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NOAA Technical Memorandum NWS NMC-62

ADDITION OF OROGRAPHY TO THE SEMI-IMPLICIT VERSION OF THE SHUMAN-HOVERMALE MODEL

National Meteorological Center
Washington, D. C.
April 1978

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Kenneth A. Campana
National Meteorological Center, NWS, NOAA
Washington, D.C. 20233

ABSTRACT. The semi-implicit version of the Shuman-Hovermale model now includes orography. The incorporation of mountains into the model was made with great difficulty and is documented in this report. Care must be taken when splitting the pressure gradient term in the equations of motion into implicit and explicit parts. The orographic effect on the pressure gradient term is exhibited in two ways--as the gradient of surface geopotential and as the gradient of surface pressure. These two effects must be calculated together as either implicit or explicit parts in order that the long time step will not cause serious orographic-related truncation errors. Necessary changes to model equations are documented.

1. INTRODUCTION

The semi-implicit time integration scheme has been reported in the literature for several years and is used in a number of multilayer numerical weather prediction models around the globe. The implicit treatment permits a long time step to be used in a forecast model because it time-averages terms in the equations which govern the fastest moving gravity waves.[1] All other terms are treated in the normal explicit sense. The computation time savings resulting from the long time step make the semi-implicit technique particularly attractive for numerical models that are being used in an operational forecasting environment. Because a set of Helmholtz equations must be solved during each time step, the savings from the semi-implicit method is not so great as would be expected from the longer time step. However, computation time savings of four to one are reported for a six to one ratio of time step intervals in semi-implicit versus explicit runs (Kwizak and Robert, 1971).

A semi-implicit version of the Shuman-Hovermale 6-layer primitive equation model (6L PE) has been developed at the National Meteorological Center (NMC) by Gerrity et al. (1973), and early experimental results without orography have been published by Campana (1974). It is a simplified research model patterned after the 6L PE, but uses none of its physical parameterizations and has twice its grid length. Tests that included orography were initially unsuccessful, and it was with great difficulty that mountains were incorporated into the model. The purpose of this report is to document the solution to the mountain problem in the semi-implicit model. The first section will briefly describe the splitting of the equations into implicit and explicit parts. The next section will discuss the mountain problem and its solution. The final section will

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[1]Pressure gradient term in the equations of motion and divergence term in the continuity equation.

present the model equations which must be adjusted to fit the above solution. The actual model is not discussed in great detail, so the reader is referred to Gerrity (1973) for all the particulars. In this report, the terminology used by Gerrity (1973) will be used where appropriate.

2. SEMI-IMPLICIT TRANSFORMATION

In order to more easily discuss the mountain problem in the next section, a brief description of the transformation of the equations of motion to semi-implicit time differencing is helpful. The equation of motion for the v component of the wind is used for this discussion:

$$\frac{\partial}{\partial t}\frac{v}{m} + \frac{\partial \phi}{\partial y} + \alpha\frac{\partial p}{\partial y} = - \hat{f}\frac{u}{m} - u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - \frac{\dot{\sigma}}{m}\frac{\partial v}{\partial \sigma} + \text{Friction}, \tag{1}$$

where

- t = time,
- u = horizontal wind component in the x-direction,
- v = horizontal wind component in the y-direction,
- $\dot{\sigma}$ = vertical wind component in the σ-direction,
- p = pressure,
- α = specific volume,
- ϕ = geopotential,
- $\hat{f}$ = Coriolis and map factor terms = $f - v\frac{\partial m}{\partial x} + u\frac{\partial m}{\partial y}$,
- m = map factor, and
- f = Coriolis force.

Note that, unlike other models at NMC, this one uses temperature and pressure as the thermodynamic variables.

First, eq. (1) is simplified by employing a linearization procedure. Each variable, X, is assumed to be composed of a basic state, $\tilde{X}$, varying only with σ, and a deviation from this basic state, X',

$$X = \tilde{X} + X' . \qquad (2)$$

Implicit calculations are done only on the resulting linear terms. Basic state values for the thermodynamic variables are obtained from the U.S. Standard Atmosphere (1962) using "representative" σ-layer pressures. The basic state wind field is one of no motion ($\tilde{u} = \tilde{v} = 0$).

