea-level pressure distribution over that part of the northern hemisphere from which daily weather observations are currently obtainable, the five-day mean three kilometer pressure from the western Pacific to the eastern Atlantic, and the five-day mean pattern of isopleths of the mixing ratio w as forecast for the next mean isentropic chart. The order in which these prognostic charts are drawn is not rigidly fixed, the forecast procedure being somewhat elastic at this point. The isentropic moisture pattern is always drawn last, but the two pressure maps, surface and three kilometer, have really to be considered together. The practice has been in the past to draw the surface map first. But that practice has been followed only because the surface maps covered most of the northern hemisphere, while the three kilometer maps were restricted to only part of North America. Actually the flow pattern aloft as shown by the three kilometer pressure distribution, with its system of standing or moving waves, represents directly in its basic elements the true state of the general circulation which is reflected indirectly in the sea-level pressure distribution.

As the sea-level mean pressure maps have gradually become more restricted in the territory they cover, as the three kilometer maps have been extended to include most of the Atlantic and the Pacific, and as the advent of the summer season has weakened the characteristics of the general circulation pattern observed at sea level compared with that observed aloft, it has become more customary to draw the three kilometer chart first. Since this is the more logical procedure, other things being equal, it is followed in this discussion.

The drawing of the prognostic three kilometer chart depends principally on the latitudinal spacing of the isobars (strength of the poleward pressure gradient) the position, number, and spacing of the pressure troughs and ridges aloft (i.e., orientation and wave length of the flow pattern aloft) and the amplitude of the trough formations. These characteristics are based largely on the index forecasts. The poleward pressure gradient is directly proportional to the three kilometer index as forecast. The number and spacing of troughs and ridges depends upon high, low or intermediate index forecasts. The pressure patterns corresponding to different index values are not rigidly defined, but experience gradually teaches an appreciation of the basic patterns which are permissible with different index forecasts. Usually the pattern and index of the current week serve as a starting point. When a radical increase or decrease of the index is forecast, then a radical lengthening or shortening of the wave length can be expected, and probably also, due to the slowness of the readjustment of wave length to the zonal westerlies, in the first case there occurs an eastward displacement of the wave system and the principal centers of action, in the second case a westward displacement. In the first case single large surface pressure centers are likely to be formed (see p. 21), in the second case small split or double centers form in accordance with the doubling of the upper level pressure troughs and ridges. It is possible to apply the formula developed by Rossby (2) to the computation of the longitudinal velocity which should be shown by these upper level pressure waves as an aid in drawing the prognostic three kilometer map. But it is only recently that H. Wexler has standardized and simplified the technique of making this computation to a point where it can be made a part of the forecasting routine (Section III, p. 76) so that as yet it has received no practical test.

When the forecast of the zonal indices calls for little change from the current week, then the basic trough pattern of the three kilometer map is little changed, except that if the system has been in motion during the current week, similar motion can be expected to continue.

The amplitude of the troughs and ridges as forecast in the prognostic three kilometer chart is an important element of the forecast. In general, with a strong circulation, the isobars are crowded and the wave pattern of the isobars long and flat, so that the north-south component of the air flow is usually small, and the surface pressure centers are oriented largely along west-east axes. When the circulation is weak, the isobars are spread apart, while the wave pattern of the isobars shows very large amplitude with a short wavelength, so that the north-south component of the air flow is large, and the surface pressure centers are oriented largely along north-south axes. Under these conditions it is not uncommon to find even on the mean three kilometer map a closed center of low pressure at low latitudes, or a closed high pressure center well to the north. Such formations are important locally for the temperature and precipitation anomaly forecasts.

There are also synoptic indications which should not be neglected in drawing the prognostic three kilometer chart. Such are definite trends of development of the pressure distribution aloft which may be shown by the preceding sequence of mean three kilometer charts, ending with the current number. Especially valuable in this connection is the use of the latest daily three kilometer maps, which show whether the particular trend of development in question is continuing unabated or showing change. In the same way the latest daily maps are used quite generally in conjunction with the current mean map and prognostic chart to check to what extent the trend of development indicated from the current to the prognostic chart is verified by the appearance of the latest daily map.

Also the temperature distribution shown by the daily three kilometer charts is significant of the depth and permanence of the pressure formation. Areas of low pressure in which the three kilometer temperatures are particulartly low, or of high pressure in which the temperatures are particularly high, usually turn out to be more persistent than pressure formations in which the temperatures are less extreme. The pressure formations at three kilometers on the daily maps characterized by extreme temperatures always show up strongly on the daily ten kilometer pressure maps, and it has been remarked, though not as yet proved statistically, that pressure formations at three kilometers which appear undiminished or even intensified at the ten kilometer level are likely to prove both persistent and either stationary or only very slowly moving.

Finally, the prognostic three kilometer map must be entirely consistent with the prognostic surface map. The final adjustment of these two maps one to the other, and to the zonal index forecasts, can be made only after the surface prognostic map is drawn.

The mean surface pressure prognostic chart, which is intended to cover the northern hemisphere but which on present data can be extended only from the western Pacific to the eastern Atlantic, is based essentially on three considerations, namely; the forecast values of the circulation indices, the synoptic indications, and the prognostic three kilometer chart.

The northern hemisphere circulation patterns which are characteristic of different values of the zonal index are really much better known for the surface pressure maps than for the three kilometer maps, due to the much longer experience with surface maps covering a far larger part of the northern hemisphere. The principal characteristics of the surface pressure patterns (number and arrangement of the centers of action) for markedly high or low values of the zonal index (zonal westerlies) may be summarized as follows:

(a) High index pattern: Subtropical highs strong single cells, west-east axes, somewhat north of normal winter latitude, centered toward the eastern side of the Atlantic and Pacific, and tending to extend inland over the western United States and western Europe. Continental polar anticyclones entirely missing, or weak and centered to the north of the normal positions. Pacific and Atlantic lows single strong cells, centrally located near normal positions over southwestern Aleutians and southwest of Iceland, pronounced west-east orientation of axes with tendency of low pressure troughs to extend far inland over northern continental areas.

(b) Low index pattern: Subtropical highs weak, south of normal winter latitude, and tending to split into two cells with north-south axes, and active frontal zone between. Western cells usually located in mid-ocean, eastern cells pushed southeastward against the continents. Continental polar anticyclones strongly developed, centrally located, and tending to push southward into the continental areas. Pacific and Atlantic lows weak, split into two centers, one center located well west of the normal central position, the second center tending to be displaced southeastward against the west coast of the United States in the Pacific and against the coast of northwestern Europe in the Atlantic. These southeastern centers belong to the frontal system which develops between the two weak cells of each subtropical high.

Although these high and low index patterns are not always fulfilled in every detail, nevertheless the tendency to fulfill them is striking. A more difficult problem arises when intermediate values of the zonal index are forecast, calling for intermediate or transition circulation patterns. Usually then there are characteristics remaining of the maximum or minimum index phase which has just been experienced, and at the same time the beginning of the establishment of the minimum or maximum phase which is to come. Thus on a falling index one expects to find splitting of the sub-polar lows, one center moving westward and one southeastward, the building up of continental polar anticyclones at high latitudes, and deterioration of the strong subtropical highs. On a rising index one expects to find eastward movement and intensification of the western centers of the subpolar lows, a movement inland over the continents and filling up of the southeastern centers of these lows, a southward movement of the continental polar anticyclones leading to a fusion with and regeneration of the subtropical highs which subsequently move eastward. It must also be mentioned at this point that the key to the amount of eastward or westward movement of these centers of action which is to be expected during changes from high to low or low to high index patterns is best looked for in the three kilometer pressure maps, where the changes in the wave pattern and the subsequent movement of the wave systems, which may be computed quantitatively as indicated above, must correspond to the changes in the surface pressure pattern. Also, in general, during periods of intermediate index values or transition circulation patterns the synoptic indications which are discussed below are especially useful in helping to fix some of the more uncertain details of the prognostic surface pressure map.

The limits of the complete northern hemisphere zonal index in winter which separate low from intermediate and intermediate from high values may be set at about 0.5 and 3.0 m/s. Of course, when whole quadrants of the hemisphere map are missing, these limits are open to question. In this connection it should be mentioned that there occasionally occurs in winter a false type of low index value which is characterized not by any great weakening of the zonal westerlies, but rather by an unusually far southward location of the west wind zone. A low zonal index produced in this manner is characterized by the high index type of circulation pattern of a few large centers of action, but with the centers all displaced southward from their normal positions. This raises the question of the advisability of defining zonal indices by max-min points on the northern hemisphere pressure profile, rather than by fixed latitude zones. (See Section III, p. 72.)

In summer the values of the complete northern hemisphere zonal index tend to run smaller, and to vary less than in winter. The limits between the low, intermediate, and high categories may be set at about 0.5 and 1.5 m/s (probably raised to 1.0 and 2.5 m/s when the Asiatic quadrant is missing). Also the characteristic differences between high and low index circulation patterns are weaker, and considerably changed from the winter. It is true that the upper level wave pattern shows a similar variation in the wave length and wave velocity between high and low index patterns, but it is much weaker and over North America the zone of westerlies tends to be shifted northward into Canada. The characteristic difference of the surface pressure pattern between high and low values of the index in summer is found in the behavior of the Atlantic and Pacific anticyclones. A low index is characterized by a strong northeastward push of these anticyclones, which brings the center of highest pressure, which is then much higher than normal, far up into the Gulf of Alaska in the Pacific and west of the British Isles in the Atlantic, which gives the axes of the anticyclones a pronounced north-south orientation. Active frontal systems and low pressure troughs are likely to be found over the western portions of the continents

(Rocky Mountain and Plateau regions in the United States, western and central Europe). Moderate high pressure and hot dry conditions then prevail in the central and east central United States, with a second frontal system and low pressure trough along or off the east coast. The whole system may be shifted eastward, which extends the warm dry anticyclonic conditions inland in the west and the rainy cool cyclonic conditions into the central and eastern U. S.

With a high index the Atlantic and Pacific highs are displaced somewhat southward of their normal summer position, with moderate intensity, and a west-east orientation of the axes. A moderate development of the Icelandic and Aleutian lows is likely to take place near or somewhat north of their normal winter positions. Moderate upper level low pressure troughs are likely to be found off either coast of North America, with a flat high pressure ridge covering most of the continent between them (long wave-length for summer). Under these conditions most of the northern and central United States is free of important frontal action and is moderately warm and dry.

The synoptic indications which are considered in drawing the prognostic mean surface pressure chart are similar in character to those mentioned in connection with the three kilometer pressure chart. They include the use of the entire sequence of recent five-day mean pressure charts, and particularly the five-day mean pressure change charts, to indicate any recent systematic trends of development which may be expected to continue. The mean pressure change maps are especially valuable in this connection, because the isallobaric centers are likely to be more regular in their movement than are the isobaric centers. At times they are very useful as indicators of the probable shifts in position and intensity of the centers of action. This is especially true when the general circulation changes are taking place regularly and rapidly, in such a manner that a weekly pressure oscillation, or reversal of the pressure change pattern, is well established. In those cases not only the position but also the relative intensity of the isallobaric centers for the coming week are indicated. Frequently, however, there is a little suggestion of persistent trends in the mean maps, and trend indications always have to be used with caution, for trends frequently terminate abruptly with little warning in the trend pattern. The warning has to be looked for in the indications of the general circulation pattern.

As in the case of the three kilometer prognostic charts, the latest daily northern hemisphere maps are looked to for the latest synoptic indications of the continuance or change of trends indicated by the mean maps, or the appearance of new trends. However, here again great caution must be exercised, for when daily maps are used in comparison with five-day mean maps, it is very easy to confuse short-period daily changes with the longer period changes which are reflected in the trends of the five-day mean maps. Such a confusion of trends belonging to two different cycles of change can lead to serious errors in assuming a change of tempo of the long period trend. It is necessary to check carefully through several daily maps for short period changes before accepting the indications of the latest daily map as proof of a change in the long-period trend.

One additional synoptic indication of probable developments to come in the mean surface pressure pattern may be looked for in the temperature distribution at upper levels as shown by the latest daily three kilometer maps. Strong latitudinal temperature gradients aloft can occur with strong zonal westerlies and the set-up remains quite stable for some time in the future. But strong longitudinal temperature gradients aloft indicate strong north-south air currents, and they nearly always are associated with the continuance or development of strong frontal and cyclonic action in the zone which lies west of the warmest air and east of the coldest air aloft. This is indicated even by the most general type of correlation of rainfall and upper level temperature gradient in the eastern United States (Willett 1, p. 70).

The final check on the prognostic mean surface pressure map lies in its consistency with the prognostic three kilometer map. The close correspondence which must exist between the three kilometer mean pressure pattern (upper level flow pattern) and the sea level mean pressure pattern (general circulation pattern) has been referred to repeatedly. The sea level pressure pattern must agree with the position and form of the upper level wave pattern. But the agreement of the two systems can be checked by the distribution of the mean temperature of the intervening three kilometers of atmosphere. This mean temperature is determined at every point when the sea-level and three kilometer pressure fields are drawn. The mean temperature of the air column may be obtained at once from a table or graph. These mean temperatures are plotted directly on the prognostic three kilometer chart. If the two prognostic pressure charts are inconsistent, it is shown at once by a mean temperature distribution which is not reasonable with the indicated circulation pattern. The forecaster quickly learns by experience what constitutes a reasonable and an unreasonable temperature distribution for a given circulation pattern at a given season. To help him in this estimate he has the mean temperature values computed from all the past observed mean pressure maps at sea-level and three kilometers plotted on the mean three kilometer maps. These values can be compared directly with the observed temperature anomalies for the corresponding periods. Consequently any serious discrepancy between the prognostic sea level and three kilometer maps can be detected immediately by the unreasonable mean temperature distribution which results. This is the second rigid check which is made for internal consistency between the different elements of a complete five-day forecast. The forecaster soon leans the relative positions of the different pressure centers at sea-level and at three kilometers which are characteristic of different circulation patterns at different seasons. Normally of course low pressure centers are displaced aloft in the direction of the colder air, high pressure centers in that of the warmer air. The amount of this displacement varies as the horizontal temperature gradient, and inversely as the pressure gradient. But certain seasonal contrasts quickly come to be recognized and allowed for. For instance, in the northeastern United States the westward displacement of a low pressure trough at the three kilometer level in winter is considerable, due to the coldness of the continental air flowing southward behind the trough, and the warmth of the maritime air in front of the trough. In summer, on the other hand, the reversal of the thermal influences of the continent and ocean so completely nullifies the normal temperature contrast between a polar and a tropical current, that the sea level and three kilometer low pressure troughs may coincide exactly. Many other similar cases of seasonal contrasts between the sea level and three kilometer pressure charts are recognized.

One further point in this connection should be mentioned, namely, that the method used in the extrapolation of the three kilometer chart over the oceans is much less dependable and leads to larger distortions of the upper level pressure systems in summer than in winter. This follows in part from the fact that the pressure gradients in summer are much weaker than in winter, so that an error in the extrapolated pressure of a given magnitude produces a much greater distortion of the isobar pattern in summer, but much more importantly from the fact that whereas in winter the ocean surface temperatures in middle and higher latitudes are relatively warm, so that the assumption of a saturation adiabatic lapse rate in the atmosphere above must approximate reality rather closely, in the summer the ocean surface temperatures are frequently very cold compared to the land surfaces. This usually results in large surface temperature inversions over the coldest water areas, and a mean temperature of the three kilometer air column very greatly in excess of that obtained by the assumption of a saturation adiabatic lapse rate. This can lead to extrapolated three kilometer pressures as much as ten or twelve millibars too low in such cold water areas as the Newfoundland Grand Banks. Systematic errors of this type occur also in the mean three kilometer pressure maps, and must be allowed for. An investigation aimed at improving the method of extrapolating from the sea-level to the three kilometer pressure over the oceans has been started (p. 85).

The final step in the preparation of both the surface and the three kilometer prognostic mean charts, after their mutual consistency has been checked by the reasonableness of the distribution of the mean temperature of the intervening air column which they define, is to check the two prognostic maps with the surface and three kilometer index values as forecast statistically. This is done by a quick computation of the indices obtained from the prognostic charts. If a significant difference between the forecast and the prognostic chart values of either or both indices is found, then a revision of either the index forecasts or the offending prognostic chart is necessary, if the forecast is to be internally consistent. It is unusual, however, for an experienced forecaster to have large differences between the two sets of indices, when the prognostic charts have been carefully drawn with the index values in mind. When serious disagreement is found, the tendency is usually to change the forecast values of the zonal endices rather than the prognostic charts.

The drawing of the prognostic isentropic chart is generally, in winter, based principally on the two prognostic pressure charts, and the availability of source regions of dry and moist air. In winter there is little chance over North America for the large-scale injection of moisture from lower to higher isentropic surfaces, due to the prevailing stability of the atmosphere over the cold continent. Hence the drawing of the prognostic moisture pattern for the mean isentropic chart is mostly just a matter of estimating the prevailing advective transport of air, according to the mean pressure patterns at the surface and aloft, from the known winter source regions of moist and dry air masses. The principal moist tongues are likely to enter the United States either via the north Pacific coast from the west, or via lower California from the south, or via the Gulf or south Atlantic coast from the south or southeast. Drawing of the prognostic moisture patterns depends rather much on past experience with the analysis of mean isentropic charts for the same season.

In general the mean isentropic chart in winter is lacking in the character and usefulness that it has in summer. The prevailing westerlies generally dominate the flow patterns in winter. The individual moist tongues on the daily isentropic maps are displaced rapidly eastward from day to day. The large-scale stationary anticyclonic vortices which develop the extensive interlocking moist and dry tongues in the typical cellular patterns so characteristic of mean summer isentropic maps are entirely missing in winter. The moist tongues seldom remain in the same position long enough to be distinguishable in the five-day mean pattern. About all that remains in the mean chart is a northward bulge of the moisture lines in regions of prevailing southerly winds from a moisture source region, and a southward bulge of the lines in regions of prevailing cold northerly winds. Nevertheless, the strong crowding of the moisture lines characteristic of sharp frontal zones, and the orientation of the moisture flow pattern with respect to the height lines, are characteristics of the mean isentropic chart which are frequently significant in explaining the five-day precipitation anomaly patterns.

In summer the stationary character of the isentropic anticyclonic vortex patterns is due in part to the fact that the westerlies are relatively weak and displaced to the north, so that the United States lies between the southern fringe of the westerly current and the northern edge of the subtropical easterlies, and in part to the existence of moisture source regions within the United States where moisture is injected from lower into higher isentropic surfaces by thermal and topographic convection. The result is that five-day and even longer-period mean isentropic charts show the characteristic anticyclonic cellular patterns. These cells, with their moist and dry tongue components, change their size and positions somewhat with changes in the general circulation pattern, but the moisture flow pattern can, on the basis of experience, be very successfully forecast in relation to the mean pressure patterns, that is, from the prognostic mean pressure maps. The pattern of upper level pressure troughs and ridges largely determines the size and location of the isentropic cells. When this is known it becomes possible, with a knowledge of the active moisture source regions in the United States in summer, to draw quite successfully prognostic charts of the moisture flow patterns. The most important moisture source areas in the United States in summer are the southern and central Rocky Mountain regions and the southern and central portions of the western plains. These source regions are effective both because the strong heating brings the isentropic surfaces to their lowest levels here, and because convection carries the moisture upward. Of course, it is necessary, for any of this source area to be effective as a point of injection of moisture into the higher isentropic surfaces, to have the air flow below the selected isentropic surface such that moisture is transported into the source region from the Gulf of Mexico. This is, however, the normal flow pattern which is seldom interrupted in summer.

The use of the prognostic isentropic moisture pattern in precipitation forecasting in summer is just as much more significant than in winter as are the moisture patterns themselves.

The drawing of the prognostic isentropic chart completes the second step in the five-day forecasting procedure, that of preparing the basic prognostic charts. This step completes the basic synoptic forecast. The third step is concerned with the statistical expression of the basic synoptic forecast contained in the prognostic charts in the form of temperature and precipitation anomaly patterns for the entire United States. The fourth step is concerned only with the introduction of the timing element into the formulation of the district forecasts.

c. The prognostic temperature and precipitation anomaly charts

The third step in the five-day forecast procedure, that of drawing the prognostic charts of the five-day mean temperature and precipitation anomaly patterns, is based entirely on the basic prognostic charts just discussed. The forecaster knows, when he starts to draw the anomaly patterns, the statistical probability of the occurrence of each class of anomaly in any given region. For temperature, the probabilities are $12\frac{1}{2}\%$ each for much above or much below normal, 25% each for above or below normal, and 25% for near normal. For rainfall they are $33\frac{1}{3}\%$ for each of the three classifications, heavy, moderate, and light. The forecaster also has charts available, for both the temperature and precipitation anomalies, which show him for the calendar month, section by section over the entire country, just what the numerical limits of the different anomaly classifications are in degrees of departure from normal of the five-day mean temperature, and in inches of total five-day precipitation. However, the forecaster, when he draws his prognostic anomaly patterns, does not expect at all to carry in mind all of these numerical limits. He bears in mind rather merely the probability of occurrence of each of the anomaly classifications, and weighs that against the combined indications of the basic prognostic charts as requiring an extreme, moderate or small temperature anomaly, and an essentially wet, an essentially dry, or a moderate precipitation condition. At the same time, in borderline cases, where the forecaster is undecided between two anomaly classifications, the numerical limits are carefully considered.

The temperature anomaly pattern, being much more simply and directly related to the basic prognostic charts than the precipitation pattern, is usually drawn first. Nevertheless, the two anomaly patterns are by no means mutually independent. Especially in summer the precipitation pattern strongly affects the temperature anomaly pattern.

The drawing of the prognostic temperature anomaly chart is based essentially on the two prognostic pressure charts. When these two charts are drawn they rigidly define the expected mean air flow pattern, relative to the well-known air mass source regions, at both sea-level and the three kilometer level, and consequently pretty much throughout the lower troposphere, which is expected during the coming five-day period. Furthermore, as already pointed out, these two charts rigidly define the geographical distribution of the mean temperature of the layer of atmosphere between sea-level and three kilometers. Obviously, then, when they are drawn, the flow pattern which they represent relative to the air mass source regions must be considered implicitly for its advective effect on the mean temperature of the lowest three kilometers of the atmosphere. Already at that stage of the forecast procedure the forecaster must develop a good idea of the temperature distribution which his prognostic pressure charts call for, and consequently a rough idea of the major features of the surface temperature anomaly pattern which he should expect.

This roughly approximate picture of the larger features of the expected surface temperature anomaly pattern may be further clarified somewhat by referring back to the five-day period just ended. For that period the forecaster has before him the observed mean sea-level and three kilometer pressure charts, the observed mean surface temperature anomaly pattern, and the distribution of the sea-level to three kilometer mean temperature based on the observed mean pressure charts. When his prognostic mean pressure charts call for a continuance of the existing basic pressure patterns, perhaps only with some displacement of the entire system, then he can assume a temperature anomaly pattern similar to the current week's observed pattern, but with a displacement corresponding to that forecast for the basic pressure pattern, and with minor changes corresponding to minor changes in the basic pressure pattern. Especially in winter such regular displacements of persistent pressure and anomaly patterns may be observed for several periods. In such cases the continuance of the regular trend up to the last day of observations may be checked by comparing the current day's sea-level and three kilometer pressure maps, and the chart prepared on the forecast day showing the current day's temperature anomaly pattern, with the corresponding mean maps for the five-day period just ended.

