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March '52 38pp charts

Weather - Forecasting

Meteorology (30)

Typhoons

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AIR WEATHER SERVICE  
TECHNICAL REPORT NO. 105-88

REPORT ON  
TASK FORCE WEATHER CENTRAL ACTIVITIES  
DURING OPERATION GREENHOUSE



MARCH 1952

HEADQUARTERS  
AIR WEATHER SERVICE  
ANDREWS AIR FORCE BASE  
WASHINGTON 25, D. C.

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AWS TECHNICAL REPORT)  
NO. 105-88 )

HEADQUARTERS  
AIR WEATHER SERVICE  
ANDREWS AIR FORCE BASE  
Washington 25, D. C.

April 1952

FOREWORD

1. General. Air Weather Service Technical Report No. 105-88, "Report on Task Force Weather Central Activities during Operation GREENHOUSE," (Unclassified) is published for the information and guidance of all concerned.

2. Scope. This report is primarily a summary of the meteorological problems encountered by Air Force and Navy forecasters on Eniwetok during the planning and operational phases of GREENHOUSE. (Unclassified) There is, in addition, some discussion of the techniques utilized by the forecasters and some general remarks and conclusions about forecasting in the Eniwetok area.

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A. PLANNING AND CONCEPTS

1. Initial Plan.

The staff weather officer for Joint Task Force THREE in cooperation with the chief of the weather central developed the over-all plan for meteorological support of Operation GREENHOUSE. After reviewing the results of investigations of meteorological data from Operation CROSSROADS by the tropical Pacific research group under Dr. C. E. Palmer at the Institute of Geophysics, University of California at Los Angeles, it was decided to incorporate many of the techniques used by this research group into the operation. Special charts and codes were designed to fit the proposed operation. New codes for reporting 1,500-ft winds, turning of the wind in the vertical, and characteristics of tropical clouds received the greatest attention. A simple weather code was also devised for use by patrol aircraft to increase the density of data close to Eniwetok.

2. Training.

Six of the Air Force officers worked with the research group on the CROSSROADS data at the Institute of Geophysics, University of California at Los Angeles for about two months prior to assignment to duty in the weather central. On-the-job training was scheduled for a few months as soon as enough data became available at Eniwetok, so that teamwork among the

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forecasting staff could be fully developed before the final phase of Operation GREENHOUSE. Dr. Palmer and two research assistants were to be at or near the weather central to conduct research, to assist with the daily streamline and southern-hemisphere analysis, and to evaluate carefully all weather reconnaissance data. The Institute of Geophysics contributed special graph paper, tabulation sheets, and other material necessary for smooth functioning in the proposed manner.

3. Operational Modification.

The weather central was not operated exactly as planned. Changes, compromises, and improvisations had to be effected due to the limitations of the data, materiel, space, time, and personnel. The weather central memoranda and operating procedures, the unit historical reports, and other miscellaneous papers contain accounts of actual operation over and above the purely meteorological aspects covered in this summary.

B. WEATHER DATA

4. Routine Sources of Data.

All types of weather data were collected including surface reports (hourly, three-hourly, six-hourly), upper-air reports (Pibals, raobs, rawinsondes), weather reconnaissance reports, POMARS, terminal forecasts, storm bulletins, and miscellaneous reports. The sources of data are listed below with brief explanations as to the method of transmission and scope of data available.

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a. Intercept of Radioteletype Broadcast from Guam. This collection contained all types of weather data from the central and western Pacific, which included Hawaii, Japan, the Philippines, ships at sea, and key island stations such as Wake, Marcus, Johnston, Ponape, and Truk.

b. Intercept of Weather Broadcasts from Townsville, Australia. This collection contained all types of weather data from Australia and the islands north of Australia, but chiefly surface reports from Australia proper.

c. Intercept of Weather Broadcasts from Nandi, Fiji Islands. This collection contained all types of data from the south Pacific islands including New Zealand, but chiefly surface reports with only a few pibals and raobs.

d. Intercept of Scheduled Transmissions from GREENHOUSE Network. This collection included three-hourly surface reports and six-hourly rawinsonde reports (0300Z, 1500Z, 2100Z only) plus additional surface and upper-air reports on request.

e. Intercept of Weather Reconnaissance Observations. This collection contained all types of weather reconnaissance data at 1,500 feet, 700 millibars, 500 millibars, aircraft spiral ascent and descent soundings with winds and dropsondes, plus additional data on request.

f. Intercept from Patrol Aircraft Reports. These reports were intercepted from P2V2 aircraft and included weather, cloud data, and estimated surface winds within 300 miles of Eniwetok.

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g. Miscellaneous Sources of Data. Weather data was received from GCI radar-scope interpretation, reports from base and transient aircraft, and de-briefings of air crews.

h. Data from Other Weather Centrals. This collection contained facsimile weather maps and charts received by radio facsimile from Washington, D. C.; Tokyo, Japan; and Hickam AFB, Hawaii.

5. Special Kwajalein Data.

Special mention must be made of Kwajalein as a source of data. The weather station at Kwajalein was not part of the Task Unit 3.4.5 GREENHOUSE network. However, all Kwajalein data were sent directly to Eniwetok by radioteletype. This procedure insured prompt receipt of valuable data including special added data not available through the Guam broadcast, which was the usual source for Kwajalein data.

6. Usefulness of the Data.

a. Routine Reports. The raw in data and surface reports from fixed land stations in and near the Marshall Islands were the most useful information received. Wind and weather reports from reconnaissance aircraft filled in the blank spaces between fixed stations and proved invaluable for determining the composition of the atmosphere. Patrol aircraft reports, radar, and reports from locally based aircraft filled in the details of local weather distribution (200 to 300 mile radius from Eniwetok). The large amounts of varied data from the Guam broadcast and the southern

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hemisphere data from the Townsville and Nandi broadcasts served as background data for analysis of the over-all Pacific weather situation.

b. Special Data. Additional data on winds and clouds were available from all stations in the GREENHOUSE network, Kwajalein, and the reconnaissance aircraft. The 1,500-ft wind data from these stations were used for the 1,500-ft streamline chart together with the reported 1,500-ft double-drift winds from reconnaissance aircraft. The 1,500-ft level is the standard operating level for most low-level weather reconnaissance flights; hence it was selected as the primary and lowest level for streamline analysis. Data on wind turning with height were used by forecasters to analyze the upper-wind structure more accurately. The additional cloud data from land stations supplemented the regular synoptic code in describing tropical characteristics. The best use of additional cloud data was made in the reconnaissance reports; the added cloud code groups were utilized to describe conditions off-course and between regular reporting positions over and above the usual limited code for past weather and weather-off-course.

7. Unreliability of Facsimile Reception.

The radio reception of facsimile charts from other weather centrals left much to be desired. It had been planned to rely on the USAF Weather Central for northern hemisphere charts for over-all background analysis, so that maximum effort could be devoted to detailed analysis of the Marshall Islands area. The unreliability

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of reception from Washington, however, prevented the realization of such a plan. Reception from Hickam and Tokyo was fair to good, but the charts available from those sources were not so useful as the northern hemisphere charts from Washington. The quality of all facsimile analyses was very good when legible charts were received, and they were of great value as a check on the area covered by local analysis and as a description of boundary conditions in the areas beyond the local-analysis area.

8. Adequacy of Data.

The weather information received at the weather central gave excellent coverage of all types of charts plotted, although the individual map coverage was not always complete due to poor radio reception and/or other causes beyond reasonable control.

