A Hybrid Lagrangian/Eulerian View of the Atmospheric Mass Circulation: Annual Cycle

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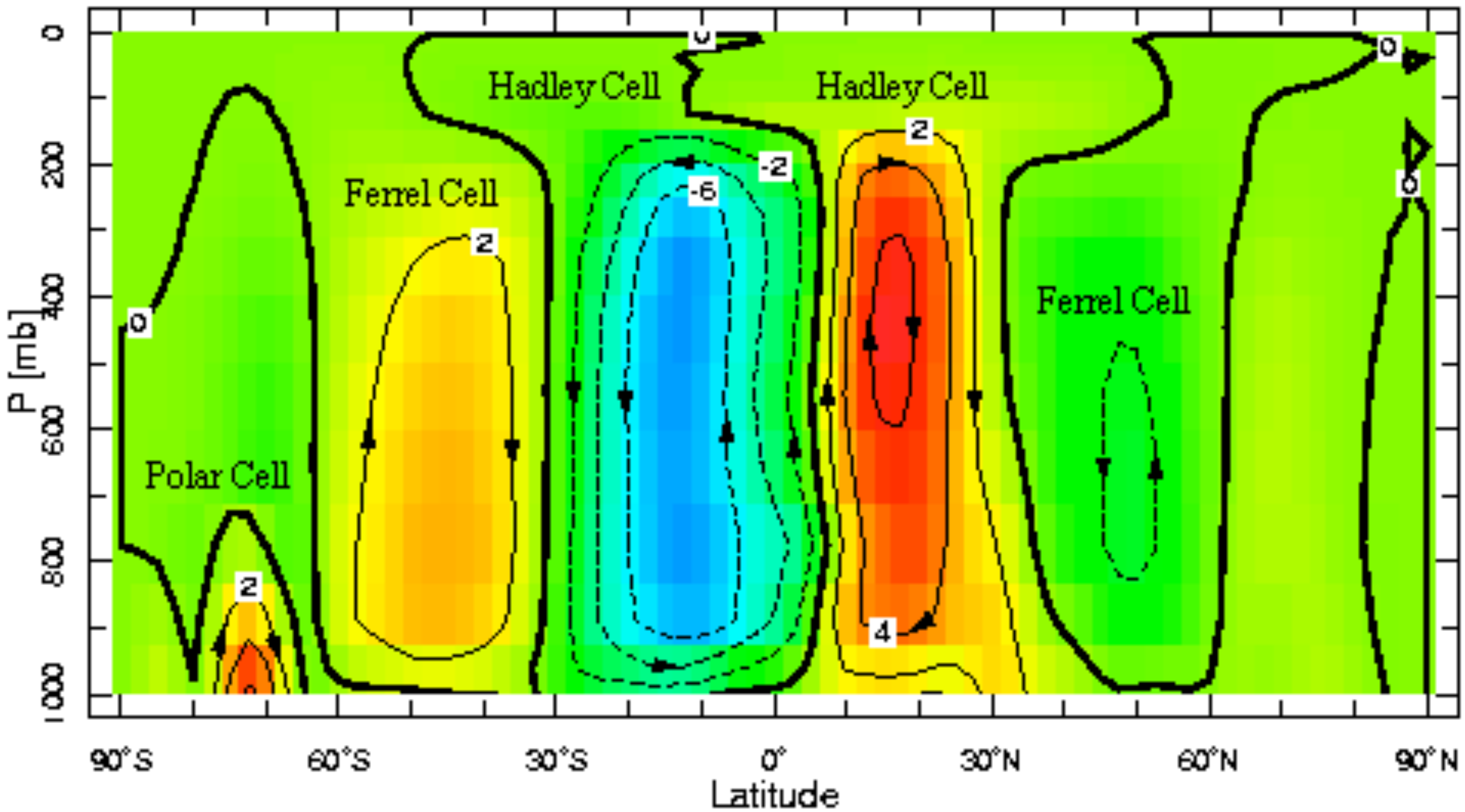
Chul-Su Shin's Dissertation Research

Outline

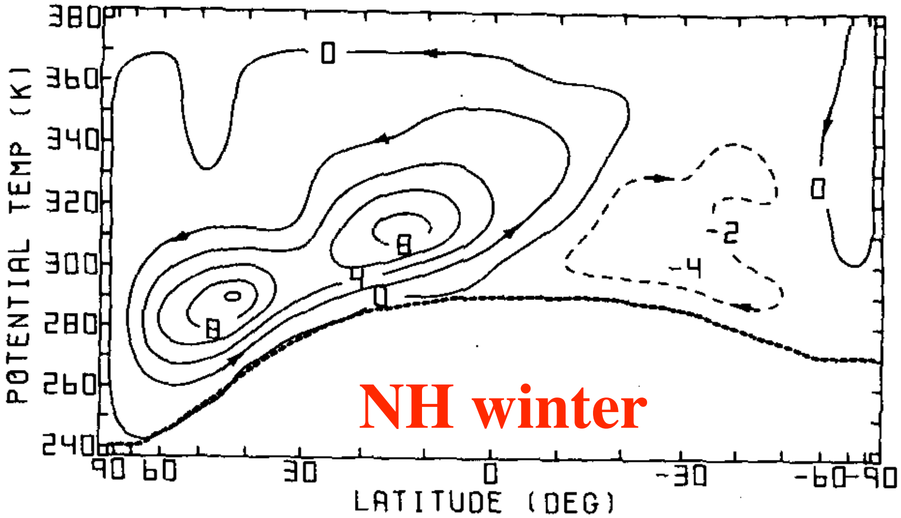
- Velocity circulation versus mass circulation.
- Objectives
- Basic concepts
- Diagnostics procedures and data
- Annual cycle of global mass circulation and stratosphere-troposphere coupling.
- Summary

