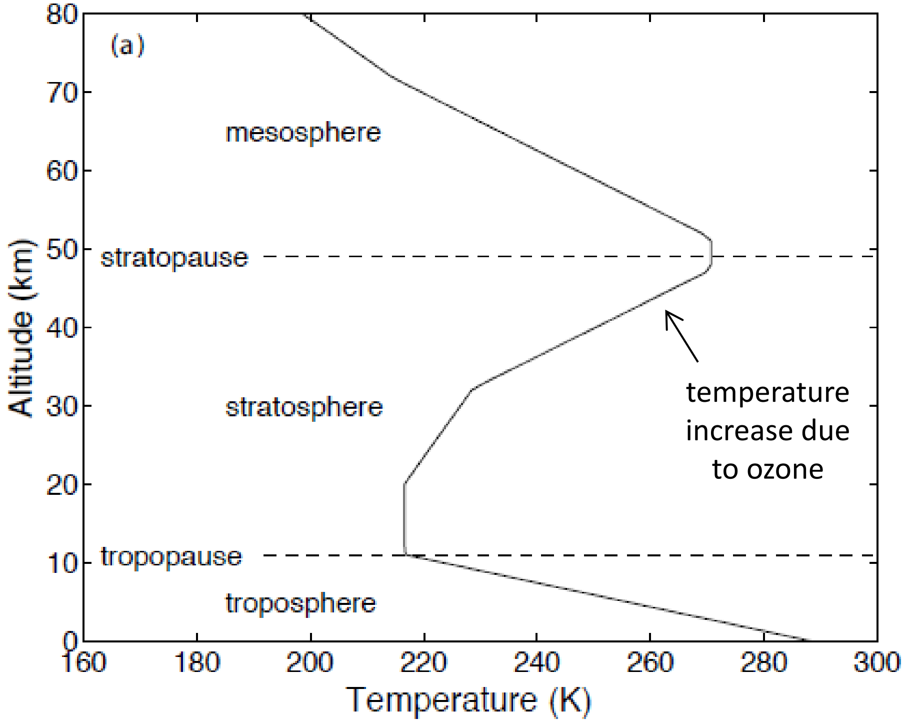
Overview of this week's lectures:

- Global circulation and transport
- Satellite observations of stratospheric temperature and water vapor
- Global upper troposphere - lower stratosphere (UTLS)
- Circulation and transport near the tropical tropopause layer (TTL)
- UTLS monsoon circulations and water vapor isotopes
- Research seminar: tropical dynamics with GPS radio occultation data

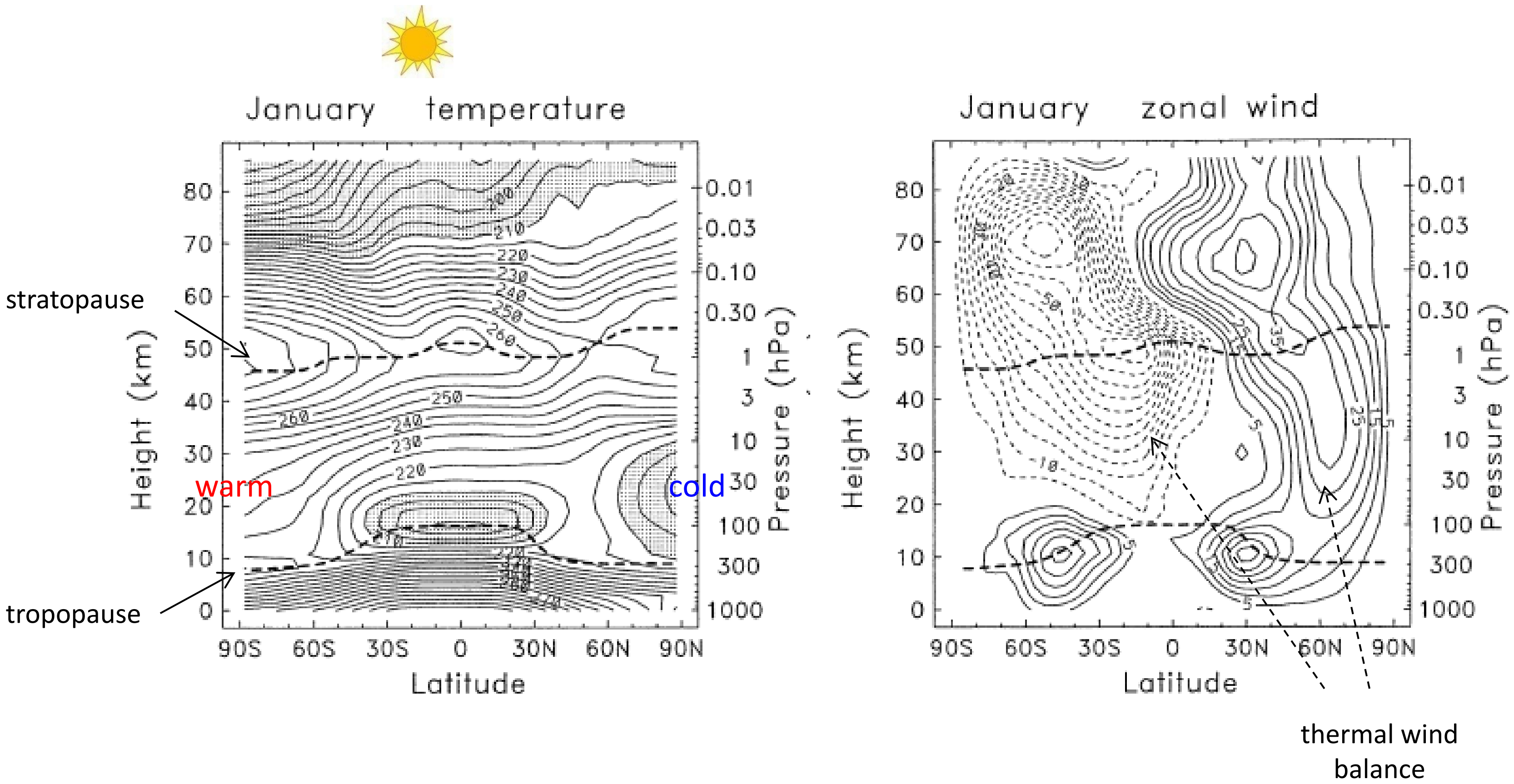
Lecture 1: Global atmospheric circulation and satellite observations

- large-scale circulation of the troposphere and stratosphere
  - Climatology and variability of the stratosphere
  - wave forcing of the zonal mean flow
  - Rossby waves: propagation and dissipation (critical layers)
  - Tropospheric baroclinic wave life cycles
  - large-scale tropical circulations
  - QBO and ENSO
- Large-scale transport

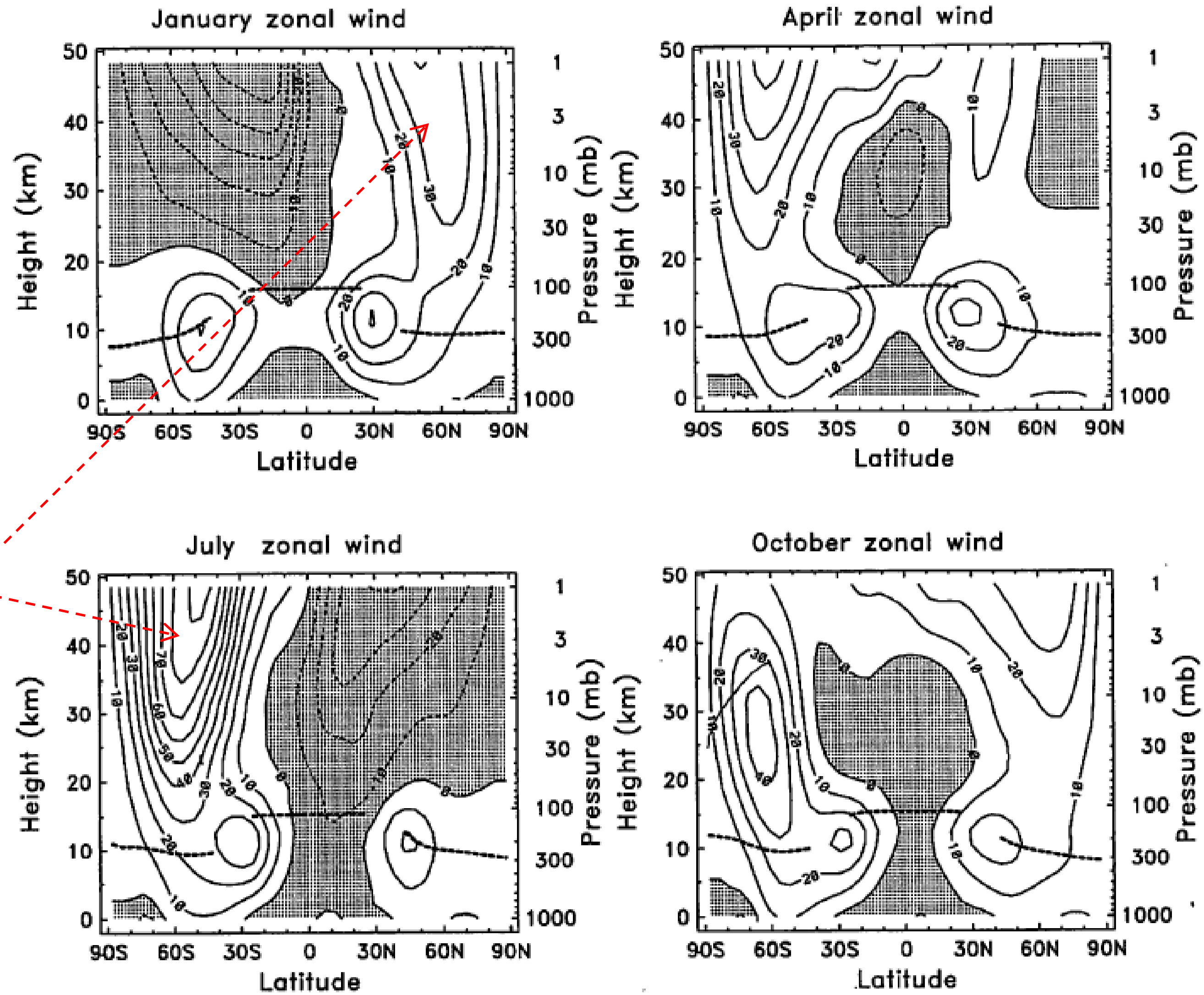
The Standard Atmosphere



Climatological temperatures and zonal winds in January

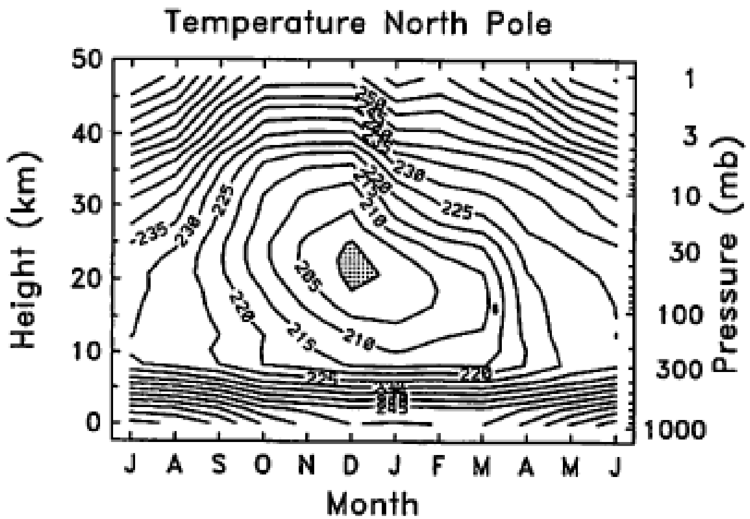


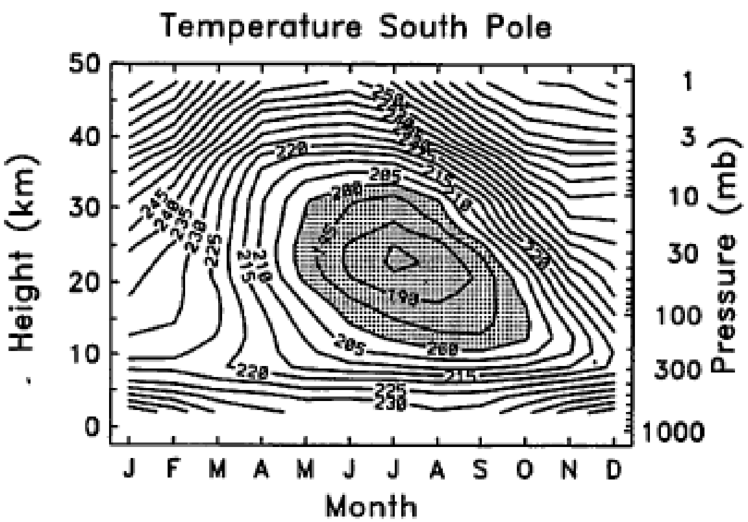
Seasonal cycle of zonal mean zonal winds



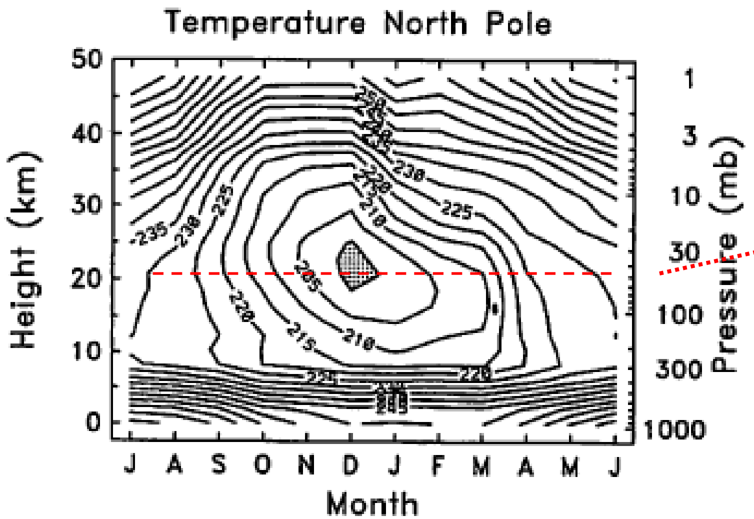
polar night jet
stronger in SH
than in NH

