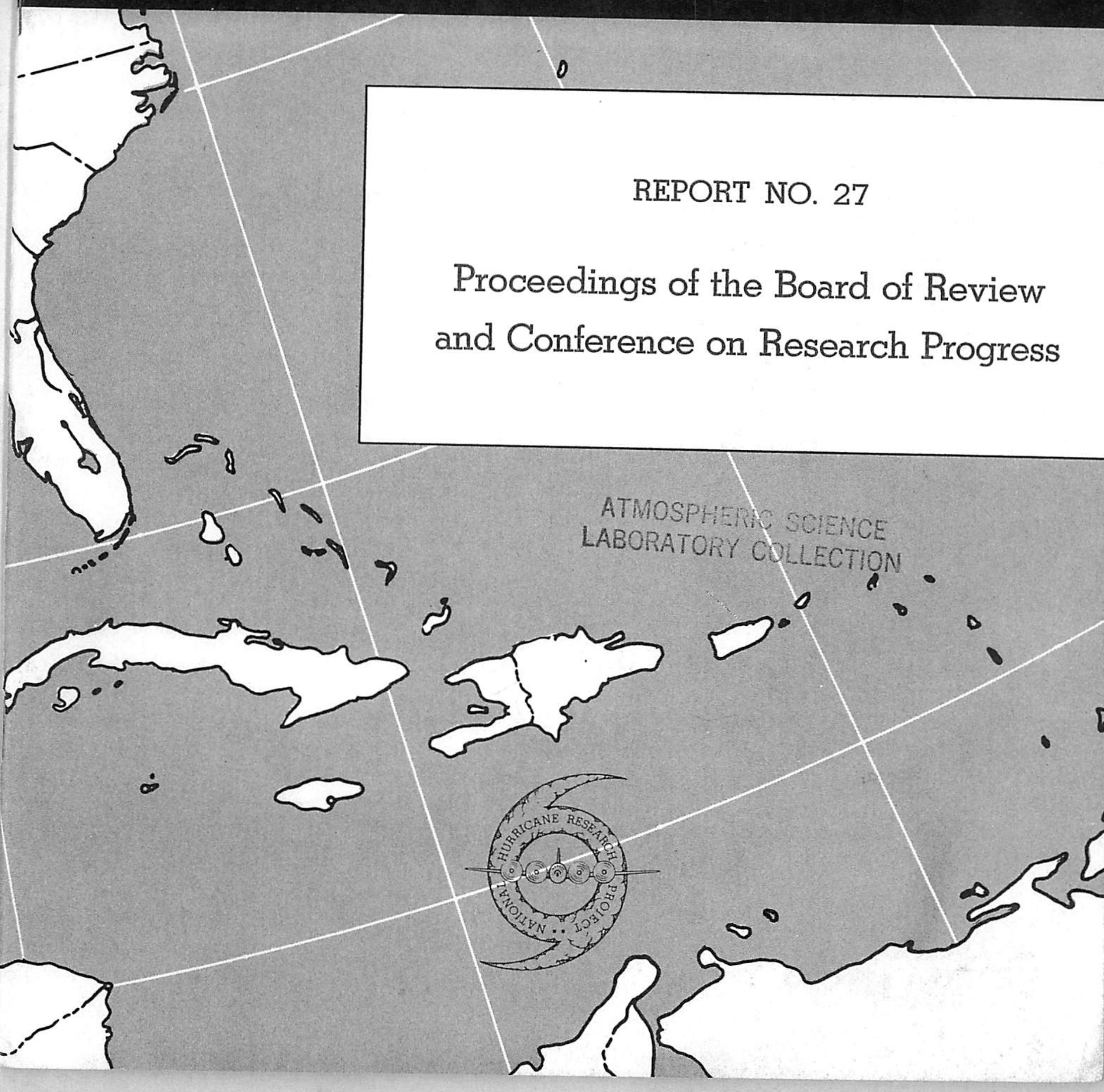
ONAL HURRICANE RESEARCH PROJECT



REPORT NO. 27

Proceedings of the Board of Review and Conference on Research Progress

U. S. DEPARTMENT OF COMMERCE
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NATIONAL HURRICANE RESEARCH PROJECT

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Proceedings of the Board of Review and Conference on Research Progress

Final Session of Technical Conference on Hurricanes*
Sponsored by American Meteorological Society
Miami Beach, Fla., November 22, 1958

*This conference will be designated as the First Technical Conference on Hurricanes if the AMS Council approves the recommendation of the Committee on Severe Storms.

Washington, D. C.
March 1959

NATIONAL HURRICANE RESEARCH PROJECT REPORTS

Reports by Weather Bureau units, contractors, and cooperators working on the hurricane problem are pre-printed in this series to facilitate immediate distribution of the information among the workers and other interested units. As this limited reproduction and distribution in this form do not constitute formal scientific publication, reference to a paper in the series should identify it as a pre-printed report.

No. 1. Objectives and basic design of the NHRP. March 1956.
No. 2. Numerical weather prediction of hurricane motion. July 1956.
Supplement: Error analysis of prognostic 500-mb. maps made for numerical weather prediction of hurricane motion. March 1957.
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No. 7. An index of tide gages and tide gage records for the Atlantic and Gulf coasts of the United States. May 1957.
No. 8. Part I. Hurricanes and the sea surface temperature field.
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No. 9. Seasonal variations in the frequency of North Atlantic tropical cyclones related to the general circulation. July 1957.
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No. 11. Instrumentation of National Hurricane Research Project aircraft. August. 1957.
No. 12. Studies of hurricane spiral bands as observed on radar. September 1957.
No. 13. Mean soundings for the hurricane eye. September 1957.
No. 14. On the maximum intensity of hurricanes. December 1957.
No. 15. The three-dimensional wind structure around a tropical cyclone. January 1958.
No. 16. Modification of hurricanes through cloud seeding. May 1958.
No. 17. Analysis of tropical storm Frieda, 1957. A preliminary report. June 1958.
No. 18. The use of mean layer winds as a hurricane steering mechanism. June 1958.
No. 19. Further examination of the balance of angular momentum in the mature hurricane. July 1958
No. 20. On the energetics of the mature hurricane and other rotating wind systems. July 1958.
No. 21. Formation of tropical storms related to anomalies of the long-period mean circulation. September 1958.
No. 22. On production of kinetic energy from condensation heating. October 1958.
No. 23. Hurricane Audrey storm tide. October 1958.
No. 24. Details of circulation in the high energy core of hurricane Carrie. November 1958.
No. 25. Distribution of surface friction in hurricanes. November 1958.
No. 26. A note on the origin of hurricane radar spiral bands and the echoes which form them. February 1959.

INTRODUCTION

The need for a series of technical conferences to discuss progress of research on hurricanes was recognized by the AMS Committee on Severe Storms in 1956. In 1957 plans were laid for the meetings which culminated at Miami Beach in November 1958.

The objectives of the conference were to review and evaluate progress of research on the hurricane problem in recent years, and to point the course toward which future research can be most profitably directed. Participation was specifically invited of all agencies and institutions known to be engaged in or directly concerned with research on tropical cyclones, and invitations were also sent to weather services of other countries.

A Board of Review, comprised of senior members of the profession who have gained universal recognition of their competence in their meteorological specialty or in meteorology as a domain, was chosen well in advance. Before coming to the meetings all Board members were furnished expanded abstracts of the papers to be presented and were asked in turn to preside over particular sessions of the conference.* At the final session these mature scientists were then asked: to sum up the salient points of the particular sessions, to place new findings in reasonable perspective, to evaluate the progress of work so far undertaken, and to point out the most promising approaches for research in the immediate future. The following is a nearly verbatim account of the proceedings of the Board of Review, which has been subjected to minor but necessary editing.

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*Authors and titles of papers presented in the sessions of the conference are listed in the Appendix. The program and Abstracts of these papers were published in the Bulletin of the American Meteorological Society, vol. 39, No. 9, Sept. 1958, pp. 496-501. Expanded abstracts of the papers were reproduced by the American Meteorological Society in Proceedings of the Technical Conference on Hurricanes, Miami Beach, Fla., Nov. 19-22, 1958.