In cases where a radical change in the pressure patterns is indicated by the prognostic mean pressure charts, the latest daily pressure charts and temperature anomaly chart show how far that change has progressed from the mean conditions of the five-day period just ended. However, under these conditions it is usually best to forget entirely the temperature anomaly pattern of the past period or even of the last day, as being too misleading. The best comparison to be made with the period just ended in such cases is that of the changes indicated in the mean sea-level to three kilometer temperature distribution as given by the observed pressure patterns for the period just ended as against that given by the prognostic pressure patterns for the period to come. As a first approximation it may be assumed that the change of the mean surface temperature in any region from one week to the next will be about that given by the change in the mean sea-level three kilometer temperature. This gives a first approximation for drawing the prognostic temperature anomaly chart. However, this assumption leads to considerable errors where large changes in the mean lapse rate occur from one week to the next, because this affects the difference between the mean surface temperature and the mean sea-level three kilometer temperature. Such significant changes in the mean lapse-rate frequently do accompany radical changes in the mean flow patterns. The largest errors from this source occur where normal lapse rates one week are replaced by conditions of extreme stability the next week, or vice versa. Under the extremely stable conditions, a surface temperature anomaly occurs which is very much greater negatively than that indicated by the sea-level three kilometer mean temperature. This effect can be very large in winter over snow-covered continental areas under stagnant anticyclonic conditions, where shallow layers of extremely cold air next to the ground may be very persistent. Such extremes occur also in summer in coastal areas over which air moves from adjacent cold water areas, such as the coast of California or the north Atlantic coast with onshore winds. Other conditions which lead to a less extreme relative cooling of the surface air but which must be allowed for locally in the form of larger negative or smaller positive surface temperature anomalies than are indicated by the local sea-level three kilometer mean temperature include the following:

(1) Anticyclonic curvature of the mean isobars, particularly at upper levels, indicating horizontal divergence and subsidence aloft.

(2) In summer, excessive cloudiness and especially precipitation. This is most effective, in those cases when it occurs, in the drier interior continental regions. In this connection the precipitation anomaly chart is useful.

Conditions which lead to relative heating of the surface air and which must be allowed for locally in the form of larger positive or smaller negative temperature anomalies than indicated by the sea-level three kilometer mean temperature include the following:

(1) A mean flow pattern calling for the rapid transport of cold air masses over a relatively warm surface. An example is that of the local influence of the Great Lakes on a northwesterly flow in winter.

(2) Cyclonic curvature of the mean isobars, particularly at upper levels, which indicates horizontal convergence, vertical stretching, and steep lapse rates aloft.

(3) In winter, excessive cloudiness and storminess. This is most effective, when it occurs, in the interior of continental regions. In this connection the precipitation anomaly pattern is consulted.

(4) The Föhn influence appearing on the lee side of major mountain systems with prevailing cross winds.

From what has been said above it is evident that the prognostic temperature anomaly pattern, when completed, must be consistent with the mean prognostic pressure charts as they define the distribution of mean temperature of the lowest three kilometers of the atmosphere. The check offered by this required consistency is the third of the routine checks which are made of the internal consistency of the complete five-day forecast. At the same time it is evident that in this case the criterion of the consistency is not so exact as it is in the case of each of the first two checks. But at least when apparent inconsistency is found by this check, it can be required that the inconsistency be given a definite explanation in terms of the special conditions listed above which can affect the correspondence between the surface temperature anomaly pattern and that of the lowest three kilometer stratum of the atmosphere.

There is one further point which should not be overlooked when the prognostic temperature anomaly pattern is drawn. There are available to the forecaster running graphs of the sequence of five-day temperature anomalies, and of five-day precipitation totals, during the past year, in ten selected districts representing all sections of the country. It occasionally happens that the temperature anomaly graphs show very persistent long-term departures from normal of the temperature in certain parts of the country. These long-term anomalies may be recognized as due to the unusual persistence of certain circulation patterns, as in the case of the persistent subnormal temperatures in the southeastern states during the late winter and early spring of the past year, or they may appear to be due to some persistent condition outside the atmospheric circulation pattern, such as the persistence of above normal temperatures along the entire west coast during most of the past year, which gives the impression of being due to abnormal warmth of the surface water of the Pacific during the past year. In cases of persistent temperature anomaly of the first type, caution should be exercised in drawing prognostic charts which radically change the persistent circulation pattern unless the evidence for it is strong. On the other hand, it is particularly important to forecast such changes when they do occur. In cases of persistent temperature anomaly of the second type, the usual procedure is to shade the temperature anomaly forecast to about one class warmer (or colder as the case may be) than the anomaly that would normally be called for in the affected region by the prognostic pressure charts.

The observed precipitation anomaly patterns are much less clearly determined by the observed mean charts than are the temperature anomaly patterns. Furthermore the observed five-day precipitation patterns are likely to be much more broken and irregular than the temperature anomaly patterns. This greater irregularity and lack of correspondence between the mean precipitation patterns and the five-day mean charts renders correspondingly difficult the prognosis of the precipitation anomaly patterns from the basic prognostic charts. The reasons for the relatively poor correspondence of five-day precipitation patterns with the mean charts compared with that of the temperature anomalies are probably two:

(1) The five-day temperature anomaly at any point, and consequently the five-day anomaly pattern, represents the integrated effect of the conditions prevailing during each day equally throughout the five-day period. But the rainfall total at any point, and consequently the rainfall anomaly pattern, depends only on the conditions prevailing during that small part of the five-day period when precipitation is actually falling. Thus only a few hours at the very beginning or the very end of the period may determine the precipitation anomaly pattern over large areas, yet the conditions prevailing during these few hours play only a very small part in the makeup of the other five-day mean charts.

(2) The temperature pattern is largely determined by the simple two-dimensional flow pattern, in other words, it is mostly a question of where the air comes from, how fast it comes, and what temperature it brings with it from the source region. But the same information about the transport of moisture by the circulation pattern, as it appears for instance on the mean isentropic chart, does not go very far in accounting for the precipitation pattern. For it is not the horizontal transport of moisture, but the small vertical

component of motion of the moist air which largely determines the amount of the moisture which is precipitated. Thus the prognostic precipitation anomaly pattern is based on the expected moisture flow pattern (prognostic isentropic chart) and all available means of forecasting the zones of systematic vertical ascent of the moist air.

The lack of any close correlation between observed precipitation anomaly patterns and the mean isentropic moisture pattern can be confirmed by the casual inspection of a few mean charts. This correlation is probably least in winter. Nevertheless, some positive correlation between the two has been shown to exist even in winter (Smith, 7). Obviously, the moisture flow pattern of a single isentropic surface does not give a complete picture of the distribution of the moisture supply available for precipitation in the atmosphere, but it probably does so as effectively as any simple chart can. The use of one or two additional isentropic surfaces does not add a great deal. Consequently the main problem in drawing the prognostic precipitation anomaly pattern is to locate the zones of systematic upward motion of the moisture flow represented on the prognostic isentropic chart. This is possible by means of the prognostic mean charts for such zones as persist during a considerable part of the period. Some effort is made also to catch significant rainfall of short duration by other means.

The following are some of the indications on the basic prognostic charts which are used to some extent to identify areas of persistently wet or persistently dry conditions during the coming five-day period:

(1) The prognostic isentropic chart. (a) Merely the presence or absence of moisture, as shown by the distribution of the mixing ratio, w. This is probably a better indication in summer than in winter. It is best used where the isentropic surface is expected to lie between 600 and 800 millibars. Smith(7) found even in winter a highly significant correlation between the occurrence of light or heavy precipitation anomalies and the w values taken from the mean isentropic chart for all sections of the country except in northern sections east of the Rockies. It is in this region that the isentropic surface tends to be highest in winter. Rainfall is usually light where the isentropic surface becomes extremely high.

(b) The crowding of moisture lines, usually on the left side of the moist tongue. This indicates a steep slope of the isentropic surface, probably a strong frontal zone, where heavy rain is likely to occur, irrespective of cyclonic, anticyclonic, or no curvature of the moist tongue. To the right of the axis of an anticyclonic moist tongue it is usually dry.

(c) The splitting or spreading of a moist tongue with a crowding of the moisture lines at the point of division. This indicates the flow of warm moist air against resisting cold air, with probability of heavy rain at the point of spread. It is interesting to note that Smith(7) found no highly significant correlation between the orientation of the potential flow lines toward or away from the height lines of the mean isentropic chart and the rainfall anomaly in the same region. Although height lines of the isentropic surface are not drawn on the prognostic isentropic chart, their orientation and relative gradient can be quite closely estimated from the distribution of the mean temperature of the lowest three kilometers contained on the prognostic three kilometer chart.

(d) The advance of a well-developed moist tongue into or against the higher mountain ranges of the west, especially where there is a sharp crowding of the moisture lines on the western edge of the moist tongue. This indicates a thermal trough system with cool Pacific air masses on the west side and a deep southerly current aloft of tropical maritime origin. It is likely to produce widespread heavy thundershowers in the Rockies.

(2) The prognostic mean pressure charts. (a) The curvature of the isobars. Cyclonic

curvature of the sea-level isobars indicates horizontal convergence and ascent of air, favoring rainfall. A low pressure trough with sharp curvature of the isobars gives the mean position of an active frontal system. Anticyclonic curvature of the isobars indicates horizontal divergence, subsidence, and lack of rain. Smith (7) found the wintertime correlation between the curvature of the isobars of the mean sea-level pressure maps and the precipitation anomalies to be highly significant in all sections. The same correlation computed by using the mean three kilometer instead of sea-level isobars was not as good.

(b) Closed centers of low pressure at three kilometers in southerly latitudes. These are usually sluggish systems frequently of tropical origin which give excessive precipitation. Closed centers of high pressure at three kilometers are usually dry wherever they occur.

(c) A wide separation of low pressure troughs between the sea-level and the three kilometer prognostic charts. This means a strong longitudinal temperature gradient towards the west, consequently a large air mass temperature contrast, and an active frontal system in the pressure trough. Heavy rain is to be expected in the region between the two troughs. When the two troughs are close together or coincide, the air mass contrasts are small, and the rain associated with the system is likely to be light.

(d) Turning of the isobars between sea-level and three kilometers. In certain regions, particularly in the west in wintertime, the normal temperature and moisture distribution is such that a clockwise turning of the isobars between the ground and three kilometers leads to the forced ascent of warm moist air (of Pacific origin) over cold air (Polar continental), causing heavy precipitation. A counterclockwise turning indicates a descent of the upper current, and dry conditions. This indication should not be used, however, without reference to the prognostic patterns of moisture (isentropic chart) and temperature (three kilometer chart).

(e) Orientation of the surface isobars with respect to certain topographic features. Since the surface isobars indicate the prevailing flow pattern to be expected during the coming period, and consequently also the characteristics of the air masses which will constitute the air flow, the orientation of these isobars with respect to certain topographic features is important for the precipitation pattern. Thus the strong transport of cold P_c air across the Great Lakes in late autumn or early winter may lead to rather heavy local convective precipitation. Likewise strong transverse flow across the higher mountain ranges in the west leads to excessive precipitation on the windward slopes, and deficient precipitation on the lee side.

Effort is made in forecasting the precipitation anomaly pattern also to catch some of the precipitation action which is too shortlived to leave its mark on the pattern of the basic prognostic charts. Such efforts include the following:

(a) The careful delineation of areas of falling precipitation at the beginning of the period, where the expected prompt termination of the precipitation action early in the period may completely determine the anomaly pattern for the entire period. Since frontal systems usually progress eastward, this condition is more likely to define the western than the eastern boundary of an anomaly area. The same problem may arise less definitely in the form of defining the eastern boundary of an anomaly area at the eastern limit of the region that a given frontal system may affect by the end of the period. This, however, is a very difficult thing to do, and can be attempted only on the basis of the circulation patterns, surface and aloft.

(b) A similar problem is posed by the rapid passing of a single frontal system, which may produce considerable precipitation and yet be followed by so rapid a return to dry anticyclonic conditions that it leaves little mark on the basic prognostic charts. Occurrences of this kind, as well as the limits of precipitation action at the beginning and ending of the period mentioned under (a), can be forecast, if at all, only by an attempt to estimate the daily weather sequence. The drawing of the daily prognostic charts referred to below (p. 40) is of some assistance on these troublesome details of the prognostic precipitation pattern.

(c) The estimation of scattered summer convective precipitation, which may be very spotty yet locally heavy in the absence of definite topographic controls. It is quite impossible to forecast any details of a precipitation pattern of this type, but it may be possible to forecast generally moderate precipitation for the area concerned and indicate its locally convective character. Such conditions occur in areas of strong insolational heating where the prognostic isentropic chart indicates an adequate moisture supply and the three kilometer shows a notable absence of pressure gradient and of either cyclonic or anticyclonic curvature of the isobars.

It is not possible to give any set rules by which the rainfall in a given region is to be characterized as light, moderate, or heavy, even in terms of the characteristics of the basic prognostic charts. The final decision depends to a considerable extent on the geographical location, the season of the year, and past experience. However, in general it may be said that where the prognostic charts indicate an adequate moisture supply and conditions favorable to systematic upward motion of the moist air, heavy rainfall is forecast. Where they indicate either a marked lack of moisture or systematic sinking of the lower atmosphere, light rain is forecast. Where they indicate a circulation pattern favoring ascent of the lower atmosphere but without much supply of moisture, or in regions where active precipitation of the local or short-lived varieties are indicated, moderate rain is forecast. In general, light is usually forecast in any region in which there is not some fairly definite reason to expect rain.

d. The formation of the final five-day forecasts as transmitted to the forecast centers

The final step in the five-day forecast procedure is the formulation of the forecast for transmission to the district forecast centers. As pointed out in Section I, the final formulation of the forecast for public consumption, and the dissemination of the forecasts to the public, is handled by the district forecasters.

It should be stressed at this point that the entire emphasis of the five-day forecast has been placed on the forecasting of the mean conditions for the coming period in terms of departures of temperature and precipitation from the normal. This emphasis is inherent in the system, which is based on the study of the statistical or mean conditions of the general circulation during successive five-day periods, and the extrapolation of such mean conditions into the future. There is a very real reason for placing the emphasis in this manner, namely, that the sequency of daily changes of the weather is so utterly complex in its detail of form and of cause and effect, that it is hopeless to expect to forecast these minor variations with any real success more than a very few days ahead. Probably such forecasts will never be extended with any fidelity in detail even as far as five days into the future. On the other hand, the weather conditions prevailing for relatively long periods undergoes variations which are of great practical significance and which are easily characterized statistically. The correct forecasting of these longer period variations can be of great practical value. Furthermore, such forecasts can be extended almost in-definitely. It is true that as the period is lengthened, the amplitude of the statistical weather variations becomes smaller, but the longer the period the greater becomes the significance of variations of small amplitude. The possibility exists in this manner of getting information of great practical value about the weather at a considerable distance in the future, whereas probably the extreme limit to which information of any value whatsoever about the future weather can ever be obtained by the methods of daily synoptic forecasting will remain less than a week, except perhaps insofar as information gained and concepts developed by the statistical method may be used to interpret the daily maps in terms of the long-period trend.

This emphasis on the statistical aspect of the five-day forecasts is not intended to exclude consideration of the daily sequence of weather. In fact a single five-day period is still short enough to come within the time range to which the daily forecast methods are to some extent applicable. In fact, the statistical forecast for a period as short as five days really needs a careful consideration of the daily sequence of changes to be made as accurate in detail as possible. Furthermore, the value of the forecasts to the general public, and public demand, requires that the forecasts of the daily sequence of weather be made as detailed as possible in the five-day forecasts. Recently, as is explained below, an attempt has been made to render more objective the study of the daily weather sequence which is expected to constitute the five-day mean pattern. This procedure has helped to clarify the timing and trend elements which have been included from the beginning in the formulation of the district forecasts.

The formulation of the five-day forecasts as transmitted to the district forecast centers has during most of the past fiscal year been handled by the official forecaster (the man who prepares the official prognostic charts) in the following manner:

The information which is transmitted in the general outlook is taken directly from the basic prognostic charts. This includes the numerical value of the northern hemisphere zonal index as forecast, and a brief description of the outstanding features of the mean sea-level pressure distribution, the mean three kilometer pressure distribution, and the mean isentropic moisture pattern as forecast. The description covers that part of the northern hemisphere for which the past maps are reasonably complete, and which is expected to have any direct bearing on the weather in the North American quadrant.

The information which is contained in the general outlook and which defines the boundaries of the temperature and precipitation anomaly patterns is taken directly from the prognostic anomaly charts of temperature and precipitation. A few words of explanation of the principal anomaly areas are added, to indicate briefly in terms of the basic prognostic charts the reason for placing the anomaly area where it was placed.

The individual district forecasts as transmitted, each one to the forecast center of the district to which it applies, contain two parts to the forecast of each of the two elements, temperature and precipitation. The first part, which is definite, is the forecast of the anomaly distribution of each element for that district as taken directly from the prognostic anomaly charts of the two elements. The only qualifying words which are used in this part of the forecast are two. The word "indicated" is used to show a lesser degree of certainty on the part of the forecaster than when the forecast is unqualified, and the word "generally" is used to show that the forecast anomaly may not occur uniformly at all points in the indicated area.

The second part of the forecast of each element introduces into the forecast some timing during the period. The effort is made to indicate all major trends of the prevailing conditions which are expected to occur during a considerable part of the period, trends from wet to dry or from warm to cold and vice versa, or when one part of the period is expected to be characterized by one class of anomaly and another part by another class, this is indicated. But up to the present no attempt has been made to forecast in detail the daily sequence of weather. This would be rather difficult to do for a large forecast district over a five-day period. It would lead to a very cumbersome message, and increase the cost of transmission. At present, the amplification of the forecast by the inclusion of the daily sequence of the weather is left to the district forecaster to make in whatever detail he may wish.

However, the forecast procedure has recently been modified so as to direct more attention to the daily weather sequence. Formerly the timing element was introduced into the district forecast by the official forecaster only in the course of the dictation. No special prognostic charts were preapred for this purpose. It was done by the forecaster with the latest daily maps and the last day's temperature anomaly pattern in front of him, on the basis of the general picture of the synoptic development which he had in mind when he drew the basic prognostic charts. The lack of any prognostic charts tended to make this part of the district forecast less objective, and not infrequently lacking in consistency between districts.

This procedure has been modified by the introduction of a number of daily prognostic charts. As it is now handled, a second forecaster is detailed to this job. He begins by carrying out the analysis of the latest Atlantic-Pacific surface map (7:30 a.m.), and by studying the latest daily aerological maps. He then proceeds, on the basis of the methods ordinarily used in daily forecasting, to draw prognostic synoptic surface maps, showing the distribution of pressure, principal frontal systems, and falling precipitation 24, 48, and 60 hours ahead. For the map 60 hours ahead he also draws the corresponding three kilometer pressure distribution. These two prognostic synoptic charts 60 hours ahead (reckoned from 7:30 a.m. of the forecast day) are the first of the five daily maps which will verify the coming five-day period.

In the meantime the official forecaster has drawn his three basic prognostic mean charts. The two forecasters then have a discussion as to the mutual agreement or disagreement of their respective prognostic efforts. By the time that the two sets of maps have been made reasonably consistent, assuming that they were inconsistent to start with, the five-day forecaster and the daily forecaster must have reached fairly good agreement both as to the short range development of the daily weather sequence, and the long-range development of the mean conditions. From that point the daily forecaster proceeds to draw two more sets of daily prognostic surface and three kilometer charts for the third and fifth days of the five-day period, similar to those which he has drawn for the first day. They are drawn as a reasonable extrapolation of the maps representing the conditions on the first day, and to fit the mean conditions represented by the official forecaster's mean prognostic charts, and in general agreement with his idea of the basic synoptic developments to occur.

Meanwhile the official forecaster proceeds with the drawing of his prognostic temperature and precipitation anomaly patterns, for which he is now able to consult the daily prognostic maps which are being prepared by the second forecaster. In this manner some of the doubtful features of the prognostic anomaly charts are somewhat clarified, in particular those of the precipitation anomaly pattern which depend upon the limits of the areas of falling precipitation at the beginning and end of the period, and upon the quick passage of a frontal system which may produce considerable precipitation without affecting the patterns of the mean prognostic charts appreciably.

When the official forecaster has completed all the prognostic charts, he dictates the general outlook and forecast in readiness for transmission to the district centers, and then gives the formal forecast discussion. In the course of his explanation of the basic forecast as expressed in all of the mean prognostic charts, he presents also the daily prognostic maps and explains how they fit into the mean picture, and at the same time follow logically from the latest daily maps. Following the formal forecast discussion, suggestions and criticisms are offered by the forecasters present. Sometimes changes in the mean prognostic charts are made as a result of these suggestions. In that case the general outlook and forecast which has been prepared for transmission to the district forecast centers is corrected accordingly.

At the conclusion of the forecast discussion the general outlook and forecast is transmitted in its corrected form. Then the district forecasts are dictated, not by the official forecaster, but by the forecaster who prepared the daily prognostic charts. He bases the statistical part of these forecasts entirely on the official forecasters prognostic anomaly charts of temperature and precipitation. The timing and trend part of the forecast he bases on his own prognostic daily charts. This procedure makes the timing element of the district forecasts somewhat more definite, objective, and consistent from district to district than it could be made by the former procedure. In fact it makes it possible to include more of the daily sequence of the weather than has been attempted up to the present. It also relieves the official forecaster of the last step of what has become a long and exhausting forecast routine.

The record of forecasts prepared with the use of the daily prognostic maps is too short to serve as a basis of any estimate of the success of the method. In fact, its success will be very difficult to verify, since up to the present only the statistical part of the forecasts has been verified. However, there can be no doubt but that it must lead to some improvement in the timing element of the district forecasts. Furthermore, it can scarcely harm the statistical part of the forecast, and may well lead to some improvement there also.

The following illustration of the five-day forecast procedure, selected and discussed by Mr. Namias, does not include the recent innovation of the daily prognostic charts. These have been in use only since the second week of July, which is too short a period to permit of the selection of a good illustrative case and the preparation of all the necessary maps and diagrams for inclusion in this report.

C. Illustration of the Five-day Forecast Procedure by Means of a Selected Example

The following example of the forecast procedure was taken directly from the files ot the five-day forecasting project. The forecast explanation is rewritten from an outline made on the evening of February 20 when the forecast was issued. It is essentially the verbal discussion given that evening. No changes have been introduced in the prognostic charts. The "post-mortem" discussion is essentially that delivered at the conference held on the afternoon of February 27. Factors considered in the preparation of the forecast issued on February 20 for the period February 22–26, 1941:

Indications are that the zonal index will fall during the coming week. The statistical indications for a fall are expressed partly by the fact that the index has fallen for only one week, and on the basis of a study of past behavior of index variations, a fall of one week's duration has a 70% probability of being followed by a further fall. Moreover, the behavior of the curve during the past couple of months suggests slow, gradual trends rather than abrupt and irregular variations (Fig. 1). Then again the index values for the last two days average much less than the mean value for the last five days. Statistically, this favors a further drop in the mean value of the index for the five-day period for which we are forecasting.

There are also certain indications of a synoptic nature which suggest a further decline in the index. One of these is expressed in the pressure profiles (Fig. 2, a, b, c), which suggest the movement southward of general circumpolar rings of rising and falling pressure. For example, the dip in the profile change curve between latitudes 50°–60° during the period February 8–12, seems to have shifted southward to latitudes 35°–45° in the period February 15–19. Similarly, in the area of rising pressure over the polar region is increasing

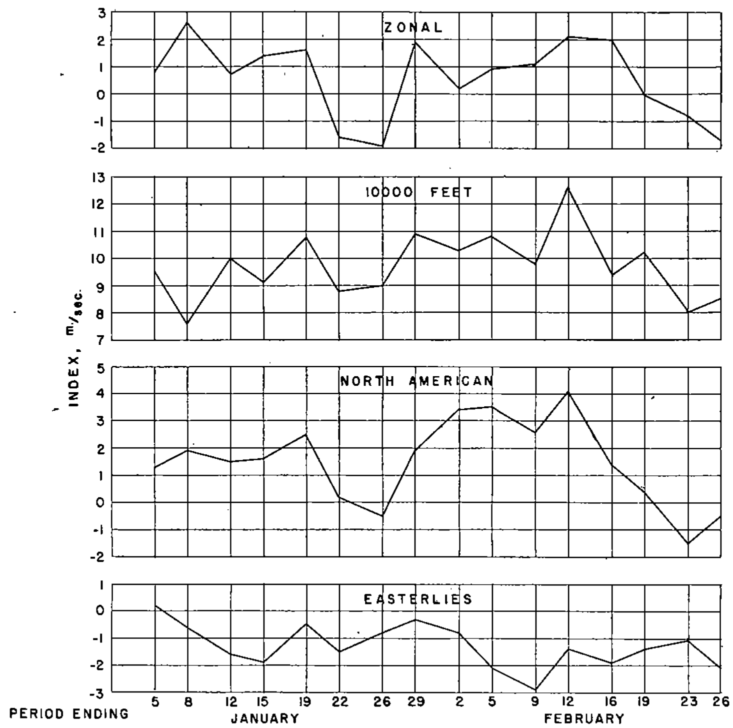

FIG. 1. Time graphs of circulation indices.

and spreading southward. At the rate this southward progression of circumpolar pressure change is going on, the profile during the coming week should show relatively high pressures in northern latitudes and relatively low pressures in the average over low latitudes. This would result in a low index, and in this case in a negative value.

