Use of Incomplete Historical Data to Infer the Present State of the Atmosphere

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One of the principal objectives of the Global Atmospheric Research Program (GARP) is the acquisition of data which define the synoptic state of the atmosphere globally for use in long-range prediction. Since all proposed global sounding systems suffer limitations, the concept has arisen of a combination of several such systems permitting trade-offs among the meteorological parameters and between space and time.[2] The system

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[2] See preface in "Plan for U. S. Participation in the Global Atmospheric Research Program," National Academy of Sciences, Washington, D. C., 1969.

nearest of realization is the temperature sounding satellite. The successful launching of the Nimbus III presently permits the calculation of temperatures down to cloud top, and a satellite equipped with high-resolution, scanning-infrared and microwave radiometers would be capable of sensing temperature-dependent radiances through broken and non-precipitating clouds as well. If it should prove to be possible to obtain the large-scale wind field from temperatures alone, the time-table for the implementation of GARP might be substantially advanced. And if instantaneous low-level temperatures and winds could be inferred from a continuous monitoring of their values at higher levels, and, say, surface pressure, the time-table might be advanced still more rapidly.

We have considered each of these possibilities in a simplified mathematical context. With respect to the first, it is well known that a good approximation to the instantaneous wind field at middle and high latitudes can be obtained from pressure observations through use of the geostrophic or balance approximations, but we wish to point out that a wind approximation can be obtained at *all* latitudes, and from temperature observations alone, if only the temperature history is added. This may be made plausible from the following considerations. It is known from the linearized hydrodynamical equations and can be shown generally that initial conditions on the velocity components can be replaced by initial conditions on the first and second time-derivatives of pressure. The pressure, in turn, is determined hydrostatically from the temperature and the surface pressure. Since large-scale atmospheric motions are coupled vertically, it is to be expected that only one space-time field of pressure will correspond to a given space-time field of temperature. Hence, the winds as well as the surface pressure variations, are determined, in principle, from historical temperature data. In practice, the winds may be calculated for a time $t=t_0$ by integrating the equations of motion from $t=0$, while supplying artificial heat impulses to bring the temperatures periodically to their correct values. If t_0 is greater than the characteristic dissipation time, the winds can be expected to approach their correct values by $t=t_0$. If the temperature field has an error ϵ, then the other fields can be determined to within an error whose statistics can be inferred from those of ϵ.

The second problem, to determine all of the dynamical and thermodynamical variables in an intermediate layer of the atmosphere from a knowledge of their time variations above and below this layer, is a difficult inverse interpretation problem. It has some analogies to the scattering problem in atomic physics or to the problem of determining the solid earth structure from elastic scattering data at the surface. The existence of a solution is made plausible by the fact that the governing differential equations have characteristic surfaces which are inclined to the horizontal, i.e., which permit vertical signal propagation. The presence of

energy sources and sinks will not render the problem indeterminate if, as in the atmosphere, they are dependent on the dynamical variables.

Since the existence of solutions to the linear problem does not guarantee solutions to the nonlinear problem, and since, operationally, the nonlinear problem must be viewed within the finite framework of the difference approximation to the equations of motion and the discrete observations, we have commenced two series of numerical experiments at the Goddard Institute for Space Studies using the Mintz-Arakawa global circulation model.[3] The model predicts winds and temperatures at 800 and 400 mb and pressure at sea level. The grid spacing is 7° in latitude and 9° in longitude.

In the first experiment a "history tape" was generated by carrying the numerical integration of the Mintz-Arakawa model forward for 170 days. This tape was treated throughout the remainder of the study as the "correct" model. That is, it was taken to represent the actual circulation within the physical limitations of the model. At day 85 a random temperature "error" perturbation of 1C was introduced, just as in the predictability study, and the flow was recalculated for 10 days to day 95, at which time the root-mean-square (rms) errors in the Northern Hemisphere for T, and for u and v, the zonal and meridional velocity components, were respectively, 2.8C, 2.0 m sec^{-1} and 2.1 m sec^{-1} at 800 mb, and 2.0C, 3.9 m sec^{-1} and 4.4 m sec^{-1} at 400 mb. At day 95 the "correct" temperatures were inserted at intervals of 1, 6, 12 or 24 hr, and, in each case the flow was calculated for 60 additional days to day 155. The greatest reduction of error variance was achieved when the "correct" temperatures were inserted every 12 hr. A more frequent insertion of these thermal impulses seemed to give rise to inertio-gravity oscillations which prevented the dissipative forces from adjusting the wind field to the temperature field.