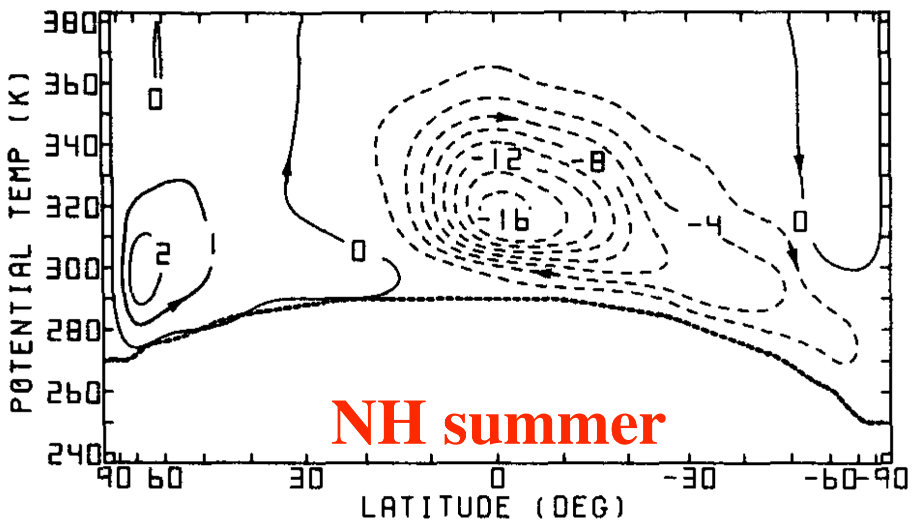
The Zonally Averaged Circulation



The annually-averaged atmospheric mass circulation in the latitude pressure plane (the meridional plan). The arrows depict the direction of air movement in the meridional plane. The contour interval is 2x10 ^{10} Kg/sec - this is the amount of mass that is circulating between every two contours. The total amount of mass circulating around each "cell" is given by the largest value in that cell. Data based on the NCEP-NCAR reanalysis project 1958-1998.

Global mean mass circulation viewed from isentropic coordinate

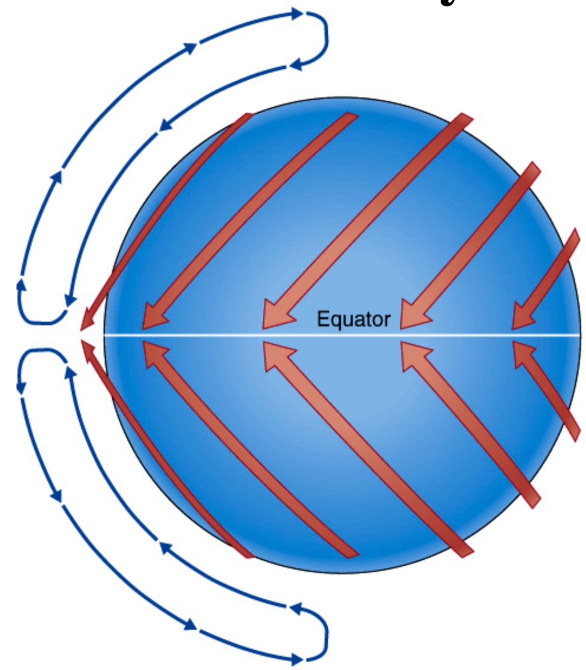




Townsend and Johnson (1985)