C. CHARTS PLOTTED AND ANALYZED

9. Objectives of the Analyses.

The general objective of the chart work at the weather central was to obtain maximum utilization of all useful data. The most useful and important data were usually plotted on several different charts in various forms to insure thorough consideration and evaluation by all forecasters. Details of the plotting and analysis of the various charts are given in weather central memoranda and operating procedures. In the discussion, below, of each chart and its value in analysis and forecasting, it should be noted that forecasters had differing views. Where possible, these differences of opinion have been reconciled and a consensus presented in this report. In some cases, however, the differences were too great and

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could not be fitted into this brief discussion, which is not intended to be a treatise on techniques of tropical analysis. A list of the charts prepared follows:

Surface map	Weather distribution chart
700-mb chart	Weather Recon cross sections
1,500-ft chart	Wind-time graphs
10,000-ft chart	Adiabatic diagrams
20,000-ft chart	Wind tabulation sheets
30,000-ft chart	Three-hourly station logs
40,000-ft chart	Patrol aircraft reports chart
50,000-ft chart	

10. The Surface Map.

Each day, four surface maps were plotted and analyzed for the area from 120°E to 150°W and from 25°S to 45°N. The principal value of these maps was the generalized weather picture presented, especially in the equatorward portions of the temperate-latitude storm tracks. The surface map was used for background briefing and for the construction of prognostic charts, which were also used for briefing purposes. The movements of fronts and pressure systems in the temperate latitudes were carefully checked to detect direct or indirect influences on tropical weather. The position of the equatorial pressure trough was determined, when possible, from the surface map, although in many cases no clean-cut trough was evident.

11. The 700-mb Chart.

The 700-mb charts were plotted and analyzed each day for 0300Z and 1500Z covering the same area as the surface map. By

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plotting a selection of PCMARS for appropriate times and altitudes in addition to the regular 700-mb upper-air reports, an excellent coverage of data was usually obtained for this chart. Conventional contour analysis was used in the westerlies, but in most cases the area south of 20° N in the equatorial regions was analysed using streamlines. No serious problems were encountered in combining the two methods of analysis on the same chart, since the transition zone was nearly always in the main anticyclonic belt across the Pacific. The large area covered by this chart made it a valuable background chart like the surface map. The 700-mb chart aided in the analysis and prognosis of the surface map; it was the best chart for forecasting flight level winds for long-distance MATS operations and it enabled forecasters to determine direct and indirect influences on weather in the Marshall Islands due to trough passages in the westerlies to the north of Eniwetok.

#### 12. Streamline Charts.

Streamline analysis for constant levels from 1500 feet up to 50,000 feet was carried on daily for 0300Z, 1500Z, and 2100Z, which were the times when the most rawin data were available. The method of streamline analysis used was that described by Bjerknes<sup>1</sup> and applied

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<sup>1</sup> Bjerknes, V., and Others: Dynamic Meteorology and Hydrography, Part II, Kinematics; Washington, Carnegie Institution, 1911.

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to tropical situations by Palmer<sup>2</sup>. Remarks about the individual charts will be made separately, although some general remarks can be noted for all the streamline charts. The lack of forecasters and trained supervisors with experience in this type of analysis resulted in poor continuity of analysis both in the vertical and with time. Of course, very little previous work has been done, especially on high level analysis in the tropics, and what has been accomplished must be subject to considerable doubt due to the sparsity of data. The analysis improved, however, as forecasters developed more skill and confidence in evaluating the data. According to original plans, only the Marshall Islands area was to be analyzed; facsimile charts, especially the upper levels, from the USAF Weather Central in Washington were to furnish the over-all background and continuity. However, due to poor and unreliable radio facsimile reception, the original plan had to be abandoned when the demands for greater accuracy in wind forecasts increased. Therefore, midway through the project the chart area for the upper levels was increased; this proved to be a very wise move. Continuity improved immediately, and the added over-all understanding of air flow aloft was reflected in the improved accuracy of upper wind forecasts. Discussion of individual charts or groups of charts follows:

13. 1500-ft Chart.

This chart was plotted and analyzed for an area from 150°E to 175°W and from 5°S to 25°N, centering on the Marshall Islands.

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<sup>2</sup> Palmer, C. E., and H. Elsasser: Notes on Tropical Meteorology; Technical Bulletin, 2143d Air Weather Wing, Tokyo, 1949.

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When data permitted, a detailed isogon-isovel-streamline analysis was made. Continuity on this chart was usually fair to good. The best results were obtained during periods of unusual weather with well-developed waves, vortices, and tropical storms showing up clearly on the 1500-foot streamline chart. During periods of normal trade flow the analysis was not too significant, and the minor variations in velocity divergence could not be detected. Good correlation could usually be found between this chart and the composition of the atmosphere as shown by the weather distribution chart. Forecasting from the 1500-foot chart by pure extrapolation for twenty-four hours or less proved to be fairly accurate. The forecasters' lack of experience and confidence in streamline analysis undoubtedly limited the utilization of this chart for forecasting purposes.

14. 10,000-ft Chart.

This chart was plotted and analyzed for an area similar to that covered by the 1500-ft chart, since the larger 700-mb chart provided the necessary background. Usually, the flow pattern at this level fitted well with the pattern at 700-mb, and showed details of the wind field over the Marshall Islands more clearly than the small-scale 700-mb chart. Unfortunately, during February, March, and most of April the 10,000-ft level was in the main shear or transition layer between the trade winds and the upper westerlies. Therefore, the analysis was very complex and difficult to interpret. However, later in the season, after mid-April, the 10,000 ft level was mostly in the easterlies and showed good correlation with the 1500 ft chart.

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15. High-Level Charts.

Due to a general lack of data, the 50,000 foot chart was limited to the Marshall Islands area during the entire project. The other high-level charts (20,000, 30,000, and 40,000 feet) plotted to cover a larger area from 120°E to 150°W and from 10°S to 20°N after facsimile reception was found to be unreliable. This larger area was comparable to that of the surface and 700-mb charts and on the same scale. The main part of the streamline analysis was for the latitude strip between 5°S and 35°N. The several cells of the North Pacific anticyclone were usually in this belt and made the analysis quite complex because of their erratic movements. Coils or neutral points in the velocity field also showed very erratic movements. Frequent cases of closed lows or cyclonic singular points in the velocity field were noted in the regions from 10°N to 20°N; most of these disturbances were best developed in the upper troposphere and associated with extensive sheets of cirrus and cirrostratus above 25,000 feet. In such cases the base of the upper westerlies was lower at Eniwetok than at Wake and also lower at Kwajalein and Majuro than at Eniwetok. These situations were characterized by great persistence.

16. The Weather Distribution Chart.

The area covered by this chart was the same as that of the 1,500-ft and 10,000-ft charts. All reports of clouds and precipitation (weather and past weather) plus additive data groups were plotted for a twelve hour period centering around 0000Z, or Eniwetok local noon.

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This procedure included plotting all the regular weather reconnaissance reports for each day, all land station reports, and all POMARS for the appropriate times. The weather distribution chart gave an excellent picture of the composition of the atmosphere over the Marshall Islands. It was usually easy to correlate with the surface, 1,500-ft, and 10,000-ft charts. Areas of poor weather could be watched and sometimes tracked on this chart. Extensive areas of middle cloud cover and precipitation indicated on this chart were usually associated with marked areas or zones of velocity convergence in the lower levels of the troposphere. The weather distribution chart was an excellent briefing tool, especially when separate overlays, in different colors, were constructed for low clouds, middle clouds, high clouds, and precipitation.

