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The NMC Global Data Assimilation System

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I. Introduction*

The NMC global data assimilation system consists of two main elements. First, the numerical representation of the atmosphere is carried by a global prediction model. Periodically, the model is corrected, or updated, by available observations through the second element, the optimum interpolation procedure described in the previous lecture. It is assumed that the prediction model is reasonably accurate at all times. Under this assumption, it follows that

1) at gridpoints for which observations are nearby, the corrections determined by the optimum interpolation procedure are small and reflect a blend of predicted and observed information according to estimates of their respective reliabilities; and

2) at gridpoints for which no observations are available, no arbitrary or incidental corrections should be made.

These statements reflect the dominant role of the prediction model, a view that emerged from data assimilation research and strongly influenced the design of the NMC assimilation system.

These design considerations have introduced some departures from previous analysis practice at NMC. Foremost among these is performing the update in the prediction model's vertical coordinates, rather than on standard isobaric levels. In previous operational systems at NMC and elsewhere, the prediction model was used to provide a "background" or "first-guess" field for the isobaric analyses. For prediction models cast in the normalized pressure (σ) vertical coordinate, this necessitated an interpolation from the model's coordinate to isobaric levels at every gridpoint, whether data were available or not. Following the analysis, the adjusted fields were then reinterpolated to the model's coordinate so that prediction could resume. At gridpoints not influenced by observations in the analysis, this amounted to an unnecessary double vertical interpolation which resulted in excessive smoothing. Moreover, because an operational system cycles with a fairly short period, the double interpolation was repeated frequently. Thus the cumulative effect could be quite large in data-sparse areas. Updating locally--only at points defined by the prediction model's coordinates and affected by data--helps to reduce (but not eliminate) this problem.

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*Material in this lecture based largely on a recent paper by McPherson, Bergman, Kistler, Rasch, and Gordon (1979).

Another departure results from the design consideration requiring a blend of prediction and observation. To illustrate, consider an observation located precisely at a gridpoint. Prior to the present system, if the observation was of sufficient quality to pass the quality control procedures, it was accepted in place of the predicted fields. Phillips (1976) refers to this as a "credulous" analysis of data. As long as the operational data base consisted largely of radiosonde observations--generally homogeneous and possessing random errors--the credulous method was satisfactory. The present data base is no longer homogeneous but consists of data from disparate sources with widely varying error characteristics, including nonrandom errors. Given realistic information on the error characteristics of the observations and the prediction, statistical interpolation can effect the desired blending.

Subsequent sections of this lecture describe the application of statistical interpolation to a particular global prediction model within the context of data assimilation concepts. In the following section, a description of the present NMC global prediction model is given. Section 3 provides a brief outline of the update procedure, which is invoked each 6 hours. This is followed by a section on data weighting and the treatment of observational and forecast error variances. The final section discusses imminent and planned modifications of the system.

II. The NMC global prediction model

The vehicle for carrying forward in time the representation of the atmosphere is a primitive equation prediction model covering the global domain (Stackpole, 1978). The governing finite-difference equations are formulated in spherical coordinates on a regular latitude-longitude grid mesh with a 2.5° resolution.

In the vertical, structure of the atmosphere is resolved by nine layers, bounded by the earth's surface and the 50-mb level. A unique form of the normalized pressure (σ) system (Phillips, 1957) is used as the vertical coordinate. It features a division of the atmosphere into two "σ-domains," wherein the lower domain represents the troposphere and the upper domain the stratosphere. The domains are bounded by material surfaces at the pressure of the model terrain, the tropopause and the 50 mb level. Figure 1 illustrates this vertical structure. The material-surface tropopause is a unique feature, and has the effect of enhancing the vertical resolution without adding computational layers. It has a long record of operational use, having been introduced in the first primitive equation model used operationally at NMC (Shuman and Hovermale, 1968) beginning in 1966.

Prognostic variables in the model are the following: for the thermal structure, potential temperature (θ); for the motion field, the eastward (u) and northward (v) wind components; for moisture, the specific humidity (q); and for the mass, the pressure-thickness of the two σ domains, Δp_T(= P[surface] - P[tropopause] and Δp_S [=P tropopause] - 50 mb).

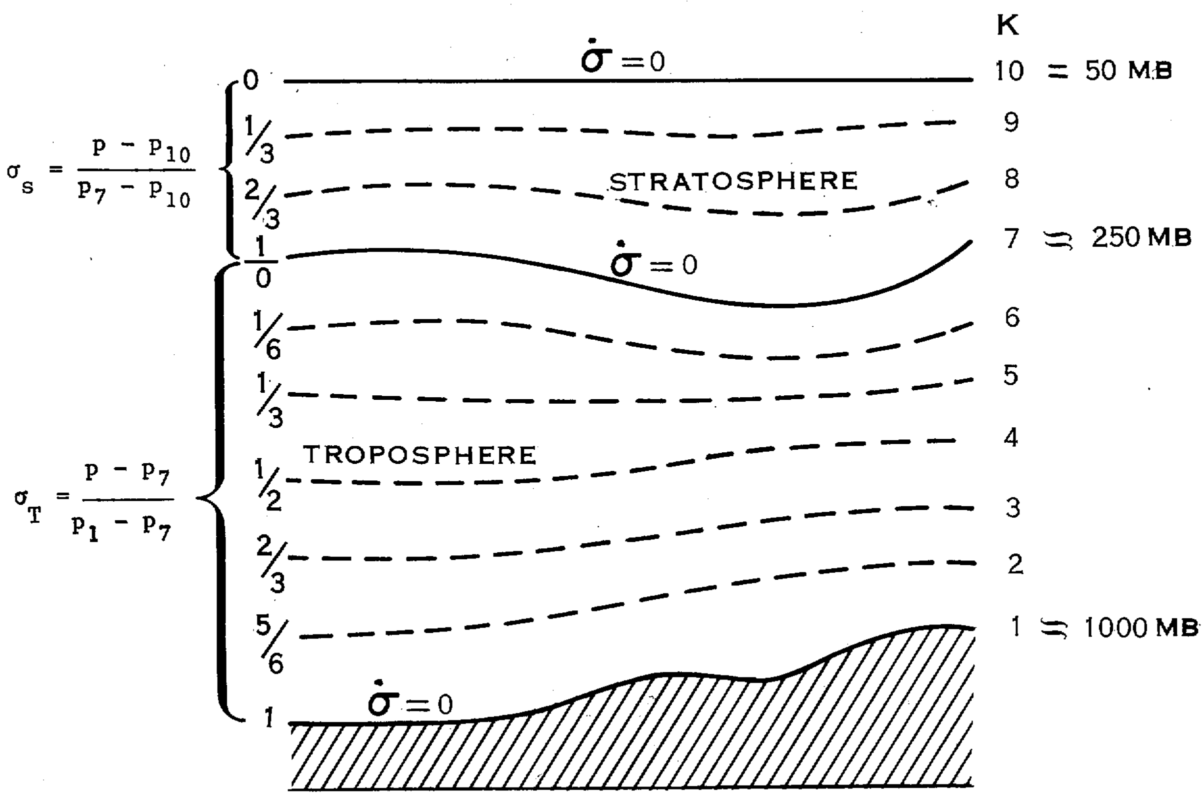

Figure 1. Vertical structure of the NMC nine-layer global prediction model.