The calculations were repeated with the temperatures inserted at intervals of 12 hr and with random errors at each grid point of 1, 0.5 or 0.25C. In each case the rms errors in the winds and surface pressure decreased rapidly for the first day or two, then more slowly, and finally levelled off at approximately 20 days. The final reduction of variance was of course a decreasing function of random error and greatest for the case of zero random error. The results are shown in Figs. 1–3. The first two figures show the rms error in the 400-mb zonal wind component as a function of time at latitude 49° and at the equator, respectively. It is seen that the errors are reduced to acceptable values at 49° but not for all cases near the equator. A similar behavior is observed for the meridional component.
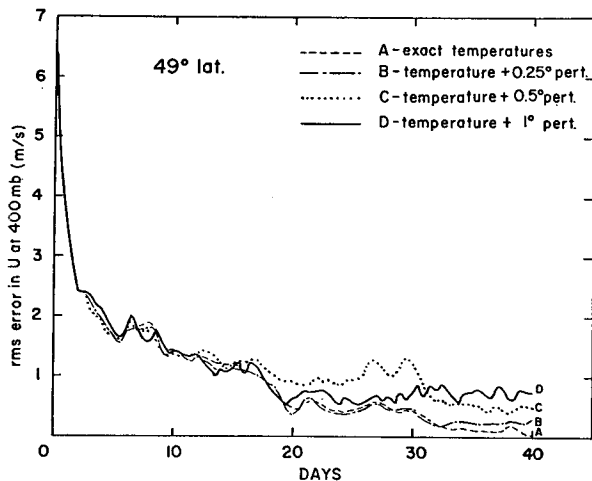
FIG. 1. The rms error in zonal wind (m sec^{-1}) at 400 mb at 49° latitude, in cases where temperatures with random error perturbations of 0, 0.25, 0.5 and 1C are inserted every 12 hr at all grid points.
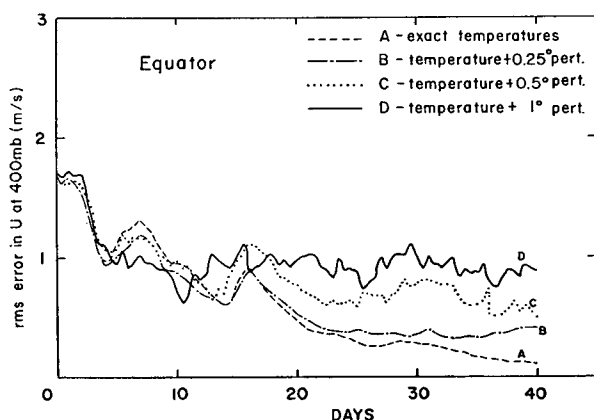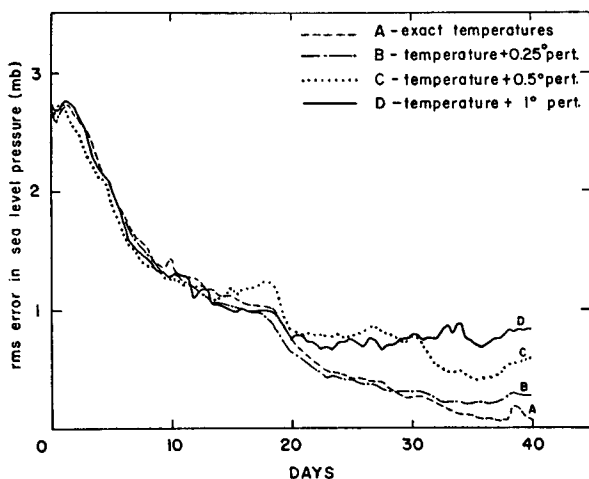

FIG. 2. Same as Fig. 1 for the equator.

FIG. 3. The rms error in sea level pressure anomaly (mb) for the Northern Hemisphere, in cases where temperature with 0, 0.25, 0.5 and 1C random error perturbations are inserted every 12 hr at all grid points.

The operational system we have in mind is a pair of polar orbiting Nimbus satellites. A single Nimbus satellite corresponds approximately to an insertion of temperature every 24 hr at intervals of about 12° in longitude. The wind errors in this case also turn out to be acceptable for the model if the temperature error is sufficiently low.

A quasi-geostrophic adjustment of the wind to the temperature field is to be expected at middle and high latitudes, but it must be borne in mind that the wind is not determined by the temperature alone, since the constant of integration of the hydrostatic equation, e.g., the surface pressure, must also be known. The wind inference is made possible by the fact that the surface pressure is also determined by the temperature history, as may be seen[4] from Fig. 3.

