Skylab S193 and the Analysis of the Wind Field Over the Ocean* 15

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Abstract

The present status of the program to provide proof of concept for the idea that simultaneously observed radar scattering cross section measurements and passive microwave measurements can be used to determine the winds in the planetary boundary layer over the ocean is given. The role of S193 in Skylab is providing the final clinching proof that an operational instrument will obtain data of great value to both meteorology and oceanography is described.

Introduction

A combined program of theoretical and applied research on the problem of determining the winds over the oceans by means of both active and passive microwave measurements has been under way for several years in the Department of Meteorology and Oceanography at New York University and at the Center for Research at the University of Kansas. The overall concept has been described by Moore and Pierson (1971).

The fundamental hypothesis is that the ocean surface gets rougher as the wind increases and that radar backscatter and passive microwave emission vary with this increased roughness. In terms of this conference topic, the sea surface topography for waves with lengths of centimeters to meters changes rapidly in response to the wind. These changes cause changes in radar sea return and in passive microwave emission (especially when whitecaps are considered) that can be interpreted in terms of the wind speed in the planetary boundary layer.

This research as supported by NASA through the Spacecraft Oceanography Project (now called Remote Sensing Oceanography) and through AAFE at Langley has lead to many achievements that fit together into a combined theoretical and observational matrix to provide sound reasons why S193 will prove to be a successful experiment and to give guidance on how the radar radiometer under AAFE development should be used and on how S193 should be operated.

The combined theoretical and observational matrix contains the following results.

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(1) Time histories of capillary gravity waves generated in wind-water tunnels for winds corresponding to anemometer height winds from calm to 60 knots and for a variety of fetches up to 19 or 20 meters as obtained at New York University, Stanford University, and Kyoto University show that the spectral energy in gravity-capillary waves ($f \geq \sim 4$ Hertz) increases with increasing wind speed and does not depend on fetch.

(2) Photographic data from Kyoto University show that this increase in spectral energy at these frequencies is simultaneously accompanied by an increased roughness in the spatial scales of a gravity capillary waves. The instantaneously rough surface as a function of position becomes rougher with increasing wind speed.

(3) Two improved theories of radar sea return have been derived, one at the University of Kansas and another at New York University, that show how knowledge of the spectrum of the waves permits the theoretical calculation of the radar scattering cross section.

(4) Measurements at 13.3 GHz by MSC Earth Resources aircraft for winds from nearly calm to about 50 knots have shown that for both upwind-downwind and crosswind conditions, the radar scattering cross section is a function of wind speed.

(5) Theoretical considerations on the differences to be expected between radar and passive measurements at the sea surface in the presence of clouds and rain compared with the same conditions at the sea surface without clouds and rain have lead to the development of concepts on how to account for the effects of clouds and rain on these measurements.

(6) Since both theory and observation suggest that radar sea return will depend slightly on the larger waves in the wave spectrum and since the observations show that the passive microwave sea surface emission will depend on the amount of foam (as well as on the wave structure), procedures for specifying these features of the sea surface in terms of the gravity wave spectrum and the whitecap production index have been developed.

(7) Numerical models of the wind field in the planetary boundary layer that account for atmospheric stability have been developed.

(8) Simulations of the data that might be obtained by a radar radiometer on a polar orbiting spacecraft have been used to show that such data, plus a few scattered ship reports, permit the analysis of the vector wind in the planetary boundary layer and of the surface pressure field.

(9) Procedures have been developed so that the various scanning modes of S193 can be used to augment and re-verify the variation of sea return with wind speed and to obtain data similar to the data that

would be obtained by an operational spacecraft so as to permit the analysis of the wind field over a large ocean area.

Wave Data and Sea Return Theories

Our work under AAFE sponsorship during the past year has just been reported by Pierson et al. (1971). Summarized quickly, our findings are that the capillary wave spectrum does not saturate. To the contrary, the spectral energy as a given frequency band increased with increasing wind speed for winds up to 60 knots, at least. If the spectrum is given as a function of frequency by

$$S(\omega) = \frac{D(4.05 \times 10^{-3})}{[k(\omega)]^3} \frac{dk(\omega)}{d\omega} \quad (1)$$

where $k = k(\omega)$ is the equation relating wave number to frequency for all waves; gravity--capillary and in between, it is found that this form for $S(\omega)$ fits a wide range of estimated frequency spectra from the frequency at which the spectrum is a maximum upward.

The quantity D is dominantly a function of wind speed as shown in Fig. 1 from the report by Pierson et al. (1971). The inverse of $k = k(\omega)$ is $\omega = \omega(k)$, and when this inverse is used equation (1) becomes

$$S(k) = \frac{D(4.05 \times 10^{-3})}{k^3} \quad (2)$$

(which was really the starting point based on the concept of an equilibrium spectrum by Phillips (1966)).

The constant, 4.05×10^{-3} seems well established as an equilibrium range for the gravity wave spectrum with wave periods of 2 seconds or longer. Fig. 1 shows that the capillary spectrum can be 10^{-4} weaker than the gravity spectrum for very low winds and that for winds above a certain threshold value the capillary spectrum is higher than the equilibrium gravity value and shows a strong dependence on wind speed.

Given the observed dependence of the spectrum on wind speed, any theory of radar-sea return would predict a variation with wind speed if the spectrum was changing with wind speed at the Bragg scattering wave numbers.

The newer theories of sea return as given by Fung and Chan (1969) and by Jackson (1971), as extensions of the work by Chia (1968), require knowledge of the full two-dimensional wave number spectrum as a function of wind speed and would yield changes in sea return caused by effects other than Bragg scattering.

Our goal in this program is to define the full wave number spectrum as a function of wind speed and compute sea return using those new theories.

Measurements of Sea Return at 13.3 GHz

NASA has carried out three remote sensing missions using a 13.3 GHz fan beam doppler scatterometer. The missions were Mission 88 based at Shannon, Ireland, Mission 119 based in Bermuda, and Mission 156 based at Patuxent, Maryland. Data were obtained on radar sea return covering winds from about 7 knots to 49 knots. The data have to be studied in terms of the radar scattering cross section normalized to 10°, but they clearly show that sea return is a well defined function of wind speed over this range of speeds.

A thorough analysis of the instrument and of the data will be given in a forthcoming report by G. Bradley of the University of Kansas. Table 1 summarizes the results of least square fits to all of the available data.