17. Weather Reconnaissance Cross Section.

For each regular reconnaissance track, a chart was plotted and analyzed in the form of a vertical cross section of the weather observed. Such charts were helpful for briefing purposes and as a complement to the weather distribution chart.

18. Wind-time Graphs.

A graph was maintained for each of the GREENHOUSE network stations, except Nauru. A graph was also kept for Kwajalein. Graphs for other stations were plotted as required. These wind-time graphs are essentially the same as the more common wind-time cross sections. The graphs provided a readily available graphic representation of wind structure at stations in a continuous log form.

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19. Wind Tabulation Sheets.

A complete tabulation of winds was kept for each of the GREENHOUSE network stations plus Wkajalein, Wake, and Ponape. The plotting of wind tabulation sheets preserved the accuracy of the original data and provided a highly visual, neat, quick, and easy reference for wind data from key stations.

20. Adiabatic Charts.

The upper-air temperature, pressure, and humidity data from certain key stations were plotted on Herlofson diagram. Weather reconnaissance aircraft ascents, descents and dropsonde data were plotted on ML-124 adiabatic charts. These charts were used to check the height of the tropopause, the height of the surface "moist layer", and the temperatures aloft.

21. Three-Hourly Logs.

Logs of three-hourly surface reports from 20 key land and ship stations in the Pacific were maintained. Events at any one station could be analyzed quickly and the results applied to the surface map analysis.

22. Patrol Aircraft Reports Chart.

Weather reports from patrol aircraft (P2V2) were plotted on a large chart covering an area within a radius of 250 miles of Eniwetok. This chart supplemented the weather distribution chart and gave an up-to-date picture of weather conditions close to Eniwetok.

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FORECASTING

23. Requirements.

The forecasts required for Operation GREENHOUSE comprised detailed wind and temperature forecasts from the surface to 60,000 feet as well as the more usual types of planning and operational forecasts. Temperature and tropopause-height forecasts were based almost entirely on persistence, since the temperature structure and the tropopause height showed only small changes with time. The forecasting of clouds, precipitation, and winds was more difficult. Apparently, it required only very small changes in the field of motion to produce pronounced changes in cloud structure and shower activity. The winds aloft were highly variable, much more so than previous experience and perusal of available literature would indicate.

24. Final Decisions on Forecasts.

In forecasting for the Marshall Islands, the weather central forecasters tried most of the known methods used in tropical regions. It was necessary to reconcile variations in interpretation and application of various methods by individual forecasters. Therefore, most of the planning and operational forecasting was done by a few supervising forecasters, who took all methods by individual forecasters. Therefore, most of the planning and operational forecasting was done by a few supervising forecasters, who took all methods and opinions into account before making a final decision; this system proved very effective from an operational standpoint. It should be noted that often, after careful

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investigation, the differences in methods and opinions proved to be only differences in nomenclature.

25. Basic Forecasting Techniques.

The experience of the forecasters on Operation GREENHOUSE agrees fairly well with that of the forecasters on Operation CROSSROADS, as described in the CROSSROAD report<sup>3</sup>. The section entitled "General approach to Tropical Forecasting in the Marshall Islands", page 3 of the CROSSROADS report, gives an excellent background for the forecasting problem; it is assumed that the reader is familiar with that report. Fundamentally, extrapolation of trends based on complete and accurate analysis was the main forecasting tool. Recognition of certain flow patterns and of phenomena usually accepted as useful for tropical forecasting was constantly sought. In many cases, it was extremely difficult to find any definite physical basis or logical sequence upon which to base forecasts. Apparently, many of the changes in cloud and wind structure from day to day were caused by variations of meteorological elements that could not be measured or observed even with all the data from the increased network of land stations and aircraft reconnaissance flights activated for Operation GREENHOUSE. A brief discussion of some of the general ideas and phenomena usually accepted as useful in tropical forecasting is given in the succeeding paragraphs.

26. Troughs in the Westerlies (Polar Troughs).

No strong, clearly defined troughs were noted in the Marshall Islands area. Weak, indefinite troughs were traced across Wake Island.

<sup>3</sup> Command, Joint Task Force One: Aerological Report on Operation CROSSROADS (OPNAV-JTF-P1001)

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The lack of data to the northwest, north, and northeast of Eniwetok made exact analysis of these situations impossible, but it appeared that the weak troughs in the westerlies moved slowly from west to east. It also appeared that some of these troughs stagnated in the region between Wake Island and Eniwetok, i. e., 10°N to 20°N, and gradually assumed an east-west orientation. The passage or proximity of these ill-defined troughs lowered the base of the upper westerlies at Wake and Eniwetok. On many occasions, the base of the westerlies would lower more at Eniwetok than at Wake. Closed cyclonic circulations were often along the axis of the general east-west trough suspected in such situations. Most of the troughs were more pronounced at the higher levels, especially above 20,000 feet. These trough situations did not produce any prolonged bad weather or extensive cloudiness; it was even difficult to correlate directly small increases in middle clouds and showers with these troughs. Above 20,000 feet, however, the more pronounced troughs were usually associated with increased cirrus clouds, and it was suspected that, by some indirect influence on the lower easterly flow, small increases in middle clouds and shower activity could have been produced. Unfortunately, no definite relationships were discovered.

27. Easterly Waves.

Few, if any, easterly waves of the Caribbean type were found in the Eniwetok area. Some forecasters attempted to follow pseudo-easterly waves on the surface pressure map, but continuity left much to be desired.

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Waves in the easterly flow could be found more easily on the 1,500 ft chart, where they appeared as weak waves of small amplitude. Most of them were sharply limited in extent. The majority of these remained south of 5°N. A few seemed to bring increased precipitation to Kwajalein, but rarely could weather at Eniwetok be associated with their passage.

28. Convergence Lines and Zones.

Many lines and zones of convergence were found in the analysis of the streamline charts. Usually, poor weather was accompanied by obvious streamline convergence at the 1,500-ft level. However, convergence at upper levels was not necessarily associated with any definite weather pattern.

a. Persistent Convergence Zone.

The daily 1,500-ft and 10,000-ft streamline analyses indicated that, in the mean, the most pronounced line or zone of convergence extended from near Tarawa westward between the equator and 5°N. It varied from day to day in position, orientation, extent, and intensity. On some days it could not be found. Although the weather in this zone varied greatly, all strong zones of convergence were accompanied by extensive altostratus. It is interesting to note that the preferred track of the small waves in the easterlies, described above, seemed to coincide with this mean line of convergence.

b. Problem of nomenclature.

Some forecasters referred to this main line of convergence as the "Intertropical Convergence Zone"; others recognized the convergent

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character of the line only when the streamline analysis and associated weather justified it. According to most studies, the "Intertropical Convergence Zone" should have been south of the equator during March, April, and May. Whether it existed in the Southern Marshalls during Operation GREENHOUSE was a matter of lively discussion among forecasters. It appeared that the mean line of convergence mentioned above marked the boundary between the strong, northeast trade winds and a wide belt of relatively light, variable winds that extended to approximately 15°S. In order to avoid misunderstandings and undesirable connotations, especially in weather briefings, it was decided that no weather officer connected with the Project would use the terms, "Intertropical Convergence Zone", "Intertropical Front", or "Equatorial Front".

c. Convergence Lines Associated with Typhoons.

Only two intense convergence lines influenced the weather at Eniwetok during March, April and May. Both were asymptotes of streamline convergence connected with well-developed vortices, the tropical storms "Georgia" and "Joan". In each of these cases, broken to overcast clouds at all levels, rain, and heavy showers persisted for about 48 hours.

d. Difficulty in Extrapolating Convergence Zones.

