APPLICATION OF A VARIATIONAL BLENDING TECHNIQUE TO NUMERICAL ANALYSIS IN THE AUSTRALIAN REGION

R. S. Seaman*, R. L. Falconer†, and J. Brown‡

(Manuscript received December 1976)

ABSTRACT

Numerical analyses in the Australian region are heavily dependent upon the interpretation of cloud imagery over oceanic areas. Also, particularly at 1200 GMT, observations of wind outnumber those of geopotential. Recurrent analysis deficiencies have arisen from an unsatisfactory mix of conventional and interpretatively based input (the 'data-no data' problem), and the failure of geopotential analyses based primarily on winds to adequately reflect the observed winds (the 'wind only' problem). The frequency and severity of both these problems have been significantly reduced through application of the variational 'field information blending' technique (Holl and Mendenhall 1971). The first deficiency is ameliorated by placing a greater reliance on the gradients and Laplacian rather than on the absolute value of field variables dependent on interpretative input; the second by performing separate scalar analyses of thicknesses and wind components, and subsequently blending these analyses to produce fields of geopotential, stream function and velocity potential. A similar technique may be useful for exploiting the information in future observational systems which define gradients more reliably than absolute values.

INTRODUCTION

Since 1970, the National Meteorological Analysis Centre (NMAC) of the Bureau of Meteorology has routinely issued numerical analyses for the Australian region. These analyses serve the dual purposes of guidance material for Regional Forecast Centres, and input to a filtered baroclinic prediction model (Maine 1972, Noar and Young 1972). The basis of the numerical analysis system in its original form has been described by Maine (1966), and Maine and Seaman (1967). During its lifetime, however, there have been a number of unpublished additions and refinements to the original system design. An important such change, due to R.L. Falconer and J.C. Langford, was the formalisation of interaction by the analyst through insertion of manually analysed mean sea level (MSL) pressure and 1000 to 500 mb thickness fields to incorporate cloud pattern interpretation over oceanic areas. A summary of the system as it stood immediately prior to the innovations to be reported appears in the Appendix.

The purpose of this paper is to describe a technique, based on the calculus of variations, which has proved successful in ameliorating some recurrent analysis deficiencies. The original aim of the application was to make better operational

* Australian Numerical Meteorology Research Centre, Melbourne.
† Head Office, Bureau of Meteorology, Melbourne.
use of the available conventional and interpretative data. However, similar variational techniques are applicable to the incorporation of new types of data. These include (i) vertical temperature profile radiometer (VTFR) data, which at the time of writing were utilised through the manually inserted 1000 to 500 mb thickness field, and (ii) winds derived from time-lapse cloud pictures, which should become available following the launching of the Japanese geostationary satellite.

RECURRENT PROBLEMS

Numerical analysis systems encompassing grid point domains of comparable resolution and extent to the Australian system have been operational in the northern hemisphere for almost twenty years (e.g. Cressman 1959). However, our experience has indicated that northern hemisphere numerical analysis systems are not directly applicable to the Australian region, because of essential differences in both the kind and coverage of available data.

The most important of these differences is the much greater reliance, in the Australian region, on cloud imagery observed from satellites, and on interpretative techniques for translating these pictorial data into quantitative terms. To blend interpretative input of MSL pressure and 1000 to 500 mb thickness fields with quantitative data at many levels from irregularly (and often sparsely) spaced observing stations, and produce acceptable multi-level analyses of geopotential, wind, temperature, and moisture has proved a difficult task. A recurrent deficiency, symptomatic of both a lack of quantitative data and an unsatisfactory mix of quantitative and interpretative data, has been termed the 'data-no data' problem. This effect, which most frequently occurs in geopotential and wind fields above 500 mb, has arisen in the Australian application from the use of a poor initial estimate (guess field) in the successive correction method (SCM) of analysis (Cressman 1959). This guess field is adjusted by data in the vicinity of observing stations, but remains uncorrected elsewhere, resulting in improbable patterns between 'data' and 'no data' areas, which in turn affect the wind field. An admittedly extreme example (Fig 1(a)) shows an improbable 200 mb small scale ridge near (35, 105) and an implied wind speed of about 200 kn, which are quite inconsistent with the 500 mb geopotential field implied by manual interpretation (Fig 1(b)). Attempts to obtain better guess fields either by incorporating numerical prediction feedback, or by improved statistical extrapolation procedures from the 500 mb level (Seaman 1972) have not eliminated the problem.