Taking the $\alpha\frac{\partial p}{\partial y}$ term in eq. (1) and defining

$$\alpha = \tilde{\alpha} + \alpha'$$

and

$$p = \tilde{p} + p' \text{ with } \frac{\partial \tilde{p}}{\partial y} = 0, \text{ since } \tilde{p} \text{ is a function of}$$

σ only; one obtains

$$\alpha\frac{\partial p}{\partial y} = \tilde{\alpha}\frac{\partial p'}{\partial y} + \alpha'\frac{\partial p'}{\partial y} . \qquad (3)$$

In the semi-implicit treatment of eq. (1), terms on the left side are time-averaged (implicit calculation). Rewriting eq. (1) using the linearization process for all terms except $\frac{\partial \phi}{\partial y}$, one obtains :

$$\frac{\partial}{\partial t}\frac{v'}{m} + \frac{\partial \phi}{\partial y} + \tilde{\alpha}\frac{\partial p'}{\partial y} = -\alpha'\frac{\partial p'}{\partial y} - \hat{f}\frac{u'}{m} - u'\frac{\partial v'}{\partial x} - v'\frac{\partial v'}{\partial y} - \frac{\dot{\sigma}'}{m}\frac{\partial v'}{\partial \sigma} + \text{Friction} . \qquad (4)$$

Note that the $\alpha'\frac{\partial p'}{\partial y}$ term is nonlinear and is calculated on the explicit (non-time averaged) side.

Letting superscripts τ-1, τ, and τ+1 denote quantities evaluated explicitly at past, present, and future time levels, the following definitions of the time average, $\overline{X}^{2t}$, and the time derivative, $\frac{\partial X}{\partial t}$, are useful when transforming eq. (4) to its semi-implicit counterpart,

$$\overline{X}^{2t} = \tfrac{1}{2}(X^{\tau+1} + X^{\tau-1})$$

$$\frac{\partial X}{\partial t} = \frac{X^{\tau+1} - X^{\tau-1}}{2\Delta t} = \frac{\overline{X}^{2t} - X^{\tau-1}}{\Delta t} \ .$$

Implicit treatment of the left side of eq. (4) and dropping the primes from all variables leaves the following:

$$\frac{\overline{v}^{2t}}{m} + \Delta t\left(\frac{\partial\overline{\phi}^{2t}}{\partial y} + \tilde{\alpha}\frac{\partial\overline{p}^{2t}}{\partial y}\right) = \frac{v^{\tau-1}}{m} + \Delta t(\ldots\ldots)^{\tau} \ , \qquad (5)$$

where $(\ldots\ldots)^{\tau}$ represents all terms on the right side of eq.(4).

In the actual model equations, σ-layer pressure thicknesses, $\partial p/\partial\sigma$, are used in the pressure gradient term, rather than pressure itself. Further, in order to close the system of equations, $\overline{\phi}^{2t}$ is transformed into implicit terms involving $\overline{\frac{\partial p}{\partial\sigma}}^{2t}$ and $\overline{\dot{\sigma}}^{2t}$, and into other terms, R, calculated explicitly. Replacing $\overline{\phi}^{2t}$ by these terms in eq.(5), and using the actual model variables, one obtains:

$$\frac{\overline{v}^{2t}}{m} + \frac{\partial}{\partial y}\sum_{j=1}^{3} g_{k,j}\ \overline{\left(\frac{\partial p}{\partial\sigma}\right)_j}^{2t} + \frac{\partial}{\partial y}\sum_{j=1}^{4}\hat{h}_{k,j}\ \overline{\dot{\sigma}}_j^{2t} = \frac{v_k^{\tau-1}}{m} - \Delta t\frac{\partial R_k^{\tau}}{\partial y}$$

$$+ \Delta t(\ldots\ldots)_k^{\tau} \qquad (6)$$

k = vertical index,

where $\frac{\partial R_k^{\tau}}{\partial y}$ and the matrices $g_{k,j}$ and $\hat{h}_{k,j}$ all result from the transformation of $\overline{\phi}^{2t}$ (section 4 in Gerrity, 1973). By solving a set of Helmholtz equations, one obtains the three $\overline{\frac{\partial p}{\partial\sigma}}^{2t}$ and the four $\overline{\dot{\sigma}}^{2t}$ which are needed to compute $\overline{v}^{2t}$ from eq. (6).