Extrapolation of the erratic displacements of convergence zones was attempted and proved to be of value in forecasting. It was noted that a pronounced southerly flow over the Southern Marshalls at 10,000 to 40,000 feet was associated with a northward displacement of the strong convergence zones. A pronounced northerly flow aloft was associated with southward displacement, weakening, and even dissipation of such zones. The usefulness of this principle was limited by the difficulty of predicting the general southerly and northerly currents.

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29. Surges and Areas of Convergence.

Surges and areas of convergence in the northeast trade flow appeared to play a dominant role in causing shower activity at Eniwetok. In this report, the term "surge" means general speed convergence over a large area and is used only for such situations in the trades. Large-scale surges or sudden strengthening of the trades which progressed down-stream similar to compressional waves were most common following the passage of a polar anticyclone just north of the trade wind belt. The position, movement, and strength of polar anticyclones were all considered important in forecasting surges. Qualitative rules of thumb were applied by various forecasters with a fair degree of success. In general, surges were expected shortly after the passage of strong, polar anticyclones north of Wake Island, provided the southern portion of the associated polar front had dissipated and the anticyclone was forecast to merge with the sub-tropical high pressure "belt". Increased shower activity associated with these large-scale surges persisted at Eniwetok about 12 to 26 hours. No other explicit rules on surges can be given in this report. Small areas of speed convergence were observed in trade flow that was otherwise uniform. The resulting small-scale shower areas were impossible to predict, because the observations were too sparse or possibly because such situations were too short-lived. Analysis of the speed field left much to be desired even when special air reconnaissance missions took fifteen-minute observations on an upwind track from Eniwetok. Only limited success was achieved with such attempts to analyze the wind-speed field. Shower activity associated with these smaller areas of speed convergence persisted usually for 6 to 12 hours. At Eniwetok,

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both large surges and small areas of speed convergence in the trades resulted in similar weather activity. The trade cumulus increased in amount and vertical extent, the tops reaching 8,000 to 12,000 feet. Showers became more frequent. Patches of altocumulus or stratocumulus were associated with the trade cumulus in the shower areas.

30. Tropical Storms.

According to known studies and previous weather data available, tropical storms are rare in the Marshall Islands during the months of March, April, and May. However, during Operation GREENHOUSE, two storms developed in this region and reached typhoon intensity. Both storms had marked effect on the weather at Eniwetok. Histories of these typhoons are included in this report as Annexes I and II.

D. GENERAL REMARKS AND CONCLUSIONS

31. Local Showers.

Except under conditions of pronounced low-level divergence, showers were always prevalent in the area around Eniwetok. When very many reports were available, land station and "POMAR" reports being supplemented by patrol aircraft, local flights, and air reconnaissance, it was evident that scattered light showers were quite common, the normal situation. This type of shower covered only a small area, seldom, if ever, the whole of Eniwetok Island, which is only about two and one half miles in length. Such showers were seen frequently over the ocean and over the lagoon. They fell from cumulus, usually ordinary trade

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cumulus grouped in a small family or short line with bases near 1,800 feet and tops seldom above 10,000 feet and sometimes as low as 6,000 feet. Light sprinkles of very small drops fell frequently from low clouds no more than 2,000 to 3,000 feet thick. Due to the moderate to strong wind, showers gave an impression of heavy rain, but their duration was usually short, five to ten minutes, and seldom did the rain gage collect enough rainfall to measure; the amount was usually recorded as a "trace". A particularly striking case of the complete precipitation of tropical cumulus was observed by three forecasters. In this case, a rainbow extended from a very small wisp of isolated cloud to the ocean surface. No other cloud was within several miles of this rainbow.

32. Cloud Cover.

The normal cloud cover at Eniwetok comprised scattered trade cumulus at 2,000 feet with tops to 6,000 or 8,000 feet and scattered to broken cirrus above 30,000 feet. Relatively few middle clouds were observed. The middle clouds observed were above 10,000 feet, mostly in the 12,000 to 20,000-foot range. It was difficult to get measurements on the height of cirrus-type clouds, but in one case the base was checked by a reconnaissance aircraft as variable 26,000 to 28,000 feet. On another occasion, a jet fighter reported the base of the cirrus above his flight altitude of 38,000 feet.

a. Middle and High Clouds

Middle and high clouds appeared to increase and thicken with a prolonged southerly flow aloft; they appeared to decrease and dissipate with prolonged northerly flow aloft.

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b. Cirrus.

A marked increase in cirrus-type clouds was also observed with westerly winds aloft, especially when a sharp east-west shear line or trough existed near the station above 20,000 feet. This situation appeared many times between Eniwetok and Wake. Reports from reconnaissance aircraft showed a sharp boundary to the cirrus clouds at the trough axis or shear line, no cirrus appearing to the north. South of the trough axis, variable amounts of cirrus clouds mostly broken, were found in an east-west bend about 300 miles wide. On several occasions, when reliable reconnaissance wind reports were available near the east-west trough or shear line, it was apparent that this line consisted of small cyclonic eddies and related cols. Upper east-west troughs below 20,000 feet with variable amounts of associated middle clouds, usually altocumulus, were also observed. These lower level troughs appeared much less frequently than the higher ones.

c. Diurnal Variations.

Diurnal variations in cloud cover were small. When the trades in the local area were undisturbed, the low cloud cover frequently reached a maximum at, or just before sunrise. A tendency for a maximum of showers between midnight and sunrise was also observed. Both of these maxima were much more pronounced when, above the surface moist layer, usually 4,000 to 6,000 feet thick, the following set of conditions were satisfied: (1) a temperature inversion existed immediately above the moist layer; (2) the air above the inversion was very dry; (3) there were no significant amounts of middle or high clouds. Apparently, the

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top of the moist layer was an effective radiating surface under these conditions. On several occasions, a decrease of three to four degrees Centigrade was noted at the top of the moist layer, which was also the base of the inversion. These changes were found by comparing the evening and early morning soundings. Therefore, it seems logical to assume that radiation played a large part in the diurnal maxima of cloudiness and precipitation at Eniwetok.

### 33. Upper Wind Structure.

The upper wind structure above the trades seemed to be very complex. The North Pacific anticyclone was usually split into several large cells at 10,000 feet and above. The movements of these cells and their associated cols or neutral points were difficult to follow with the limited reports available. The stagnation of the southern portion of troughs between 10°N and 20°N also complicated the upper flow patterns. Cyclonic circulations between Wake and Eniwetok were observed frequently above 20,000 feet. In spite of these difficulties careful streamline analysis of the upper levels south of 25°N, using the increased amount of data available in the Marshall Islands area, enabled forecasters to use limited extrapolation in upper-wind forecasting with a fair degree of success.

### 34. Verification.

All forecasts issued at the weather central were verified by checking against the actual weather conditions at or during the verifying time. A rough check of the verification of forecasts against persistence

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showed that persistence was very good for 24 to 36 hours, but the forecasts issued were always better. Most forecasters on Operation GREENHOUSE became aware of the fact that many of their previous concepts about tropical meteorology in the Central Pacific required revisions in light of the extensive data available for the Marshall Islands area. It appears that knowledge of tropical meteorology is indeed meager, and that much work remains to be done before satisfactory solutions can be found for specific and detailed forecasting problems. The large amount of weather data collected during Operation GREENHOUSE offers an excellent opportunity for continued research in tropical meteorology.