PROCEEDINGS

The Board of Review and Conference on Research Progress was convened by Professor Erik Palmén at approximately 2:15 p.m., EST, November 22, 1958. Constitution of the Board was:

CHAIRMAN: Professor Erik Palmén, Institute of Meteorology, University of Helsinki, Helsinki, Finland

MEMBERS*: Professor Jule G. Charney, Massachusetts Institute of Technology, Cambridge, Mass.
Dr. Thomas F. Malone, The Travelers Insurance Companies, Hartford, Conn.
Mr. Jerome Namias, U. S. Weather Bureau, Washington, D. C.
Professor Sverre Petterssen, The University of Chicago, Chicago, Ill.
Professor Herbert Riehl, The University of Chicago, Chicago, Ill.

Prof. Palmén: We are now confronted with the challenging task of summing up the contributions made in individual sessions, pointing out their significance, and assessing the problems facing us in the future. I am going to call upon the chairmen of the individual sessions to outline the findings of their particular meetings and to highlight the problems thus brought into evidence. Their comments, however, need not necessarily be confined to those specific sessions at which they presided. I will call on Mr. Namias first with reference to Session A - Climatology and Synoptic Climatic Studies.

Mr. Namias: First let me say that this symposium has been most enlightening. One cannot help being impressed with the vast amount of basic data which have been gathered as well as with the painstaking analysis which has been made of this material. My remarks are designed to suggest how our efforts might be directed to get still further ahead with understanding and prediction of hurricanes.

As for the papers on Climatology, mainly synoptic climatology, these have furnished background material which can be exploited by further specialization. In a large sense, the function of hurricane climatology is to provide background for forecasting and research activities. There is ample opportunity for Climatology to contribute significant information on aspects of formation as well as motion of tropical storms. For example, a few years ago, Professor Palmén produced a fundamental paper on hurricanes by combining climatological, synoptic, and dynamic considerations. This type of work might serve as a model for climatological-synoptic studies.

On another front, one can only deplore the seemingly worldwide tendency of official climatological organizations to continue to amass statistics almost entirely on a calendar basis; that is, mainly in units of calendar months, even though nature frequently disregards the month as a meteorologically significant unit. With respect to hurricanes we might profitably explore the possibilities of singularities as Captain Church did in his paper

*Prof. Horace H. Byers, University of Chicago; Dr. George P. Cressman, U.S. Weather Bureau; and Mr. J. J. George, Eastern Air Lines of the original board were unable to attend.

when he showed a strong coherence of hurricane tracks during individual successive 10-day periods in August over the typhoon area of the Western North Pacific.

It is also quite apparent that the researcher dealing with the climatology of hurricanes must consult more frequently with forecasters and research workers so that his selections of indices and his stratifications become more physically meaningful. Currently the forecaster is being overwhelmed with masses of climatological data which, while suitable for some planning purposes, are quite unwieldy for direct application, and there appears to be considerable room for more efficient forms of representation.

Dr. Arakawa indicated that hurricane paths may be influenced by coastal effects, particularly in the Japanese and Hatteras areas. Further studies along these lines would certainly be valuable both to the forecaster and in the quest for understanding the dynamics of hurricanes.

The paper by Veigas and Miller, statistically relating hurricane motion to sea level pressure and preceding storm motion, is encouraging in that it points a way toward improved prediction. Even though the statistical technique employed neglects upper level phenomena, it is remarkable to note the extent of the predictability achieved. Here again, it is possible that the bias shown in these methods might be explained with the help of long range concepts. That is, the residuals resulting from imperfect statistical forecasts might well be associated with properties of time-averaged circulations.

Finally, with regard to my own paper, I might explain that long range forecasters usually develop a somewhat different philosophy regarding synoptic evolutions than do short range prognosticators. The long ranger's predominant philosophy is deterministic in nature. He regards the phenomenon of recurrence of circulation types as a primary instigator of weather. For this reason he believes that medium range prediction of hurricanes of the order of three to seven days is bound to particular forms of the general circulation recurring within a given month or season, and that improved methods of medium range prognosis are therefore within grasp. It is not inconceivable that even short range hurricane forecasting could improve materially through the objective use of extended and long range concepts.

Prof. Palmen: Are there any comments by members of the Board?

[There were no comments. There were, however, comments from the audience.]

Prof. Palmén: Are there any comments by members of the Board?

If there are not going to be any remarks I feel we will have to proceed.

At the second session at which I presided, and which was held simultaneously with the first session, we had a discussion of storm surges. I would like to make some brief remarks. Mr. Lee Harris presented very impressive maps of the flooding during hurricane Audrey, and he pointed out the importance to the warning system of having more tidal gages just at the coastline.

Two other papers concerned computations of the slope of water surface, under different conditions, and concerned basins of different shapes with variable or constant depth. A fourth paper concerned maximum height of swell or waves connected with hurricanes during the 1957 season.

My impression was that most of these papers dealt essentially with the emphasis on engineering or the applied approach, which is quite natural because the problem of warning and prediction is extremely complicated, but nevertheless most essential in the saving of lives. One has to remember that the height of a storm surge depends not only on the wind stress, the fetch of the wind, and the pressure deviation from normal; it also depends on the varying depth of the sea, upon the coastal configurations, and on all kinds of minor complications. However, I feel perhaps that the time is now coming when it will be also appropriate to look at the problem from a little more physical and theoretical viewpoint. I know that Mr. Lee Harris has begun such an approach, but is it not remarkable that oceanographers and meteorologists are still not quite in agreement on such an important parameter as the wind stress, and its dependence upon wind velocity and the stability of the lowest layers of the atmosphere? The wind stress also depends upon the roughness of the sea and consequently upon the different types of waves. It is of the utmost importance that we investigate the stress parameter more thoroughly, and I also feel it would be very interesting to make a theoretical investigation of the storm surge in the open ocean.

The problem is obviously a very complicated one. In the case of a hurricane we have a strong field of divergence in the wind stress following the movement of the hurricane itself. This naturally results in variations in the level of the sea which are very difficult to study in detail. We have seen in some maps that hurricanes have in their wake a region of somewhat colder water, and I feel that this is a clue concerning the divergence of the wind stress connected with the moving hurricanes. Where such divergence is marked there should be some kind of upwelling of deeper water resulting in a temperature decrease. This is one phase of the problem I feel should be considered in further investigation. Further, it is obvious that since storm surges can cause very serious catastrophes, one has to look upon the problem practically and it is only natural to first attempt a realistic forecast arrived at, if it is necessary, by empirical means in order to avoid such catastrophes. The question of theoretical approach to forecast and prediction of storm surge should naturally be next considered. It almost goes without saying that the forecasting of storm surges is a more complicated field than that of meteorological prediction itself, because we must first have a good weather prediction in order to make a reasonable prediction of water level changes. In addition to which we must take into cognizance all kinds of local effects which are exceedingly difficult to treat theoretically, so one must be realistic in his expectations of the results to be realized from such approach.

Since I have not worked in this field for a long time, I would like very much to hear the opinions of some of those persons who presented papers, and I take this opportunity to ask Mr. Harris whether he has anything to add.

Mr. Harris (U. S. Weather Bureau): I would like to say first that we have been trying to follow an approach which Dr. Malone described on Thursday night. We are trying first to describe, then to explain, and finally to predict. My purpose was to give a description to show what it is that needs explanation. In our office we are also working on the other two phases: Bob Reid and his group have made a number of analyses of the effect of the storm in the open ocean, including the divergence of the wind stress. We have also begun to approach the prediction problem from an empirical point of view, since we have not yet reached the point where a theoretical approach seems indicated. We believe it first necessary to get a good physical description.

Prof. Palmén: Now I had no intention of criticizing this particular approach, namely, to start with the description of the phenomena - and we certainly obtained a very good description of the storm surge in the case of hurricane Audrey. However, I felt it opportune to speak a little about what could be done in the future concerning the interaction between the wind and the water surface. Are there any other comments?