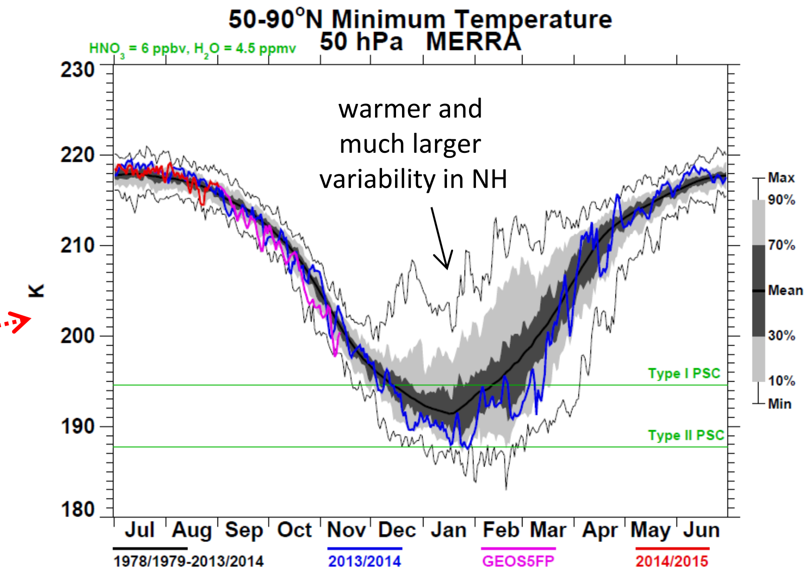
climatological polar temperature

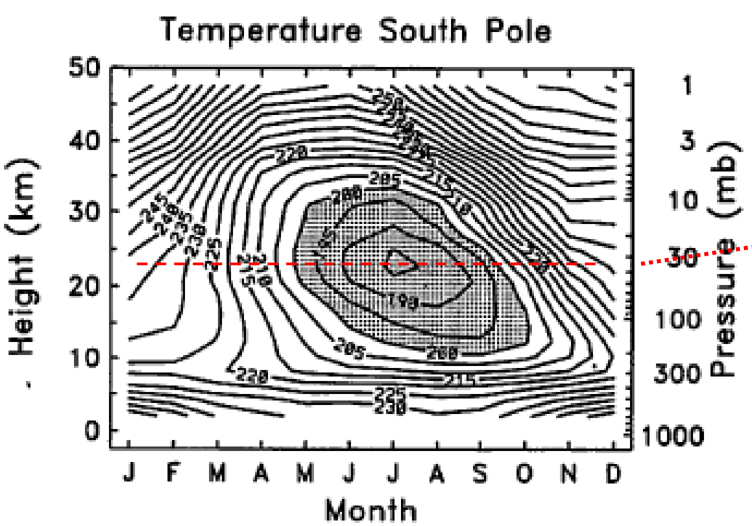


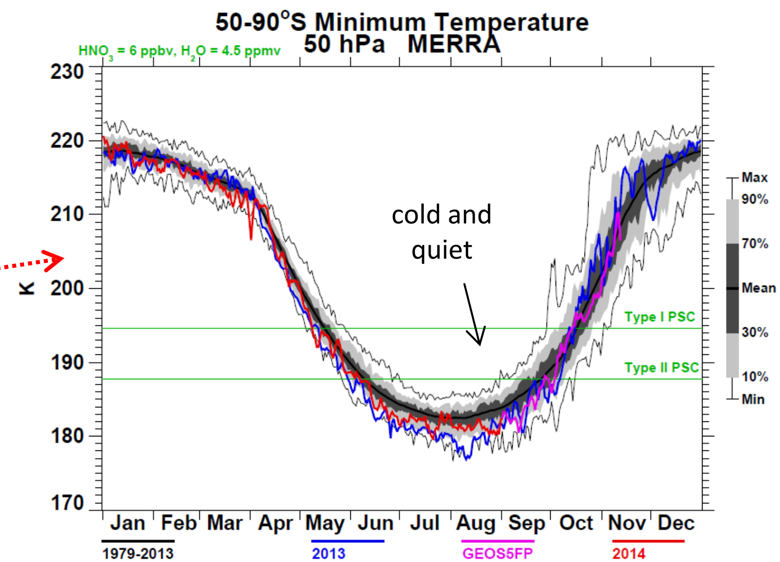


climatological polar temperature

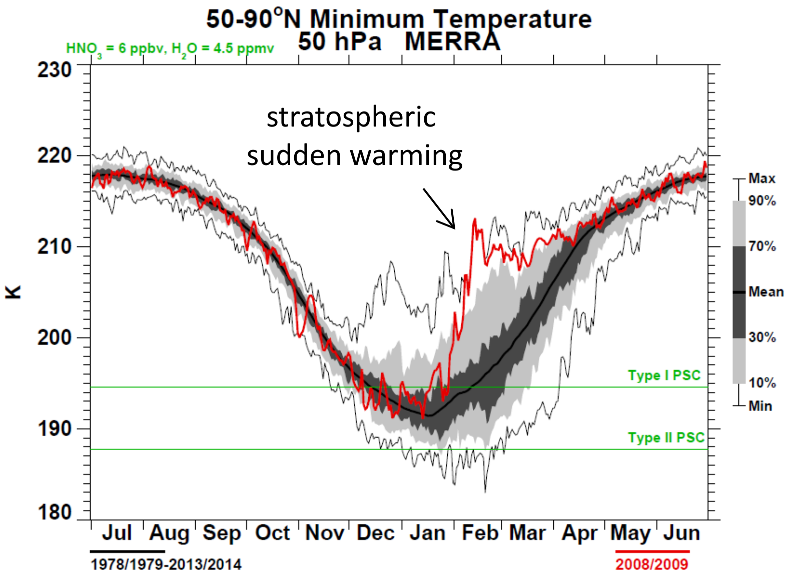


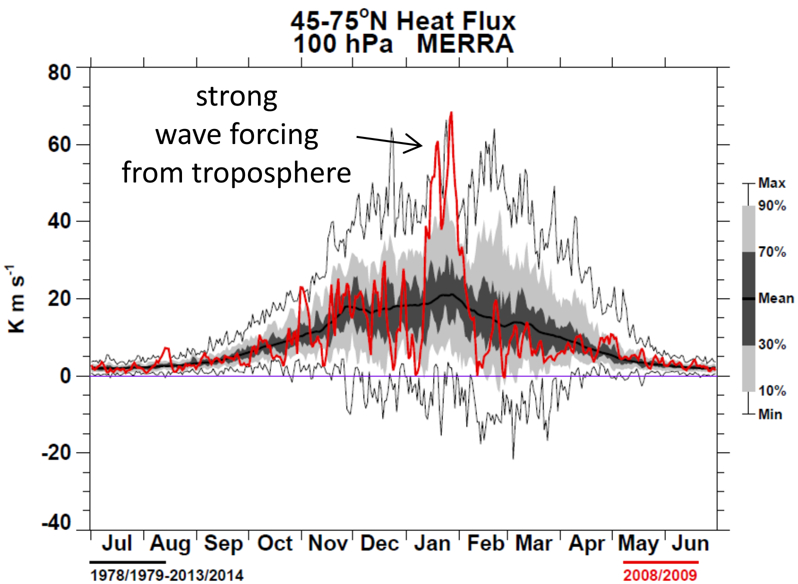


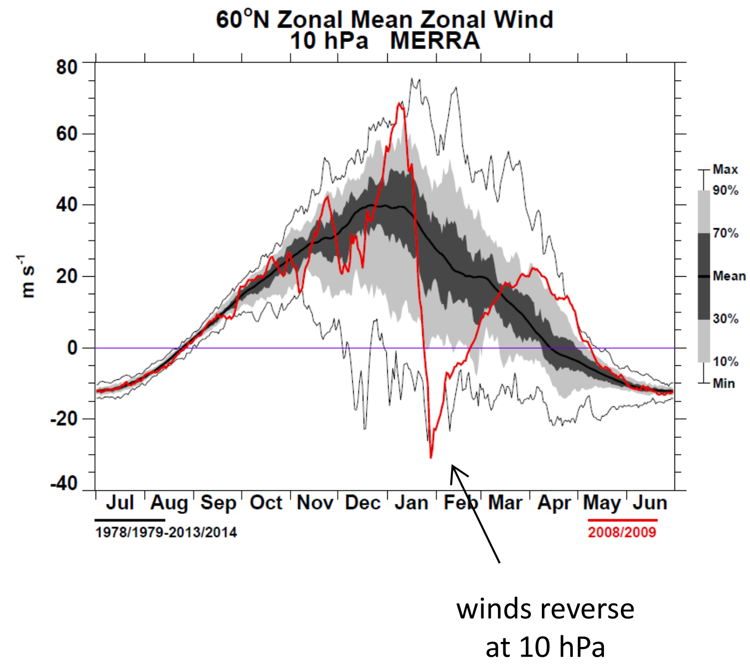




- Variability in NH winter stratosphere tied to large-scale forcing from troposphere.
- Episodic forcing produces ‘stratospheric sudden warming’ events.
- Largest observed stratosphere sudden warming in January 2009







A Major Stratospheric Sudden Warming Event in January 2009

YAYOI HARADA, ATSUSHI GOTO, HIROSHI HASEGAWA, AND NORIHISA FUJIKAWA

Climate Prediction Division, Japan Meteorological Agency, Tokyo, Japan

JAS 2010

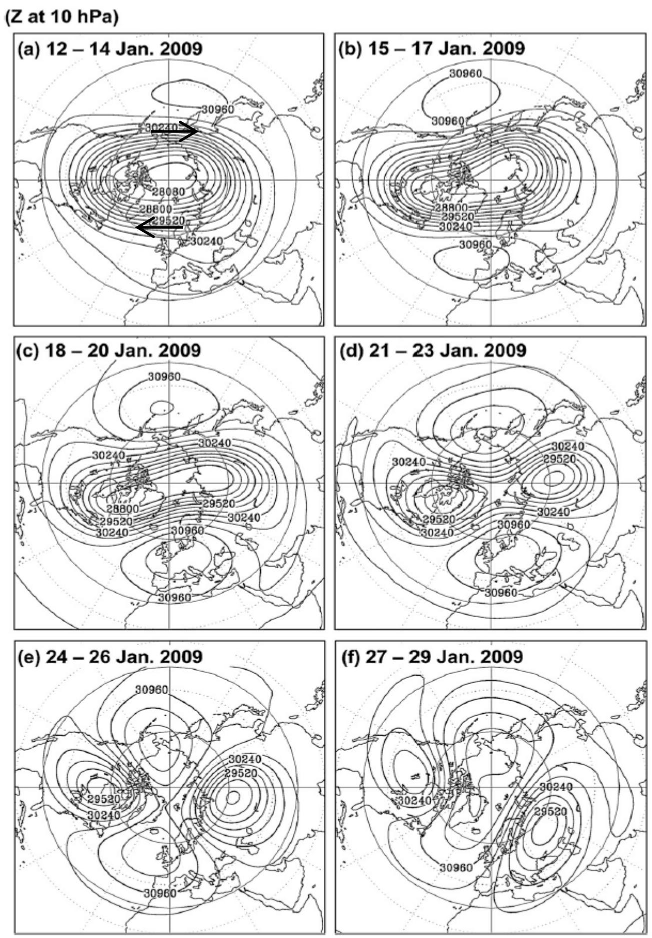
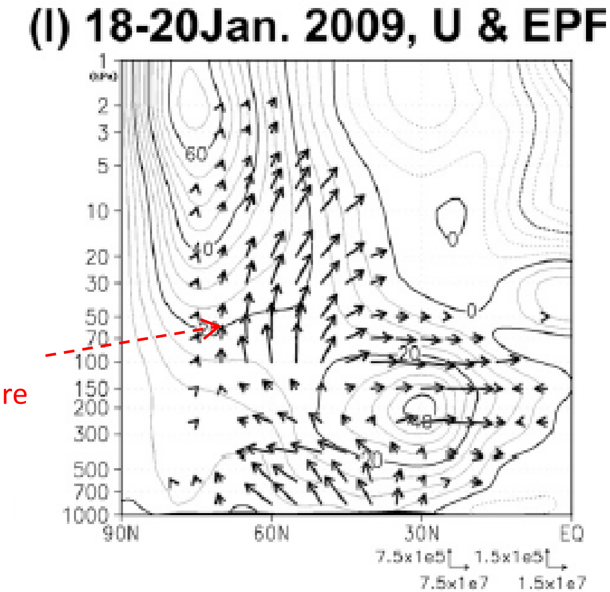


FIG. 3. The 10-hPa geopotential heights for six successive 3-day means in January 2009. The contour interval is 240 m.

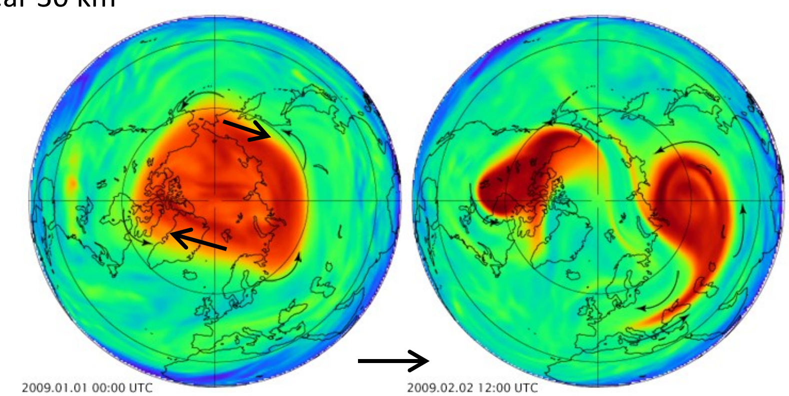
EP flux



wave forcing
from troposphere

polar vortex
near 30 km

potential vorticity



split of polar vortex

A Dynamical Model of the Stratospheric Sudden Warming

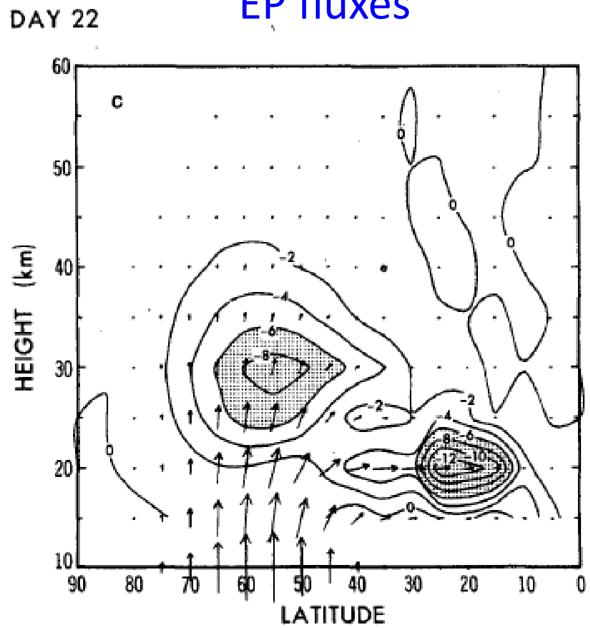
Taroh Matsuno[1]

Geophysical Fluid Dynamics Laboratory, NOAA, Princeton University, Princeton, N. J.