$\neq$

Hadley Cell



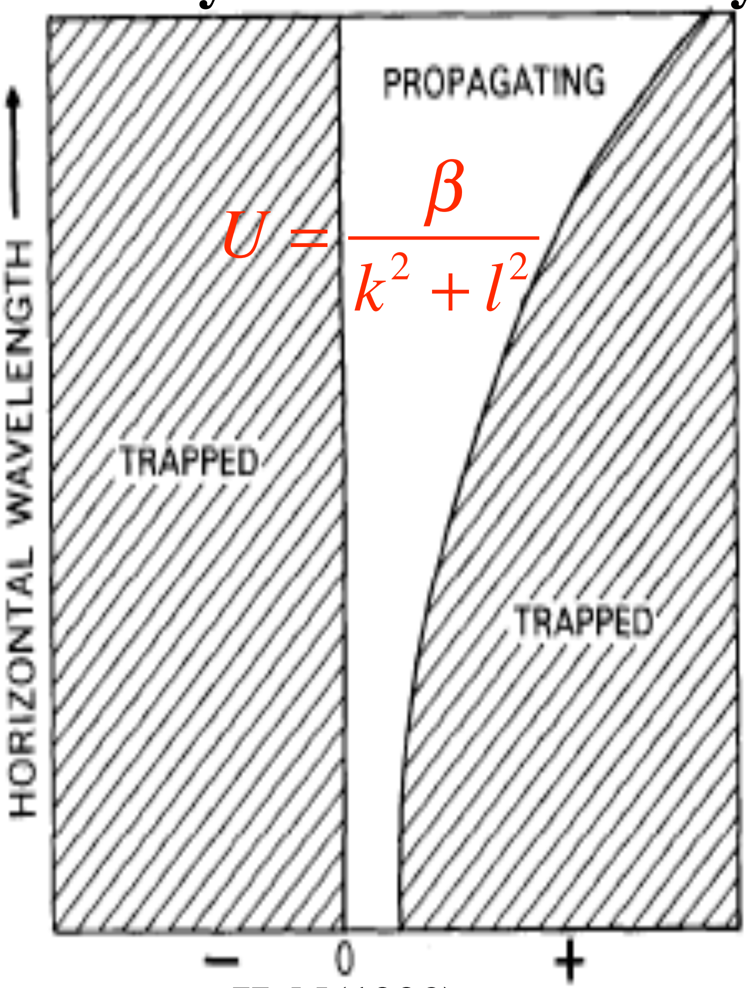
$$\frac{1}{a\cos\phi}\frac{\partial < m_\theta v \cos\phi >}{\partial\phi} + \frac{\partial < m_\theta \dot{\theta} >}{\partial\theta} = 0$$

$$\frac{\partial\psi}{a\partial\phi} = \cos\phi m_\theta \dot{\theta}, \quad \frac{\partial\psi}{\partial\theta} = -\cos\phi m_\theta v$$

Tropospheric forcing mechanism (Matsuno 1971)

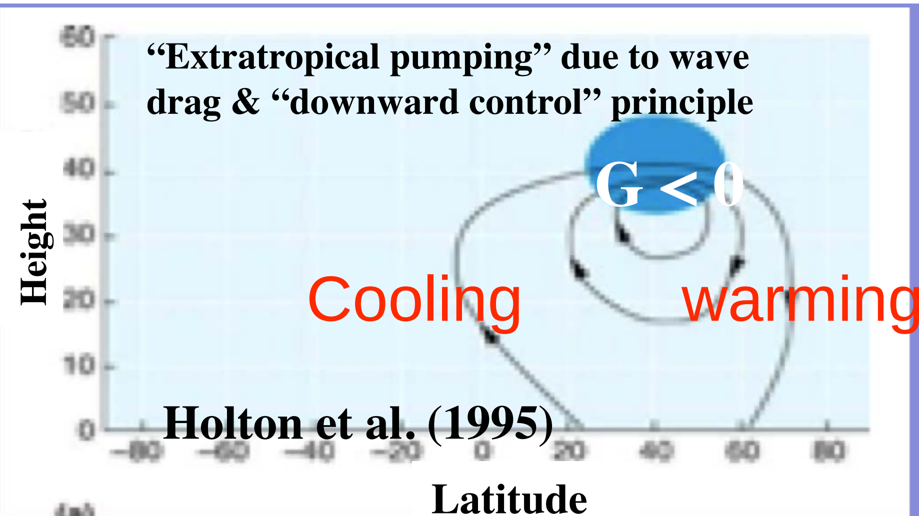
- **Haynes (2005) provided most updated review on the stratospheric dynamics and the coupling of the stratosphere and troposphere.**

Charney & Drazin's Theory



Held(1993)

- **A stronger polar jet => upward propagation of planetary Rossby waves**
- **Wave-break => wave drag (deposit momentum in the direction of wave propagation) =>** $\partial[U]/\partial t < 0$
- **Restricting upward propagation from penetrating the critical level into stratosphere => descending of the negative U anomalies and the critical level.**
- **Lack of wave-breaking and diabatic cooling => restoration of the stratosphere polar jet. => descending of positive U anomalies**
- **No downward propagation of information.**



A few overlooked factors in the existing theories

- The role of diabatic heating/cooling has not explicitly explored:

  (i)Although the TEM residual circulation should be directly related to both diabatic heating and convergence of E-P fluxes, the downward control principle tends to emphasize role of eddies.

  (ii)The changes in the thermal field are regarded mainly as adiabatic processes => secondary circulation in QG.

- The continuous "breaking" of upward propagating planetary Robby waves would have to imply an upward transfer/transport of easterly angular momentum from the troposphere to stratosphere:

  (i) Where does the extratropical atmosphere acquire easterly angular momentum?

  (ii) Would this require intensification of westerly wind in the extratropical troposphere prior to the wave-breaking in the stratosphere? If so, is there observation evidence suggesting that?

A few overlooked factors in the existing theories

- Most of study does not discuss source of westerly angular momentum for intensification or movement of polar jet (other than thermal wind balance):

  (i) Intensification or movement of polar jet is presumably from convergence of eddy momentum flux.

  (ii) During the "recovery period" of the polar jet, wave activities in the stratosphere are supposed to be minimal (lack of vertical propagation).

  (iii) Meridional propagation of wave activities (y component of E-P flux) could provide source of wave activities => meridional and vertical propagation would be decoupled => two types of wave activities, one accelerates jet and the other decelerates?