The thermal, motion and moisture variables are defined at the mid-point of each layer (specific humidity only in the lowest five layers). Diagnostic variables such as geopotential and vertical motion are calculated at the interfaces between layers.

Physical processes such as radiation, precipitation and evaporation, sensible heat exchange and friction are included in the model, although with less sophistication than is the case in general circulation models. The radiation treatment includes both shortwave and longwave components, and features a budget calculation at the earth's surface. Precipitation from both large-scale saturation and convection is included. Sensible and latent heat exchange are explicitly modeled for marine areas. Frictional effects are confined to the lowest layer of the model.

For use in a data assimilation system, it is important that the prediction model have an economical time integration scheme which rapidly damps out gravitational waves resulting from an update. The NMC model uses the centered-difference method with a time filter (Robert, 1966; Asselin, 1972). The time filter inhibits the tendency of the centered-difference method to develop "separation of solutions" between odd- and even-numbered time steps. It also aids in the suppression of gravity wave "noise" resulting from the updating procedure.

III. Update[1] procedure

Surface pressure

Because the assimilation system works in the prediction model's coordinate system, and because the -coordinate is itself a function of time, the first step in the updating procedure is to update the vertical coordinate. This is done in two stages: first, an updating, or analysis, of the surface pressure; and second, an updating of the model tropopause pressure.

The surface pressure update is done as follows: The prediction model produces a forecast of the pressure at the elevation of the model gridpoints. The dominant variation of this field is due to terrain. In order to separate this variation from that due to meteorological phenomena, the standard atmosphere pressure at the terrain elevation of each gridpoint is subtracted from the predicted surface pressure. The resulting field of departure from standard atmosphere (D-values of surface pressure) is the field to be updated.

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[1]The terms "update" and "analysis" are used interchangeably in these lectures. Both refer to the correction of a prediction by timely observations.

The data are station pressure observations, if available; if not reported, mean-sea-level observations are accepted only if the station elevation is less than 500 m. Conversion to D-values is done by subtracting the standard atmosphere pressure at the station elevation from the reported station pressure. A hydrostatic adjustment is performed to allow for the difference between the actual elevation of the reporting station and smoothed model elevation. The adjusted observations are then subjected to a gross error check; those not rejected are passed to the interpolation routine.

The updating procedure uses a two-dimensional version of the statistical interpolation method. Observations of both station pressure and wind are used over marine areas; only the former are used over land. At present, the surface pressure update is performed on the same 2.5° latitude-longitude grid used by the prediction model. After each gridpoint has been considered, the interpolated residuals are recombined with the background field of predicted D-values. At this point the recombined field is filtered by a spherical harmonic operator with triangular truncation at 36 modes. The filtered field is then added to the standard pressure field to complete the update.

Tropopause Pressure

The second step in updating the mass field is the treatment of the model tropopause pressure P_{**}. Here the emphasis is somewhat different than in the surface pressure update. It is important for the stability of the prediction model that the material surface which initially represents the tropopause be well-behaved numerically. Therefore, the tropopause update procedure emphasizes smooth variation of the surface in space, strong controls to keep it within climatological limits, and restrictions on the magnitude of permissible changes in a given update.

The background field for the tropopause update is the predicted tropopause pressure smoothed by the spherical harmonic filtering operator with resolution of 24 modes. This tends to reduce any numerical difficulties which may have developed during the course of the prediction.

Deviations from this background field are interpolated to the model gridpoints by application of a univariate, two-dimensional version of the statistical interpolation method. The deviations are calculated through bilinear interpolation of the predicted P_{**} values to the locations of the observations, followed by subtraction from the observed data. Observations of tropopause pressure as reported by radiosondes are used directly and are assigned the rather large rms error level of 40 mb. Values of tropopause pressure are calculated for remote soundings by a least-squares fit of mandatory level temperatures to a fifth-order polynomial. The minimum of the polynomial is taken as the tropopause pressure. It is assigned the even larger error level of 50 mb. By contrast, the assumed rms error of the prediction is 20 mb. This assignment of error levels tends to suppress large changes in the background field.

The tropopause update is done on a 5° latitude-longitude mesh. When the statistical interpolation is complete, the field of interpolated deviations is passed to the spherical harmonic filtering operator with 24 modes. This serves the dual purpose of smoothing the deviations and distributing them to the remaining points of the 2.5° prediction grid. After recombining with the background field, the result is compared to climatological limits on the tropopause pressure. Any value outside the limit is reset to the limit.

Adjustment of the Vertical Coordinate

Once the updates of the terrain pressure and tropopause pressure are completed, the updated fields are used to redefine the vertical structure of the model according to the formulas

$$\sigma_T = \frac{P - P_{**}}{P_* - P_{**}}, \qquad P > P_{**},$$

$$\sigma_S = \frac{P - 50}{P_{**} - 50}, \quad 50 \text{ mb} < P < P_{**}.$$

Changes in P_* and P_{**} are thus distributed through the nine layers of the model. Typical changes in the pressures at the midpoints of the layers are a few millibars.

The predicted values of the thermal, motion and moisture history variables, defined at the midpoints of the original layers, must be adjusted to the updated structure. This is done by interpolation which is linear in the Exner function π. For the wind components and the specific humidity, separate interpolations are performed for each sigma domain, i.e., interpolation across the tropopause is not permitted. The interpolations are done from the midpoints of the old layers directly to the midpoints of the new layers without an intermediate transformation to isobaric coordinates.