The trends in the mean sea-level pressure charts show features typical of falling index conditions. The polar anticyclone is reaching its maximum stage of development, the Aleutian Low remains split into two cells, and the Icelandic Low is far southwest of its normal position. The sub-tropical Highs are fairly weak. The trends in the mean maps during the preceding few periods have been sufficiently slow and clear cut so that one can clearly follow the progressive splitting apart of the Aleutian Low, the gradual development of the Polar anticyclone and the southward shift of the Icelandic Low.

A careful study of the latest daily Northern Hemisphere charts shows that the slow trends established in the mean charts are continuing. Thus, the Polar High continues very strong with no indication of breaking down. Cyclonic activity is continuing in southerly latitudes in the Pacific, and the polar front is displaced far south of its normal position. The Aleutian Low remains split, and the Icelandic Low remains a deep vortex centered east of Labrador (Fig. 3).

Inasmuch as the zonal index is expected to fall, it is reasonable to forecast a corresponding fall in the 3 km index. Synoptic features which suggest this fall are expressed in the closer spacing of 3 km troughs on the latest mean 3 km maps (Fig. 4 shows the latest one only) and in the tenacity of the extremely intense Polar Low over Labrador. The 3 km index forecast is 8.5 m/s.

With the indices forecast it is now possible to combine them with synoptic indications and arrive at a set of prognostic charts (Fig. 10a, b, c, d, e). In the first place, the forecast of a negative zonal index in itself places rather rigid limitations on the pattern of mean sea-level pressure. In order to obtain such an index it is almost necessary to incorporate into the prognostic charts an extensive Polar anticyclone (Fig. 10a), and with such a low index, it is highly probable that the Aleutian Low would remain split into two cells, and that there might be a tendency of the Icelandic Low to do likewise. One of the cornerstones upon which a mean pressure pattern can be based in this case is the deep Icelandic vortex, which, since it extends high up in the atmosphere may be assumed to make little progress during the coming week. The Polar anticyclone must, therefore, tend to rotate around the deep Icelandic vortex, and yet, in order to contribute in the correct sense to the negative index expected, must remain well developed in northern latitudes. Inasmuch as the air

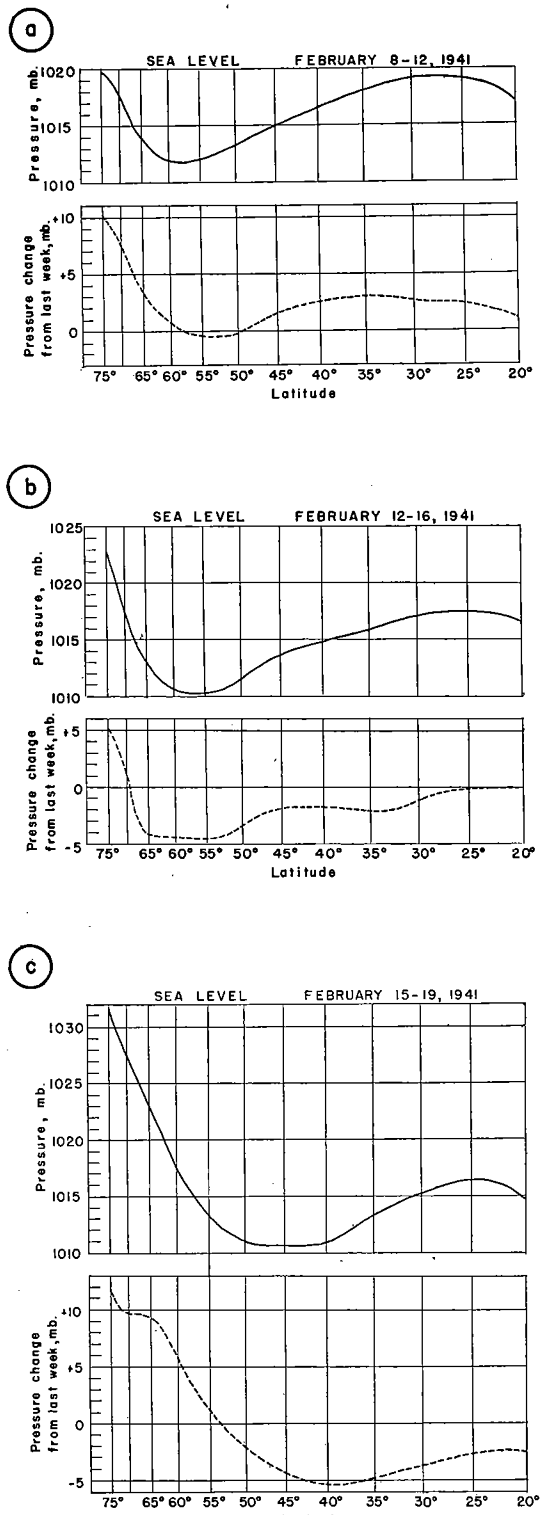

FIG. 2. Northern hemisphere mean pressure and pressure change indices.

composing the Polar anticyclone and circulating in part cyclonically around the Icelandic Low will be cold, it is reasonable to suppose that some wave formation will occur between this Polar air and air of maritime tropical origin to its east. This is represented as a trough extending southward from the Icelandic Low. During the last few periods, as the

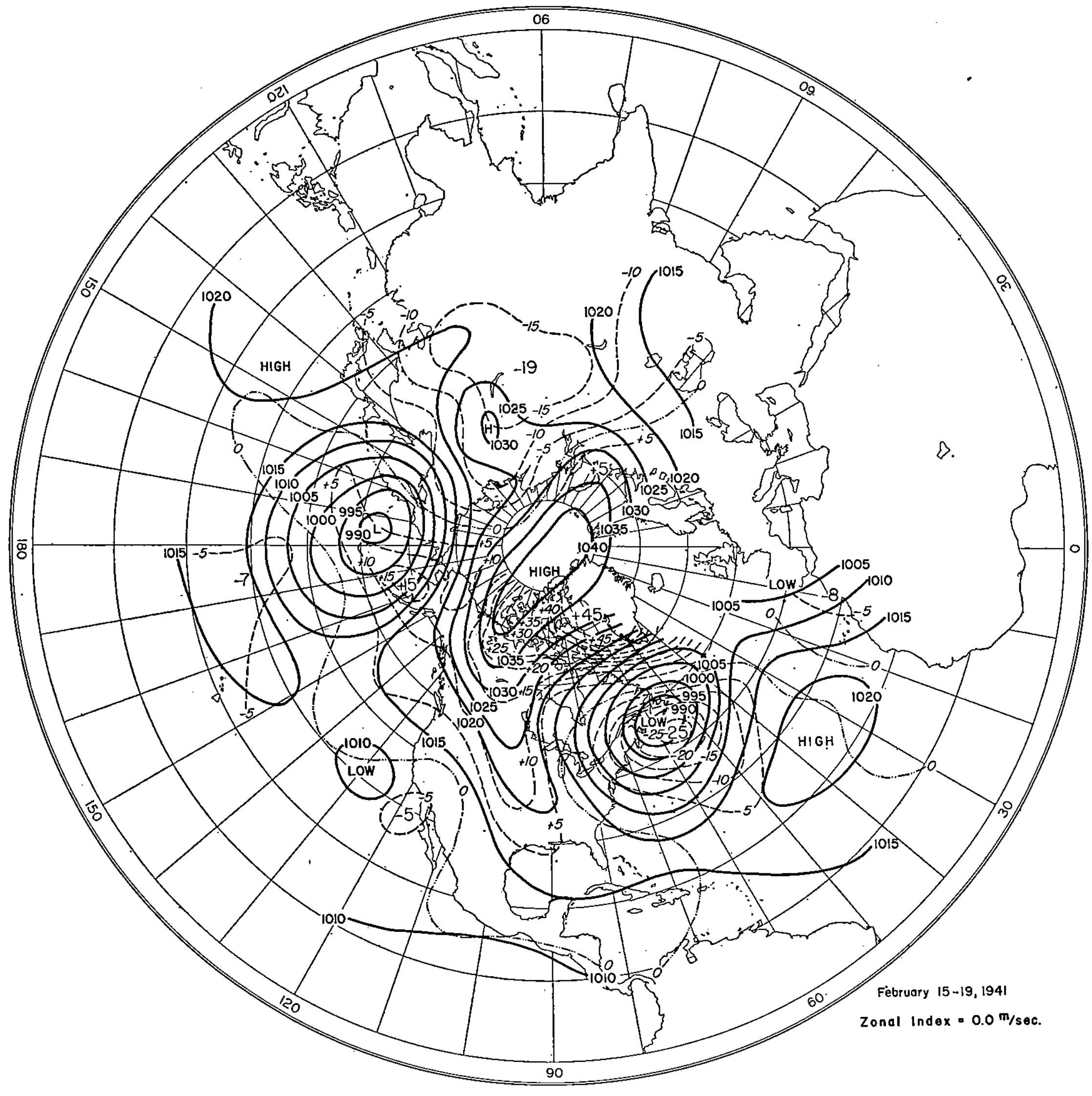

FIG. 3. Northern hemisphere mean pressure and pressure change map.

Aleutian Low has split there has been the tendency to formation of a ridge extending southwestward into the Pacific from the continental anticyclone. This tendency is incorporated into the prognostic chart, inasmuch as the last daily chart indicates the possibility of continental air from northwestern Canada's flowing out at higher latitudes over the Pacific.

The 3 km prognostic chart (Fig. 10b) is drawn within the limitations prescribed by the low index as forecast, and at the same time is drawn to be consistent with the distribution of sea-level pressure as predicted.

The unusually strong Polar Low is the same system as the Icelandic Low on the surface

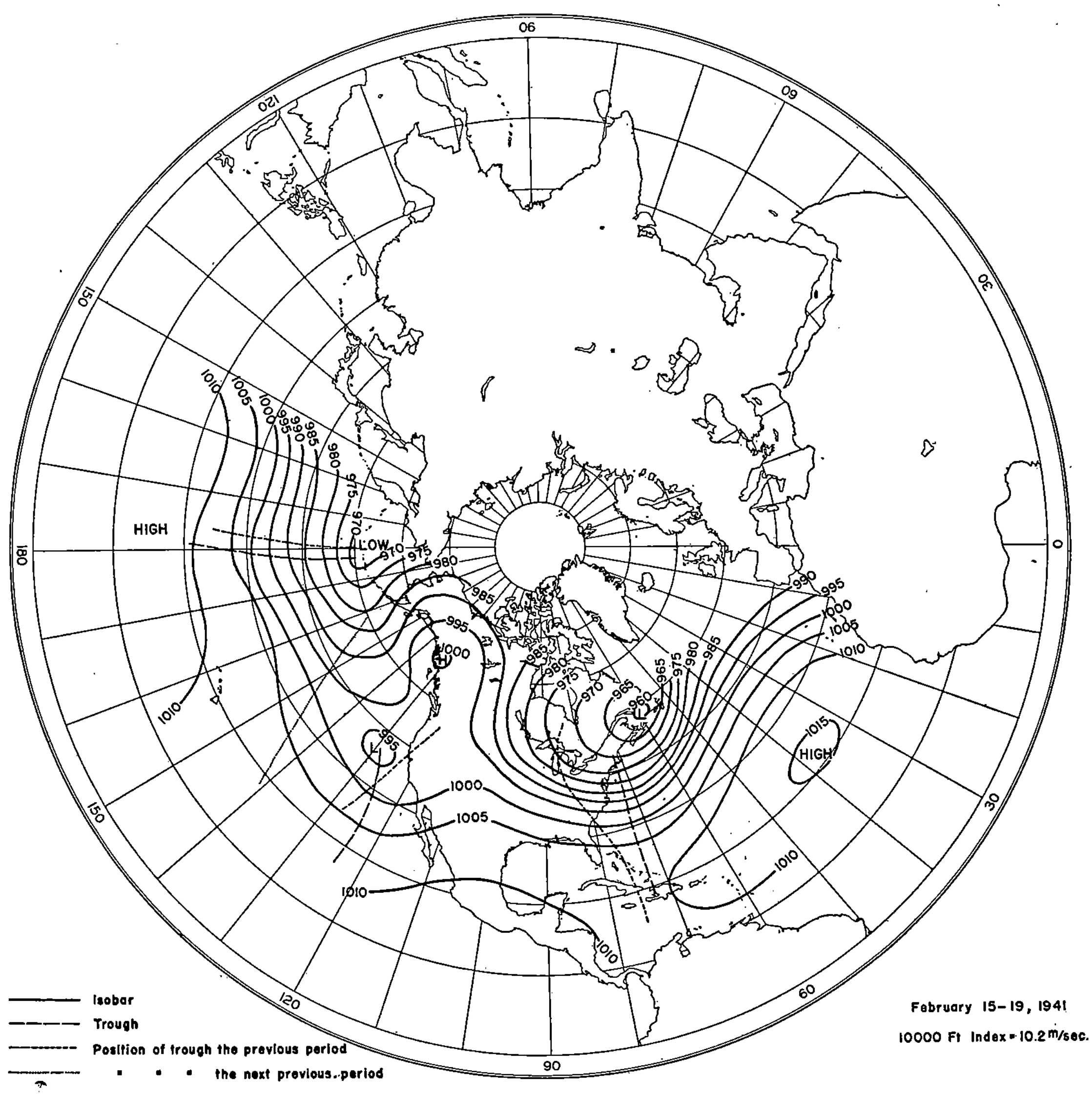

FIG. 4. Extended mean 10,000 ft. pressure map.

prognostic chart. This serves as one of the keystones for the forecast pattern. Since the index is forecast to fall the spacing of troughs is not increased over last week, and the amplitudes of waves is made somewhat greater than on last week's map (Fig. 4). An outstanding feature of this prognostic chart is the extensive cyclonic flow over the entire

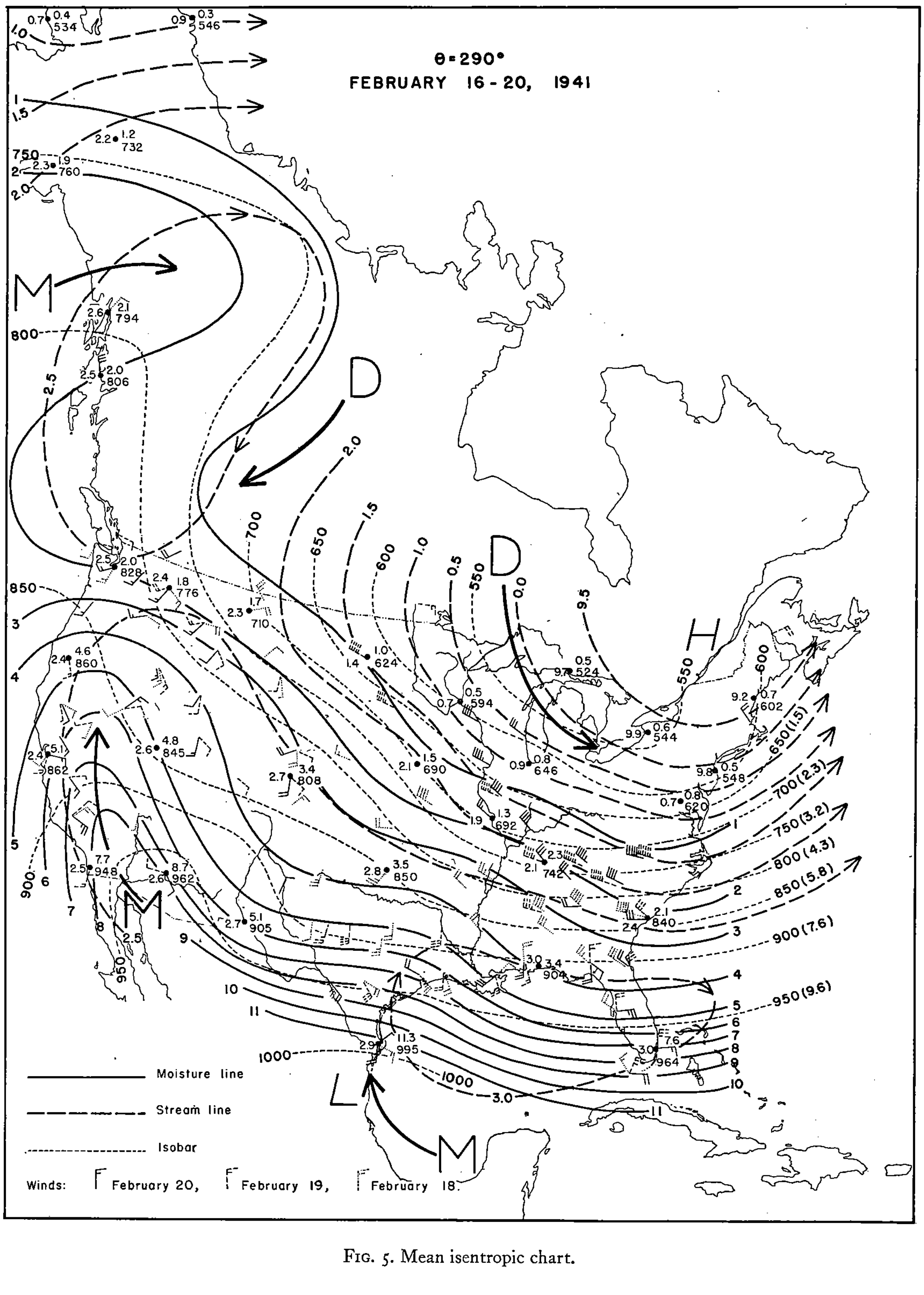

FIG. 5. Mean isentropic chart.

eastern portion of the United States. This type of activity is one associated with a cold anticyclone.

The isentropic chart (Fig. 10c) is drawn to conform with the surface and 3 km prognostic chart (Fig. 10a, b). As there are indicated no closed vortices over the United States, and as the flow is chiefly west-east there, the moisture pattern should be one with cold dry air (of the polar high) to the north and moist tropical air in the south—in other words, there will be an extensive cyclonic flow of dry Polar air in connection with the continental anticyclone, while the steep moisture gradient to the south should result from the inflow of some moisture into the southwest from the frontal system off the coast of California, while new injections of moisture into the Gulf States should occur as the activity from California disturbances spreads eastward and starts tropical Gulf air moving northward.

From these three basic prognostic charts, the mean sea-level pressure map, the mean 3 km chart, and the mean isentropic chart, it is possible to forecast the temperature (Fig. 10d) and precipitation (Fig. 10e) anomalies for the five-day period covered by these charts. The extensive nature of the Polar anticyclone over eastern United States suggests that all the area east of the Great Divide should average below normal, with the exception of a region in the northeast where the vast circulation around the Labrador center is expected to bring around a quantity of maritime air. Indeed, this maritime air shows up on the latest daily Northern Hemisphere map behind a warm front moving southward over eastern Canada. Since the Polar air for the most part is expected to move southward in a cyclonic path, little subsidence is anticipated, and thus little heating. The coldest air with respect to the normal should therefore occur in the southeast. Here low temperatures will be favored by night time radiational cooling taking place in the ridge of high pressure. The computed mean air column temperatures, based upon the prognostic sea-level and 3 km pressure charts and shown on the latter, indicates these temperature anomalies. West of the Great Divide, where the Polar continental air is not expected to reach directly, the temperatures should be more moderate. The cloudiness and cyclonic southerly flow associated with the southwestern low should result in above

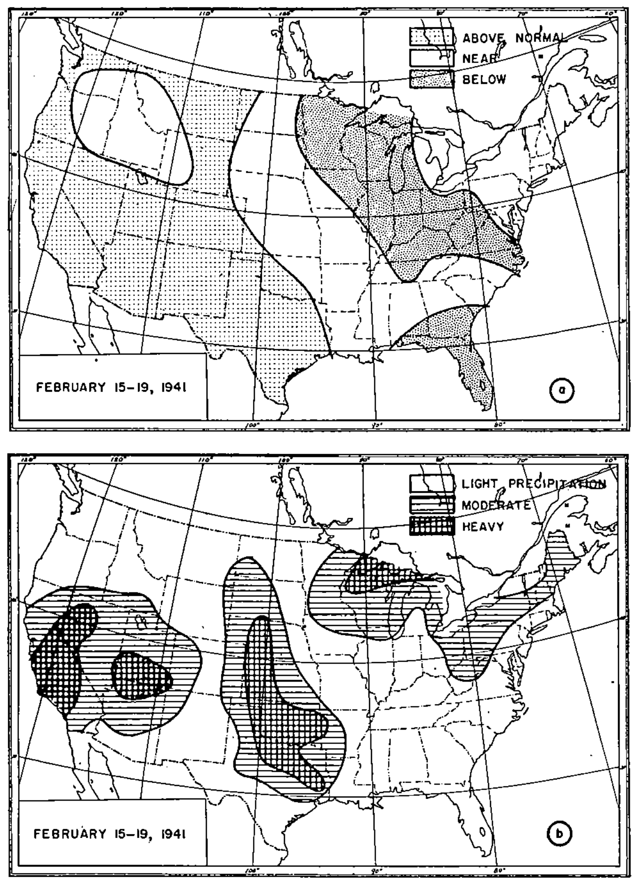

FIG. 6. Observed temperature and precipitation anomaly charts.

normal temperatures over the southwest. The slow infiltration of Polar continental air west of the divide in the northwest, should result in near normal temperature there, except along the northwest coast where the föhn effects associated with an easterly current may produce above normal temperatures.