- Change in surface pressure is largely not addressed (only in the context of balanced dynamics: positive PV anomalies => low pressure and negative PV anomalies => high pressure. The diabatic processes are largely neglected).

Objectives

- To delineate the simultaneous couplings among diabatic heating, meridional mass transport, meridional angular momentum transport, and form drag associated with baroclinically amplifying waves
- To examine time-evolving aspect of the atmospheric (mass) circulation (instead of "steady" or "time-mean" state).
- To link the extratropical stratosphere-troposphere coupling to the tropical-extratropical coupling.
- To understand climate variability/changes from global atmospheric mass circulation perspective.

The question

- How does the (meridional) mass circulation cause changes in angular momentum distribution, in (meridional) temperature gradient, in longwave radiative cooling rate, in large-scale dynamic irreversible mixing, and in surface pressure?

Governing equations (for dry air) on isentropic coordinate

$$\frac{\partial m_\theta}{\partial t} + \frac{1}{a\cos\phi}\frac{\partial(m_\theta u)}{\partial\lambda} + \frac{1}{a\cos\phi}\frac{\partial(m_\theta v\cos\phi)}{\partial\phi} + \frac{\partial(m_\theta\dot\theta)}{\partial\theta} = 0 \qquad m_\theta = -\frac{1}{g}\frac{\partial p}{\partial\theta}$$

$$\frac{\partial A}{\partial t} + \frac{u}{a\cos\varphi}\frac{\partial A}{\partial\lambda} + \frac{v}{a}\frac{\partial A}{\partial\varphi} + \dot\theta\frac{\partial A}{\partial\theta} = -\frac{\partial M}{\partial\lambda} + a\cos\varphi F_\lambda \qquad A \equiv (ua\cos\phi + \Omega a^2\cos^2\phi) \equiv A_r + A_e$$

$$\frac{\partial v}{\partial t} + \frac{u}{a\cos\varphi}\frac{\partial v}{\partial\lambda} + v\frac{\partial v}{\partial\varphi} + \dot\theta\frac{\partial v}{\partial\theta} + (f + \frac{u\tan\varphi}{a})u = -\frac{\partial M}{a\partial\varphi} + F_\varphi \qquad M = c_pT + \Phi$$

$$\frac{\partial[m_\theta]}{\partial t} = -\frac{1}{a\cos\phi}\frac{\partial[m_\theta v\cos\phi]}{\partial\phi} - \frac{\partial[m_\theta\dot\theta]}{\partial\theta}$$

$$[\frac{\partial m_\theta A}{\partial t}] = -\frac{1}{a\cos\varphi}[\frac{\partial v m_\theta A\cos\varphi}{\partial\varphi}] - [m_\theta\frac{\partial M}{\partial\lambda}] - [\frac{\partial\dot\theta m_\theta A}{\partial\theta}] + [a\cos\varphi m_\theta F_\lambda]$$

