NOTES AND CORRESPONDENCE

Semigeostrophic Theory

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20 June 1984 and 4 April 1985

ABSTRACT

The geopotential tendency form of semigeostrophic theory is derived and compared with the potential vorticity form. The tendency form is compact and particularly convenient for non-Boussinesq, nonuniform potential vorticity flows.

1. Introduction

By combining the geostrophic momentum approximation (Eliassen, 1948) and the geostrophic coordinate transformation, Hoskins (1975) and Hoskins and Draghi (1977) have derived a filtered, three dimensional system of equations (semigeostrophic equations) which are nearly as simple as the quasi-geostrophic equations but which apply to more general physical situations such as fronts, jets, occluding baroclinic waves, etc. With a specified, height independent deformation field, two dimensional versions of the semigeostrophic equations (Hoskins, 1971; Hoskins and Bretherton, 1972) give fairly realistic simulations of both surface fronts (uniform potential vorticity model) and upper-level fronts (discontinuous potential vorticity model). In the three dimensional case uniform potential vorticity jet flows develop unstable baroclinic waves which evolve into the nonlinear regime, producing fronts and an occluding warm sector (Hoskins, 1976; Hoskins and West, 1979; Hoskins and Heckley, 1980). Three dimensional nonuniform potential vorticity jet flows produce similar evolution except that upper tropospheric frontogenesis is more realistic (Heckley and Hoskins, 1982).

In this note we derive the “geopotential tendency” form of semigeostrophic theory. This form is convenient because the geostrophic circulation remains implicit and only one elliptic equation needs to be solved each time step. From the computational point of view integrations of the nonuniform potential vorticity case become almost as easy as integrations of the uniform potential vorticity case.

2. Review of semigeostrophic theory

a. Geostrophic momentum approximation

Our starting point is the f-plane system of equations with the geostrophic momentum approximation [see Eqs. (1)-(5) of Table 1]. Here we use the pseudo-height z = [1 - (p/p₀)²]c₀ρ₀/g as the vertical coordinate. The pseudo-density ρ = ρ₀[1 - gz/c₀ρ₀]^{(1-γ)/γ} is then a known function of z. In (1)-(5), (uₚ, vₚ) = f⁻¹(-∂φ/∂y, ∂φ/∂x) are the geostrophic components of the wind, (u₉, v₉) the ageostrophic components, and (u, v) = (uₚ + u₉, vₚ + v₉) the components of the total wind.

Although the derivation is lengthy, it can be shown that the above system has the three-dimensional vorticity equation

\[ \frac{D\mathbf{q}}{Dt} = (\xi \cdot \nabla)u + \xi w \frac{\partial \rho}{\partial z} - \frac{g}{\theta₀} k \times \nabla \theta, \]

(6)

where \( u = (u, v, w), D\mathbf{q}/Dt = \partial \mathbf{q}/\partial t + u(\partial \mathbf{q}/\partial x) + v(\partial \mathbf{q}/\partial y) + w(\partial \mathbf{q}/\partial z) \), and

\[ \xi = \left( \begin{array}{c} -\frac{\partial v_ζ}{\partial z} + \frac{1}{f} \frac{\partial (u_ζ, v_ζ)}{\partial y} \frac{\partial u_ζ}{\partial x} + \frac{1}{f} \frac{\partial (u_ζ, v_ζ)}{\partial x} \frac{\partial u_ζ}{\partial y} \\
\frac{\partial v_ζ}{\partial x} - \frac{\partial u_ζ}{\partial y} + \frac{1}{f} \frac{\partial (u_ζ, v_ζ)}{\partial x} \frac{\partial u_ζ}{\partial x} \end{array} \right). \]

(7)

Combining (6) with the continuity equation (4) and the thermodynamic equation (5) we obtain the potential vorticity equation

\[ \frac{Dq}{Dt} = 0, \]

(8)

where

\[ q = \frac{g}{\rho₀f} \xi \cdot \nabla \theta. \]

(9)

b. Semigeostrophic equations

Introducing the geostrophic coordinates

\[ (X, Y, Z, T) = \left( x + \frac{u_ζ}{f}, y - \frac{u_ζ}{f}, z, t \right) \]

(10)

and the potential function

\[ \Phi = \phi + \frac{1}{2} (u_ζ² + v_ζ²), \]

(11)

Hoskins (1975) has shown that the geostrophic and hydrostatic relations take the form
Table 1. Semigeostrophic theory: Equations.