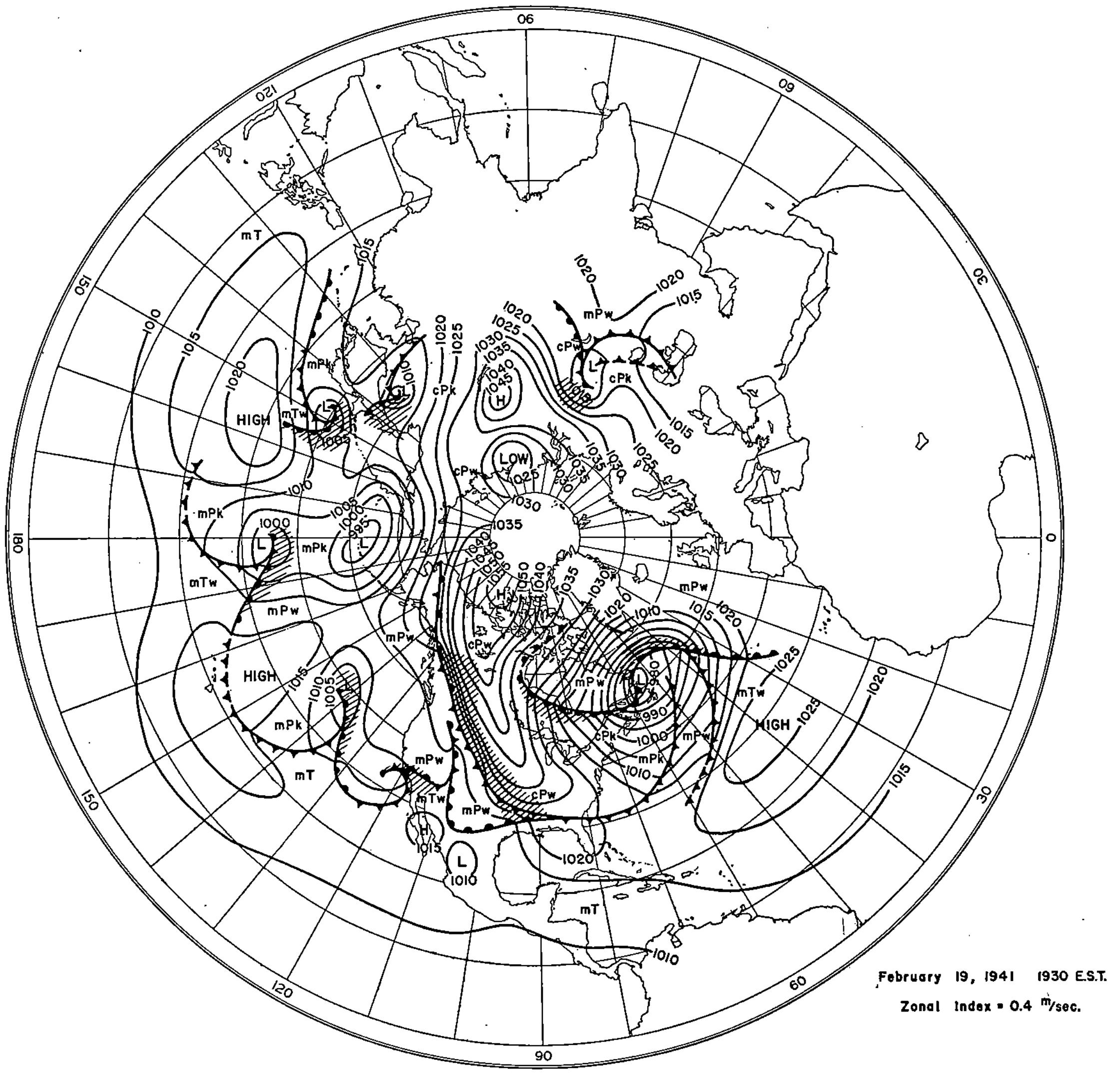

FIG. 7. Daily northern hemisphere surface map.

As for the precipitation anomalies (Fig. 10e), we can make appreciable use of the prognostic mean charts (Fig. 10a, b, c). While cyclonic curvatures of both surface and 3 km isobars in the northeast is indicated as favoring convergence, this air is expected to be too cold and dry (see prognostic isentropic chart) to produce any appreciable precipitation except moderate to heavy instability snow flurries on the leeward shores of the Great

Lakes. In the crest of the Polar High little precipitation should be observed owing to the prevailing divergence here. In the southwest, however, where cyclonic isobars are drawn around the California Low, where this cyclonic curvature extends to the 3 km level, and where there is high moisture concentration (Tropical Pacific Air), heavy precipitation

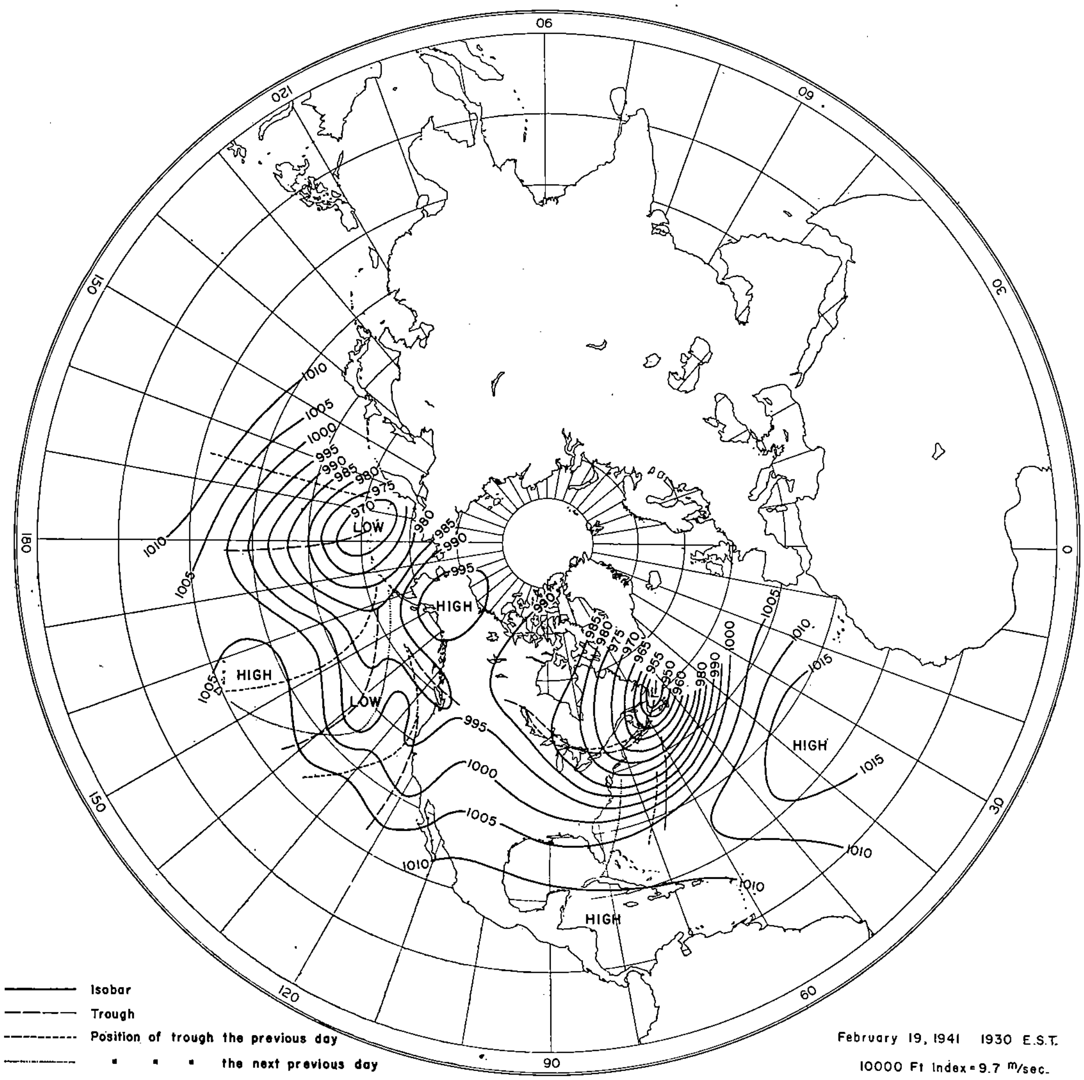

FIG. 8. Daily extended 10,000 ft. pressure map.

may be expected. The spread of this precipitation will be eastward with the prevailing westerly flow at upper levels. In the southeast, that is along the Gulf Coast, the combination of moisture laden air masses and up-slope motion of this moist air over the cold Polar continental air should result in a band of heavy precipitation. The general orientation of precipitation boundaries in this region is suggested by the intense upper level Polar cyclone which should readily deflect any cyclonic waves southeastward around the deep

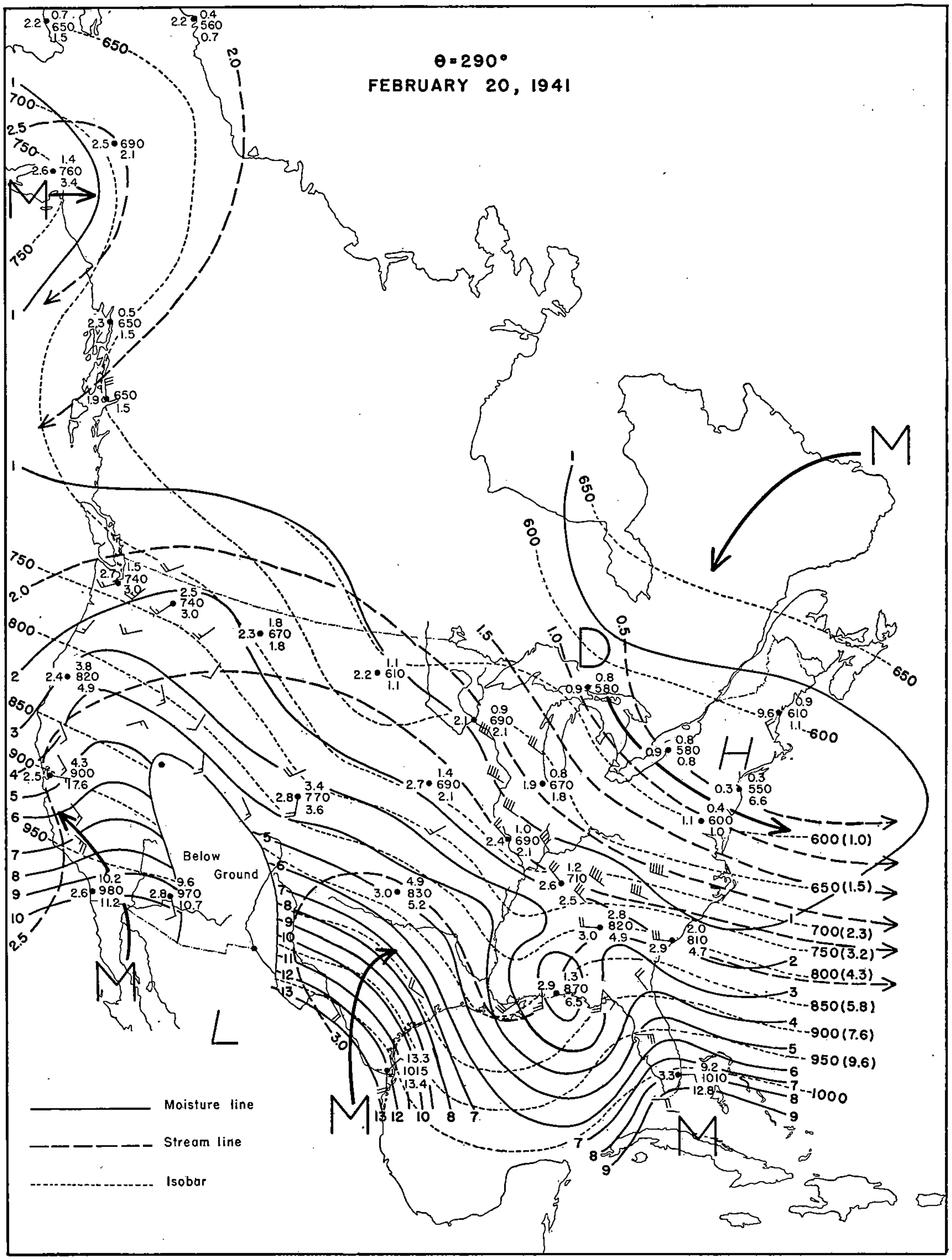

Fig. 9. Daily isentropic chart.

vortex. The sharp fall off of precipitation from heavy to light is based on the premise that the frontal boundary of Polar air will be quite steep.

The type of action forecast to make up the mean patterns consists of slow southward migration of the Polar High, rotating around the deep Icelandic Low. Weak, cold fronts will probably precede each new thrust of Polar air into the east and southeast. The mid-west should be occupied practically throughout the period by Polar anticyclonic conditions. Weak disturbances are expected to enter the southern California region, and move eastward, and southeastward, remaining as flat waves, affecting the Gulf Coast region, and then moving northeastward into the Icelandic Low. Little frontal or cyclonic activity is indicated in the Pacific northwest, although some weak frontal activity is expected along the quasi-stationary $P_p - P_c$ front along the Great Divide.

Following is a copy of the text transmitted to the district forecast centers on the evening of February 20. It is based entirely on the prognostic charts just discussed (Fig. 10a, b, c, d, e).

GENERAL OUTLOOK AND FORECAST, FEB. 22–26, 1941

Zonal index diminish slightly. Icelandic Low split into two centers, one over southwest Europe. Other centered eastern Labrador, central pressure 995 mbs. Bermuda High not much change position or intensity. Polar continental anticyclonic well developed ridge with crest just eastward of Rockies and southeastward ridge extension into southeastern U. S. with also extension into Pacific just north Canadian border. Trough from Icelandic Low between Bermuda and Polar High 60 west. Remnant of low pressure center off California coast. Aleutian Low 1000 mbs. centered latitude 50 longitude 170 east. Moderate trough extending southeastward separating extension of Polar continental High from weak Pacific high centered latitude 30 longitude 170 east.

3 Km. Intense Polar Low centered latitude 50 longitude 75 west surrounded by strong cyclonic flow penetrating southwestward to Gulf. Well developed trough separating northeasterlies from westerlies extending Montana southwestward. Other troughs longitudes 15 west 170 west.

Isentropic. Broad cyclonic dry flow over eastern portion of country. Anticyclonic dry tongue northwest. Sharp zonal increase of moisture south of latitude 35 with greater moisture inundations in southwest and Florida.

Continued flow of Polar air will cause below normal east of continental divide except much below normal 31813 19136 90367 6//// and near normal northern New England. Prevailing southerly flow due to activity off California coast will cause above normal 49224 22341 10310 9////. Otherwise near normal. Deep continental air masses will result in light 33803 49541 02442 4//// except moderate to heavy snows leeward shores of Lakes. Activity off California coast combined with ascent of Pacific air over continental air with some over-running by Gulf air farther east will cause heavy 39233 90332 94318 1////. Otherwise moderate.

Observer, Washington, D. C. Temperature below normal except much below Tennessee. Not much trend indicated. Precipitation light. Little or none indicated except snow flurries in mountains.

Observer, Jacksonville, Fla. Temperature much below normal except below Florida. Not much trend. Precipitation light Carolinas northern Georgia moderate southern Georgia heavy Florida. Precipitation in moderate and heavy areas will occur intermittently throughout period. Otherwise little or none indicated.

Observer, New Orleans, La. Temperature below normal except much below Alabama, Mississippi. Not much trend indicated. Precipitation heavy except moderate northern Louisiana central Mississippi central Alabama and light Arkansas northern Alabama northern Mississippi. Precipitation in heavy and moderate areas will fall mainly middle of period.

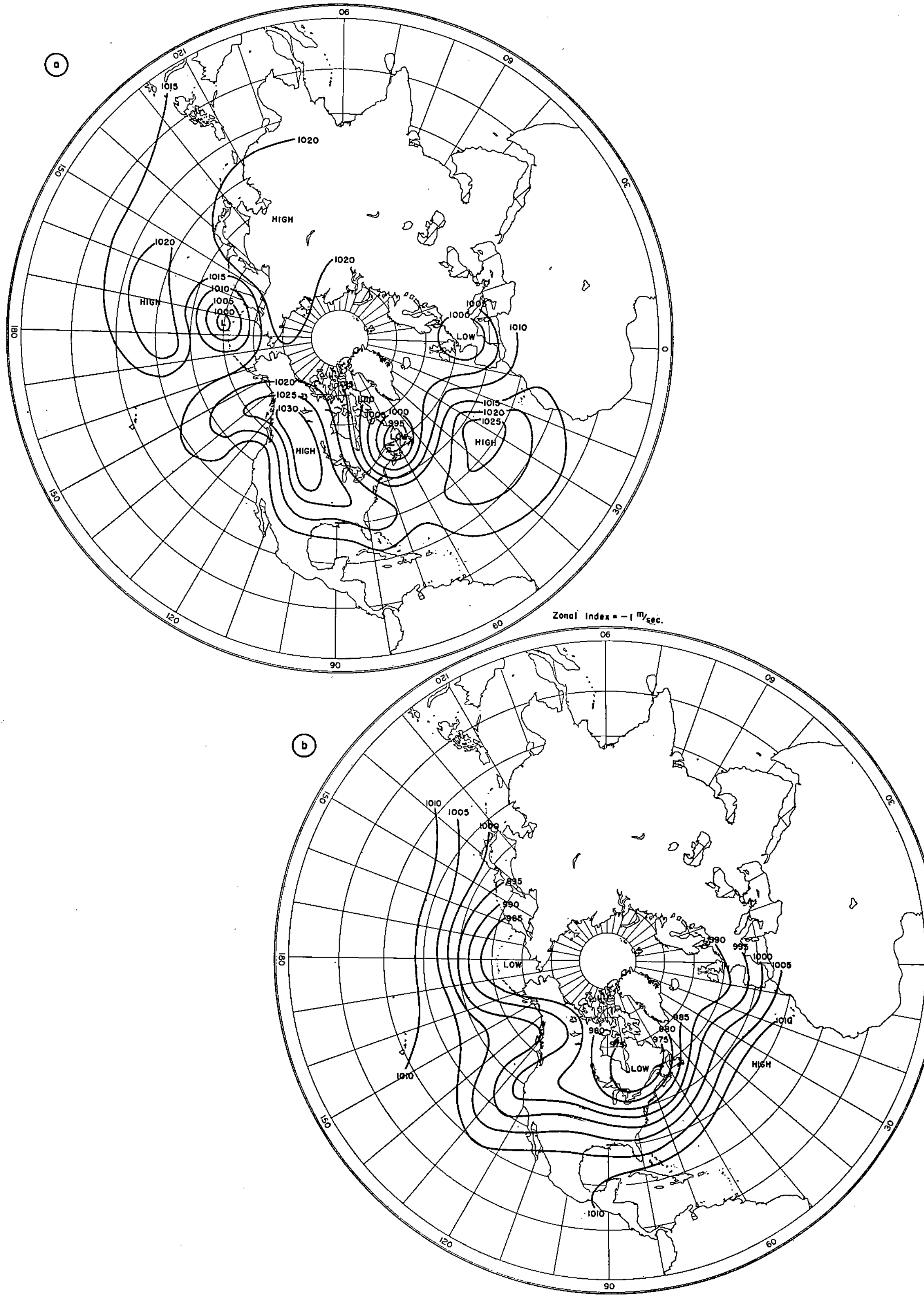

FIG. 10a,b

(*See next page*)

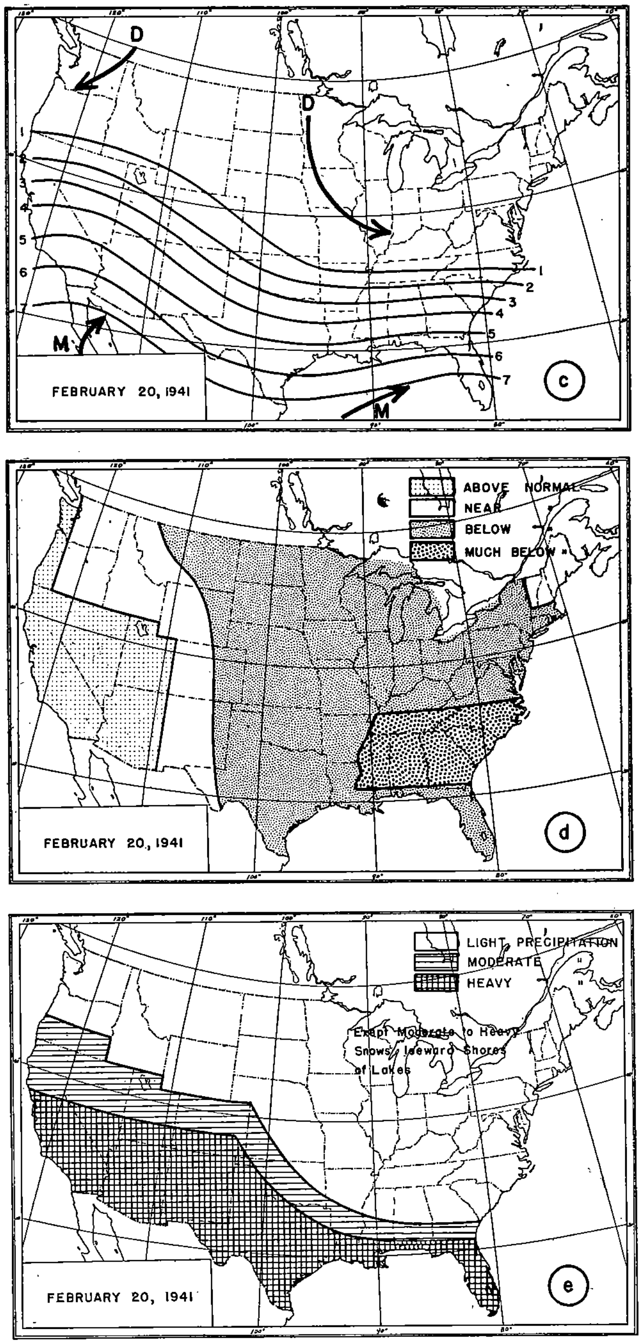

FIG. 10. Complete set of mean prognostic charts for the period February 22–26, 1941, as prepared on February 20.

Observer, Kansas City, Mo. Temperature below normal. Not much trend indicated. Precipitation light except moderate southwestern Oklahoma extreme southwestern Kansas. Precipitation in moderate area will occur middle of period. Otherwise little or none indicated.

Observer, Chicago, Ill. Temperature below normal. Not much trend indicated except cooling

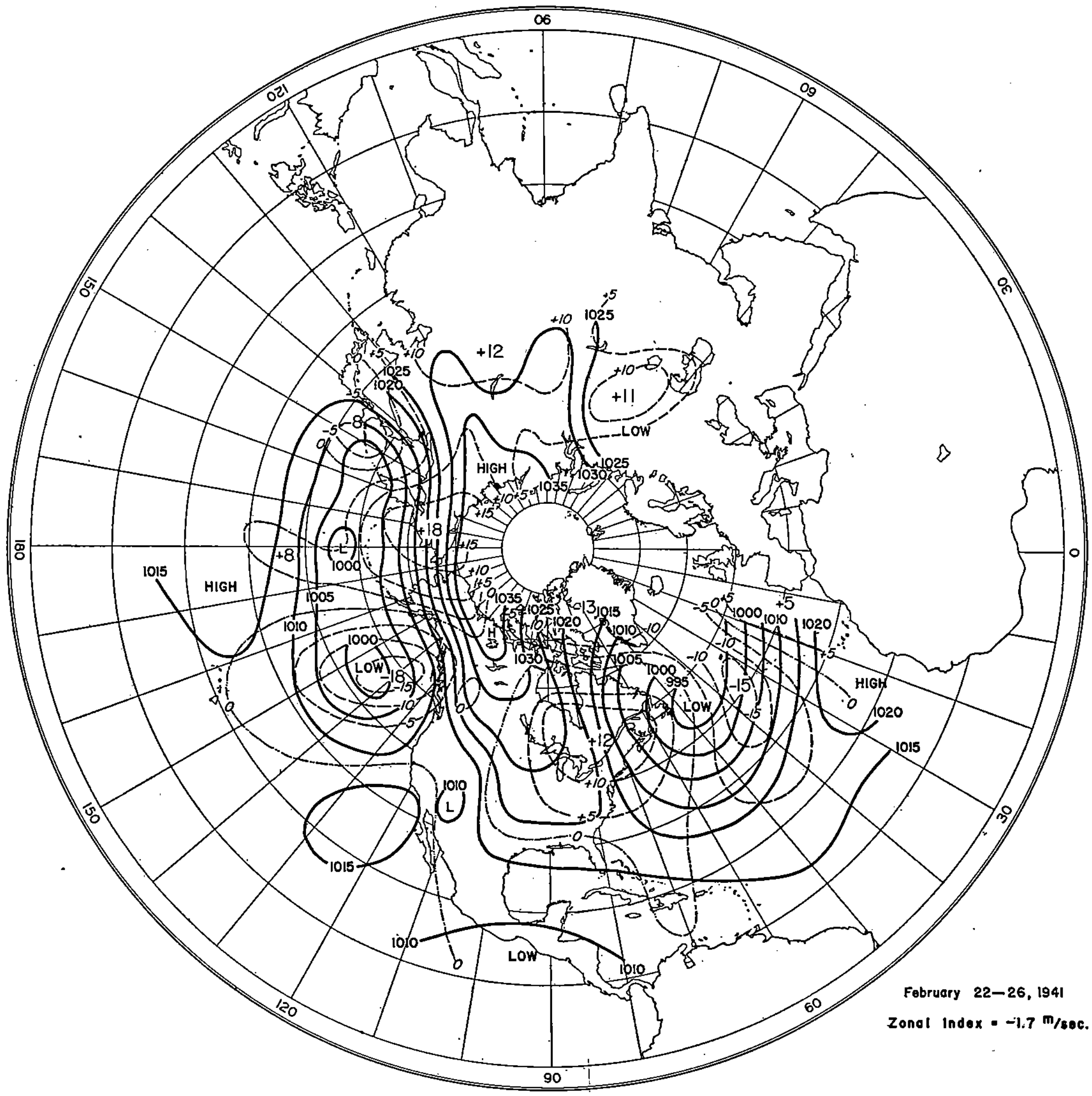

Fig. 11. Northern hemisphere mean pressure and pressure change map.

eastern portions middle of period. Precipitation light except moderate to heavy snows leeward shores of lakes, especially middle and end of period. Otherwise little or none indicated.