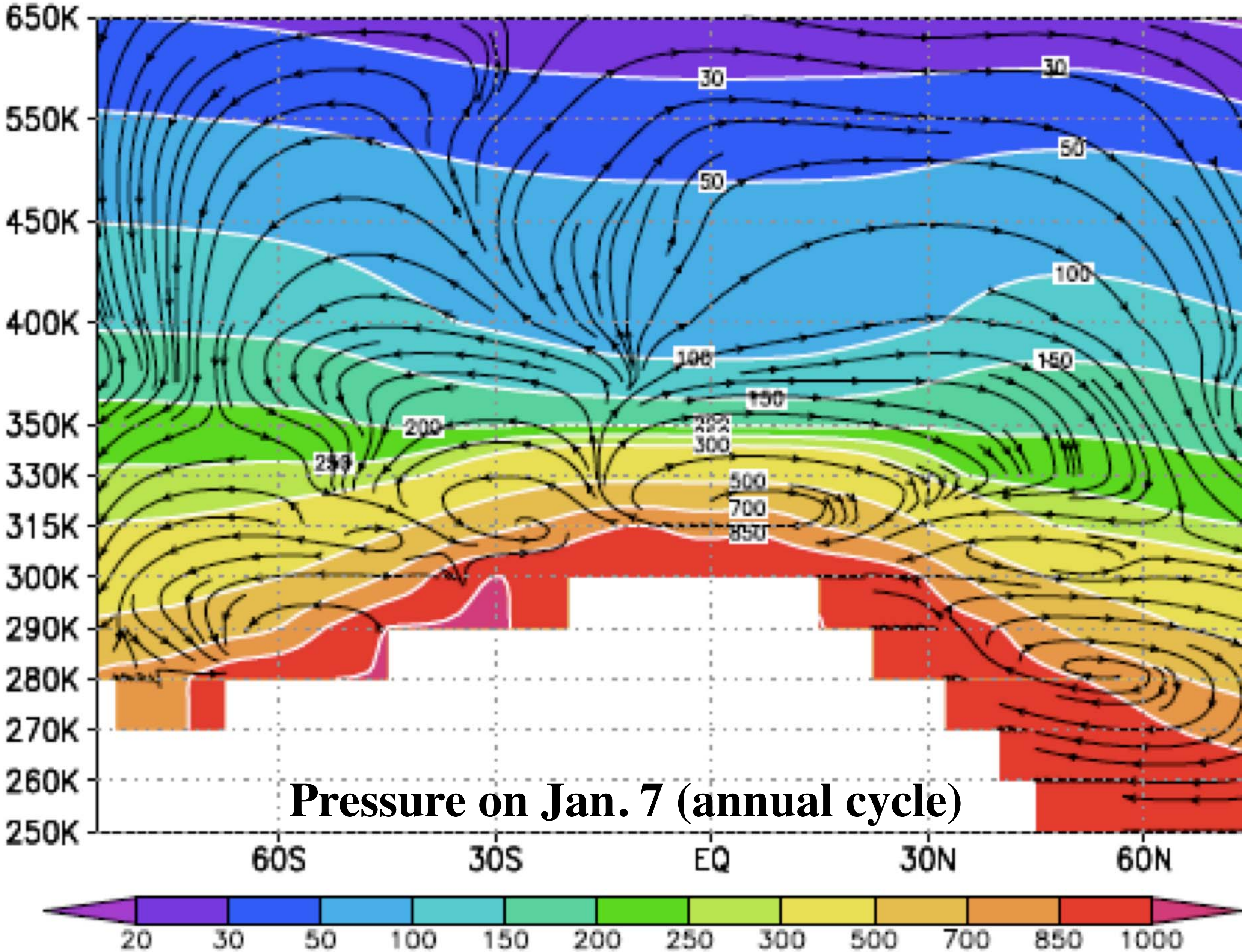
Advection of A

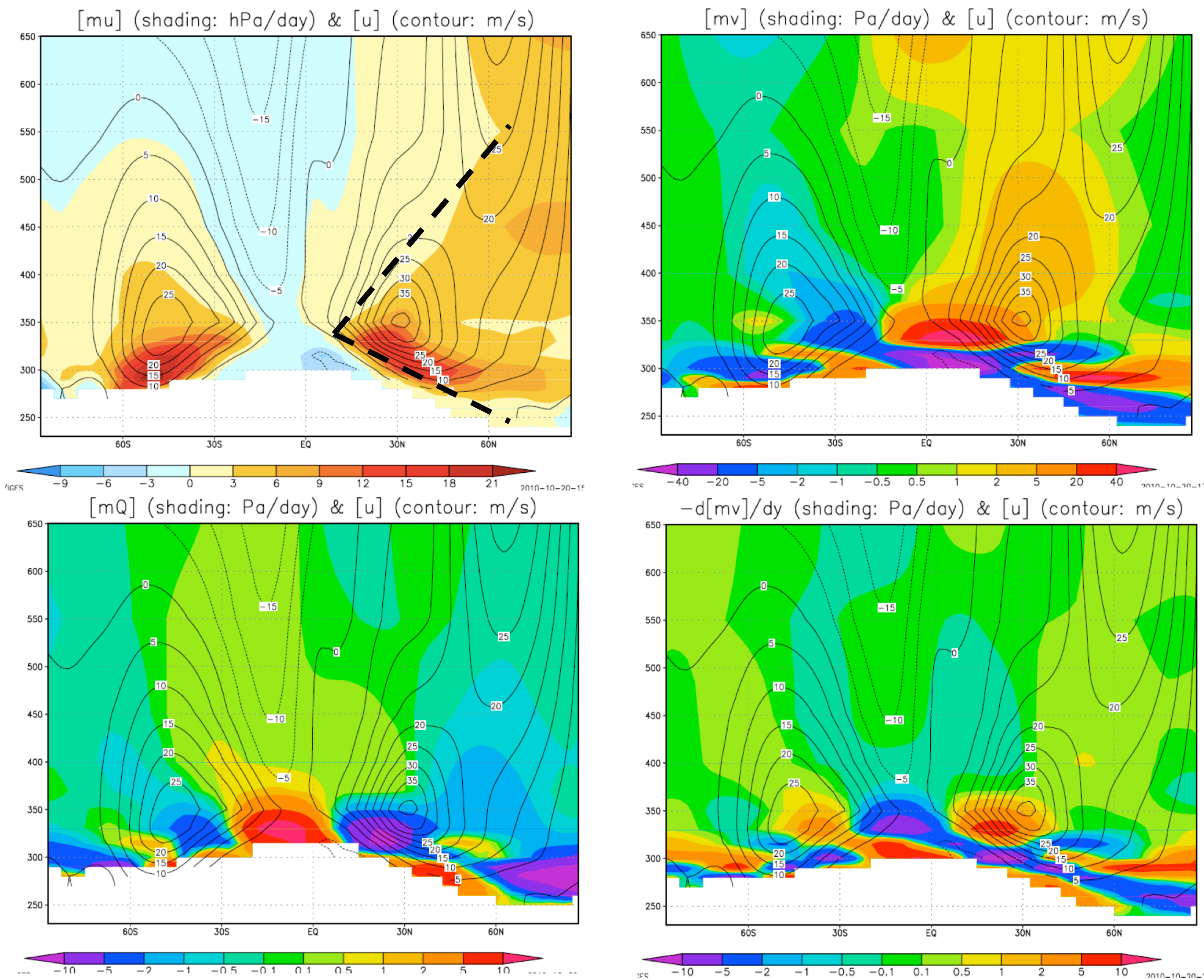
Form Drag

$$-\frac{1}{a\cos\varphi}[m_\theta u\frac{\partial A}{\partial\lambda} + \frac{1}{a\cos\varphi}\frac{\partial v m_\theta A\cos\varphi}{\partial\varphi}] \sim fv + \frac{1}{\rho_0}\frac{\partial F_y}{\partial\varphi} \quad \text{and} \quad -[m_\theta\frac{\partial M}{\partial\lambda}] \sim \frac{1}{\rho_0}\frac{\partial F_z}{\partial z}$$

