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From the Shelby White and Leon Levy Archives Center, Institute for Advanced Study, Princeton, NJ, USA

THE INSTITUTE FOR ADVANCED STUDY

THE METEOROLOGY GROUP

PROGRESS REPORT

July 1, 1952 to September 30, 1952

Contract No. N-6-ori-139,
Task Order I

#14

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From the Shelby White and Leon Levy Archives Center, Institute for Advanced Study, Princeton, NJ, USA

DIRECTOR:	John von Neumann
MEMBERS:	Jule Charney (full period)
	Ernst Hovmöller (full period)
	Norman Phillips (full period)
	Joseph Smagorinsky (full period)
CODERS:	Norma Gilbarg (full period)
	Glen Lewis (full period)
	Edward Stone (July 1, 1952 to September 8, 1952)

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QUARTERLY PROGRESS REPORT

Contract No. N-6-ori-139,
Task Order I

During this period, the series of barotropic forecasts for the period 23 - 26 November 1950 were completed. These forecasts used 500-mb heights as input data. Altogether six 24-hour forecasts were made using a time interval of one hour and a precision of 2^{-10} in the solution of the Poisson equation. The 12-hour forecasts were quite good except during the period 1500 GCT 24 November - 1500 Z 25 November when baroclinic effects seem to have been quite important. The correlation between predicted and observed 12-hour 500-mb height changes was generally greater than 0.8 except during the above period. The 24-hour forecasts were somewhat less accurate.

The first 12-hour baroclinic forecast was finished on August 25. The model for this forecast is based on the use of two grid points in the vertical at p = 300 and p = 700 mb. With some slight simplification this reduces to a two-level barotropic (but not non-divergent) model. The initial data consisted of 700- and 300-mb heights over North America at 1500 GCT 24 November 1950. This was the time at which the baroclinic deepening of the storm seemed to be most pronounced. A 500-mb forecast can be obtained from this model if it is assumed that the 500-mb height change is proportional to the 300- and 700-mb height change. Using a relationship of this kind based on the assumption that $\partial \ln \vartheta / \partial p$ = constant (ϑ = potential temperature), a prediction was made of the 500-mb height changes from 1500 Z on the 24th to 0300 Z on the 25th. The correlation

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coefficient between these baroclinically forecast changes and the observed changes was 0.78^+ compared to a figure of 0.74^+ for the correlation between the barotropically forecast changes and the actual changes.

However, the initial 500-mb tendencies from the two-layer model seemed to promise a greater improvement over the barotropic forecast than was given by the actual finite 12-hour forecast. The reason for this is as yet unknown. In attempting to go on to a 24-hour forecast, the potential vorticity (which is supposedly conserved and is scaled in the machine to lie initially between about + 3/32 and + 7/8) became negative at a grid point to the east north-east of the storm center. This occurred at the 39th time step, the length of the time step being 1/2 hour. The poor showing of the 12-hour finite change vs. the initial tendencies was due primarily to a weakening of the initial height fall center to the south-east of the storm. This could be due to a systematic truncation error whereby the potential vorticities became smaller with time. Before attempting a more complete analysis of this phenomenon, however, it was considered advisable to make another forecast. We are therefore at the moment in the process of making a 2-layer prediction based on initial data from the 23rd of November 1950.

The input data for the barotropic forecasts and the 2-layer forecasts have been obtained directly from analyzed charts of the 500- or 300- and 700-mb levels. (The two latter having been analyzed by Hovmöller and the former by Phillips.) There is some reason to suspect that the use of data at a given level as opposed to the use of data which is averaged with respect to the vertical coordinate vitiates any comparison between various models. We therefore hope to redo some of the barotropic and 2-layer

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computations using initial data which has been "smoothed" in this manner.

Vertical velocities may be computed from the 2-layer model. They have been computed for 1500 GCT on the 24th and show a good correlation with the actual distribution of cloudiness and precipitation.

The change from the barotropic to the 2-layer model (~ 17 July 1952) coincided with the beginning of a period during which error-free functioning of the computer has been somewhat rarer than during the preceding months. To aid in diagnosing malfunctions of the machine, a form of the barotropic code has been rewritten by Glen Lewis to check all of the major arithmetic operations which occur in the normal form of the barotropic code, and has proved quite useful. The barotropic code itself has been rewritten with the object of "speeding it up". As a result we now believe that a 24-hour barotropic forecast for the region of North America can be made in about 10 minutes of full speed computation time on the Princeton machine. A major feature in this revision requires the storage of additional past values of the stream function ψ . In every time step prior to the Liebmann solution of the Poisson equation for ψ , an initial guess for ψ is made by extrapolation from the past ψ -values at each interior grid point. It is believed that this method will give an initial estimate of ψ differing from the true finite-difference solution of the Poisson equation by a quantity of the order of 2^{-9}. Since the accuracy required for ψ is only 2^{-10}, only one binary place need be relaxed by the Liebmann process. The absolute saving in time made possible by this method will be greatly increased in the more complicated models where the convergence rate of the Liebmann process is less.

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Joseph Smagorinsky has completed his study of the effects of zonal asymmetries in the distribution of seasonal mean heating on the large-scale quasi-permanent motions of the atmosphere. His computations, based on an idealized distribution of heating, indicate that this effect is quite important in the lower levels (where the longitudinal variation in heating is greatest) but less so at upper levels where it seems to be of the same order of magnitude as the orographical effect investigated earlier by Charney and Eliassen. It is planned to publish this study in the Quarterly Journal of the Royal Meteorological Society.

Phillips has made calculations of the northward transport of heat and generation of kinetic energy by amplifying disturbances in the two-layer model. These indicate that the typical large scale baroclinic disturbances "produce" kinetic energy fast enough to balance the estimated dissipation by friction and at the same time transport enough heat energy poleward to approximately balance the net radiational deficit. These results agree in general with the recently published work by Kuo in the Journal of Meteorology (vol. 9, no. 4).

In mid-August Jule Charney left on a trip to visit European meteorologists concerned with numerical forecasting and to attend a conference in Stockholm on this subject during October.

On August 5th, a meeting was held at the Institute under the chairmanship of Professor von Neumann to explore the possibilities of routine preparation of numerical forecasts by the Weather Bureau and the Air Force and Navy meteorological services. It was decided that a representative from each of these agencies visit the group at Princeton to obtain experience with our methods. A copy of the minutes of this meeting is being

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sent to each participant. Representatives from the Weather Bureau, Air Weather Service, Naval Aerology, Office of Naval Research, Geophysical Research Directorate of the Air Force, and the University of Chicago attended the meeting.

Respectfully submitted,

Norman A Phillips

Norman A. Phillips,
Meteorology Group Member

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THE INSTITUTE FOR ADVANCED STUDY

THE METEOROLOGY GROUP

PROGRESS REPORT

April 1, 1952 to June 30, 1952

Contract No. N-6-ori-139,
Task Order I

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From the Shelby White and Leon Levy Archives Center, Institute for Advanced Study, Princeton, NJ, USA

DIRECTOR: John von Neumann

MEMBERS: Jule Charney (full period)

Norman Phillips (full period)

Joseph Smagorinsky (full period)

CONSULTANTS: Victor P. Starr (Professor, Massachusetts Institute of Technology, May 26, 1952 to June 4, 1952)

Edward N. Lorenz (Doctor, Massachusetts Institute of Technology, May 27, 1952 to June 4, 1952)

CODERS: Norma Gilbarg (full period)

Glen Lewis (full period)

Edward Stone (April 14, 1952 to June 30, 1952)

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QUARTERLY PROGRESS REPORT

Contract No. N-6-ori-139,
Task Order I

This period was the first in which the I. A. S. electronic computer became available for general use. A series of test computations had been planned and much of the Group's effort during this time was devoted to running a series of barotropic test forecasts for the 500 mb. level. The following is a summary of the nature and extent of the results:

1) The synoptic period for the forecasts was November 23 to 26, 1950, a period during which an unusually severe storm developed at the ground and aloft over the eastern half of the United States. The situation had originally been chosen as being extremely baroclinic and therefore a suitable one on which to test various three-dimensional models. It was felt desirable to have a series of barotropic forecasts for the same period for comparison purposes. Forecasts for 12 and 24 hours were prepared from initial data for the times 23 November 0300 Z, 24 November 0300 Z, 24 November 1500 Z, 25 November 0300 Z, and 25 November 1500 Z. Altogether six 12-hour forecasts and six 24-hour forecasts were made.

2) The present memory capacity of the I. A. S. computer is more than adequate for a two-dimensional forecast but becomes marginal for a three-dimensional forecast, particularly if forecast time is a consideration. To ascertain the minimum amount of digital significance needed, several predictions were made for an identical period but with varying degrees of precision in the stored data. It was found that 10 binary digits, an accuracy of 1 in 2^{10}, was sufficient. This much accuracy is not inherent in the raw data

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but must be retained in the computation to prevent a destructive accumulation of round-off errors.

The tests also furnished evidence that the computations were computationally stable. If they had not been, the round-off errors would have become so magnified as to produce large differences between forecasts with differing storage precisions.

3) As a more systematic check on the computational stability, forecasts were again made for an identical period but with different time intervals. With a space grid interval of 300 km the computation became unstable at a time interval of 80 minutes. This agreed with the theoretical calculation, according to which the space interval Δx and time interval Δt must satisfy the condition $\Delta x / \Delta t > \sqrt{2}\, U_m$, where U_m is the maximum particle velocity in the forecast region.

4) To reduce the forecast time a method was devised for extending the time interval beyond 80 minutes while keeping the computation stable. This method was tested and was found to be only moderately accurate. An improved method was suggested by Dr. Goldstine but was not tested.

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It may be of interest to show what is involved in a 24-hour two-dimensional forecast. The grid contains 19 grid points on a side and covers an area about the size of North America. The forecast is made in 24 one-hour steps. In each step some 17,000 multiplications and divisions as well as 54,000 additions and subtractions are required; altogether 296,000 orders are executed. This takes less than four minutes at full speed. Thus, at full speed a 24-hour forecast requires about 1 1/2 hours. Actually, however, the machine operated at only half speed most of the time. The input and output is at the moment

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slow. It consists of a teletype reader and printer. Nearly an hour is required to read the data in and out and to verify that what has been read in and out is correct. Making allowance for the personal equation, slightly more than 50% of the total forecast time was spent in merely communicating with the machine. This is an obvious incongruity and will soon be remedied by input-output devices that will reduce the communication time to a negligible amount. It will eventually be possible to go from the memory of the machine directly to an analyzed meteorological chart in two or three minutes. Methods now exist for reducing the total time involved in a 24-hour forecast to less than one-half hour.

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In addition to the activities described above, work was continued on preparations for three-dimensional baroclinic forecasts. This, together with work of a more general character, will be described below:

5) A simple three-dimensional prediction model involving two upper levels (700 and 300 mb) was programmed and coded. Forecasts with this model are expected to begin during the week of July 14.

6) Another simple three-dimensional model involving only one upper level but utilizing both temperature and pressure data was programmed and coded.

7) To test the utility of the machine for performing statistical-meteorological computations, a program was drawn up with the aid of Dr. Tukey at Princeton University to calculate power spectra and lag and multiple correlations for a time series of zonal and meridional indices compiled by Dr. Willett of M. I. T. The results will be of interest to Drs. Starr and Lorenz of M. I. T. in their study of general circulation problems, as

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well as to ourselves.

8) Mr. Smagorinsky's work was completed on the influence of heat and cold sources on the mean circulation in middle latitudes. He is now preparing the paper for publication.