<table>
<thead>
<tr>
<th>Geostrophic momentum approximation</th>
<th>Semigeostrophic equations</th>
</tr>
</thead>
</table>
| \[
\frac{\partial u_x}{\partial t} + u_x \frac{\partial u_x}{\partial x} + v \frac{\partial u_x}{\partial y} + w \frac{\partial u_x}{\partial z} - f u_y = 0
\] |
| (1) | \[
\frac{\partial u_x}{\partial T} + u_x \frac{\partial u_x}{\partial X} + v \frac{\partial u_x}{\partial Y} + w \frac{\partial u_x}{\partial Z} - f u_y = 0
\] |
| \[
\frac{\partial u_y}{\partial t} + u_x \frac{\partial u_y}{\partial x} + v \frac{\partial u_y}{\partial y} + w \frac{\partial u_y}{\partial z} + f u_x = 0
\] |
| (2) | \[
\frac{\partial u_y}{\partial T} + u_x \frac{\partial u_y}{\partial X} + v \frac{\partial u_y}{\partial Y} + w \frac{\partial u_y}{\partial Z} + f u_x = 0
\] |
| \[
\frac{\partial \Phi}{\partial z} = g \frac{\partial \theta}{\partial z}
\] |
| (3) | \[
\frac{\partial \Phi}{\partial Z} = g \frac{\partial \theta}{\partial Z}
\] |
| \[
\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial w}{\partial z} = 0
\] |
| (4) | \[
\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial w}{\partial z} = 0
\] |
| \[
\frac{\partial \theta}{\partial t} + u_x \frac{\partial \theta}{\partial x} + v \frac{\partial \theta}{\partial y} + \frac{\partial \theta}{\partial z} = 0
\] |
| (5) | \[
\frac{\partial \theta}{\partial T} + u_x \frac{\partial \theta}{\partial X} + v \frac{\partial \theta}{\partial Y} + \frac{\partial \theta}{\partial Z} = 0
\] |

\[
\left(f u_y, -f u_x, \frac{g}{\theta_0} \frac{\partial \theta}{\partial Z}\right) = \left(\frac{\partial \Phi}{\partial X}, \frac{\partial \Phi}{\partial Y}, \frac{\partial \Phi}{\partial Z}\right),
\]

while the potential vorticity becomes

\[
q = \frac{g}{\rho \theta_0} \frac{\partial \theta}{\partial Z},
\]

where \(\xi\) is the vertical component of absolute vorticity. Since \(\partial / \partial T = \partial / \partial X + \partial u_x / \partial X + v_x \partial / \partial Y + w \partial / \partial Z\), the horizontal advection is now geostrophic. Then, introducing the transformed geostrophic components

\[
(u_x^*, v_y^*, w^*) = \left(u_x + \frac{w}{f} \frac{\partial v_y}{\partial z}, -u_y + \frac{w}{f} \frac{\partial u_x}{\partial z}, \frac{f}{\xi} w\right),
\]

(12) can be written \[D_\Phi \left(\frac{g}{\theta_0} \nabla \theta\right) + \nabla (\rho q w^*) = \frac{1}{2} Q.\]

Hoskins and Draghi (1977) showed that (1)–(5) can be written as (15)–(19) of Table 1.

Although the system (15)–(19) can be regarded as closed, it is not convenient for calculation. The geostrophic components \((u_x^*, v_y^*, w^*)\) are implicit and must be determined in such a way that the predictions of \((u_x, v_y)\) from (15)–(16) and \(\theta\) from (19) are consistent with a continued state of geostrophic and hydrostatic balance. In Sections 3 and 4 we discuss two alternate forms of the semigeostrophic equations.

3. Potential vorticity form

From (15) and (16) we can obtain

\[
D_\Phi \left(f k \times \frac{\partial v_y}{\partial Z}\right) - f^2 \frac{\partial v_y^*}{\partial Z} = \frac{1}{2} Q,
\]

(20)

where \(D_\Phi = \partial / \partial T + u_x \partial / \partial X + v_y \partial / \partial Y + w \partial / \partial Z\) and \(Q = -2g / \theta_0 \partial \Phi / \partial Z \cdot \nabla \theta, \partial \Phi / \partial X \cdot \nabla \theta, \partial \Phi / \partial Y \cdot \nabla \theta\), with \(\nabla\) denoting the horizontal del operator in geostrophic space. From (19) we can also obtain

\[\Phi_T = f \phi,\]

where \(\Phi_T\) is the geopotential tendency form.