- **Lagrangian Sense:** Calculate source/sink terms from angular momentum/mass fluxes of total flow (no reference to geostationary flow pattern)=> each time step is Lagrangian.
- **Eulerian Sense:** Examine change of total flow (temporal/spatial variation of wind, mass, heating /cooling) at the geo-stationary lat-long coordinate.
- **Semi-Lagrangian/Eulerian Sense**: Potential temperature as the vertical coordinate: Conservation Potential temperature only in the absence of heating.

Example of mass circulation inferred from mass budget




[mu] (shading: hPa/day) & [u] (contour: m/s)
[mv] (shading: Pa/day) & [u] (contour: m/s)
[mQ] (shading: Pa/day) & [u] (contour: m/s)
−d[mv]/dy (shading: Pa/day) & [u] (contour: m/s)
650
600
550
500
450
400
350
300
250
60S
30S
EQ
30N
60N
−9 −6 −3 0 3 6 9 12 15 18 21
−40 −20 −5 −2 −1 −0.5 0.5 1 2 5 20 40
−10 −5 −2 −1 −0.5 −0.1 0.1 0.5 1 2 5 10
−10 −5 −2 −1 −0.5 −0.1 0.1 0.5 1 2 5 10

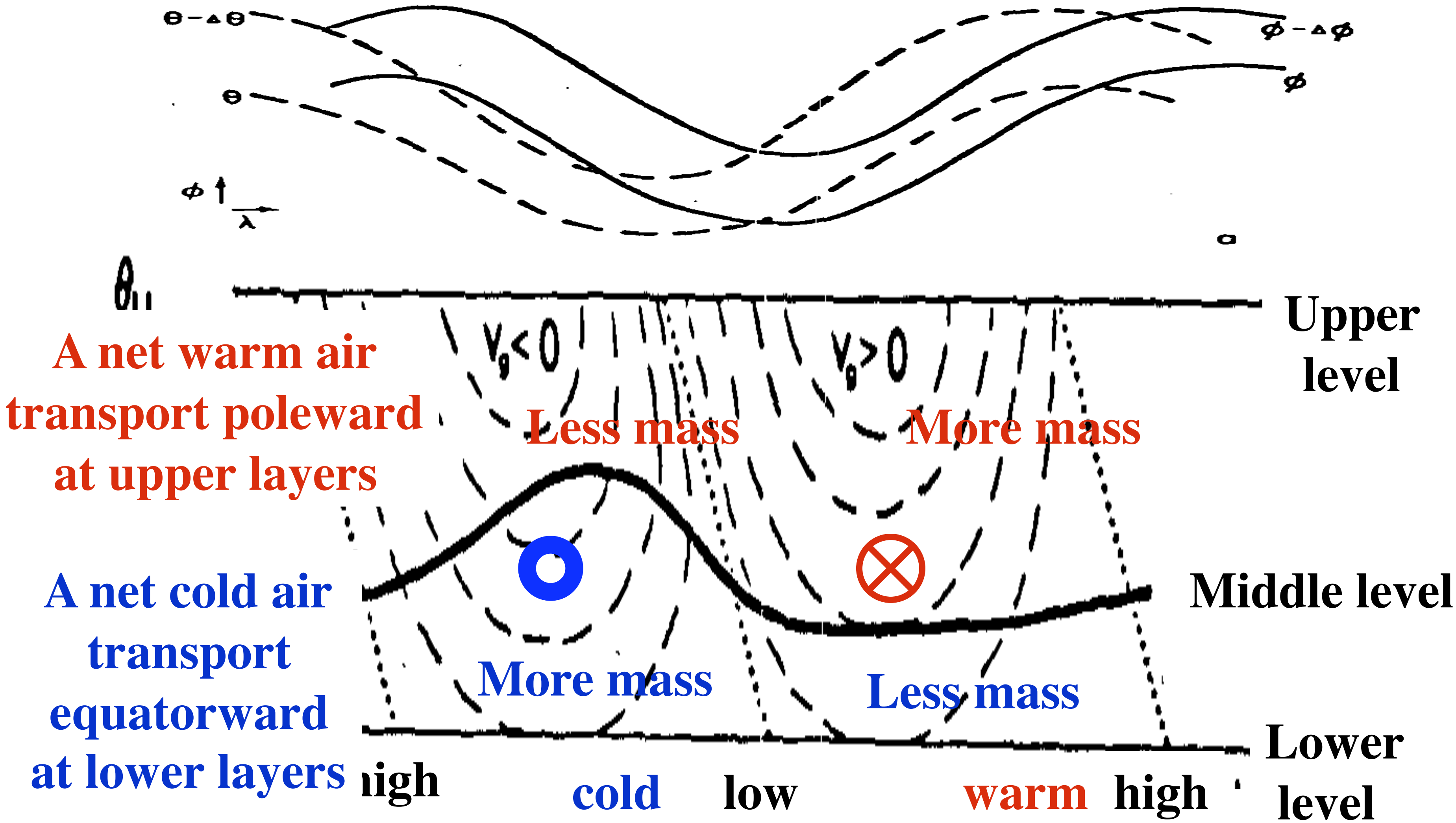
Principles for global mass circulation

- Gravity: (hydrostatic balance=> temperature variation below => pressure/elevation variation aloft => “thermal mountain”: equivalent to “upward propagation of waves”)
- Ideal gas law: (adibatic expension/contraction)
- (dry) Air mass conservation (continuity equation)
- Angular momentum conservation (zonal wind equation).