Mr. Bretschneider (U. S. Corps of Engineers): One thing I would like to emphasize very much is the importance of obtaining accurate information on hurricanes. We are also interested particularly in the question of maximum probable or maximum possible hurricane; that is, what is the ultimate hurricane that might actually strike a given coast? In some cases it becomes almost an academic question since it is not economically possible nor practical to protect by levies, dams, seawalls, etc., any particular coast against the maximum possible storm. However, we can afford to avoid augmenting and exploiting death traps where protection is a minimum.

Prof. Palmén: If I may add, I remember one of these papers mentioned that it would be necessary to obtain local topographical maps of the sea floor and coastal regions and to distribute them to the people living in the regions where storm surges can occur. They would then be aware of the danger and know what action they should take.

Mr. Harris: While this part might well be held until further discussion of the forecast problem, it may be appropriate to mention here that such maps as these are not expensive on the scale at which they are projected. The major point is that it is frequently necessary to interpret a forecast, if you want the public to act upon it in the proper way. The meteorologist is the best and most competent man we have to interpret the forecast, but he doesn't know all of the necessary fundamental facts - some of these would be provided by such maps. These, I maintain, should be made available at least to every forecaster concerned.

Prof. Palmén: [The third session dealt with the Radar Analysis of Severe Storms, and Mr Vaughn Rockney was called on to give a summation.]

Mr. Rockney (U. S. Weather Bureau): I should like first to agree with Professor Riehl's remarks of this morning, wherein he said that at the moment radar is a superb observational tool. It tells us with a great deal of precision where a hurricane is and where it has been, but so far there has been very little work done that would directly apply radar to the forecast problem.

We have heard from Mr. Gentry a suggestion as to how the resultant wind at a particular level, as measured by aircraft, may be a predictor of the hurricane movement. We should investigate whether the resultant movement of echoes at a particular level at various distances from the storm center might also be a predictor of the hurricane's movement. I would like to suggest to people who work with the hurricane now, that they should take into account what the radar shows so that the models they study are at least realistic in terms of the available observations. I personally feel very strongly that anyone who comes up with a model without taking into account the dynamic and thermodynamic properties as they are revealed by radar, is ignoring available essential facts.

The papers presented from the University of Miami by Professors Hiser and Senn seem to me to contribute a great deal to the understanding of storm structure. The spiral overlays as developed for practical observational use in locating the eye of the hurricane when it is off the scope show great promise. There is also another part of the radar display which should be investigated and was mentioned this morning; that is, the location of the main precipitation area with respect to the eye of the storm, and whether such areas are predictive of a trend in the track. In summary, we are so far only scratching the surface in using radar as a forecast tool. It is at present essentially an observational instrument.

Prof. Palmén: Are there any comments?

Prof. Hiser (University of Miami): There is one other comment I would like to make. Since Dr. Atlas is not here I am sure he would like someone to mention the idea of using Doppler Radar as a measure of wind within the hurricane structure. There was a paper given on the use of this Doppler radar in measuring winds in a tornado and a number of us in the weather radar business feel that this is certainly a fine tool and that pulse Doppler radar would make a fine instrument for measuring winds within a hurricane.

Prof. Palmén: Can you tell us exactly how you measure these winds?

Prof. Hiser: You get the frequency shift due to differential motion of different masses of the rain droplets in different areas of the storm. A Doppler radar simply measures frequency shifts due to these differential motions. This same principle is applied in aircraft detection. The speed of motion determined with Doppler radar can be used in the measurement of wind shear and wind speed within the precipitation structure of the storm.

Mr. Simpson (U. S. Weather Bureau): There are a number of reasons why the suggestions of Prof. Hiser and Mr. Rockney concerning the development and further application of pulse Doppler radar to the hurricane tracking and analysis problem are important. One of the earlier findings of NHRP revealed that the maximum wind in the hurricane tends to be conserved with height to a much greater degree than was previously recognized. Moreover, the Project has found that the most conservative hurricane center which can be identified is the geometric center of the ring of maximum winds. Hence, a pulse Doppler radar might not only be able to identify a hurricane center more accurately, but also see it from greater distances. Moreover, such a radar could provide useful information concerning both the present intensity and the future movement of the hurricane, as brought out by Mr. Gentry's paper.

Another area of radar meteorology which needs development is that of the RHI presentation. There are all too few observations of precipitation patterns in a hurricane which permit analysis on any volumetric or three-dimensional basis.

Finally, it would seem apropos to emphasize here the need for radar meteorologists and dynamicists to work more closely together, first as a means of understanding better the role which is played by the spiral rainband in the energy processes of the storm, and secondly, as a means of interpreting more intelligently the kinematic behavior of rainbands. A good beginning along these lines has been made through the work of Dr. Kessler and Dr. Tepper, reported during these sessions.

Prof. Palmén: Thank you. Personally I must confess that I was a little confused when I listened to part of that session. Nevertheless I felt it was very important for studying the structure of storms. However, people seem to be of varying opinions concerning the meaning of radar bands. It seems obvious that specialists in the two fields - radar and dynamic meteorology - should really try to come together and solve some of these problems jointly.

Mr. Showalter (U. S. Weather Bureau): Just one point in connection with the radar. I do not believe anyone this afternoon has mentioned the fact that you can easily identify the melting level via the bright band on radar, which should give us very valuable information on the effects of the thermal distribution within the rain pattern around the hurricane circulation.

Prof. Palmén: This matter of the bright band was brought up at the session, however I did not feel myself enough of a specialist to comment upon it.

Since Dr. Malone has to leave shortly I will call for his summarization next.

Dr. Malone: As one who has not been intimately associated with hurricane work I must say that this has been an exciting, stimulating, and heartening conference. Our session was devoted to Observing and Tracking Facilities and to Communication and the Dissemination of Warnings. Tremendous progress has been made during the past three years on the matter of probing hurricanes. It is quite clear that this work is in very good hands. The use of aircraft as a platform for instrumentation has been developed to a very high degree. The sophistication of the techniques and the equipment is nothing short of fantastic. It is especially reassuring to note that measurements are reproducible with different pieces of equipment. This is gratifying from the standpoint of the instrumentation developed and it also indicates a measure of stability in the parameters being measured. Moreover, there is obviously considerable feedback from the measurement program into the scientific research. This was apparent at other sessions where the scientific analysis and interpretation was possible only because of the kind of data that these instrumented aircraft made possible.

It seems likely that the pioneering work now going on in the use of aircraft as a probe in hurricanes might well have application in the detailed analysis of extratropical cyclones. The continuous records that could be made available would do much to augment our knowledge in middle latitudes by filling in the gaps that exist between radiosonde stations.

One of the most impressive things that was discussed is that it is now possible to set up a reconnaissance designed to answer specific scientific problems and not merely to collect more data.

In looking forward to the future we would be very remiss if we didn't take proper cognizance of the momentum which has been developed in the National Hurricane Research Project. People are working on these problems and new equipment is being developed every season. It is essential for the scientific progress in tropical meteorology that nothing should happen to disrupt the continuity of this program. I feel that this Board should go on record as supporting the kind of proper program which has been carried on here. Once stopped, it would be difficult to set it in motion again. The people who have had the foresight to envision the instrumentation that is now available and to keep their nerve when everything didn't go as it should, are to be congratulated because the information thus being garnered is going to provide the basis for extending our knowledge.

I would like to comment particularly on the excellent paper on hurricane warnings by Mr. Harry B. Williams. As meteorologists we have a professional responsibility in the area of communications and semantics. Mr. Williams pointed out, quite correctly I thought, that much remains to be done to improve individual decision making based on information provided by the hurricane forecaster. In general meteorologists have not paid enough attention to the work now underway on decision making in business and economics. Much has been accomplished during the past few years on this score, but much remains yet to be done, and we are sometimes prone to overlook the fact that this is a legitimate field of research.

Prof. Palmén: I really didn't know, but it surprised me that there has not been any systematic use of aircraft in studying extratropical cyclones except for special flights in and across jet streams.

Dr. Malone: What I had in mind here was the type of question which Dick Reed out in Washington and Fred Sanders and many others have asked about the detailed structure of extratropical cyclones. I feel quite confident that such knowledge is practically within our grasp with this AMQ-15 program which has been described here, but if it is possible to do half of the things suggested, it will be possible to answer many of these questions on the fine scale structure of extratropical cyclones, and will undoubtedly provide a very valuable tool which we should not overlook.