When the background fields have been adjusted to the updated vertical coordinate, the thermal, motion and moisture fields are smoothed by application of the spherical harmonic filtering operator with 36-mode resolution. This ensures that small-scale noise does not accumulate from one update to the next.

Temperature, Wind, and Moisture

Data Preparation. All upper air observations are subjected to several preparatory manipulations. Geopotential heights of standard isobaric surfaces from radiosonde reports are converted to mean temperatures of the layers bounded by the isobaric surfaces. Remote temperature soundings are also converted to mean temperatures for the same standard layers.* No single-level temperatures, as from aircraft, are presently used. Aircraft and cloud-motion winds are assigned to the pressure of the report, rather than adjusting to the nearest mandatory pressure level. It is worth noting that surface pressure and wind reports from ships are also available to the upper air wind analysis. Finally, dewpoint-depression observations from radiosondes are converted to specific humidity, the moisture history variable of the prediction model. All observations from any source are then ordered by latitude and longitude in order to facilitate the procedure within the analysis of searching and selecting the proper reports to update a particular gridpoint. Each report (soundings are considered a single report for this purpose) is stratified according to its longitude within 2.5° latitude bands.

After these manipulations have been completed, the vertically-adjusted background field variables are bilinearly interpolated to the locations of each observation, and the difference--observed minus forecast--is formed. These residuals are then transferred to the next step in the statistical interpolation procedure.

Search Procedure

The update proceeds gridpoint by gridpoint, beginning with the South Pole and working northward by rows and eastward within each row. For any given gridpoint, care is taken to ensure that all data in a 30° latitude band, centered on the grid point, is available for consideration. To assist the search procedure, a subset of data within a square of 15° latitude length, and centered on the point, is considered first. If there are a minimum of six reports within the subset, the search procedure terminates and all data within the 15° square are considered by the selection procedure. If there are insufficient reports, the square is expanded to 20° latitude per side and the process repeated. If still an insufficient number is found, expansion continues until the maximum size--30°--is reached. All searching ceases after the 30° square has been considered, and the data identified by the search are passed to the selection procedure.

Selection Procedure. In principle, all data should be used in forming the correction at every gridpoint. This would require both the calculation of a large number of correlations and the inversion of enormous matrices at each gridpoint, which would quickly exhaust the available computational resources. Moreover, it is generally conceded that, for example, the radiosonde taken at New York does not contain much information about the analysis at Beijing. Indeed, most of the time, the the analysis at any point is determined largely by a few--perhaps only five or six--observations near the point. The problem then reduces to the selection of a small number of observations which contain the most information about the update to be performed at a particular gridpoint.

*Except that the layers 300-200 mb and 200-100 mb are not subdivided.

It is believed that a statistical technique called multiple screening regression would serve this function optimally. The technique determines the set of observations--or predictors--that together explain the greatest fraction of the variance of the analyzed parameter. Unfortunately, this is also too costly to perform at every grid point of a global mesh.

The NMC method is a compromise between the theory and practical reality. It selects the eight pieces of information which have the highest correlation with the analyzed parameter at the gridpoint--essentially the right hand sides of the covariance equations (13) of the second lecture. The eight reports may be located anywhere in the volume defined by the search box extending through the depth of the atmosphere, and mass or motion reports may be selected to update temperature or wind. One serious deficiency of this procedure is that it does not take into account the interobservational correlations. Situations may therefore arise in which a cluster of observations containing largely redundant information might be selected in preference to a report somewhat less highly correlated with the gridpoint, but isolated and offering more independent information. Nevertheless, the procedure works reasonably well under most circumstances: it generally selects the three or four "best" reports to perform the update, but the three or four "next best" can occasionally be criticized.

One important consequence of the decision to limit each update to eight pieces of information and the resulting selection procedure is that the eight reports selected to update a particular variable are most often observations of that variable, if available. That is, in areas of adequate data coverage of both temperature and wind, temperatures tend to be updated by temperature observations and winds by wind observations. Only where there are data of only one kind is the multivariate aspect of the statistical interpolation actually used. For example, in midtroposphere over the oceans wind reports are rare; only remote temperature soundings are available. Under these circumstances, some adjustment of the wind field will be effected by the temperature data. As was noted in the previous lecture, the entire sounding--or its equivalent--is required to produce an appropriate adjustment.

In practice, if an appropriate modification to the motion field is not induced where only temperature data exist, the geostrophic adjustment process during the subsequent prediction will tend to adjust the mass field toward the wind field; i.e., toward what the mass field would have been in the absence of data. Thus, temperature information, unaccompanied by supporting wind data (real or induced), will quickly be rejected or "forgotten" by the prediction model and the influence lost to the system. Geostrophic adjustment theory predicts that the winds will adjust to the temperatures at high latitudes and large scales, and that the reverse is true for low latitudes and small scales. In practice (see, for example, Rutherford and Asselin, 1972), it is found that the scale of the correction fields is small enough that the mass field adjusts to the wind field under most circumstances. It may therefore be argued that it is more important to obtain wind than temperature observations; but it is certainly true that if no wind data are available the wind field must nevertheless be adjusted artificially to agree with mass data.

Quality Control

The observational data base is subjected to two error checking routines in order to eliminate bad or unrepresentative observations. The first of these is a gross error check, done after the observation-minus-forecast residuals are computed but before the analysis routine is entered. A residual is rejected if it is excessively large, i.e., differs from the forecast by an improbably large amount. The gross rejection limits are functions of latitude and are quite liberal, erring in the direction of accepting bad observations at this point rather than risking the rejection of good ones.

After the selection procedure, each observation is compared with its neighbors of like kind. If an observation is too inconsistent with its neighbors, it is rejected. This comparative check is done in the following way. For each pair of observations of the <u>same</u> meteorological variable, the following inequality is required to hold:

$$|\hat{f}_i - \hat{f}_j| \leq (a - b\rho_{ij})\sigma$$

where ρ_{ij} is the correlation function between the observations, a and b are empirical constants (currently a = 6 and b = 3), and σ is the mean forecast error standard deviation for the level at which the observations are located. If the above condition is not met, the observation with the presumed lower quality is flagged; if both observations are of the same presumed quality, both are flagged. Presumed quality is currently determined for rawinsonde soundings only, on the basis of vertical consistency checks. Depending on the outcome of this check, a quality indicator is assigned to each rawinsonde observation. Other kinds of observations are assigned an indicator lower than any of the acceptable rawinsonde observations; thus, no other kind of observation is allowed to flag a rawinsonde observation, and rawinsonde observations can only be flagged by other rawinsonde observations of equal or higher quality.