The above problem is not a peculiar characteristic of the SCM, and would arise in any analysis scheme that attempted to combine observations with a guess field whose absolute value was much different. The major lead towards a new approach to the 'data-no data' problem was provided by the recognition that the value of fields derived from interpretative information lay not so much in absolute value, as in differential characteristics, or pattern.

A second characteristic of the Australian region is the difference between the data bases at 0000 GMT and 1200 GMT. At the former time, many standard level upper wind reports are accompanied by a geopotential, but at 1200 GMT the conventional upper air data base consists largely of winds without geopotentials. The incorporation of wind information into a geopotential analysis using the SCM requires horizontal extrapolation from a geopotential guess at the location of the wind report. When geopotential information is scarce, as at 1200 GMT, and the guess is poor, this procedure may produce a geopotential analysis which does not adequately reflect the observed winds. (See Fig 2, again an extreme example.) This deficiency has been termed the 'wind only' problem. When such a geopotential analysis is subsequently used to diagnose a stream function, via a balance equation, to initialise a numerical prediction model, the effects of the above deficiency are reflected in the resultant predictions of both wind and geopotential.
Fig 1(a) 200mb geopotential (full lines) and wind speed (dashed) analysis for 0000 GMT 19 June, 1975 without the use of variational blending. Units are geopotential dekametres and knots. Compare with Fig 5.
Fig 2 200mb geopotential analysis for 1200 GMT 30 January 1976 without the use of variational blending. Units are geopotential dekametres. Compare with Fig 6.
Other analysis schemes used in the northern hemisphere incorporate wind information into geopotential analyses in a different manner to the SCM. For instance, the multivariate optimum interpolation approach (Rutherford 1973, Schlatter 1975) uses geostrophically coupled autocorrelation and cross-correlations between geopotential and wind corrections to adjust predicted fields. There are areas in the northern hemisphere where winds outnumber geopotentials in a similar way to the Australian region. However, there is little evidence available about how the optimum interpolation method performs when a priori geopotential information is unreliable, and the observational data consist mainly of winds.

In common with the 'data-no data' problem, the 'wind only' problem was recognised as being caused in part by too great a contribution from absolute values of the geopotential guess fields. An additional common factor was the need to incorporate differential information (fields derived from interpretation of cloud imagery, and gradients implied by wind observations) in a better way. These considerations led us to investigate an alternative approach to combining absolute and differential information in the analysis of a scalar field.

**VARIATIONAL METHOD**

The use of the calculus of variations in objective analysis was first suggested by Sasaki (1958, 1970), with the underlying idea of simultaneously analysing fields of several meteorological variables subject to an explicit dynamical constraint. Sasaki's theoretical concepts were applied to two and three dimensional synoptic scale analyses, respectively, by Lewis and Grayson (1972) and Lewis (1972). The somewhat different, but not unrelated problem of combining absolute and differential information in the analysis of a single field was addressed by Holl and Mendenhall (1971), who developed the 'field information blending' (FIB) technique, which was also based on the variational calculus. Although it was not specifically formulated for incorporating interpretative data, we have found that the FIB technique is well suited to this purpose.