- Thermodynamics equation (heating => change in density /potential temperature => change in elevation of air mass)
  - Radiation heating/cooling (solar radiation and longwave radiation: higher temperature => larger cooling rate via thermal radiation).
  - Non-radiative heating: turbulent mixing, irreversible large-scale eddy mixing, latent heating release.
- Rotating fluid dynamics: Preferred (or growing) wave structure, which is mainly determined by rotation direction and spatial variation of external (solar) heating.

What are the things that baroclinically amplifying (westward tilting) waves do? (Johnson 1989)

- A net poleward (adiabatic) transport of warm air mass aloft and a net equatorward (adiabatic) transport of cold air mass transport below.
- Poleward (adiabatic) transport of of westerly angular momentum aloft and equatorward (adiabatic) transport of easterly angular momentum downward.
- A net downward (adiabatic) transfer of westerly angular momentum downward via upper positive (toward east) pressure torque of upper layer air mass to lower layer air mass (eastward acceleration in the upper layer and westward acceleration in the lower layer).

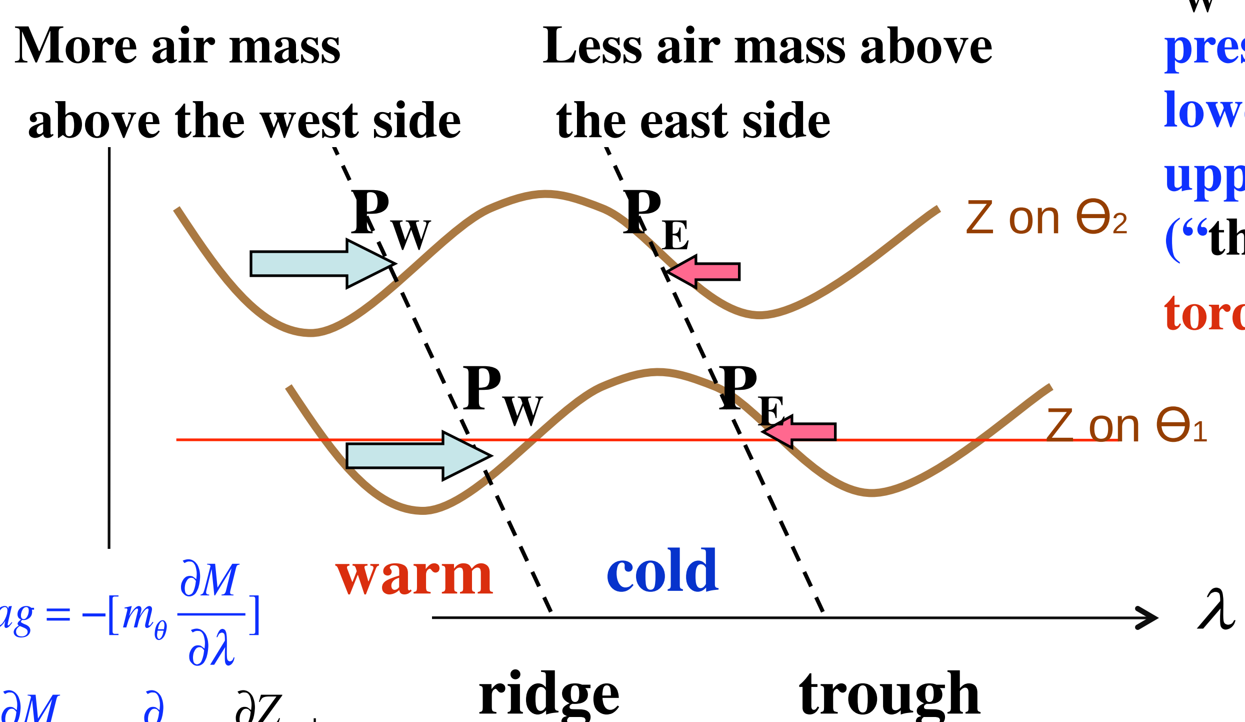
Baroclinic amplifying waves and meridional mass transport



Johnson (1979) and Townsend and Johnson (1985)

Baroclinic amplifying waves and meridional/vertical angular momentum transport/transfer

