7.4 QG Diagnosis: Vertical Motion

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Diagnose vertical motion in the atmosphere:

Our Challenge:

- We do not observe vertical motion
- Intimately linked to clouds and precipitation
- Actual vertical motions are often several orders of magnitude smaller than their collocated horizontal air motions [w ~ 0.01 → 10 m/s] [u, v ~ 10 → 100 m/s]
- Synoptic-scale vertical motions must be estimated from widely-spaced observations (i.e. the rawindsonde network) every 12-hours

Methods:

- Kinematic Method — Integrate the Continuity Equation; Very sensitive to small errors in winds measurements

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = 0,$$

to estimate ω at p,

$$\omega(p) = \omega(p_s) + (p_s - p)\left[\frac{\partial\langle u\rangle}{\partial x} + \frac{\partial\langle v\rangle}{\partial y}\right]_p . \qquad \text{H(3.38)}$$

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- Adiabatic Method
  From the thermodynamic equation
  Very sensitive to temperature tendencies (too coarse)
  Difficult to incorporate impacts of diabatic heating

$$\omega = \frac{1}{S_p}\left[\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right]. \qquad \text{H(3.41)}$$

- QG Omega Equation
  Least sensitive to small observational errors
  Widely believed to be the best method

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The Quasigeostrophic Omega Equation:

- We can also derive a ***single*** diagnostic equation for ω by, again, combining our vorticity and thermodynamic equations (the height-tendency versions from before):

$$\frac{1}{f_0}\nabla_p^2\chi + u_g\frac{\partial}{\partial x}\left(\frac{1}{f_0}\nabla_p^2\phi\right) + v_g\frac{\partial}{\partial y}\left(\frac{1}{f_0}\nabla_p^2\phi\right) = f_0\frac{\partial\omega}{\partial p} - \beta v_g$$

ω

$$\frac{\partial\chi}{\partial p} + u_g\frac{\partial}{\partial x}\left(\frac{\partial\phi}{\partial p}\right) + v_g\frac{\partial}{\partial y}\left(\frac{\partial\phi}{\partial p}\right) = -\sigma\omega$$

- To do this, we need to eliminate the height tendency (χ) from both equations

Step 1: Apply the operator $f_0\frac{\partial}{\partial p}$ to the vorticity equation

Step 2: Apply the operator ∇_p^2 to the thermodynamic equation

Step 3: Subtract the result of Step 1 from the result of Step 2

A diagnostic equation of ω can the be derived.

The Quasigeostrophic Omega Equation:

$$\underbrace{\left(\nabla_p^2 + \frac{f_0^2}{\sigma}\frac{\partial^2}{\partial p^2}\right)\omega}_{\text{Term A}} = \underbrace{-\frac{f_0}{\sigma}\frac{\partial}{\partial p}\left[-V_{\mathbf{g}} \cdot \nabla_p\left(\zeta_g + f\right)\right]}_{\text{Term B}} \underbrace{- \frac{R}{\sigma p}\nabla_p^2\left(-V_{\mathbf{g}} \cdot \nabla_p T\right)}_{\text{Term C}}$$

- The above equation can be simplified to be

$$w = \frac{\partial}{\partial z}\left[-V_{\mathbf{g}} \cdot \nabla_p\left(\zeta_g + f\right)\right] - V_{\mathbf{g}} \cdot \nabla_p T$$

Term A: Local Vertical Motion

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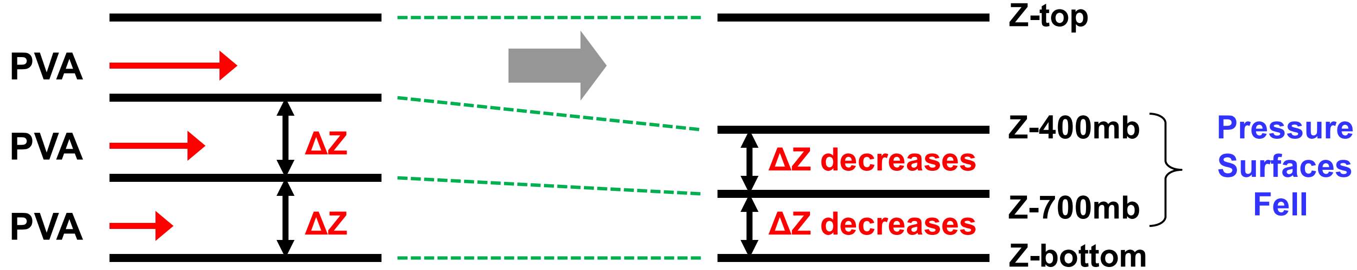
Further Explanation of The QG Omega Equation (Term B):

$$w = \frac{\partial}{\partial z}\left[-V_{g} \cdot \nabla_{p}\left(\zeta_{g} + f\right)\right] \quad -V_{g} \cdot \nabla_{p} T$$

Term A **Term B** **Term C**

Term B: Change in Absolute Vorticity Advection with "Height"

- Recall, positive (relative) vorticity advection (**PVA**) leads to local height falls
- Consider a three-layer atmosphere where cyclonic vorticity advection increases with height, or **PVA** is strongest in the upper layer:



- Hydrostatic balance (and the hypsometric equation) requires ALL changes in thickness (ΔZ) to be accompanied by temperature changes…