Since the variational aspect of Holl and Mendenhall's computational design has been used essentially unaltered, it will be summarised only briefly. To analyse a scalar s, we minimise the so-called error functional defined by

\[ F = \sum [a(s - \tilde{s})^2 + b \left( \frac{\partial s}{\partial x} - \frac{\partial \tilde{s}}{\partial x} \right)^2 + \left( \frac{\partial s}{\partial y} - \frac{\partial \tilde{s}}{\partial y} \right)^2 + d(\nabla^2 s - \nabla^2 \tilde{s})^2] \]

where the summation is over all points in the analysis domain. \( s, \tilde{s}, \frac{\partial s}{\partial x}, \frac{\partial s}{\partial y}, \nabla^2 s \) and \( \nabla^2 \tilde{s} \) are independent estimates of the absolute value and corresponding derivatives of \( s \). a, b, and d are reliability weights that reflect the confidence in a point value of the scalar or its differential, and are inversely proportional to the corresponding error variances. In an application where these variances are not well known, the reliability weights may need to be optimised by experiment.

Using the finite difference approximations to \( \frac{\partial s}{\partial x}, \frac{\partial s}{\partial y} \), and \( \nabla^2 s \), and the grid configuration of Fig 3, \( F \) is minimised using the calculus of variations by setting

\[ \frac{\partial F}{\partial s_{i,j}} = 0 \]

for all \( i, j \). This yields a system of linear equations of the form

\[ A \tilde{s} = B \]
The coefficient matrix $A$ and forcing matrix $B$ depend only upon the known values of $s$, $\frac{\partial s}{\partial x}$ etc., and the reliability weights. The system is solved for $\tilde{z}$, a column matrix containing the blended solution at all grid points. Inversion of $A$, a square matrix of dimension equal to the number of points in the analysis domain, was achieved in our application by standard successive over-relaxation, although other methods may be more efficient.

The specific applications of the foregoing general formulation to Australian region analyses, and the corresponding revision to the overall analysis strategy, are detailed in the following section.

APPLICATION

The following application differs from previous procedures (see Appendix) in several essential respects. Interpretative data and numerical predictions are incorporated not only through absolute values, but also through the gradients and Laplacians of derived fields. Geopotential and wind observations are no longer used together in an SCM analysis of geopotential. Instead, thickness and wind observations are used separately in respective scalar SCM analyses. Fields of stream function ($\Psi$), velocity potential ($\chi$), and geopotential ($\phi$) are subsequently diagnosed from the thickness and wind component analyses by variational blending. In the way that the geopotential field is obtained, our application is similar mathematically to Lewis (1972), although we have the additional motivation of incorporating interpretive information.

The revised procedures for any standard level are shown schematically in Fig 4, and the functions of each segment are detailed in the following subsections. The level above which variational blending supersedes the Appendix procedures is optional. The major purpose of deriving the two additional fields of stream function and velocity potential was to provide an alternative to the balance equation for initiating the currently operational filtered baroclinic prediction model. In the absence of this requirement, the analysed wind components may be used directly in geopotential blending, since our tests have indicated that the two intermediate steps have little effect on the final blended geopotential. The relevance of the following applications to the initialisation of primitive equation models, such as that of Gauntlett et al. (1977), which may soon be used in the NMAC, will be discussed briefly in the concluding section.

(i) Wind component guess and analysis

The wind component guess is a weighted mean of three ingredients. A geopotential ($\phi$) is obtained by adding the already analysed adjacent lower thickness to the geopotential of the level below. A first estimate of the wind components is derived from the gradient of $\phi$, using the wind law described in the Appendix.

A second estimate is obtained from the already analysed wind component field at the next lower level by adding the predicted shear. A third estimate, which has non-zero weight equatorward of latitude 20°, is the monthly climatological mean. Using observed winds and the above guess, the $(u, v)$ components are analysed by the SCM.

(ii) Velocity potential blending

The main reason for obtaining a velocity potential is to provide a facility for testing a divergent wind initialisation of prediction models. Fields $\chi$, $\frac{\partial \chi}{\partial x}$, $\frac{\partial \chi}{\partial y}$, $\nabla^2 \chi$ and the associated reliability fields used in Eqn 1 are obtained as follows:
\[ \frac{\partial s}{\partial x} = \frac{S_{i+1,j} - S_{i,j}}{D} \]

\[ \frac{\partial s}{\partial y} = \frac{S_{i,j+1} - S_{i,j}}{D} \]

\[ \nabla^2 s = \frac{S_{i+1,j} + S_{i,j+1} + S_{i-1,j} + S_{i,j-1} - 4S_{i,j}}{D} \]

