THE INSTITUTE FOR ADVANCED STUDY

THE METEOROLOGY PROJECT

Summary of work

under contract N-6-ori-139 (1), NR 082-008

during the calendar year 1952

1. The problem of primary interest at present is the prediction of changes of atmospheric flow over periods of 24 to 48 hours. The prediction of the field of motion is a necessary, though not a sufficient, prerequisite for predicting cloudiness and precipitation. The philosophy guiding the approach to this problem has been to construct a hierarchy of atmospheric models of increasing complexity, the features of each successive model being determined by an analysis of the shortcomings of the previous model.

The primitive equations of motion reflect the fact that the atmosphere is capable of sustaining a wide spectrum of disturbances. For the purpose of short-range weather prediction, only those disturbances of planetary dimensions with periods of 3 to 7 days are of importance. These motions may be characterized as quasi-hydrostatic and quasi-geostrophic. One can take advantage of these characteristics by applying the hydrostatic and geostrophic approximations to the equations of motion. The effect is to filter out the meteorologically irrelevent noise motions. The prediction problem is thus greatly simplified from an observational and computational point of view, with scarcely any loss of applicability. For the initial conditions one needs in general only a knowledge of the three-dimensional pressure field.

2. The work during the calendar year 1952 was geared to the use of the Institute computer which was completed early in the year. It was decided that the most logical procedure was to test the various models on a single sequence of weather events. For this purpose the storm of November 25, 1950 over the eastern United States was admirably suited. This storm was one of the most rapid and intense developments ever to

have been recorded by a modern observational network. Since its development involved large conversions of potential to kinetic energy and since it was well documented it appeared to be an excellent laboratory in which to apply the various models.

Two models were treated by the machine; the equivalent barotropic model and a simple baroclinic model. The barotropic model does not take into account variations of the vertical structure of the atmosphere since it predicts for only the flow in the 500 mb pressure surface. It is implicitly assumed that no potential energy is available for conversion to kinetic energy. With this constraint the model is capable of predicting only redistributions of the initial kinetic energy.

Barotropic forecasts had already been made for a number of separate situations on the ENIAC in 1950*. It was decided to prepare barotropic forecasts for the November storm to serve as a control for the more general models. The method of solution of the equations was somewhat modified from that used on the ENIAC in order to gain experience with methods that were also adaptable to more complicated models. The programs, flow diagrams and coded instructions for the machine were prepared by the Meteorology Group. A number of preliminary tests were made to decide on the proper length of the time increment in the finite difference equations and the requisite digital significance of the initial data. The time increment must be small enough so that round-off errors are not amplified. First experience showed that an automatic internal checking system was required to prevent the computation from going too far after a machine error had been committed. As a further check, all calculations were performed twice.

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* Charney, Fjörtoft, and von Neumann, 1950: Numerical Integration of the Barotropic Vorticity Equation, <u>Tellus</u>, <u>2</u>.

It is of some interest to indicate the amount of work done by the machine to produce a 24 hour forecast even by means of the relatively simple barotropic model. The square grid contains 361 grid points about 200 miles apart 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. At full speed a 24-hour forecast requires about 1 1/2 hours. Since an experienced person with a desk calculator is about 10,000 times slower, it would take almost 8 years for one person working a 40 hour week. Actually the machine operated at half speed most of the time. However, methods have recently been developed for decreasing the 24-hour forecast time to approximately 10 minutes. Until October teletype apparatus was used to read data into and out of the machine. Because this device was very slow, more than half the time was spent in communicating with the machine. With the introduction of IBM equipment the input and output operations are accomplished in one-tenth the time previously taken.

Six barotropic forecasts were prepared for 12 and 24 hours from initial data at 0300 Z and 1500 Z for the dates November 23 to 25, inclusive. As was suspected this model was incapable of fully predicting the extremely rapid and intense development of the storm over a period of 24 hours. Although the areas of pressure rise to the west of the storm were satisfactorily predicted, invariably the falls in advance of the storm were not great enough and were centered too far north.

As a first step in attempting to overcome the errors by taking the three-dimensional character of the atmosphere into account a simple baroclinic model was constructed. The model consists essentially of two barotropic layers and requires initial data at the 700 mb and 300 mb levels. It was necessary in order to avoid computational instability to proceed in half-hour time steps. The total computation time for a 24-hour forecast was approximately 2 1/2 hours at full speed. However, the machine usually operated at half speed.