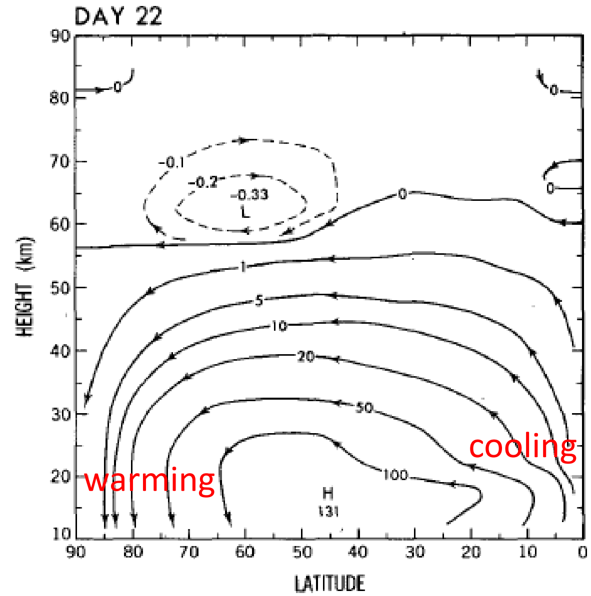
(Manuscript received 29 March 1971, in revised form 16 August 1971)

solution to puzzle of stratospheric warmings

EP fluxes



overturning circulation



Some Eulerian and Lagrangian Diagnostics for a Model Stratospheric Warming[1]

T. Dunkerton, C.-P. F. Hsu[2] and M. E. McIntyre[3]

Department of Atmospheric Sciences, University of Washington, Seattle 98195

(Manuscript received 30 May 1980, in final form 11 December 1980)

Governing equations for the zonal mean flow (Transformed Eulerian mean)

EP flux divergence (wave forcing)

zonal momentum balance

$$\frac{\partial \overline{u}}{\partial t} - \hat{f}\overline{v}^* = \mathrm{DF}$$

diabatic forcing

thermodynamic balance

$$\frac{\partial \overline{T}}{\partial t} + \overline{v}^* \frac{1}{a}\frac{\partial \overline{T}}{\partial \phi} + \overline{w}^* S = \overline{Q},$$

continuity equation

$$(a\cos\phi)^{-1}\frac{\partial}{\partial \phi}(\overline{v}^*\cos\phi) + e^{z/H}\frac{\partial}{\partial z}(\overline{w}^* e^{-z/H}) = 0,$$

geostrophic thermal wind

$$f\frac{\partial \overline{u}}{\partial z} + \frac{R}{aH}\frac{\partial \overline{T}}{\partial \phi} = 0.$$

Andrews et al, 1987

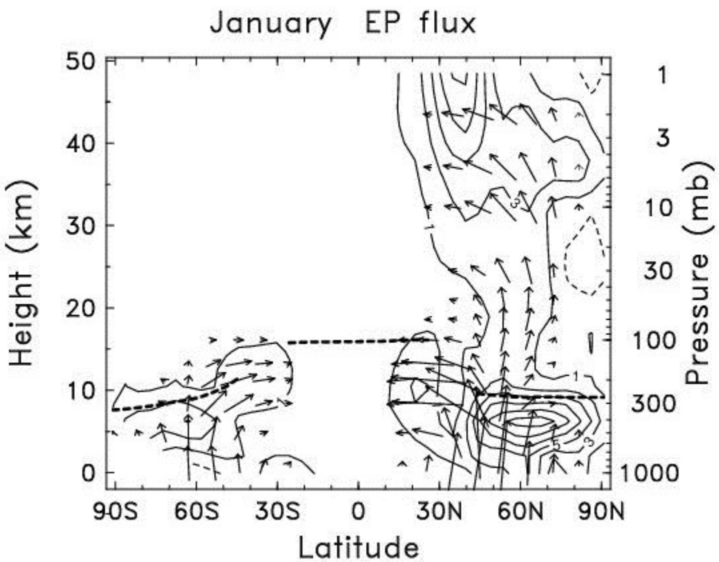
Eliassen-Palm fluxes:

EP flux divergence (wave forcing)

$$\frac{\partial \bar{u}}{\partial t} - \hat{f}\bar{v}^* = \mathrm{DF}$$

$$\mathrm{DF} = \frac{\exp(z/H)}{a\ \cos\phi}\nabla \cdot \mathbf{F},$$

climatology



components:

momentum flux

latitudinal flux

$$F_\phi = \exp(-z/H)a\ \cos\phi\left[-\overline{u'v'}\right],$$

vertical flux

$$F_z = \exp(-z/H)a\ \cos\phi\left[\hat{f}\frac{\overline{v'T'}}{S}\right],$$

heat flux

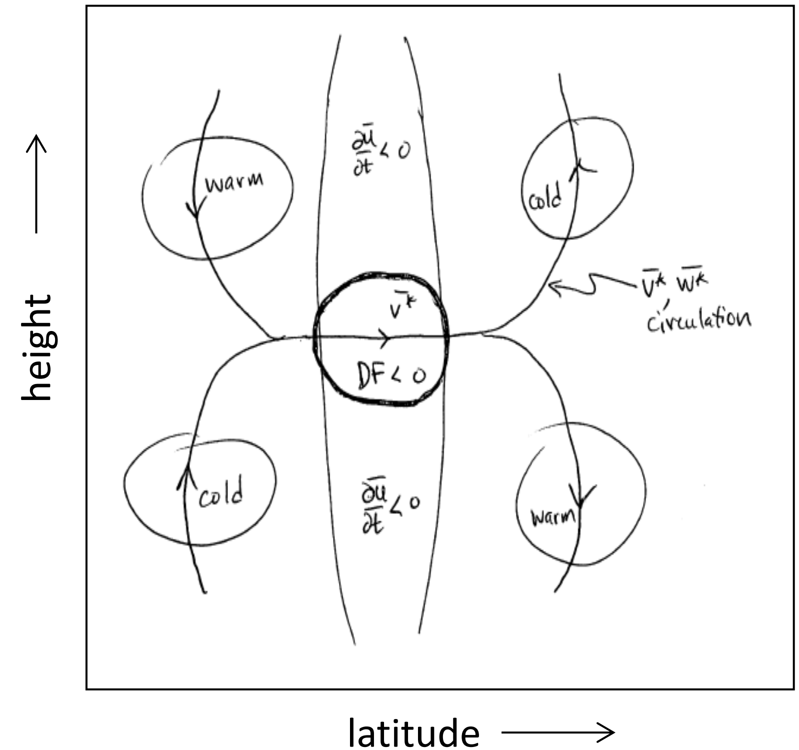
Important points:

- DF quantifies zonal momentum forcing
- **F** proportional to 'wave activity' flux
  (DF shows sources and sinks of waves)
- F_ϕ and F_z indicate direction of wave propagation

Response of a balanced vortex to localized EP flux forcing (DF)

$$\frac{\partial \bar{u}}{\partial t} - f\bar{v}^* = DF$$

- response is balanced between $\partial \bar{u}/\partial t$ and $f\,\bar{v}^*$
- $\bar{v}^*$, $\bar{w}^*$ and $\partial \bar{u}/\partial t$ act to extend DF forcing non-locally
- overall circulation maintains thermal wind balance



Circulation response depends on frequency of forcing:

Combine equations:

$$\frac{\partial}{\partial z}\left(\frac{1}{\rho_0}\frac{\partial(\rho_0\hat{w})}{\partial z}\right) + \left(\frac{i\sigma}{i\sigma+\alpha}\right)\frac{N^2}{4\Omega^2a^2\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{\cos\phi}{\sin^2\phi}\frac{\partial\hat{w}}{\partial\phi}\right)$$

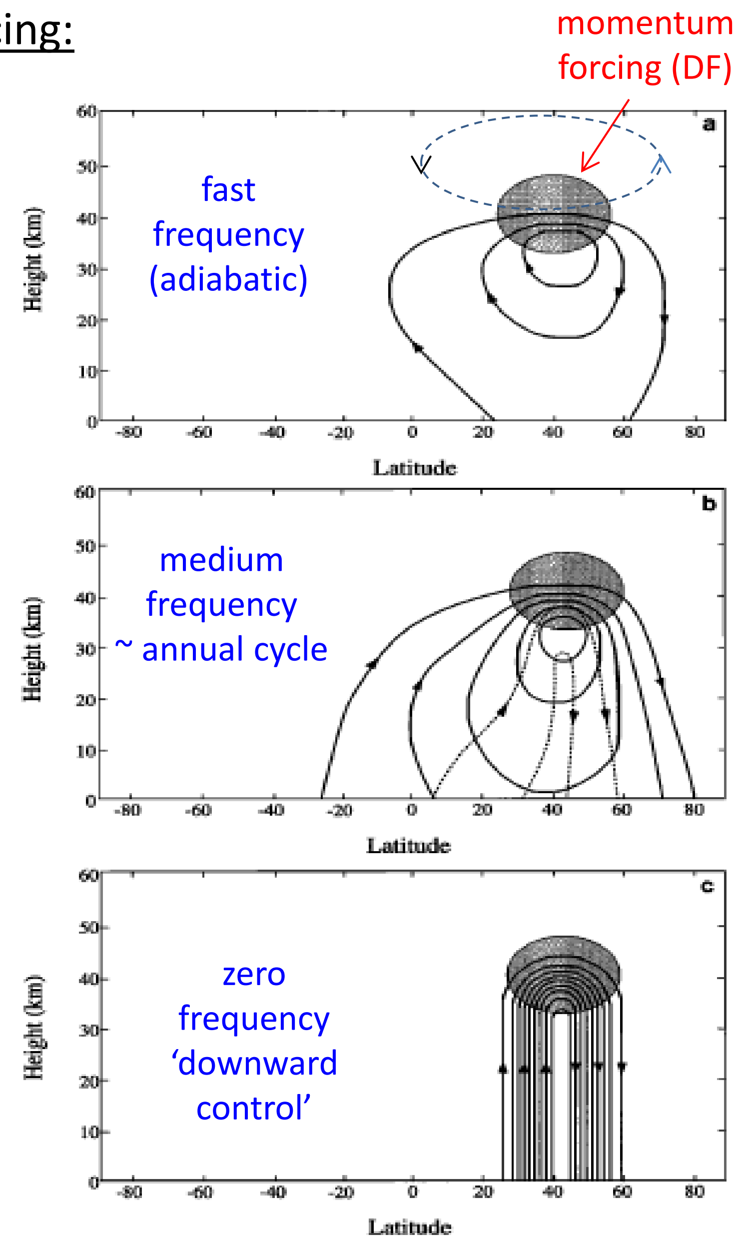
$$= \left(\frac{i\sigma}{i\sigma+\alpha}\right)\frac{(R/H)}{4\Omega^2a^2\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{\cos\phi}{\sin^2\phi}\frac{\partial\hat{Q}}{\partial\phi}\right)$$

$$+ \frac{1}{2\Omega a\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{\cos\phi}{\sin\phi}\frac{\partial\hat{G}}{\partial z}\right)$$

time dependence

diabatic heating

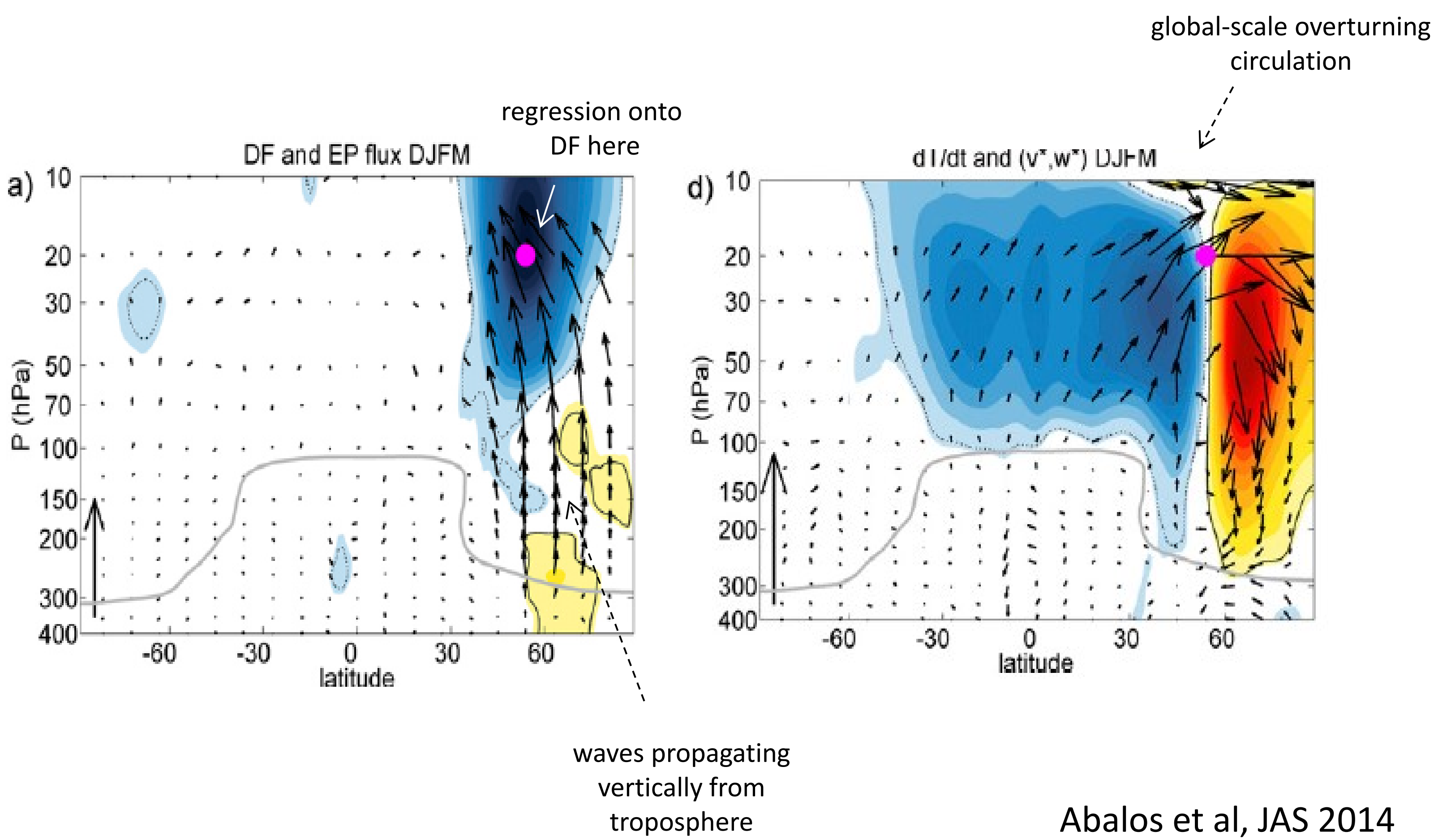
momentum forcing (DF)



In general both Q and DF drive the mean circulation. These plots show the response to isolated forcing from Rossby wave EP flux divergence. The lower cell becomes more important for slower forcing.