Observer, Denver, Colo. Temperature near normal except below east of Divide. Not much trend in below normal area. Gradual cooling in near normal area. Precipitation light except moderate northern Colorado and heavy southern Colorado. Precipitation in Colorado will fall beginning and middle of period. Otherwise little or none indicated.

Observer, Salt Lake City, Utah. Temperature above normal. Not much trend. Precipitation heavy south moderate north occurring beginning and middle of period.

Observer, Albuquerque, N. M. Temperature above normal Arizona. Near normal New Mex-

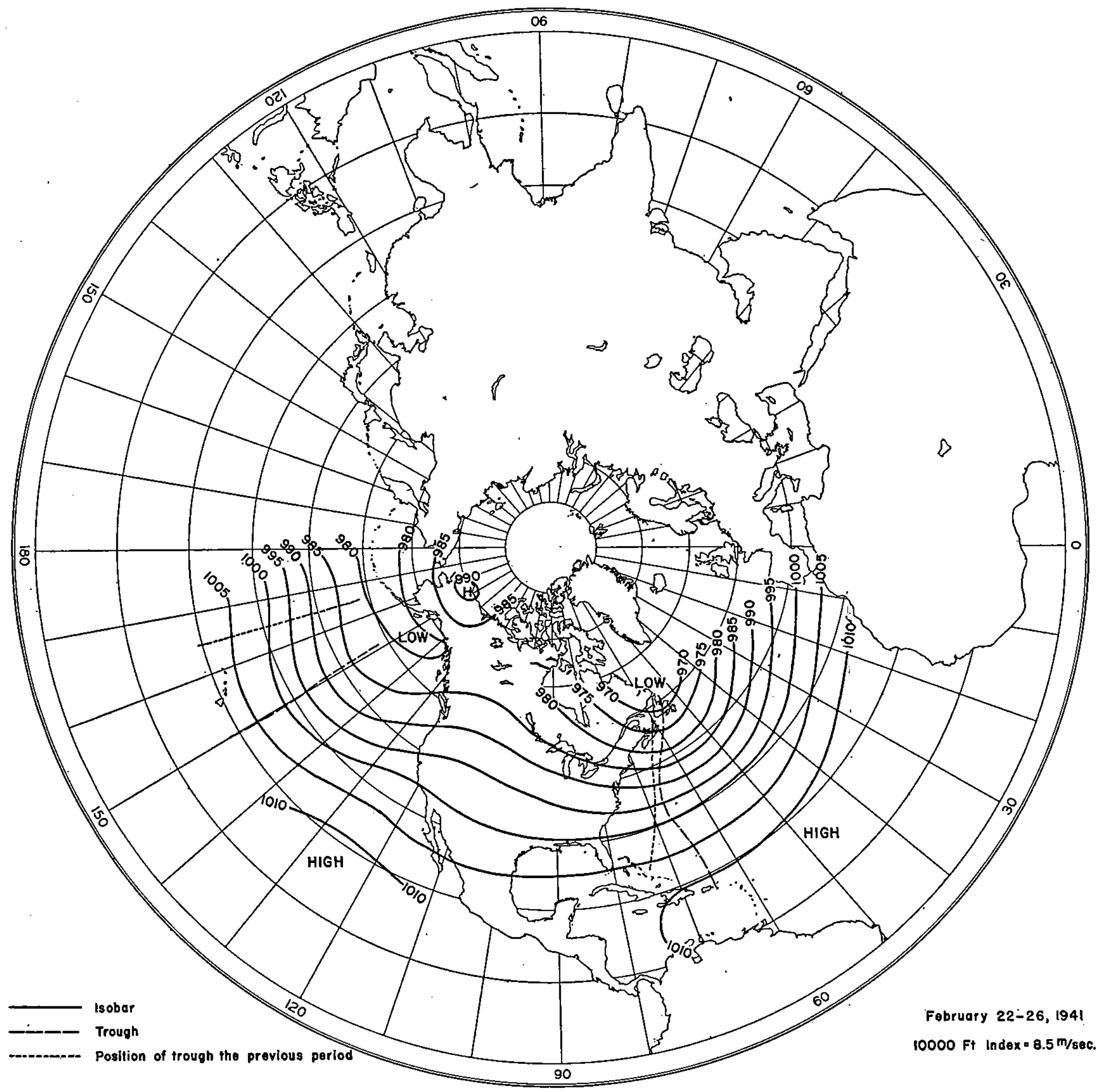

FIG. 12. Extended mean 10,000 ft. pressure map.

ico except below normal east of Divide and below normal Texas. Not much trend. Precipitation heavy falling mainly beginning and middle of period.

Observer, San Francisco, Calif. Temperature near normal except above normal Nevada central and northern California and coastal regions of Washington and Oregon. Not much trend indicated except gradual cooling in Washington Oregon throughout period. Precipitation light Washington northern Oregon and Idaho and heavy central California southern Nevada. Otherwise

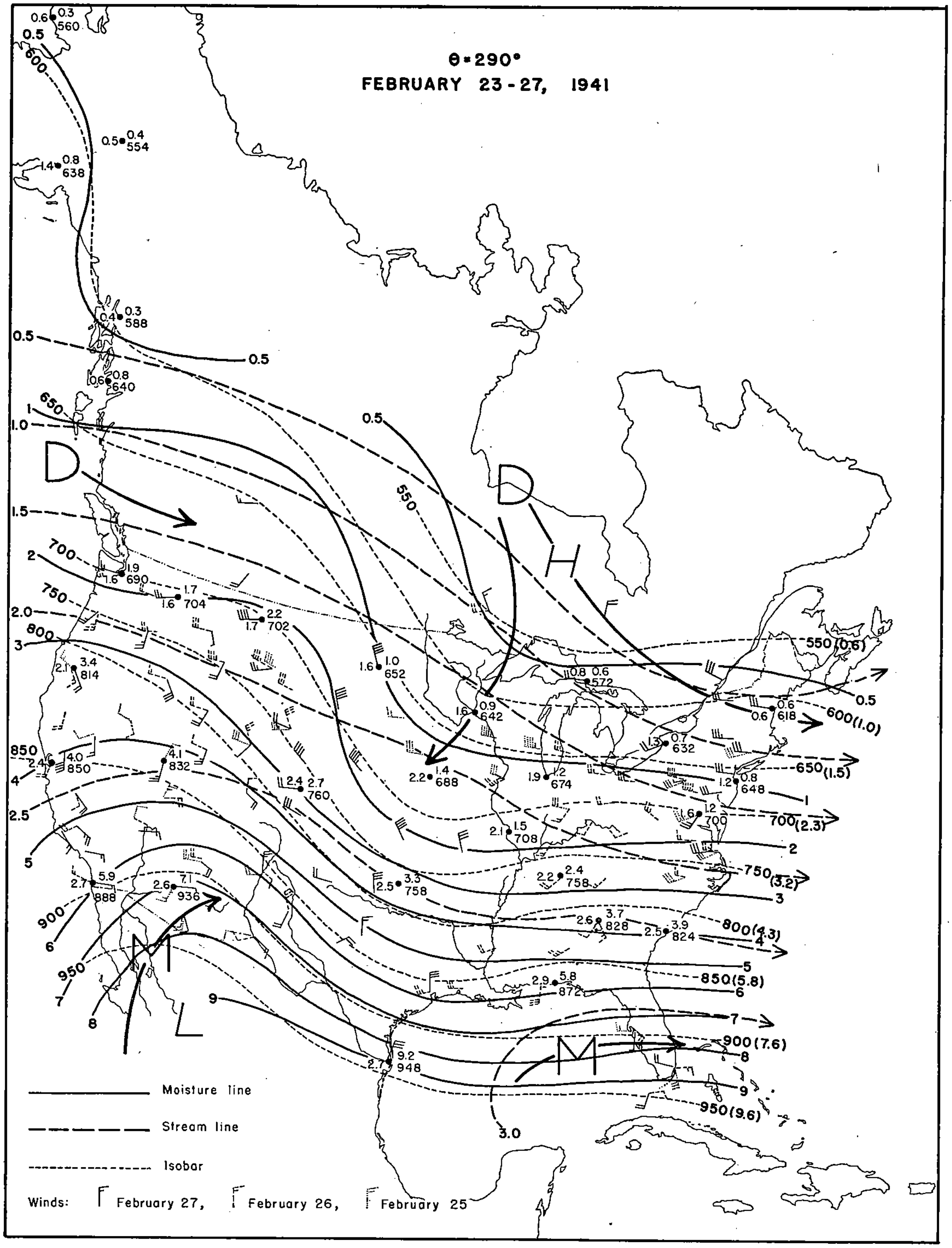

Fig. 13. Mean isentropic chart.

moderate. Precipitation in heavy and moderate areas will occur mainly beginning and middle of period.

Observer, Los Angeles, Calif. Temperature above normal. Not much trend. Precipitation heavy falling beginning and middle of period.

"Post Mortem" Discussion of the Forecast Made for the Period February 22–26.

Index Forecasts

	Forecast	*Observed*
Zonal Index	−1 mps	−1.7 mps
3 km. Index	8.5 mps	8.5 mps

These index forecasts were very good, and leave little room for improvement. The mean surface pressure map was also forecast quite well over the area affecting the weather of the United States, although there were some large scale errors in other portions of the hemisphere. (Compare Fig. 10a with Fig. 11.) The Atlantic High was farther east and less extensive than forecast, and a large portion of the Atlantic was under the domination of the Icelandic Low rather than the Bermuda High. The position and intensity of this center of action do not differ much from the forecast. The lack of data over western Europe makes it impossible to verify the existence of another Low pressure center there. The general nature of the Polar anticyclone and the orientation of its ridge were correctly forecast, although the main center of High pressure remained farther north than forecast. This failure, however, has little influence on the forecast for the United States. The Aleutian Low was split into two centers, as forecast, although the positions were not as forecast. The western cell was quite correctly placed, but the cell off the California coast moved farther eastward than forecast, and was centered over Arizona. A serious error arises in the region of the Gulf of Alaska where there is found another cell of the Aleutian Low, rather than a ridge as was forecast. It appears possible that the extremely low

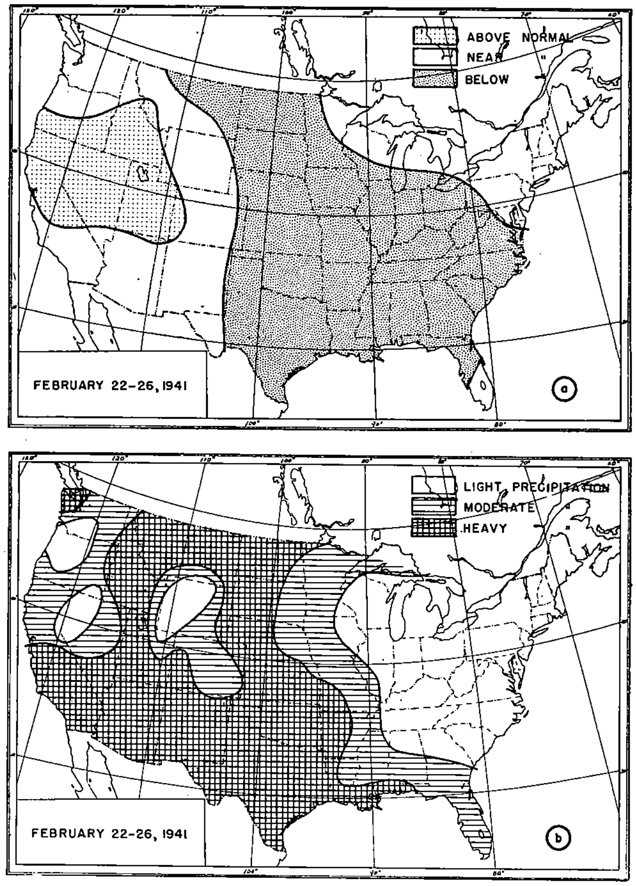

Fig. 14. Observed temperature and precipitation anomaly charts.

index (-1.7 mps) may have lead to a second splitting of the Aleutian Low observed in the western Pacific during the period February 15–19, while the previously formed eastern cell drifted inland. The weak nature of the Pacific High was correctly forecast.

The 3 km chart agrees with the prognostic chart over the eastern two-thirds of the United States, and shows the extensive influence of the deep Polar Low. (Compare Fig. 10b with Fig. 12.) This center was slightly farther east than forecast, an error associated with a similar error in placement of the Icelandic Low at the surface. In the western

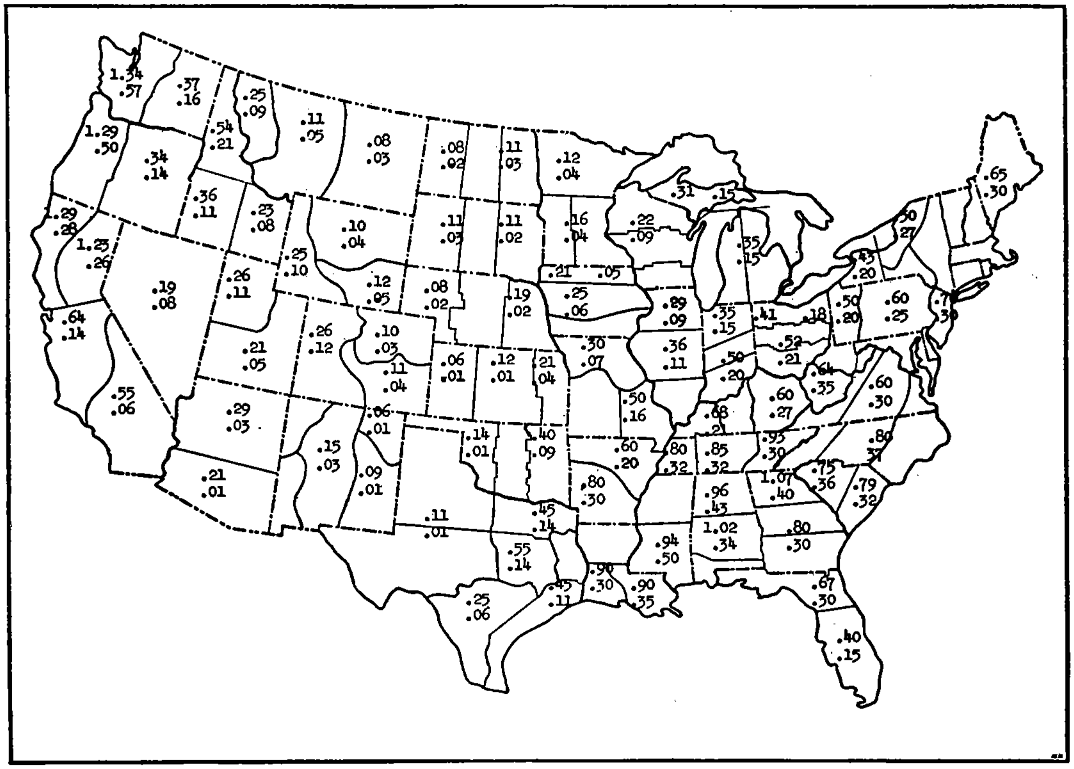

FIG. 15. Regional limits for five-day precipitation forecasts for weeks 5–8, January 29–February 25.

United States and in the Pacific the forecast leaves much to be desired. The wave length of the observed trough system is greater than that forecast, and the amplitudes are less. Corresponding to this the trough forecast for the mid-Pacific, and the ridge of high pressure to the east of it, occur farther west than forecast.

The mean isentropic chart was forecast as correctly as one could wish for. (Compare Fig. 10c with Fig. 13.) Aside from the fact that slightly more moisture infiltrated the northwest than the forecast called for, the agreement between forecast and observed charts is excellent.

Inasmuch as the outstanding features of the prognostic charts were forecast correctly over the United States, it would be expected that the forecast of temperature anomalies and total precipitation would verify well. The general pattern of observed temperature anomalies compares very favorably with that forecast. (Compare Fig. 10d with Fig. 14a.)

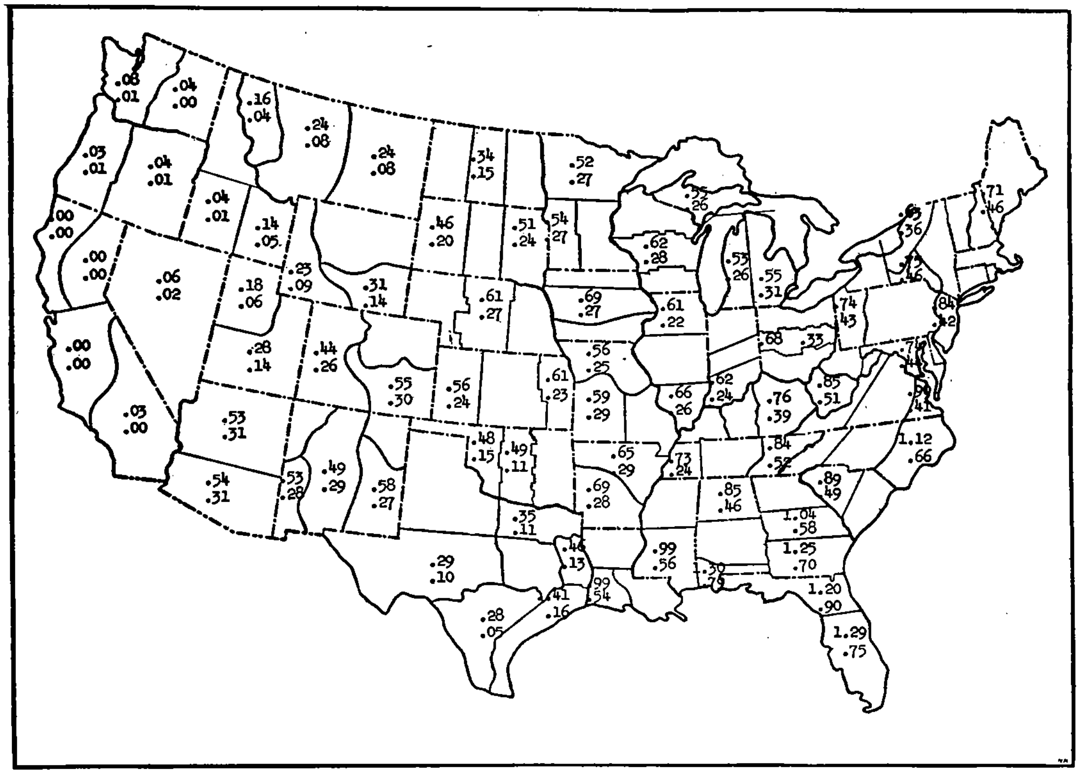

FIG. 16. Regional limits for five-day precipitation forecasts for weeks 29–32, July 16–August 12.

The outstanding features are the extensive flow of cold Polar air east of the Great Divide bringing with it below normal temperatures, the smaller departures from normal in the northeast and the larger departures over the southeast. Except for the extreme southwest, the western section of the country was also forecast correctly. There are no errors of more than one class out of the way, and even the one class errors are not of a serious nature. For example, in the southeast departures need have been only a couple of degrees colder to make this area fall into the classification of "much below normal." In the southwest temperatures were slightly lower than forecast, because the California Low was farther inland than expected, and hence gave more of a northerly prevailing flow than was forecast. The warming effect of maritime air circulating around the deep Icelandic Low produced a more extensive band of near normal than was forecast.

The precipitation forecast is also very good, the only serious error being the failure to forecast the precipitation in the northern plains and northern Rocky Mountain States. (Compare Fig. 10e with Fig. 14b.) This precipitation resulted from over-running of Polar continental air masses by Polar Pacific air and this type of precipitation occurs when the continental air is fairly deep. Since the fundamental prognostic charts were reasonably correct in this area, the failure is one of internal inconsistency between prognostic and anomaly charts.

A summary showing the results of a statistical verification of the forecast is given in Table I. 65.1% of the country was forecast exactly in the correct temperature category, as against 25% which a pure chance forecast would give. The remaining area, in which there appears one class error, comprises 34.9% of the country, as against 41.8% which would be obtained by pure chance. There are no errors of two, three or four classes, although a chance forecast would have resulted in 25% of 2 class error and 8.2% of three class error. In precipitation, about 60% of the country was forecast in exactly the correct division while only 33.3% should be attained by chance; 23.6% of the country had an error of one class (42.2% by chance), and 16.6% was poorly forecast, as against 24.5% which might have resulted had the forecast been made by a random method.

Basically, this forecast was so good, at least in the United States, that there is not much which appears in retrospect as not properly having been taken into consideration

TABLE I
FORECAST VERIFICATION (FEBRUARY 22–26, 1941)

ERROR	TEMPERATURE		PRECIPITATION	
Class Intervals	Actual %	Expected %	Actual %	Expected %
0	65.1	25.0	59.8	33.3
1	34.9	41.8	23.6	42.2
2	0	25.0	16.6	24.5
3	0	8.2		
4	0	0		

at the time the forecast was made. Although there are some errors in the basic prognostic charts, they are not errors for which there now appears in retrospect any particular indication by which they might have been foreseen.

There is, however, the one failure in consistency between the basic prognostic charts and the prognostic anomaly charts shown by the failure to catch the precipitation in the northern Rockies and northern plains states. Since the basic prognostic charts were essentially correct in this region, and since this type of precipitation generally does occur there to a greater or lesser extent under the conditions which these charts represent, there should have been more of it forecast in this case. Otherwise there is little to suggest.

D. VERIFICATION OF THE FIVE-DAY FORECASTS

The immediate practical success of the five-day forecasts is best shown by the verification of the temperature and precipitation anomaly forecasts, as expressed by the mean prognostic anomaly charts of these elements. However, the fact must not be lost sight of that these charts represent a late stage in the preparation of the final forecast. They are based almost entirely on the anticipated mean state of the general circulation, as expressed by the various index forecasts and the basic mean prognostic charts. Consequently their success depends on two different prognostic steps which should be verified individually if the reason for the success or failure of the final forecast is to be determined.

The first prognostic step which should be checked by verification is that represented by the correctness of the basic prognostic mean charts. In other words, how correctly can the mean state of the general circulation be forecast? The success of the basic prognostic charts is very difficult to verify quantitatively. Numerical values of the zonal indices as forecast, and perhaps also of the positions and intensities of the principal centers of action, can be verified. A crude verification of this kind is being attempted, but the results are not yet ready for publication. However, it seems probable that the basic prognostic charts will have to be verified in some more comprehensive manner if their success as a prognostic tool is to be properly judged. This may be possible later on the basis of the punch card classification of mean map types.