9) Judging by the agreement that is now obtainable between the observed and calculated mean circulation patterns one may be justified in at least attempting to explain certain of the long-period weather anomalies in terms of statistical-mechanical concepts. Some thinking has been directed towards the utilization of machine methods to deal with this problem.

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The Meteorology Group is not equipped or staffed to perform extensive synoptic analyses. Accordingly such analyses have had to be performed by outside organizations. We acknowledge with pleasure the valuable assistance of the U. S. Weather Bureau in collecting, processing and plotting all the necessary isentropic data for the 1950 November storm period. This data will be used for the full three-dimensional forecasts. We are also indebted to Dr. Newton and Lt. Hubert (USN) of the Stockholm University Institute of Meteorology for two series of synoptic analyses of 500 mb. American and European data. These will be used for additional barotropic forecasts.

Respectfully submitted,

Jule G. Charney

Jule G. Charney,
Group Leader

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THE METEOROLOGY GROUP

PROGRESS REPORT

December 22, 1951 to March 31, 1952

Contract No. N-6-ori-139,
Task Order I

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From the Shelby White and Leon Levy Archives Center, Institute for Advanced Study, Princeton, NJ, USA

DIRECTOR: John von Neumann

MEMBERS: Jule Charney (full period)

Norman Phillips (full period)

Joseph Smagorinsky (full period)

CONSULTANT: George Platzman (University of Chicago, January 27, 1952 to March 2, 1952)

CODERS: Norma Gilbarg (full period)

Glen Lewis (February 4, 1952 to March 31, 1952)

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QUARTERLY PROGRESS REPORT

Contract No. N-6-ori-139,
Task Order I

With the completion of the computing machine at the Institute for Advanced Study the primary activity of the Group turned from general physical and dynamical studies of the numerical forecasting problem to the specific tasks connected with the immediate utilization of the machine. It was apparent that the degree of difficulty inherent in the three-dimensional forecast problem was too great to justify the use of a three-dimensional model in the initial test computations. It was, therefore, decided to deal first with the two-dimensional barotropic model, a model that had already been investigated to some extent on the ENIAC. Since the results of the ENIAC experiments were too meager to permit drawing general conclusions, an intensive series of tests with varying grid sizes, time intervals, relaxation methods, and numerical storage specifications were planned for the Princeton machine. In addition, it was planned to perform some numerical integrations using two-dimensional models incorporating essential baroclinic features. Programs, flow diagrams, and codes were prepared for these test forecasts.

After the Group's first experience with the machine it was realized that the best way of keeping a check on the accuracy of a very high-speed calculator was not to inspect the results at the end of the complete calculation, but to instruct the machine to check itself and to stop when it had made an error. Accordingly, a series of automatic checks were added to the coded instructions. A code was also prepared

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for converting the stream functions, read from the weather charts as decimal numbers, directly into the initial binary vorticities needed by the machine at the start of the computation. Heretofore, the stream-function had been taken as the dependent variable, but it was found that round-off errors could be considerably reduced by taking instead the absolute vorticity for the dependent variable. The stream-function, which is needed for the time extrapolation of the vorticity, was determined from the vorticity field by solving a Poisson's equation.

A more basic change in the formulation of the barotropic problem was demanded by the decision to solve the Poisson equation by a systematic relaxation method (modified Liebmann) rather than by finite Fourier transforms. This required a complete change of all previous barotropic programs and codes. As the Liebmann method will be used in the three-dimensional integrations, it was decided to use it in the two-dimensional integrations as well in order to gain experience. Also, relaxation methods are logically simpler and require fewer machine orders.

The initial integrations were used primarily for locating malfunctions in the machine and to a lesser extent to remove inaccuracies in code and program. Several forecasts were made in one hour steps for time intervals of four, eight, and nine hours. Because of the likelihood that machine errors were made, there was no attempt to draw conclusions from these forecasts.

Research was continued into the problem of the general circulation and long range forecasting through a study of the influence of large scale heating on the mean seasonal flow pattern. Preliminary

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results indicate that heating influences are virtually absent at 500 mb, but that at low levels they, in conjunction with those of topography, account for the general structure of the observed patterns.

The Group was again indebted to Professor Platzman of the University of Chicago for his help and advice in various phases of the programming and coding work.

Respectfully submitted,

Jule G. Charney

Jule G. Charney,
Group Leader

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THE METEOROLOGY GROUP

PROGRESS REPORT

October 1, 1951 to December 21, 1951

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Task Order I

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DIRECTOR:	John von Neumann
MEMBERS:	Jule Charney (full period)
	Norman Phillips (full period)
	Joseph Smagorinsky (full period)
CONSULTANTS:	George Forsythe (Institute for Numerical Analysis, U. C. L. A., October 7, 1951 to November 7, 1951)
CODER:	Norma Gilbarg (full period)

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1. The majority of the Group's time in the third quarter of 1951 was spent in programming the integration of the three-dimensional quasi-geostrophic equation of atmospheric motion by the Institute for Advanced Study Electronic Computing Machine, now physically completed. This was the goal toward which the group had been working for some time, but a number of preliminary problems had first to be solved. The decision to attack the three-dimensional integration was taken after discussions with Professor von Neumann in which it became evident that the amount of real information in pressure-temperature data is so small that the large number of values of the dependent variable needed for the integration could probably be stored internally. The task of programming, being a large one, was broken into the following parts, each of which was dealt with in turn:

(a) Selection of an appropriate coordinate system. The quasi-geostrophic equation with ζ as vertical coordinate contains mixed derivatives, and the non-homogeneous terms are extremely complicated to evaluate. A more suitable vertical coordinate turns out to be the potential temperature, θ , the mixed derivative terms disappear and the equation becomes simpler in other respects. But even the θ system presents difficulties because the ground is not a coordinate surface. A third coordinate system was finally selected which preserves most of the advantages of the θ -system and in which the ground is a coordinate surface.

(b) Determination of boundary conditions. The lateral boundary conditions were determined by a heuristic method analogous to that which was

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employed for the barotropic model. For a number of reasons, which were regarded as sufficient, the upper boundary was taken to be the 400°K isentropic surface and was assumed to remain rigid. The upper boundary conditions were then determined in the same manner as for the ground.

(c). Selection of the finite difference net: Estimates of truncation error for nets of different sizes were made and it was decided to use a horizontal grid interval of 300 km and a vertical interval corresponding to about 150 mb on a pressure scale. The choice of the horizontal interval was considerably aided by previous experience with two-dimensional models. The whole grid will embrace an area of 4000 km x 4000 km and will contain some 1200 points.

(d). Method of solution. Various relaxation techniques were investigated and it was decided to use the modified Liebman method with an empirically determined constant of overrelaxation.

The programming will be completed by the end of the year and work will then begin on the code for the machine.

2. Work was continued on the problem of long-range prediction. In an attempt to explain the factors influencing the seasonal mean upper flow patterns the effects of variations in surface frictional stress along latitudes is being investigated and in addition the effects of thermal sources and sinks.

3. In anticipation of the time when the quasi-geostrophic equations will have been fully exploited a method was constructed for passing to higher approximations. These approximations were tested on dynamical models in which the geostrophic approximation is known to fail because

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of the smallness of the scale ~~as~~ or the magnitude of the vorticities. In each case the higher approximations were found to be satisfactory. It can be said with some confidence that we know where to go from here.

Respectfully submitted,

Jule Charney

Jule Charney,
Group Leader

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J von Neumann

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PROGRESS REPORT

July 1, 1951 to September 30, 1951

Contract No. N-6-ori-139,
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From the Shelby White and Leon Levy Archives Center, Institute for Advanced Study, Princeton, NJ, USA

Director: John von Neumann

Members: J. Charney (University of Chicago, June 15-August 15; Europe August 19-September 21)

J. Smagorinsky (full period)

Consultants: Norman Phillips (University of Chicago)

George Platzman (University of Chicago)

Coder: Norma Gilbarg (full period)

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1. The Eniac integration of the barotropic vorticity equation for a series of idealized initial states was completed by the end of June 1951. Altogether four models were studied. These consisted of four wave-like perturbation patterns superimposed on a zonal jet. Two were stable in the sense that the kinetic energy of the perturbation was converted into kinetic energy of zonal flow, and two were unstable, with an opposite conversion. During the third quarter of 1951 the output data was analyzed to determine the variations in the stream pattern and absolute vorticity and the transfer of energy between the stream pattern and the basic current. Part of this work was performed at the University of Chicago under the direction of J. Charney with Messrs. N. Phillips and G. Platzman serving as consultants, and part in Princeton by J. Smagorinsky, N. Gilbarg, and later N. Phillips. It was felt, however, that the results were too meager to warrant any general conclusion. The interpretation was, therefore, postponed until more integrations of a similar nature can be made on the Electronic Computer now nearing completion at the Institute for Advanced Study. In particular, the integrations will have to be carried out for a larger time interval to determine what ultimately becomes of the perturbation kinetic energy in stable and unstable flows.

2. In a continuation of efforts to find a rational approach to the problem of long-range weather prediction (Item 7, Progress Report for July 1, 1950 to March 31, 1951) J. Smagorinsky succeeded in determining a simple Green's function for the solution of the partial differential equation governing the influence of continental topography and friction

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on a given jet-like westerly current. This will make possible an evaluation of the effects produced by the displacement and intensity changes of the zonal jet stream. It is expected that the perturbations produced by topography will localize the centers of action in the upper atmospheres and thus provide a means for a rational introduction of the heat and cold sources and the large-scale turbulent stresses that are responsible for the variations in the mean jet stream structure.

3. One of the major problems in dynamic meteorology is to explain the mechanism by which angular momentum and kinetic energy are fed into the middle latitude westerlies. It has been determined empirically that the horizontal eddy transfer of angular momentum in the large-scale perturbations is sufficient to account for its loss due to surface friction. While at the University of Chicago, J. Charney completed a theoretical investigation of the transfer mechanism in barotropic and baroclinic wave systems. It was found that both stable and unstable baroclinic perturbations give an increase in the zonal kinetic energy. The purely barotropic effect was also evaluated by calculating the momentum changes that occurred in the 24-hour Eniac forecasts made in 1950. In each of the four cases studied the change was a net increase in middle latitudes.

4. During a trip to Europe J. Charney visited a number of institutions that have recently taken up the study of numerical weather prediction and discussed questions of mutual interest with the personnel. The research group of the British Meteorological Office, Air Ministry, headed by R. C. Sutcliffe have performed some computations with the quasi-geostrophic advective model and have found it to be wanting. This is in accord with

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the group's findings. On the other hand, when the vertical advection of entropy was taken into account the calculations agreed with observation as far as could be ascertained. This experience was also shared by a number of other investigators with whom Charney consulted. One cannot, therefore, escape the conclusion that nothing less than an integration of the complete three-dimensional quasi-geostrophic model can lead to a major improvement in forecasting. Accordingly, the entire group is now turning its efforts toward programming the three-dimensional problem for the Princeton machine. In conversations with C.-G. Rossby in Stockholm it was decided that the International Meteorological Research Institute, of which he is the director, will perform a large part of the preliminary testing and synoptic analysis.