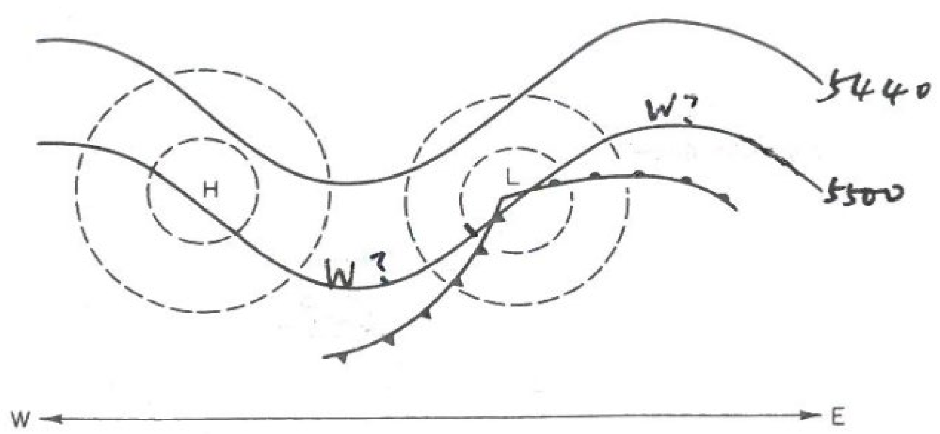
The Quasigeostrophic Omega Equation:

$$\underbrace{\left(\nabla_p^2 + \frac{f_0^2}{\sigma}\frac{\partial^2}{\partial p^2}\right)\omega}_{\text{Term A}} = \underbrace{-\frac{f_0}{\sigma}\frac{\partial}{\partial p}\left[-\mathbf{V_g}\cdot\nabla_p\left(\zeta_g + f\right)\right]}_{\text{Term B}} \underbrace{-\frac{R}{\sigma p}\nabla_p^2\left(-\mathbf{V_g}\cdot\nabla_p T\right)}_{\text{Term C}}$$

- The above equation can be simplified to be

$$w = \frac{\partial}{\partial z}\left[-\mathbf{V_g}\cdot\nabla_p\left(\zeta_g + f\right)\right] - \mathbf{V_g}\cdot\nabla_p T$$

Term B: Differential Advection

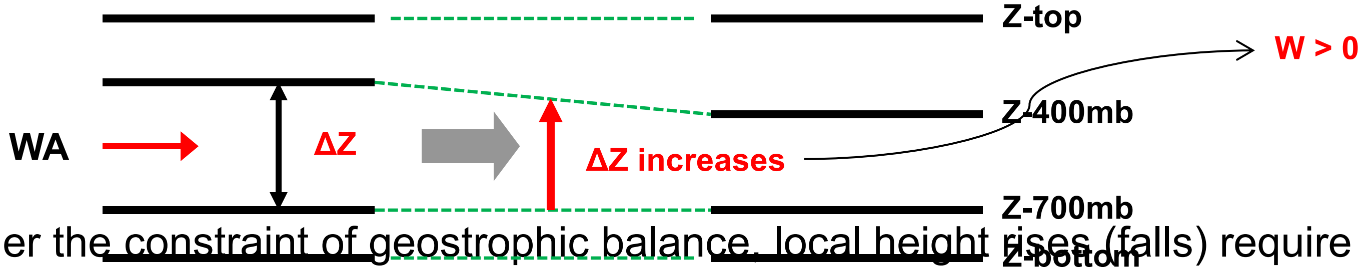


Further Explanation of The QG Omega Equation (Term C):

$$\underbrace{\left(\nabla_p^2 + \frac{f_0^2}{\sigma}\frac{\partial^2}{\partial p^2}\right)\omega}_{\text{Term A}} = \underbrace{-\frac{f_0}{\sigma}\frac{\partial}{\partial p}\left[-\mathbf{v_g}\bullet\nabla_p\left(\zeta_g + f\right)\right]}_{\text{Term B}} + \underbrace{-\frac{R}{\sigma p}\nabla_p^2\left(-\mathbf{v_g}\bullet\nabla_p T\right)}_{\text{Term C}}$$

Term C: Horizontal Temperature Advection

- Warm air advection (**WA**) leads to local temperature increases
- Consider the three-layer model, with **WA** strongest in the middle layer



- Under the constraint of geostrophic balance, local height rises (falls) require a change in the local pressure gradient, a change in the local geostrophic wind, and thus a local decrease (increase) in geostrophic vorticity…..

References

Bluestein, H. B, 1993: Synoptic-Dynamic Meteorology in Midlatitudes. Volume I: Principles of Kinematics and Dynamics. Oxford University Press, New York, 431 pp.

Bluestein, H. B, 1993: Synoptic-Dynamic Meteorology in Midlatitudes. Volume II: Observations and Theory of Weather Systems. Oxford University Press, New York, 594 pp.

Charney, J. G., B. Gilchrist, and F. G. Shuman, 1956: The prediction of general quasi-geostrophic motions. *J. Meteor.*, **13**, 489-499.

Hoskins, B. J., I. Draghici, and H. C. Davis, 1978: A new look at the ω–equation. *Quart. J. Roy. Meteor. Soc.*, **104**, 31-38.

Hoskins, B. J., and M. A. Pedder, 1980: The diagnosis of middle latitude synoptic development. *Quart. J. Roy. Meteor. Soc.*, **104**, 31-38.

Trenberth, K. E., 1978: On the interpretation of the diagnostic quasi-geostrophic omega equation. *Mon. Wea. Rev.*, **106**, 131-137.