After all comparisons have been made, the total number of flags assigned each observation is determined, and the observation with the greatest number of flags is deleted first, provided that the number of flags is at least 2. As further caution against rejecting extreme but good reports, no report is deleted if at least two other reports support it. Any flags which a deleted observation caused to be placed against other observations are also removed, and the process is repeated until all remaining observations have no more than one flag. This procedure requires that two or more observations of equal or better quality must be in disagreement with an observation in order for it to be rejected, and it ensures that bad observations are not allowed to reject good ones. The comparative check is done separately at each grid point, so it is possible for an observation to be accepted for the analysis at one grid point and rejected at a neighboring grid point, but the actual instances of this are few and usually occur when the accepted observation is peripheral to the grid point and receives a very small weight in the analysis. Nevertheless, this occasionally leads to analysis problems.

Solution of the Linear System. Once the eight (or fewer) observations have been selected and checked, the elements of the coefficient matrix are calculated using assumed analytic forms for the field correlations. The coefficient matrix is symmetric and positive definite. An iterative method--the method of conjugate gradients--is used to determine the solution. Experience has shown that convergence is customarily quite rapid. Rarely, an ill-conditioned matrix is encountered which leads to slow convergence or divergence and an unreliable solution. Such cases invariably arise because of a pair of observations located very close together. The difficulty is circumvented by dropping the one of the pair that has the lower correlation with the grid point, and repeating the solution process.

After the mass and motion updates, the moisture field is considered. Specific humidity is the model's moisture variable, carried in the lowest five layers. The predicted specific humidity is updated in those layers, using optimum interpolation. At present, only humidity data from radiosondes and subjective reports inferred from cloud imagery are used. No data from remote soundings are accepted.

Filtering the Correction Field. One of the consequences of the decision to limit the number of observations affecting an update is that the stations selected tend to be those closest to the gridpoint to be updated. The result is a field of corrections which contains significant spatial "noise." Before adding the corrections to the guess, the noise is eliminated by the spherical harmonic operator with resolution of 36 modes. The reconstructed correction field therefore does not contain modes with wavenumbers higher than 36. It is then added to the predicted field in the adjusted model coordinate, and the update is complete.

The update is presently performed on a Kurihara-type (Kurihara and Holloway, 1967) grid with approximately 3.75° latitude equal-area resolution. This grid was chosen to avoid unwarranted and unnecessary updating in high latitudes associated with the convergence of meridians on a regular latitude-longitude grid. Representation of the correction fields by the spherical harmonic operator accomplishes the transformation of the corrections on the analysis grid to the regular 2.5° latitude-longitude grid of the prediction model.

Initialization

As indicated previously, most of the updates prove to be univariate in data-dense areas. As a result, the introduction of fresh data on a local basis invariably disturbs the balance between the mass and motion fields to some degree. In general, the larger the correction the greater the resulting imbalance. Restoration of balance through the geostrophic adjustment process requires a period of time. Its length depends in part on the characteristics of the prediction model and in part on the magnitude of the initial imbalance--if the adjustment interval is greater than the update interval, an accumulation of gravitational noise may result.

Accordingly, a dynamic initialization option is incorporated into the system after the update has been completed. The procedure consists of integrating forward and backward around the time of update using a modification of the Euler-backward damping time integration method (Dey, 1979), much like the procedure suggested by Nitta and Hovermale (1969). The duration of the initialization period is specified in advance. Irreversible physical processes, such as precipitation, are not permitted during the initialization. Figure 2 illustrates the effect of Dey's procedure on the rms surface pressure tendency. The procedure has obviously suppressed much of the gravitational noise resulting from the initial imbalance.

IV. Data Weighting

It was shown in the previous lecture that the influence a given datum has on the analysis depends to some extent on the estimated quality of the datum. For a set of observations which are equally correlated with the parameter to be analyzed at the gridpoint, and are equally correlated with each other, the weight each receives relative to the other data and the background field is a function of the ratio of the observational error variance ε^2 to the forecast error variance $\sigma_f{}^2$. The treatment of these two components is considered in this section.

Observational Errors

Estimates of observational error variances must be prespecified. In the NMC assimilation system, this is done by classes of observations; i.e., radiosondes, satellite soundings, etc. Table 1 presents the values currently in use. The source for the radiosonde temperature error is the study by Bruce et al., (1977). That study reported on a set of carefully-designed simultaneous radiosonde ascents from different points in the White Sands Missile Range, New Mexico. Variability of the temperature error with season or latitude is not accounted for. Furthermore, the RMS error is for temperatures at specific isobaric levels, rather than layer-mean temperatures. This is also neglected in the NMC system.

RMS errors for remote soundings are monitored routinely and the values in Table 1 are adjusted if necessary.

Table 1. Observational errors assigned to different observation systems.

For Temperatures (°C)

Data Source	Error
Rawinsonde	0.8

For Winds (m sec^{-1})

Data Source	Error
Rawinsonde	1.5
Aircraft	2.0

Remote Sounding:

Layer (cb)	Clear	Cloudy
850-700	1.0	2.2
700-500	1.4	2.2
500-400	1.5	2.3
400-300	2.0	2.2
300-250	1.8	1.8
250-200	1.7	1.5
200-150	1.6	1.4
150-100	1.4	1.1
100-70	2.0	
70-50	2.0	

Cloud Winds:

	Low Level	High Level
U.S. Atlantic	4.2	7.5
U.S. Pacific	5.4	7.0
Japanese	6.1	13.3
European	7.2	8.4

Radiosonde winds are presently treated as much more accurate than is justified by observational studies (see, e.g., Bauer, 1976). As will be shown in the next lecture, an estimate of 5.9 m sec^{-1} is assumed for the purpose of correcting colocation differences between higher level cloud motion vectors and radiosonde winds to obtain error estimates for the cloud winds. More realistic treatment of radiosonde winds will be incorporated shortly.

Aircraft wind errors are not based on solid information. However, a study of the accuracy of winds determined from the inertial navigation systems of modern jet aircraft is presently being conducted at NMC. Results of the study will be used to adjust Table 1.

RMS errors for cloud motion wind vectors are based on the colocation statistics mentioned previously. The particular set of numbers derives from the period January through March 1979. Errors from the various sources are comparable, except for Japanese high-level vectors. The large error appears to be due to the wind vectors being assigned to too high an altitude, on the average.

