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APPLICATION OF SATELLITE DATA IN VARIATIONAL ANALYSIS  
FOR GLOBAL CYCLONIC SYSTEMS

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## 1. Introduction

Summaries of work underway during the first year of Grant NAG8-059 are presented in the following sections. Some of the research has progressed sufficiently for the preparation of manuscripts and the status of these is noted. Other ongoing research is not yet ready for publication. A bibliography of all papers and abstracts presented as part of development of the variational objective analysis follows the summaries.

The goal of our research is a variational data assimilation method that incorporates as dynamical constraints, the primitive equations for a moist, convectively unstable atmosphere and the radiative transfer equation. Variables to be adjusted include the three-dimensional vector wind, height, temperature, and moisture from rawinsonde data, and cloud-wind vectors, moisture, and radiance from satellite data. This presents a formidable mathematical problem. In order to facilitate thorough analysis of each of the model components, we defined four variational models that divide the problem naturally according to increasing complexity. The first variational model (MODEL I) contains the two nonlinear horizontal momentum equations, the integrated continuity equation, and the hydrostatic equation.

MODEL II contains MODEL I plus the thermodynamic equation for a dry adiabatic atmosphere. The introduction of this additional constraint violates the requirement that the number of subsidiary conditions (dynamic constraints) must be at least one less than the number of dependent variables (Courant, 1936). Inclusion of the same number of constraints as dependent variables overdetermines the problem and a solution is not

guaranteed. Therefore, we must develop a scheme to circumvent this problem or else the dynamically adjusted meteorological variables will not satisfy the closed set of primitive equations.

MODEL III includes MODEL II plus radiance as a dependent variable and the radiative transfer equation as a constraint. MODEL IV contains MODEL III plus an additional moisture variable, a moisture conservation equation and a parameterization for moist adiabatic processes.

In addition, the variational models will be made more responsive to the original observations. The direct methods for calculating derivatives require that the data be pregridded. As noted by Achtemeier (1975) and Williamson and Daley (1983), pregridding removes the dependence of the final analysis upon the original observations. This dependence can be reestablished by merging the variational models with the successive corrections interpolation method (SCM) through a cyclical procedure. Independently interpolated meteorological variables are merged variationally. The variational fields then serve as first guess fields for the next SCM analysis, and so on.

The research currently is expanding into six areas. These are 1) conversion of MODEL I to the ISWS VAX 750 computer, 2) completion of MODEL II, 3) development of MODEL III (radiative transfer equation), 4) making the model more responsive to the observations, 5) extension of MODEL I analysis periods from one to three, and 6) development of MODEL IV (moisture). Progress in each of these research areas and future research plans is briefly summarized in the following sections.

## 2. Conversion of MODEL I to the ISWS VAX 750 Computer.

We have taken a module approach to the development of MODEL I. Mathematical equations, data gridding, vertical interpolation, nondimensionalization and etc have been programmed separately. The advantages of this approach are that modules can be replaced by improved versions without disrupting the flow of other programs, revisions can be made within modules without extensive reprogramming, coding is easier and less error prone, and debugging is faster and less costly. The disadvantage is that the MODEL I requires a large number of data files.

Table 1 summarizes the 84 modules of MODEL I. Even though the modules are small relative to the whole program several have large storage requirements that can be handled by the University of Illinois CYBER 175 computer only during hours of minimal demand (late at night). The advantages of transferring MODEL I to the ISWS VAX 750 with its virtual memory are 1) the model can be run at any time, 2) useful peripheral equipment such as the ZETA plotter and VT100 compatible terminals are linked directly to the VAX, and 3) the VAX-VMS operating system is compatible with the operating system of the CRAY X-MP/24 supercomputer operated by the National Center for Supercomputing Applications. Plans are underway to move MODEL I to the supercomputer once compatibility is achieved.

The transfer of MODEL I to the ISWS VAX was completed in February 1987. Runs with the VAX version reveal significant discrepancies with the CYBER version. Investigations to reveal the source of the discrepancies are still ongoing. Computer truncation cannot be ruled out at this time.

Table 1. Summary of program modules that make up MODEL I.

Program Description	Number of Programs
TIROS-N and Rawinsonde data read and format	4
Grid definition and map projection	1
Data gridding	2
Transformation into nonlinear sigma coordinate	1
Nondimensionalize variables	1
Initial variable fields	13
Coefficients and forcing functions calculated from initial data only	12
Variational adjustment model - programs in cyclical solution sequence	42
Model statistics	6
Tendency term recomposition	2

The VAX has a 32-bit word in comparison with the 64-bit word of the CYBER and the CRAY.