Respectfully submitted,

Jule G. Charney

Jule G. Charney
(Group Leader)

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THE INSTITUTE FOR ADVANCED STUDY

THE METEOROLOGY GROUP

PROGRESS REPORT

April 1, 1951 to June 30, 1951

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In March and April 1950 the meteorology group carried out a series of numerical integrations on the Electronic-Numerical Integrator and Computer (Eniac) at the U. S. Army Proving Ground, Aberdeen, Maryland. At that time the initial data were taken from the observed heights of the 500 mb surface. The interest then was to determine to what extent the barotropic model served as an approximation to the actual motion of the atmosphere at the level of non-divergence, c.a. 500 mb. Another purpose was to gain experience in the mathematical formulation and programming of a numerical forecast problem for a large scale machine. The agreement of prediction with observation was sufficiently close to warrant further exploration of the nature of barotropic processes in the atmosphere. In early 1951 it was decided to plan another series of barotropic integrations on the Eniac, this time using as initial conditions a series of idealized flow patterns. Here the purpose was not to obtain forecasts that could be compared with observation, but rather to investigate the properties of the general circulation of the atmosphere that could be explained in terms of horizontal redistribution of energy and angular momentum. Accordingly the second quarter of 1951 was devoted to this work. Among the questions to be answered were the following:

(1) How does a wave in a zonal flow that is unstable for small perturbations develop?

(2) What redistributions of energy and momentum in the mean flow are produced thereby?

(3) What redistributions of energy and angular momentum occur with the damping of a stable wave?

(4) Since it is demonstrable that a wave can never be completely damped, what kind of motion finally ensues?

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(5) How does amplification and damping depend on wave length? Amplitude? Zonal velocity distribution?

(6) What are the laws governing the motion of a vortex in a mean zonal flow with variable vorticity?

(7) Under what conditions does the transition zone between a narrow and a broad jet become sharper, i.e., when are blocks formed?

In order to answer these questions a series of wave, vortex, and jet models were constructed, and the integrations were programmed for the Eniac. A certain amount of recoding was required and was carried out with the aid of a group from the Ballistics Research Laboratory in Aberdeen. In all the work we were fortunate in obtaining the cooperation and active participation of Messrs John Freeman, Norman Phillips and George Platzman of the Meteorology Department of the University of Chicago. The actual computations were begun on June 5 and are still in progress at the date of writing. The results of the integrations, which are scheduled to be completed by June 29, will be described in the next report.

Respectfully submitted,

Jule Charney
(Group leader)

June 18, 1951

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THE INSTITUTE FOR ADVANCED STUDY

THE METEOROLOGY GROUP

PROGRESS REPORT

July 1, 1950 to March 31, 1951

Contract No. N-6-ori-139

#8

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Director:	John von Neumann
Members:	Bert Bolin (January 1, 1951 to March 31, 1951)
	Jule G. Charney (full period)
	Thomas V. Davies (January 1, 1951 to March 31, 1951)
	Ragnar Fjörtoft (September 1, 1950 to January 7, 1951)
	Joseph Smagorinsky (September 1, 1950 to March 31, 1951)
	Margaret Smagorinsky (September 1, 1950 to January 31, 1951)
Consultants:	G. C. McVittie (October 23. 1950)
	Morris Neiburger (January 27, 1951 to February 16, 1951)
	George Platzman (October 1, 1950 to December 20, 1950)
	Carl-Gustav Rossby (January 15, 1951 to March 10 1951)
Computers:	Norma Gilbarg (full period)
	Mary Lewis (January 29, 1951 to February 28, 1951)
	Chih Li Tu Yang (March 1, 1951 to March 31, 1951)

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1. The analysis of the 24-hour barotropic two-dimensional forecasts performed on the Eniac was completed and the final results and method were described in an article entitled "Numerical Integration of the Barotropic Vorticity Equation:" by J. G. Charney, R. Fjörtoft, and J. von Neumann published in Tellus, Vol. 2, No. 4, 1950.

2. The results of the Eniac forecasts served to strengthen the conviction that had already been gained from the preliminary one-dimensional computations that weather forecasting can be treated successfully by numerical methods, but the forecasts were too few to permit any conclusive evaluation of the barotropic model, particularly in view of the fact that errors due to lack of grid resolution were in some instances so great that they very probably obscured the model errors. It was, therefore, decided to program further barotropic computations for the I.A.S. electronic computer whose capacity is such that one is able to use a sufficiently fine grid. The method adopted was a modification of the procedure employed for the Eniac calculations and necessitated certain recalculations of the computational stability criteria. These were performed by von Neumann, who also aided in setting up the general program for the machine. The final program and flow-diagram were drawn up by Platzman who also, with the aid of Mrs. Smagorinsky. prepared the detailed code of instructions. This work was completed in December. When the I.A.S. computer is ready for operation it is planned to run forecasts from both actual and ideal initial situations. The latter will consist of various wave and vortex models.

3. The Eniac results indicated clearly that conventional map analysis and subjective interpolation of grid values are inadequate for

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numerical computation. In consequence several methods of objective smoothing and interpolation were investigated by Platzman and Mrs. Smagorinsky. With the aid of this experience it is now planned to program one or more such objective analysis schemes for the machine.

4. A good deal of attention was devoted to what may be called "retooling" for three-dimensional forecasts. It was early recognized that two-dimensional models, while important for a physical understanding of the atmospheric motions, are limited in applicability, and that the time had arrived for a concerted attack upon the three-dimensional problem. As the three-dimensional quasi-geostrophic equations present great difficulties for machine integration, work was continued on a simplified model devised by Fjörtoft embodying an advective assumption. It had already been observed in connection with one of the Eniac forecasts that this model leads to a significant improvement over the barotropic forecast. Another computation was carried out by Bolin for the November 24-25, 1950 East Coast windstorm situation with results similar to those already obtained; the calculated height tendencies at 500 mb were better than those obtained two-dimensionally, but the surface tendencies were poor.

5. While it may be too early to say definitely, the indications are that the advective three-dimensional model will prove inadequate, and an effort will have to be made to solve the general three-dimensional equations. In anticipation of this state of affairs von Neumann and Charney have begun to investigate various relaxation procedures for solving these equations. One, a modified Liebmann method, has already been applied to a two-dimensional model with reasonably good results. It is now planned to try out the method on a three-dimensional forecast for a

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very restricted region of the atmosphere.

6. In an effort to test the applicability of the two-dimensional barotropic model, as well as a certain highly simplified two-dimensional baroclinic model, a program was set up for calculating initial height tendencies at 500 mb for a 12 hourly sequence of current weather maps. It had been found previously that the initial tendencies give good indications of the success of a finite forecast. As a means of verification the calculated tendencies were compared with the observed 24-hour height change. Altogether some 25 computations were made.

With so large a sample it was expected that certain apriori criteria for predicting the success or failure of a barotropic forecast would be induced, and indeed some advance has been made in this direction. Neiburger and Rossby, who were present at the analysis of the computations, participated in the task of evaluation and interpretation.

In the hope that other research groups will take up this type of work and thus add to the present fund of experience it is planned to publish a description of the method of computation and of some of the results.

7. In the course of some work by Charney and Eliassen (Tellus, Vol. 1 No. 2, 1949) on the prediction of small perturbations in a barotropic zonal current it was found that the quasi-stationary perturbations appearing on normal seasonal 500 mb charts can be explained by the movement of air over the large-scale topographical irregularities in the earth's surface. This result may be of value for the explanation of the changes in the monthly mean circulation which have been dealt with by the Extended Forecast Section of the U. S. Weather Bureau and may thus provide a means for

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attacking the problem of long-range weather prediction. If one regards the mean perturbations merely as an orographical response to a mean zonal current varying only with latitude the problem reduces to the simpler one of predicting the variations of this current. To test this hypothesis Smagorinsky has begun a theoretical determination of the changes in the stationary perturbations that may be expected to result from prescribed changes in the zonal current.

8. Davies has conducted a theoretical investigation into the process of formation of cols and cut-off vortices in the atmosphere.

9. Charney has continued to work on a statistical theory of barotropic vortex motion.

Respectfully submitted,

Jule G. Charney

Jule G. Charney

March 28, 1951

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THE INSTITUTE FOR ADVANCED STUDY

THE METEOROLOGY GROUP

PROGRESS REPORT

July 1, 1949 to June 30, 1950

Contract No. N-6-ori-139

#7

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From the Shelby White and Leon Levy Archives Center, Institute for Advanced Study, Princeton, NJ, USA

Director:	John von Neumann
Members:	Jule G. Charney (full period)
	Arnt Eliassen (July 1, 1949-August 31, 1949)
	Ragnar Fjörtoft (September 1, 1949-June 30, 1950)
	John C. Freeman (full period)
Consultants:	George Platzman, University of Chicago (October 12, 1949-December 20, 1949)(March 2, 1949-March 22, 1949)
	Tu-cheng Yeh, University of Chicago (December 5, 1949-December 12, 1949)
Weather Bureau personnel on loan:	Joseph Smagorinsky (January 16, 1950-February 3, 1950) (March 6, 1950-April 4, 1950)

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An account of much of the work done during the period covered by the first progress report appeared in two published articles: (1) "On a physical basis for numerical prediction of large-scale motions in the atmosphere", J. Charney, Journal of Meteorology, December 1949; and (2) "A numerical method for predicting the perturbations of the middle latitude westerlies", J. Charney and A. Eliassen, Tellus, May 1949. Both articles suggested strongly that much would be gained in procedural experience and knowledge of fundamental atmospheric processes by integration of the non-linear barotropic equations. Accordingly the full efforts of the staff were directed toward this end, beginning about October 1949. As it was not expected that the Princeton machine would be in operation for at least one year, the problem was planned for the Eniac. This machine was obtained for the Group's use at the request of the U. S. Weather Bureau and through the courtesy of the U. S. Army Ordnance Department.

The following problems were attacked and solved, principally by von Neumann:

1) To find a method of solution adaptable to Eniac computation of the quasi-geostrophic barotropic vorticity equation:

$$\nabla^2\left(\frac{\partial z}{\partial t}\right) = \frac{\partial(\eta, z)}{\partial(x, y)} \; ; \quad \eta = h(x,y)\nabla^2 z + f(x,y) .$$

2) To find the nature of the boundary conditions.

3) To find the computational stability criteria.

4) To find reasonable limits to the area into which influences from the boundary of the forecast region propagate.

After the completion of this work the task of programming and coding was begun and completed by March 1, 1950. The Eniac was used continuously

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in three daily shifts of eight hours each for five weeks beginning March 6, 1950. During this time two twelve-hour and four twenty-four-hour forecasts were made from observed initial data. The participants in this phase of the work were Charney, Fjörtoft, Freeman, Platzman and Smagorinsky.

Subsequently Charney and Fjörtoft turned to the analysis of the Eniac results and to the preparation of an article for publication describing these results. This work occupied the greater part of the time from the completion of the Eniac computations to the end of the fiscal year. One noteworthy by-product of the analysis was the construction of an elementary three-dimensional model to account for the errors in the Eniac forecasts due to non-fulfillment of the barotropic assumptions. Preliminary hand calculations were begun at the U. S. Weather Bureau in Washington under the direction of Mr. Smagorinsky. The Weather Bureau also co-operated in carrying out the necessary computations for an objective evaluation of the Eniac forecast errors.

In addition to the main task of integration of the barotropic equations, the following research was done: Freeman completed a treatment of blocking as a shock phenomenon by the method of characteristics. This work is to be published as an interim project report. Charney completed an expository article entitled "Dynamic Forecasting by Numerical Process" for a compendium of meteorological research which will be published by the American Meteorological Society.

The work in progress at the end of the fiscal year consisted of:

1) Studies in the applicability of the primitive hydrodynamical equations for numerical weather prediction by Charney.

2) Investigation of the upper boundary condition for the three-dimensional model by Charney.