Prof. Palmén: Are there comments?

Mr. Lee Harris: I would like to say a little bit more about the warning problem which Mr. Williams has talked about. As was shown in Mr. Gentry's paper, the accuracy of the forecast we are currently getting is such that there are a lot of protective measures a person is not justified in taking on any 24-to 36-hour forecasts we can make today. I am sure that will still be the situation ten years from now. I think we can justifiably spend some effort in determining how well we can solve specific problems. If it turns out that we cannot make a 36-hour forecast with sufficient accuracy to justify any action, then it doesn't matter how badly someone needs it, there is little point in making it. I believe that it is obvious that if the forecast is not useful in decision making or in taking protective action then research must be diverted to the problem, and continued to the point where the forecast is of economic utility. We must spend effort on evaluation for that purpose. There are some purposes for which a 6-hour forecast is highly useful, but others for which a 48-hour forecast is not sufficient. We should work at both ends in determining what is needed for certain protective action and what is possible on reasonable expenditure and effort. I believe this is in line with the paper of Mr. Williams and with Dr. Malone's remarks.

Mr. Namias: I didn't realize that this question was going to arise in this session, but I think it is just as well that it has - the problem, let's say, of usefulness of prediction. As I think it over, I believe it is quite possible that perhaps some work ought to be carried on by the Hurricane Project in assaying that very problem; that is, the usefulness of the different kinds of prediction at all time scales and various problems associated with them. As I pointed out, we are all aware of one type of alert that might be made of a long period nature, and there is a question of whether it does have any usefulness. There is, however, also a question of the moral responsibility of scientists that enters here. If we have some knowledge of something that has a possibility of occurrence, is the public entitled to that knowledge? These questions, both moral, and the problem of ethical usage, the practical usefulness, and the threshold which must be achieved before a thing becomes useful, might very well be a rather important phase of investigation by the Hurricane Project.

Prof. Palmén: We must proceed to a question which may lead to a fairly general discussion. I propose that we combine the session about Circulation and Energy Processes in the Storm Core and Energy Cycles and Models. I would like to ask Prof. Petterssen to review his part first. This should not prevent him from discussing anything in the other sessions also.

Prof. Petterssen: I would like to point out that I am here not as a member of the Review Board, but as a replacement for Professor Byers who, unfortunately, could not attend. Since the change was made only a few days ago, I have not had time to become acquainted with the operations and results of the Hurricane Project to the extent that I would have liked. However, I wish to say that what I have seen and heard at the Conference has impressed me greatly. More specifically, my impressions may be summarized as follows:

1. It seems to me that the Hurricane Project has been very successful in planning its observational program. Much of this planning was done before the research commenced, and I think the results have shown that the planning has been excellent. The Project has been very successful in collecting and analyzing a large amount of valuable data, as a result of which we have gained a considerable amount of new knowledge concerning the structure, circulation,

and energy sources of the hurricanes. It has pleased me immensely to see that it has already become possible to provide numbers which describe the internal consistency of mature hurricanes. This, indeed, is a major achievement. On the other hand, it is well that we remind ourselves that we have gained little knowledge about the genesis of hurricanes. This, I think, will remain a major problem until the Project has provided data on a larger number of cases.

2. The data presented at this Conference seemed to indicate that we have hurricanes of various types, and that we are not yet in a position to provide a family of hurricane models or a satisfactory classification of hurricanes. I think, therefore, that the Project must plan for a continuation of data collection and analyses over a period of several years.

3. From the papers presented at the symposium of which I was chairman, it seems that there has been a considerable amount of progress along theoretical lines. It is most desirable that we try to progress beyond the descriptive stage and arrive at some understanding of the basic processes. I think, therefore, that it would be wise for the Project to place increased emphasis on the theoretical work. On the whole, the scientific component of the Project should be broadened as much as at all possible, for only in this way can we make full use of all the valuable data which the Project will provide.

4. Eventually the Hurricane Project might wish to collect data and investigate the devastating hurricanes which redevelop in relatively high latitudes.

Finally, I would like to suggest that the hurricanes should be studied not only as isolated phenomena, but also as disturbances superimposed upon larger systems. I was very pleased to see that the climatology of hurricanes has received considerable attention. A logical next step will be to investigate the occurrence and development of hurricanes in relation to the large-scale synoptic situations. The placing of the hurricane in its larger environment, its relation to the monsoon system, and the interactions between the tropical belt and the mid-latitude westerlies, would seem to be an important extension of the empirical as well as the theoretical work. Thank you, Mr. Chairman.

Prof. Palmén: I would like to add just this remark. Wouldn't it be practical to have the aircraft, during the winter season when there are no hurricanes, used in the study of extratropical cyclones?

Mr. Simpson: Yes. It is the present planning of the Weather Bureau in extending the work that has been done on hurricanes, to use the facilities which we are now having developed in just such a manner. In view of the fact that they cannot be leased and equipped economically on a short seasonal basis, the proposal is that they will be used continually for hurricane work in the hurricane season, and to launch into some tornado investigations during the tornado season, and for such use as was suggested by Professor Petterssen to explore extratropical cyclones and special other problems, that we have not been able to study in this fashion heretofore.

Prof. Palmén: I would now like to call on Professor Charney to discuss the sessions in general, and, if possible, to comment specifically on the session on Energy Cycles and Models.

Prof. Charney: Before making any specific comments I should like to express a feeling that I have, and which is perhaps shared by most of you here. It is a feeling of excitement, generated largely by the progress evidenced in this conference, that we are on the verge of solving a problem that has baffled humanity for millenia. Just as in the last 20 years or so great progress has been made in our understanding of such atmospheric phenomena as extratropical cyclogenesis and the general circulation, so I feel that, certainly within our lifetime and probably within a very few years, a continuation of the kind of work that has been reported here will lead to an explanation of the causes of hurricanes. We are in a very privileged position; we posses the scientific technology and are rapidly assembling the theoretical knowledge that will be required to unravel the hurricane problem. My impression is based on the rapidly increasing quantitative character of the modern hurricane studies. As Kelvin remarked: until one can measure a thing, until one can express it in quantitative form, one really does not understand it, or at best one's understanding is of a very meager kind. To me the outstanding attribute of the present conference on the hurricane problem lies in the removal of the problem from the realm of speculation and qualitative description into the realm of quantitative analysis. Indeed, as Dr. Malone has pointed out, the tools that have been developed for probing the hurricane have been so successful that they might very well be applied to the measurement of extratropical systems. Of course, new measurements create new problems, and in a certain whimsical sense one may know a phenomenon too well. The more closely one examines the atmosphere, the more fine-grained structure it is found to have, and the more new problems arise. I was therefore interested in the statement of Mr. Rockney to the effect that one will never understand the hurricane until one understands the nature of the rain bands as revealed by radar. I hope that this is not true. If it is, I may have to revise my prediction of an early solution to the hurricane problem. I do not mean to say that the energy released in the rain bands is not important, but only that one may hope for understanding of the hurricane as a whole before the details of its fine-grained convective structure are completely understood.

From these general remarks I should like now to come to some specific thoughts on the papers concerned with circulation and energy processes. Let me begin with the excellent study of the energy problem presented by Professor Palmén. Here is a beautiful example of a quantitative analysis which, to a considerable extent, has pinned down for us the constraints within which our understanding of the physical processes in hurricanes has to proceed. We now have numbers for the rate of energy dissipation in a hurricane; we know where the dissipation occurs; we know what the energy source is - it is condensation - and we know where the energy is released. More work should be done in this direction. For example, Professors Palmén and Riehl have demonstrated that the energy released by condensation is some 50 times the energy needed for driving the storm. This gives an efficiency of the order of two percent. Similar efficiencies have been measured for the circulation of the atmosphere as a whole. Thus the rate at which solar radiation is absorbed by the atmosphere is some 50 times the rate of frictional dissipation. The reason for this is that most of the solar energy does not become available for conversion into mechanical work. Lorenz, following

Margules, has discussed the so-called "available potential energy" in the atmosphere and it is this quantity with which we are really concerned. It occurs to me that a study of the generation of available energy might reveal a great deal more about the nature of the hurricane. The increase of available potential energy is a quantity which is roughly proportional to the integral of the heat added times the temperature at which the heat is added divided by the static stability. Hence, for given horizontal temperatures and heat sources, the energy release increases with the approach to indifferent stability. In this connection I should like to harken back to a remark made by Professor Riehl to the effect that large conditional instability in the atmosphere is not favorable for the occurrence of hurricanes. Professor Riehl suggested that with too unstable a lapse rate the energy would be used up in the form of cumulus convection. But cumulus activity is, after all, the way in which energy is supplied to the storm. The more cumulus activity you get in an organized way, the more energy you get, so that it may be better to think in terms of the release of available potential energy.