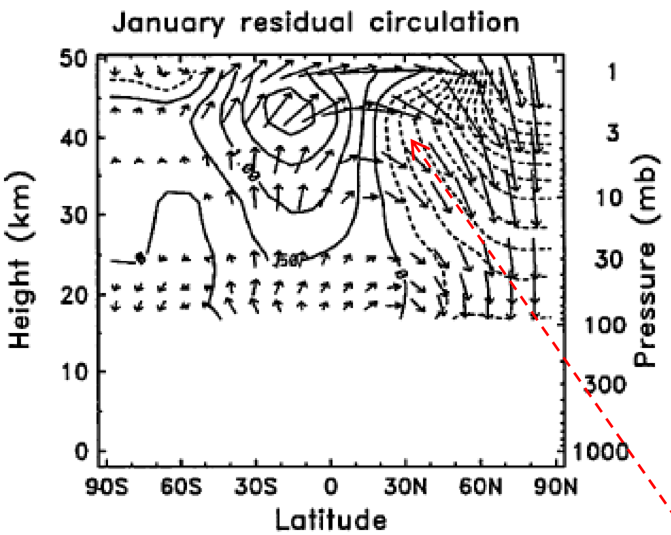
Haynes et al 1991
Holton et al 1995

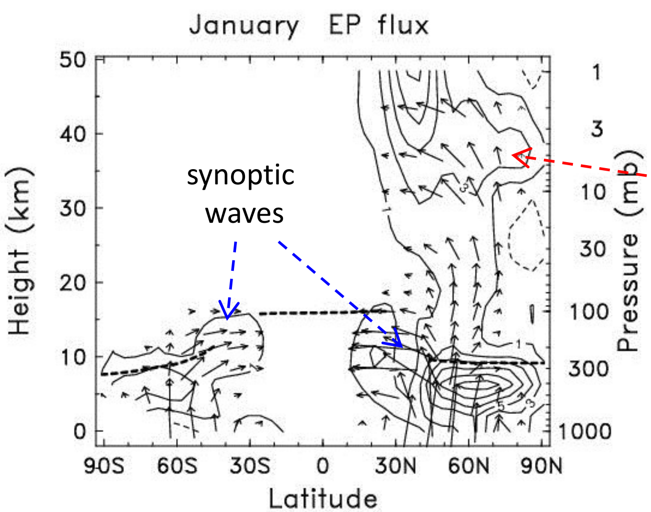
Wave – mean flow patterns from observations (reanalysis data)



Abalos et al, JAS 2014

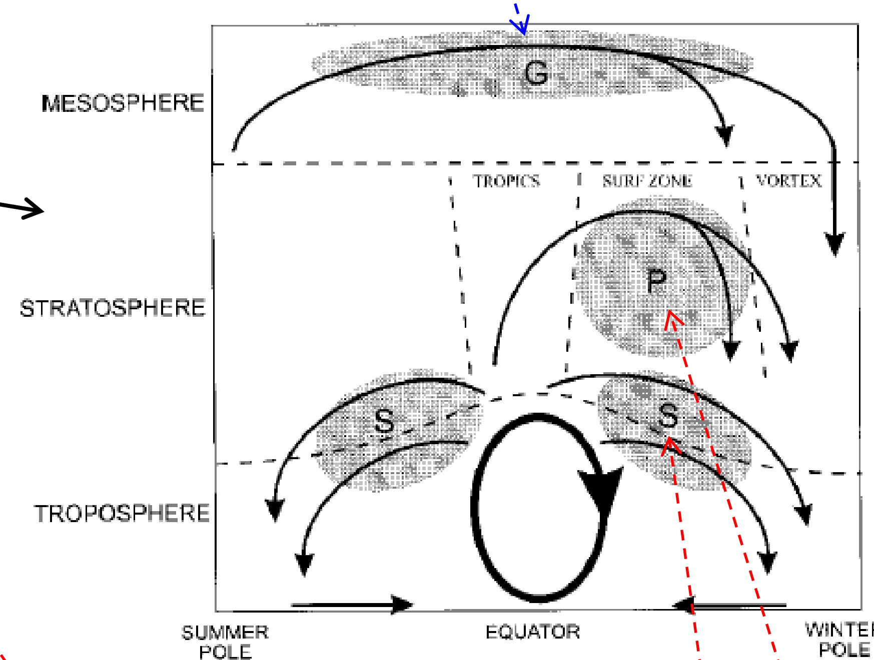
Climatology of stratospheric overturning circulation





gravity waves

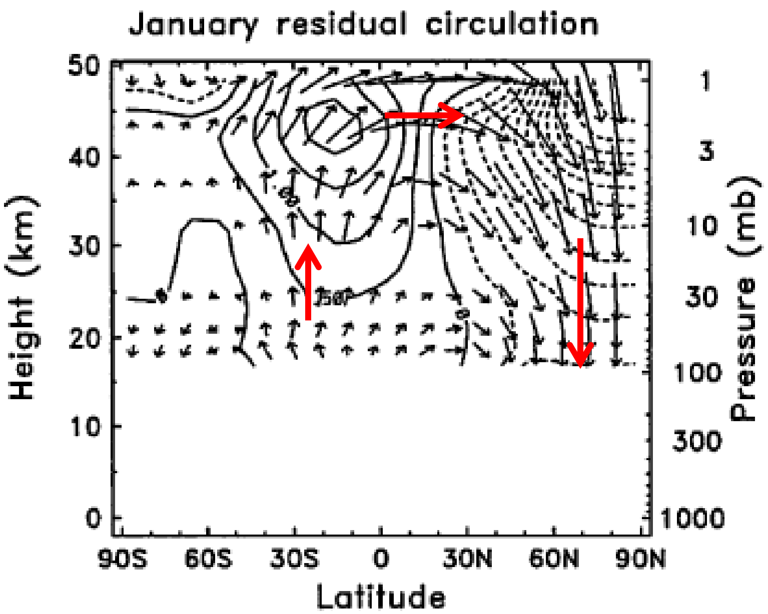
Plumb 2002

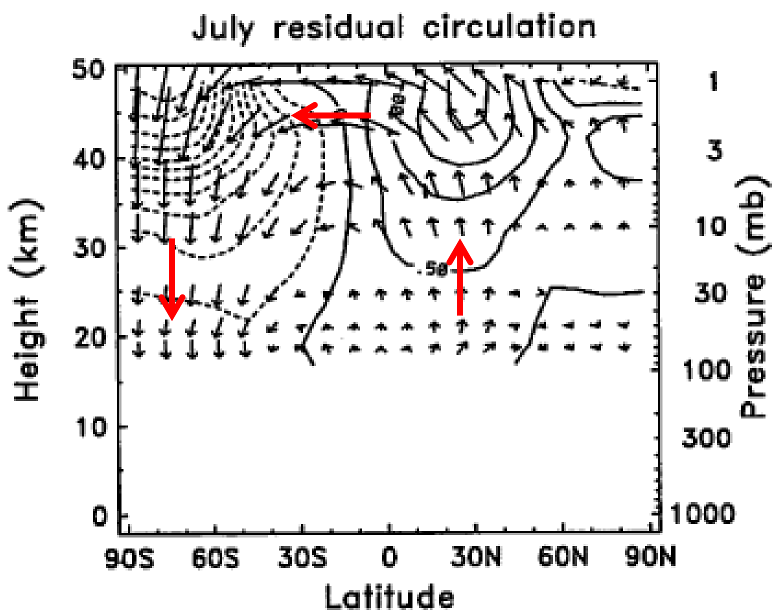


winter planetary waves help drive the overturning circulation

upper and lower branches of the circulation driven by **Planetary** and **Synoptic** waves

The overturning circulation reverses between solstice seasons

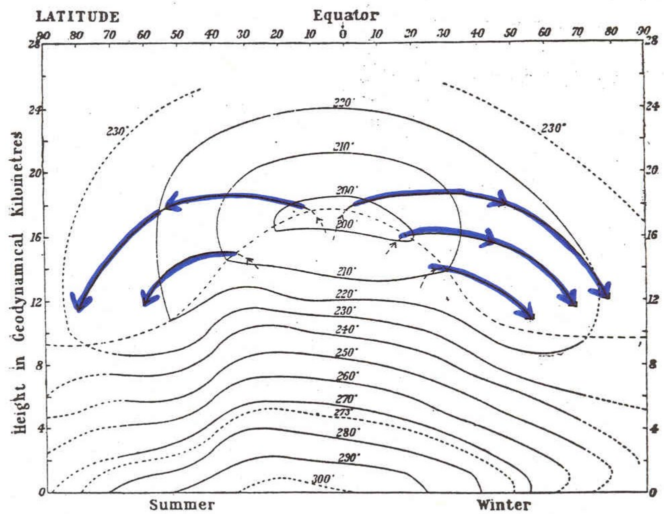




circulation is stronger during NH winter, related to stronger wave forcing from troposphere

The stratospheric overturning circulation is often termed the Brewer-Dobson circulation (closely related to the Lagrangian or transport circulation)

deduced by Brewer (1949) studying stratospheric water vapor and Dobson (1956) studying stratospheric ozone



Isotherms over the Globe

FIG. 5. A supply of dry air is maintained by a slow mean circulation from the equatorial tropopause.

see recent review by Butchart 2014

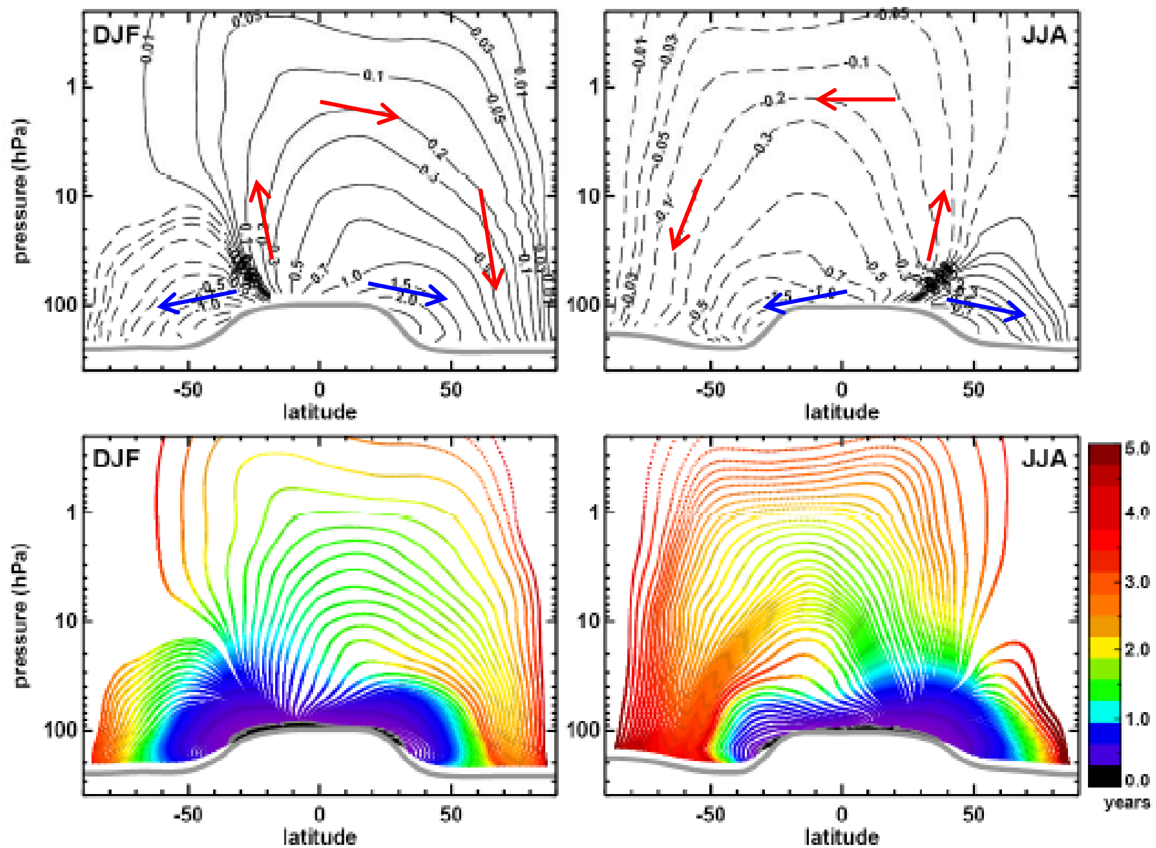
Residual circulation trajectories and transit times into the extratropical lowermost stratosphere

T. Birner[1] and H. Bönisch[2]

ACP 2011

renewed appreciation that there are upper and lower branches of the BDC

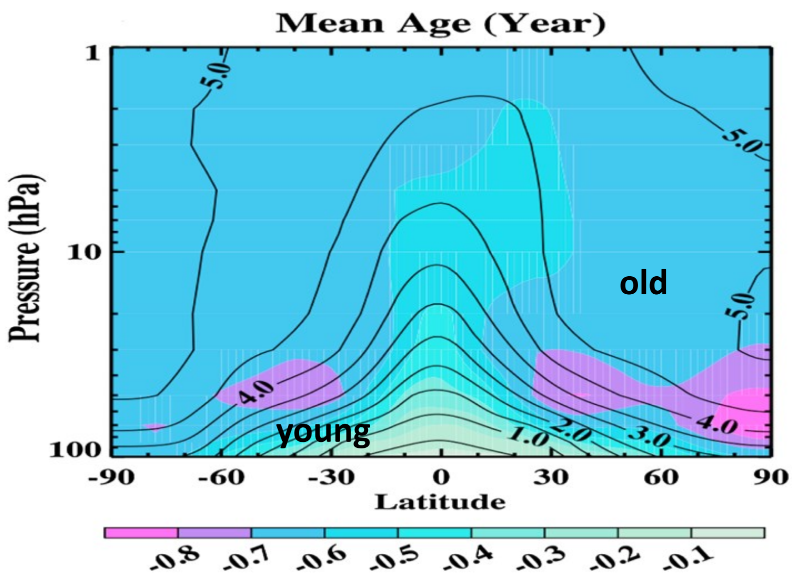
Red: deep branch (slow)
Blue: shallow branch (fast)



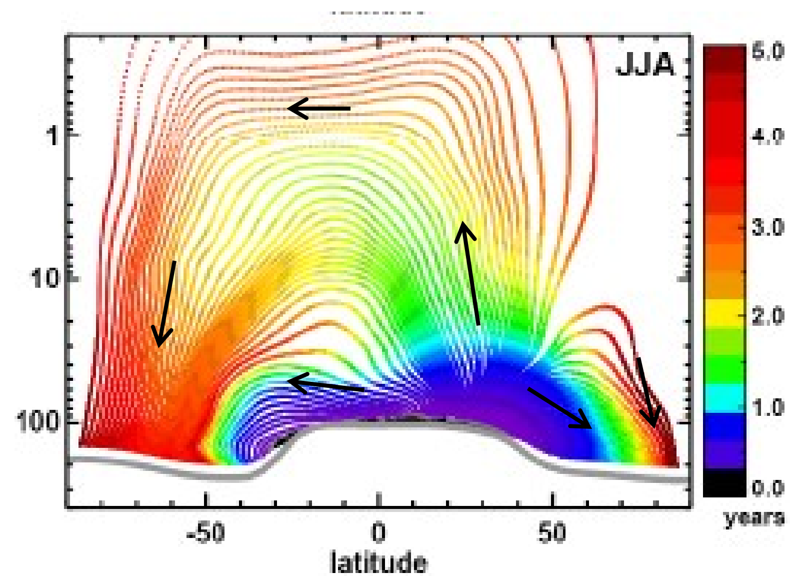
streamfunction

transit time along constant streamlines

Transit time is closely related to 'mean age' (time since air entered stratosphere)



transit time



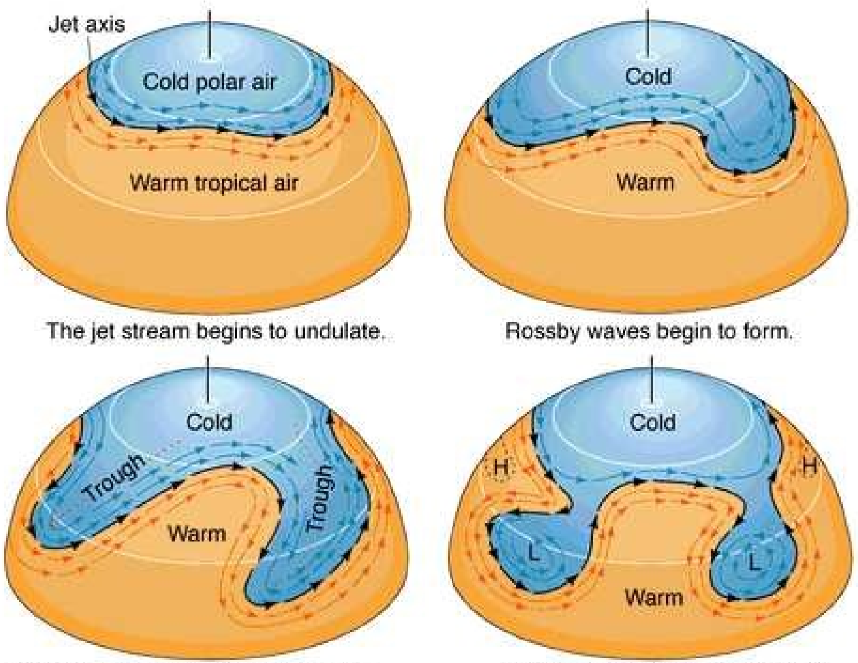
Air at any particular location is characterized by a distribution of transit times and ages (so-called age spectrum)

Birner and Bönisch, 2011, Atmos. Chem. Phys.