The preceding general description of the semi-implicit transformation now allows one to proceed to a discussion of the orographic problem.

3. OROGRAPHY

Semi-implicit model experiments without orography were quite successful using a time step of 1 hour. When mountains were introduced, however, erroneous orographic scale features developed over large mountain masses and were amplified with time. An example of this problem over the Rockies and Himalayas is shown in figure 1. Tests with lower mountain elevations only lessened the real difficulty. When the model was run in an entirely explicit mode (and thus a shorter time step) the problem disappeared (fig. 2). Further tests with the semi-implicit version, using a time step as short as the explicit mode above, also yielded trouble-free forecasts. There appeared to be severe time truncation errors near orography when using a long time step.

After a great deal of reflection and experimentation, the problem appeared to be related to the implicit/explicit splitting of the pressure gradient term[2] in the tropospheric sigma domain. Recalling eq.(1), the pressure gradient near mountains is made up of two relatively large terms having opposite signs $\left(\frac{\partial\phi}{\partial y}, \alpha\frac{\partial p}{\partial y}\right)$. Through the semi-implicit transformation on this equation, these terms are further broken into implicit and explicit parts. Close examination shows that these two parts also can be large terms of opposite sign in the vicinity of mountains. Since the basic state pressure, $\tilde{p}$, is not a function of (x,y), gradients of pressure near orography remain in the deviation part, p'. Thus a good portion of the large $\alpha\frac{\partial p}{\partial y}$ term near mountains remains on the implicit side of eq.(4)

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[2]In the equations of motion.