Another comment is related to a topic that Professor Palmén mentioned toward the end of his talk. He stated that the hurricane cannot be regarded as a closed system, that exchange of momentum and energy with the environment is important. One can say a great deal about this problem. There is no question but that Palmén, Riehl, and Pfeffer have shown that there is considerable angular momentum exchange with the environment and some energy exchange. The direct energy exchange (excluding latent heat) does not seem to be essential, but the hurricane constantly loses angular momentum to the earth by friction; hence, if the hurricane is to maintain itself in a quasi-steady state, this momentum must be taken from its environment. I think, however, that the way in which this comes about depends more upon the nature of the environment and the motion of the hurricane as a whole than upon any intrinsic process in the hurricane itself. In other words, I believe that the momentum exchange is not an essential process, but that the hurricane adapts itself to whatever large-scale eddies happen to be present at its periphery. However, this is only an opinion, and I would certainly like to see more work on the problem.

Two other papers that impressed me very much were those presented by Dr. Malkus on her work in collaboration with Professor Riehl. Here is a good illustration of the kind of accurate quantitative analysis that is made possible by modern observations. One of her conclusions was that in order to account for the pressure deepening near the center of the storm one needs surface air of greater heat content than the surface air outside the storm. I was quite convinced by her argument that the extra energy is picked up by evaporation and by transfer of sensible heat from the ocean surface. But again, when one thinks in terms of complete dynamical models, the question arises: are these essential mechanisms? What would happen if one were to spread some kind of heat or evaporation inhibiting film on the surface of the ocean? Would this prevent hurricanes from forming? I do not know the answer to this question, but my feeling is that hurricanes would still form and that they would still be deep, because of the existence of other dynamical requirements for low pressure at the center of the storm. Thus, if the heat sources and sinks that produce vertical circulation in the storm are given, then the tendency towards conservation of angular momentum in a converging ring of air and the necessity for maintaining near-gradient balance will in themselves require low pressures. Moreover, the frictional loss of angular momentum at the ground and the necessity for maintaining near-hydrostatic balance will require a warm core in the storm. The actual hurricane acquires its low pressures, as Dr. Malkus has demonstrated, by absorbing heat from the ocean. If it didn't, one could imagine other mechanisms; for example, moist-adiabatic ascent outside a diverging eye wall followed by dry-adiabatic descent within the eye could conceivably produce enough heating of the upper air to account for the low pressures.

The concept of ventilation and cyclogenesis as introduced by Riehl and Simpson belongs, in my mind, to the same category as that of excess heat content and low pressures. Ventilation has been shown to exist, but its role as a brake on cyclogenesis is still not clear to me. A person who had never seen a hurricane before but had been told that it was a large-scale convective system would, it seems to me, predict some form of ventilation. One cannot expect all of the air that enters the region of active precipitation to come only from the surface. Some of it must come from midtroposphere, where its wet-bulb potential temperature is lower than that of the surface air. Why the normal tropical air at midtroposphere is wet-bulb potentially colder than it is lower down or higher up is a question which is bound up with the problem of the entire general circulation of the Tropics. However, I should like to pose the simpler question: is ventilation a necessary concomitant of hurricanes, or is it a quasi-independent factor of such a nature that it can prevent the formation of hurricanes? I think that this question, or the one raised by Dr. Malkus, will be answered only by studying complete dynamical models. If, for example, it were found that hurricanes could be generated without local transfer of heat from the boundary surface or with ventilation, we would know that the presence of the former factor or absence of the latter are not necessary attributes of hurricanes.

Professor Riehl's and Mr. Ramage's remarks on hurricane formation were very interesting to me. Both speakers emphasized the necessity of interaction between a pre-existing surface depression and an upper system for hurricane formation. Precisely what kinds of interactions lead to intensification and what kinds do not are not yet completely understood. Here is obviously an important clue to hurricane formation and a field for fruitful synoptic and dynamic investigation.

Lack of time prevents me from commenting as much as I would wish on Professor Fultz's paper on model experiments. Work of this nature is of utmost importance and should be encouraged in every way. The obvious advantage of the model experiment is that one has complete control over the external conditions. If it should prove possible to produce hurricane-like circulations, one would know exactly what the relevant factors were. The method of numerical computation with hypothetical dynamical models possesses similar advantages. Just as a great deal of light has been shed on other meteorological problems by numerical experiments, it seems to me that results of equal value could be obtained by numerical studies of hypothetical models of hurricanes and tropical depressions.

Prof. Palmén: Now before the meeting I really promised Professor Riehl not to ask him to say anything on this subject; however, I feel that he probably has some appropriate comments which should be entered at this point.

Prof. Riehl: Well, in a meeting of this kind there is some subject or other of importance which doesn't quite get the attention which it deserves, and in this case I think the subject which was cheated a little is the mark of distinction which appears to exist, not just between the tropical depression and the hurricane, but between what is known as the tropical storm and the hurricane.

Now the tropical storm is a disturbance which has been observed to exist as a steady state phenomenon, and in at least several instances, as has been demonstrated by the Hurricane Project data, is a warm core type of disturbance and appears to have all of the characteristics of the hurricane, except it lacks the wind concentration at low altitudes. There is any amount of release of latent heat in these, and a tremendous amount of generation of kinetic energy, just as much apparently as in the hurricane. But, the winds do not become concentrated near the center, the maximum wind remains at a radius of 150 miles, or thereabouts, with a strength of something about 40 to 50, maybe 55 knots with a solid rotation profile existing in the interior inside of the maximum wind radius. This I find to be a really most extraordinary phenomenon. One can see by studying, for instance, the net mass inflow into the tropical storm, that when one goes some 4 or 5 degrees from the center, and then takes mass inflow, that this is not very different in vertical distribution from the hurricane. The level of nondivergence is very high in both of these systems, 400 to 500 mb., and the mass inflow through a deep layer of the troposphere is very appreciable. One finally comes in the end to a conclusion which has been emphasized by Dr. LaSeur, as much as anyone, that in most of these hurricanes there is an outer envelope of wind which is greatly similar to the distribution of winds in the tropical storm; for instance, even in such cases as Ella, where the eye was destroyed over the Cuban mountains, the tropical storm structure is retained and that which really distinguishes the tropical storm from the hurricane is the existence of the eye in itself. Dr. LaSeur has mentioned to me cases where he has been able to find, from detailed flight data, two rings of maximum wind in passing in cross-section flight through the disturbance; namely - one the outer ring, the tropical storm maximum, then some decrease, and finally, a secondary inner rise to a maximum near the eye.

Consequently, when Dr. Charney says that there would be hurricanes with or without the extra pick-up of heat from the ocean, I think that another question might be asked - namely, why are there any hurricanes at all? A tropical storm is the principal vehicle and the predominant vehicle for the release of the major convective activity which is pent up in a certain way. The principal thing to be determined is the reason for the existence of the tropical storm rather than the hurricane (the thing that one would ordinarily think of as natural, so to speak, would be the hurricane, but it isn't). The formation of an eye within a general envelope is, I would say, an event which would be questionable without special surface conditions. Since the energy problem has come up I would like to emphasize this point - that one really has a double problem here: namely, there is a general tropical storm as one thing, and then the extra but much rarer formation of an eye with particularly strong winds within it as a secondary phenomenon.

Prof. Palmén: Now although time is running short, I would still like to ask the one who, in my opinion, presented the most interesting papers here, namely, Dr. Malkus, to say a few words about the subject, and to inquire whether she has anything to add to what she has already presented.