Key points:

- Asymmetry in winter stratosphere circulations: more disturbed in the NH, cold and quiet in the SH
- The stratosphere is forced by waves from the tropopshere (stronger forcing in NH; episodic stratospheric sudden warmings)
- Dynamical response of balanced vortex to wave forcing (non-local temperature and wind changes)
- Eliassen-Palm (EP) fluxes quantify wave forcing
- Brewer-Dobson transport circulation (deep and shallow branches)

Rossby waves

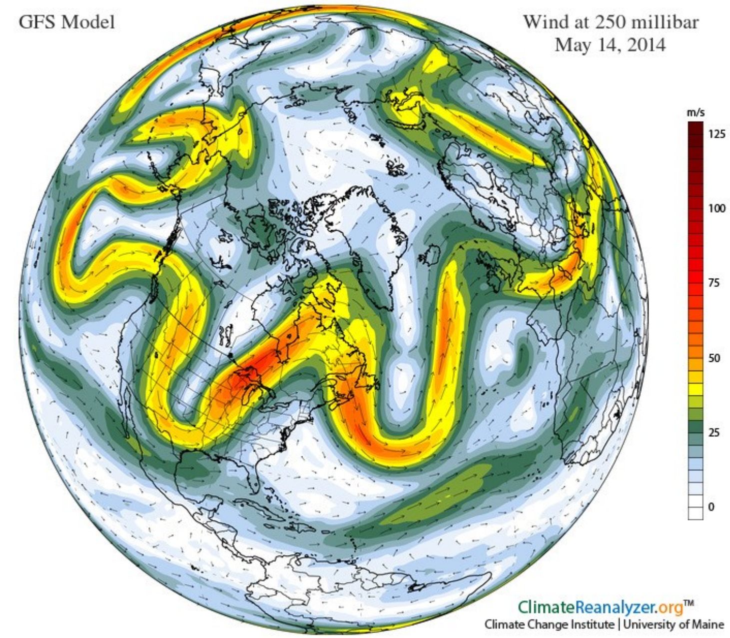


The jet stream begins to undulate.

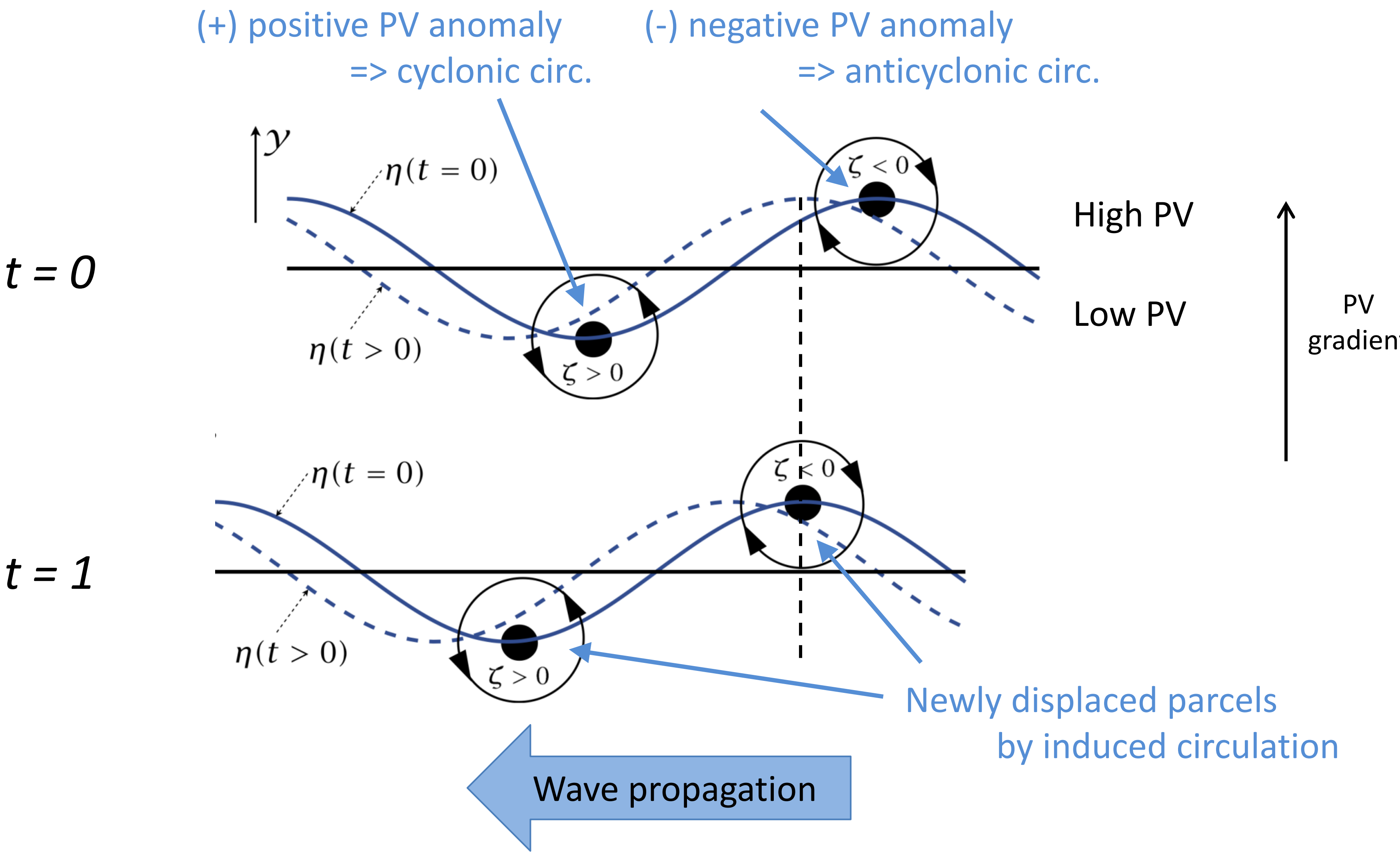
Rossby waves begin to form.

Waves are strongly developed. The cold air occupies troughs of low pressure.

When the waves are pinched off, they form cyclones of cold air.



Rossby wave (potential vorticity wave)



Vallis 2006 (Atmospheric and Oceanic Fluid Dynamics, 2nd Ed.)

Rossby wave propagation: quasi-geostrophic linearized PV equation

$$\left(\frac{\partial}{\partial t}+\frac{\bar{u}}{a\cos\phi}\frac{\partial}{\partial\lambda}\right)q'_{(\mathrm{M})}+a^{-1}\bar{q}_\phi v'=0,$$

eddy PV

background PV gradient

$$\bar{q}_\phi=2\Omega\cos\phi-\left[\frac{(\bar{u}\cos\phi)_\phi}{a\cos\phi}\right]_\phi-\frac{a}{\rho_0}\left(\frac{\rho_0 f^2}{N^2}\bar{u}_z\right)_z.$$

wave solution:

$$\Phi'=e^{z/2H}\,\mathrm{Re}\,\Psi(\phi,z)e^{is\lambda}$$

$$\boxed{\frac{f^2}{a^2\cos\phi}\left(\frac{\cos\phi}{f^2}\Psi_\phi\right)_\phi+\frac{f^2}{N^2}\Psi_{zz}+n_s^2\Psi=0}$$

wave equation:
propagation for
$n_s^2 > 0$

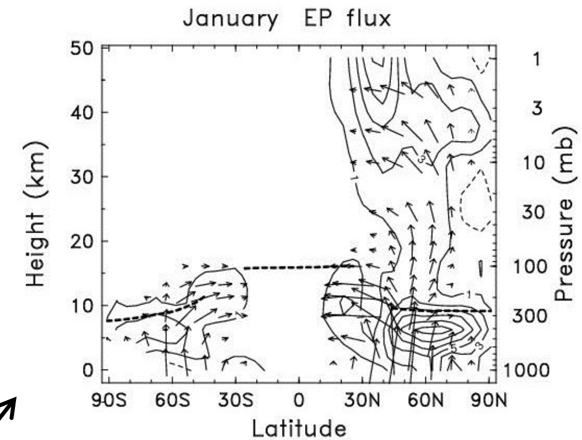
$$n_s^2=\frac{\bar{q}_\phi}{a\bar{u}}-\frac{s^2}{a^2\cos^2\phi}-\frac{f^2}{4N^2H^2}$$

refractive index

Propagation of Planetary-Scale Disturbances from the Lower into the Upper Atmosphere

J. G. Charney and P. G. Drazin[1]

JGR 1961

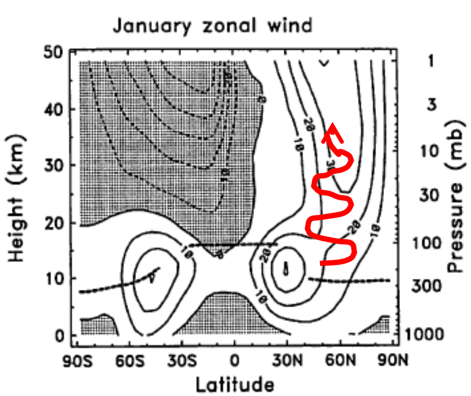


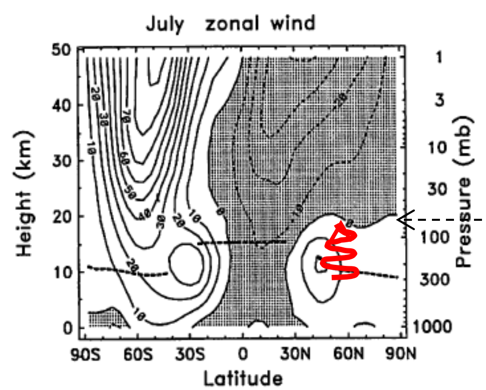
~ cos (lat) + U terms

$$n_s^2 = \frac{\bar{q}_\phi}{a\bar{u}} - \frac{s^2}{a^2\cos^2\phi} - \frac{f^2}{4N^2H^2}$$

<u>2 key points:</u>

- n_s^2 proportional to ~cos (lat) (Rossby wave refraction towards low latitudes)
- vertical propagation for U > 0 and small zonal wavenumbers
  (planetary waves propagate to stratosphere only during winter)





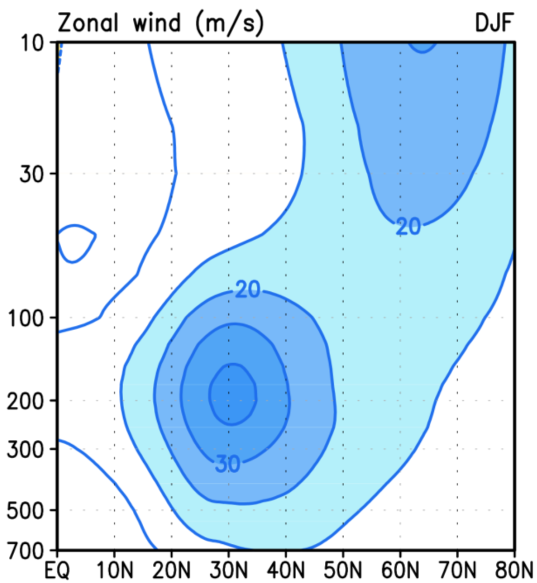
no propagation in summer easterlies

Refractive index squared (Matsuno 1970)

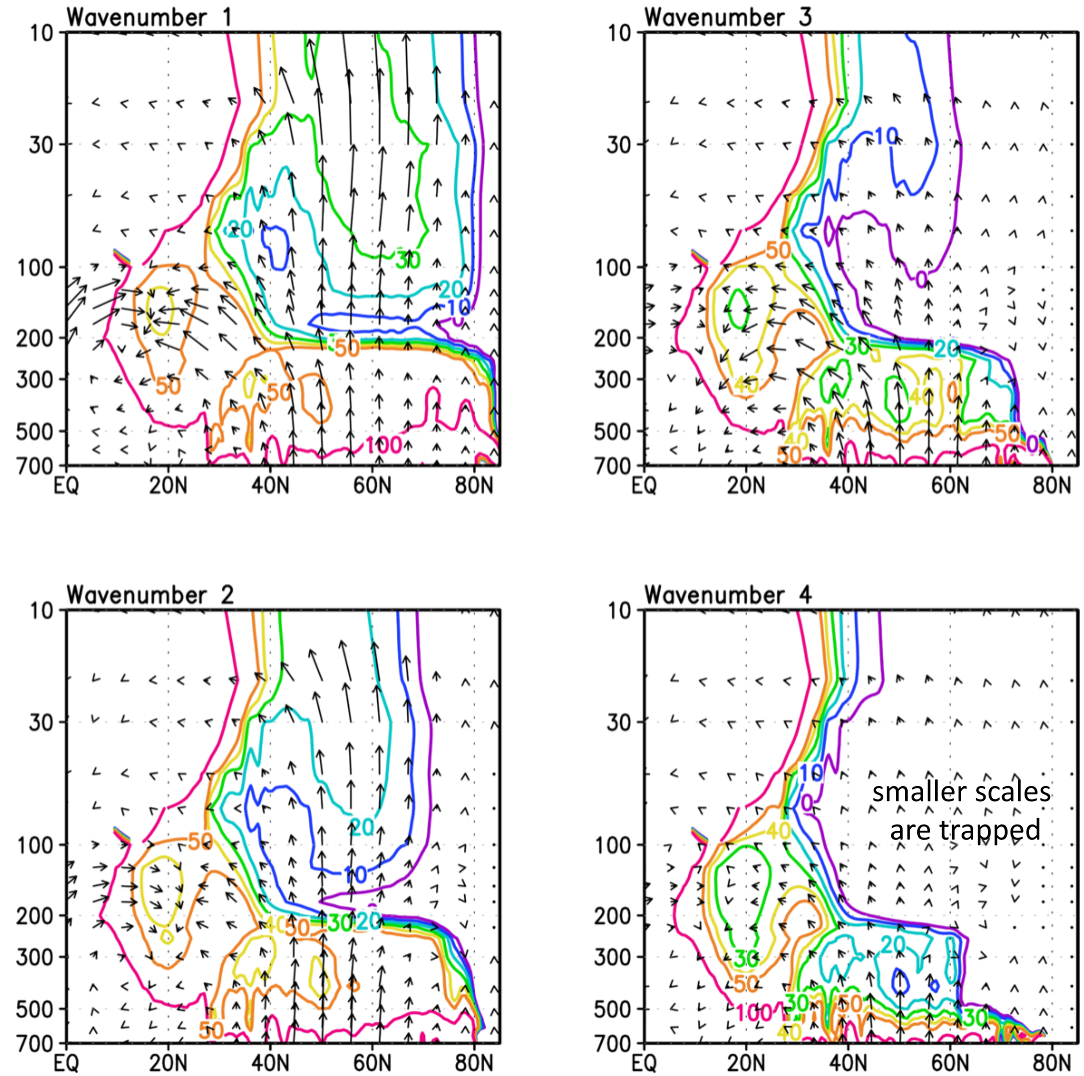
zonal wave 1 and 2 can propagate vertically in climatological basic state

calculated n_s^2 and observed EP fluxes

$$n_s^2 = \frac{\bar{q}_\varphi}{a\bar{u}} - \frac{f^2}{4H^2N^2} - \frac{s^2}{a^2\cos^2\varphi}$$