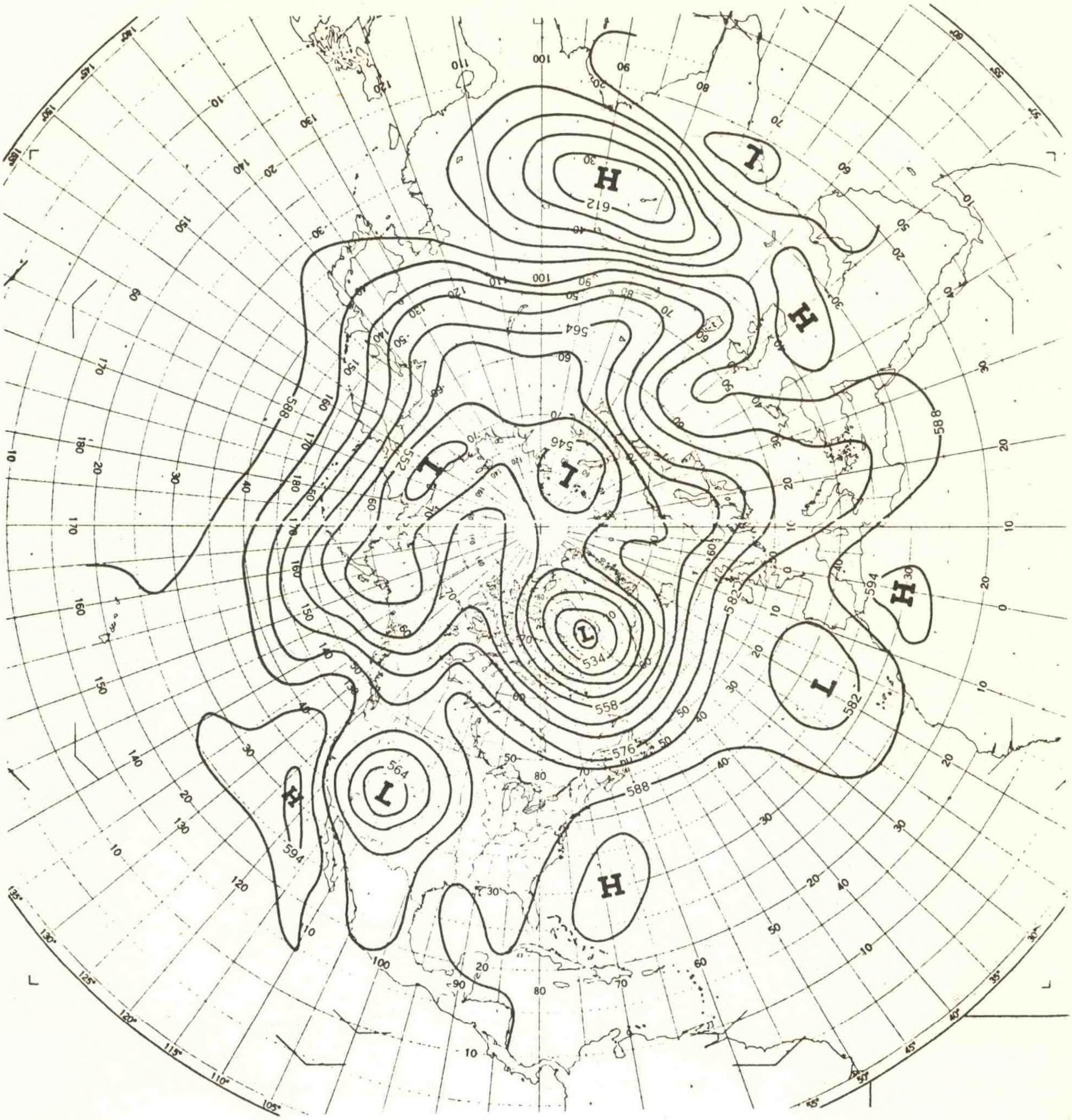

Figure 1.--Semi-implicit 500-mb heights (dekameters), time step = 3600 s, 11-hr forecast from 0000 GMT 24 August 1972. Contour interval 6 dekameters.