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3) Theoretical studies of simplified three-dimensional atmospheric models by Fjörtoft.

4) Studies in the statistical-mechanical properties of two-dimensional incompressible flows by Charney and Fjörtoft.

Upon completion of the Princeton computing machine it is planned to perform some additional integrations of the barotropic equations with a more refined finite-difference space lattice and to begin the programming of problems in three-dimensions. At the same time we shall pursue our theoretical studies into the physical nature of the atmospheric motions.

Respectfully submitted,

Jule Charney

October 6, 1950

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From the Shelby White and Leon Levy Archives Center, Institute for Advanced Study, Princeton, NJ, USA

PROGRESS REPORT
OF THE METEOROLOGY GROUP
AT THE INSTITUTE FOR ADVANCED STUDY

July 1, 1948 to June 30, 1949

Jule G. Charney

Arnt Eliassen

John C. Freeman

Gilbert A. Hunt

June 30, 1949

Report #6

Records of the Electronic Computer Project / Box 3 / Folder 34 / Navy progress reports, N-6-ori-139, T.O.I. July 1, 1946-September 30, 1952
From the Shelby White and Leon Levy Archives Center, Institute for Advanced Study, Princeton, NJ, USA

I. Introduction.

The ultimate aim of the Meteorology Group is the development of a method for the numerical integration of the meteorological equations which is suitable for use in conjunction with the electronic computing machine now under construction at the Institute for Advanced Study. Before this aim can be realized a number of preliminary problems must be solved. These may be divided roughly into three categories: There is first the problem of the physical determination of the atmospheric motion, i.e., what are its governing laws? Secondly, given these laws in the form of differential equations, how may they be integrated numerically? And thirdly, what are the data requirements? To answer these questions it has been proposed to consider a hierarchy of "pilot problems" embodying successively more and more of the physical, numerical, and observational aspects of the general forecast problem. The work of C.-G. Rossby and others has shown that the motions most susceptible of quantitative treatment at the present time are the large-scale (planetary) circulations of the atmosphere. Hence it was decided to confine the preliminary investigations to these motions. From a methodological point of view this is clearly the logical procedure. One should proceed from the known to the unknown. Too little is known about the smaller scale motions and too many factors must be included to warrant their inclusion in a first attempt at numerical forecasting. Just as one achieves a degree of certainty in predicting the motion of a gas by transferring attention from the individual molecules to certain space and time averages, so by restricting attention to the major weather-producing motions of the atmosphere, whose scale is of the order of 1000 km or more, the

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random effect of the micro-meteorological motions is minimized. For these large-scale motions the laws may be assumed know to a just approximation and to be expressed by the hydrodynamical equations for a non-viscous adiabatic fluid. Modifications can then be introduced as their need is made apparent from the discrepancies between the numerical forecast and the observed motions. By introducing new physical factors one at a time into these numerical experiments one has a control over their effect; if they were introduced all together it would be impossible to ascertain the factor or factors responsible for the discrepancies. Hence the need for the above mentioned type of hierarchical study based in the large-scale motions. The primary reason for Richardson's failure may be attributed to his attempt to do too much too soon.

II. The Quasi-geostrophic Approximation.

The hydrodynamical equations govern every conceivable type of macroscopic atmospheric motion. This is a serious defect from the meteorological point of view. It means that one must take into account the inconsequential sound and gravity motions of the atmosphere if one wishes to accurately predict the meteorologically significant large-scale motions. Thus if one does not select the space and time differences for the finite difference analogues of the hydrodynamical equations in a manner which leads to a convergent approximation to the small-scale sound and gravity motions, the latter will amplify in the computation process to such an extent that they will utterly obscure the important large-scale motions. It has been shown by the Group that this difficulty can be overcome by the introduction of the geostrophic approximation as a device for filtering out the 'noise' motion

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from the hydrodynamical equation. Other methods exist for accomplishing the same result, notably a method proposed by Professor J. von Neumann, and are also being studied.

III. Signal Velocities in the Atmosphere.

The quasi-geostrophic equations have the further advantage of analytic simplicity and can be used to solve a number of the so-called 'pilot problems'. One of these concerns the magnitudes of the influence or 'signal' velocities in the atmosphere. If a forecast is to be made for a certain region and for a certain period of time, it is necessary to know from what distances influences will spread into the forecast region during the forecast period. By considering the spread of influences in a motion consisting of small perturbations on a zonal current, estimates have been obtained for the maximum signal velocities to be expected in an actual situation. The horizontal velocities were found to be such that predictions for one or two day periods are now possible for those areas of the earth covered by an extensive observational network. The magnitudes found for the vertical signal velocities imply that stratospheric influences will not appear in the lower troposphere in less than a day or so. For this reason, it is likely that present observations extend to a sufficiently high level to permit short period forecasts for the lower troposphere.

IV. The Equivalent-barotropic Atmosphere.

The numerical problem of predicting the motion of a continuous system with four independent variables (time and the three space coordinates) is an exceedingly difficult one, even with the aid of the most versatile automatic computing machinery. It is therefore of the greatest importance,

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especially in the beginning work, where many numerical experiments must be performed, to invent atmospheric models with fewer degrees of freedom. Here one may take advantage of the fact that the large-scale atmospheric motions exhibit a kind of degeneracy with respect to the vertical coordinate. It has been possible to define a mean motion for the atmosphere which approximately satisfies the equations for two-dimensional autobarotropic flow. The motion is the same as the horizontal motion of the actual atmosphere at what may be called the equivalent-barotropic level, a level found in the vicinity of 500 mb. Much of the work of the Group during the past year has dealt with the study of the equivalent-barotropic motion.

As one phase of the work a model in which the flow at the equivalent barotropic level is idealized as a small perturbation in a uniform westerly current has been found adequate to explain many features of the observed wave-like disturbances of the upper westerlies, providing topographic and functional influences are also taken into account. It has been demonstrated that the quasi-permanent perturbations of the middle latitude westerlies can be satisfactorily explained as a result of the forcing of a westerly current over the continental elevations.

A method has also been developed for predicting the day to day variations of the 500 mb motion. This method seems to hold promise of practical use. A series of tests have been made by U. S. Weather Bureau personnel under the supervision of the Group and are being continued at the Weather Bureau in Washington. Independent tests have also been made at the Swedish Meteorological Institute in Stockholm under Professor Rossby's supervision. The results indicate that the method will be a useful adjunct to standard forecast practice.

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It should be pointed out, however, that the method is merely a byproduct of more basic research and is not to be judged exclusively for its practical merit. Of theoretical importance was the evidence presented that topography and friction exert only a minor influence on the short range variations of the large-scale free atmosphere motions and can therefore probably be ignored in a first attempt at short range weather prediction. Perhaps the most important result is that the accuracy obtained with the rather crude linearized model appears to justify the expectation that the use of the non-linear barotropic model will yield predictions of definite practical and theoretical value.

V. Data Requirements.

The heuristic value of the simplified barotropic model may be illustrated by another example. It has often been questioned whether the observations of wind , pressure, and temperature are sufficiently accurate to permit accurate forecasts from the available data. It is known that although the pressure and horizontal velocity fields in the lower tropopause can be determined with reasonable accuracy this accuracy is not enough to enable one to calculate the fields of horizontal acceleration, horizontal divergence, and vertical velocity. The Group has shown, however, that for a stable flow in a barotropic model a method of integration can be found in which the errors in the predicted horizontal wind and pressure fields do not increase in time despite the fact that the errors in the initial fields of horizontal acceleration, horizontal divergence, and vertical velocity may be great. The result has also been extended to small perturbations of a stable baroclinic circular vortex, and investigations are under way to show that the rate of error increase is not great in the large-scale unstable perturbations as well. Again it appears probable that the existing data are sufficiently accurate to permit forecasts for short periods.

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VI. Convergence Criteria for the Finite Difference Equations.

The non-linearity of the hydrodynamical equations makes it impossible for the present to establish exact upper limits for the error incurred by replacing the differential equations by difference equations. One can only hope to obtain rough estimates by the use of linearized models. The barotropic model in which the motion is a small perturbation in a linear flow is useful also for this purpose. It has been shown that, in order to obtain an accuracy or 90% in a 24 hour forecase of the pressure field, it is necessary to choose the time increment less than about one hour and the space increment less than about 400 km. Reliable criteria have not yet been obtained for the vertical space difference, but work now in progress indicates that such criteria will soon be found.

VII. Use of the Primitive Hydrodynamical Equations in Forecasting.

The geostrophic approximation has the disadvantage that it filters out as noise smaller scale motions which may be of considerable meteorological importance; for example, the small-scale frontal cyclone. Looking forward to the time when one would wish to consider these motions as well, efforts have been made to devise methods for their treatment. In this case it appears necessary to use the primitive equations, taking care to choose the finite differences so as to avoid the explosive phenomena associated with the computational amplification of the gravity and sound motions. By making the hydrostatic approximation and choosing the space and time differences to satisfy the Courant-Lewy-Friedrichs criterion, $\Delta x > C \Delta t$, where C is the speed of gravity waves, about 300 m sec^{-1}, it has been found possible to obtain good approximations to the meteorologically significant motions in the linearized barotropic model. Whereas influences would appear in this case to spread at the rate of 300 m sec^{-1} it is found that one may make

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use of the signal velocity studies already mentioned to place a more reasonable limit on the influence region.

It is possible to apply the primitive equations to large-scale barotropic motions also. Here the advantage lies in the simplicity of the associated numerical integration procedure. The time increments of the field variables can be obtained by a simple arithmetic computation, whereas the quasi-geostrophic equations suffer from the disadvantage that one has to solve a second order elliptic differential equation with each time step. On the other hand the latter have the advantage that the time steps may be chosen much larger. Studies are under way to determine which of the two methods is more suitable in both the barotropic and baroclinic cases.

VIII. Future Plans.

The first experiment to be tried on the machine now being built at the Institute for Advanced Study will be a 24 hour forecast of the horizontal motion at the equivalent-barotropic level. To this end data have been collected, and it is planned to compute a few time increments by using ordinary desk calculators or possibly one of the existing large-scale computing devices. The results are expected to shed light on the difficulties to be encountered when the full-scale problem is programmed for the Princeton machine.

Note: A part of the work referred to in the above report can be found in a manuscript submitted by J. Charney to the Journal of Meteorology and to be published in 1949. The article is entitled, "On Numerical Weather Prediction by Dynamical Methods". Another part will appear as an article by J. Charney and A. Eliassen in Tellus in July or

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Note: August 1949. It is entitled, "A Numerical Method for Predicting the Perturbations in the Middle Latitude Westerlies". The error evaluations for the finite difference equations exist in the form of a memorandum by G. A. Hunt, as does the work by J. C. Freeman on the primitive equations.

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C O P Y

METEOROLOGY PROJECT

INSTITUTE FOR ADVANCED STUDY

PRINCETON, NEW JERSEY

Report of Progress
during the
Period from 15 June 1948 to 15 September 1948
as provided for under
Contract N6-ori-139, Task Order I

15 September 1948

#5

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C O P Y

REPORT ON

WORK DONE ON

PROJECT N6-ori-139

DURING THE PERIOD

June 15 - Sept. 15

1948

It has been the purpose of this work to coordinate a considerable amount of matter which has accumulated in the course ot time, in such a way that the significance of the phenomena of the earth's liquid core as a branch of geophysical hydrodynamics becomes apparent. A lengthy report has been finished, entitled "The Earth's Interior and Geomagnetism." This is a comprehensive critical review of all the known data on the subject. Enclosed herewith is copy of a brief note entitled "Non-Uniformity of the Earth's Rotation and Geomagnetism," which contains new results that have been obtained by the writer during the present year and partly in connection with this project.