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APPENDIX I

HISTORY OF THE MY AREA "CONTROL"

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HISTORY OF THE TYPHOON "GEORGIA"

In the latter part of March 1951, a typhoon developed and affected the Marshall Islands in a most unusual way. In the first place, although, vortices often form in the Marshalls, they seldom develop into typhoons until they have moved farther westward. In the second place, the most favorable season for the development of such violent storms is in the autumn, and the least favorable season is in the early spring. And finally, the typhoon "Georgia" was characterized by a most unusual track. After it was first definitely located, it moved eastward for eight hundred miles before turning about and starting on a westward track.

The tropical storm, later named typhoon "Georgia", was first detected by the Eniwetok Weather Central on the 1500 foot streamline chart for 2100Z, 17 March 1951. The storm was then between Kusaie and Ponape. Post analysis shows a number of previous indications of the vortex development.

One possible hypothesis (see map, attachment #1) is that the vortex originated in the southern hemisphere. On 15 March at 2100Z, there was evidence of a vortex passing to the south of Nauru. The evidence consisted mainly of appropriate wind shifts at the various levels, together with a thunderstorm observed at 151200Z. If a closed circulation existed at the 10,000 foot level it must have passed to the north of Nauru. In any case, the vortex was carried on the 1500 foot streamline chart until 161500Z, after which it was dropped for lack of data.

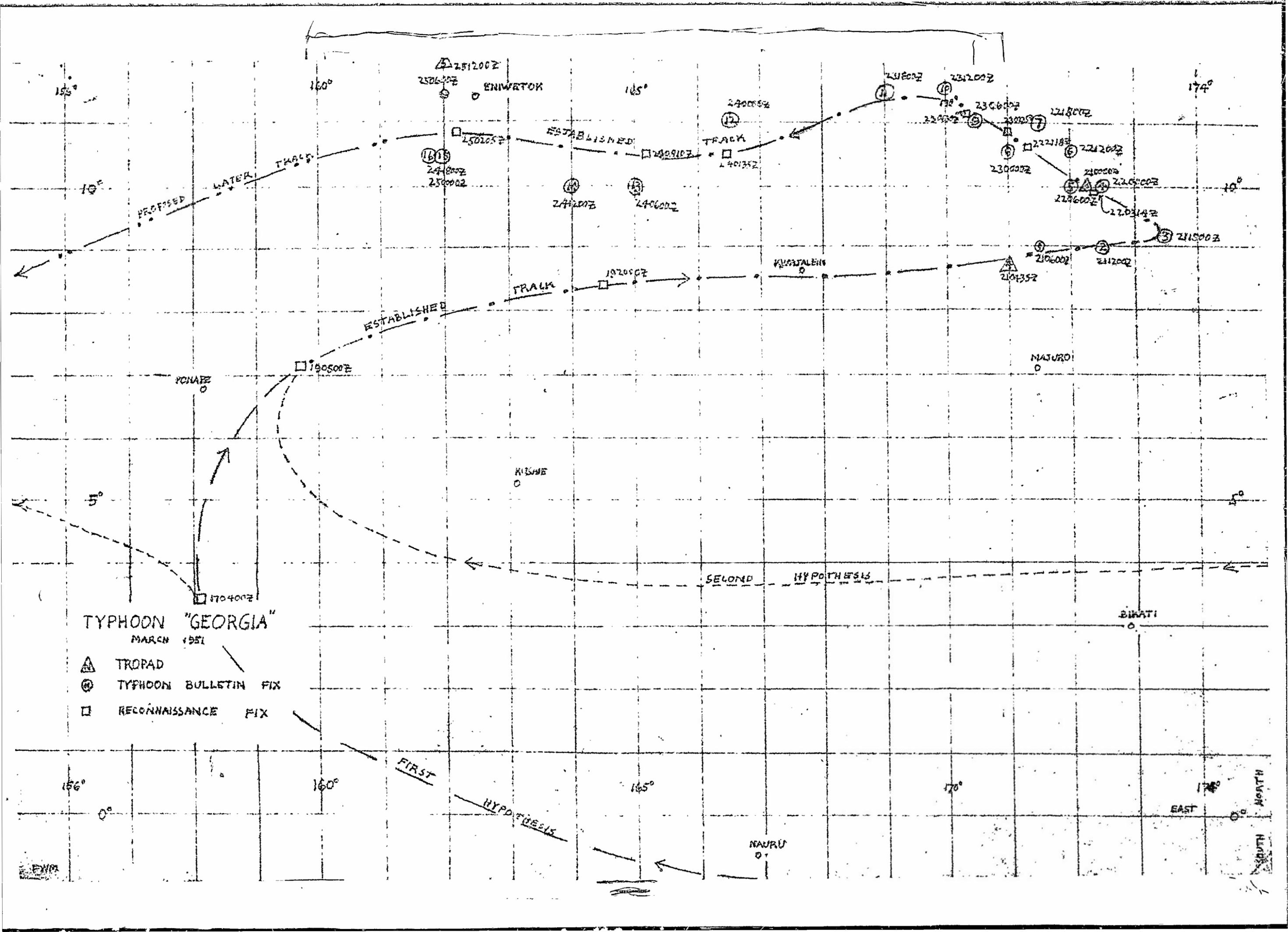
At the upper levels, during the early part of March, the basic flow was from the south. At 40,000 feet the flow had been southwesterly in the region about Nauru, Kusaie, and Ponape, but <sup>at 30,000 feet</sup> to a south-easterly direction about 11 March. At 30,000 feet the flow was also southeasterly by 14 March and at 20,000 feet after 141500Z a persistent cyclonic point was observed south of Kusaie. The strong southerly flow over the Marshall Islands appears to have been associated with an unusually large high pressure cell centered over northeastern Australia. Cyclonic shear in this southerly current west of Kusaie may have contributed to the final development of the cyclonic circulation and deepening that developed in typhoon "Georgia".

On 17 March the Vulture George flight reported a vortex about  $3^{\circ}$  N,  $158^{\circ}$  E, and on 19 March at 0500Z, Vulture George again noted a pronounced but weak circulation at  $7^{\circ}$   $18'$  N,  $159^{\circ}$   $48'$  E. Between 0300Z and 1500Z on 18 March, Ponape reported a wind shift at 1500 feet from northeast to northwest, consistent with the passage of a cyclone from south-southwest to north-northwest. Had the southern hemisphere vortex, after passing Nauru, been carried toward the northwest in accordance with the upper flow, it could have been the same vortex noted by the Vulture flight, now in the process of recurvature. A second possibility is that the southern hemisphere vortex which passed Nauru moved on to the west, south of Ponape and Truk. It could still have been the vortex noted by Vulture George on 17 March.

The second hypothesis (see map, attachment #1) is that a minor wave had developed somewhere to the east of the Marshalls, and was moving westward. There is fairly good evidence of a wave passage at Bikati at 151500Z, and somewhat more tentative indications of a wave at Majuro at 160300Z. This wave

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**TYPHOON "GEORGIA"**  
MARCH 1951

- ▲ TROPAD
- ⊙ TYPHOON BULLETIN FIX
- RECONNAISSANCE FIX

FIRST HYPOTHESIS

SECOND HYPOTHESIS

PROPOSED WATER TRACK

ESTABLISHED TRACK

TRACK

KUSATALENG

NATURU

KISWE

NAURU

BIRATI

ENIWATOK

PONAPE

EAST

NORTH  
SOUTH

FWP

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could have moved just south of Kusaie between 0300Z and 1500Z on 17 March. Unfortunately, no upper winds were available for Kusaie at that time, and so it is impossible to determine whether or not there was the northerly wind to be expected ahead of a wave. By 172100Z the coincidence of the wave and the southerly flow aloft might have resulted in the observed vortex whose later development is so well established.