Table 1. Dependence of Radar Scattering Cross Section on Wind Speed

Angle	Wind direction	Dependence	RMS error
15°	upwind	$\sigma^\circ \sim W^{0.37}$	0.68 db
25°	upwind	$\sigma^\circ \sim W^{1.11}$	1.01 db
35°	upwind	$\sigma^\circ \sim W^{1.44}$	1.63 db
15°	crosswind	$\sigma^\circ \sim W^{0.30}$	0.76 db
25°	crosswind	$\sigma^\circ \sim W^{0.98}$	1.39 db
35°	crosswind	$\sigma^\circ \sim W^{1.35}$	1.49 db

Numerical Models for Wind Fields, Waves and Whitecaps

The integration of space obtained data into the total of all conventional data requires computer based procedures. The winds over the oceans in the planetary boundary layer vary with height as a function of atmospheric stability and the thermal wind. Procedures for the analysis of the wind field over the oceans that use conventional ship report data have been developed by Cardone (1969), and the computer products that result for an analysis four times as dense as the NWP grid have been illustrated by Pierson (1970).

Theories of radar sea return in one way or another, and to various degrees, all suggest that the radar scattering cross section is changed by changes in the spectrum of longer waves even if the smaller-scale structures, most responsible for the return, remain unaltered. These longer waves take a while to be generated and can propagate great distances across the ocean. One of the goals of our research has been to produce better wave specification and forecasting computer based procedures, and, as a by-product of this goal, the capability also exists to describe the gravity wave part of the spectrum as a possible "vernier" correction to the sea return measurements.

Several different wave forecasting computer models have been developed. One described by Pierson (1970, 1971) yields 360 numbers at about 4000 points in the North Pacific. This model, though having been run on a test basis, is difficult to run operationally on available facilities.

The model, as first developed, has been made less complicated by doubling the grid spacing so that only about 1000 points cover the North Pacific. This model could also be run.

However, at FNWC the requirement is for coverage of both the South Pacific and the North Pacific and so the spectral angular resolution of the original model has been reduced from 24 direction bands each 15° wide to 12 direction bands each 30° wide so that the number of grid points can be increased.

Some combination of the above wave specification and wave forecasting methods should soon be operational at FNWC. Other larger capacity, higher speed computer complexes would be able to use the smaller grid higher spectral resolution models that have been developed.

Passive microwave measurements of the emission from a wind roughened sea have shown that the whitecaps and foam on a wind sea increase the microwave emission drastically. Whitecaps and the percentage of foam cover on the sea surface are predictable as a part of these numerical wave specification and forecasting procedures. The concepts involved have been described by Cardone (1969), Ross and Cardone (1970), and Pierson (1970).

Simulation of Space Data

Under the assumption that a scanning radar radiometer would gather data that could be used to determine the wind speed on a grid of points, the data that could be obtained by such an instrument have been simulated by Druyan (1971). Analysis procedures based on conventional ship coverage and the simulated space data have been developed that show that good analyses of the vector wind field and the surface pressure field can be obtained.

A sample analysis based on conventional data coverage and then on only a few ships and simulated data are shown in Figs. 2 and 3.

Plans are under way to study a mix of space data and data buoys such as might be the result of the National Data Buoy System.

Once the surface pressure field is defined over the oceans, measurements of temperature as a function of pressure as obtained by presently operating remote sensing systems of which SIRS was the forerunner (Wark and Hilleary, 1969), make it possible to define the entire atmospheric structure over the oceans as it would be needed for the forward integration in time of the primitive equations defining atmospheric motions. A radar radiometer should prove of great value, combined with an atmospheric sounding device on a spacecraft, as a data source for numerical forecasts in the southern hemisphere. Southern hemisphere numerical models are described by Gauntlett and Hincksman (1961).

Passive Microwave Measurements

Passive microwave measurements of a wind roughened sea have been reported by Hollinger (1970) and others. Clearly, both the change in the small-scale roughness elements and the presence of whitecaps and foam cause an increase in microwave emission with increasing wind speed. If the sea surface is viewed through clear air from spacecraft altitudes, it would be expected that both the radar scattering cross section measurements and the passive measurements would give independent estimates of the wind speed. The radar measurements would be less sensitive to the variations with fetch and duration of the larger gravity waves on the sea surface, whereas the microwave measurements would be affected by whitecaps and foam, which are fetch and duration dependent.

From a spacecraft, measurements will also be made through the clouds of varying thicknesses and water content as well as through clouds with precipitation in the beam. For various reasons no airborne measurements through clouds and clouds and rain have yet been made for varying wind conditions at the surface. Various theories exist as to how clouds and rain affect microwave measurements, but no combined theory is available for simultaneously varying sea surface conditions and clouds and rain.

Efforts to define this problem have been made by Mr. John P. Claassen of CRES and these results have been incorporated in a joint proposal prepared by NYU, CRES, ESG (of NOAA) and Lamont for the study of S193 data (McClain et al., 1971). The ideal system for such a study is, of course, S193 on Skylab and the results that can be obtained from it are the subject of the following sections of this paper.

Skylab S193

The step from laboratory wind-water tunnel measurements, tower microwave measurements and airborne photographic, laser radar and microwave measurements to space measurements by means of S193 or Skylab introduces a number of important new variables. They are:

1. Increased data rates, compared to past airborne missions, covering a full range of surface wind speeds and wind wave directions relative to the radar beam.

2. A change from the microscale and mesoscale, as encountered during platform and aircraft measurements, to the synoptic scale with resulting measurements that are more representative of the values needed for synoptic meteorological analyses.

3. An opportunity through the scanning mode of S193 to obtain real data for trial computations of the computer based procedures for integrating spacecraft data and conventional data.

4. A variety of intervening atmospheric conditions ranging from clear air, through many types of clouds, finally to clouds with varying amounts of precipitation.

These various new features are illustrated by the simultaneous study of Figs. 4, 5, 6, and 7. Fig. 4 illustrates a typical cloud pattern off the east coast of USA. Fig. 7 illustrates a conventional analysis of the winds at the ocean surface near the time of the cloud imagery. Fig. 5 shows a schematic analysis of the cloud pattern shown in Fig. 4 with indicated areas for showers, rain and drizzle. Fig. 6 illustrates two of many possible Skylab S193 data passes that might have been made over these conditions.