Fig 3 The grid configuration and finite difference approximations used in variational blending for a scalar $s$. 
Fig 4 Schematic representation of variational blending procedures at each level. These supersede that part of previous procedures within the dashed lines of Fig 3.
\( \tilde{\chi} = 0 \)
\[ \frac{\partial \tilde{\psi}}{\partial x}, \frac{\partial \tilde{\psi}}{\partial y} \text{ as explained below} \]
\( \nabla^2 \tilde{\chi} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \)
\( a = 1 \) at boundary points
\( 0 \) elsewhere
\( b = 5 \)
\( d = 1 \)

The wind component analyses obtained as in (i) are not accurate enough to adequately define the divergence field. In the future it is hoped to use the predicted divergence as an estimate of \( \nabla^2 \chi \). In the meantime, in order to obtain a velocity potential field that at least implies inflow and outflow from synoptic pressure systems, the divergent wind components \( \frac{\partial \chi}{\partial x} \) and \( \frac{\partial \chi}{\partial y} \) are computed on the basis of a cross-isobaric flow of the total wind. It is assumed that the divergent wind component is normal to the streamline, and the inflow angle is dependent only on height.

(iii) Stream function blending

Fields of \( \tilde{\psi}, \frac{\partial \tilde{\psi}}{\partial x}, \frac{\partial \tilde{\psi}}{\partial y}, \) and \( \nabla^2 \tilde{\psi} \) and the associated reliability fields used in Eqn 1 are obtained as follows:

\[ \tilde{\psi} = \frac{\phi_0}{f_{40}} \]
\[ \frac{\partial \tilde{\psi}}{\partial x} = -v + \frac{\partial \chi}{\partial y} \]
\[ \frac{\partial \tilde{\psi}}{\partial y} = u - \frac{\partial \chi}{\partial x} \]
\[ \nabla^2 \tilde{\psi} = K \left( \frac{\partial v}{\partial y} - \frac{\partial u}{\partial x} \right) \]
\( a = 1 \) at boundary points
\( 0 \) elsewhere
\( b = 2 \) at grid points more than 1125 km from data, 10 at remaining grid points
\( d = 0.1b \)

where \( f_{40} \) is the Coriolis parameter at latitude 40\(^o\), and \( K \) is an empirical constant introduced to compensate for numerical truncation effects which tend to underestimate the intensity of the subtropical jet stream. Tests have indicated an optimum value of \( K \approx 1.2 \).

The above distribution of reliability weights constrains the stream function to reflect the analysed wind components most closely in areas of greatest reliability. The geopotential guess \( \phi_0 \) sets the absolute value of \( \psi \), but has little effect on gradients except near the boundary.

(iv) Geopotential blending

Fields of \( \tilde{\phi}, \frac{\partial \tilde{\phi}}{\partial x}, \frac{\partial \tilde{\phi}}{\partial y}, \) and \( \nabla^2 \tilde{\phi} \) for use in Eqn 1 are obtained as follows:
\[ \phi = \phi_0 \]
\[ \frac{\partial \phi}{\partial x} = f \left( \frac{\partial \psi}{\partial x} - \frac{\partial \chi}{\partial y} \right) \]
\[ \frac{\partial \phi}{\partial y} = f \left( \frac{\partial \psi}{\partial y} + \frac{\partial \chi}{\partial x} \right) \]
\[ \nabla^2 \phi = \begin{cases} \nabla^2 \phi_0 & \text{in data areas} \\ \nabla^2 \phi_p & \text{in no-data areas where } \phi_p \text{ is the predicted geopotential} \end{cases} \]

The Coriolis parameter \( f \) is held constant equatorward of latitude 15\(^\circ\). On the basis of several years' experience, this choice of latitude appears to result in the best agreement between observed wind and geopotential gradients in the tropics. Reliability weights are assigned according to the proximity of a grid point to a specified type of observation (Table 1). The effect of this weight distribution is to constrain absolute values of \( \phi \) only at points close to geopotential observations. At points close to observations of wind without geopotential, the blended geopotential will reflect the geopotential gradient implied by the total wind and there will be no contribution from the absolute value of \( \phi \). At grid points remote from observations, the blended geopotential will tend to reflect the gradients and Laplacian of vertically extrapolated and predicted fields.