Either of these hypothesis is tenable, although the first seems more in accord with the observation of the Vulture flight and those at Kusaie and Ponape. If the second hypothesis is accepted it will have to be assumed that the vortex observed at  $3^{\circ}$  N,  $158^{\circ}$  E moved on off to the west, south of Ponape and Truk. It is also possible that the actual development of "Georgia" might have been a combination of the two, or some still different sequence of events.

The principal feature of the pressure field during the early period, before 17 March, was the displacement of the equatorial pressure trough to a position unusually far to the north for the season. By 16 March it appeared to be between Kusaie and Nauru and between Majuro and Bikati. Kusaie reported a thunderstorm shortly before 170000Z, and at 171800Z a ship about one hundred miles southwest of Eniwetok reported lightning. No closed low pressure center was noted until 180600Z, when Ponape reported the somewhat low pressure of 1003.1 MB in a thunderstorm. As early as 170000Z the reports from Ponape and the Vulture George flight indicated a disturbance in that region. The Vulture George 190000Z showed that the disturbance was still to the east of Ponape, and therefore could not now be an ordinary wave. Also, the ship south of Eniwetok was still reporting thunderstorms.

An indication that the disturbance was gaining in intensity was given by the upper winds at Kusaie at 182100Z, when at 8000 feet and above, winds of approximately 50 knots were observed from the southwest. On the 18th of March, Kusaie had 0.94 inches of rain; on the 19th 0.74 inches; and on the 20th 3.72 inches fell. During the period 180300Z - 200300Z the surface winds were very gusty with gusts estimated to be more than 50 knots.

Up until this time the disturbance had not been considered to have particular significance for operations at Eniwetok. However, on 19 March (GMT) a special Gooney flight was dispatched to investigate the region between Eniwetok and Kusaie. This flight fixed the center of the storm, and established that its movement was toward the east. The previous Gooney flight had suggested that the associated hyperbolic point was to the northwest of the vortex, another indication of a basic eastward flow.

At 0600Z, 20 March the storm passed over or to the south of Kwajalein, very near the station. Strong surface winds and a maximum upper wind of 65 knots at 6000 feet were reported at the time of storm passage and in addition 3.28 inches of rainfall occurred between 0000Z - 1800Z. The storm was then moving in an easterly direction approximately 18 - 20 knots, but decreased in speed of movement and became practically stationary, with a slight curvature to the north.

The first typhoon bulletin was issued by the Guam Typhoon Warning Center at 210600Z. This placed the center at  $9^{\circ}$  N,  $171.5^{\circ}$  E on the basis of a reconnaissance fix by a special Vulture flight. The maximum winds were reported

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at 100 knots. At 210440Z a reconnaissance aircraft measured the central pressure at 978.2 MB. The typhoon was then moving northeastward about 5 knots or less, but it soon curved to the west or west-northwest, reaching a position of  $10^{\circ} 36' N$ ,  $171^{\circ} 18' E$  at 222118Z, according to a report from the Vulture flight. At this time the eye was 15 by 25 miles across, with light winds in the eye, but winds in excess of 500 knots within 50 miles of the center.

The Guam typhoon bulletin for 231200Z gave a gale warning for Kwajalein, placing the center at  $11.5^{\circ} N$ ,  $170.0^{\circ} E$ , with 110 knot winds within a radius of 60 miles. Observed winds at Kwajalein were exceptionally light, hardly exceeding 20 knots, except at 221500Z, when they reached a maximum of 45 knots at 6000 feet. The lightness of the winds at Kwajalein was indicative of the fact that the hyperbolic point of the typhoon was in the vicinity of Kwajalein. The significance of this is twofold; first, the orientation of the hyperbolic point indicated a motion of the typhoon to the west or west-southwest, and second, the proximity of the hyperbolic point and the vortex indicated decreasing intensity of the circulation. As a matter of fact, the reconnaissance flight at this time could not locate a definite eye, and the maximum 1500 foot wind reported was only 57 knots.

Up until this time, in accordance with Air Weather Service practice, special forecasts for JTF-3 operations had not been made at the Eniwetok Weather Central. The Guam Typhoon Bulletins were disseminated to all responsible personnel, but since no effect of the typhoon was expected within 24 hours, local typhoon forecast were not issued. By 24 March the storm had moved close enough to affect our mission in the next 24 hours, and the Weather Central issued a Special Wind Warning. On the basis of the indicated dissipation of the typhoon, maximum winds of 30 to 40 knots with gusts to 45 or 50 knots were forecast. The center was forecast to degenerate into a wave, whose crest was to pass Eniwetok near 241500Z (250300 local time). The timing was based on a forecasted acceleration in the speed of the storm to 14 knots, as compared with the previous speed of 11 knots. Actually, the closed circulation did not disappear so quickly, and its speed of propagation remained 11 to 12 knots. As a result, the storm did not pass until some time between 242100Z and 250300Z, with winds in the lower levels shifting sharply from northeast to southeast, and in the upper levels from northwest to southwest. Wind speeds were slightly lower than forecast, but 0.59 inches of rain fell on the 25th. Considerable improvement occurred on the 26th. On the 27th a line of convergence associated with the storm moved slowly over Eniwetok, resulting in 2.03 inches of rain.

The last typhoon bulletin issued by Guam was dated 250600Z. At this time the center was located by reconnaissance aircraft at  $11.5^{\circ} N$ ,  $162.0^{\circ} E$ , although the circulation by now was so poorly defined that this position is open to some question. During the time the storm was near Eniwetok a large search radar was run continuously, and it failed to show a clearly defined vortex. This was possibly due to the fact that the clouds in the area covered by aircraft reporting the center, were mainly stratiform and gave little or no radar echo. On the other hand, the clouds of vertical development giving the best echo were distributed in an indefinite pattern and mostly to the north of Eniwetok.

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The movement of the disturbance after leaving the Eniwetok area is open to considerable question. Had the movement continued in a west-southwest direction at 12 knots, it would have reached a point northeast of Truk by 270300Z. A routine Vulture flight actually showed a pronounced cyclonic circulation near this location.

In connection with the dissipation of the typhoon "Georgia" it is of interest to note that this occurred simultaneously with the development of a new vortex between Kwajalein and Kusaie. This new vortex was first noted at 10,000 feet at 221500Z. It was first drawn on the 1500 foot streamline chart at 240300Z, and thereafter it showed a regular westward movement. It passed directly over Kusaie at 251500Z, and continued on at 12 - 15 knots to the vicinity of Truk. Although this vortex never caused much weather, it is conceivable that its formation drained energy from the typhoon "Georgia" hastening its dissipation. At one time the surface pressure map showed a small depression north of Maura, but this did not develop, and was not carried on later maps. Even as late as the 28th, however, the equatorial pressure trough was far to the north of its mean position for the season.

In the initial detection and later tracking of "Georgia" aircraft reconnaissance was invaluable. Among the first definite indication of a vortex between Kusaie and Ponape were the reports of the Vulture George flight on the 17th and 19th of March. On the 20th, the Gooney Special entered the vortex and definitely ascertained its position and motion. Thereafter there were two or more Vulture or Gooney Special flights per day to locate the center of the storm and to determine the wind velocity and weather distribution about it. In addition there were the regular Gooney Charlie and George tracks, which bracketed the storm area and gave an indication of the more widespread effects on the weather. The special flights were continued until 25 March, when it became no longer possible to locate a definite eye or any weather or winds considered to be operationally hazardous.