WALTER M. ELSASSER

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C O P Y

Non-Uniformity of the Earth's Rotation and Geomagnetism.

By W. M. Elsasser

The existence of a secular deceleration of the earth's angular velocity at a rate,

$$dw/dt = -2.5 \cdot 10^{-22} \sec^{-2} \qquad (1)$$

has long been established from astronomical data[1)]. The classical work of G. H. Darwin and of Jeffreys, culminating in Jeffreys' computation of the frictional torque of the oceanic tide seemed to have settled the problem[2)]. Quite recently it has been necessary to reopen the question as new geophysical information has become available. It can now be said that in all probability the decelration of the earth is produced by two independent agencies, the oceanic tide, and a still very obscure effect in the earth's liquid core. While nothing is as yet known about the dynamics of motions in the core, there is good reason to believe that an appreciable fraction of the retarding torque operates in the core rather than in the oceans. This is perhaps close to the original ideas of Darwin, but the observations that lead to this conclusion are novel.

Let us first give a brief idea of the mechanics of the deceleration. We shall ignore the small solar tide as compared to the lunar tide. The angular momentum of the system earth-moon must be conserved. Darwin and Jeffreys have shown that the orbital motion of the moos takes up the angular mementum lost by the earth; the moon gradually recedes from the earth. Now the ratio of energy to angular momentum for the earth's rotation is $1/2\ w_e$, the same ratio for the moon's orbital motion is $-\ 1/2\ w_m$. But $w_e/w_m = 28$, and it follows that per unit angular momentum transmitted to the moon only

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1/28 of the rotational energy of the earth is transmitted; the remainder must be used up by friction or other transformations of energy in the earth. The frictional forces produce a couple that retards the earth, and at the same time a force acts on the moon that tends to push the latter away from the earth. One of the more gratifying features of this theory is the fact that the observed deceleration is of the right general order to account for a gradual removal of the moon from an original position very close to the earth to its present distance during the known lifetime of the earth.

The new evidence arises from rather unexpected quarters; it is based on geomagnetic observations. As the present writer has endeavored to show[3)] the secular variation of the geomagnetic field can be explained by means of motions of the matter in the earth's fluid metallic core. Such motions induce electric currents in the core, of magnitude $\mathfrak{J} = \sigma v \times \mathfrak{B}$ where σ is the conductivity, v the velocity of the fluid, $\mathfrak{B}$ the existing magnetic field. More recently, Bullard has arrived independently at altogether similar conclusions, as reported in "Nature"[4)]. In general, an electromagnetic field in the presence of internal motions in a fluid conductor is non-conservative, energy is being exchanged between the field and the motion of the fluid. On the other hand, it can be shown[5)] that so long as a parcel of the fluid moves without deformation, or if its deformation is negligible, it carries its electric currents and magnetic field with it unchanged except for the free decay of the currents. One immediate consequence of this is the fact that the observed irregular magnetic field rotates with the earth. Another important consequence will be indicated below.

We have recently come into possession of a most remarkable set of world-wide maps of the secular geomagnetic variation constructed by Vestine

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and collaborators[6]. These are based on an exhaustive evaluation of magnetic data and cover the period from 1912 to 1942 in intervals of 10 years. The maps show that there are a number of centers of the secular variation scattered about the earth; these centers undergo rapid changes of intensity and also displacements of the position. The similarity of these maps and of ordinary weather charts is amazing, and there is no better way of conveying the idea that the secular variation owes its origin to fluid motions in the core than a contemplation of these maps. There are two independent ways in which the velocity of the fluid can be estimated, first by direct inspection of the displacement of the centers and secondly from the rate of change of the field, using the electromagnetic theory[3][4]. Both methods give velocities of the order of 1 mm/sec. The most interesting feature, however, exhibited by these maps is a general drift of the whole pattern of the secular variation in the direction from east to west. It is difficult to assign an exact numerical value to this drift motion since it is superposed upon the irregular displacements of the centers and is of the same order of magnitude as the latter. In order to have a convenient figure we may estimate a value of 0.5°/year which at the equator of the core represents a linear velocity of 1 mm/sec. Since this corresponds to an overall displacement of 15° over the period of 30 years covered by Vestine's maps, it is clear that the westerly drift is a conspicuous effect. There can be no doubt as to its reality. It occurred to the writer that if such a mean motion exists it might not have escaped the attention of earlier students of the secular variation. In fact, Bauer[7] stated in 1895 that he found a "westerly wave" of the secular variation and he traces it back to the middle of the sixteenth century. The mean angular velocity, as far as

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can be said from his data, seems about half the value given above. The cause of the discrepancy is not clear; it is no doubt connected with the great irregularity of the secular pattern. Also, Carlheim-Gyllenskold[8)] indicates a strong preponderance of westerly displacements in the secular variation.

On the basis of the theory which explains the secular variation as the results of fluid motions in the core, these observations must needs be interpreted as representing a bodily displacement of the core in the direction from east to west. This result agrees with the above mentioned theorem, that the magnetic field is carried along unchanged if a bodily displacement of the conductor occurs. In spite of great efforts the writer has been unable to devise any other even remotely satisfactory interpretation of the pehnomenon. It will be noted that the direction of the drift is such as to indicate a lag of the core behind the rotation of the earth. This is the opposite of what one would expect if the earth was decelerated by a frictional torque in the oceans. From quite elementary considerations of mechanics one would expect the core to rotate faster than the mantle. The difference in angular velocity would be determined by the amount of eddy friction at the boundary of the core.

Our first and natural reaction would be to try to explain the phenomenon away. As already noted it would be practically impossible to explain it as due to comulative or systematic errors in the observations. Students of meteorology might be reminded of the belts of alternating easterly and westerly winds which are a well known feature of the atmosphere and which adjust themselves so that the mean torque between the atmosphere and the solid earth vanishes. A careful study of Vestine's maps has not revealed any indication of an opposing drift motion; the existing westerly

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drift seems rather evenly distributed over the whole earth. Again, one might think that the present condition of the core is in the nature of a temporary deviation from its average state. If we assumed that there is no oceanic tide and that the core alone is decelerated at the rate given by (1), it is readily found that it takes 2600 years to build up a difference in angular velocity of 0.5°/year. Since the mean lifetime of the centers of the secular variation is much smaller, a few hundred years at the most, it seems well-nigh impossible to interpret the westerly drift motion as a mere fluctuation.

Hence we must conclude that the earth's core actually rotates more slowly than the solid "mantle" surrounding it. It follows at once that owing to eddy friction at the boundary of the core angular momentum migrates from the mantle into the core. The core must continuously lose angular momentum, and this is impossible unless there is a direct gravitational interaction between the core and the moon such that the angular momentum lost can reappear in the orbital motion of the moon. Perhaps the interpretation of these results is facilitated by the recent discovery[9)] that the core is not homogeneous but contains a central body of as yet unknown constitution. This is indicated by the peculiar behavior of seismic waves at great depths. The boundary of this central body seems the natural <u>locus</u> of any tidal effects in the core.

It is one of the results of the theory of tidal friction that the dissipation in deep seas is negligibly small. The frictional effects of the oceanic tide computed by Jeffreys arise in shallow basins such as the Bering Sea, the Irish Sea, etc. It is in the nature of such a theory that no great numerical accuracy can be expected from it. We have just indicated

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that in place of one retarding couple acting on the earth there are two, one in the oceans and one in the core. It is difficult to estimate the relative magnitude of the two, as Jeffreys' theory of tidal friction can hardly afford a quantitative clue. The moment of inertia of the core is about one-tenth of that of the earth. Hence if the "inner" couple decelerated the core alone and the "outer" couple acted on the mantle alone, their ration would be one to ten. Since, however, angular momentum migrates into the core, the inner couple must actually be larger. Just what fraction of the whole retarding torque it constitutes can only be said when it becomes possible to estimate the magnitude of the eddy friction at the boundary of the core.

The existence of the westerly drift motion throws an entirely new light on the physics of the earth's interior. It strongly corroborates the theories which connect the phenomena of geomagnetism with fluid motions in the core in that it reveals the existence of a supply of power for the maintenance of such motions throughout the earth's life. As the present writer has shown[5)] the magnetic field in the interior of the core must be much stronger than the field at the outside and the energy of this internal field is directly supplied by the fluid motion. Numerical estimates make it appear possible that the conversion into magnetic field energy replaces mechanical friction in the core as the agent productive of the retarding torque. Whatever the ultimate outcome of these theories, it seems certain that the discovery of the westerly drift motion by Vestine opens up a new branch of geophysical dynamics.

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References:

1). J. K. Fotheringham, M. N. 80, 578; 81, 104 (1920)

2). H. Jeffreys, The Earth, 2nd. ed. (1929).

3). W. M. Elsasser, Phys. Rev. 69, 106; 70, 202, (1946)

4). S. Chapman, Nature 161, 462 (1948)

5). W. M. Elsasser, Phys. Rev. 72, 821, (1947)

6). E. H. Vestine et al., Carnegie Inst. of Washington, Publ. No. 578 (1947)

7). L. A. Bauer, Am. J. of Sci. 50, 109, 189, 314 (1895)

8). V. Carlheim-Gyllensköld, Ark. J. Mat. Astr. och Fys. 3, No. 7, (1906)

9). H. Jeffreys, M. N. Geophys. Suppl. 4, 548, 594, (1939)

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This report was prepared for the METEOROLOGY PROJECT of the Institute for Advanced Study by members of the Project, and approved by Professor John von Neumann, supervisor of the Project.

APPROVED: (signed) John von Neumann

May 18, 1948

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REPORT OF PROGRESS
ONR METEOROLOGY PROJECT
THE INSTITUTE FOR ADVANCED STUDY
PRINCETON, NEW JERSEY

Period covered: 15 December 1947
to 15 May 1948

This report was prepared under Contract N6ori-139,
between the Office of Naval Research and
The Institute for Advanced Study.

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I. Introduction

The following report will briefly summarize the activities of the ONR Meteorology Project at the Institute for Advanced Study during the period from 15 December 1947 to 15 May 1948. Our present investigations are centered around two main problems:

1. Prediction of day-to-day changes of large scale systems.

2. Reconstruction of the general circulation of the atmosphere.

However, for lack of an organized and already established meteorological theory, the most immediate objectives and subheadings of the main problems -- as, for instance, empirical estimation of large scale eddy stresses, representation of initial conditions, and formulation of a practicable mathematical theory -- are correspondingly remote from each other. These activities fall into roughly three categories: Semi-Empirical and Theoretical Research, and Numerical Methods.

II. Semi-Empirical Research

In order to characterize the zonally symmetric general circulation of the atmosphere, it is necessary to form average values of the meteorological variables over large intervals of longitude and time. The differential equations accordingly must be revised to apply to those mean values, for the process of averaging introduces additional and very real forces analogous to the Reynolds Stresses. Lacking a priori knowledge of the latter, we have been forced to resort to empirical means.