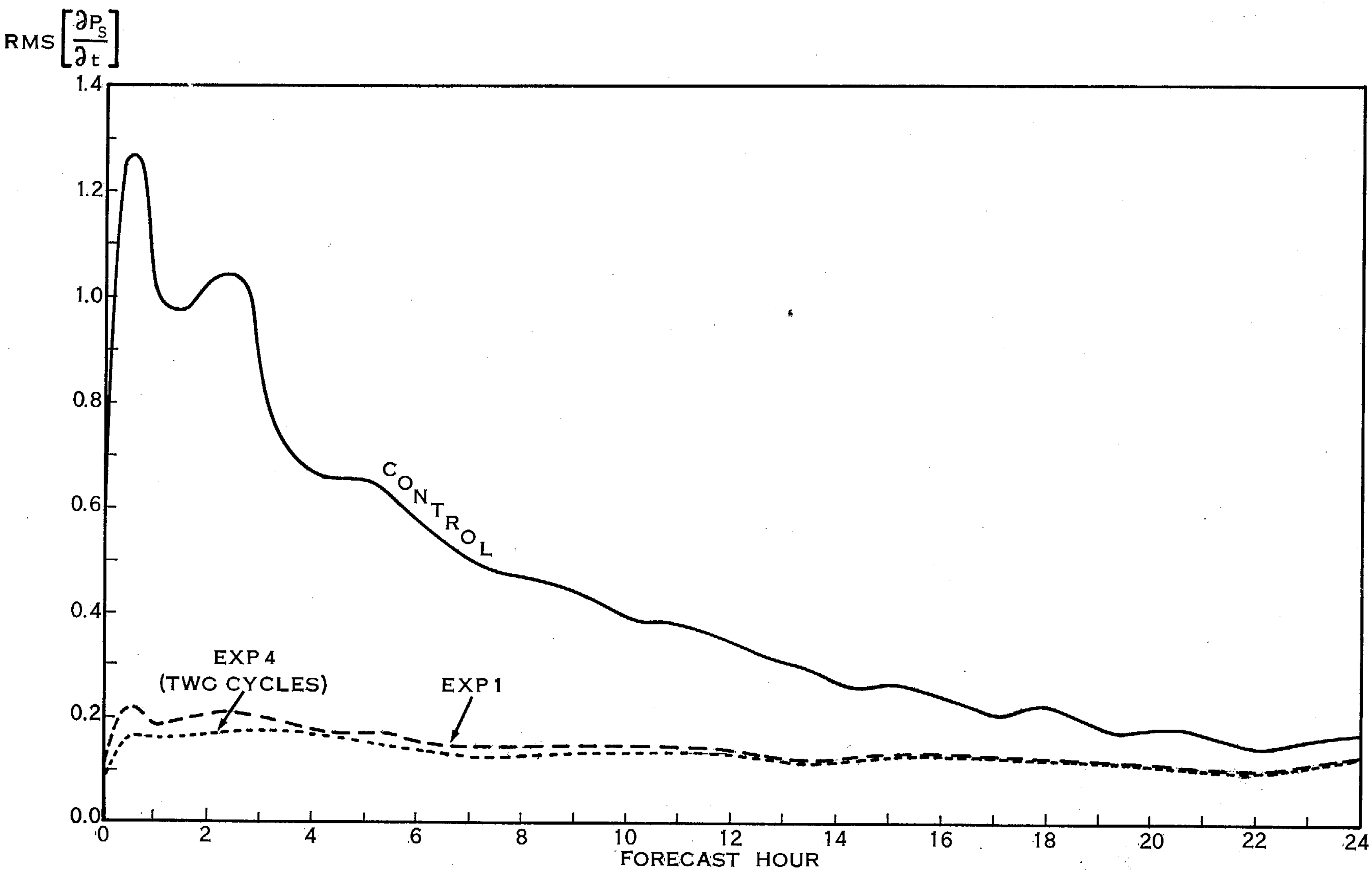

Figure 2. RMS surface pressure tendency as a function of time from the NMC global prediction model without initialization (CONTROL) and with two variations of Dey's dynamic initialization (EXP 1, EXP 4). From Dey (1979).

The effect of these errors, all else being equal, is to give more influence to radiosonde temperatures than to remote soundings, where both are present. Likewise, preference is given to radiosonde winds over other types of wind reports. All else is not equal, of course, because of the presence of the forecast error variance.

Forecast Error Variance

In the NMC system, the forecast error variance is allowed to evolve with time at each gridpoint. From the second lecture, it will be remembered that optimum interpolation is based on minimization of the interpolation error. After the interpolation for a particular point has been completed, the analysis coefficients can be used to evaluate the estimated standard error of interpolation, or "analysis error." It can be shown that the estimated analysis error depends only on the quantity, quality, and distribution of data that affected the interpolation. Its dependency on data density and observational error characteristics is discussed by Seaman (1977) and Bergman and Bonner (1976). To transform the estimated analysis error into the estimated prediction error σ_f, the former is augmented by an amount approximating the error growth rate of the prediction model. Values presently in use are given in Table 2.

At each update time the estimated prediction error may be reduced by the statistical interpolation process, assuming corrective observations are available. If there are no observations affecting a given gridpoint, the estimated prediction error will be augmented again when the prediction resumes. It thus evolves with time. For a particular update time and gridpoint, it is a function of how recently the point has been updated and of the quantity, quality, and distribution of observations that

Table 2. Estimates of prediction error growth rate for the 9L Global Model based on verifications of 30 12-h forecasts from August 1975.

Layer	T (°C)	u ($m\ s^{-1}$)	v ($m\ s^{-1}$)	q ($g\ g^{-1}$)
9	1.4	3.1	2.2	-
8	0.9	1.5	1.3	-
7	1.2	2.2	2.2	-
6	1.0	2.4	2.2	-
5	0.6	1.9	1.7	0.00010
4	0.6	1.4	1.4	0.00015
3	0.6	1.0	0.9	0.00020
2	1.0	1.0	1.1	0.00030
1	1.2	1.4	1.2	0.00040

affected the most recent update. Limits are imposed to prevent unbounded growth in areas of infrequent updating: σ_f^2 is not permitted to exceed the climatological variance for parameter, level and latitude in question. Furthermore, the field of σ_f is filtered in the same way as the interpolated residuals in order to account for some diffusion of information from data-rich to data-sparse areas.