In Fig. 6, the northbound pass illustrates the alternate side scanning mode. At each open ellipse, six quantities are measured, radar scattering cross section in the HH, VV, VH and HV modes and passive microwave emission in the H and V modes, and thus 900 numbers become available in seven minutes of instrument operation. If, at each spot, the data could be used to infer wind speed, the result would be a pattern quite similar, except for orientation, to the pattern that would be scanned by a spacecraft in a 100° retrograde sun-synchronous orbit. For the total area scanned, these would be numerous forms of surface truth available, such as conventional ships and, by 1973, buoys of the National Data Buoy System. The area illustrated is one in which the surface truth should be quite dense compared to most other areas of the world. For such an area, a streamline isotach plus computer based analysis of the wind field based on all available conventional data, as suggested in Fig. 7 then provides a value of wind speed and a wind direction relative to the radar beam for each set of six observations.

The southbound orbit segment shows a second scanning mode. Each black ellipse represents 30 observations, 6 combinations of radar and passive microwave, times five different angles for essentially the same areas of illumination. This particular southbound orbit, if it actually had occurred, might have made measurements for essentially downwind conditions for winds from 20 to 70 knots in just a few minutes.

Each spot on the sea surface scanned by S193 is about 14 by 12 kilometers and represents a large area of the sea surface. Application of the Taylor hypothesis suggests that this brief spacecraft observation would be the equivalent of having about ten duplicate MSC aircraft flying parallel to each other a kilometer apart for a distance of 14 kilometers and averaging radar data recorded by each aircraft to obtain single values for estimates of the scattering cross section and microwave measurements. The instantaneous spatial variability over the area of the scanned spot is the equivalent of several hours of variability in an anemometer record of the turbulent wind at a fixed point above the sea surface. The space average is therefore a very stable measure of a properly averaged wind over an appropriately chosen area suitable for use in synoptic scale analyses.

All of the above are the advantages of making these measurements from space as the next step in the development of an operational instrument. Figures 4 and 5 show, of course, the disadvantage, and the major problem that still has to be overcome. The disadvantage is the clouds, and the problem is to infer wind speed at the sea surface below the clouds from these measurements.

Global cloud mosaics and geostationary cloud imagery show that about 60 to 70% of the ocean surface can be viewed through clear air by a radar radiometer. For these data points there will be no problem.

For the S193 experiment, it will be necessary to obtain an independent decision from other sources of space imagery as to whether or not a particular surface cell is being viewed through clouds. If it is being viewed through clouds, it then becomes important to determine cloud thickness, and whether or not there is precipitation.

If clouds are present in the beam, the effects on the radar and passive microwave measurements are quite different. As pointed out in McClain et al. (1971), the passive measurements soon lose "contact" with the surface, or, stated another way, liquid water in clouds is "hot" compared to the sea surface and the microwave temperature is expected to rise as soon as clouds enter the beam. The radar pulse can, however, pass through the cloud without too much attenuation, be scattered back by the sea surface through the cloud again to the spacecraft, and still contain information on the roughness of the underlying sea surface. As discussed by Moore and Pierson (1971) high microwave temperatures along with reasonable scattering cross section values can be interpreted as a cloud effect and the value of the microwave temperature can be used to correct the sea return value for the slight effect of the clouds on it. It is to be expected that the effects of most non-precipitating stratus decks can be easily removed.

Very thick wet clouds with precipitation are another problem. It may only be possible to identify characteristics of such data points that go with these conditions and eliminate the measurements from further analysis. It is believed, however, that a substantial portion of the measurements through clouds can be interpreted in terms of the winds over the sea surface. Loss of data due to thick clouds and rain should not seriously affect the usefulness of the instrument.

A plan for the stratification and analysis of the radar and passive microwave data in terms of the effects of clouds and precipitation and in terms of the various sources of "sea" truth was given by McClain et al. (1971). The plan essentially proposed proceeding from clear air measurements to thin clouds and finding the effects of the thin clouds to be followed by the increasingly more complex problems of thick clouds and clouds with rain and snow. Airborne measurements with the AAFE radar radiometer below the clouds are an important part of the program. The full scheme is shown in Figs. 8 and 9.

Conclusion

To summarize briefly, various parts of the problem of using a radar radiometer as a remote sensing device to determine the winds over the ocean have been identified and solved. There remains only one real problem connected with going to spacecraft and that is the problem of clouds intervening between the spacecraft and the sea surface. Ways to study this problem are available and suggest that useful data will still be obtainable through many kinds of cloud conditions.