- **A net poleward (equatorward) air mass transport in the upper (lower) levels implies a net poleward (equatorward) westerly (easterly) angular momentum transport in upper (lower) levels.**



$P_W > P_E$ => positive pressure torque to lower layer air by upper layer air ("thermal "mountain" torque)

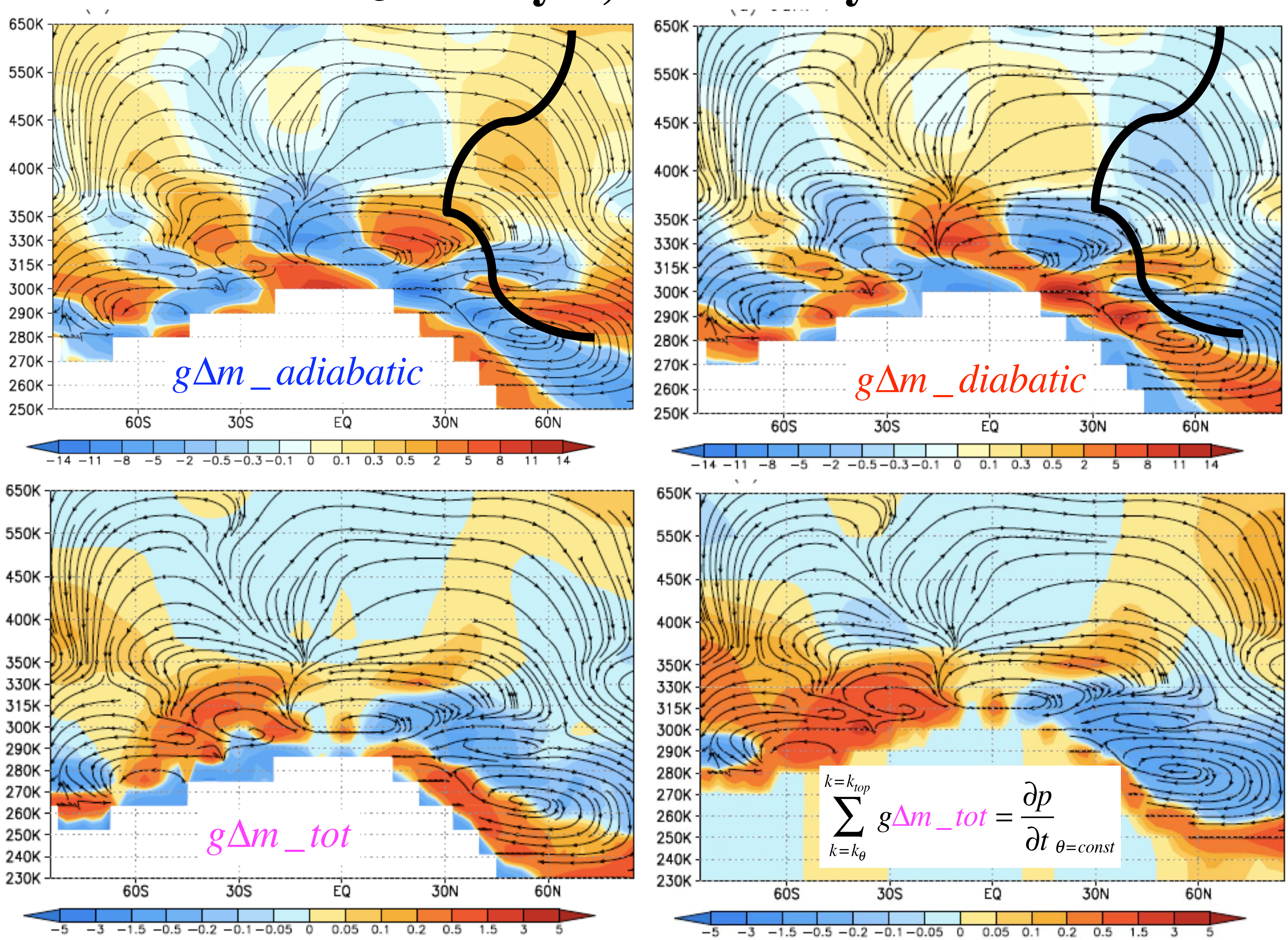
Transfer westerly angular momentum from upper layer to lower layer

$$form\ drag = -[m_\theta \frac{\partial M}{\partial \lambda}] \equiv \frac{\partial}{\partial \theta}[\frac{p}{g}\frac{\partial M}{\partial \lambda}] \equiv \frac{\partial}{\partial \theta}[\underbrace{p\frac{\partial Z}{\partial \lambda}\Big|_{\theta=const}}_{pressure-turque}]$$

Two “newly” explained dynamic-radiation coupling

1. Adiabatic mass convergence/divergence due to mass transport by motions aloft implies accumulation/depletion of mass above and correspond to descending/arising of isentropic surfaces. Such change in elevation gives rise to adiabatic warming/cooling,=>(i) (adiabatic) changes in meridional temperature gradient and (ii) increase/decrease air radiative cooling rate.
2. Dynamic heating (latent heat, turbulent and irreversible large-scale dynamic mixing) increases air temperature, which in turn increases its radiative cooling rate.

January 7, Annual Cycle



January 7, Annual Cycle