Table 1  Reliability weights for geopotential blending. A grid point takes its reliability weights for the leftmost applicable column within the topmost applicable row.

<table>
<thead>
<tr>
<th>Grid point closest to an observation</th>
<th>Geopotential and wind</th>
<th>Wind only</th>
<th>Geopotential only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid points between 0 and 375 km</td>
<td>a = 20</td>
<td>a = 0</td>
<td>a = 5</td>
</tr>
<tr>
<td></td>
<td>b = 20</td>
<td>b = 20</td>
<td>b = 5</td>
</tr>
<tr>
<td></td>
<td>d = 1</td>
<td>d = 1</td>
<td>d = 1</td>
</tr>
<tr>
<td>Grid points between 375 and 1125 km</td>
<td>a = 1</td>
<td>a = 0</td>
<td>a = 0</td>
</tr>
<tr>
<td></td>
<td>b = 1</td>
<td>b = 1</td>
<td>b = 1</td>
</tr>
<tr>
<td></td>
<td>d = 1</td>
<td>d = 1</td>
<td>d = 1</td>
</tr>
<tr>
<td>Grid points greater than 1125 km</td>
<td>a = 0</td>
<td>a = 0</td>
<td>a = 0</td>
</tr>
<tr>
<td></td>
<td>b = 5</td>
<td>b = 5</td>
<td>b = 5</td>
</tr>
<tr>
<td></td>
<td>d = 1</td>
<td>d = 1</td>
<td>d = 1</td>
</tr>
</tbody>
</table>

**EXAMPLES**

On the basis of results over several months of comparative testing, the techniques just described were implemented operationally by the NMAC in December 1976. The results, both during testing and since operational implementation, have strongly
suggested a reduction in both the frequency and severity of the 'data-no data' and 'wind only' problems. The following examples have been selected to illustrate the benefits of the new techniques. In all cases, variational blending was operative at levels above 500 mb.

(a) 0000 GMT 19 June 1975 (compare Figs 1(a), 5)

Situations of this type, with a large amplitude trough in the Indian Ocean and a ridge with its axis near the western coast of the continent, have frequently been associated with the 'data-no data' problem. The crux of the problem in these instances is that the absolute values of geopotential in the trough are not well known. The use in the SCM analysis of geopotential and wind reports on the coast, together with adherence to absolute values of the geopotential guess field near the trough axis, result in the improbable geopotential-isotach configuration in the fringe area (Fig 1(a)). Use of the variational blending procedure, with its greater emphasis on gradients and lesser emphasis on absolute value in the area remote from observational data, results in a 200 mb geopotential analysis (Fig 5) which appears both inherently more probable, and also more consistent in pattern in the data fringe area with the 500 mb geopotential implied by manual interpretation (Fig 1(b)).

(b) 1200 GMT 30 January 1976 (compare Figs 2, 6)

This situation illustrates some typical symptoms of the 'wind only' problem, which arise when the geopotential guess field is poor, and insufficient geopotential data are available to define broad scale gradients. Over the Northern Territory and northern Queensland, the 200 mb geopotential field fails to reflect adequately the anticyclonically curved flow indicated by the observed winds. The isolated geopotential observations at Perth (31.9°S, 116.0°E) and Williamtown (32.8°S, 151.8°E) have produced anticyclonic centres in positions which are inconsistent with flow patterns implied by winds in the vicinity. Winds at Mildura (34.2°S, 142.1°E) and Noumea (22.3°S, 166.5°E) are also poorly reflected. The blended geopotential (Fig 6) has largely rectified these defects. The absolute values of geopotential over continental areas remote from observations have also been raised by several dekametres. These raised values were in fact closer to observed geopotentials twelve hours later.