Acknowledgments

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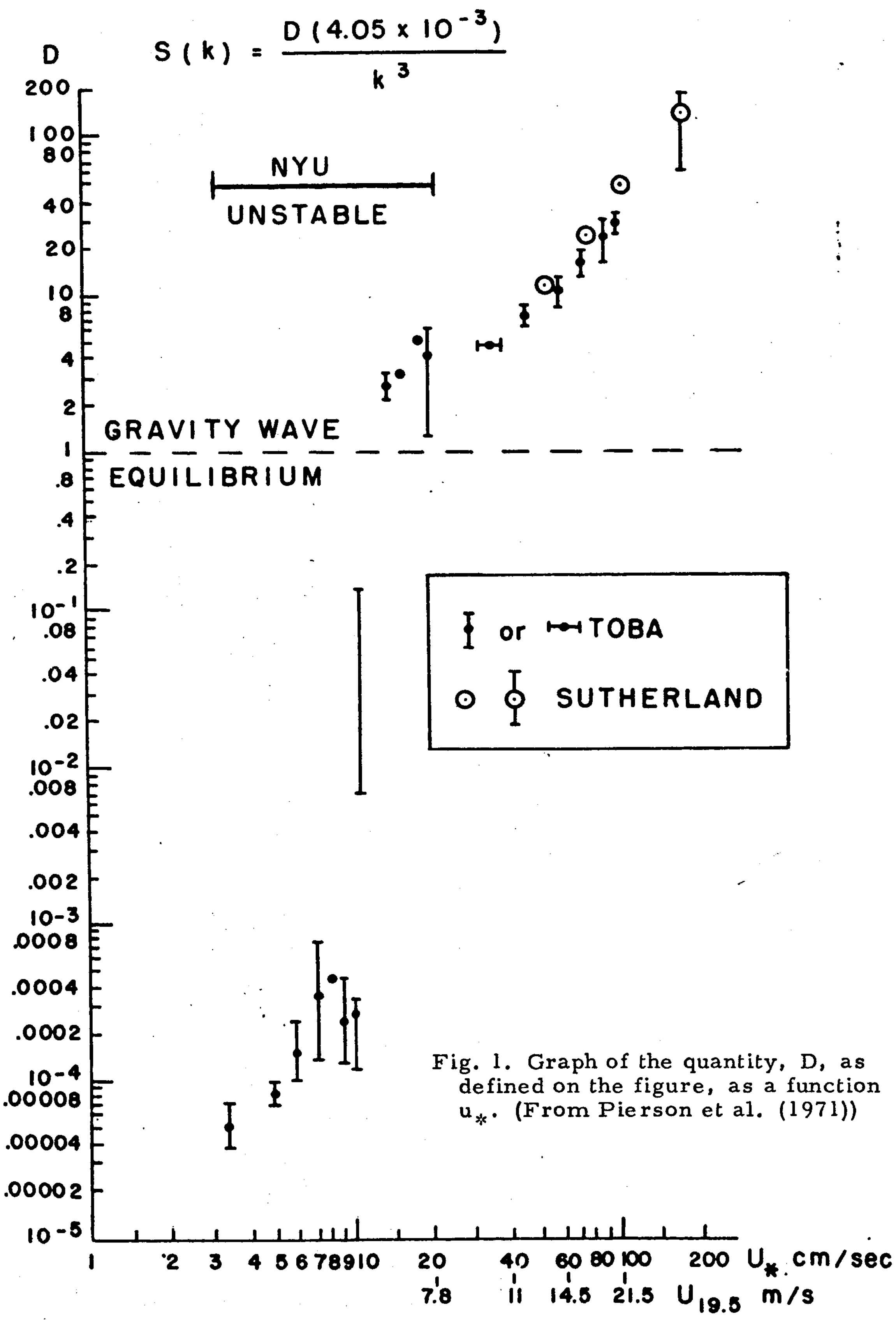
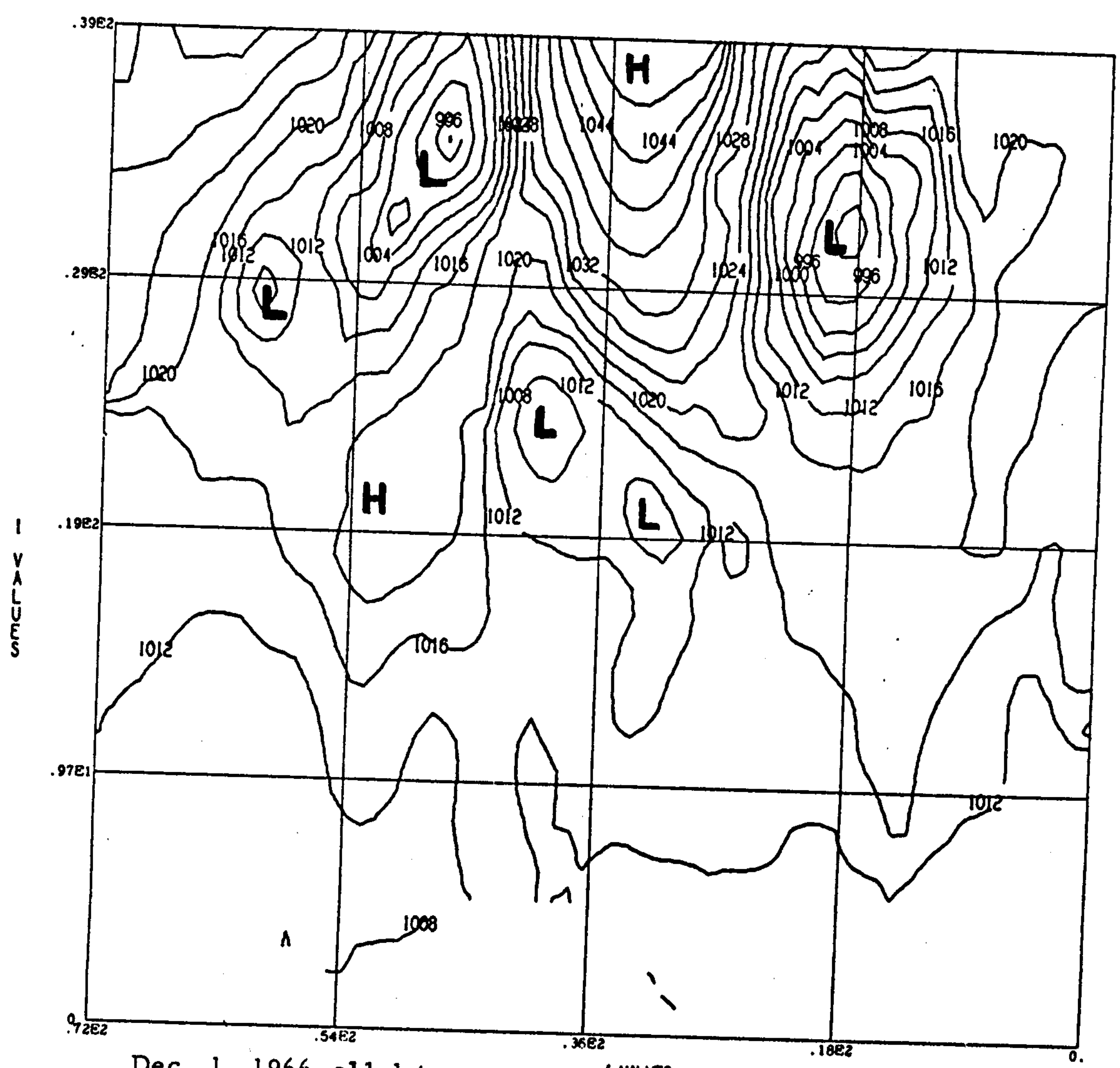


Fig. 1. Graph of the quantity, D, as defined on the figure, as a function u_*. (From Pierson et al. (1971))



Dec. 1, 1966 all data.

Fig. 2. Analysis of the surface pressure field over the North Pacific Ocean for December 1, 1966 based on all available conventional data. (From Druyan, 1971).