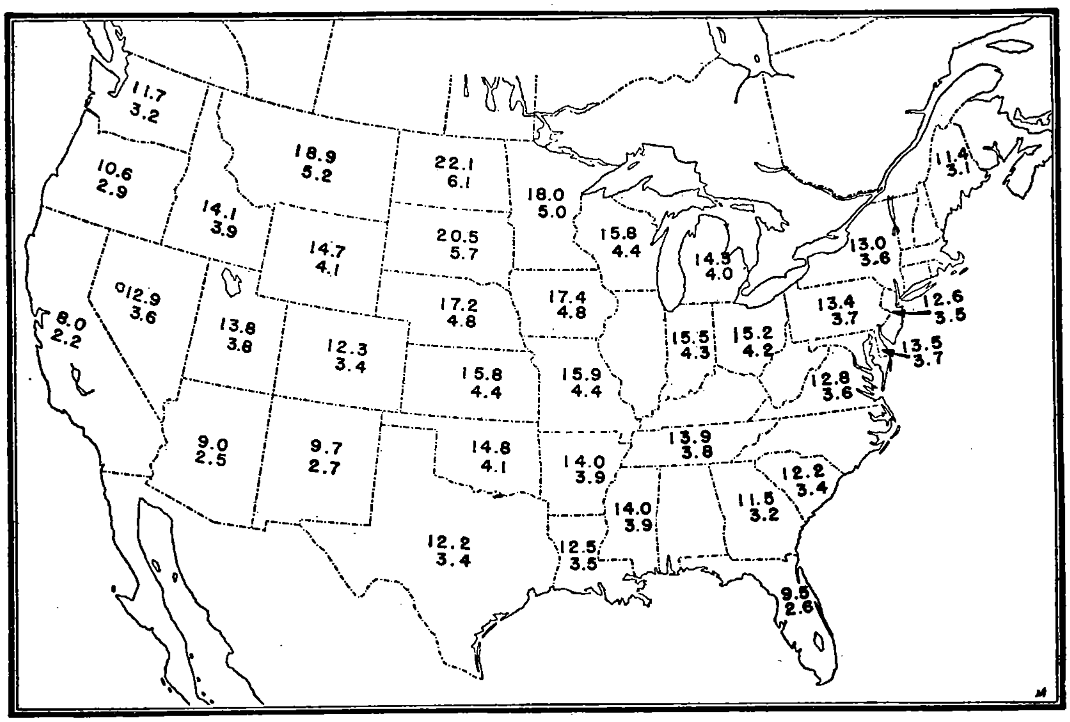

FIG. 17. Regional limits for five-day mean temperature forecasts for February.

The second prognostic step which can be checked by verification is that of the extent to which the mean state of the general circulation, as expressed by the basic prognostic charts, does uniquely determine the anomaly patterns of temperature and precipitation. Obviously it does not help much to forecast the basic prognostic charts correctly unless they do determine the principal features of the anomaly patterns of temperature and precipitation.

One of the gratifying results of the past year's work is the extent to which this unique determination of the anomaly patterns has been established. It is very rarely that there occur serious extensive errors in the prognostic anomaly patterns that there do not occur exactly corresponding errors in the basic prognostic charts. Sometimes the errors are shown to be the result of inconsistency between the prognostic anomaly charts and the basic prognostic charts, but usually the large errors are those which were made first in the basic prognostic charts. This is particularly true of the temperature element, for which the mean value between sea-level and three kilometers is absolutely determined by the mean pressure charts. The agreement of the precipitation anomaly pattern with the basic mean charts is somewhat less satisfactory than that of temperature, but on the whole the agreement has been found to be surprisingly good (Smith, 7). Certainly the experience of the past year has proved that five-day temperature and precipitation anomaly forecasts derived from correct basic prognostic charts will possess a high degree of accuracy.

The following verification of the five-day temperature and precipitation anomaly patterns includes the effect of errors from the two sources mentioned above, without any possibility of distinguishing between the part played by the errors of each source separately. However, it can be assumed that much the more important source of error is that

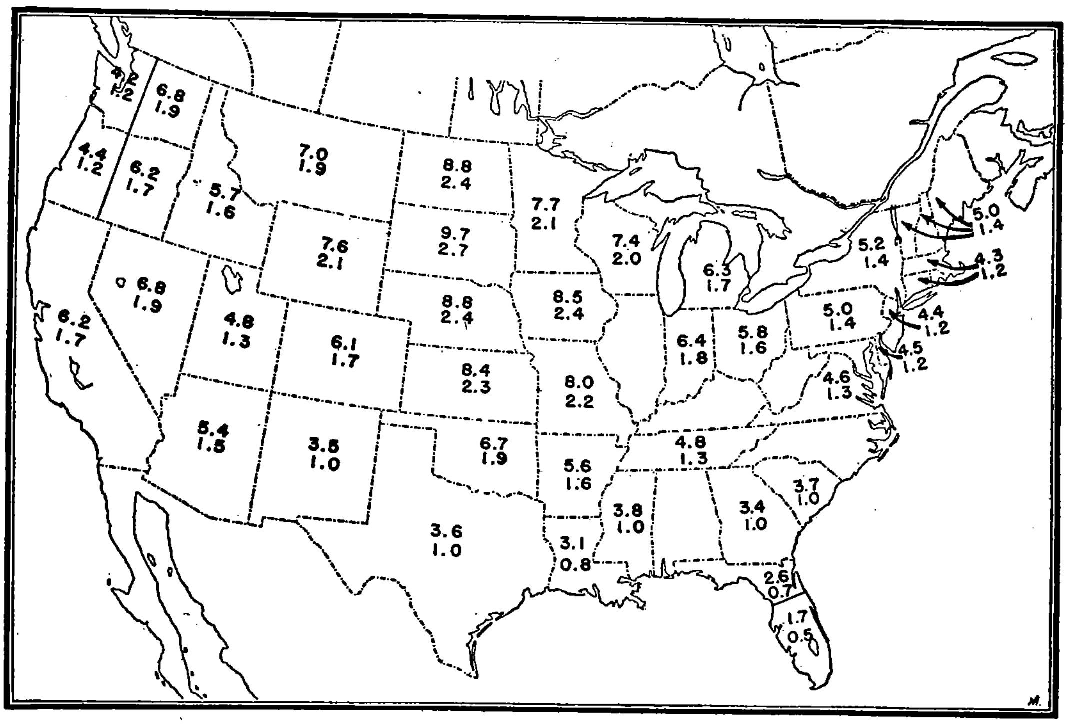

FIG. 18. Regional limits for five-day mean temperature forecasts for July.

represented by the errors in the basic prognostic charts. It should be noted that the timing element of the forecasts has received no verification up to the present. This also offers a difficult verification problem which probably will be attacked by means of the daily prognostic charts.

A discussion by Mr. Allen of the statistical verification of the five-day temperature and precipitation anomaly forecasts follows:

When the program of preparing extended forecasts was first set up, it was recognized that the most valid and objective measure of the immediate value of the method is to be obtained by a rigid statistical verification of the forecasts themselves. This has been particularly true during the past year, when most of the effort has been to produce actual forecasts and little time has been spent in developing and particularly in testing new fundamental methods. For that reason, considerable care was given to the choice of ele-

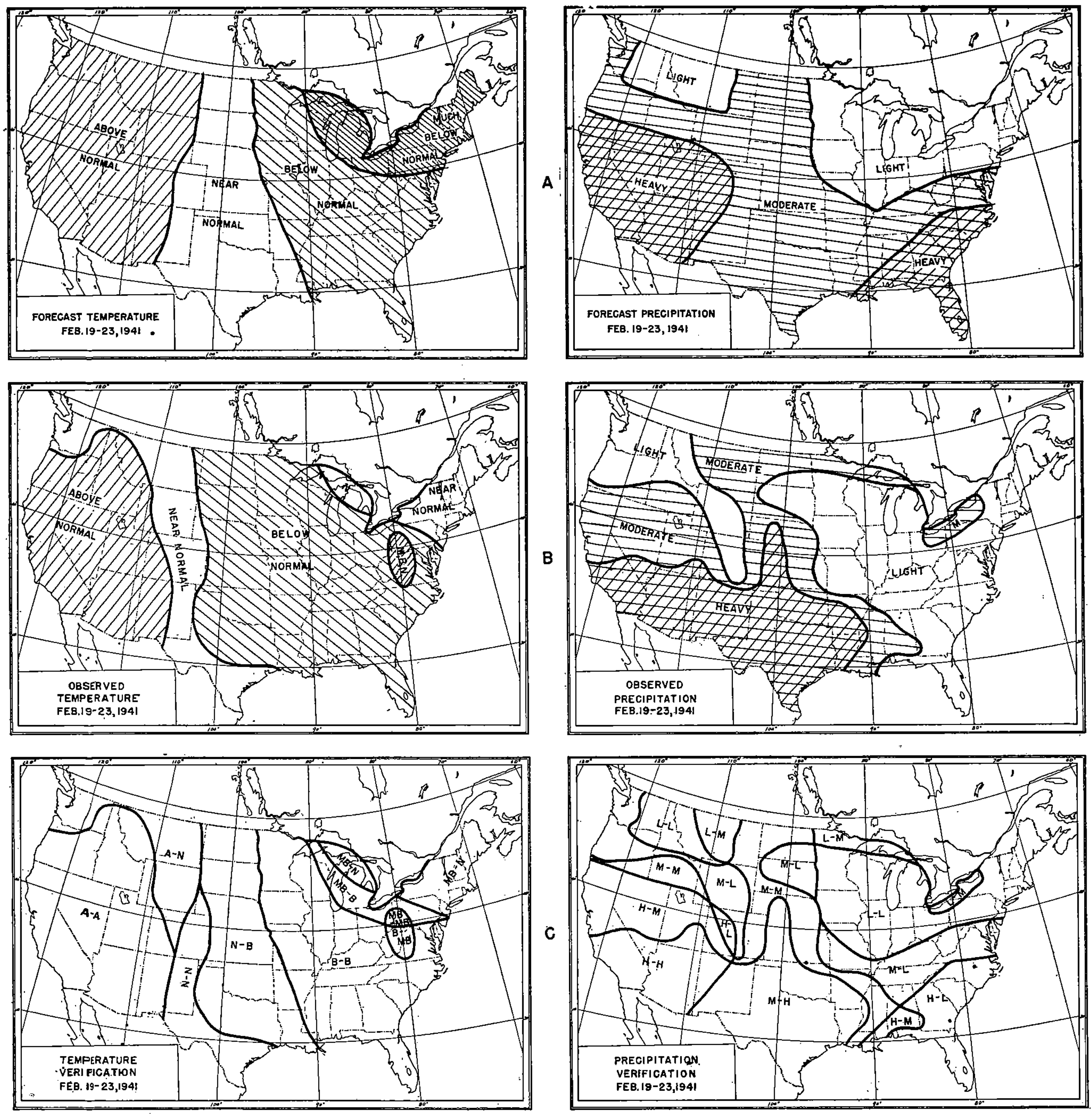

FIG. 19. Verification of prognostic anomaly charts by area method.

ments to be forecast and the terms to be used in expressing the forecasts, so that the forecasts would be in commonly understood terms, and at the same time would have rigidly defined meanings.

Since every forecast has a certain chance of success regardless of the ability of the forecaster, it was essential to choose terms such that the probability of success could be determined for each forecast. It was desirable, further, that these probabilities be nearly the same for all forecasts, or at least that there be only a small number of different probabilities involved. This would permit the grouping of forecasts according to the probability of success, and a comparison of the actual number of correct forecasts to the number expected correct by chance.

For the five-day forecasts, temperature has been measured in five classes and precipitation in three. The five temperature classes are "much below normal," "below normal," "near normal," "above normal," and "much above normal," which are defined to have probabilities of occurrence of $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{4}$, $\frac{1}{4}$, and $\frac{1}{8}$ respectively. The three precipitation classes are "heavy," "moderate" and "light," each with a probability of occurrence of $\frac{1}{3}$.

TABLE II

Distribution of Areas for Forecast for February 19–23, 1941. The Figures in the Table Are Percentages of the Total Area of the United States

		Forecast Temperature Departure					Total
		Much Below	Below	Near	Above	Much Above	
Observed Temperature Departure	Much Below	0.4	0.				1.2
	Below	3.5	27.3	18.8			49.6
	Near	6.0		7.6	8.6		22.2
	Above				27.0		27.0
	Much Above						
	Total	9.9	28.1	26.4	35.6		100.0%

		Forecast Precipitation			Total
		Heavy	Moderate	Light	
Observed Precipitation	Heavy	8.8	17.1		25.9
	Moderate	10.1	12.5	4.7	27.3
	Light	7.3	17.5	22.0	46.8
	Total	26.2	47.1	26.7	100.0%

An attempt is made to determine the numerical limits of the various classes from past records in such a way that "much below normal" temperature, for instance, has occurred at a given place one out of every eight five-day periods, "below normal" temperature has occurred one out of every four five-day periods, etc. For precipitation, "heavy," "moderate" and "light" have each occurred one out of every three five-day periods, on the average. The obvious way to obtain these limits is to use a long series of actual five-day mean temperature departures and five-day precipitation totals for a complete network of stations.

The labor of obtaining these data is prohibitive, however, and substitute methods have had to be used. For precipitation there were available for a 30-year period, weekly totals averaged for all stations in a relatively small area. These weekly averages were tabulated in a frequency distribution, and the numerical limits of the classes obtained by counting off the lower one-third for the "light" classification, the middle one-third for the "moderate" classification and the upper one-third for the "heavy" classification. The boundary limits of these classes were then multiplied by 5/7 to obtain the corresponding limits for five-day totals. In Figures 15 and 16 are shown the limits as computed for one winter and one summer month. The lower number in each district is the upper limit (in inches) of

TABLE III

EXPECTED DISTRIBUTION OF AREAS FOR FORECAST FOR FEBRUARY 19–23, 1941. THESE ARE THE PERCENTAGES THAT WOULD BE EXPECTED FROM A RANDOM FORECAST

		FORECAST TEMPERATURE DEPARTURE					Total
		Much Below	Below	Near	Above	Much Above	
OBSERVED TEMPERATURE DEPARTURE	Much Below	0.15	0.30	0.30	0.30	0.15	1.2
	Below	6.20	12.40	12.40	12.40	6.20	49.6
	Near	2.78	5.55	5.55	5.55	2.78	22.2
	Above	3.37	6.75	6.75	6.75	3.37	27.0
	Much Above						
	Total	12.5	25.0	25.0	25.0	12.5	100.0%

		FORECAST PRECIPITATION			Total
		Heavy	Moderate	Light	
OBSERVED PRECIPITATION	Heavy	8.63	8.63	8.63	25.9
	Moderate	9.10	9.10	9.10	27.3
	Light	15.60	15.60	15.60	46.8
	Total	33.3	33.3	33.3	100.0%

the class "light" and the lower limit of the class "moderate." The upper number is the upper boundary of "moderate" and the lower limit of "heavy."

For the temperature limits, use has been made of a relation between the distribution of five-day means and monthly means. If it is assumed that successive five-day means are independent and normally distributed, then

$$\sigma_5 = \sqrt{6}\sigma_{30}$$

where σ_5 is the standard deviation of five-day means and σ_{30} is the standard deviation of monthly (30-day) means. Having the standard deviation of five-day mean departures, the departure which will be exceeded three times out of eight and that which will be exceeded one time out of eight are easily computed. This method is subject to errors introduced by the above assumptions, especially in winter and in the Plains States, which tend to reduce the number of occurrences of much above normal and much below normal, and to increase the occurrence of above normal. These limits in degrees Fahrenheit are given in Figures 17 and 18 for one winter and one summer month.

As has been explained in an earlier section, the forecast of temperature and precipitation consists of a set of maps of the United States on which are indicated the forecast regions of above normal temperature, below normal temperature, etc. and regions of heavy precipitation, moderate precipitation, etc. (Fig. 19A). The observed charts for the corre-

TABLE IV

Summary of Areas Correct and Incorrect for Forecast for February 19–23, 1941. Also Given Is the Over-all Score Obtained by Weighting the Errors

Error in Class Intervals	Temperature			Precipitation		
	Actual %	Expected %	Difference %	Actual %	Expected %	Difference %
0	62.3	24.8	+37.5	43.3	33.3	+10.0
1	31.7	40.1	+ 8.4	49.4	42.5	− 6.9
2	6.0	25.0	+19.0	7.3	24.2	+16.9
3	0	9.9	+ 9.9	Temperature: Score $=\frac{214.2}{307.6}=69.6\%$		
4	0	0.2	+ 0.2	Precipitation: Score $=\frac{252.8}{623.9}=40.5\%$		

sponding five-day period consist of observed temperature departures for 140 scattered stations, and observed precipitation totals for 260 stations. Comparison of observed values with the limits shown on the accompanying charts determines in which class the observation falls. Lines are drawn on the observed chart outlining regions of heavy, moderate, and light for precipitation, and regions of much below normal, below normal, near normal, etc. for temperature (Fig. 19B).

For verification these two sets of lines, forecast and observed, are drawn on a single chart (Fig. 19C). With a planimeter it is then easy to measure the area of each separate region and assign its area to the proper box of a contingency table. These areas for each box are converted to percentage of the total area. Table II shows the resulting percentages for the forecast made for the period February 19–23, 1941. The figures in a column refer to all areas which were forecast as indicated at the top of the column; figures in a row refer to areas which were observed as indicated at the left end of the two. The totals at the bottom and right are the total areas forecast and observed respectively in each class. Thus, for temperature, for instance, a total of 9.9 percent of the area of the United States was forecast to be much below normal, of which 0.4 percent was observed much below, 3.5 percent was observed below and 6.0 percent was observed near normal. The total part of the forecast that was exactly correct was 0.4+27.3+7.6+27.0=62.3 percent. For precipitation a total of 43.3 percent was correct.

In Table III, are shown the corresponding distribution of areas that would be expected if the forecast had been made by some random process, that is with no forecasting ability implied. In order to make a random forecast, it must be assumed that, since nothing is known about the way the marginal distribution of observed will occur, the most probable distribution will be forecast, that is, one-eighth (12.5 percent) much below normal, one-

TABLE V

AVERAGE DISTRIBUTION OF AREAS FOR 38 FORECASTS MADE BY MR. NAMIAS DURING OCTOBER, 1940 TO JUNE, 1941, EXPRESSED IN PERCENTAGE OF AREA OF THE UNITED STATES

		Forecast Temperature Departure					Total
		Much Below	Below	Near	Above	Much Above	
Observed Temperature Departure	Much Below	0.3	1.3	0.6	0.3		2.5
	Below	1.5	9.4	4.8	4.0	0.2	19.9
	Near	1.3	10.6	12.7	8.8	0.4	33.8
	Above	0.3	5.4	9.8	18.7	1.2	35.4
	Much Above		0.4	1.9	5.0	1.1	8.4
	Total	3.4	27.1	29.8	36.8	2.9	100.0%

		Forecast Precipitation			Total
		Heavy	Moderate	Light	
Observed Precipitation	Heavy	8.1	6.6	10.0	24.7
	Moderate	8.5	8.2	11.3	28.0
	Light	11.4	15.0	20.9	47.3
	Total	28.0	29.8	42.2	100.0%

quarter (25 percent) below normal, one-quarter near normal, etc. Then the expected percentages in the various boxes follow in this manner: the probability that any given observed area (equal to one percent of the total, say) selected at random will be much below normal is equal to the ratio of the number of such much below areas to the total number of areas, in this case 1.2/100. The probable amount of the forecast much below that will be observed much below is then the product of 1.2/100 and total area forecast much below, that is, 1.2×12.5/100=0.15 percent. In general, the expected frequency for any box is equal to the product of the marginal totals for that row and column, divided by the grand total. The total area expected correct is obtained, as before, by adding along the diagonal. Similar considerations lead to the expected distribution for precipitation.

An index of the over-all score of a forecast is obtained from a comparison of Tables II and III. The total areas that are exactly correct, one class in error, two classes in error, etc. are first computed, as in Table IV. Similarly the expected percentages are totaled. The differences between actual and expected are then added, first giving positive signs to the difference if the actual error is smaller than the expected error (except for zero error), and weighting the difference by the square of the error.

For this forecast, the sum obtained in this way is 214.2, whereas, if the forecast had been entirely correct the sum would have been 307.6. The final score for the forecast is the ratio, or 69.6%. This method of computing a final score is somewhat arbitrary, but has the

TABLE VI

AVERAGE DISTRIBUTION OF AREA FOR 40 FORECASTS MADE BY DR. WILLETT DURING OCTOBER, 1940 TO JUNE, 1941, EXPRESSED IN PERCENTAGE OF AREA OF THE UNITED STATES

		Forecast Temperature Departure					Total
		Much Below	Below	Near	Above	Much Above	
Observed Temperature Departure	Much Below	0.6	2.3	1.4	0.4		4.7
	Below	0.7	7.1	6.8	3.1	0.1	17.8
	Near	0.6	10.1	11.2	9.6	0.4	31.9
	Above	0.1	5.7	11.3	17.0	2.5	36.6
	Much Above		1.3	1.7	4.9	1.1	9.0
	Total	2.0	26.5	32.4	35.0	4.1	100.0%

		Forecast Precipitation			Total
		Heavy	Moderate	Light	
Observed Precipitation	Heavy	12.4	10.1	5.1	27.6
	Moderate	9.6	9.8	7.3	26.7
	Light	11.2	14.5	20.0	45.7
	Total	33.2	34.4	32.4	100.0%

advantage of being zero when the forecast is neither better nor worse than chance, +100% when the forecast is perfect, and negative when the forecast is worse than chance. In computing this score for precipitation, an error of one class has been weighted by 4, and an error of two classes by 16, in order to give the same overall weighting as is used for temperature.

All official forecasts made during the nine-month period October, 1940 to June, 1941 have been verified in the above manner. Table V shows the average percentage obtained by Mr. Namias on 38 forecasts made during that period, and Table VI shows the average percentage obtained by Dr. Willett on 40 forecasts. It will be noted that a tendency existed on the part of both forecasters to forecast more below normal temperature than occurred, and somewhat less much above normal than occurred. Mr. Namias forecast

TABLE VII

SUMMARY OF 78 OFFICIAL FORECASTS FOR THE NINE-MONTH PERIOD, OCTOBER, 1940 TO JUNE, 1941. THE MARGINAL TOTALS ARE IN PERCENTAGE OF AREA OF THE UNITED STATES. THE FIGURES IN THE BODY OF THE TABLE ARE IN PER CENT OF THE COLUMN TOTAL

		Forecast Temperature Departure					Total
		Much Below	Below	Near	Above	Much Above	
Observed Temperature Departure	Much Below	17.1	6.8	3.1	0.9		3.59
	Below	41.1	30.7	18.8	9.8	3.9	18.81
	Near	35.0	38.7	38.3	25.6	11.6	32.82
	Above	6.8	20.8	34.1	49.7	53.2	36.07
	Much Above		3.0	5.7	14.0	31.3	8.71
	Total	2.72	26.76	31.13	35.86	3.53	100.00%

		Forecast Precipitation			Total
		Heavy	Moderate	Light	
Observed Precipitation	Heavy	33.5	26.2	20.2	26.19
	Moderate	29.7	28.0	24.8	27.32
	Light	36.8	45.8	55.0	46.49
	Total	30.65	32.17	37.18	100.00%

TABLE VIII

SUMMARY OF AREAS CORRECT AND INCORRECT FOR THE 78 OFFICIAL FORECASTS DURING OCTOBER, 1940 TO JUNE, 1941. THE FINAL OVER-ALL SCORE IS SHOWN ALSO

Error in Class Intervals	Temperature			Precipitation		
	Actual %	Expected %	Difference %	Actual %	Expected %	Difference %
0	39.53	23.46	+16.07	39.72	33.33	+6.39
1	45.83	40.07	− 5.76	41.50	42.44	+0.94
2	13.17	25.00	+11.83	18.78	24.23	+5.45
3	1.47	9.93	+ 8.46	Temperature: Score $=\frac{158.41}{330.62}=47.9\%$		
4	0	1.54	+ 1.54	Precipitation: Score $=\frac{97.3}{624.11}=15.6\%$		

roughly correct proportions of heavy, moderate and light precipitation, whereas Dr. Willett tended to forecast too much heavy and moderate and too little light.