The distribution of large scale stresses has been investigated by the Department of Meteorology, New York University, under subcontract with the Meteorology Project. The results of those correlation studies and their bearing on the general circulation are discussed in the "Progress Report on the General Circulation of the Atmosphere" by Prof. H. A. Panofsky, under whose direction the work was done. That report is

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III. Theoretical Research

Considering the problems of meteorological hydrodynamics from the viewpoint of mathematics, one would certainly inquire into the uniqueness of solutions, and it is a question of more than academic interest to know that the solution following a sequence of numerical calculations is the only one possible or, if not, which of the possible courses to take. It is conjectured that this point is particularly critical as it concerns turbulent flow. This problem has already been treated by Oseen and Leray, who have shown that the state of an internally viscous fluid is regular under weak conditions of regularity on the initial state; however, these results, although of great generality, apply only to two-dimensional flows. Dr. Gilbert Hunt, who joined the Meteorology Project in February 1948, has sought to extend those earlier results in establishing conditions for regularity of three-dimensional flows, and has succeeded in simplifying Leray's arguments by applying the Fourier transform to the Navier-Stokes equations; it has been shown, furthermore, that the kinetic energy of a viscous fluid free of external forces must tend to zero, a result suspected but not proved by Leray.

To characterize the states of the atmosphere that are peculiarly meteorological and pertain to large scale systems, the initial conditions must be statistically "smoothed" or filtered to remove the small scale irregularities reflected in meteorological data. On the other hand, the hydrodynamical equations apply not to "statistical functions" of the variables but to the variables themselves. Lt. Thompson has studied the additional stresses introduced by the non-linearity of the equations, and will continue in efforts to formulate a system which governs the behavior of the atmosphere. This must be effected in two ways:

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1. The governing differential equations must refer to the averaged variables which characterize the initial state.
2. By inserting additional and necessarily empirical information about the atmosphere's large scale behavior, the differential equations must be rendered incapable of propagating high frequency "noise" -- i.e. sould waves, gravity waves, etc.

The latter has been given analytical treatment by Dr. Jule Charney, who will join the staff of the Meteorology Project in June 1948.

Lt. Thompson has completed a study of rotational waves which, although it deals with surface disturbances in particular, has direct bearing on the theory of atmospheric waves. This work has not been reported separately, but reprints from the Annals of the New York Academy of Sciences will be available in July 1948.

IV. Numerical Methods

The Department of Meteorology at New York University has continued to develop techniques of objective weather map analysis -- i.e., of analytic representation of initial data -- under the terms of its subcontract. Since 15 December 1947, that Department has constructed objective and independent analyses of pressure and wind fields according to the method of least squares outlined in the "Preliminary Report on Objective Weather Map Analysis." The work has been directed by Prof. Panofsky with Prof. von Neumann's close cooperation.

It is essential, in order to predict changes of the velocity field by numerical methods, that we be able to form an accurate estimate of the so-called "non-geostrophic" wind, the difference between the geostrophic and true winds. Non-geostrophic wind components have been

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measured from the independently analyzed fields of pressure and velocity mentioned above; the resulting distributions show synoptic regularity and appear to be otherwise adequate for calculating the local variations of velocity.

The first attempt to forecast day-to-day changes by numerical integration of finite differences was described in the report of progress for the period ending on 15 December 1947. The initial data have been collected and are being analyzed by the Extended Forecast Section, U. S. Weather Bureau, under the supervision of Mr. Philip Clapp. Basing the estimate on present resources, the initial data will be completely analyzed, read off, averaged to minimize spacially random error, and put into tabular form suitable for finite differencing by 1 August 1948. The routine of numerical calculations will require on the order of 500 calculator-hours per time stage; since the Weather Bureau has been able to furnish only 70 man-hours per week, it is imperative that the remainder of the computations be carried out by an agency specially equipped to handle them. Once the data are in tabular form, no meteorological knowledge is required to perform the necessary numerical operations. A proposal to procure the computational facilities of the Bureau of Standards will be forwarded separately.

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V. Turbulence and Stability Theory of a Parabolic Profile.

Some work on this subject was done by Professor John von Neumann, in cooperation with Dr. C. L. Pekeris, and some consultation with Professor C. C. Lin, of the Massachusetts Institute of Technology. A new form of the linear small-perturbation stability equations of the parabolic profile flow through a channel was developed. This new method requires the determination of one solution of a 6-th order complex linear total differential equation instead of the conventional two solutions of a 4-th order equation of the same type. It is expected that it will be less insensitive in furnishing the desired criteria and permit evaluation with a less important loss of digital precision. Arrangements are being made for orienting calculations, probably through the Computation Laboratory of the National Bureau of Standards (New York), and for a more complete survey with the help of the new, large-scale electronic computer of the International Business Machine Company (New York). The negotiations in connection with the latter, which are being conducted through the Pure Science Division of the International Business Machine Company, are developing in a promising way. It is expected that this work will clarify the question of stability-instability problem of the parabolic profile ("Poiseuille") flow. This is the classical Sommerfeld-Heisenberg-Lin approach to the theory of turbulence.

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This report was prepared for the METEOROLOGY PROJECT of the Institute for Advanced Study by Mr. Philip D. Thompson, and approved by Dr. John von Neumann, supervisor of the project.

APPROVED: ______________________________

December 16, 1947

Report #3

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METEOROLOGY PROJECT
INSTITUTE FOR ADVANCED STUDY
PRINCETON, NEW JERSEY

Report of Progress during the Period from 1 April 1947 to 15 December 1947 as provided for under Contract N6-ori-139, Task Order I

1 December 1947

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I. General Remarks on Objectives

The terms of Contract N6-ori-139, between the Office of Naval Research and the Institute for Advanced Study, provide for the following services, quoted in part from that contract.

(a) "research on the application of electronic computation to dynamic meteorology"

(b) "an investigation on the theory of dynamic meteorology to make it accessible to high speed, automatic computing techniques, and"

(c) "investigations which will give indications as to what new observational techniques are necessary, both of the laboratory and of the field type, in order to make more fully effective the theoretical work to be supported by high speed computing."

The necessity for such a program of research is too evident to merit much emphasis. The atmosphere or, for that matter, any continuous fluid medium is composed of a multitude of small mass-elements, whose behaviour is so interrelated that none can be dissociated, even in effect, from all the rest. Theoretical -- that is to say mathematical -- formalization of such complex physical phenomena leads to simultaneous systems of partial differential equations. These latter, except in certain special and rarely realized instances, are unfortunately non-linear and cannot be solved explicitly by any known method of analysis.

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In the past, theoretical meteorology has borrowed from techniques previously invented for more mature branches of inquiry. Since atmospheric changes are by nature interactive, or "non-linear", we have been forced to resort to devices for artificially "linearizing" the governing differential equations; in particular, the method of small perturbations, a scheme for finding solutions in the immediate neighborhood of some physically possible known state, has contributed much to the theory of growth and propagation of atmospheric disturbances. The usefulness of these improvisations cannot be denied or belittled. We are not, however, obviously justified in ascribing the properties of infinitesmal perturbations to disturbances in the atmosphere, in which the perturbation-variables are of exactly the same order of magnitude as the values characteristic of an "undisturbed" state.

It has long been recognized that a closed system of differential equations, ordinary or partial, linear or non-linear, may be regarded as a set of instructions for constructing its solution from known boundary and initial values. Until now, however, the time required to carry out those "instructions" has been prohibitive or, in any case, weighed heavily against any desire to manufacture exact solutions. Development of already existing or projected high speed computers has only recently brought direct, broadside attack on these problems within the realm of economic feasibility. But, although numerical analysis, implemented by automatic high speed computers, is a necessary remedy for our meteorological shortcomings, it must also be recognized that it is not sufficient in itself.

Owing to these and other circumstances, we are at present concerned with Objectives (a) and (b), and, most immediately, with (b). Objective (c) can be approached directly only when (a) is attained; that is, moreover,

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contingent on the availability of a satisfactory computer. In view of the present state of meteorological theory, Objective (b) tacitly implies that we have not only to translate mathematical statements into computational orders that are intelligible to a machine, but also to formulate much of the mathematical theory which is to be made accessible to high speed computing techniques. Indeed, at this point it is economical even to reconsider empirical evidence before launching an expensive program of numerical analysis.

II. Implementation.

In the course of negotiating the aforementioned contract, it was estimated that personnel of the Meteorology Project would include four senior and three junior scientists, and two clerks to handle any laborious manual calculations. Subsequent events have shown that the original estimate was overly optimistic about the number that could devote full-time to our purposes. Of the four senior scientists, Drs. Wexler, Queney, Montgomery, and Haurwitz, who tentatively considered full-time positions, only Dr. Queney has been able to contribute more than part-time assistance. Lieut. Thompson has been permanently stationed with the Project since November, 1946. The remainder of the Project's personnel have been available for part-time consulting and research, as indicated below:

Dr. Harry Wexler, Chief, Special Scientific Services Division, U. S. Weather Bureau, direction and consulting.

Dr. C. L. Pekeris, Columbia University, one third time consulting and research.

Dr. B. Haurwitz, New York University, consulting.

Dr. H. Panofsky, New York University, one third time research.

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In addition to directing the Meteorology Project and contributing to its researches, Professor von Neumann has been available for discussions of all phases of its activity.

In accord with the decision stated in an earlier report (Progress Report for the Period of 1 July 1946 to 15 November 1946), we have deliberately limited the Meteorology group to a compact, flexible body of theoreticians; until specific objectives were outlined, it was neither necessary nor desirable to take on a larger, less coherent group which might later prove unwieldy and require considerable administrative attention to keep it extricated from its own diffuse cross-purposes. Since that time, however, preliminary investigation of relevant subobjectives has suggested the course of further research, and the Project is prepared to increase the number of full-time personnel. We hope to secure, by the spring of 1948, the services of Mr. Gilbert Hunt, who was informally associated with the Meteorology Project in 1946, and Dr. Jule Charney, now at the Oslo Institute of Meteorology as a National Research Fellow.

In order to foster necessary semi-empirical investigations, which would be difficult to pursue in Princeton, the Meteorology Project has commissioned the Department of Meteorology, New York University, to undertake an extensive program of synoptic meteorological research. Subcontract for this work, which is already well under way, has been approved. This arrangement also insures the cooperation of Professor Haurwitz and Dr. Panofsky in matters of theory as well.

Adequate office space in the Electronic Computer Laboratory of the Institute for Advanced Study has been provided for the group permanently located in Princeton. At present this comprises about fifteen percent of the Laboratory's total office space.

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The Project has had to procure only a very few meteorological texts and periodicals, for the Institute's library, which has an excellent collection of mathematical and technical literature, has been placed at the disposal of the Princeton group.

It is imperative that some routine numerical calculations be carried out before an electronic computer will be available. Arrangements have been made with the National Bureau of Standards and with the U. S. Weather Bureau to handle at least one numerical forecast. The computational problems that have arisen so far were modest enough to be resolved by already existing devices; we are indebted to the Princeton Research Laboratories of Radio Corporation of America and the Mathematical Tables Group of the Bureau of Standards for contributing their facilities.

Last, but certainly not the least, of circumstances that have favored our interests, the housing development, built and operated by the Institute for Advanced Study, is open to Project personnel who are otherwise eligible (preference for veterans).

III. Subobjectives

In August 1946 a conference of eminent meteorologists met at the Institute for Advanced Study to decide what meteorological or allied problems should serve as immediate objectives of the Project (see account of Conference on Meteorology, 29-30 August 1946). Particular emphasis was laid on reconstruction of the general circulation, stability problems, indirect measurement of eddy viscosity, and forecasting by numerical integration. Although the Meteorology Project has treated these as distinct problems, they are not entirely unrelated. It can be shown, for instance, that the circulation of a non-viscous, zonally symmetric atmosphere is not completely determined; consequently, some large-scale measure of eddy stress

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is essential to a realistic model of the general circulation. Likewise, in connection with formulating methods of numerical forecasting, we are concerned about the stability of laminar flows.