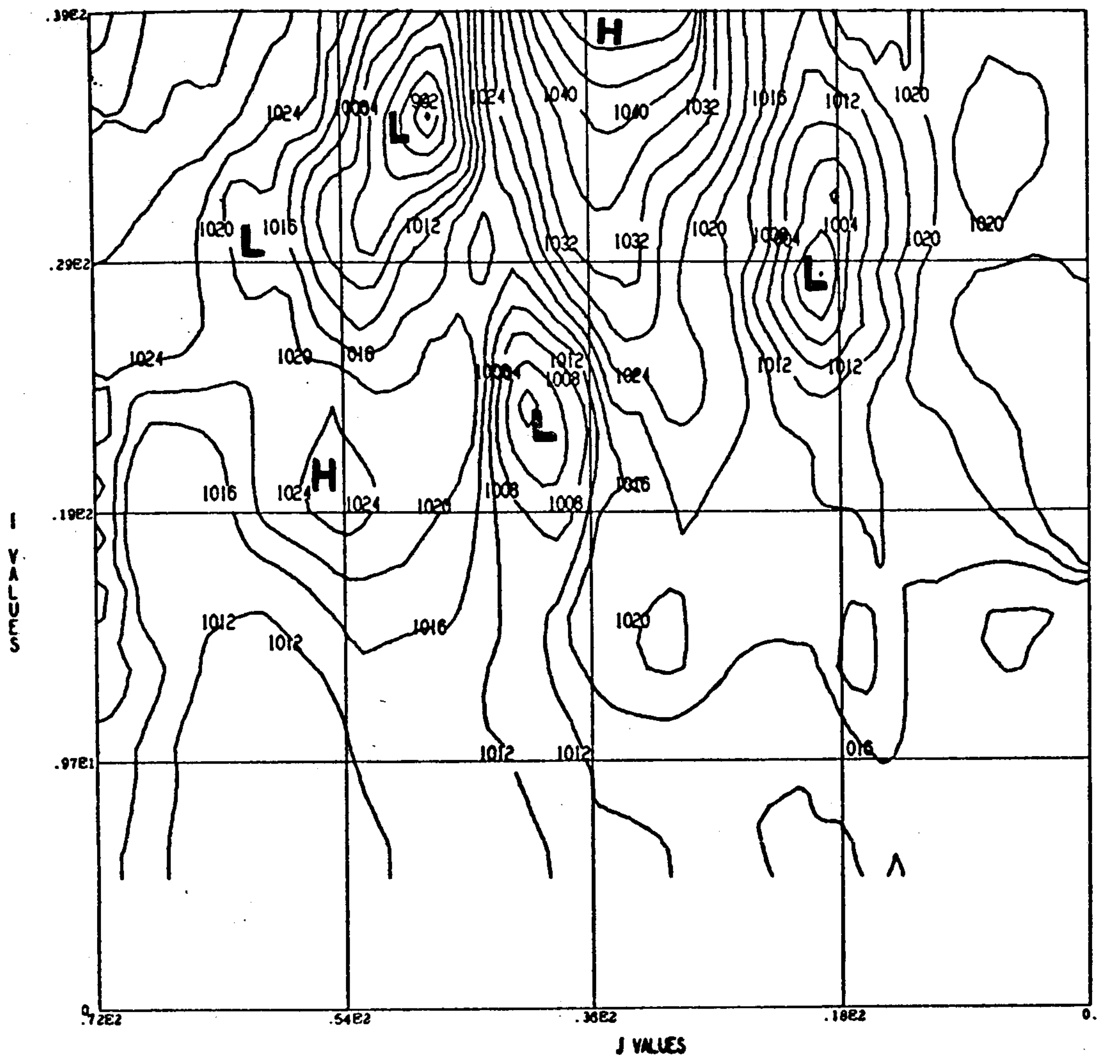


Fig. 3. Analysis of the surface pressure field over the North Pacific Ocean for December 1, 1966 based on 5% of the available conventional ship reports and simulated space data.