(a) 0000 GMT 3 April 1978

Over the relatively data-rich continents, observed winds and geopotentials sometimes indicate a departure from the geostrophic-gradient relation used in the geopotential blending. Figs 7(a) and 7(b) illustrate a not uncommon situation, where the observed winds at Tennant Creek (19.6°S, 134.2°E), Mount Isa (20.7°S, 139.5°E), Alice Springs (23.8°S, 133.9°E), Cairns (16.9°S, 145.7°E), Townsville (19.2°S, 146.8°E), and Willis Island (16.3°S, 150.0°E) indicate a direction of flow of about 250 degrees across northern Queensland. Geopotential contours corresponding to this direction could not simultaneously fit the observed geopotentials at Alice Springs, Mount Isa, Townsville, and Willis Island, without introducing small scale features into the pattern. In such a case, a stream function (Fig 7(a)), which directly reflects the non-divergent components of the winds without significant contribution from geopotential, provides a better representation of the observed flow pattern in this area than does the blended geopotential (Fig 7(b)), which tends to compromise between the observed wind and geopotentials. The stream function of Fig 7(a) is therefore likely to provide a better initial field for a prediction model than a stream function diagnosed by a balance equation from the geopotential of Fig 7(b).
Fig 6 200mb geopotential analysis for 1200 GMT 30 January 1976 using variational blending. Units are geopotential dekametres.

Compare with Fig 3.
Fig 7(a) 250mb stream function analysis for 0000 GMT 3 April 1976. Units are scaled so that the wind speed corresponds to the indicated wind scale for a contour interval of 100 units.
A similar effect is noticeable over South Australia, where the observed winds at Ceduna (32.1°S, 133.7°E), Woomera (31.2°S, 136.8°E), and Adelaide (34.9°S) (138.5°E) are reflected better by Fig. 7(a) than by Fig 7(b).

CONCLUDING REMARKS

Variational blending techniques appear to have improved the utilisation of the existing data base for the Australian region. Nevertheless, in the absence of quantitative observations over oceanic areas, the resultant analyses still essentially reflect both the ability to interpret from cloud pictures the MSL pressure and 1000 to 500 mb thickness, and the procedures used to derive other fields from interpretative data. In particular, the frequently large differences between guess fields and observed values of wind and thickness above 500 mb at continental and island stations suggest that, despite their 'reasonable' appearance, the corresponding analyses over oceanic areas are subject to even larger errors.

While mathematical techniques are obviously no substitute for improvements in the basic data, variational methods are also likely to be applicable to the assimilation of new types of data, such as remotely sensed temperatures and winds from geostationary satellite time-lapse pictures. Our initial experimentation has indicated a more satisfactory incorporation of VTPR data in the variational scheme just described than in the system described in the Appendix. Lewis (1972) has already demonstrated the potential of the variational approach for dynamically based downward extrapolation of wind data from a data-rich upper level. The extension of the blending scheme to an explicitly three-dimensional (x, y, p) configuration, using observed VTPR thicknesses hydrostatically to determine \( \frac{\partial p}{\partial p} \), is also conceptually straightforward and already underway.

Observations whose errors are significantly correlated in space define gradients more accurately and absolute values less accurately than do similar observations with random error. Preliminary evidence (Hayden 1976) indicates that temperature retrievals based on radiance measurements from the research satellite Nimbus 6 have the former characteristic. Future operational soundings are likely to be similar to these. The ability of the variational approach to exploit the gradient information inherent in such data might be tested.

Initial experiments with the primitive equation model of Gauntlett et al. (1977) have indicated better results using initial mass fields derived by variational blending and winds computed from the blended stream function, than with alternative initial wind fields either derived from a balance equation or including a divergent component from the blended velocity potential. Nevertheless, further refinements to the analysis are probably necessary for best results with models of this type. For instance, the stream function field, currently derived from SCM wind component analyses, reflects wind observations at the expense of geopotential observations when both are present in the same area. The three-dimensional variational scheme currently under development will permit explicit use of thicknesses, with a preassigned reliability, in wind analyses via the thermal wind relation. The use during analysis of a wind law (geostrophic/gradient) which is not entirely consistent with the model dynamics is also open to criticism, but the computational expense of theoretically better methods must be considered. The possibly beneficial effects of model feedback, particularly through the divergent component of the wind, also remain to be explored.