4. Geopotential tendency form

We now derive the form of semigeostrophic theory which involves \(\Phi_T\). Since \(\Phi_T = f \phi\), we call this the geopotential tendency form.
TABLE 2. Potential vorticity and geopotential tendency forms of semigeostrophic theory.

<table>
<thead>
<tr>
<th>Potential vorticity form</th>
<th>Geopotential tendency form</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nabla \cdot (\rho q w^<em>) + f^2 \frac{\partial}{\partial Z} \left( \frac{\partial q w^</em>}{\rho \partial Z} \right) = \nabla \cdot Q )</td>
<td>( \rho q = \frac{f^3 q_{zz}}{Z^2 - (\Phi_T + \Phi_T)} )</td>
</tr>
<tr>
<td>( \sum \frac{1}{\rho \Phi^<em>} \frac{\partial}{\partial \Phi^</em>} \left( f \frac{\partial}{\partial \Phi^*} \right) q = 0 )</td>
<td>( \nabla \cdot \left( \frac{f^2 q_{\Phi_T}}{q} \frac{\partial}{\partial Z} \right) = \nabla \cdot P )</td>
</tr>
<tr>
<td>[ \frac{1}{f^2} \frac{\partial}{\partial Z} \left( \frac{\partial}{\partial \Phi} \right) ]</td>
<td>( \text{B.C} ) at ( Z = 0, Z_T )</td>
</tr>
</tbody>
</table>

Adding \( \sum \frac{1}{\rho \Phi^*} \frac{\partial}{\partial \Phi^*} \left( f \frac{\partial}{\partial \Phi^*} \right) q \) (15) \( \frac{\partial}{\partial Y} \) \( \Phi^* \) (19) \( \frac{\partial}{\partial Z} \), then using (12) and (18) we obtain

\[
\frac{\partial}{\partial X} \left[ \rho D_x \left( \frac{\partial \Phi^*}{\partial X} \right) \right] + \frac{\partial}{\partial Y} \left[ \rho D_y \left( \frac{\partial \Phi^*}{\partial Y} \right) \right] + \frac{\partial}{\partial Z} \left[ f^2 \frac{\partial}{q} D_z \left( \frac{\partial \Phi^*}{\partial Z} \right) \right] = 0. \quad (27)
\]

Defining

\[
P = \left( \rho \frac{\partial q}{\partial X} \nabla \Phi^*, \rho \frac{\partial q}{\partial Y} \nabla \Phi^*, \frac{\partial^2 q}{\partial Z^2} \nabla \Phi^* \right), \quad (28)
\]

(27) can be written as Eq. (30) of Table 2. Equation (26) can now be rearranged to the form given by (29). Equations (29) and (30) constitute a closed set in \( \Phi_T \) and \( q \). Only one elliptic equation needs to be solved each time step. The semigeostrophic circulation remains entirely implicit. If \( w^* \) is desired, it can be easily computed from (19) using the known \( \Phi_T \). In the special case of uniform potential vorticity flow it can be shown that \( \nabla \cdot P = 0 \), so that (26) and (30) become essentially equivalent.

Equation (30) is somewhat analogous to an equation derived by Eliassen (1974) in a \( \theta \)-coordinate type model with the geostrophic momentum approximation. The relationship between (30) and the potential vorticity equation (25) has been discussed in the context of Eliassen's balanced vortex model (Schubert and Hack, 1983; Schubert et al., 1983) by Thorpe (1985).

5. Concluding remarks

The main result obtained here is the right-hand side of Table 2. This geopotential tendency form of semigeostrophic theory is compact and allows numerical integration of non-Boussinesq, nonuniform potential vorticity flows to be implemented almost as simply as the Boussinesq, uniform potential vorticity case. The word “almost” must be used because for the Boussinesq, uniform potential vorticity case the interior part of (26) can be solved analytically and numerical integration need be implemented only on the boundary condition part of (26), as described by Hoskins (1976); in contrast, the non-Boussinesq, nonuniform potential vorticity case requires that we numerically solve the interior part of (30). Although repeatedly solving three dimensional elliptic problems can be time consuming, fast multigrid solvers are becoming available. Finally we note that the distinction between the potential vorticity form and the geopotential tendency form disappears when the additional quasi-geostrophic approximations are introduced into (1)-(5).

Acknowledgments. The author is grateful to S. Fulton, M. DeMaria, P. Ciesielski and H.-C. Kuo for their valuable comments, and to O. Panella for her help in preparing the manuscript. This research was supported by NSF Grant ATM-8207563.

REFERENCES