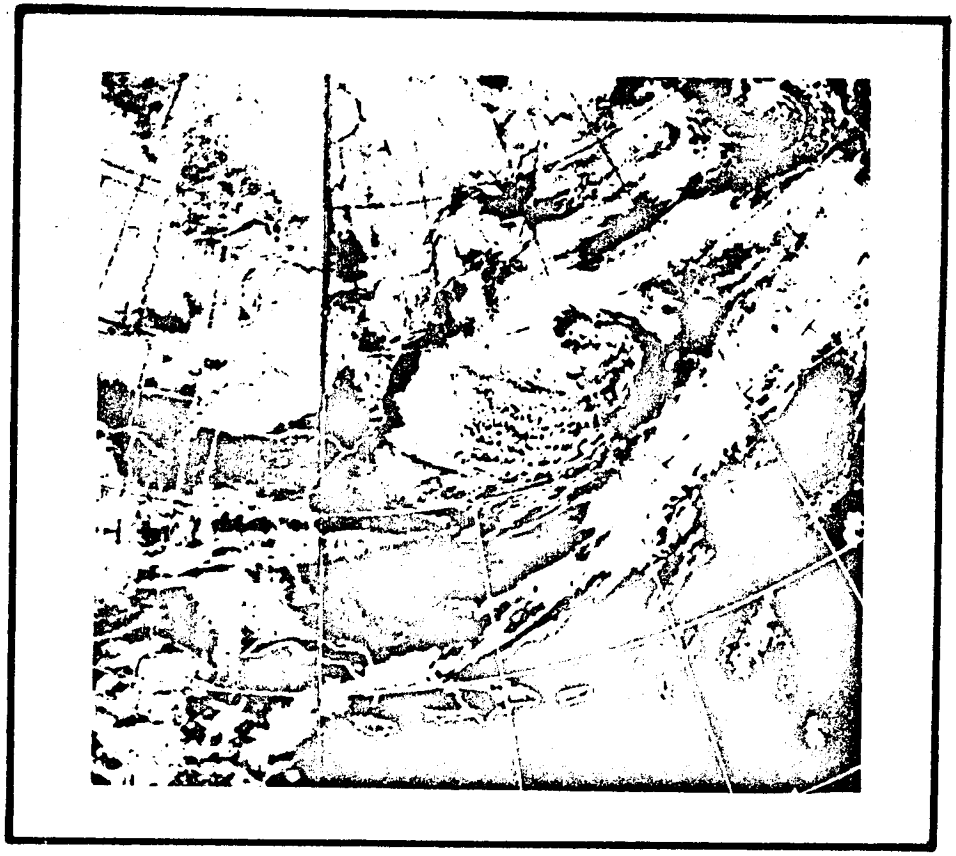
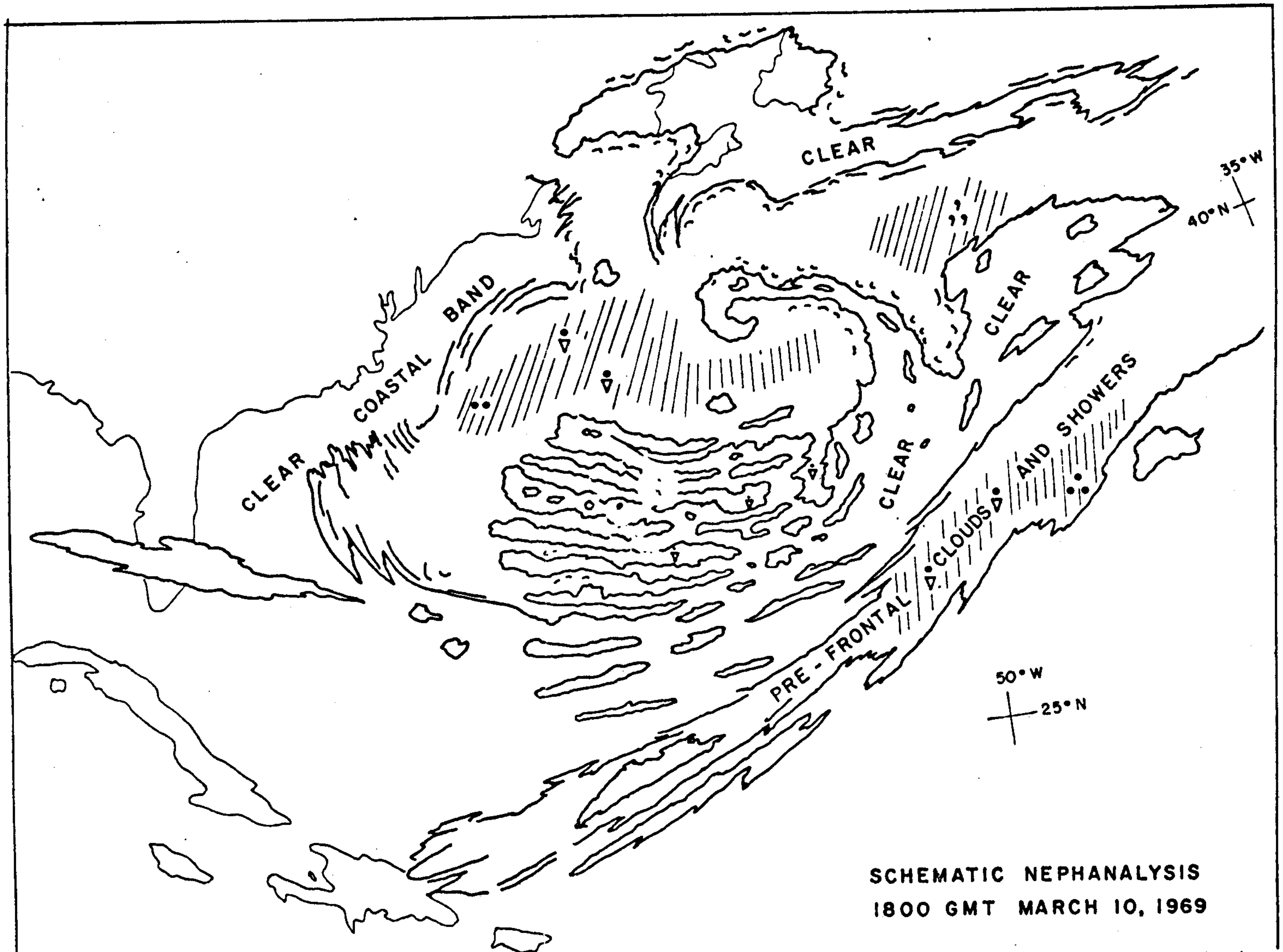
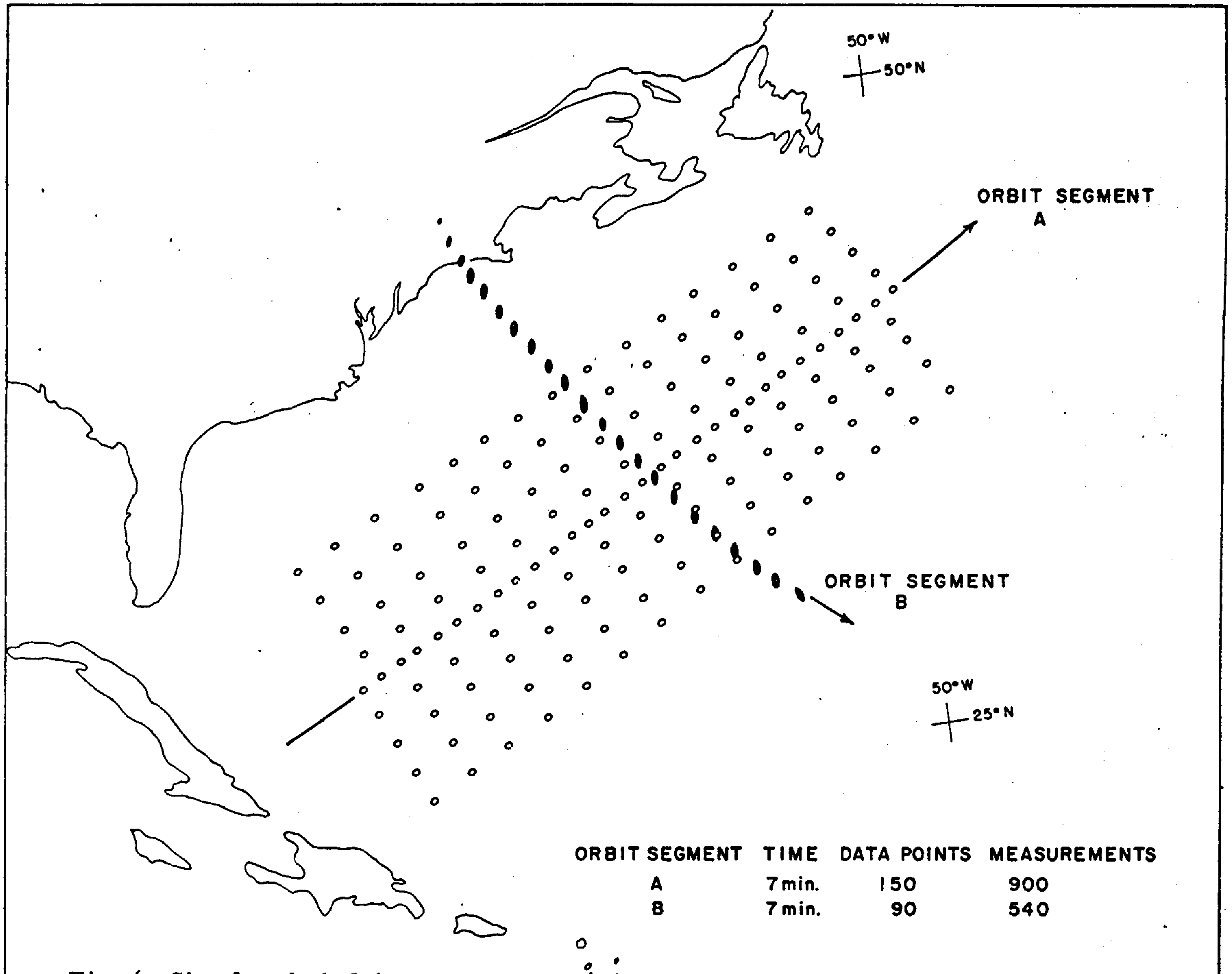


FIG. 4. ESSA SPACECRAFT CLOUD MOSAIC FOR MARCH 10, 1969 1800 GMT.