Dr. Malkus (Woods Hole Oceanographic Institution): I have only one thing to add in connection with the interesting question which Dr. Charney has asked. I am not interested in hurricanes only for the practical reason that they exist, but also as a prototype of thermal circulations in a rotating system. The question of how we get such a circulation is a very interesting one. I was glad to note Dr.Fultz's paper which showed that we can simulate some of the essential features of the hurricanes, by somewhat different techniques in the laboratory models. Just what comprises the essential ingredients is unknown as yet, I am sure; however, apparently for a real hurricane this extra heat source is of significant importance. It is certainly not beyond controversy that this kind of circulation necessarily requires it, but from what Dr. Fultz said it looks to me as if we do have to get a special arrangement of heat input. But this is certainly only one aspect of the problem. It would be interesting to look not only at real hurricanes, but at all types of thermal circulations of which the hurricane might be one kind of solution.

Prof. Palmén: Are there any other comments? Dr. Charney has already taken up the question of the formation of cyclones which rather belongs to the next question to be discussed here, but I feel that something should be said in addition, because it is a problem on which no real progress has yet been made. I would like to inquire whether Professor Riehl would like to add anything on this subject in view of the fact that for the forecasting problem this is an extremely important point.

Prof. Riehl: I would say that it may be entirely possible, at least in areas of observation, to arrive at schemes for predicting the formation of hurricanes without actually understanding the precise physical process. This is entirely within the realm of possibilities. Also, very little work has been done on this subject, partly because of the fact that formation, in particular, occurs in the areas without observations of the routine type, and that the dispatching of special aircraft for investigation into these very formative stages, has proven, at least so far, a particularly difficult task because there are always several of these potential areas on the map, and one never knows which one should be explored. Certainly one of the most important factors I think everybody recognizes, in the future of this program, is the systematic investigation of these early stages. Nevertheless, it may very well be possible that one can arrive at a forecasting scheme in regions with observations without actually understanding the process itself.

Prof. Palmén: As I remember in Professor Charney's very interesting paper, he also touched on, to some extent, this same question, in spite of which he never discussed the type of disturbance that really should start the process of formation, not necessarily tropical hurricanes, but tropical cyclones. However, perhaps Professor Charney would like to add something on this subject.

Prof. Charney: In my paper I tried to show that the formation of a tropical cyclone is due to a kind of secondary conditional instability whereby the large-scale circulation and the small-scale convective motions support each other: the cumulus cell by supplying the heat energy for driving the large-scale circulation, and the large-scale circulation by producing the low-level convergence for maintaining the cumulus convection. When the necessary mean conditions for instability exist one does not have to look for the initial disturbances, since small disturbances are always present. To pursue these studies further what is lacking is a knowledge of the dynamics of the moist-adiabatic process. I thoroughly agree with Dr. Malkus that it is necessary to study general convective motions of rotating systems, and would add that these studies should include cases where the heat of condensation plays an important role. It is impossible any longer to avoid the study of the influence of condensation on small and large-scale convective processes. The dynamics of the hurricane, of its eye structure, of the rain bands, and the cumulus convection are all directly bound up with the precipitation process. In particular, with regard to the rain bands, it seems to me that the approach that has been followed by Dr. Tepper might well be combined with a study of the dynamics of the moist-adiabatic process to yield a more realistic model of the rain bands. Other mechanisms for rain band formation and maintenance are also possible. There is a near one-to-one correspondence between the rain bands and local maxima in the tangential velocity field. One can imagine a number of possible mechanisms for associating enhanced convective activity with these velocity variations. A small increase in kinetic energy along a streamline near the ground would give rise to an increased frictional convergence on the cyclonic-shear side of the wind maximum, which would increase cumulonimbus activity, and this enhanced activity might in turn react on the wind profile in such a way as to produce a self-amplifying mechanism. There is also the possibility that the rain bands are associated with inertial instability since small regions of inertial stability can be observed on the anticyclonic-shear side of the velocity maxima. Here again is a possibility for a self-amplifying interaction between the convective activity and the unbalanced centrifugal forces occurring in the presence of dynamic instability. I mention these possibilities only to emphasize that condensation must be considered as an active ingredient in the dynamical explanation of all hurricane phenomena, whether large or small. I do not think that we shall be able to account for the peculiar properties of hurricanes without taking this ingredient into account. Professor Fultz's work may be an illustration of this point. He was apparently unable to obtain concentrated symmetric vortices without using temperature sources so intense that they produced large horizontal temperature gradients, baroclinic instability, and a breakdown of symmetry. With condensation, however, one may obtain the necessary energy release with much smaller horizontal temperature gradients. One should, of course, add that the kind of experiment that Fultz is performing is of fundamental importance for elucidating phenomena taking place in thermally driven vortices, whether they bear a close resemblance to the hurricane or not.

<u>Prof. Palmén</u>: Should we not now proceed to the last session, because I feel we have to finish this meeting in a reasonable amount of time? I will ask Professor Riehl to comment about the session on Prediction of Hurricane Movement.

<u>Prof. Riehl</u>: Several of the papers dealing with movement have already been mentioned, for instance, the work by Mr. Gentry on verification, and Kasahara's numerical work. I think we must realize when it comes to the prediction of movement in contrast with some of the other topics we have

just heard about, that they are very brave souls who undertake this kind of investigation. They, in a manner of speaking, jump directly into the middle of the firing line more so than anyone else working in the general subject.

One of the main things that came out of this morning's session and was emphasized by Mr. Gentry was this: that while most calculations that one now makes are for a 24-hour interval from the time the data are taken, the interval is too short for practically all warning purposes. It is true that sometimes a 6 or 12 hour warning can do a great deal of good; but for the most part, for warning of coastal populations and the making of preparations against inundations, and things of this type, it is necessary to have a warning some 36 hours from map time, which is about 30 hours from the time the forecast is issued. I realize, of course, that for certain special purposes much longer warnings than this are necessary, to close down and protect factories and military installations, etc. The 72-hour forecast verifications shown by Mr. Hubert, indicate that they were too far off to warrant much discussion. Essentially then, the aim, at least for the present, should be a 36-hour prediction from map time, and possibly a discussion of what types of calculations should be undertaken.

Mr. Gentry's method involving computations made directly from aircraft data is a very appealing one. They were, however, only for 24 hours, but could perhaps be extended to 36 hours. It is possible that this time may be too long and the general circulation features alter too greatly to make this extension practicable. Nevertheless, it is a very appealing scheme whereby one simply lets an airplane run around the storm, takes certain observations, and directly obtains the forecast. This, of course, was also the essence of the little scheme which I once worked up with several collaborators at the Project AROWA of the U. S. Navy. Now with faster jet planes coming into operation the very exciting possibility arises that this can be done at high altitudes, where there are not enough rawin stations available at any time to get satisfactory statistical samples, or from balloon soundings. It would have to be purely an aircraft program. The few complete B-47 flights that already exist with the National Hurricane Research Project should be thoroughly investigated for this purpose. Again the sample is too small, but one of the approaches that should be encouraged for the future is: to deploy the high altitude aircraft which NHRP and perhaps others hope to have in the future years in such a manner that one can see whether a useful scheme for 36-hour movement can be directly taken and calculated during the aircraft flights in a short period of time.

Other methods of computations depend on charts with calculation schemes of one sort or another. Here one has to distinguish between charts which have a certain amount of obervational stability in them and charts which do not. The question of observational stability arises of course from the fact that the hurricane exists over water where there are very few weather observation stations. This situation is much worse in the Atlantic than in the Pacific. There have been two types of charts mentioned which seem to have the required stability; one is the 5-day mean charts. It should be a matter of great interest to develop these computations further and to investigate the possibilities of using these 5-day charts to serve for 48- to 72-hour forecasts. The other stable chart is the surface map where, of course, there are the most data. This has recently been exploited by the group of Tom Malone in Hartford, using this statistical forecast system, which has shown what, to many people, has been a surprising amount of success. This also has been a 24-hour scheme which, however, one should certainly try to extend to 36 hours or more, and also to include parameters not currently used in this statistical treatment. There are some fairly clear ways to proceed here - one of the most attractive things is that the surface map, with relatively copious data, can probably be processed entirely numerically without any hand analysis. This means that in the end we would not encounter the situation where one forecast center gets one answer and another forecast center gets something else. Consequently, for computational purposes these two stable charts seem to offer interesting possibilities.