Once the conversion is complete, the following studies are to be done:

- 1) The precision moduli will be varied over a large range of values to determine the model sensitivity to varying levels of input data accuracy. This study will also determine the ranges of the precision moduli for which the cyclical solution sequence will converge.
- 2) The precision moduli will be varied horizontally. Although MODEL I was formulated for horizontally varying precision moduli, so far all analyses have been done with only vertically varying precision moduli. Horizontal derivatives of the precision moduli appear in the equations for the adjusted geopotential height and the adjustment velocity potential. These equations are general second order partial differential equations which are solved by traditional relaxation methods. This study will determine the impacts of horizontally varying precision moduli upon convergence to a solution.

This effort has progressed to a limited extent through an extension of Barbara Chance's thesis. (See project bibliography for details of her report.) Her work with mesoscale data showed the equation for the adjustment velocity potential to be particularly sensitive to large horizontal variations in the precision moduli.

- 3) The adjustment of the velocity components tendencies will be further analyzed. To date, the results for these important hypersensitive terms have been very encouraging. However, the adjustment process has not been

understood as fully as the adjustments for the remaining variables. Some preliminary results obtained with the few model runs available point to inadequacy of the currently used tendency term formulation when the advective current is unusually strong. (The advective current is a smoothed version of the gridded 500 mb wind field.) An alternative formulation that corrects for this problem has been derived but is not yet coded.

### 3. Completion of MODEL II.

The components of the variational adjustment equations that arise from the application of the Euler-Lagrange operator to the thermodynamic equation for dry, adiabatic flow were derived during mid 1986. These terms were, as a matter of course, expressed compatible with the staggered grid used for MODEL I. These terms were coded into the appropriate modules and the programs are now in the final check-out stages. Test runs with MODEL II are expected within the next month.

### 4. Development of MODEL III (radiative transfer equation).

In collaboration with Dr. Stanley Kidder, the variational equations for the radiative transfer equation for the four microwave TOVS channels were derived for the nonlinear sigma coordinate system during spring of 1986. It was apparent that the solution of these equations with radiance and temperature as dependent variables was another temperature retrieval algorithm. The advantage of the variational formulation over other retrieval algorithms is that other meteorological variables such as winds and heights can be entered into the retrieval process.

Reprogramming of the microwave channel weights for compatibility with the MODEL I vertical coordinate was begun. Dr. Kidder left the project for a one-plus year leave of absence in August 1986.

5. Making the Model more Responsive to the Observations.

The direct methods for calculating derivatives for the various terms of the variational model require that the data be pregridded. Past approaches (Achtemeier, 1975) have treated the gridding and adjustment processes separately and sequentially and therefore the dependence of the final analysis upon the original observations is removed. This dependence can be reestablished by merging the variational models with the successive corrections interpolation method (SCM) through a cyclical procedure. Independently interpolated meteorological variables are merged variationally. The variational fields then serve as first guess fields for the next SCM analysis, and so on.

Before the SCM is merged with the variational model, we must take into consideration 1) how the data is to be gridded and 2) the best SCM method to grid the data. As regards how the data is to be gridded, we have investigated the calculation of the geopotential gradients by triangulation and then gridding the gradients directly. The current approach calculates the geopotential gradients from the gridded heights. The advantages of the triangulation method are as follows: a) The locations of the data points are at triangle centroids not at the observation locations. Therefore the interpolation error caused by irregular distribution of the geopotential gradient will be independent from the error of interpolation for the geopotential. These errors therefore can be more easily removed by the



variational adjustment. b) The gradients are not calculated from the same grid as that used for the variational adjustment. This better satisfies the theoretical requirement for the variational analysis namely that the observations be mutually independent.

The disadvantages of the triangulation method are currently not known.

As regards the best method to grid the data, much effort has been expended to determining the best SCM method. We have undertaken a thorough analysis of the Barnes (1964, 1973) objective analysis method. Some of the results appear in the papers (Achtemeier 1986, 1987) that accompany this interim report. Still further work is being done on the Barnes methods and will be the subject of a third article to be published in the near future. We have found that replacing the traditional 2-pass Barnes method with a three-pass version a) better restores short but resolvable wavelengths without introducing undesirable shorter wavelengths into the analyzed fields, b) does not introduce high frequency noise caused by irregular station spacing, and c) gives smoother, more meteorologically realistic derivatives. The later improvement is crucial to the variational analysis which requires the calculation of numerous first and second derivatives from analyzed fields of data.

It is anticipated that these new methods will lead to improved analyses of the initial fields along with the incorporation of the SCM into the variational analysis. We plan to continue this research effort.