Aside from semi-empirical and theoretical investigations of turbulent viscosity, the following general pursuits have been considered most urgent:

(1) To formulate systems of differential equations which best describe the general circulation and the day-to-day large-scale changes of the atmosphere.

(2) To anticipate as much as possible, on mathematical or other grounds, what difficulties will be encountered in numerical analysis of those equations, and to overcome or circumvent such inconveniences.

(3) To experiment with the resulting temporary methods in order to test for obstacles that might not be suspected for a priori reasons.

The remainder of this report will deal with the progress of the Meteorology Project toward the subobjectives stated in the section above.

IV. Synoptic and Theoretical Investigations of Viscosity

Due to the extreme mathematical difficulties involved, classical hydrodynamics and the physical hydrodynamics of meteorology have dealt almost exclusively with non-viscous fluids or with simplified and, from our viewpoint, trivial models. In point of fact, distressingly few closed solutions of the Navier-Stokes Equation, which takes into account only the internal viscosity of a fluid, are known at the present time. There is no complete theory of eddy viscosity in a turbulent fluid.

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There is some justification for supposing that purely internal viscosity of the atmosphere does not figure significantly in the propagation of atmospheric disturbances, and as an interim measure, for lack of any more definite hypothesis, we have chosen to exclude all effects of viscosity from the routine of numerical forecasting. As soon as they are known, however, particular attention should be paid to critical conditions under which laminar flow "breaks down" and eddy stress becomes a powerful force.

For the past year, Dr. C. L. Pekeris has conducted numerical investigations of the Heisenberg-Lin problem, concerning the dynamic stability of laminar viscous flow to small perturbations. Thus far, it has been ascertained that the second mode, for unit wave number, is stable for all values of the Reynolds Number. The computational phase of this work will be complete, with determination of the characteristic values for the first mode, by the end of January, 1948. Although it must be kept in mind that Dr. Pekeris' studies have been confined to Poiseuille flows, this preliminary estimate of the problem of laminar stability establishes a sound position from which further inquiry into atmospheric turbulence can be directed.

As remarked before, viscosity is a causa sine qua non of the general circulation of the Earth's atmosphere. If there were none, the boundary conditions and differential equations of motion in the absolute frame would be independent of the Earth's rotation -- that is to say, the motions of the envelope of air could not be affected by the rotation of the Earth inside.

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Primarily, the theory of large-scale stress has suffered a great dearth of substantiating evidence. To alleviate this condition, the terms of the Project's subcontract with New York University provide for semi-empirical measurement of the large scale, horizontal components of stress. These stresses are identified, properly speaking, with an indirectly measured "residue" force, the difference between observed changes in momentum and the forces that have already been taken into account -- i.e., the pressure, gravitational, and Coriolis forces. This program of research will gradually and quite naturally merge with studies of the general circulation, both of which are being carried on at the Department of Meteorology, New York University under the supervision of Drs. Haurwitz, Panofsky, and Miller.

V. Initial Values

Numerical methods of rational weather prediction are not entirely untried; L. F. Richardson in 1917 and, at a somewhat later date, R. D. Elliott attempted to calculate local derivatives of meteorological elements by the Method of Finite Differences. The results of neither of these trials were within the realm of reality. Both Richardson and Elliott were inclined to attribute most of their errors to those engendered in the initial values of the variables. To minimize "non-representativeness" and human error among the initial data, Richardson assigned mean values of the variables, taken over an interval of time, to the central moment of that interval. But, although his decision was undoubtedly forced by an insufficient number of data, local peculiarities and procedural errors are by their nature systematic in time, but nearly random in space. It is most reasonable, therefore, to remove those errors from the initial values by averaging over regions of space.

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Utilizing this principle, Professor von Neumann and Dr. Panofsky have devised objective methods for representing the initial state of affairs. Those techniques involve determination of the algebraic polynomial whose "least squares" fit with respect to a given set of raw observational data is the best. The number of terms in a particular polynomial is about one-fourth the number of observations it seeks to represent; hence, in a manner of speaking, each coefficient is the "mean value" of four others, averaged spacewise.

The labor of calculating the matrix coefficients of these polynomials has been undertaken by New York University under its subcontract. The Princeton Research Laboratories of RCA and the Mathematical Tables Group of the National Bureau of Standards have obligingly furnished additional facilities and assistance. Resulting representations are found to agree better with subjective synoptic analyses than do the individual subjective analyses agree among themselves. This work is presented in detail in the "Preliminary Report on Objective Weather Map Analysis" by Dr. Panofsky.

However, until we can avail ourselves of a high speed computing machine, the task of evaluating enough matrix coefficients to cover a considerable collection of data would be arduous indeed. The initial values of preliminary experiments in numerical forecasting will be formed simply by averaging variables over suitably partitioned regions of space.

VI. The Governing Differential Equations

The fundamental equations, even for an isentropic ideal atmosphere, are not well suited to numerical analysis as they stand. Aside from the unfortunate but hard fact that hydrostatic equilibrium is implicit in all

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standard measurements of pressure, the vertical component of acceleration is invariably the small difference between the pressure and gravitational accelerations; consequently, the local variation of the vertical speed is an even smaller quantity. Moreover, the vertical component of velocity is neither observed nor susceptible to exact measurement. In view of these considerata, it would be highly desirable to know the vertical component of velocity at any moment in time as an explicit function of the distributions of other variables at that particular instant. The required expression, an integral-differential function of the pressure and horizontal velocity fields, has been found.

Another difficulty, also stemming from innate sensitivity of the fundamental equations, must be reduced to less formidable proportions; the local derivative of pressure is an integral of the local variation of density, which is always a very small difference between large terms. This circumstance can be obviated by an alternative expression involving the local changes of potential temperature. The latter are of the same order of magnitude as the advective variations of potential temperature.

The phenomena described by the general form of the hydrodynamic equations cover the entire spectrum of events, sonic waves, gravity waves, slow inertial waves, et cetera, and it might simplify matters considerably if those equations were somehow informed that we are interested in only certain kinds of atmospheric behaviour — i.e., the propagation of large-scale disturbances. This is tantamount to constructing a "mathematical filter" to remove "noise" and otherwise unwanted regions of the spectrum.

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Several such "filters" are frequently, though perhaps unwittingly incorporated in theoretical models of the atmosphere to make them more tractable to mathematical analysis. For instance, sound waves may be precluded by supposing that the fluid is exactly homogeneous — that is to say, incompressible — simply because they are longitudinal waves. Likewise, gravity waves, although they are transverse, cannot exist in fluids which experience no change in potential energy. In fact, every idealized model is, in a manner of speaking, a filtering device. By imposing certain restrictions suggested by empirically known compensating mechanisms, it appears quite feasible to "extract the essence" of the mode of behaviour in question.

The Meteorology Project has considered several filter-models and, wherever possible, analyzed them to discover whether their properties do reflect those of the atmosphere. Detailed discussion of a barocline atmosphere is included in a recent paper by Professor Queney, entitled "A Theoretical Study of Free Atmospheric Perturbations. Elastic, Gravity, and Long-Period Waves." Lieut. Thompson has completed a study of "Permanent Waves in Homogeneous, Plane Fluids", which will be distributed as soon as it has been reproduced in quantity.

VII. <u>Numerical Routines</u>

Formulation of a suitable system of differential equations, boundary and initial values is certainly not the last of our difficulties. The usual method for numerically constructing the solution of such a system entails a routine of this sort:

(i) From the boundary and initial values calculate derivatives in the direction of integration at all possible points.

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(ii) Next, assuming that the derivative at a point applies over a small interval in the direction of integration, extrapolate values to adjacent points where they were unknown before.

(iii) Repeat the performance until as much of the space-time lattice is filled as desired.

Now it is commonly supposed that this procedure will approximate the true solution, and that the approximation becomes better and better as the mesh-size of the lattice is chosen smaller and smaller. This is apparently true for systems of ordinary total differential equations, but Courant, Friedrichs, and Levi have shown that these operations may be carried out ad infinitum, ad nauseum, et ad absurdum before converging on the solution of a partial differential equation. Unless certain critical inequalities, depending on the dimensions of a lattice element and the physical constants involved, are satisfied, the method of extrapolation over finite intervals amplifies transient error; computations are then truly unstable and "blow up". Needless to say, this rather intangible mathematical phenomenon is a very real worry.

Suspecting that the faults of the Method of Finite Differences lay in unweighted extrapolation, Professor von Neumann has outlined numerical routines which are absolutely stable to errors incurred in the course of calculation. We are reassured that there is no a priori reason why numerical methods might fail.

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VIII. Experiments in Numerical Analysis

To reveal any impedimenta that might not have been foreseen above, it is urgent that a few numerical solutions be manufactured, in the most literal sense, by hand. Although steady-state problems, owing to the small range of advective variations in the atmosphere, would be easiest to approach, we are concerned principally with the resolution of variables in time, and have therefore chosen to produce a mathematical forecast.

Mr. Philip Clapp, of the Extended Forecast Section, U. S. Weather Bureau, has discussed all aspects of numerical forecasting, including boundary conditions, with Professor von Neumann and Lieut. Thompson. Mr. Clapp has selected the initial synoptic data and will supervise computations, which are to be carried out by the National Bureau of Standards and the statistical section of the U. S. Weather Bureau. Several variants of the Method of Finite Differences will be tried in the course of this experiment.

One other steady-state problem, apart from the previously mentioned investigations of the general circulation under way at New York University, has been posed for numerical solution. Mr. Colson, a graduate student at NYU, has undertaken to reconstruct flows over irregular terrain according to a numero-geometrical method suggested by Lieut. Thompson. This work will require no expense to the Project.

IX. Coding of Numerical Problems

In order to make the theoretical problems of meteorology completely accessible to the techniques of high speed computing, corresponding numerical problems must be stated in a form that computing machines can understand -- i.e., expressed in the sequence of numerical operations to be performed by machines. The language of operations and translation or coding of mathe-

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matical problems, with which the Meteorology Project must ultimately concern itself, is discussed in "Planning and Coding of Problems for an Electronic Computing Instrument" by Drs. Herman Goldstine and John von Neumann, of the Electronic Computer Project, Institute for Advanced Study.

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PROGRESS REPORT FOR THE PERIOD OF NOVEMBER 15, 1946 TO APRIL 1, 1947 UNDER CONTRACT N6-ori-139, TASK I (METEOROLOGY PROJECT)

A. General Remarks

This report, like the preceeding one, is being prepared after a relatively long interval and for the same reason; the project is still in its preparatory stage and progress has therefore been slower than it should be when the main phases have been reached.

It may be useful to refer at this point to the earlier reports made in connection with this project. They are as follows:

(1) Report on a conference on meteorology, held in Princeton on August 29-30, 1946. This report comprised five typewritten pages and was submitted in a letter to Lt. Commander D. F. Rex of the ONR.

(2) Progress Report for the period of July 1, 1946 to November 15, 1946. This report comprised three typewritten pages and was also submitted in a letter to Commander Rex.

B. State of the Project

The problems of office space and of housing, which were the main difficulties when Reference (2) was written, have been overcome. The Institute's Computer Building was completed in early January, 1947, and has been occupied since, in particular by the members of the Meteorology Project. The Institute's housing project, also referred to in Reference (2), has been in the main completed. About three fourths of the housing referred to is already occupied. Among the personnel of the Institute connected with the Meteorology Project who are living there are Drs. H. H. Goldstine and C. L. Pekeris, and Lt. P. D. Thompson.

The office space and housing problems which caused us decisive

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difficulties in securing personnel at the time of the start of the project are now, therefore, very greatly reduced.