REFERENCES


APPENDIX

Australian Region Numerical Analysis prior to Introduction of Variational Blending

1. Overview

The analysis is based upon two principal fields, the MSL pressure and 1000 to 500 mb thickness, which incorporate both conventionally observed and interpretive data. Guesses for all other fields are derived dynamically and statistically using these two principal fields and numerical predictions. The guess fields are corrected by observed data using the successive correction method. Levels analysed are MSL, 1000, 850, 700, 500, 300, 250, 200, and 100 mb.

2. Analysis sequence (Fig 8)

Subject to later exceptions, fields are analysed in the following order: MSL pressure, 1000 to 500 mb thickness, and for each standard level and layer upward from 1000 mb to 100 mb, geopotential, wind components and speed, temperature, dew point, and thickness. A lower thickness is recomputed by subtraction following the analysis of an upper geopotential. Exceptions to the above are the 250 mb geopotential, winds, and temperature, which are analysed after 100 mb, and dew points above 500 mb, which are not analysed. Fields of total precipitable water, maximum wind, and tropopause pressure are obtained diagnostically.

3. Guess fields

Guess fields are not needed for MSL pressure and 1000 to 500 mb thickness, since manual bogus data provided a complete coverage. For other fields, the guesses are obtained as follows:

(a) Thicknesses. Below 500 mb, the guesses $(\Delta Z)_k$ for the thickness of the three individual layers are computed from the 1000 to 500 mb thickness $(\Delta Z_{10.5})$ analysis, according to

$$(\Delta Z)_k = a_k(\Delta Z_{10.5}) + S_k \quad k = 1,2,3$$

where $a_k$ are constants depending only on $k$, and $S_k$ are stability parameters which are weighted combinations of a numerical prediction and the monthly mean. Above 500 mb, the thickness guesses are a weighted combination of a non-linear extrapolation procedure based on 500 mb temperature (Seaman 1972) and a numerical prediction.

(b) Geopotentials. The 1000 mb geopotential guess is obtained hydrostatistically from the MSL pressure, and a mean temperature estimated from the 1000 to 500 mb thickness. Guess fields for all other levels, except 250 mb, are obtained by adding the thickness of the layer below to the geopotential of the level below. The guess field at 250 mb is obtained from the 300 and 200 mb geopotentials and temperatures.

(c) Wind components. Guess fields are obtained from the geopotential analysis, using a weighted combination of the geostrophic and gradient wind. The relative weights vary smoothly so that in strongly cyclonic areas the gradient wind has full weight, while in anticyclonic areas the geostrophic wind has full weight. This relationship has been derived empirically, on the basis of past experience.
Fig 8  Schematic representation of major analysis program functions prior to developments in this report. The section enclosed by dashed lines is superseded by variational blending procedures.
(d) Temperatures. Below 500 mb, the temperature guess is computed from the thickness analysis (ΔZ) for the layer below, according to

\[ T = K_S (ΔZ) \]

where \( K_S \) is a stability parameter that is a weighted combination of a numerical prediction and the monthly mean. In the tropics, \( T \) is further regressed towards the monthly mean temperature. Above 500 mb, the temperature guess is obtained by extrapolation as in (a).

(e) Dewpoints. At all levels, the dew point guess is obtained from the analysed temperature and numerically predicted dewpoint depression.

4. Successive correction method of analysis

Although essentially similar, the procedure for correcting a guess field using scalar and vector observations differs from Cressman (1959) in a few respects. Manually inserted bogus data cannot be rejected, and conventional data are rejected only on the first pass (i.e. by comparison with the uncorrected guess). Grid points that are near the fringes of single observations' influence are partially weighted back towards the current guess field value, a procedure introduced in an attempt to prevent unrealistic discontinuities arising from isolated observations. Other minor differences are described by Maine and Seaman (1967).