Two-layer model forecasts were prepared for the same periods as for the barotropic forecasts. Appreciable improvements over the barotropic forecasts were noted. Correlation coefficients for the predicted and observed 12 and 24 hour changes for the two different models are given below:

Initial date	Barotropic forecast for 500 mb		2 layer-model forecast for 700 mb	
	12 hour forecast	24 hour forecast	12 hour forecast	24 hour forecast
Nov. 23/50, 0300Z	.89	.72	.89	.90
23/50, 1500Z	.81	.77	.86	.87
24/50, 0300Z	.88	.75	.86	.73
24/50, 1500Z	.74	.51	.77	.62
25/50, 0300Z	.61	.61	.58	.56
25/50, 1500Z	.81	.59	.73	.87

These correlation coefficients indicate that the degeneracy of the forecast from 12 to 24 hours is generally not nearly so great for the 2-layer model as it is for the barotropic model. This leads us to believe that useful results may be obtained with the 2-layer model for forecast periods up to 36 and possibly 48 hours. We are therefore planning to extend the two-layer forecasts to longer periods. The vertical velocity field and therefore cloudiness and precipitation are also forecast by the two-layer model. Preliminary calculations indicate fairly good agreement with observation.

3. No account can be taken of the horizontal variations of the static-stability in the two-layer model. A diagnosis of the nature of the two-layer model's shortcomings indicates that this artificial constraint may be of importance. In order to remove it, a model with information at a minimum of three levels is required. Such a model is now in the process of preparation for the machine.

Much thought has been given to the construction of a full three-dimensional model which will adequately describe the vertical variability of the atmospheric motion. The theoretical and programmatical problems are manifold. Since non-adiabatic effects must at present be neglected for lack of adequate knowledge, the motion is regarded as adiabatic. The potential temperature is then a conservative quantity and may be used as the vertical coordinate in a semi-Lagrangian coordinate system. In this system the equation of motion has a beautifully simple form and is well-adapted to numerical integration. The complete integration of this equation has now been programmed for the I. A. S. machine. The actual coding and computation now awaits the completion of a magnetic drum auxiliary memory, which is needed in a computation of so large a magnitude as this.

We plan eventually to consider the influence of non-adiabatic effects, large-scale orography, and friction at the earth's surface. Also since the geostrophic approximation does not always appear to be valid, investigations are being made of higher order geostrophic approximations.

Even with the present crude models, cursory comparison with subjective prognoses made by experienced forecasters indicates at least comparable accuracy. Moreover, whereas subjective methods have not shown significant improvement in the past 20 years, the present approach may be refined in a logical manner. It is therefore expected that more realistic atmospheric models will yield predictions becoming progressively and significantly better.

The activities of the Meteorology Group at Princeton have created much interest in numerical weather prediction throughout the world. Research in this direction is concurrently being conducted in England, Norway, Sweden, Denmark, Germany and Japan. In this country the Weather Bureau and the weather services of the Navy and Air Force have expressed their desire to investigate the possibility of preparing numerical forecasts on an operational basis. At a conference held at the Institute on August 5th it was decided that each of the weather services should send one representative to Princeton to obtain experience in the methods of numerical forecasting. They will arrive about January 1st, 1953 and will remain for a period of approximately one year.

4. In addition to the problems directly connected with short-range forecasting, the Group has also been studying the problem of the general circulation. An understanding of the processes governing the general circulation is essential for longer range forecasting. In this connection a study was made of the influence of large-scale longitudinal asymmetries in heating on the mean seasonal flow pattern. The calculations indicate that this effect is of primary importance in explaining the observed normal patterns in the lower troposphere and is of equal importance with the orographic influence at higher levels.

The role of unstable baroclinic disturbances in maintaining the energy balance has also been investigated. The results show that amplifying large-scale baroclinic disturbances convert sufficient potential to kinetic energy to balance the frictional loss and at the same time are capable of transporting enough heat poleward to balance the net radiational loss.

In cooperation with Professor Starr and Dr. Lorenz of M. I. T. a program was drawn up with the aid of Professor Tukey at Princeton University to calculate power spectra and lag correlations for a time series of zonal and meridional indicies by means of the machine.

5. Article in press: J. Charney "On Baroclinic Instability and the Maintenance of the Kinetic Energy of the Westerlies" - Transactions of the International Association of Meteorology, Brussels, 1951.

Article to be published in May issue of the Journal of Meteorology, 1953: J. Charney, N. Phillips - "Numerical Prediction of Barotropic and Baroclinic Flow"

Article to be published in the Quarterly Journal of the Royal Meteorological Society, 1953: J. Smagorinsky "The Dynamical Influence of Large-Scale Heat Sources and Sinks on the Quasi-Stationary Mean Motions of the Atmosphere"