SCHEMATIC NEPHANALYSIS
1800 GMT MARCH 10, 1969

Fig. 5. Schematic Nephanalysis of Fig. 4.



ORBIT SEGMENT	TIME	DATA POINTS	MEASUREMENTS
A	7 min.	150	900
B	7 min.	90	540

Fig. 6. Simulated Skylab passes for March, 1969, 1800 GMT.

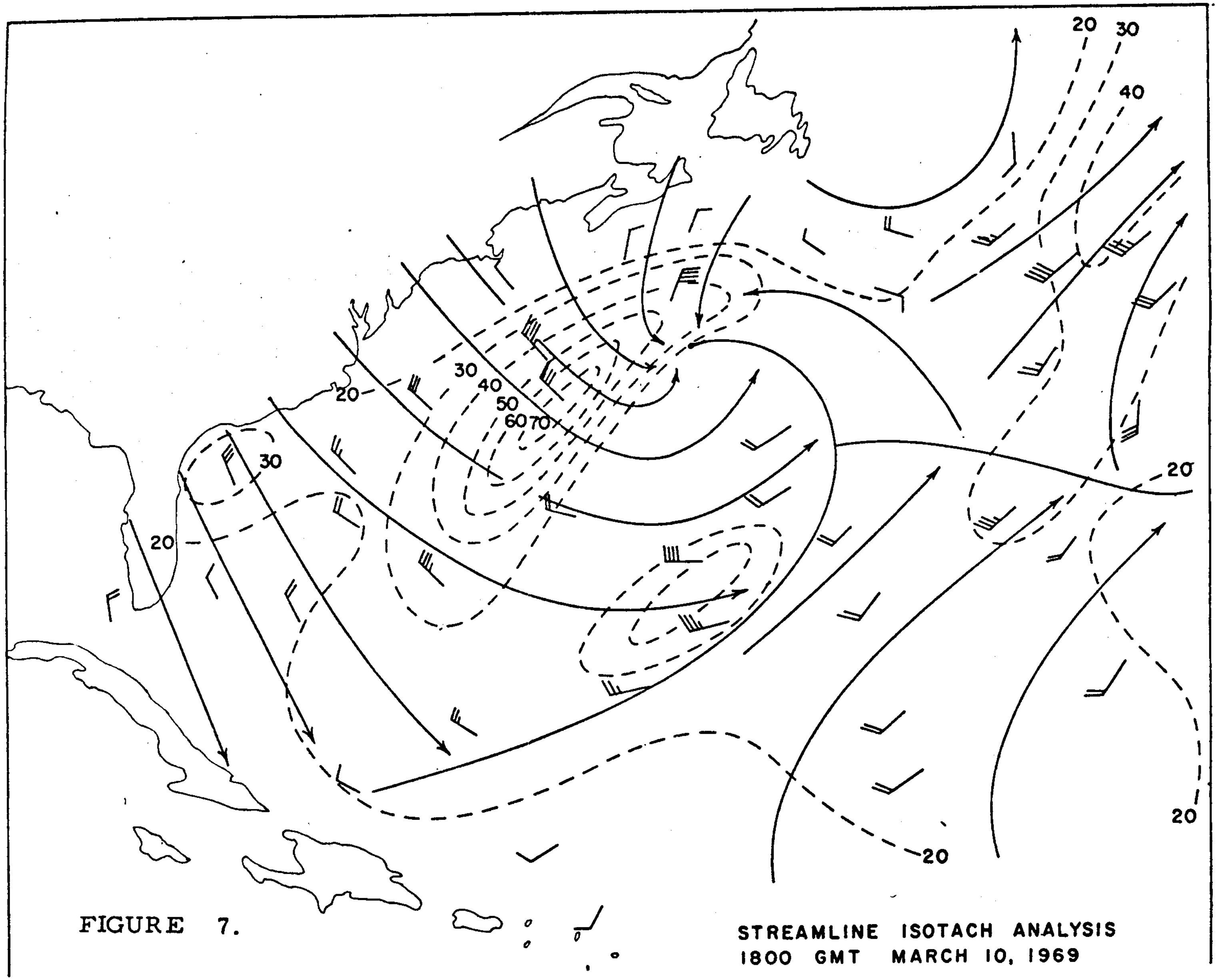
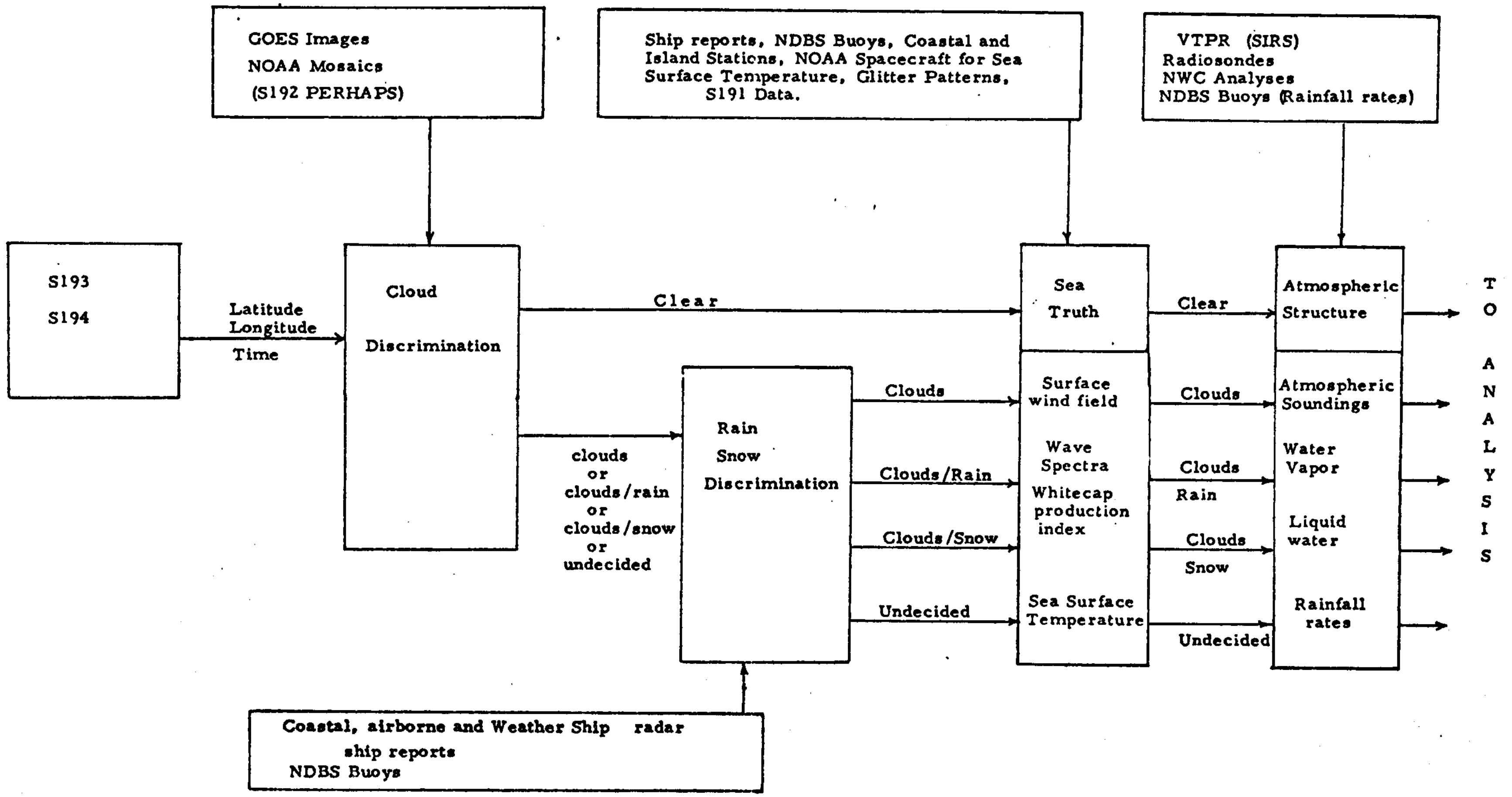