Table VII shows the combined summary for both forecasters. In this table, however, the figures in the body of the table are percentages of the column total. That is, of the 2.72% of the area of the United States that was forecast to be much below on the average, 17.1% was correct, 41.1% was observed to be below, etc.

Table VIII gives a summary of the errors for all 78 forecasts. It will be noted that about 40% of all forecasts were correct, but that less than 24% would have been correct by chance for temperature, and about 33% correct by chance for precipitation.

TABLE IX

SUMMARY OF SCORES ON ALL OFFICIAL FORECASTS MADE DURING OCTOBER, 1940 TO JUNE, 1941, INCLUSIVE. THE SCORES FOR ALL MONTHS ARE COMPUTED FROM THE DATA IN TABLES V AND VI. THE SCORES FOR ALL FORECASTS ARE AVERAGES OF THE SCORES FOR NAMIAS AND WILLETT. FIGURES IN PARENTHESES GIVE THE NUMBER OF FORECASTS

	Namias		Willett		All Forecasts	
	Temperature %	Precipitation %	Temperature %	Precipitation %	Temperature %	Precipitation %
October November December 1940	48.6 (12)	22.5 (12)	43.3 (14)	28.6 (14)	45.9 (26)	25.5 (26)
January February March 1941	58.6 (13)	0.7 (13)	55.6 (13)	18.9 (13)	57.1 (26)	9.8 (26)
April May June 1941	41.5 (13)	1.3 (13)	42.9 (13)	20.0 (13)	42.2 (26)	10.6 (26)
All Months	49.4 (38)	8.1 (38)	46.6 (40)	22.8 (40)	47.9 (78)	15.6 (78)

Table IX gives a final summary of the scores for all forecasts, broken down by forecasters, by element forecast, and by seasons. It is found that the greatest success in forecasting temperature has come in the winter and the least success in the spring. For precipitation the greatest success was in the autumn and the least success in the winter. It is difficult to explain the pronounced drop in skill between autumn and winter for Mr. Namias' precipitation forecasts, but it is significant that the seasonal differences are in the same direction for both forecasters. The outstanding difference, however, is that between temperature and precipitation for both forecasters for all seasons. The conclusion is very definite that more is known about forecasting temperature than about forecasting precipitation.

SECTION III. SPECIAL INVESTIGATIONS SUPPLEMENTARY TO THE FIVE-DAY FORECASTING PROCEDURE

This section includes brief reports on a number of special investigations undertaken during the past year to supplement certain parts of the five-day forecasting procedure. In the majority of cases the results obtained were not sufficiently conclusive or final to affect the forecasting procedure during the past year. In fact, in several cases the investigation has reached only a preliminary stage during this year. However, reference is made in the following discussion to each investigation which was started. The purpose and general procedure of each such undertaking is indicated, and insofar as possible either preliminary (incomplete) or final results are listed. The following listing and discussion of these investigations is in the order in which the subjects are related in the five-day forecasting procedure.

A. The Statistical Analysis of the Northern Hemisphere Sea-level Pressure Maps for the Winter Half of the Second Polar Year, from October 1, 1932 to March 31, 1933 Inclusive

Because the daily surface weather maps of the northern hemisphere were more complete during the Second Polar Year than they have been before or since, it was decided to use the sea level pressure data from the maps for the winter half of that year to investigate a number of statistical interrelationships between the various partial and total circulation indices. That year is the only one on record for which sufficient reliable observations are available so that the daily sea level pressure distribution is known from equator to pole of the entire northern hemisphere. Consequently that is the only period for which all of the sea level circulation indices can be computed in reliably complete form.

The routine tabulation and treatment of the pressure data for the winter half of the Polar Year, most of which was performed by Miss Scofield, included the following:

1. Averaging of all the daily pressure data for the northern hemisphere in overlapping five-day means, corresponding to the current treatment of such data, instead of the weekly seven-day means in which it was originally averaged.
2. Plotting and drawing of the northern hemisphere mean pressure maps for the fifty-two overlapping five-day periods.
3. Taking of the weekly five-day mean pressure changes, and plotting and drawing of fifty such mean pressure change maps for the northern hemisphere.
4. Computing and drawing the mean pole to equator pressure profile of each northern hemisphere mean pressure map.
5. Tabulation from the mean pressure profiles, converted to meters per second, of the max-min values of the indices of the subtropical easterlies, of the zonal westerlies, and of the polar easterlies, and the regular zonal indices of the subtropical easterlies (35°–20°) and the westerlies (35°–55°).
6. The computation of the regular zonal index (35°–55°) by quadrants for the Asiatic (130°–20°E), the Atlantic (10°E–70°W), the North American (80°W–130°W), and the Pacific (140°W–140°E) quadrants.
7. Reading from the daily maps of the pressure differences around each five degree latitude circle from 20° to 70°N to give the daily meridional indices, and averaging of the daily values to give the mean meridional indices.

The completion of this mass of routine statistical work proved to be so much of an undertaking that it was not accomplished before the beginning of July. Consequently the statistical analysis of the data has not yet been carried nearly to completion. Many possible lines of statistical analysis of the data have not been even considered as yet. However, some preliminary results have been obtained bearing on a few questions which were in mind when this investigation was started. Some of these preliminary results which have been found by Miss Scofield may be summarized as follows:

1. The max-min zonal index appears definitely to be a more useful index of the general circulation than does the present northern hemisphere zonal index. The behavior of these two indices is closely parallel, as shown by a correlation of +0.86 between the simultaneous five-day mean values of the two quantities during the six month period studied. But in the few cases where the two indices are widely divergent, which are cases of the false type of low index due to a latitudinal shift of the zonal westerlies rather than a real diminution of the intensity of the general circulation, the general circulation pattern corresponded much better to the high value of the max-min index than to the low value of the northern hemisphere index. Furthermore Miss Scofield finds at least for this period a more regular behavior of the max-min than of the 35°–55° zonal index, a fact which favors the application of extrapolation methods to the forecasting of the max-min index changes. However the number of index cycles (only seven) included in this six month period was too small to justify any further discussion of these statistical extrapolation methods of forecasting the index changes until they can be checked over a longer period. A final fact which favors the use of the max-min rather than the 35°–55° zonal index is that the former index shows consistently higher lag correlations with the meridional indices at all latitudes. Thus the meridional indices have more prognostic value for the max-min than for the 35°–55° zonal index.

2. The only really significant lag correlations which Miss Scofield finds between the different zonal indices are those between the Asiatic quadrant zonal index (35°–55°) and (a) the 35°–55° zonal index one week later (+0.52), (b) the max-min zonal index one week later (+0.41) and (c) the Atlantic quadrant zonal index (35°–55°) one week later (+0.48). These coefficients are in agreement with similar results obtained by Mr. Namias (p. 73), and with lag correlations previously found (Willett, 4).

3. Miss Scofield computed a number of correlations between the meridional indices at different latitudes and with different time lags. Several interesting results appeared. In the first place, they showed the greatest proportion of significant coefficients (8 out of 17 exceeded 0.42). In the second place, although they included time lags of from one to five periods, and applied to latitude circles from 25° to 70°, every single coefficient was positive (lowest value +0.15). No explanation of this surprising fact is offered. Furthermore, without exception, every correlation between a high latitude index and a subsequent low latitude index is significantly greater than the reverse correlation between the low latitude index and the subsequent high latitude index. This suggests that the changes affecting the meridional indices progress principally from pole to equator.

4. A number of correlations were computed, at from one to eight periods lag, between meridional indices at different latitudes and subsequent values of the max-min and 35°–55° zonal indices. Here again some interesting results were obtained. Although only a few of the coefficients obtained appear to be significant individually, every single one of the twenty-two coefficients is negative. This is the more surprising since independent theoretical considerations would lead one to expect positive coefficients. Furthermore, without exception, when the same correlation is computed between a meridional index

and the subsequent max-min and 35°–55° index, the max-min coefficient is the larger, the difference becoming greater the higher the correlation. Finally, the only correlations which appear to be significant individually are those between the meridional indices at lower latitudes (25° and 30°) and the subsequent max-min index. The coefficients increase consistently as the latitude of the meridional index is decreased.

A great deal remains to be completed in the way of statistical checking of the preliminary results obtained from the Polar Year data. It may be possible thus to find explanations for some of the surprising results already obtained.

B. Investigation of the Relationship between Polar Anticyclogenesis and Variations of the Zonal Index

As the result of a detailed synoptic study of a case of strong Polar anticyclogenesis during the month of February 1941, Mr. Namias draws conclusions as to both the synoptic sequence, by which strong Polar anticyclogenesis is established at high latitudes, and the mechanics by which the accompanying modification of the general circulation pattern is effected. This development represents the initial stage, that of the primary fall of the zonal index, of a major cycle of zonal index change, and the corresponding cycle of change of the general circulation pattern. The synoptic analysis of the initiation of one such cycle of change is insufficient evidence on the basis of which to construct a general scheme for all such developments, consequently the sequence of events as described by Mr. Namias for this particular circulation cycle is not repeated in this summary. Further evidence of similar developments in other cases is needed to establish the general character of this particular sequence. However, there is little doubt but that nearly all major declines of the zonal index in winter originate with strong Polar anticyclogenesis in the Arctic. It is therefore important to know where and under what conditions this anticyclogenesis can occur. Mr. Namias is convinced that the initiation of the cycle of change takes place in northern Asia. In verification of this hypothesis he shows that for two winters during which the data were quite complete (1938–39, 1932–33) there was a high correlation between the Asiatic quadrant zonal index one week and the northern hemisphere zonal index a week later. During the Polar Year winter he obtained his correlations between the indices based on seven-day weekly mean maps. Almost the same correlation was obtained by Miss Scofield for the same winter by using the overlapping five-day means with one week's lag (p. 72). However, some doubt is thrown on the causal significance of the correlation in the Polar Year data by the fact that the change of the Asiatic quadrant index one period failed to show any correlation with the change of the northern hemisphere zonal index a week later. In any case, further corroboration is needed of the influence of the continent of Asia as the seat of the major changes in the state of the general circulation in winter.

C. The Effect of the Meridional Transport of Water Vapor on the State of the General Circulation as Expressed by the Circulation Indices

According to Rossby's scheme of the general circulation, the release of latent heat of condensation at the Polar Front is the principal heat source which directly drives the Polar cell and indirectly the middle cell or zonal westerlies of the general circulation (p. 16). In accordance with this hypothesis, Commander Anderson tried by simple inspection of the daily synoptic charts to estimate qualitatively the relative intensity of the northward transport of tropical maritime air from day to day. Thus when the subtropical high pressure belts are broken by frequent frontal systems having a north-south orientation into a number of cells with north-south axes (a typical low index pattern), conditions favor a maximum transport of tropical maritime air (moisture) to higher latitudes. Such a condition should then, if Rossby's hypothesis is correct, be followed shortly by an increase of the zonal index. On the other hand, a uniform belt of high pressure in the subtropics, with little north-south component of the winds in middle latitudes (high index pattern), should be a condition favoring a decline of the zonal index. Although admittedly crude, Commander Anderson has been encouraged by practice attempts to feel that this inspection method can be quite useful, in many cases, in forecasting the zonal index.

A more exact estimate of the north-south exchange of air masses in the lower atmosphere, and consequently of the poleward transport of water vapor, can be obtained from the daily values of the meridional indices, or, the same thing, from pressure profiles taken along selected latitude circles at different latitudes. Commander Anderson tried the method of pressure profiles taken along latitude circles for a few selected maps during the Polar Year, but he found the procedure so laborious that he preferred to leave the statistical checking of the method until the completion of the tabulation of the Polar Year data by Miss Scofield.

Miss Scofield proceeded to check the hypothesis by correlating five-day mean values of the meridional indices with the mean values of the zonal indices for subsequent five-day periods. The mean meridional indices are obtained by averaging the five daily values so that they really indicate the mean state of meridional transport existing during the five-day period. If Rossby's hypothesis has any prognostic value for five-day forecasts of the zonal index, its usefulness should be evaluated by such correlations. According to his concept, positive correlation should be found between the meridional indices and the subsequent zonal indices.

Actually, as pointed out above (p. 72) very consistent negative coefficients were obtained from these correlations. This surprising result cannot be explained simply by saying that latent heat of condensation plays no part in driving the general circulation. It would have to be assigned a negative role in its influence on the general circulation (a possibility which is not entirely excluded) in order to explain these negative correlations. But the explanation of the negative correlations is more likely to be found in one or more of the following possibilities:

1. That the meridional index is not a reliable indicator of the northward transport of water vapor. That is quite possible, in view of the irregularity of the earth's surface and the resultant longitudinal variations of the moisture content acquired by different air masses at the same latitude. However, it is inconceivable that there should be a negative correlation between meridional air mass exchange and the poleward transport of water vapor.

2. That the effect of the poleward transport of water vapor is so quickly reflected in the speeding up of the general circulation that the variations of the two sets of indices, meridional and zonal, tend to parallel each other, or at least to vary with less than one week's time lag.

3. That the effect on the general circulation of the latent heat of water vapor transported to higher latitudes is realized so slowly, and affects the zonal westerlies so indirectly, that its influence is not shown within the period covered by most of these lag coefficients.

The application of further statistical checks is now in progress to decide between these alternate possibilities.

D. The Use of Tropopause Contour Maps and Pressure Maps in the Upper Troposphere

Early in March Major Moorman began to draw regular daily tropopause contour maps, based on the North American network of daily radio balloon sondes. He was induced to try this because he felt that the upper troposphere was being neglected in the five-day forecasting routine. A few preliminary experiments with the tropopause contour maps convinced him that there is a close correlation between the occurrence of strong surface anticyclogenesis or the filling of a surface cyclonic system and the appearance of a high tropopause in the same region on the one hand, and strong surface cyclogenesis or dissipation of a surface anticyclonic system and the appearance of a low tropopause in the same region on the other hand. Shortly after the daily tropopause contour maps were started by Major Moorman, Mr. Boucher began to plot and draw the daily ten kilometer pressure maps. It soon appeared that the two maps were so nearly identical, that the ten kilometer pressure map could serve the same purpose as the tropopause contour map. As the pressure map is easier to plot and draw, the contour map was soon dropped as a daily feature. When the project was moved to Washington, the ten kilometer map also had to be dropped temporarily, but it was soon started again along with the daily thirteen and sixteen kilometer pressure maps. Of these three maps the ten kilometer map really meets best the limited needs of the five-day forecasting project. The other two maps are superfluous for this purpose, but they are prepared as part of an outside research project.

The significance of the ten kilometer pressure map lies in the stabilizing effect which it has on those features of the lower circulation which are reflected at that level. In other words, cyclonic and anticyclonic systems which appear equally well pronounced at three kilometers and at ten kilometers are usually both persistent and slow moving phenomena. Those which aren't reflected at the higher level are likely to be more migratory and temporary than the deep centers. To this extent the ten kilometer pressure map may be said to have some prognostic significance. However, the original hope that these persistent features of the general circulation might appear first at ten kilometers and become evident later as developing pressure centers at lower levels does not appear to be fulfilled. If there is any perceptible lag in changes of the pressure pattern between these two levels, it seems to be, at least during this summer, a lag of from half a day to a day from the lower to the upper level.

E. The Movement of the Wave Systems Observed at the Three Kilometer Level

In the discussion of the five-day forecasting procedure, repeated reference was made to the basic importance of the orientation and state of development of the system of troughs and ridges normally present on the three kilometer pressure chart. Forecasting the movement of this trough system from week to week is frequently the most important single element of the five-day forecast. It was pointed out that a quantitative forecast of this movement is possible on the basis of theoretical considerations developed by Rossby. But this computation has been too cumbersome to make a part of the regular forecast procedure. Recently, however, H. Wexler has simplified the procedure for routine application to a point where the computation may be made rather quickly in a routine manner. It has been used frequently of late, in a number of cases quite successfully qualitatively, if not quantitatively. It should be increasingly useful with the approach of winter. For these reasons Wexler's simple explanation of the use of the formula is given in full at this point.

By assuming purely horizontal motion of air columns, each of which conserves its absolute vorticity, Rossby (2 and 3) derived the following formula for the motion of waves created in the westerlies by an external disturbance:

$$c = U - \frac{\beta L^2}{4\pi^2}$$

where c is the west-east velocity of the waves,

U is the west-east velocity of the air,

L is the wave length of the waves,

$\beta = \frac{2\Omega \cos \phi}{R}$ is the rate of increase of Coriolis' parameter northward,

Ω is the angular velocity of the earth's rotation,

ϕ is the latitude,

R is the radius of the earth.

If now c and U are expressed in degrees of longitude per day, and L in degrees of longitude, then this formula may be written as

$$U - c = \frac{2.360.\cos^2 \phi}{n^2} = \frac{2.\cos^2.\phi}{360} L^2$$

where n is the number of waves around the earth at latitude ϕ. The following is a table of values prepared from the above formula:

n	L (in ° Long.)	U-c (in ° Long. per Day)			
		30°	45°	55°	60° lat.
4	90	33.8	22.5	14.7	11.3
5	72	21.6	14.4	9.4	7.2
6	60	15.0	10.0	6.5	5.0
7	51	11.1	7.4	4.8	3.7
8	45	8.4	5.6	3.7	2.8
9	40	6.6	4.4	2.9	2.2
10	36	5.4	3.6	2.4	1.8
11	33	4.5	3.0	2.0	1.5
12	30	3.8	2.5	1.6	1.3
13	28	3.1	2.1	1.4	1.1
		$U=1.21\Delta p$	$U=1.05\Delta p$	$U=1.12\Delta p$	$U=1.21\Delta p$
			(Δp in mbs.)		

In using the table it is necessary to find L and U from the latest five-day mean 3 km chart:

Measurement of L: At the selected latitude, L is conveniently found by measuring the difference in longitude between successive isobaric troughs. The original formula assumes uniform wave-lengths of all waves, a condition rarely found in practice. Hence, computations should be made separately for troughs which are part of waves of differing wave-lengths. The question of definition of a trough enters. In Rossby's ideal waves the troughs and ridges are always tangent to the circles of latitude and are also characterized by maximum cyclonic and anticyclonic curvature, respectively. In practice, it is seen that not all waves have troughs and ridges combining the two characteristics mentioned above. Quite often the trough is identified by a line of maximum cyclonic curvature but whose isobars at this line are not tangent to the circles of latitude. In this case the formula is not strictly applicable. Caution should be used in not overlooking seemingly minor troughs. Remember that (U-c) is proportional to the square of L; hence small errors in L lead to larger errors in c. Sometimes a trough is so broad that it is not possible to define the trough-line closer than 2°–3° of longitude; this leads to a corresponding uncertainty of velocity determination.

Measurement of U: U is found from the mean difference in pressure from a latitude 5° to the south to a latitude 5° to the north of the selected latitude. To convert difference in pressure into velocity in degrees of longitude per day use the factors shown at the bottom of the table. Density (ρ) assumed is:

$$0.92 . 10^{-3}\text{gm/cc}; \; U = \frac{0.962 . 10^{-3}}{\sin 2\phi} \frac{\Delta p}{\rho} \;^{\circ} \text{ long. per day.}$$

Formerly the over-all value of U (3 km index) was used but better results were obtained by use of the "local" U, that is, the mean velocity found by measuring the difference in pressure in the 10° zone extending from the trough-line whose velocity is sought to the trough-line immediately to the west of it.

At the lower latitudes (e.g., 30°), it is found that the computations yield almost always retrograde motion for troughs which nevertheless are observed to travel eastward. This is probably so because the maximum westerly velocities are rarely found below 45° latitude, and the formula seems to work best in the region of maximum velocity. (The formula is really based on uniform velocity of the westerlies in a north-south direction.) However, it is still possible to use computations at 30° lat. if one assumes about −8° long. per day as the zero point. (This value seemed to work in April and May 1941, but a more accurate value should be determined from a longer period of observations.)

After the velocities of the various troughs have been found these should not be applied blindly in determining the position of the troughs after 7 days has elapsed, which is the interval used in constructing the prognostic 3 km charts. Remember in the ensuing 7 days, the wave-lengths can change considerably, particularly if the troughs are moving at different speeds. Consequently modify the computations by consideration of changes in wave-lengths. The change in velocity of the westerlies is usually too small to affect the motion of the waves considerably, but small changes in the wave-length may lead to appreciable changes in the velocities.

Nothing concerning deepening and filling of troughs can be deduced from this formula. This must be considered as a separate problem. Also because of short-period accelerations computations of the velocities of waves on the daily 3 km maps are not likely to be so accurate as those on the fiive-day mean charts.

An example of a computation is shown below:

July 24, 1941
55° latitude

λ =	65°		110°		170° (trough-lines)
L =		45°		60°	
Δp =		7.6 mb.		6.7 mb.	
U =		8.5		7.5	
$U - c$ =		3.7°/day		6.5°/day	
c =		+ 4.8°/day		+ 1.0°/day	

One other theoretical method of forecasting the velocity of movement of the three kilometer pressure wave system has been applied. In this case also the development of the practical procedure was made by H. Wexler on the basis of some purely kinematical considerations set forth by C.-G. Rossby (not yet published). The reasoning is based on three assumptions, which are reasonably well justified:

(1) That the air flow in the zonal westerlies (in which the wave system is observed at the three kilometer level) is purely horizontal.

(2) That the temperature T of a moving particle remains constant.

(3) That waves in the three kilometer isobars and isotherms move with the same velocity c, and preserve their shapes.

It can then be shown by simple kinematical reasoning, if U = the west-east velocity of the undisturbed westerlies in the field of observation, that

(1) When the waves are stationary ($c=0$), but the air moves eastward ($U>0$) then the three kilometer isobars (stream lines) and the three kilometer isotherms (trajectories) must coincide, or the ratio of the amplitudes of the isobar and isotherm waves is unity, i.e.,

$$\frac{\text{ampl. } T}{\text{ampl. } p} = 1.$$

(2) When the waves move eastward ($c>0$) and the air moves faster ($U>c$), then the moving air particles oscillate further north and south than in (1), i.e., $\frac{\text{ampl. } T}{\text{ampl. } p} > 1$. In the limit, when $U=c$, the amplitude T becomes infinite.

(3) When waves move toward the west ($c<0$) and the air to the east, then the air particles will oscillate less north and south than in (1), i.e.,

$$\frac{\text{ampl. } T}{\text{ampl. } p} < 1.$$

A running graph of the ratio $\frac{\text{ampl. } T}{\text{ampl. } p}$, and graphs of the positions of the principal pressure troughs as taken from the five-day mean three kilometer maps since last January 1, have been prepared. Correlation between the sign of c (positive eastward) and the current sign of $\frac{\text{ampl. } T}{\text{ampl. } p} - 1$ was found to be $+0.50$. This indicates fair agreement with the kinematical theory. A similar correlation between the sign $\frac{\text{ampl. } T}{\text{ampl. } p} - 1$ of the current period and the sign of c one week later gave a correlation of only $+0.28$. Hence the current kinematical state is shown to have only slight prognostic value for the future movement of the three kilometer pressure trough. It should be noted that the application of either the wave velocity formula or the kinematical reasoning to the prediction of the movement of the three kilometer pressure troughs depends on the presence of reasonably clearly defined wave pattern aloft. In the absence of a clearly defined wave train these two methods become relatively useless.

F. Correlation of the Five-day Precipitation Anomaly Pattern with the Mean Maps

In the discussion of the forecast procedure it was pointed out how much less rigidly the precipitation anomaly pattern is defined by the mean maps than is the temperature anomaly pattern. This fact makes it much more difficult to derive the precipitation anomaly pattern from the basic prognostic charts than to derive the temperature anomaly pattern. The degree to which this is the case may be seen immediately by the comparative skill ratings in temperature and precipitation obtained by the official five-day forecasts.