It is therefore considered reasonable to begin with a cautious expansion, as discussed in Reference (2). It must be emphasized, however, that this has to be done very slowly and carefully, since a great deal remains to be done towards the integration of the group, and since the organization of our computing facilities will still take considerable time. Specifically, two steps toward expansion are now contemplated:

(1) We are endeavoring to secure the services of Dr. R. Elliot, of the California Institute of Technology

(2) We are taking the necessary steps, in cooperation with the head of the Meteorology Department of New York University, Dr. B. Haurwitz, to carry on our cooperation with that department on a broader and more systematic basis.

C. Work Done

(1) Dr. H. Panofsky and myself are working together towards developing objective methods for the analysis of weather maps. We feel that it is absolutely necessary to develop non-subjective, mathematical methods to fit streamlines, isobars, and other characteristic curves to the observed wind and pressure maps. The ideal procedure would be a rigorous application of the least square method for the entire United States. The functions to be used might be polynomials or, in view of the largeness of the area, appropriate spherical harmonics. The number of observed points is of the order of 150; the desirable amount of "smoothing" and "compressing" these data would suggest fitting with expressions of about 40 parameters. This will be feasible with the electronic computer which we develop; however, it is entirely beyond the range of any equipment and technique now available. We have, therefore, developed a method which permits to piece together this 40 parameter fit from several 10-parameter fits. Equipment and methods for a 10-parameter fit are

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available. For this purpose we have used a 10-equation, 10-variable electrical linear equation solver, which the Princeton laboratories of the Radio Corporation of America have developed and obligingly made available to us. We are also trying digital methods. We have obtained for this purpose the help of the Mathematical Tables Project (New York) of the U. S. Bureau of Standards. The latter organization has been very helpful in various other numerical tasks as well. We have already carried out a number of 10-parameter fits and the results so far are encouraging. A good deal more experience is still required, both in order to study the inner consistency of this method and its relation to present, subjective methods. As long as we are in this preliminary stage the necessary computing work cannot be very rigorously routinized and must therefore be disproportionately time-consuming. It is expected that we will outgrow this preparatory stage in a few months, and will then set up an organization to do this work at a much greater speed and in a routine fashion.

(2) At present, the main purpose of the objective weather map analysis described in (1), above, is to obtain divergence and vorticity maps. Various other applications are also contemplated; all of them will be coordinated and correlated with work now being done by New York University in similar fields. It is expected that their work and ours will be of considerable mutual help.

(3) The work referred to under (1) will be reported in a technical report as soon as a sufficient number of fits have been carried out and a logically rounded picture of its first phase is obtained. This is likely to become possible in two or three months.

(4) I have studied the numerical methods of integration for the hydrodynamical equations of meteorology - in particular, in view of their stability. I have found that they are unstable under those conditions of

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spatial and temporal resolution which are essentially characteristic of the problem of meteorological prediction. This instability explains certain difficulties in past attempts at prediction by numerical calculation; it is closely connected with certain methematical results of R. Courant, K. Friedrichs and H. Levi. They make it imperative to develop entirely new methods of numerical integration. I have developed one method which can be shown to be stable and which appears to be suitable for numerical procedure if electronic equipment is available. Further studies of the subject are necessary and in progress.

(5) The studies referred to under (4), above, also show the desirability of carrying out certain meteorological calculations under the assumption of incompressibility, although this assumption might otherwise seem physically unjustified. Lt. Thompson is now studying this aspect of the problem.

(6) An effort is being made to attract Dr. R. Elliot from the California Institute of Technology to the Project, since his past interests are very much in the direction of meteorological forecasting by numerical integration. He would probably be of very considerable help in furthering the studies referred to under (4), above.

(7) A technical report on the work mentioned under (4) will be issued as soon as the subject has been given a mathematically satisfactory presentation, which I expect to be the case in a few months.

(8) Dr. P. Queney is continuing his work on perturbations in the atmosphere. He has developed a theory of perturbation waves of atmospheric flows, allowing for inhomogeneities in the underlying flow velocity field, as well as the underlying temperature, vertical stability, and Coriolis fields. He has obtained significant results on the classification of these waves and their stability properties. He is now engaged in preparing a complete presentation of his results.

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(9) It is contemplated to send Dr. Queney on a trip of about 14 days to various meteorological centers in the Middle West and the Pacific West, to study work which is done there and which parallels his own. His conclusions will be reported subsequently.

(10) Dr. Pekeris is continuing his work on the stability of the Poiseuille flow (laminar viscous flow through a pipe). The region in which his calculations are now proceeding coincides with the critical region of the previous work of Heisenberg and Lin. The numerical difficulties in this domain are very considerable and calculations will probably have to continue for some time.

(11) Dr. Pekeris is also engaged in studies of various atmospheric wave motions, but it is still too early to report on these.

John von Neumann
Project Supervisor

April 8, 1947

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Progress Report for the Period of July 1, 1946 to November 15, 1946, on Contract N6ori-139, Task I. (Meteorology Project)

I. General Policy

This report is being prepared after a relatively long interval because the project is still in its preparatory stages and it has therefore been necessary to proceed slowly and cautiously.

The desire to enlist a large group of collaborators * has been effectively limited by the extreme shortage of housing and almost complete lack of office space in Princeton, coupled with great difficulties in erecting new structures. The Institute had therefore planned, from the start, to provide office space for the Meteorology Project in its new Computer Building. This building has suffered delays, like all construction in this area, but it is making relatively good headway, and it is expected to become available in the course of December, 1946. In the meantime, it was necessary to provide office space under emergency conditions in the Institute's present, main building, Fuld Hall.

With regard to the housing situation, the Institute has made an exceptional effort, by acquiring 13 houses equalling 32 family units, from a Government settlement at Mineville, New York, transporting them by rail to Princeton, and re-erecting them here, all at its own expense. (The houses are unused and rated as 'permanent.') The first house has just been completed and is ready for occupancy, the entire complex is expected to be finished no later than January, 1947. These houses are expected to take care of the needs of the Meteorology Project (as well as of certain other needs of the Institute). In the meantime, it was necessary to provide emergency solutions for some of the members of the project (one family of four has been living in Fuld Hall since early November), and part-time employment which facilitates commuting to Princeton had to be encouraged.

Under these conditions the large group foreseen in Reference * (below) could not be taken on immediately. This delay, as well as various intervening changes in their personal status and aims, caused, furthermore, that several of the investigators who were ready to join the project in August/September, 1946, and were only holding back because of the lack of housing, have now become unavailable or less available. This changed the administrative needs of the project, and caused Dr. H. Wexler of the U. S. Weather Bureau to prefer a part-time scientific tie-in with the project to the original scheme, which provided, in addition, for rather extensive administrative responsibilities on his part.

After having given considerable thought to these circumstances, and after a thorough discussion with Professor C. G. A. Rossby, Dr. Reichenlderfer and Dr. H. Wexler, I decided that these new facts justified a policy different from the one originally contemplated *. The colleagues referred to above, as well as Commander D. F. Res, agreed with me on this and confirmed my judgement. For these reasons, I now propose to proceed as follows:

* See our project proposal, dated May 8, 1946, sent to O.R.I., attention of Lt. Commander D. F. Rex

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It seems clear to me that the optimum initial size for our Meteorology Group is not the large on contemplated in the footnote reference of the preceding page, but that a smaller amd more compact group is preferable - at least for the beginning, say, for the next six months. This removes the necessity for more detailed and time-consuming administrative arrangements, and permits me to maintain a closer personal contact with all members of the group. A larger group would have to develop its own program and establish its own homogeneity, and if it does not prove to be organically able to do this, then it is very difficult to intervent and correct, without a good deal of administrative machinery and a sacrifice of time which would seriously conflict with my other duties. In this connection, I must particularly emphasize my duties to the Institute's Computer Project, which has to be successfully concluded, or our Meteorological Project, too, would be seriously impaired in its usefulness. With a smaller group, on the other hand, I can see to it personally that the group works in a unified direction and acquires an inner homogeneity. After this has been achieved, the organization can stand on its own legs, and it will be time to expand it, and to bring it nearer to what the original conception was. As I mentioned, I anticipate that the conditions for such a re-expansion might exist by mid-1947. Even then, I would proceed gradually and cautiously.

These are the general principles that I propose to follow. Their discussion will have made it clear that the project is still in a very early stage, and that there is not much technical material to be reported. Also, what there is represents initial steps in various directions which will produce well-rounded, and well-reportable results only later.

I will nevertheless give a brief account of these and connected matters in what follows.

II. Personnel

The personnel of the Meteorology Project is at present as follows:

1. Dr. P. Queney of the Institut de Meteorologie et de Physique du Globe, Algiers, France, - full time.

2. Dr. C. L. Pekeris, New York, about one third time consulting. Dr. Pekeris will move to Princeton shortly when our housing becomes available, and will then be able to devote more time to our work.

3. Dr. H. Panofsky, New York University, about one third time, probably more later.

4. Dr. H. Wexler, U.S. Weather Bureau, who is spending about one day per week in Princeton.

5. Dr. A. Cahn, full time, but his work with our group will end on December 15, 1946.

6. Lt. P. D. Thompson will join the project full time before December 1, 1946.

7. Dr. (formerly Captain) G. Hunt has participated in many of our discussions. Since he is working for a Ph.D. degree in Mathematics in Princeton University, his relation to the project has not been formalised so far.

Arrangements for occasional consulting have been made with various other colleagues.

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III. Work Done

A conference was held in Princeton on August 29, 30, 31 (1946) to discuss the program for our work. It was attended by 16 meteorologists from various parts of the country and one from abroad. I have reported on its composition, its deliberations and its conclusions earlier *.

On the basis of these discussions, as well as of the experience that has been acquired since, the following investigations are now in progress:

1. Dr. Queney is continuing his work on the perturbations of the atmospheric air flow caused by the ground profile. He participates in the work of a mixed Service-Weather Bureau committee on this subject. He attended a conference on this subject on November 20, 1946, in Washington. This report concerning that conference will be submitted shortly. He has also worked out various proposals dealing with an observational program for the upper atmosphere. I will also report on this before long.

Dr. Queney's work on perturbations seems very interesting but still presenting considerable difficulties. It will be continued and expanded, and reported as the occasion arises.

2. Dr. Pekeris is continuing his work on the instability theory of turbulence in parallel flows. This work is more fluid-dynamical than strictly meteorological, but it touches on the problem of fluid-dynamics that is most critical for meteorology. His progress with this problem is remarkable, and also opens up interesting computational vistas. It will be reported as the occasion arises.

I expect that Dr. Pekeris will devote subsequently part of his attention to the questions of the upper atmosphere.

3. Dr. Panofsky is engaged in work at NYU to obtain and to assess critically observational material on the vertical motion of the atmosphere. We have reached the conclusion that this work is the best starting point for a more general mathematical effort to derive the vorticity-field and the divergence-field of the atmospheric wind-field from the observations. This will serve as a basis for a subsequent effort to integrate the hydrodynamical equations of atmospheric flow numerically.

The work dealing with the vorticity-field and with the divergence-field is now under way.

4. Dr. Wexler has been available for consultation to all members of the project.

5. Dr. Cahn is now writing a report on a system of the hydro-dynamical equations of atmospheric flow.

6. Lt. Thompson will take over Dr. Cahn's work.

John von Neumann
Project Supervisor

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* See my report on the Meteorological Conference of August 29-30, 1946, sent to O.R.I., attention Lt. Commander D. F. Rex.