The prediction error variance is essentially a device for indicating the frequency and quality of updates. It permits considerable flexibility in the use of observations of different quality. For example, in areas of dense radiosonde coverage, the estimated analysis error of the temperature field is typically less than the assigned observational errors of 0.8°C, as shown in Table 1, since the latter are assumed to be random. From Table 2, it is evident that several 6-h intervals would have to pass without updates before the estimated prediction error would exceed the observational errors assigned to the remote sounding temperatures and thus allow the data to have significant influence in the update. Since radiosondes are generally available each 12 h, remote sounding temperatures of the quality indicated in Table 1 would rarely affect the update in areas of good radiosonde coverage. However, in areas seldom updated, even observations with relatively large error levels would eventually influence the update. Examples of the evolution of σ_f are presented in the next section.

It should be noted that the NMC system assumes that the forecast error correlation ρ that has been modeled by analytic functions is valid at every grid point, while the forecast error variance $\sigma^2{}_f$ is allowed to evolve in time and space. In view of the relationship between the covariance and the correlation,

$$\text{cov}(\phi,\phi) = \sigma^2\rho(\phi,\phi),$$

the NMC system assumes that the shape of the covariance function is invariant in space but that its amplitude is variable.

Figures 3-5 are presented as examples of the character of the forecast error variance. Actually depicted are fields of σ_f prior to augmentation by the error growth rate estimates of Table 2; the diagrams therefore represent the estimated analysis error. Figure 3 presents the estimated temperature analysis error as interpolated vertically to the 250-mb level. Figure 4 is the corresponding chart for the eastward wind component; the northward wind component chart is similar and therefore not included.

Over the data-dense areas of North America and Europe, the estimated analysis errors are near 1°C for the temperature and less than 5 m s^{-1} for the eastward wind component. Over the oceans, the effect of island radiosonde stations (e.g., Hawaii) is visible. Also detectable are the orbits of remote sounding data used in this update; for example, the long strip from southern California southwestward to the equator and 130°W has values

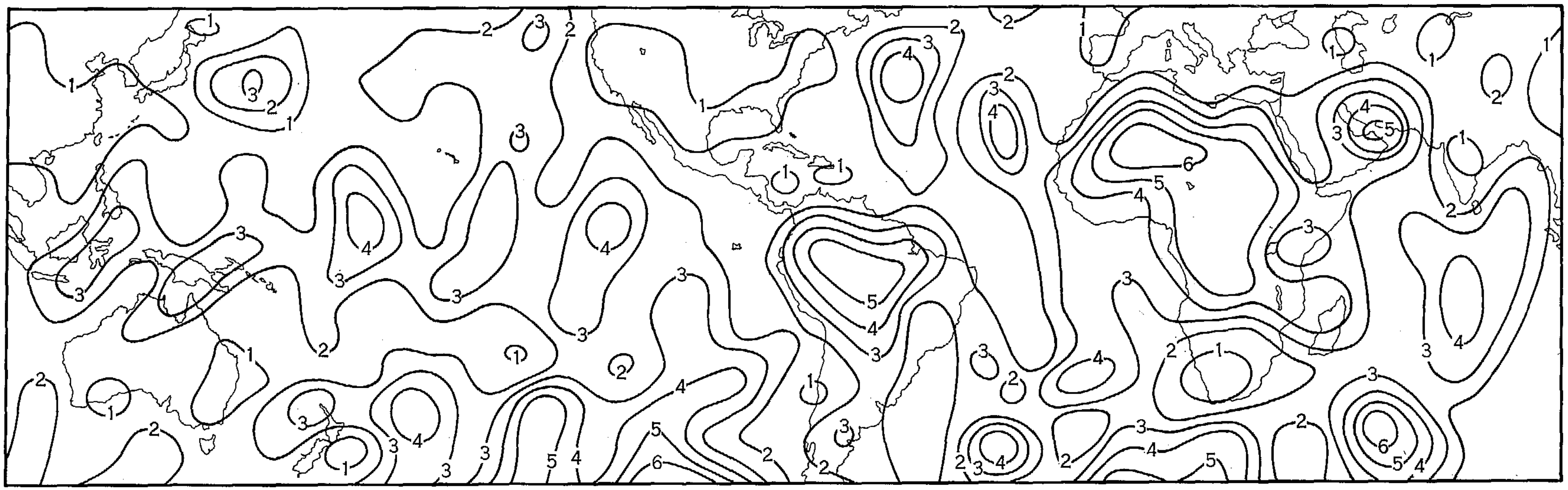

Figure 3. Estimated temperature analysis error at 250 mb for 0000 GMT 14 December 1977. Contour interval is $1^{o}C$.

3

72.5

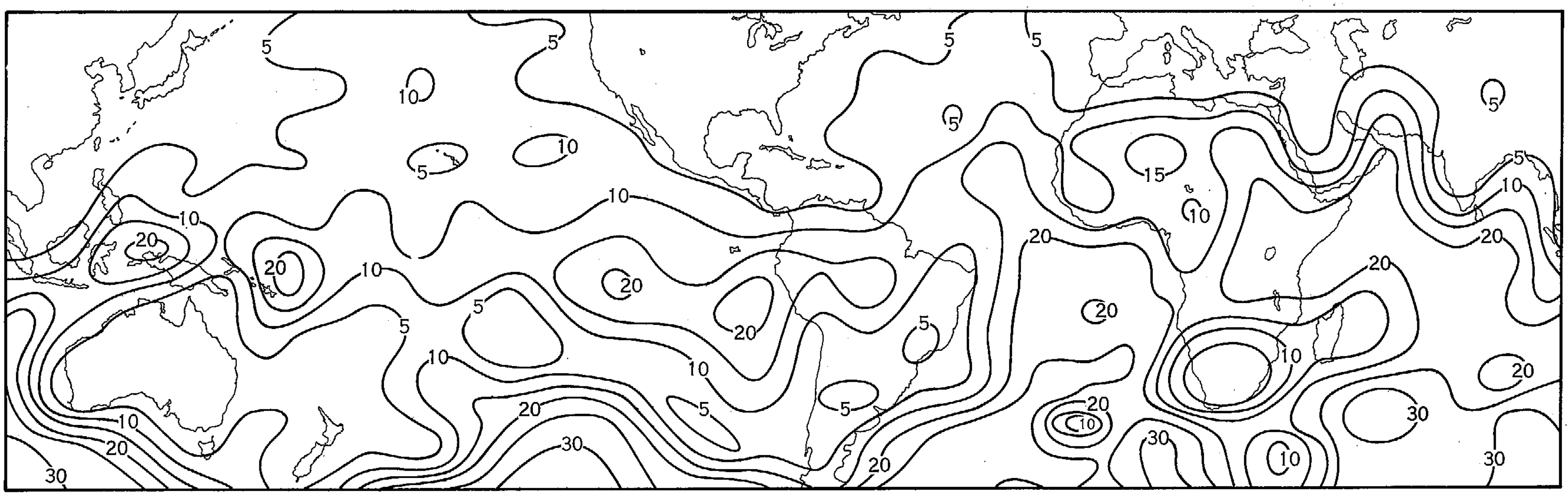

Figure 4. Estimated zonal wind analysis error at 250 mb for 0000 GMT 14 December 1977. Contour interval is 5 m sec^{-1}.