Everything else that has been done has been based on grid systems - either at 700, 500 or 300 mb. - and out over the oceans where the configurations of the chart depend on the experience and notions of the analyst. Different forecast centers do not come up with the same solution, and computations made from such charts also come out differently. One never knows then in such cases whether the errors one gets are inherent in the models or the computational schemes that have been devised, or whether they are purely in the data. This applies to the statistical objective systems, such as that of Miller in the Miami forecast office here, and the system that I have produced, as well as the numerical prognoses made on the electronic computer. Dr. Kasahara has shown a very interesting set of verifications, and another interesting set was shown for the Pacific this morning by Dr. Arakawa and Dr. Gambo. One could see from these verifications that the hope in numerical prediction of hurricanes, which existed 4 years ago at the Tokyo conference on hurricanes, has not been fully realized. Some people came away from that conference thinking that there was only one thing to do and everything else could be discontinued. Subsequent history has not borne that out, and again this need not necessarily be the fault of the models that have been employed for this purpose, but simply because the computations have been carried out over wide oceanic stretches where there are no observations.

So there is no answer at all at the present time as to whether the errors in these forecasts come from such things as the barotropic model employed, the subtraction of the storm center from the general circulation, or simply from data deficiencies. It seems unlikely we will come to any solution in this matter until such time as the data situation is clarified. But there is not in existence at the moment a single occasion in which there have been sufficient data available from the oceans to draw 500 or 700-mb. maps in a unique way so as to give an answer to this question, even in the case of a single cyclone. It almost goes without saying then that if significant improvement in working with grids is to be achieved, then there must be more observations. These observations, as nearly as one can see at the moment, have to be airplane observations. There does not seem to be anything else in the picture - perhaps constant pressure balloons at high altitudes, but certainly aircraft in the middle troposphere.

For a number of years I have advocated, as have a lot of other people, especially those working in numerical prediction (for instance, Dr. Platzman), that every effort be made to have the reconnaissance deployed in such manner that the blank sectors of the map are filled in with respect to existing hurricanes. The history of reconnaissance, if you review it in recent years, has been that there has been no change in the practice, namely, for the aircraft to fly directly to the center, to stay there, to take dropsondes, and put other devices in the center, and to relay these data to the forecaster. The winds and temperatures collected on the way to and from the storm area are also made available in due course. In addition to this, of course, when a storm is now located near land there are radar fixes, and a great deal of operational effort has been put into these aircraft fixes and land based radar fixes. Unfortunately, a considerable amount of misinformation now exists in the public mind where there is a widespread impression that in order to predict the hurricane it is necessary to have a radar trained on the storm and to have an airplane in it, and with these the forecast is given. Well, this as you all know is a completely wrong impression.

This kind of data, at least as far as we have it at the moment, is of little value in predicting except to fix the place from which the prediction starts. It can also tell you something about where the storm has been, but in a broader sense it will not help the prediction problem in itself, so that we need a complete change of heart in the reconnaissance program if any real use is to come of the physical and empirical models of hurricane prediction by means of open grids over the oceans. Even if the perfect model were developed it would be of absolutely no use if the data requisite for carrying out the model were not available. However, it is in my mind very questionable at the moment what is to be gained through continuing investigations of the type that utilize open grids as long as one has to practically imagine the data (over the oceans) that form the basis for these predictions. It is rather obvious that improvements can be made on computations utilizing the data, but there seems little use, for instance, in trying a second approximation that would be valid at 36 hours unless some improvement in the basic data is going to be possible. When one then looks at the prediction models and realizes that there are certain second derivatives involved in making these predictions, you can see that it is astounding indeed that results have been obtained as good as those of Dr. Kasahara and Dr. Arakawa.

In conclusion, my impression is this for recommendations for the future - in the first place there seems to be not very much use in trying out 24-hour forecasts since they are not for a long enough period to achieve a great deal of good. One must then aim to develop a 36- to 48-hour forecast technique, preferably the requisite data should be supplied directly from aircraft, possibly being exploited on the aircraft itself. The calculations should be based on charts that are observationally stable, mainly, the 5-day mean and the surface chart. Also, perhaps one should, at least for coastal warning purposes, abandon the notion that he should find a forecast scheme which is valid in all latitudes and all longitudes and is universally applicable. This of course would be the nicest thing if it were possible. But more realistically we must develop prediction schemes for 36 to 48 hours in advance in specific areas where regularly functioning upper air stations are available and can be relied upon. These station data can be utilized to develop regressions and other means to arrive at the requisite forecast.

This is approximately a summary of my conclusions from this morning's session, and from following the evolution of efforts in forecasting the motion of hurricanes over the past few years.

Prof. Palmén: I am afraid that it has become too late now to have a break in the program, and unless there are some very urgent questions I feel that we should go over to the last point on today's program, namely, the question of the future plans of the Hurricane Project. We have heard here all kinds of recommendations, all kinds of possible investigations. Many of these could naturally depend on the possibility of continuing the work on a large scale. We will ask if Mr. Simpson could give us a brief review of the plans for the near future: how the Project will be organized, what kind of observations made, etc.

Mr. Simpson: In discussing plans for the future I believe it would be useful to review quite briefly some of the plans, objectives, and circumstances which have guided the National Hurricane Research Project's efforts to this juncture. From the first it was planned that the Project's tasks comprise a two-pronged attack on the hurricane problem. One of these would attempt to organize information already available by statistical, dynamic-climatological, or other means which might permit early improvement in techniques of hurricane prediction. The other would comprise basic research on the physics of hurricane circulations and energy release mechanisms. In the latter, the work has proceeded along the lines outlined so well by Dr. Malone, in which the first effort has been to describe more completely the hurricane machine with a view to obtaining more complete understanding, and ultimately the development of more effective means of prediction. To describe what goes on in the core of the hurricane has required very specialized equipment, aircraft with top calibre probes and recorder systems. To supplement the aircraft program a network of rawinsonde stations was established in the West Indies.

The aircraft investigations were planned with the view that a real understanding of hurricane circulations would require the collection of data which would enable volumetric analyses to be done. First estimates of the minimal requirements of aircraft operations to accomplish these objectives called for at least three good data samples from storms in incipient or early stages of development, three samples from storms in a mature stage, and three from storms in the late or decaying stages, a good sample being defined as one in which all three research aircraft enter the storm area essentially simultaneously, and sweep out information from five or six levels. As a basis for planning it was estimated at the outset that this would require a minimum of two years to accomplish, assuming maximum utilization of aircraft and a goodly number of hurricanes to work on.

As you have seen, the first two years provided far too little opportunity to obtain the needed samples, and the program was extended an additional year. At the present time, the NHRP has completed six of the nine three-plane missions specified as a minimum to accomplish the objectives. In this time a total of nearly 100 sorties have been flown into hurricanes in all stages of development. While it now would appear that the original objectives may be approximately two-thirds complete, it is clear from the papers reported here that, while shedding light on many aspects of the storm structure and its energy problems, new and important questions have been raised which demand answers. It is doubtful whether these can all be satisfactorily handled even with another year or two of aircraft operation. For this reason the Weather Bureau for nearly a year now has been moving ahead with plans for an additional three years of aircraft operation, an operation which will not only continue to probe hurricanes as before, but which will extend the use of aircraft facilities to the investigation of tornadoes, equatorial jetstreams, and extratropical cyclones. In the future, the aircraft will be devoted to research on a year-round basis and will be operated under a civilian contract rather than through direct support of the Department of Defense.

Before proceeding, it is very appropriate here that recognition now be given to the splendid support which the NHRP has received from the Department of Defense and other public organizations in carrying out the aircraft operation to date. The Air Weather Service has provided two B-50's and a B-47, together with the flight personnel and ground support crews to keep these planes in the air, and has flown them entirely at the expense of the U. S. Air Force. In addition, the U. S. Navy has cooperated with the Project by obtaining special research data, and monitoring some of the cloud physics research flights from their WV-3 hurricane hunter planes. This type of participation by government agencies and research institutions has characterized the hurricane research effort and made it truly a National Project.