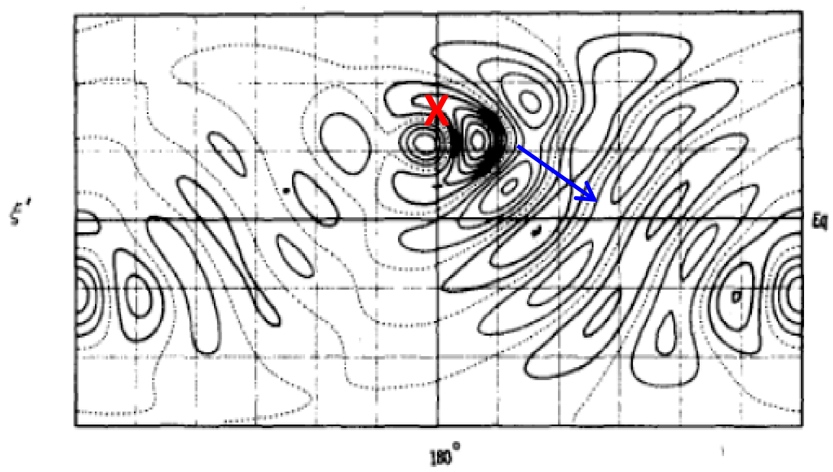


thanks to Joowan Kim



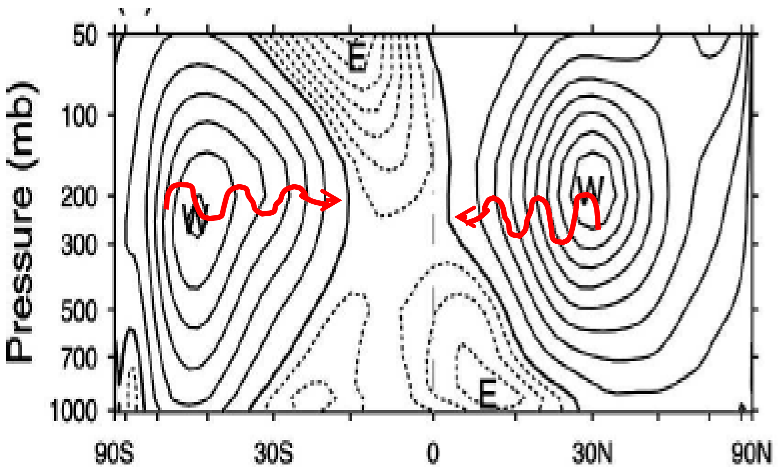
Rossby wave dispersion on the sphere: response to isolated topography

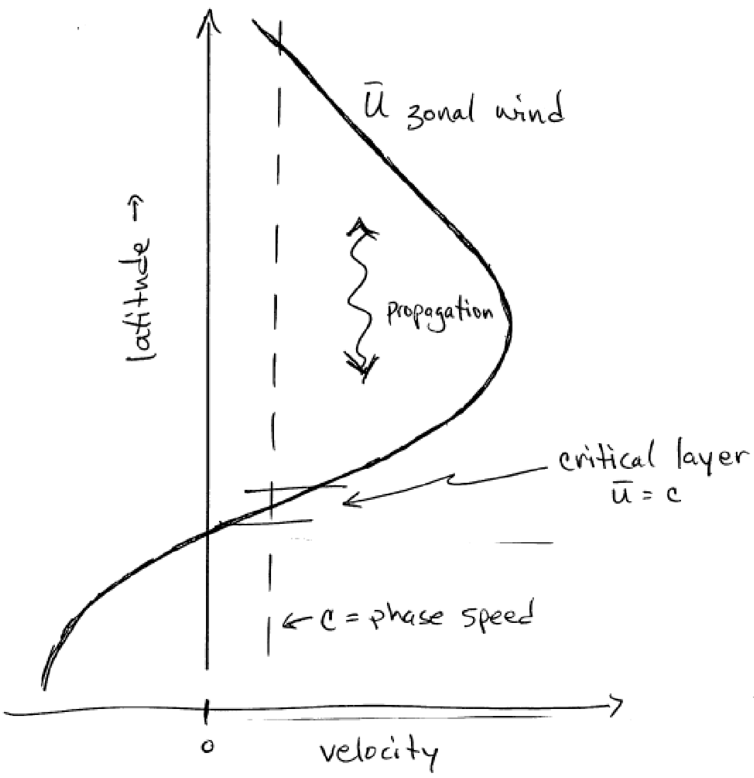
vorticity



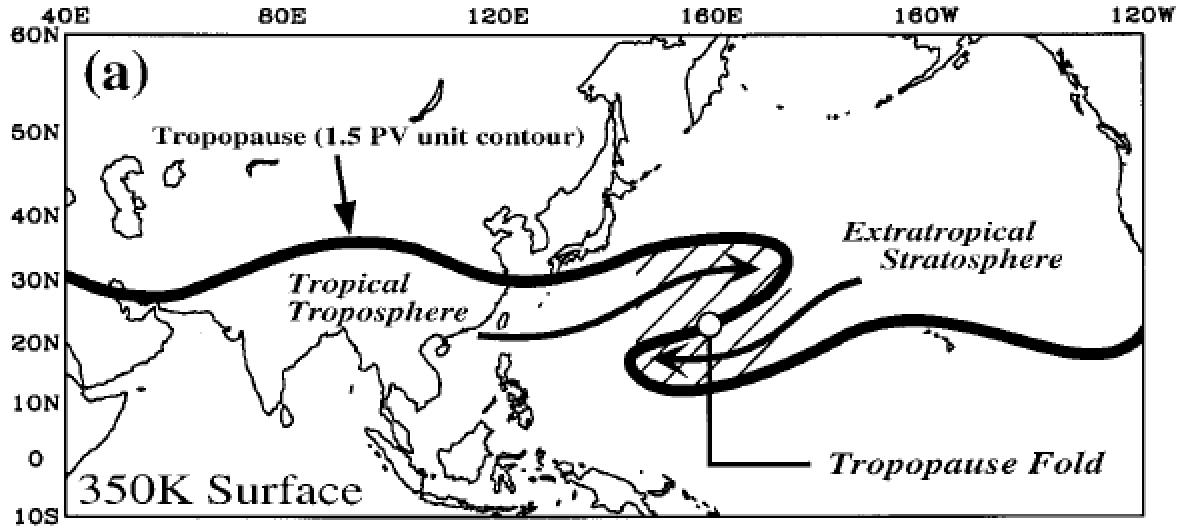
Steady state solution of the shallow water equations linearized about a constant angular velocity flow and perturbed by a circular mountain at 30°N, 180°E. The model includes linear drag. After B. J. Hoskins, *Horizontal Wave Propagation on the Sphere*. in *The General Circulation. Theory, Modeling and Observations.* NCAR Summer Colloquium 1978.

Rossby waves cannot propagate into regions where U < 0   (i.e. across equator)





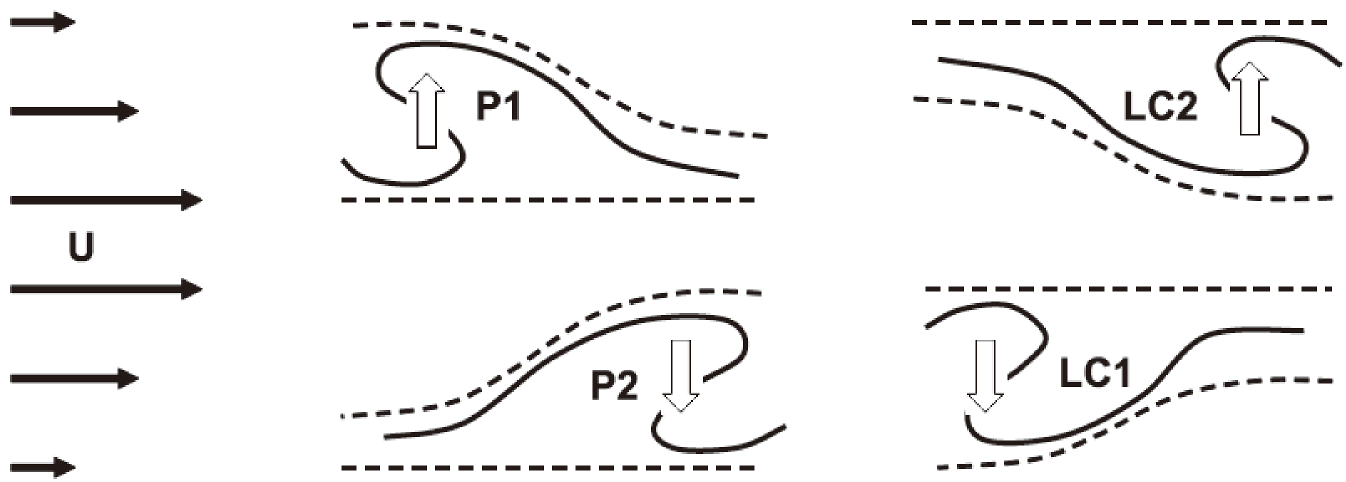
Breaking Rossby waves: overturning of PV contours



Postel and Hitchman 1999
Homeyer et al 2013

Two types of wave breaking, depending on shear of background winds

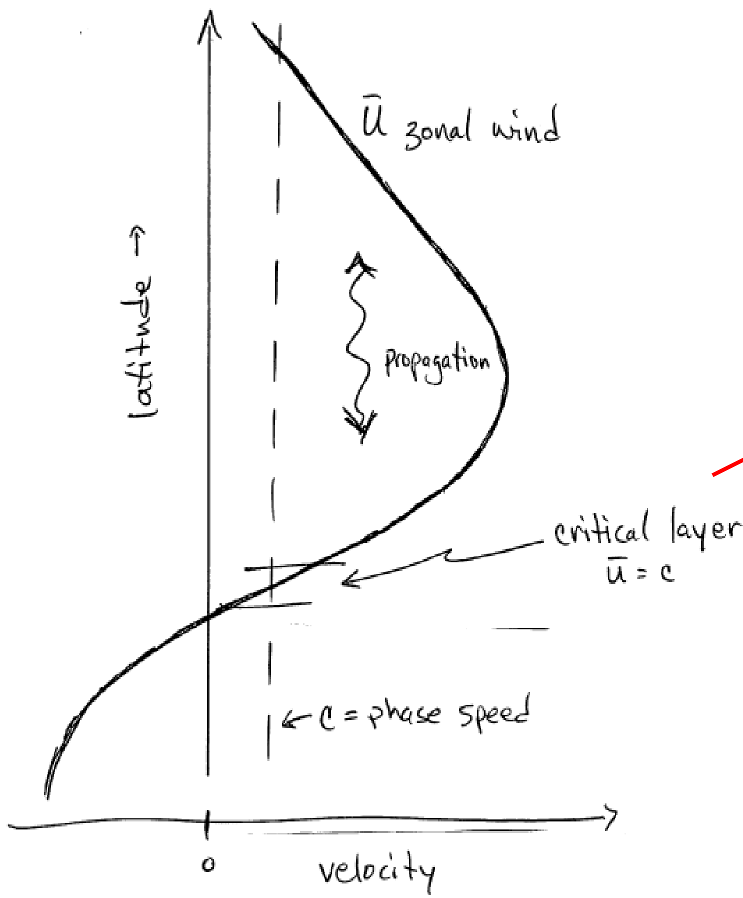
poleward breaking (cyclonic)

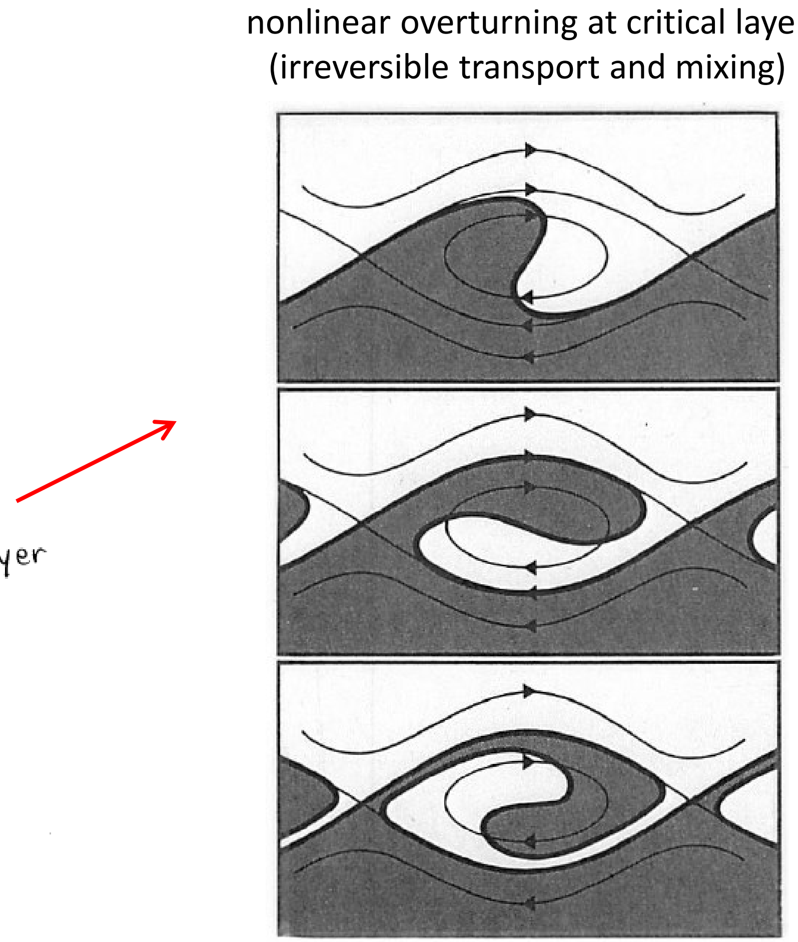


equatorward breaking (anticyclonic)