4

72.5

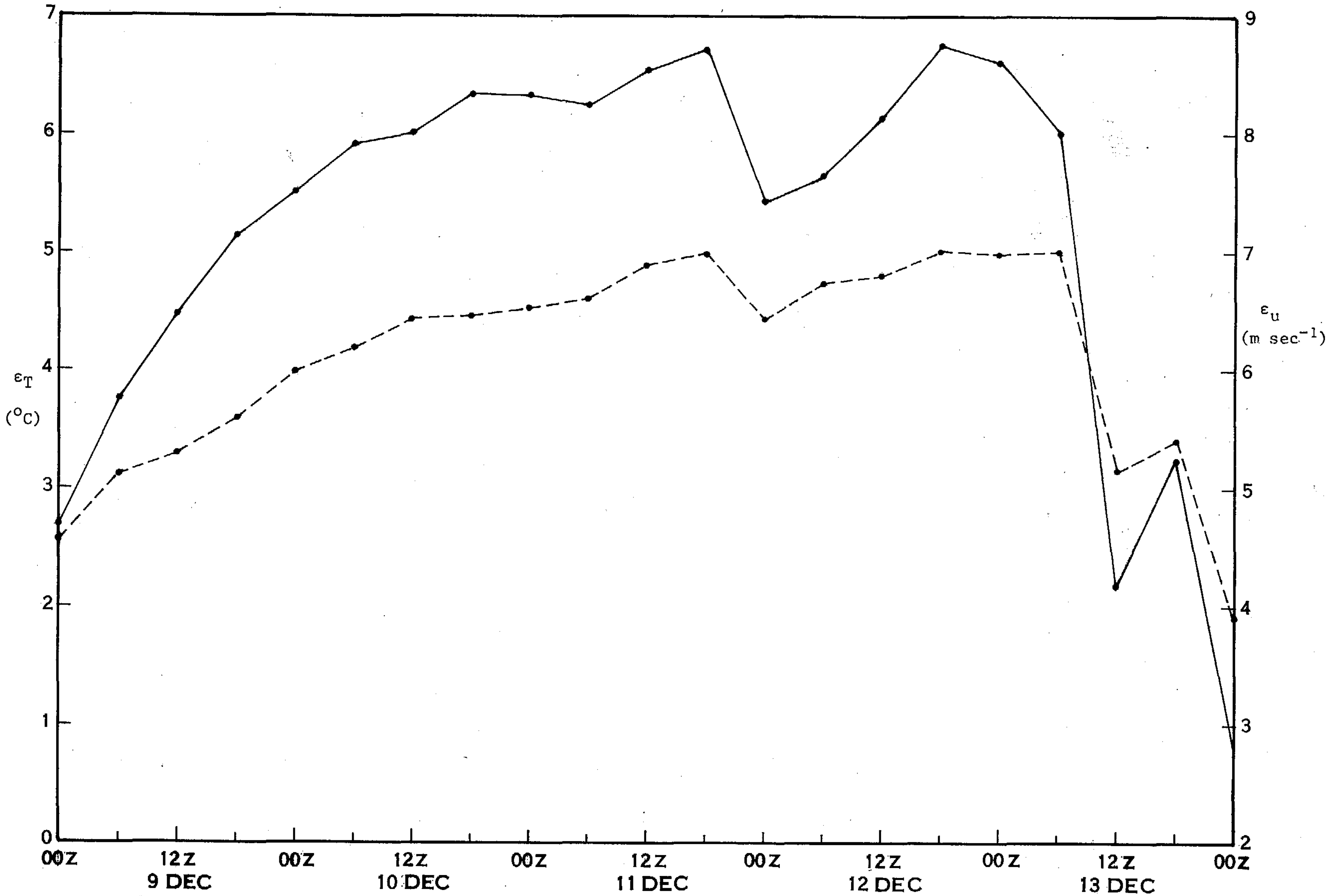

Figure 5. Estimated analysis errors for temperature (ε_T, solid line) and zonal wind component (ε_u, dashed line) as functions of time over a 5.5 day integration. Values are from the fourth σ layer of the model, near 500 mb.

66.9

between 1 and 2°C. There is also a narrow strip in the central North Atlantic with similar values. That these indicate the effect of remote sounding data is confirmed in Fig. 6 which shows radiosonde and remote sounding data coverage in the Northern Hemisphere for this time. The orbits depicted correspond to the areas noted.

Maximum estimated temperature analysis errors occur mainly over data-sparse continental areas where neither radiosonde nor remote sounding data are available. Maximum errors in the 500-mb wind occur over the oceans because neither aircraft reports, mostly from 300 mb and above, nor cloudtracked winds, mostly below 700 mb or above 300 mb, contribute much to the definition of the wind field in the middle troposphere.

The temporal evolution of the estimated analysis errors at a particular point is presented in Fig. 5. This is for the temperature and eastward wind component in model layer 4 (near 500 mb) at 30°N, 35°W. Both temperature and wind errors increase from the initial values. The influence of a distant remote sounding orbit is detectable at 0600 GMT 11 December in both curves. A closer orbit has more impact at 0000 GMT 12 December. Data are very close at 1200 GMT 13 December and 0000 GMT 14 December. Figure 6 confirms the latter time.

V. Forthcoming modifications

An operational system is of necessity an evolutionary system. External forces--new data sources, new computers--as well as internal developments based on operational evaluation and research tend always to induce changes. The NMC global data assimilation system is no exception; since its implementation in September 1978, it has undergone a number of significant modifications. Most noticeable among these is the switch from a regular 5° latitude-longitude analysis grid to the present 3.75° equal-area array. Several other changes are imminent as of this writing, and still others are planned or are under consideration.