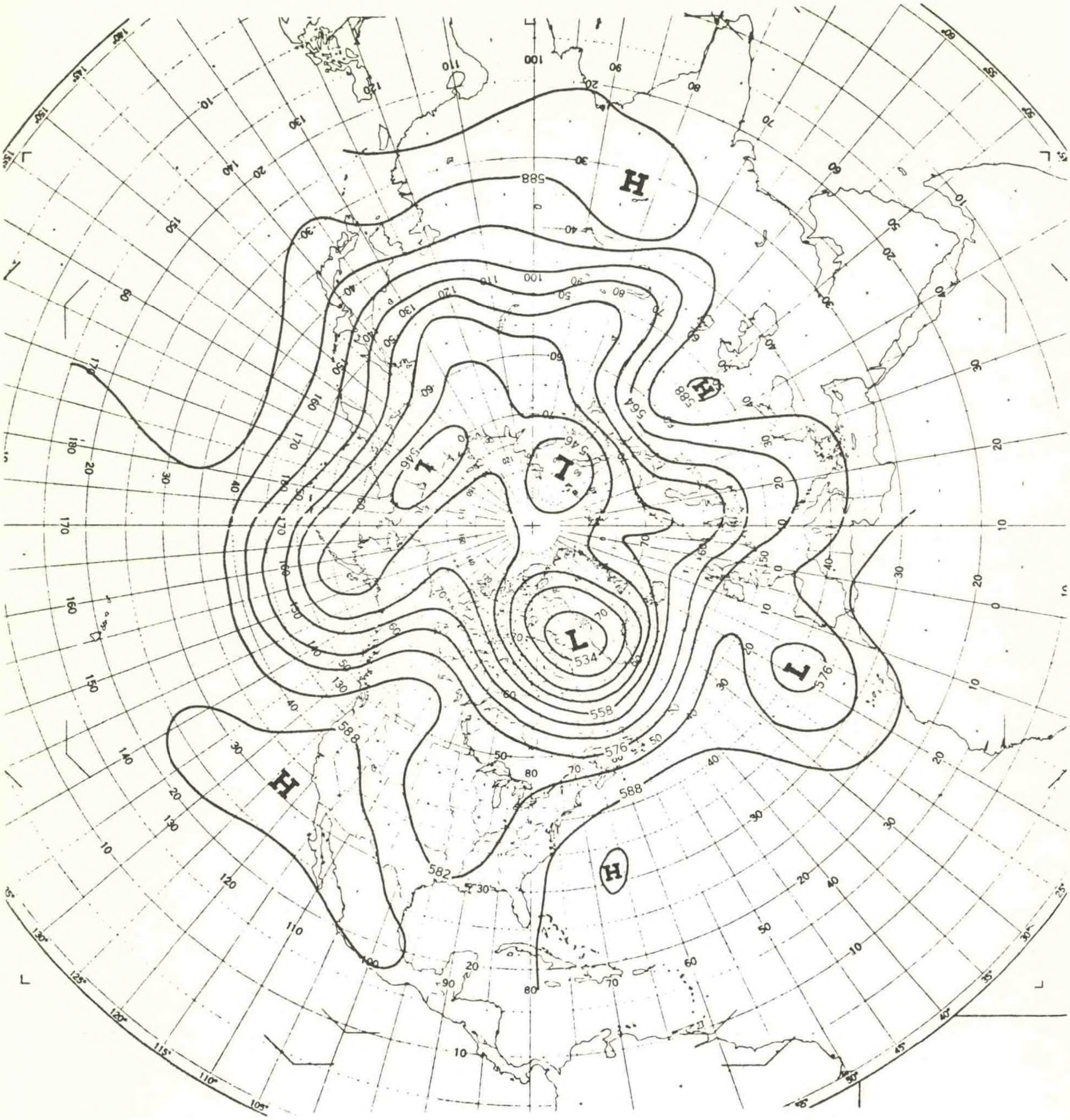

Figure 2.--Explicit 500-mb heights, time step = 600 s, 12-hr forecast from 0000 GMT 24 August 1972. Contour interval 6 dekameters.

in $\tilde{\alpha}\frac{\partial p'}{\partial y}$. Later, however, the process of transforming $\overline{\phi}^{2t}$ leaves the gradient of ground elevation on the explicit side of eq. (6) imbedded in the $\frac{\partial R_k}{\partial y}$ term. Examination of the two parts of the pressure gradient term at a grid point near steep mountains shows they both are larger than any other term in eq.(6). Table 1 displays the size of these pressure-gradient parts and their sum in the lowest tropospheric layer of the model during a semi-implicit forecast (1-hour time step). The sum amplifies with time and the implicit part seems to cause most of the increase. In only 11 forecast hours, negative model pressures appear over the mountains and produce a model failure.

Since the gradient of model ground height and the gradient of model surface pressure are of opposite sign, the magnitude of both parts of the pressure-gradient term can be reduced by calculating both of them on the same side of the equation, either explicitly or implicitly, rather than separately. In order to disrupt the model formulated by Gerrity (1973) as little as possible, a redefinition of the pressure deviation, p', is made in the troposphere:

$$p' = p'' + \tilde{p}' , \tag{7}$$

where $\tilde{p}'$ is a surface pressure at the top of the model mountains obtained from the U.S. Standard Atmosphere. All parts of eq.(7) are functions of (x,y) and $\tilde{p}'$ is time invariant. Now redefine the implicit term, $\tilde{\alpha}\frac{\partial p'}{\partial y}$, in eq. (4):

$$\tilde{\alpha}\,\frac{\partial p'}{\partial y} = \tilde{\alpha}\,\frac{\partial p''}{\partial y} + \tilde{\alpha}\,\frac{\partial \tilde{p}'}{\partial y} . \tag{8}$$

Moving the time invariant quantity $\tilde{\alpha}\,\frac{\partial \tilde{p}'}{\partial y}$ to the explicit side of eq.(4)

Table 1.--Implicit and explicit parts of pressure gradient term in eq. (6) at one grid point (k = 6) (units in m/s) expressed as effect on $\bar{v}_6^{2t}/m$.