Gabriel and Peters 2008

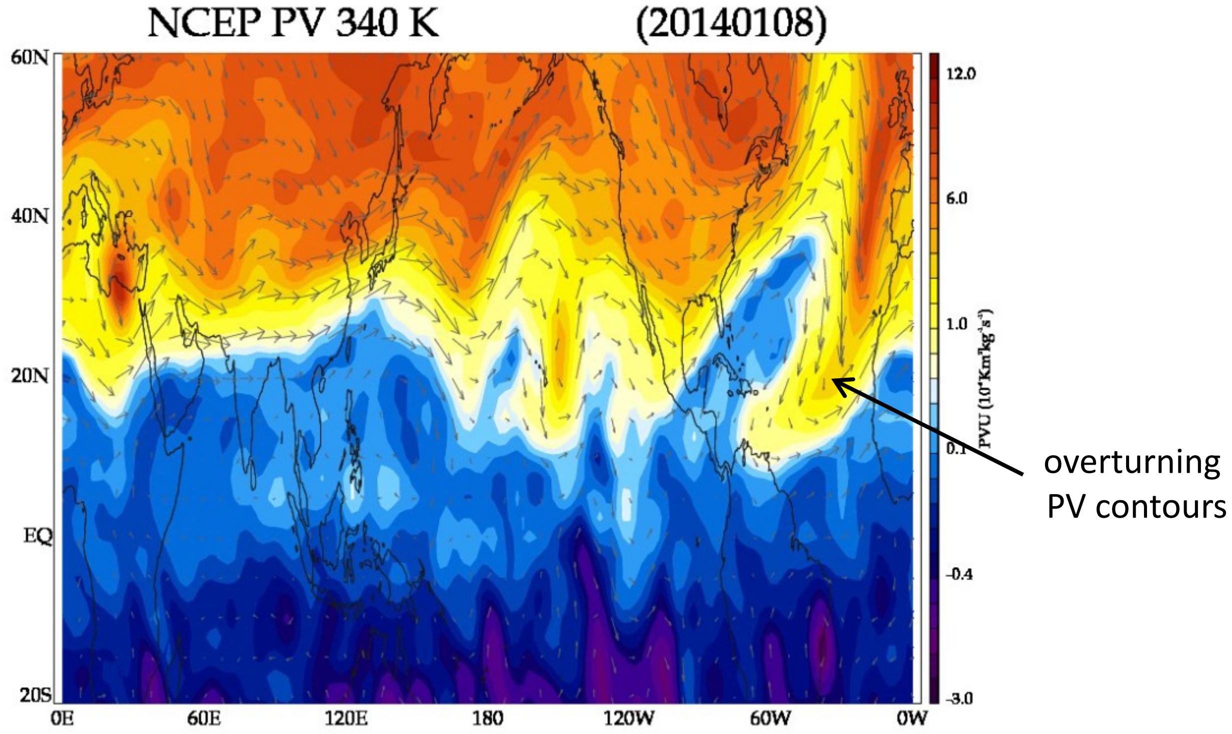
Rossby wave critical layer interactions (critical layer: U = c)



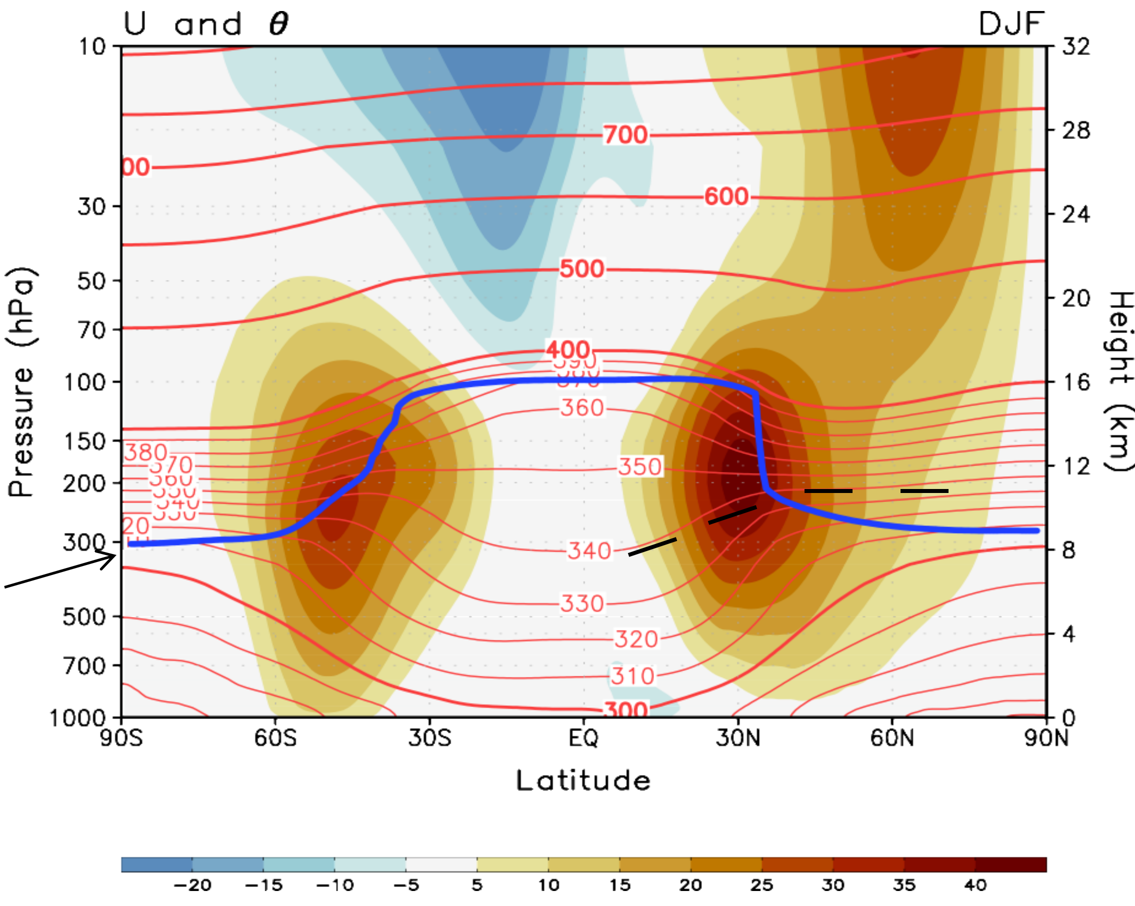


Warn and Warn 1978

Example of a large-scale breaking Rossby wave



fast, synoptic flow mainly along isentropes:



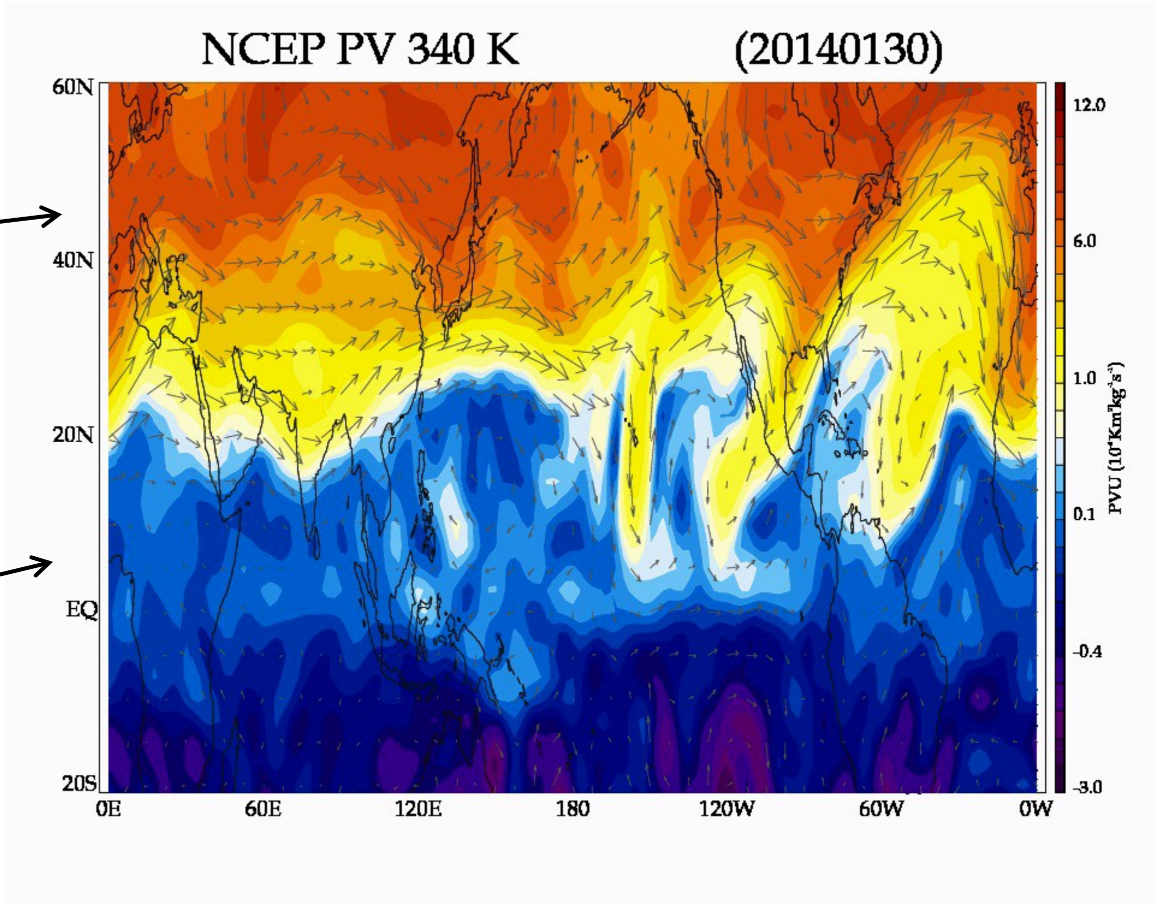
tropopause

340 K isentrope
spans tropical troposphere
to extratropical lower
stratosphere

Rossby waves during January-May at 340 K

extra-tropical lower stratosphere

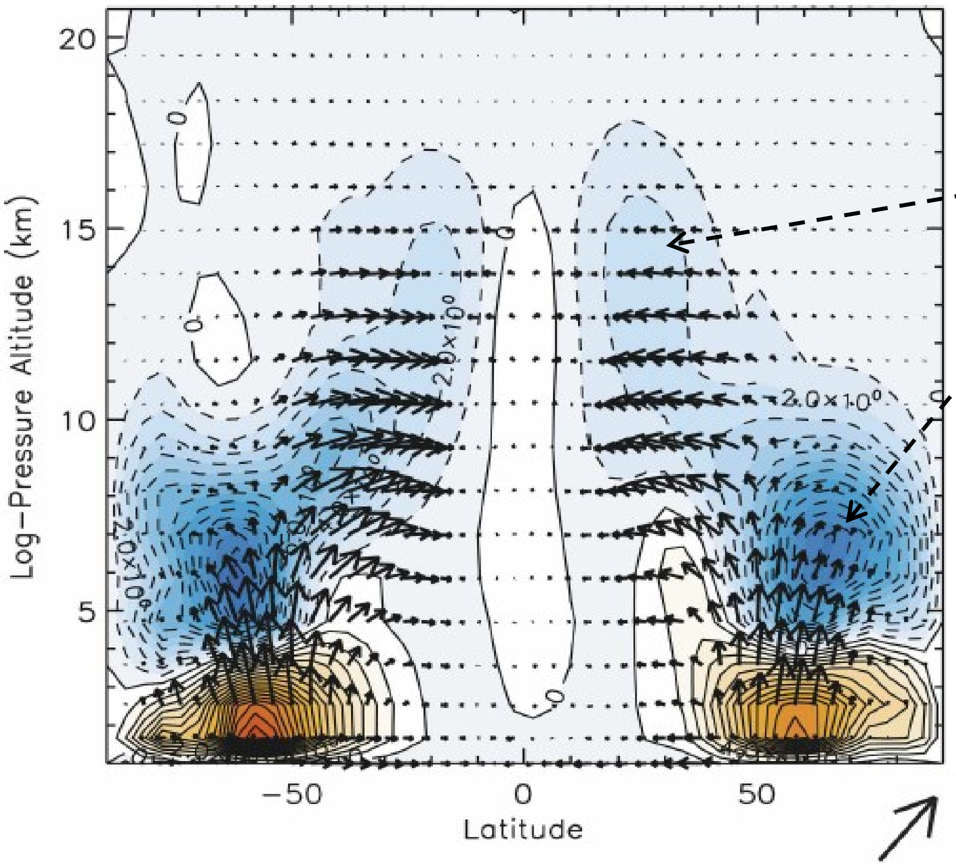
tropical troposphere



Key points:

- Rossby waves: conserve PV
- General refraction of Rossby waves towards low latitudes
- Latitudinal or vertical propagation for $U > 0$ (more generally $U > c$)
- Rossby wave breaking near critical lines ($U = c$)
- Poleward or equatorward breaking depending on background U shear
- Key mechanism for dissipation, transporting PV or trace species