Imminent changes

A decision has been made (Feb. 29, 1980) to replace the nine-layer global finite-difference prediction model with a 12-layer spectral model (Sela, 1980). Performance characteristics of the spectral model, which includes a nonlinear normal-mode initialization procedure, have demonstrated consistent superiority over its predecessor. Preimplimentation tests have been conducted with rhomboidal truncation and resolution of 24 spherical harmonic modes, but a final decision on the operational resolution has not been reached.

The spectral model is based on the standard normalized pressure vertical coordinate (Phillips, 1957) without the tropopause material surface. No explicit updating of the tropopause will therefore be necessary. Semi-implicit time integration allows the spectral model to be more efficient computationally than the finite-difference model. The increased efficiency in turn permits updating to be done at three more layers without increasing the total required computational time.

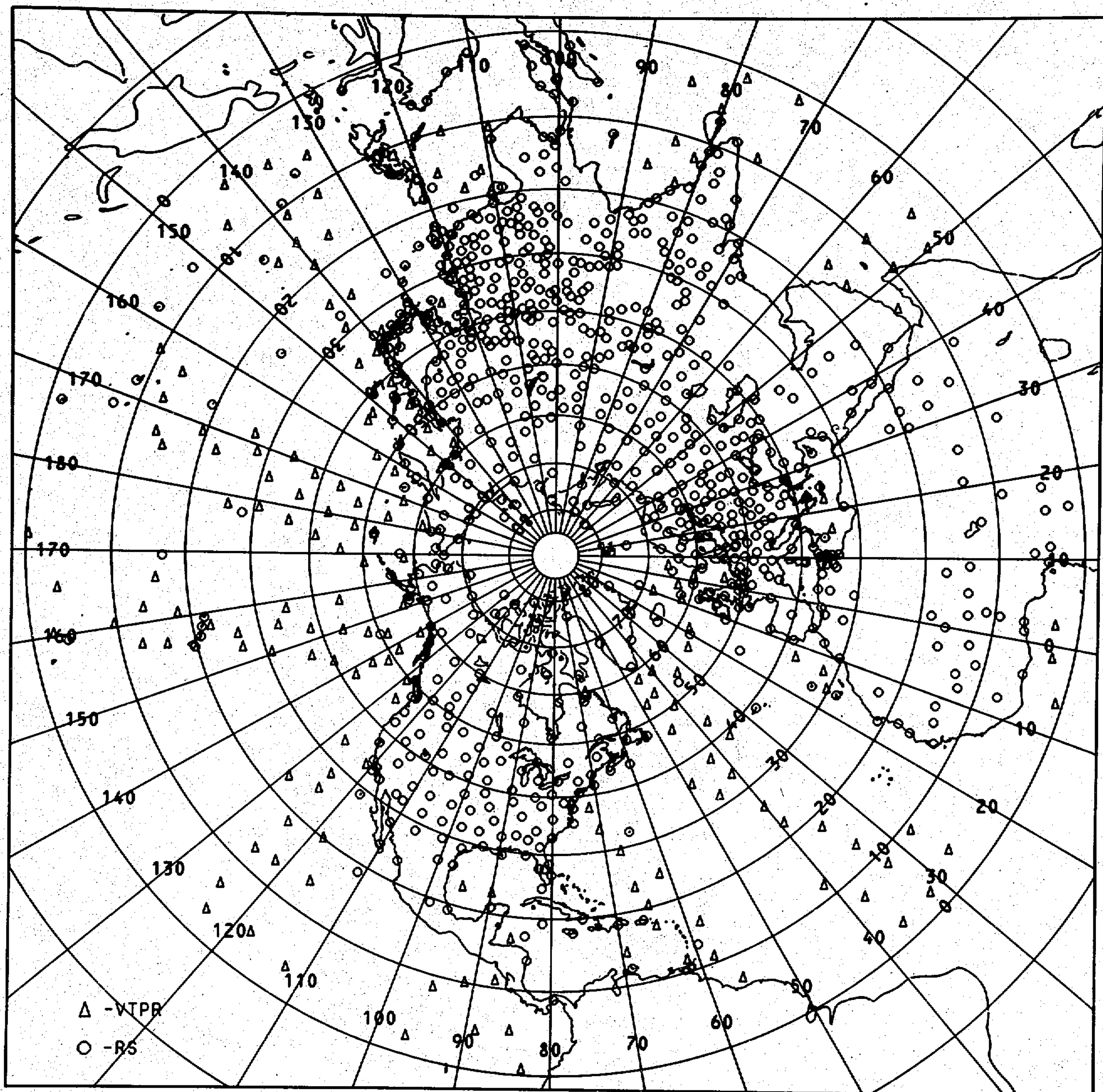

Figure 6. Coverage of radiosonde (circles) and remote soundings (triangles) for the 6h interval centered at 0000 GMT 14 December 1977.

One of the more persistent problems noted in operational performance is associated with quality control of the data base. It was noted in a previous section that the internal consistency check is presently performed on each gridpoint in dependently, so that a datum may be accepted at one point and rejected at an adjacent one. This procedure will soon be replaced by one which performs the internal consistency check in advance of the analysis; i.e., immediately after the observed-minus-forecast residuals are computed. Data rejected will not be considered further. This is expected to reduce the number of isolated but spurious features resulting from uneven inclusion of marginal data.

Under Consideration

Several different methods of artificially inducing the motion analysis to respond to mass observations are presently being tested. All involve the imposition of relatively simple wind laws--geostrophic or gradient wind equations--to assist the natural geostrophic adjustment process.

It has become apparent that for some data sources, the observations are more dense than can be used to advantage in global data assimilation. While a degree of redundancy is desirable, too much is wasteful of observational--and computational resources. Consideration is therefore being given to combining redundant, closely-spaced observations of the same type into composite observations prior to the actual analysis. Assimilation systems at the European Centre for Medium Range Weather Forecasts (Lorenc et al., 1978) as well as the British Meteorological Office (Lyne, 1979) already use this technique.

Experimentation with compositing of redundant data is one aspect of research and development on perhaps the weakest part of the NMC assimilation system--the selection procedure. Other methods, involving more efficient use of screening regression techniques, are also being contemplated.

Finally, it is worth noting that the long-term trend in the data base is toward more remotely-sensed data with greater asynopticity. More frequent updating than the present 6-h interval appears to be inevitable. This will require major increases in computing capability, as well as modifications in the assimilation system itself.

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