What is more interesting is that the wind is determined at low latitudes where the geostrophic approximation does not hold. However, a small variation in pressure or temperature now produces a large variation in wind. Fig. 2 shows that the rms temperature error must remain below 0.25C for an appreciable reduction in wind error to occur at the equator.

In the second experiment the "correct" temperature and wind were introduced at 400 mb, and the "correct" pressure was introduced at the surface. The rms errors in the 800-mb zonal wind component at 49N and the equator are shown in Fig. 4, and the rms error in the 800-mb temperature averaged over the Northern Hemisphere is shown in Fig. 5. The experiment was evidently successful in demonstrating that one can, under certain circumstances, infer the winds and temperatures in the lower layer from historical observations of temperature and wind above and pressure below.

The operational situation that we have in mind here is one in which temperatures and winds are available in the upper troposphere and lower stratosphere from satellite radiometric observations and from drifting constant volume balloons, and surface pressure is available at sea from ships of opportunity and from free-floating buoys monitored by a satellite. It is supposed that temperatures in the lower troposphere are not readily available because of the opacity of clouds in the infrared and that winds are not available because of balloon icing.

At the present stage of our study we can claim no more than to have shown the possibility of a trade-off of temperature for wind when one uses historical observations of temperature at all levels, and of time for space when one uses historical observations of temperature and wind at upper levels and surface pressure at lower levels. In the former case, the temperature accuracy required may prove to be prohibitive for the equatorial regions, although it is possible that the relative error of the temperature *gradient* as deter-

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[4] The rapid adjustment of surface pressure to the temperatures *and* winds throughout the atmosphere has already been noted by Smagorinsky and Miyakoda (1969).
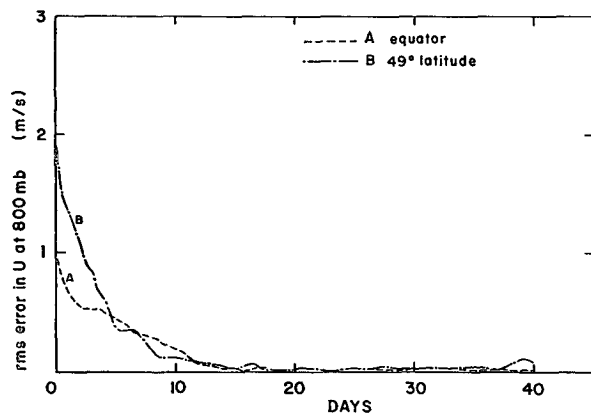
FIG. 4. The rms error in zonal wind (m sec⁻¹) at 800 mb for the equator and 49° latitude, for cases where the exact pressure at sea level and the temperature and wind at 400 mb are inserted every 12 hr at all grid points.

FIG. 5. Same as Fig. 4 except for temperature (°C) for the Northern Hemisphere.

mined from a single Nimbus pass across the equator lies within the required limit. In the latter case, the limited number of vertical degrees of freedom in the model renders the results inconclusive from the practical standpoint. We would like to see the experiment repeated with a model containing more levels before coming to any more definite conclusion as to the possibility of using historical data to fill in "silent" volumes of the atmosphere. There is little doubt that this can be done to some extent, but to what extent horizontally and vertically is not known. We are publishing these incomplete results to arouse interest in a type of interpretive problem which we believe has potentially great significance for observational and theoretical meteorology and oceanography.
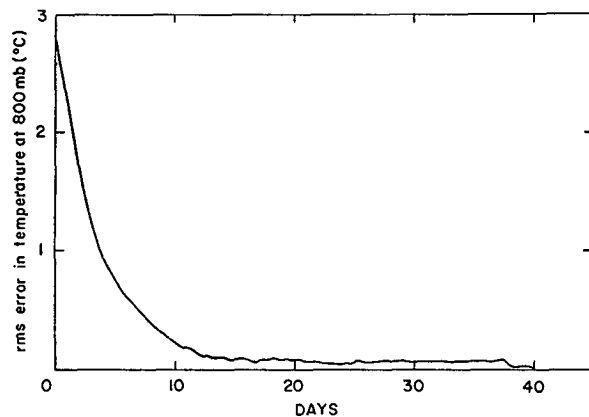
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Smagorinsky, J. S., and K. Miyakoda, 1969: The relative importance of variables in initial conditions for numerical predictions. *Proc. WMO/IUGG Symp. Numerical Weather Prediction*, Tokyo, 1968, Publ. by the Japanese Meteorological Agency.