In addition to the above mentioned participation by the military services, NHRP has enjoyed the collaboration of a number of universities and research institutions from the very first stages of planning. Florida State University has provided an active contingent, Dr. LaSeur serving as Associate Director of the Project. Dr. Riehl has been an active consultant from the very first, and during the last two seasons has flown a number of hurricane missions and assisted directly with various research studies. Dr. Malkus has made many trips to Palm Beach and worked actively from Woods Hole on various facets of the research program. Dr. Braham and his colleagues from the University of Chicago have planned and directed the cloud physics work of the Project.

Because of other requirements the military services will not be able to participate directly in the aircraft program in the future, and for this reason the research planes will be operated by a civilian contractor. Otherwise however, collaboration and operational procedures will continue without material change.

The two B-50 aircraft will be replaced by two DC-6B's and the B-47 will be replaced by a B-57. These three new aircraft will be capable of staging from many airfields which previously could not be used by the research planes. For this and other reasons the new aircraft should be more effective for flights into incipient hurricanes located remotely, and into tornadoes. Gradually the hurricane investigations will be terminated as enough data are acquired to assemble the galaxy of models suggested by Professor Petterssen. However, the aircraft will continue to probe tornadoes, jetstreams, and extratropical cyclones.

Next April, the NHRP Research Operations Base at West Palm Beach will be closed and the staff will be combined with that of the Weather Bureau Office, Miami. The new organization will be known as the National Hurricane Center and will be headed by Mr. Gordon Dunn. It will have as its objective the melding of operations and research, much along the lines employed so successfully by Mr. Namias and the Extended Forecast Section. Gradually the government research effort at the Center will become devoted almost entirely to applied research. However, it is the plan that there be a continuing program of collaboration with universities in which scientists engaged primarily in basic research will be encouraged to continue work on meteorology of the Tropics from the National Hurricane Center. This type of collaboration should provide a means of stimulating those engaged primarily in applied research and, at the same time, could provide some useful feedback into the fundamental research effort.

Prof. Palmén: At the beginning of this meeting I had at first thought that we should make some quite specific recommendations; however, so many recommendations came up here already during the discussion and the time is late. I appeal that if no one here has any objection we now could consider this meeting to be at an end. Before that, however, I would like to say that I, at least, personally feel great confidence in the future of this Project. I have read the publications published by the Project and I have listened to the papers presented at this meeting and listened to the discussions. I had several times the impression that the time has come when we can look forward to a great future in this field. By comparing this meeting with some other meetings on tropical hurricanes, I feel that this has really provided much more new information and some very promising theories. With this I would like to declare the meeting closed.

APPENDIX

Papers Presented at

TECHNICAL CONFERENCE ON HURRICANES

Miami Beach, Fla., Nov. 19-22, 1958

CLIMATOLOGY AND SYNOPTO-CLIMATIC STUDIES

A climatological index for North Atlantic tropical storm activity. William H. Haggard and George Cry, U. S. Weather Bureau, Washington, D. C.

Forms of the general circulation as related to hurricane genesis and path. Jeromė Namias, U. S. Weather Bureau, Washington, D. C.

On probabilistic methods of hurricane prediction. Keith W. Veigas and Robert G. Miller, The Travelers Research Center, Hartford, Conn.

The tracks of North Pacific typhoons from 1947 through 1956. James F. Church, Headquarters Air Weather Service, Scott AFB, Ill.

Coast effect on hurricane movement. H. Arakawa, Meteorological Research Institute, Japanese Meteorological Agency, Tokyo.

STORM SUGES

Hurricane Audrey storm tide. D. Lee Harris, U. S. Weather Bureau, Washington, D. C.

Progress report on storm induced high water levels. Basil Wilson, R. O. Reid, and Kinjiro Kajiura, A. and M. College of Texas, College Station, Texas.

Engineering aspects of hurricane surge. Charles L. Bretschneider, Beach Erosion Board, U. S. Army Corps of Engineers, Washington, D. C.

Storm data obtained in the Gulf of Mexico during the hurricane season 1957. Lars Skjelbreia, California Research Corporation, La Habra, Calif.

RADAR ANALYSIS OF SEVERE STORMS
(Joint Session)

Low-powered radar observations of tornadoes. G. E. Stout, Illinois State Water Survey, Urbana, Ill.

Observation of a tornado using the AN/CPS-9 radar. Stuart G. Bigler, A and M. College of Texas, College Station, Tex.

Patterns in hailstorms in Alberta, 1957. Walter Hitschfeld, McGill University, Montreal, Que., and R. H. Douglas, Meteorological Service of Canada, Dorval, Que.

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A theoretical model for hurricane radar bands. Morris Tepper, U. S. Weather Bureau, Washington, D. C.

CIRCULATIONS AND ENERGY PROCESSES IN THE STORM CORE

Energy problems of the tropical hurricane. E. Palmén, Institute of Meteorology, University of Helsinki, Helsinki, Finland.

Some examples of wind circulations in hurricane eyes. N. E. La Seur, Florida State University, Tallahassee, Fla.

On the thermal structure of the hurricane core. Joanne S. Malkus, Woods Hole Oceanographic Institution, Woods Hole, Mass.

Mid-tropospheric ventilation as a constraint on hurricane development and maintenance. R. H. Simpson, U. S. Weather Bureau, West Palm Beach, Fla., and Herbert Riehl, The University of Chicago, Chicago, Ill.

On the dynamics and energetics of the hurricane area. Joanne S. Malkus, Woods Hole Oceanographic Institution, Woods Hole, Mass., and Herbert Riehl, The University of Chicago, Chicago, Ill.

An exploratory experiment in hurricane seeding. R. R. Braham, Jr., The University of Chicago, Chicago, Ill.

ENERGY CYCLES AND MODELS

On the formation of tropical depressions. Jule G. Charney, Massachusetts Institute of Technology, Cambridge, Mass.

Vertical profiles of wind velocity in tropical cyclones. C. L. Jordan, Florida State University, Tallahassee, Fla.

Experimental studies of thermal vortices. D. Fultz and R. Kaylor, The University of Chicago, Chicago, Ill.

On the instability arising from the release of latent heat. Morton G. Wurtele, University of California, Los Angeles, Calif.

On the routine forecast of typhoon movement by the numerical prediction method. H. Ito, Y. Masuca, and E. Terauchi, Meteorological Research Institute, Japanese Meteorological Agency, Tokyo.

OBSERVING AND TRACKING FACILITIES, COMMUNICATIONS AND WARNING DISSEMINATION

Development of the hurricane positioning device. J. C. Payne and T. W. Kelly, Geophysics Research Directorate, Air Force Cambridge Research Center, Bedford, Mass.

Air Force reconnaissance system AN/AMQ-15. Robert F. Long, Headquarters Air Weather Service, Scott AFB, Ill. and L. B. Young, Bendix Systems Division, Ann Arbor, Mich.

Weather reconnaissance capabilities of the WV type aircraft. David A. Hurt, Jr., U. S. Navy, Naval Air Station, Jacksonville, Fla.

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Human factors in warning and response systems. Harry B. Williams, Office of Civil and Defense Mobilization, Washington, D. C.

CYCLOGENESIS AND INTENSIFICATION

Comments on the formation of hurricanes. Herbert Riehl, The University of Chicago, Chicago, Ill.

The distribution of surface friction in hurricanes. Lester F. Hubert, U. S. Weather Bureau, Washington, D. C.

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PREDICTION OF HURRICANE MOVEMENT

A re-evaluation of the problem of predicting hurricane movement. Robert C. Gentry, U. S. Weather Bureau, West Palm Beach, Fla.

A comparison of hurricane steering levels. Banner I. Miller and Paul L. Moore, U. S. Weather Bureau, Miami, Fla.

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Methods of forecasting typhoon movement. Robert C. Bundgaard, 10th Weather Group, U. S. Air Force, Tokyo.

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