In the Weather Central certain non-routine activities became routine for the duration of the storm in the region. Since this is not a typhoon forecasting center, it was necessary only to disseminate the bulletins issued by the Guam Typhoon Warning Center, and to make such local interpretations as were necessary. Immediately upon receipt of a typhoon bulletin, one copy was dispatched to the Staff Weather Officer, JTF-3, a second copy was sent to the AOC, Task Group 3.4. The third copy was retained in Weather Central files, with any pertinent information from it being given to interested parties. The CTG 3.4 was informed of all the latest developments. The central positions of the storm as given in the bulletins were used in constructing the various maps, with only slight modifications made to conform with later reconnaissance data.

The Weather Central did not have the responsibility of directing the Gooney and Vulture special flights into the storm; this was handled from Guam in accordance with usual typhoon reconnaissance procedure. The principal departure from routine in the matter of reconnaissance flights arose from the availability of ~~52nd~~ Reconnaissance Squadron aircraft and crews for typhoon tracking in addition to the usual 54th Reconnaissance Squadron facilities. The only special observations made by Task Unit 3.4.5 were a series of upper wind observations taken at Eniwetok at three hour intervals (rather than the normal six) from 230000Z to 242100Z inclusive.

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As it turned out, the effects of the typhoon "Georgia" on operations at Eniwetok were not very great. During the period the storm was severe enough to be designated a typhoon, it was so located that no effects were felt on this island, and for that matter, there were no destructive winds at Kwajalein although surface winds of at least 56 knots had been observed during the first passage on 20 March. The storm affected Eniwetok directly only on one day, 25 March, which was characterized by a low and middle overcast, more or less continuous rain, and gusty winds, however, not of destructive force. For the following two days, and especially on 27 March, Eniwetok was affected by a zone of convergence associated with "Georgia" with the result that there was a relatively large amount of precipitation and some gusty winds.

The present report is not intended to be a technical study of the typhoon "Georgia" but merely a historical report with special emphasis on the effects of the typhoon on "Operation Greenhouse".

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THE TYPHOON "JOAN"

Abstract: The second typhoon to affect the Marshall Islands in the spring of 1951 is described and its path traced. The associated weather at several islands is very briefly recounted and the airflow aloft described in general terms.

Introduction

Typhoons are rare in the Marshall Islands, but two affected the weather at Eniwetok during the months of March through May, 1951. In the Weather Service, such storms are individually named; the first was called "Georgia" and has been described in a previous report. The second was named "Joan".

This report is not a special study, but a simple description of a weather situation and its effects upon Operation Greenhouse. "Joan" was located and tracked by routine streamline analysis and serial reconnaissance reports. The official typhoon bulletins and other advisories emanating from Guam were very helpful, but not entirely adequate for this specialized operation, especially during the formative stages of the storm.

Throughout the life of "Joan", as with "Georgia", it was necessary to rely on the wind reports to determine the storm's location and intensity. Even the most careful analyses of the pressure field and constant-pressure heights proved inferior for this purpose. In fact, pressures reported by Maura gave no indication whatsoever of the developing storm. Although Kusaie, Ponape, and Eniwetok pressures reached minima (about 6 mb below normal for Eniwetok) as "Joan" passed, the poor definition and late development of these minima precluded reliance on the pressure field as a basis for forecasting. On the other hand, streamline analysis as described by Bjerknes<sup>1</sup> and applied to tropical situations by Palmer<sup>2</sup>, gave good results. At the Eniwetok Weather Central such streamline analysis was regularly performed for various levels up to 50,000 feet.

Birth of the Storm

The winds at Maura indicated a disturbance in the vicinity as early as 2100Z 29 April 1951. Analysis of the pressure field revealed a quasi-stationary trough extending from the north into the Maura area.

<sup>1</sup>Bjerknes, V., and Others: Dynamic Meteorology and Hydrography, Part II, Kinematics; Washington, Carnegie Institution, 1911.

<sup>2</sup>Palmer, C.E., and H. Elsasser: Notes on Tropical Meteorology; Tech. Bull. 2143d Air Weather Wing, 1949

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Small low pressure cells had appeared repeatedly in the Gilbert and Ellice Islands just prior to the quoted time, but no definite center of disturbance could be fixed.

On 27 April a pronounced equatorial wave passed Bikati, as evidence by the graphical wind time sections. This wave was carried westward to a longitude of 163° E on 28 May, but it was <sup>not</sup> apparent after that time. Although this was the same longitude at which the disturbance which was to become "Joan" first definitely appeared on 2 May (see Fig.1), it is believed that the time lag would preclude the possibility that the wave and "Joan" were identical. However, the wave may have had some bearing on the movement of the disturbance northward across the equator.

The disturbance in question was first analyzed as a vortex on the 1500 foot streamline chart for 0300Z 2 May 1951, at the position indicated in Fig. 1. The low level wind shifts at Nauru suggested an indraft to the east, moving northwest. It is interesting to note that this location was on or near the position of a very strong and persistent line of streamline convergence that had extended northwestward toward an older vortex during the last days of April. The new vortex moved approximately as indicated in Fig. 1 and developed slowly, reaching typhoon intensity probably about 7 May. Although the wind speeds were at first moderate, the associated weather was heavy throughout the life of the storm "Joan". The 24-hour rainfall at Nauru amounted to 8.16 inches for the period ending 0000Z 2 May; this was followed by 1.16 inches in the next 24 hours.

#### Mature Stage

As the vortex approached within 200 miles of Kusaie, the surface wind shifted from southerly to east-north-east about 20 knots, with gusts exceeding 35 knots at 2100Z 3 May. On 5 May thunderstorms with 1.61 inches of rain were reported at Kusaie. Extensive intermediate cloudiness with intermittent rain and southerly to westerly winds from the surface to about 20,000 feet prevailed at Kusaie from this time until 10 May, when the storm had moved far to the northwest, as shown in Fig.1.

At Ponape, winds remained moderate, although the approaching storm's character as a vortex was becoming more pronounced. It should be noted that "Joan" passed southwest of Kusaie, but northeast of Ponape, as shown in Fig. 1. There was considerable rain on 5 May and by 0300Z 6 May, the wind had shifted from easterly to southwesterly, continuing southerly, but very light, until 11 May. Thereafter, a period of calm was followed by light northerly winds. Throughout the area, the passing of "Joan" was followed by unusually light winds.