It was the recognition of the difficulty in correlating the precipitation anomalies with the characteristics of the mean charts which lead Mr. K. E. Smith (7) to attempt some correlations between the two. He restricted the correlation to the winter months of the past winter. The observed anomaly patterns were not available from previous winters, and he wished to restrict the correlation to a single season, since the mean conditions favoring precipitation in any locality are likely to change considerably from winter to summer. That is the reason why the study is restricted to the three month period, December to February last. The encouraging results obtained by Smith, and the difficulty experienced in forecasting rainfall during the current summer season, are two good reasons why a similar study should be made for the current summer season. Anomaly charts are not available in complete form from the previous summer.

The characteristics of the mean charts which Smith considered as significant for the occurrence of precipitation are the following:

1. The cyclonic or anticyclonic curvature of the isobars of the mean sea level pressure. Cyclonic curvature was assumed to favor horizontal convergence and heavy precipitation, anticyclonic curvature to favor horizontal divergence and light rainfall.

2. The cyclonic or anticyclonic curvature of the isobars of the mean three kilometer pressure.

3. The clockwise or counterclockwise turning of the mean gradient wind (mean isobars) from sea level up to the three kilometer level. Clockwise turning was assumed to favor heavy rainfall, counterclockwise light.

4. The presence or absence of moisture as shown by the moisture pattern on the mean isentropic chart.

5. The prevalence of up-slope or down-slope motion as indicated by the orientation of the flow lines (mean stream function isobars on the mean isentropic chart) relative to the mean pressure contour lines of the isentropic surface.

Smith systematically correlated the occurrence of each of these five characteristics of the mean maps in connection with all the "heavy" and "light" areas of five-day precipitation anomaly observed during the past winter over the country as a whole, and separately in each of the five major climatic sections into which the country was divided. These five major weather type sections are as follows:

1. West coast, west of the coastal ranges.
2. Plateau, from the coastal ranges to the continental divide.
3. Eastern slopes, from the continental divide eastward over the western plains.
4. North central and northeast, from Minnesota, Iowa and Missouri eastward to the north and middle Atlantic coast.
5. South central and southeast, from North Carolina, Arkansas, and Tennessee southward to the Gulf of Mexico and southwestward to southern Texas.

The correlation coefficients obtained by Smith were quite encouraging, probably better than might be expected from the rather poor success of the precipitation forecasts. They indicate that the best utilization of the information which they contain, and the computation of similar coefficients for summer weather, should lead to a material improvement in the precipitation forecasts.

All the correlation coefficients obtained between the occurrence of light or heavy precipitation, and the mean map characteristics as listed above, were positive. Listed in order of decreasing significance of the correlations which they yielded the mean map characteristics are:

1. Curvature of the surface isobars.
2. Moisture supply (isentropic).
3. Curvature of the three kilometer isobars.
4. Turning of the isobars with elevation.
5. Mean up-slope or down-slope component of air flow.

As computed for the whole country, the first three characteristics yielded highly significant coefficients (such that the probability of obtaining the coefficients by chance was less than 1%), the last two characteristics yielded significant coefficients (such that the probability of obtaining the coefficient by chance is less than 5%).

When the same correlations were computed individually for each of the five sections listed above, considerable irregularity was shown from section to section, as indicated by the following table in which H.S., S., and N.S. stand for highly significant, significant, and not significant, respectively.

TABLE X

Characteristic \ Section	Pacific Coast	Plateau	Eastern Slopes	North Central & Northeast	South Central & Southeast
Curvature surface isobars	H. S.	H. S.	H. S.	H. S.	H. S.
Moisture	H. S.	H. S.	N. S.	N. S.	H. S.
Curvature 3 km. isobars	H. S.	H. S.	S.	N. S.	N. S.
Turning of isobars	N. S.	H. S.	N. S.	N. S.	H. S.
Up-slope or down-slope motion	N. S.	S.	N. S.	N. S.	S.

It will be noted that the first factor is found to be highly significant in all sections. The second factor is found highly significant in three districts, but less so in the two northern districts east of the Rockies. This is probably caused by the fact that much of the time in winter the isentropic surface in these districts lies too far above the levels at which the precipitation is principally produced. The other factors were less consistently significant. However, it must be remembered that when the country is divided up into sections, the number of cases to be correlated in each section is greatly reduced from the number in the country as a whole, consequently the numerical limits of significant correlation are correspondingly raised, while the average value of the coefficients is not increased. Smith has pointed out probable reasons for some of this sectional variation of the coefficients obtained.

Smith finds further that if the areas of light and heavy precipitation are weighted according to their size, all except the last of the five correlations are considerably increased. This fact proves that where precipitation anomalies occur which are contrary to the indications of any but the last of the five characteristics of the mean charts listed above, then those anomalies tend to be of small geographical extent.

Smith points out that it is not permissible to combine these correlation coefficients into a single coefficient in order to express the combined effect of all five factors on the precipitation anomaly, because it is not known to what extent these synoptic characteristics are dependent one on another, but that interdependence is doubtless considerable.

If it were assumed that only the first two characteristics listed in Table X are mutually independent, then it can be shown that about 76% of the variation of the precipitation anomaly can be accounted for by these two factors alone. Evidently the precipitation anomalies are sufficiently well determined by all five synoptic characteristics, even allowing for considerable interdependence among them, so that a correct set of the basic prognostic charts should insure a reasonably good forecast of the precipitation anomaly pattern in winter. The correlation of the summer precipitation anomalies with the characteristics of the mean maps remains to be determined.

G. Preliminary Investigation of the Feasibility of Practical Five-day Weather Forecasts Over the Oceans

Commander Anderson's participation in the five-day forecast conferences and discussions has served as a constant reminder that the Navy is interested in the five-day project primarily as a possible source of "practical" forecasts of ocean weather conditions which affect naval operations. Any attempt to explore the possibilities of forecasting of this type is faced with two problems at the very outset:

1. The formulation of a forecast which will prove useful. Obviously a forecast of mean temperature and total precipitation is not of much use to the Navy at sea.

2. The acquisition of observations from over the oceans sufficient to verify the forecasts and so to furnish some basis for their improvement.

Before the five-day forecast methods can be applied to the ocean areas, it must be proved that there is reasonable correlation between the prevailing weather conditions at sea during any five-day period with the corresponding observed mean charts. When the existence of such correlation is established, then it remains to formulate a forecast which expresses in most useful form the weather elements of greatest practical importance to the Navy at sea.

To check the extent of correlation between the mean maps and the prevailing weather conditions over the ocean, Commander Anderson used the observed five-day mean maps of sea level pressure to mark off geographical areas at sea where he would expect strong, moderate or weak storminess (cyclonic activity) and then used the daily northern hemisphere charts to verify the actual daily occurrence of stormy conditions. He states that the correspondence between his storminess estimates and the observed was quite satisfactory. However, as he points out, the final success of such forecasts based on the prognostic mean maps must depend entirely on a rather close correspondence over the oceans between the observed and the prognostic mean maps.

Originally it was planned that following the transfer of the project from Boston to Washington, there would be extra man-power available to follow up the problem of practical ocean weather forecasting much more extensively. However, the immediate result of the transfer was to decrease, not increase, the available personnel, so that all such plans were dropped for the remainder of the fiscal year. There was some work done on one closely related problem, that of the distribution of the mean conditions of visibility, ceiling, and cloudiness with respect to the five-day mean maps. Visibility and ceiling, especially, are important elements of a practical forecast of ocean weather conditions. This investigation is discussed below in more detail.

Since August 1 Commander Anderson has renewed with considerable elaboration his earlier efforts to develop and verify five-day forecasts of storminess at sea. This renewed effort on his part has been stimulated by proposed plans for the five-day forecast unit to concentrate on forecasting weather conditions a week ahead over the North Atlantic. If present proposals are carried through, a concentrated study of recent weather over the North Atlantic will be carried out with the aid of restricted observations which have not been generally available currently, and a training program of practice forecasting for that region will be initiated. If this plan is executed the lack of attention paid in recent months to ocean weather conditions and to ocean forecasting will be more than compensated for in a short time.

H. Mean Charts of Visibility, Ceiling and Cloudiness

If the five-day forecasts are to be of much practical military use, they must include other elements than rainfall and temperature. Commander Anderson's attempt to forecast storminess at sea recognized one particular need of the Navy. Other elements of particular concern to the Air Corps as well as to the Navy at sea are the conditions of visibility, ceiling, and to a lesser extent of cloudiness. For this reason it was planned earlier in the year to prepare five-day mean charts of the observations of these elements. The immediate purpose was to compare the observed mean conditions with the five-day means of the synoptic charts. If the mean distribution of these elements is found to undergo significant changes from week to week which correlate with the mean maps, then the possibility exists of making five-day forecasts of the prevailing conditions of the elements. If, on the other hand, there appears no significant changes of the patterns of these elements corresponding to the changes in the mean map patterns, then the only possibility of including these elements in the five-day forecast is on the basis of the daily prognostic charts, which are bound to be very uncertain especially for the latter part of the period. In other words, no forecast of the prevailing state of visibility, ceiling, and cloudiness during the period can be made beyond the point to which the daily sequence of weather can be forecast in reliable detail.

During the period that the five-day project was located at M.I.T., there was no assistance available to perform the considerable amount of extra routine work involved in the preparation of mean charts of visibility, ceiling and cloudiness. After the transfer to Washington mean maps of these elements were prepared for an experimental period of one month, starting about the middle of June. Most of the extra work was performed by two enlisted men from the air corps who had been assigned to the five-day project to assist Major Moorman. Daily maps of total cloudiness, ceiling, and visibility were plotted and drawn individually on the regular Atlantic-Pacific base map, and then averaged for each 5° latitude and longitude intersection to give the five-day mean values of each element. Since ceilings are not reported from ships, the amount of low cloudiness was used in place of ceiling for all ship reports. The five-day mean map was then drawn for each element on the basis of the mean values at each intersection of the five degree circles.

There are two conditions which operate against the success of these mean maps this summer. One of these is the fact that they were prepared at the height of the summer season. During the summer the general circulation is weak, and the control of its changes over the prevailing local weather is at a minimum, whereas the local controls, such as cold coastal water areas, local thermal and orographic convection and the local predominance of monsoon winds are at their strongest. These local controls largely determine the cloudiness, ceiling, and visibility patterns in summer.

The second unfavorable condition applies only to the ocean areas. That is the lack of adequate ship reports over the greater part of the Atlantic and much of the Pacific during the past year. The usual condition over the greater part of these oceans is to have a few scattered ship reports with unreported areas between, which are hundreds or even thousands of miles across. When lines of equal cloudiness, ceiling and visibility are drawn on the basis of such reports, either one of two methods is possible. Either the lines can be drawn arbitrarily taking into consideration only the single element in question, just as isobars can be drawn without considering anything but the reported pressures. Obviously with so few reports an infinite variety of patterns might be drawn to the same observations, and the statistical mean patterns thus obtained would show little if any correspondence with the mean maps of the other elements. The other procedure is to adapt the lines of equal cloudiness, etc., to the system of fronts and isobars which has been determined by the few reports present and from considerations of day to day continuity. Obviously this procedure will define the pattern of isolines of these elements much more uniquely than the first procedure. Furthermore, it will result in a five-day mean pattern which is found to show correspondence with the other mean maps, because its determination was made dependent upon them. This correspondence will be obtained in the sense in which the analyst thinks it should exist, quite independently of whether complete observations would show it to exist in that way or in some quite different form. Thus it will be seen that these mean maps of ceiling, visibility and cloudiness have not much significance over the oceans where observations are scarce. By one procedure they are bound to show little if any correlation with the other prognostic charts, by the second procedure a correlation is imposed upon them. The second procedure is the one generally followed, because it is the only one that makes synoptic sense.

An inspection of this series of mean maps of total cloudiness, ceiling and visibility, for eight consecutive overlapping five-day periods, suggests the following remarks:

1. Total cloudiness—These maps, although perhaps of the least practical significance of the three sets, showed much the best correlation with the other mean maps, because they show much more significant changes of pattern over the continent than do the other two sets of mean maps. The cloudiness mean charts show good correspondence with the mean pressure charts, especially in the section east of the Rockies. They do show the permanent affect of the cold water zone along the North Atlantic coast, but even this influence appears with considerable variety depending upon the various mean patterns. The agreement of the total cloudiness pattern with the mean isentropic pattern is also strikingly good east of the Rockies, but in the Rockies and along the west coast the isentropic pattern shows very little about the mean cloudiness pattern. In general the correspondence of the total cloudiness pattern with the observed precipitation anomaly pattern is very close, with some notable exceptions in the plains states where heavy convective precipitation of the thunderstorm variety may occur with very little effect on the mean cloudiness.

Over the oceans the data is scant (the mean maps extend only from 50°W–180°), but there is good correspondence between the mean cloudiness patterns and the variations in position and shape of the subtropical highs. As indicated above, however, this correlation may be imposed to some extent by the drawing of the daily cloud maps.

2. Ceiling—The mean ceiling maps are drawn only for the continental area, since ceiling measurements are not made by ships at sea. In general the ceiling patterns are very much weaker, less characteristic, and less related to the other mean patterns than are those of total cloudiness. In general conditions over the continent in summer are convective, not stratified, so that even where much cloudiness occurs, the ceiling observa-

tions are predominantly high. Consequently the mean ceiling height for five days never comes very low over the continent in summer, and hence the absence of any clear cut patterns of variation. In winter the pronounced stratification especially of the warmer air masses over the continent should give a very different picture, with sharp ceiling contrasts depending on the prevailing air mass type. It is interesting to note that in spite of the elevation of the Rocky Mountain and Plateau areas, the ceilings actually average higher in those regions in summer than they do in the eastern part of the country. That is, of course, a result of the prevailing dryness of the surface air in the western section.

3. Visibility—The mean visibility maps extend from 50°W–180°, the same as the cloudiness maps. Over the continental area they are very similar to the ceiling maps, in that they show very little variation and no clear-cut patterns. This is doubtless for the same reason, that the atmosphere over the continent in summer is convectively unstable, seldom being stably stratified in any region long enough to reduce the mean visibility into the poorer classifications. Probably conditions would be very different in this respect in winter.

Over the oceans the principal influence to be seen on the visibility maps is that of the cold water areas along the coast. Their influence shows up more uniformly than in the case of total cloudiness. In general variations in the patterns are insignificant over the oceans, but they do show some correspondence with the mean patterns of the other elements. This may again be mostly the result of the method of analysis.

It may be concluded from the above remarks that in general observational data from over the oceans is not sufficient for the preparation of reliable mean maps of total cloudiness, visibility, and ceiling. Only the cloudiness maps show significant variation of pattern. Over the continent the mean maps are reliable, but again only the cloudiness charts are characterized by significant variation of pattern in summer. It seems probable that in winter the greatly increased stratification of air masses over the continent and the sharpening of moisture contrasts between the surface air masses should produce significant variation of pattern of the ceiling and visibility charts as well.

SECTION IV. SUGGESTIONS FOR ADDITIONAL RESEARCH

The following brief suggestions of possible research to be undertaken by the five-day forecast project is restricted to investigations which would be more or less directly supplementary to the methods which have been developed by this project. It does not pretend to be at all an exhaustive list of the possibilities of research in long range weather forecasting.

The basic requirement for all further research, whether it be theoretical, statistical, or synoptic, is the preparation of longer series of all the five-day mean maps and circulation indices which are made use of in the forecasting procedure. Five-day mean northern hemisphere maps extend back less than five years, with interruptions, the aerological means over the United States only three years, the extended three kilometer chart and indices only eight months, and the temperature and precipitation anomaly patterns only a year. These series are far too short for statistical treatment by which to check synoptic practice or theoretical ideas.

This lack of an adequate series of the basic mean maps can be lessened in several ways, namely:

1. By making every effort to complete the current maps with all the data that can be obtained. This applies to the surface and upper air charts equally.

2. By computing all of the five-day mean maps for past periods for which reasonably complete data are on file. This applies particularly to the extended three kilometer map, which has proved to be extremely useful considering the short sequence available. But the first thing to be done with this map is to investigate the procedure by which the extrapolation is made from sea level pressure to that at the three kilometer level over the oceans. The assumption of a saturation adiabatic lapse rate in summer leads to obvious errors, especially over cold water, where the three kilometer pressure computed in this way may be as much as ten millibars too low. In winter the errors are smaller, and errors of the same size are less significant, due to the greatly increased horizontal pressure gradients. At present a program is under way to make use of all the available aerological observations to prepare for each month of the year mean maps of the pressure and temperature distribution at the three kilometer level, extending over the oceans from 50°W–180°. These monthly mean maps will serve the twofold purpose of showing the normal three kilometer pressure distribution for any month in the year, and, when used in conjunction with maps of the normal surface temperature distribution, of showing the normal lapse rates prevailing over each part of the ocean. Then the normal lapse rate can be used in extrapolating the daily sea level pressures instead of the saturation adiabatic lapse rate. This change will doubtless greatly improve the accuracy of the extended three kilometer pressure maps in summer.

As quickly as extended series of the different mean maps are produced, they can be used for any number of theoretical, statistical, or synoptic investigations. Some of these possibilities are listed as follows:

1. Theoretical. During the past few years the development of a number of theoretical concepts as to the nature and behavior of the general circulation, notably by Rossby, has progressed faster than the statistical and synoptic basis in which it originated. Consequently a large amount of statistical and synoptic checking of Rossby's hypotheses is

now in order. This should be done statistically by means of the various circulation indices and their mutual interrelationships as shown by current and lag correlations, and synoptically by means of the observed sequences of the general circulation patterns surface and aloft as shown by the various mean charts. A start on this kind of statistical and synoptic verification was made this year with the analysis of the Polar Year data described in Section III. But a great deal remains to be done with the Polar Year data, and the investigation should be extended to the data from other years, especially the last year or two before the war, when both the surface and aerological data are reasonably complete. Some of this work will be carried on at M.I.T. during the coming year. Another statistical check of the theory which is of considerable practical import must be applied to the methods of estimating the movement of the pressure trough systems at the three kilometer level as described in Section III. This applies both to the wave velocity formula and the kinematical method as developed by Rossby and described by Wexler. A proper check of these methods will require a longer series of the extended mean three kilometer maps.

2. Statistical. There is need of a much more comprehensive classification of mean map types than has been developed up to the present. This classification should be based on the state of the general circulation as expressed by the different indices, but it should include characteristic features of all the mean maps, not just of surface pressure. This elaboration of the classification system should include subclassifications of the high and low index types, and of the intermediate types with rising index and with falling index, based in part on indices other than the zonal index. The establishment and statistical treatment of such a classification will be greatly facilitated by the use of the punch card system. For this reason no effort has been made up to the present to introduce such a classification. Also, it requires a fairly long sequence of all the basic mean maps.

Another purely statistical analysis which is badly needed, and which is waiting on a longer series of mean maps, is a further study of the correlation between the precipitation anomaly patterns (and possibly also other elements) and the basic mean maps, such as that made by Smith (Section III). A longer series of winter maps should be correlated, as well as a correspondingly long series of summer maps. Precipitation is doubtless the element most in need of such correlation, but it can be tried on temperature and other elements as well. Further checks of the significance of the correlations should be made.

3. Synoptic. There are a number of extensions of the present forecast procedure which should be made in the near future and which will require either additional or more extensive mean maps. Practice in the preparation of these extended forecasts and the necessary mean maps should be started as soon as possible. These extensions include:

a. The forecasting of new elements, in particular those which are important for military operations. Among such elements are cloudiness, ceiling and visibility, the forecasting of which was attempted first this summer, also storminess over the oceans, and the possibility of the development of serious icing conditions. Icing conditions usually do not prevail for long periods, but the possibility of the occurrence of serious icing should appear from the mean charts.

b. An extension geographically of the area for which the forecasts are made. The north Atlantic is already under consideration as a zone to be included in the forecasts, with practice to be started in the immediate future. But five-day forecasts will be useful to either military operations or civil aviation over the Pacific as well as the Atlantic. The only limit of the area to which the method may be applied is that set by the lack of adequate observational data.

c. Extension of the period covered by the forecasts. This can be effected by forecasting for two or possibly three five-day periods, just as daily forecasts can be extended for two or three days, or it may be accomplished by lengthening the period. The first method will probably never be regularly extended beyond three periods, at present its extension beyond a second period could not be justified. However, like daily forecasting, there are periods when the weather sequence is following a clear-cut regular pattern of behavior so that the changes can be anticipated several periods ahead, while at other times it is difficult to say what is going to happen even during the first period. The conditions are usually most favorable for extending the number of periods of any forecast in the fall and winter, when the general circulation is strongest and the amplitude of its changes is greatest. But it must be emphasized that however far into the future the statistical forecasts may be extended, the daily prognostic charts by which the timing element is introduced into the statistical forecast cannot be extended further. Probably five days represents the extreme limit for which any attempt should be made to forecast the daily sequence of weather.

The statistical methods applied to five-day forecasting are just as applicable to longer periods. Statistical forecasts for months or seasons can be prepared on much the same basis as for a five-day period, although the amplitude of the anomalies will be smaller. However, before such forecasts can be made, a large amount of data must be worked up in the form of long period means, and mean maps must be prepared. Work of this kind should be undertaken whenever the necessary personnel is available.

A problem closely related to the regular preparation of longer range forecasts is that of the seasonal forecast of precipitation for certain mid-western states for the summer season which is prepared by Mr. Namias at the beginning of June. These forecasts are based on certain long-period trends and persistence tendency shown by the monthly mean isentropic patterns at this season of the year. These trends are established, however, on only a few years' records. If they really exist as a permanent phenomenon, then it must appear in some form in the climatological records, in the form of certain lag correlations of precipitation. If forecasts of this type are to be continued, then their statistical basis should be much more extensively checked by the climatological records. Such a check will be undertaken at M.I.T. during the coming year.

A final synoptic step in the five-day forecast procedure which needs further development and especially some careful statistical verification, is that of the introduction of the daily prognostic charts into the forecasting routine to assist in the timing element of the forecast. Their usefulness should be evaluated by some kind of statistical verification on a probability basis. Furthermore, some method of checking the consistency of these daily prognostic charts with the mean prognostic charts must be developed as the final check of the internal consistency of the complete five-day forecast. At present this final check is obviously needed. It will probably require the drawing of all five daily prognostic charts instead of the three (first, third and fifth days) which are now drawn. In no case, however, should it be attempted to extend the daily prognostic charts beyond five days.

Many more suggestions of research needed to supplement the five-day forecast procedure might be mentioned, but the above list included those most urgently desired.

REFERENCES

1. C.-G. Rossby: *The Scientific Basis of Modern Meteorology.*
2. C.-G. Rossby: *Relation between Variations in the Intensity of the Zonal Circulation, etc.* Sears Foundation; Journal of Marine Research; Vol. II, No. 1, p. 38 (1939).
3. C.-G. Rossby: *Planetary Flow Patterns in the Atmosphere.* Quarterly Journal of the Royal Meteorological Society, LXVI, Supplement, p. 68 (1940).
4. H. C. Willett and others: *Report on an Experiment in Five-day Weather Forecasting.* Published by M.I.T., Cambridge, Mass., April, 1940.
5. B. Haurwitz, *The Motion of Atmospheric Disturbances.* Sears Foundation; Journal of Marine Research, Vol. III, No. 1, May 1, 1940.
6. B. Haurwitz, *The Motion of Atmospheric Disturbances on the Spherical Earth.* Sears Foundation; Journal of Marine Research, Vol. III, No. 3, December 17, 1940.
7. K. E. Smith, *Five-day Precipitation Patterns in the United States in Relation to Surface and Upper Air Mean Charts.* A thesis prepared for the master's degree at M.I.T., 1941.