Forecast hour	Pressure gradient (implicit)	Pressure gradient (explicit)	Total pressure gradient
1	+ 14.5	- 13.2	+ 1.3
2	+ 14.7	- 13.2	+ 1.5
3	+ 14.8	- 13.1	+ 1.7
4	+ 14.9	- 13.2	+ 1.7
5	+ 15.0	- 13.1	+ 1.9
6	+ 15.0	- 13.1	+ 1.9
7	+ 15.2	- 13.0	+ 2.2
8	+ 15.4	- 13.0	+ 2.4
9	+ 15.8	- 12.9	+ 2.9
10	+ 16.3	- 12.7	+ 3.6
11	+ 16.9	- 12.6	+ 4.3

one obtains

$$\frac{\partial}{\partial t}\frac{v'}{m}+\frac{\partial\phi}{\partial y}+\tilde{\alpha}\frac{\partial p''}{\partial y}=-\alpha'\frac{\partial p'}{\partial y}-\hat{f}\frac{u'}{m}-u'\frac{\partial v'}{\partial x}-v'\frac{\partial v'}{\partial y}$$

$$-\frac{\dot{\sigma}'}{m}\frac{\partial v'}{\partial \sigma}+\text{Friction}-\tilde{\alpha}\frac{\partial \tilde{p}'}{\partial y}. \qquad (9)$$

In essence, the tropospheric basic state pressure is adjusted to account for orography. Recalling that σ-layer pressure thickness, $\frac{\partial p}{\partial \sigma}$, is used rather than pressure, p, in the actual model, eq. (6) in the troposphere (k = 4,5,6,7) becomes:

$$\overline{\frac{v_k}{m}}^{2t}+\frac{\partial}{\partial y}\sum_{j=1}^{3} g_{k,j}\overline{\left(\frac{\partial p}{\partial \sigma}\right)_j}^{2t}+\frac{\partial}{\partial y}\sum_{j=1}^{4}\hat{h}_{k,j}\,\overline{\dot{\sigma}_j}^{2t}=\frac{v_k^{\tau-1}}{m}-\Delta t\frac{\partial R_k^{\tau}}{\partial y}$$

$$+\Delta t(\ldots\ldots)_k^{\tau}-\Delta t\,\tilde{\alpha}_k\frac{\partial \tilde{p}'}{\partial y}. \qquad (10)$$

Of course, in a like manner there is a $\frac{\partial \tilde{p}'}{\partial x}$ term in the u-equation of motion.

This redefinition of the deviation part of the pressure variable and its proper splitting into implicit and explicit parts removed the amplifying mountain features. Successful semi-implicit forecasts using an hour time step have been made beyond 48 hours. Examination of the two parts of the pressure gradient term at one grid point in table 2 shows them to be an order of magnitude smaller with the above modification than with the old formulation (table 1). The implicit part, which seemed responsible for the amplification, is now under control.

4. CHANGES TO MODEL EQUATIONS

This section documents changes to the actual semi-implicit model equations that are necessary to remove the mountain problem. Gerrity (1973) denotes sigma domain pressure thicknesses as π, so eq. (7) becomes

$$\pi_k' = \pi_k'' + \tilde{p}' \quad \text{for } k = 3\,, \qquad (11)$$

Table 2.--Implicit and explicit parts of pressure gradient term in eq. (10) at one grid point (k = 6) (units in m/s) expressed as effect on $\overline{v}_6^{2t}/m$.