At Eniwctok on 7 May the surface wind became southeast with sustained speeds as high as 32 knots. Rainfall increased to 2.20

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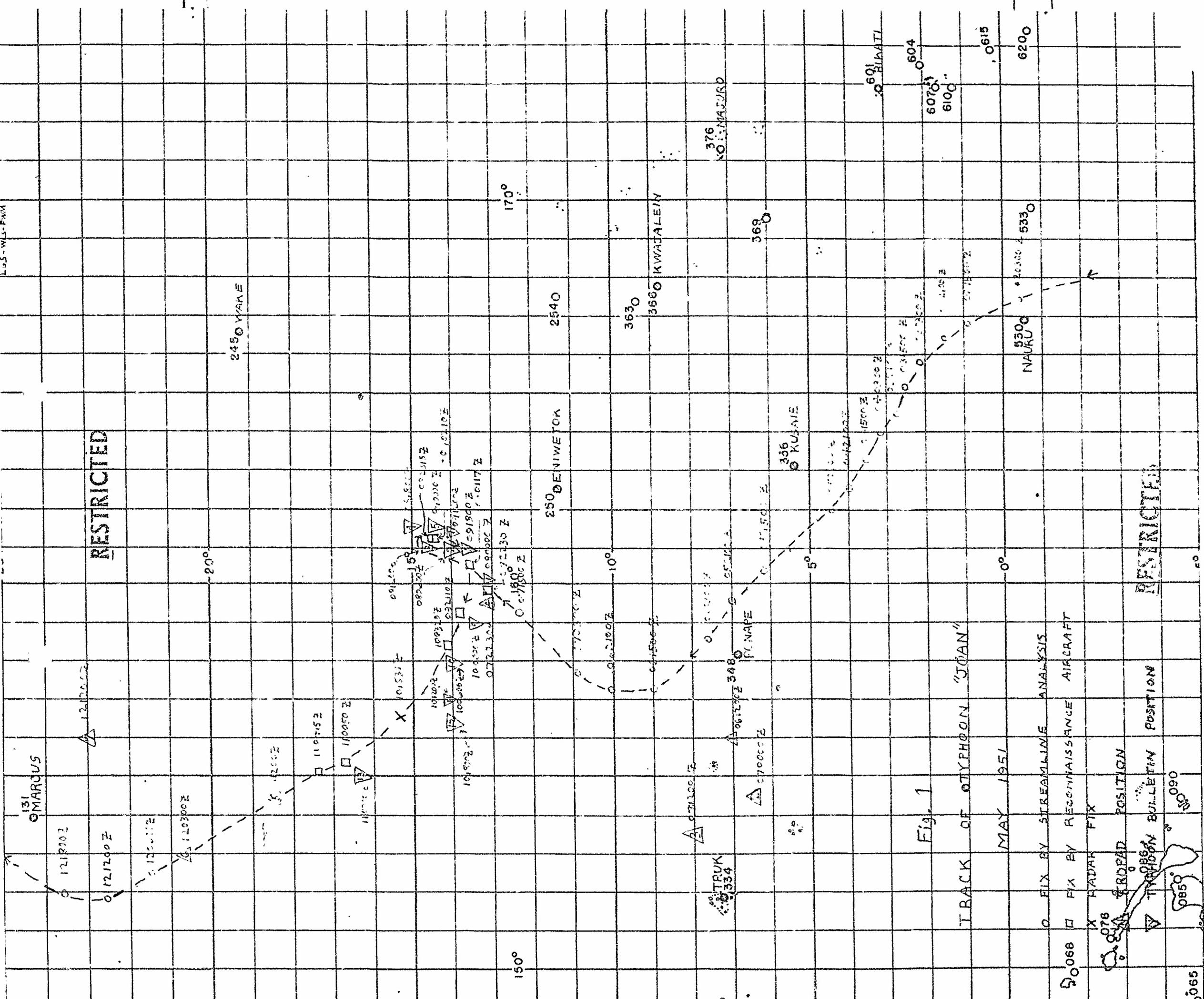


Fig. 1  
TRACK OF TYPHOON "JOAN"  
MAY 1951

- FIX BY STREAMLINE ANALYSIS
- FIX BY RECONNAISSANCE AIRCRAFT
- X RADAR FIX
- ▽ TYPHOON BULLETIN POSITION

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inches in the 18 hours from 0600Z 6 May to 0000Z 7 May and 1.51 inches for the following 24 hours. Late on 7 May southwesterly winds appeared aloft, and early on 8 May these extended down to the surface. On 8 May the Eniwetok rawinsonde station made runs every three hours in order to better track the storm while it was in the vicinity.

During the mature stage of typhoon "Joan" aerial reconnaissance was invaluable in tracking the center and determining the intensity. The first special efforts to locate the storm by aircraft were made on 5 May. However, it was not considered necessary to dispatch special search missions, but instead the regular Gooney "How" and Vulture "George" tracks were called for. Neither flight however, reached the storm center, although between Truk and Ponape Vulture "George" reached what was at first thought to be the center (note the first Troad position in Fig. 1), but what was later analyzed as the neutral point. Certain sectors about a neutral point have light convergent winds just as in the eye of a storm, and it was apparently just such a sector that Vulture "George" entered. The fact that no strong winds or especially bad weather were encountered while entering this region, combined with the definite cyclonic circulation noted to the northeast leads one to the conclusion that the storm center had already moved to the north.

In the later stages of development a number of regular and special reconnaissance flights entered the storm. On 7 May at 2230Z a Gooney Special fixed the center. On 8 May both Gooney "How" and Gooney "George" entered the typhoon. On 9 and 10 May special Gooney flights determined the storm center, and on 11 May a special Vulture flight entered the storm.

Heavy precipitation associated with the typhoon was concentrated in one or more narrow bands, which spiraled toward the center. These bands are asymptotes of streamline convergence. In the case of "Joan", only one such band was positively identified, but it was very long, vigorous, and persistent. This line is visible in Fig. 2, running from the neutral point at  $4^{\circ}$  N.  $165^{\circ}$  E, a bit west of north, then spiraling into the storm. At Eniwetok, the heaviest rain occurred as this line moved eastward over the station. The line tended to rotate counterclockwise about the storm center and reached Kwajalein about 1200Z 8 May. With its arrival, Kwajalein reported a shift from easterly to westerly winds and 2.75 inches of rain in six hours.

The upper flow during the early stages of development was easterly in the Southern Marshalls. At 30,000 and 40,000 feet, a belt of anti-cyclones near  $10^{\circ}$  N gave easterly winds over Hauru, becoming south-easterly near Kusaie and Ponape. A closed cyclonic circulation was detected at 10,000 feet on 3 May, and at 20,000 feet on 5 May, both approximately directly above the low level circulation. By this latter time, extensive southerlies had set in over the Western Marshall and the Eastern Caroline Islands. At 10,000 feet, the area covered by the

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cyclonic circulation increased until it dominated the greater part of the Marshalls and Carolines by 6 May. Thereafter, the patterns at 10,000 feet and 1500 feet remained quite similar. From 7 May to 9 May, "Joan" dominated the circulation of the entire area. The normal easterlies were replaced by westerlies over all the Northern Marshalls and the Carolines at least up to 14,000 feet.

Meanwhile an upper trough in the polar westerlies, apparent at 20,000, 30,000, and 40,000 feet, had been approaching from the west. On 7 May it extended southward between Marcus and Wake, and behind it was an anticyclonic cell bounded roughly by the Marianas, the Philippines, the Ryukyus, and the Bonins. The typhoon had been moving northward toward the upper trough, but on 8 May it came under the area of light winds at the southern end of the trough, and there it remained quasi-stationary for about 40 hours. Meanwhile the upper trough moved on toward Midway, and the anticyclonic cell moved in behind it to the north of "Joan". This placed the typhoon in a deep easterly current, and on 9 May it started moving west-northwestward about 10 knots. Reconnaissance reports indicated that it was weakening.

#### Decay of the Storm

By 11 May, the storm had moved into an area where observations were too sparse for reliable analysis, but it appeared to have weakened considerably. The winds over the Northern Marshalls and Carolines had become very light and without a definite flow pattern. The storm curved clockwise around the eastward-moving anticyclone, which had come betw on the storm vortex and the polar trough, and was absorbed by the polar westerlies near Marcus on 12 May 1951. By this time, normal trade flow had returned to all the Marshall and Caroline Islands and the storm showed no further influence in the tropics.

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