#### 6. Extension of MODEL 1 Analysis Periods from One to Three.

During the past year, we performed MODEL 1 SAT and NOSAT analyses for the 00 GMT and 12 GMT 11 April 1979 periods. As with the analyses for 12 GMT 10 April (Achtemeier, etal.; 1986) the purpose the new analyses is for model error analysis and sensitivity studies. These analyses are evaluated according to three criteria that measure a) the extent to which the assimilated fields satisfy the dynamical constraints, b) the extent to which the assimilated fields depart from the observations, and c) the extent to which the assimilated fields are realistic as determined by pattern recognition. The last criterion requires that the signs, magnitudes, and patterns of the hypersensitive vertical velocity and local tendencies of the horizontal velocity components be physically consistent with respect to the larger scale weather systems.

The percent reduction of the initial RMS error is used to determine the extent to which the SAT and NOSAT blended data sets converge to the solution of the four dynamical constraints. These results show same levels of convergence for the two new analyses as for 1200 GMT 10 April 1979; 90-95 percent error reduction for the two horizontal momentum equations, and 90-100 percent for the integrated continuity and hydrostatic equations.

Regarding the analysis of hypersensitive variables, the vertical velocity was analyzed well at 00 GMT but not for 12 GMT 11 April. This problem has been traced to the inadequacy of the currently used tendency term formulation when the advective current is unusually strong. (The advective current is a smoothed version of the gridded 500 mb wind field.) An alternative formulation that corrects for this problem has been derived but is not yet coded.

The results for the local tendencies continue to be better than expected. For reasons not yet understood, the patterns of 3-h velocity component tendencies generated by MODEL I better correspond to observed 3-h forward tendencies than to 3-h backward tendencies or to the 6-hr average centered at the analysis time.

#### 7. Development of MODEL IV (Moisture).

Our work on developing methods to meld and grid moisture data and to build the moisture conservation equation and moisture/heat parameterizations into the thermodynamic equation is at the conceptual stage.

#### 8. References

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## 9. Project Bibliography

The following is the bibliography of all publications involving the effort to develop a diagnostic variational model for data assimilation.

### a) Published Papers

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Achtemeier, G.L., 1986: Modification of a Variational Objective Analysis Model for New Equations for Pressure Gradient and Vertical Velocity in the Lower Troposphere and for Spatial Resolution and Accuracy of Satellite Data. Final Report to USRA, Contract NAS 8-36474, 28 pp.

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operationally-retrieved TOWS temperature biases. Mon. Wea. Rev., 114, 1175-1178.

Achtemeier, G. L., 1987: On the Concept of Varying Influence Radii for a Successive Corrections Objective Analysis. Mon. Wea. Rev., 115, (In Press)

b) Abstracts of Forthcoming Papers

Achtemier, G. L., 1987: A 3-Pass Near Optimum Barnes Method for the Univariate Objective Analysis of Mesoscale Phenomena. (To be presented at the Third Conference on Mesoscale Processes, August 21-26, 1987, Vancouver, B.C., Canada)

**ABSTRACT:** The Barnes objective analysis method is widely used by mesoscale meteorologists for gridding irregularly distributed weather data. Results from a thorough reanalysis of the Barnes method revealed that the filter fidelity optimizes (filter fidelity measured by how well the method restores desired wavelengths and removes undesired wavelengths) if the filter parameters that determine the influence of observations are unchanged for both the initial and correction passes (analogous to a constant radius of influence). These results were obtained from families of response curves that satisfied the requirement that the final responses were equal at an arbitrary reference wavelength.

Subject to the above requirement, the Barnes method with filter parameters unchanged (fixed method) was compared with a more traditional approach (reduction parameter equal to 0.2) through theoretical and analytical tests. The analyses with analytical monochromatic sine and cosine waves were done with uniform and highly nonuniform data distributions.

The theoretical studies and analytical analyses with uniform data distributions confirmed the superiority of the fixed method for wavelengths ranging from twice to twelve times the average observation separation (S). The greatest improvements, found for the 3S to 6S wavelengths, ranged up to seven percent of the amplitudes of the original wavelengths. These improvements were locally large and were gained without the method exciting undesirable very short wavelengths. However the traditional approach gave the best results for the longer wavelengths when the data were nonuniformly distributed. This was because the smoother first pass of the traditional method gave better representation of the area near the inflection points of these waves.

The information about how different filter parameters modify the performance of the standard 2-pass Barnes method was used to develop a 3-pass hybrid method that incorporates the advantages of both the fixed and traditional methods. Comparisons between analyses of derivatives of the height and wind fields surrounding intense jet streaks on 00 GMT 10 April 1979 by the hybrid method and the traditional method are presented in this paper. The comparisons show that (1) the hybrid method restores more of the mesoscale features inherent in the data, (2) the hybrid method better preserves linear features such as shear vorticity zones and divergence

zones, (3) the hybrid method better preserves the magnitude and shape of patterns of the laplacian of the height field, and (4) the hybrid method does not as severely contaminate the analysis with undesirable small scale centers that arise from analysis of nonuniformly distributed data.