Forecast hour	Pressure gradient (implicit)	Pressure gradient (explicit)	Total pressure gradient
1	- .7	+ 1.1	+ .4
2	- .8	+ 1.1	+ .3
3	- .8	+ 1.1	+ .3
4	- .7	+ 1.1	+ .4
5	- .6	+ 1.2	+ .6
6	- .6	+ 1.2	+ .6
7	- .6	+ 1.2	+ .6
8	- .7	+ 1.1	+ .4
9	- .7	+ 1.1	+ .4
10	- .7	+ 1.1	+ .4
11	- .7	+ 1.1	+ .4

where k = 3 is the tropospheric sigma domain. Notice that ($\tilde{}$) refers to basic state variables, that the primes on the deviation parts are dropped ($\pi_3' \equiv \pi_3$), and that the $\tilde{p}'$ notation for the standard atmosphere surface pressure at the mountain tops is retained. Changed model equations are presented below, where equation numbers noted are those from Gerrity (1973):

1. Eq.(83) becomes:

$$\vec{V}_k^\tau = \frac{\vec{v}_k^{\tau-1}}{m} - \Delta t[(\alpha_k^\tau - \tilde{\alpha}_k)\hat{\nabla}(\alpha_k \pi_3^\tau + \pi_2^\tau + \pi_1^\tau) + \frac{\hat{f}_k^\tau}{m}\vec{k} \times \vec{v}_k^\tau$$

$$+ \vec{v}_k^\tau \cdot \hat{\nabla}\, \vec{v}_k^\tau + B_k^\tau + \tilde{\alpha}_k \sigma_k \hat{\nabla}\, \tilde{p}'] \, .$$

2. Eq.(116) becomes:

$$\vec{V}_7^\tau = \frac{\vec{v}_7^{\tau-1}}{m} - \Delta t[(\alpha_7^\tau - \tilde{\alpha}_7)\hat{\nabla}(\pi_3^\tau + \pi_2^\tau + \pi_1^\tau) + \frac{\hat{f}_7^\tau}{m}\hat{k} \times \vec{v}_k^\tau$$

$$+ \vec{v}_7^\tau \cdot \hat{\nabla}\, \vec{v}_7^\tau + B_7^\tau - \vec{F} + \tilde{\alpha}_7\, \hat{\nabla}\, \tilde{p}'] .$$

Changes must also be made to other equations that contain π_3:

3. Eq.(107) becomes:

$$P_T^\tau = \pi_3^{\tau-1} + \Delta t\ \nabla \cdot[(\tilde{\pi}_3 - p_c)\vec{v}_T^\tau] - \Delta t\ \nabla \cdot[(\pi_3^\tau - p_c)\vec{v}_T^\tau] - \tilde{p}' \quad .$$

4. Eq.(112) becomes:

$$G_k^\tau = \tilde{\alpha}_k p_c - (\alpha_k^\tau - \tilde{\alpha}_k)(\pi_3^\tau - \tilde{\pi}_3) - \tilde{\alpha}_k \tilde{p}' \ .$$

5. Eq.(114) becomes:

$$I_k^\tau = \tilde{\alpha}_k p_c - (\alpha_k^\tau - \tilde{\alpha}_k)[\pi_3^\tau + \frac{1}{\sigma_k}(\pi_2^\tau + \pi_1^\tau) - \tilde{\pi}_3 - \frac{1}{\sigma_k}(\tilde{\pi}_2 + \tilde{\pi}_1)] - \tilde{\alpha}_k \tilde{p}' \cdot$$

6. Eq.(125) becomes:

$$I_7^\tau = \tfrac{1}{2}\, \tilde{\alpha}_7 p_c - [(\pi_1^\tau + \pi_2^\tau + \pi_3^\tau - \tilde{\pi}_1 - \tilde{\pi}_2 - \tilde{\pi}_3)(\alpha_7^\tau - \tilde{\alpha}_7)] - \tilde{\alpha}_7 \tilde{p}' \quad .$$

Changes also have to be made to the Helmholtz equations, since the tropospheric pressure thickness, π_3, on the implicit side of the equations has been changed to π_3'' through eq.(11).

7. Eq.(236) becomes:

$$p^T = \{ \overline{\pi}_1^{2t}, \overline{\pi}_2^{2t}, \overline{(\pi_3 - \tilde{p}')}^{2t}, \overline{w}_1^{2t}, \overline{w}_2^{2t}, \overline{w}_3^{2t}, \overline{w}_4^{2t} \}.$$

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