FIGURE 7.

STREAMLINE ISOTACH ANALYSIS
1800 GMT MARCH 10, 1969

FIGURE 8. Schematic flow chart for processing S193 data.



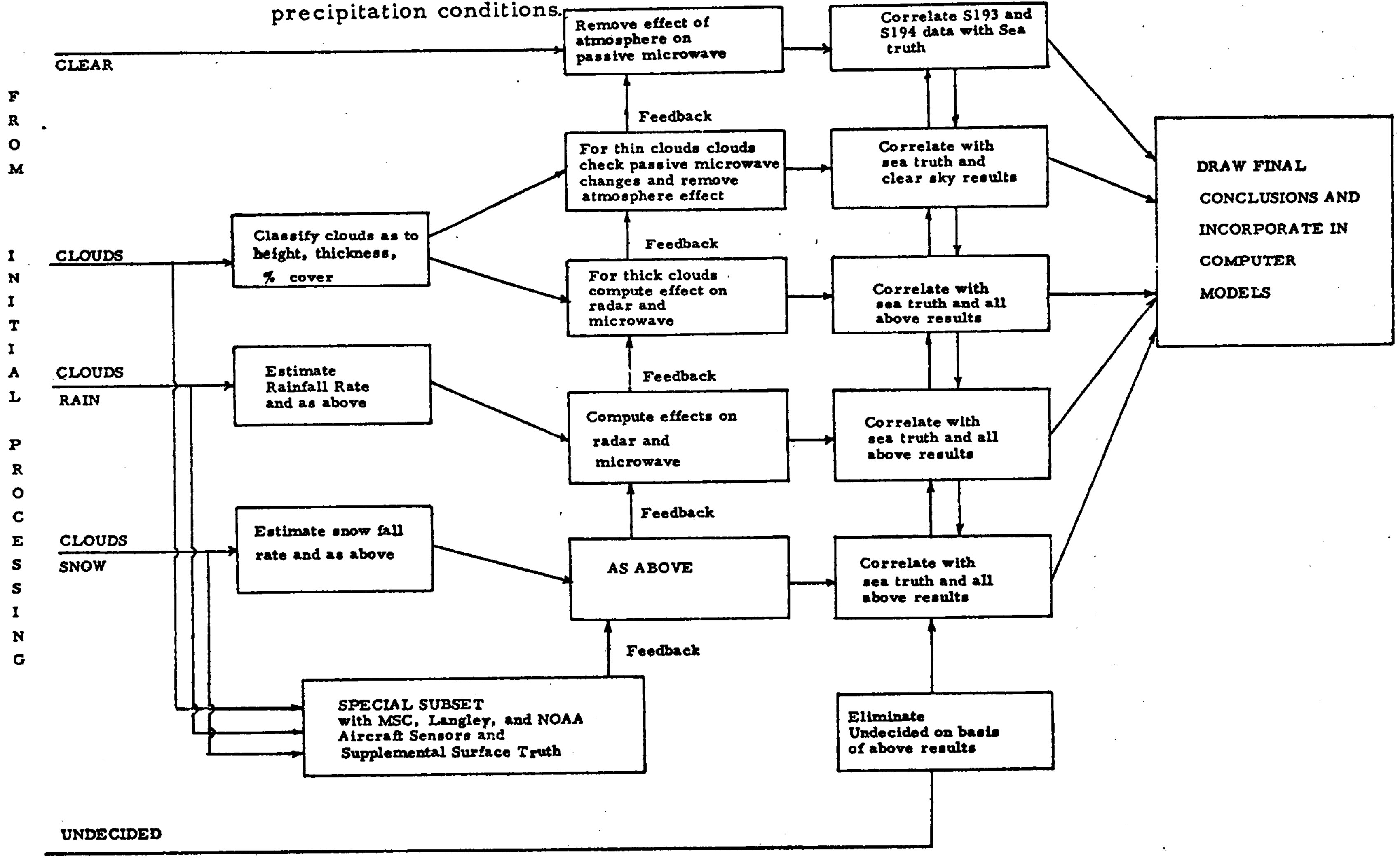


Fig. 9. Schematic flow chart for stratifying S193 data according to cloud and precipitation conditions.