Climatological EP fluxes in the troposphere

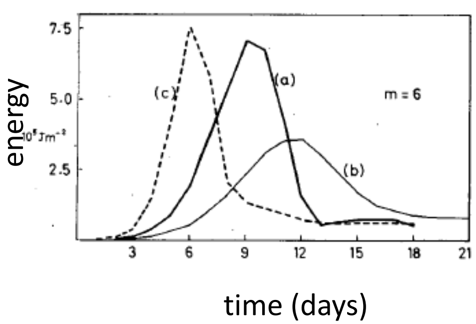


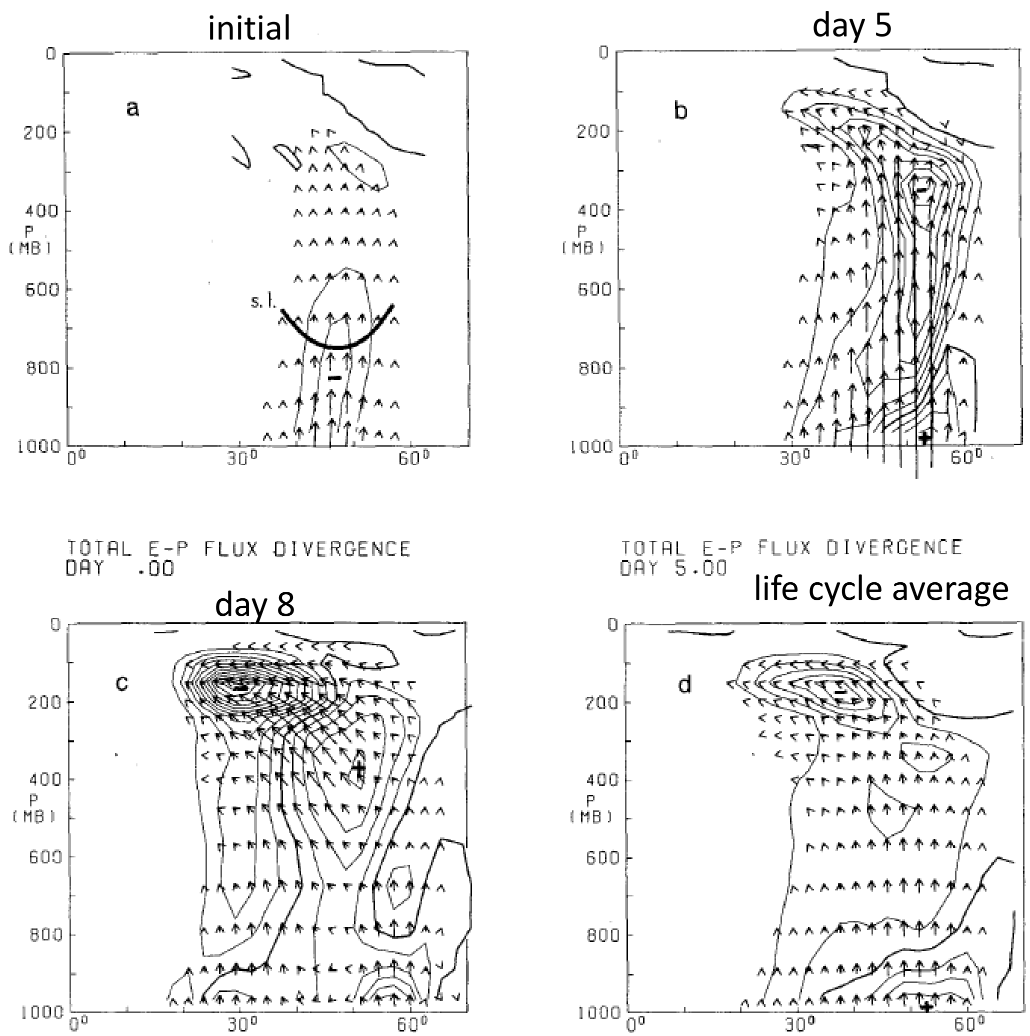
main regions of wave dissipation

Garcia and Randel, 2008

Extratropical EP flux patterns are related to baroclinic wave life cycles

idealized
zonal wave 6
baroclinic eddy
life cycle





baroclinic
growth

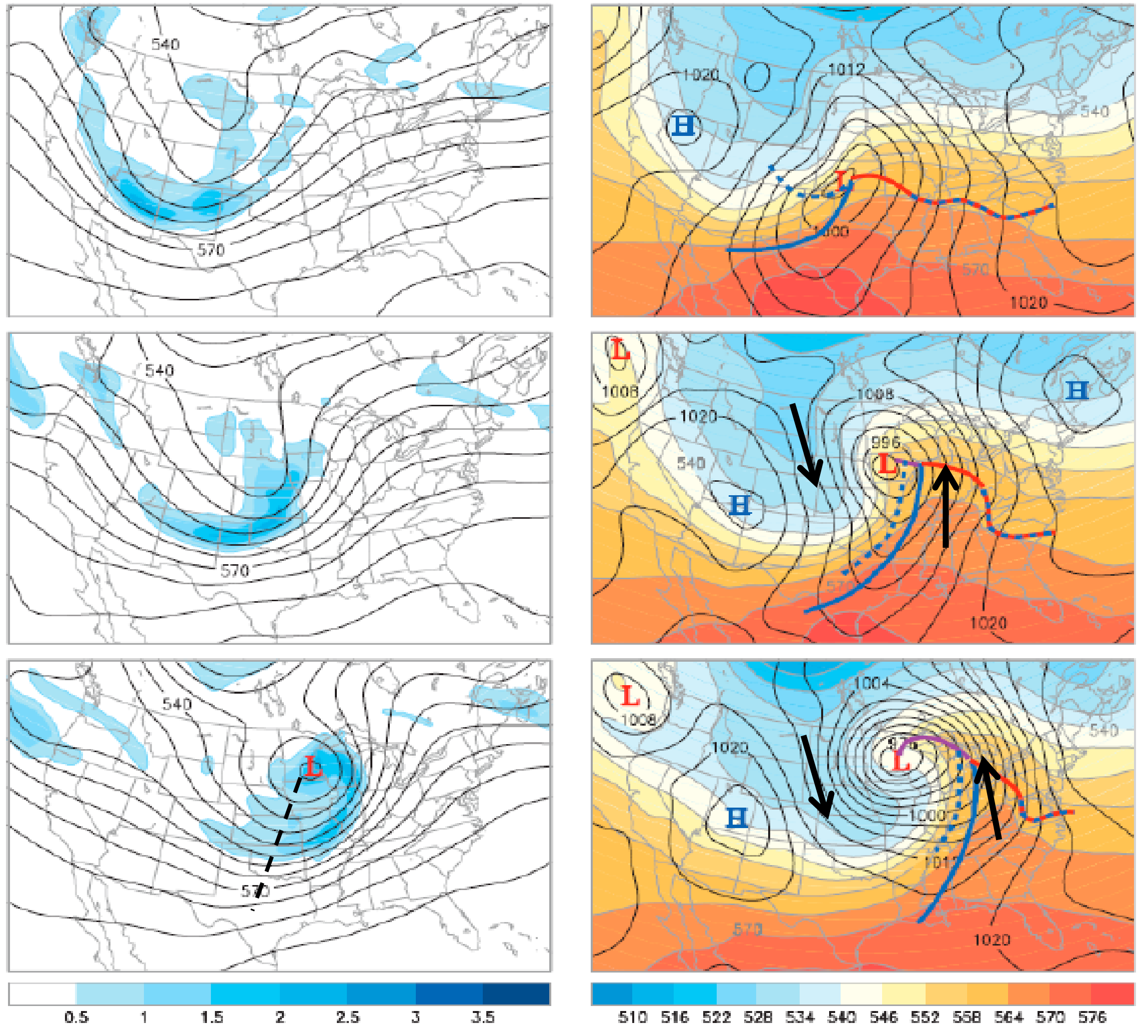
barotropic
decay

Simmons and Hoskins 1980
Edmon et al 1980

synoptic views of developing baroclinic wave

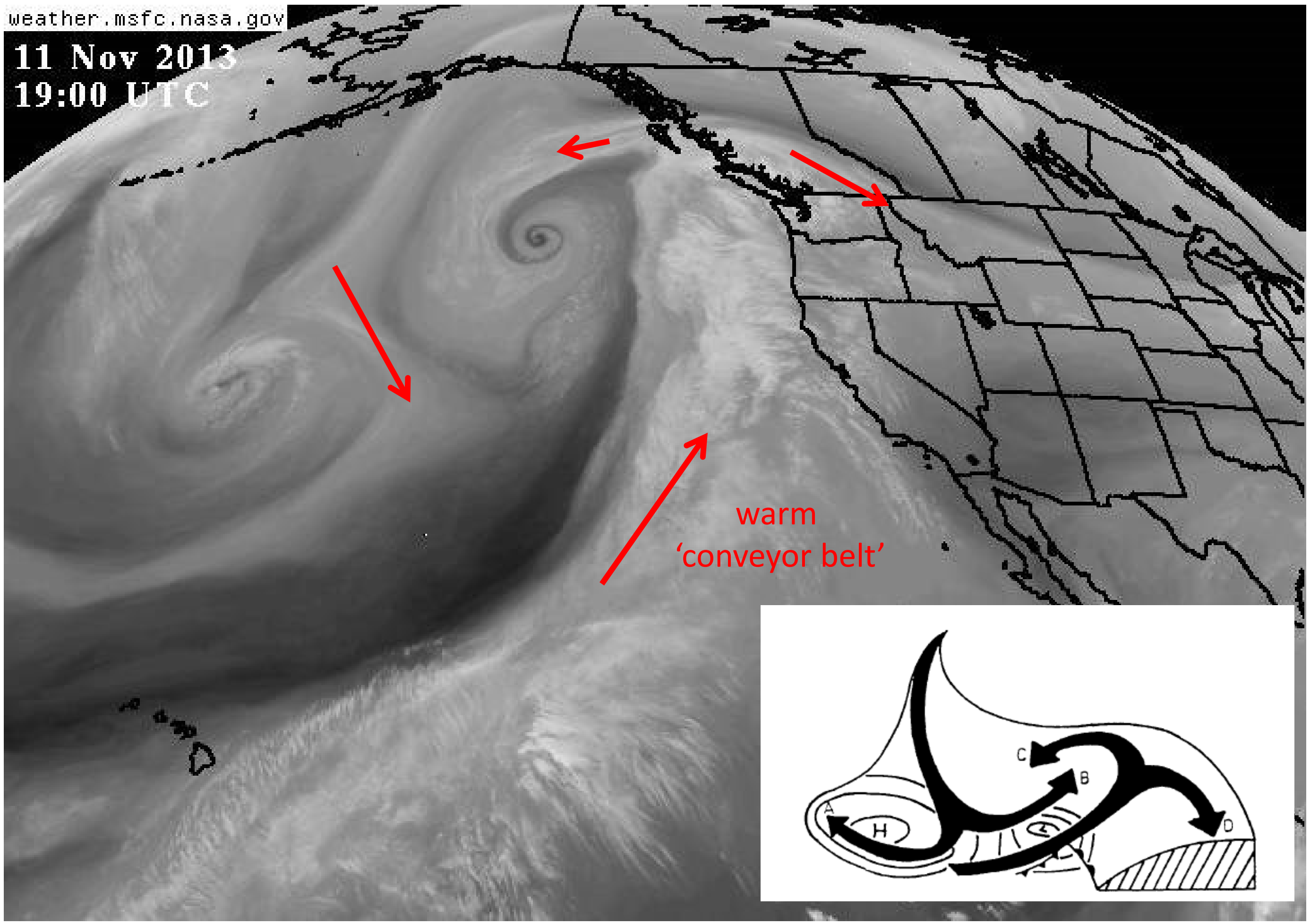
500 hPa

surface



poleward heat flux

phase tilt: equatorward momentum flux


weather.msfc.nasa.gov
11 Nov 2013
19:00 UTC
warm
'conveyor belt'
C
B
A
H
D

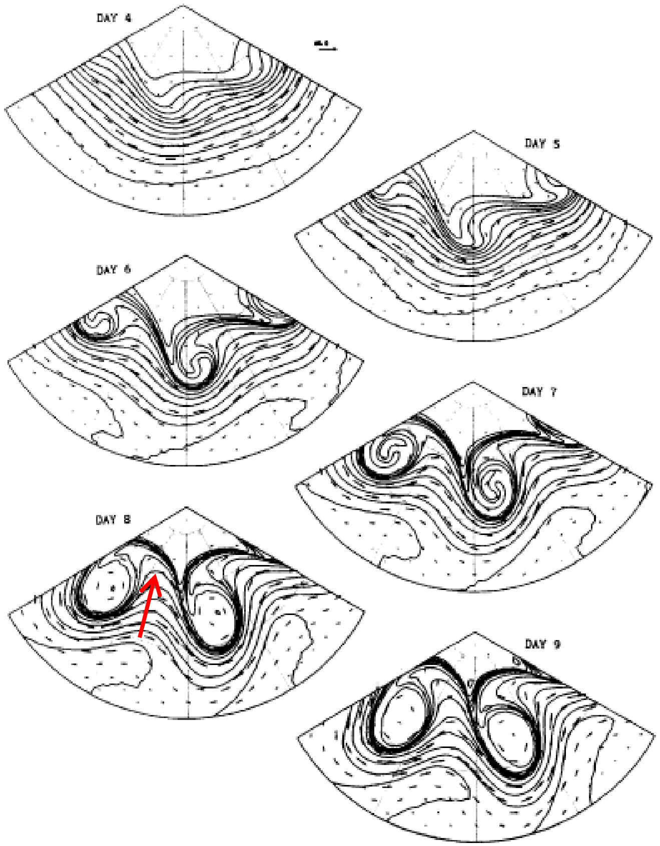
Q. J. R. Meteorol. Soc. (1993), **119**, pp. 17–55

551.511.32

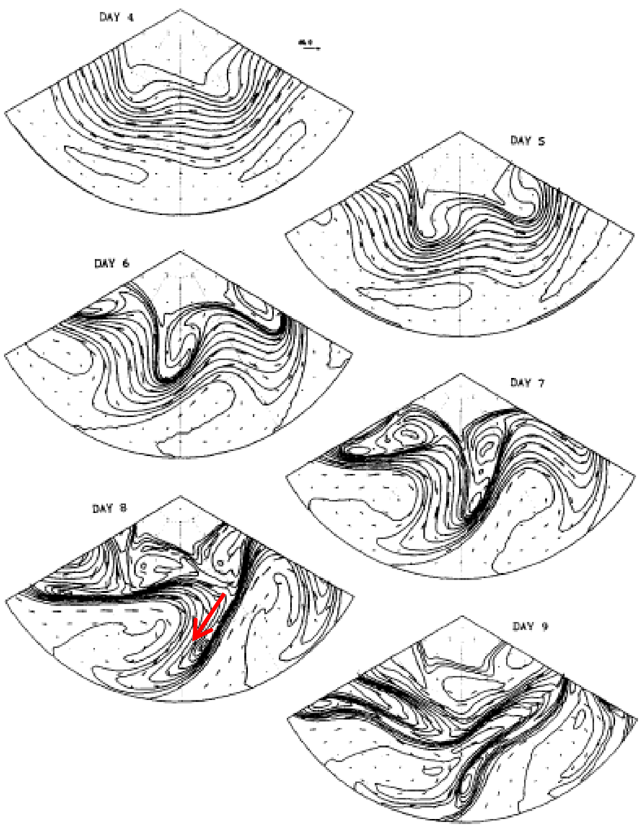
Two paradigms of baroclinic-wave life-cycle behaviour

By C. D. THORNCROFT[1*], B. J. HOSKINS[1] and M. E. McINTYRE[2]
[1]*Department of Meteorology, University of Reading*
[2]*Department of Applied Mathematics and Theoretical Physics, University of Cambridge*

LC2 poleward breaking

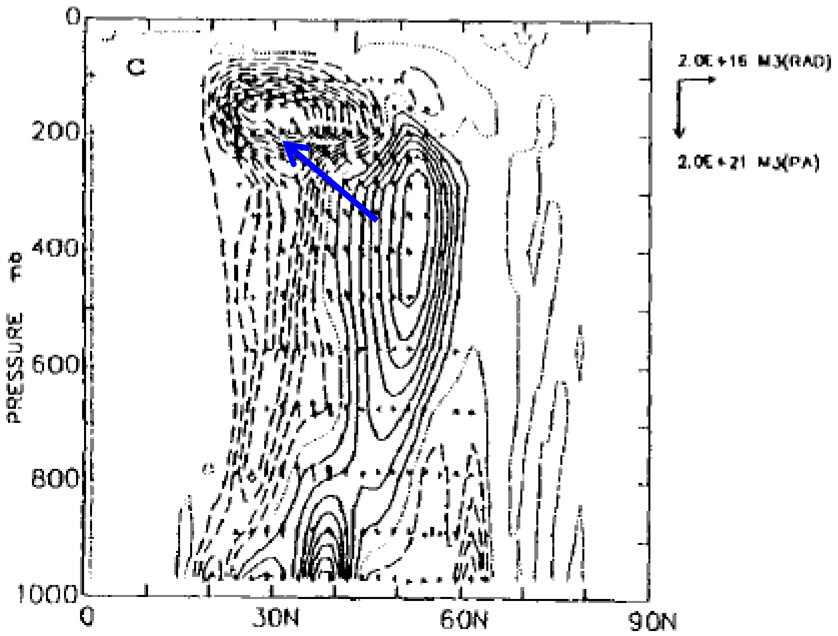


LC1 equatorward breaking

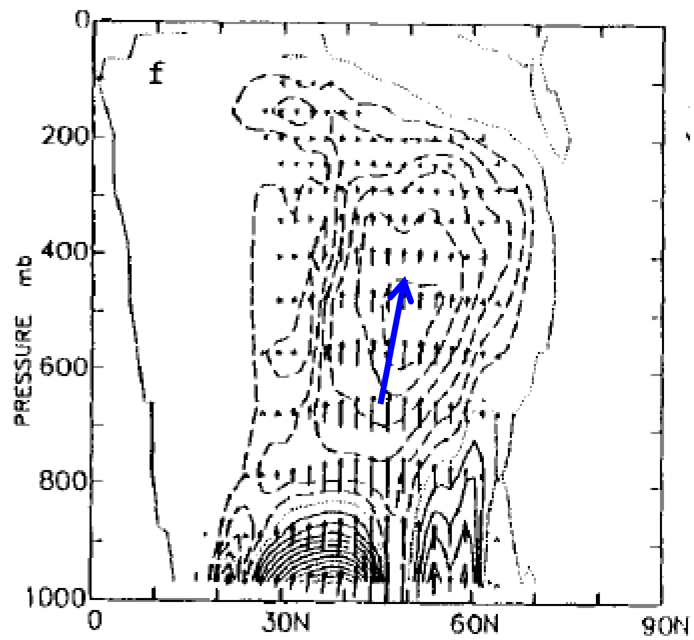


Idealized baroclinic wave life cycles

equatorward propagation (LC1)

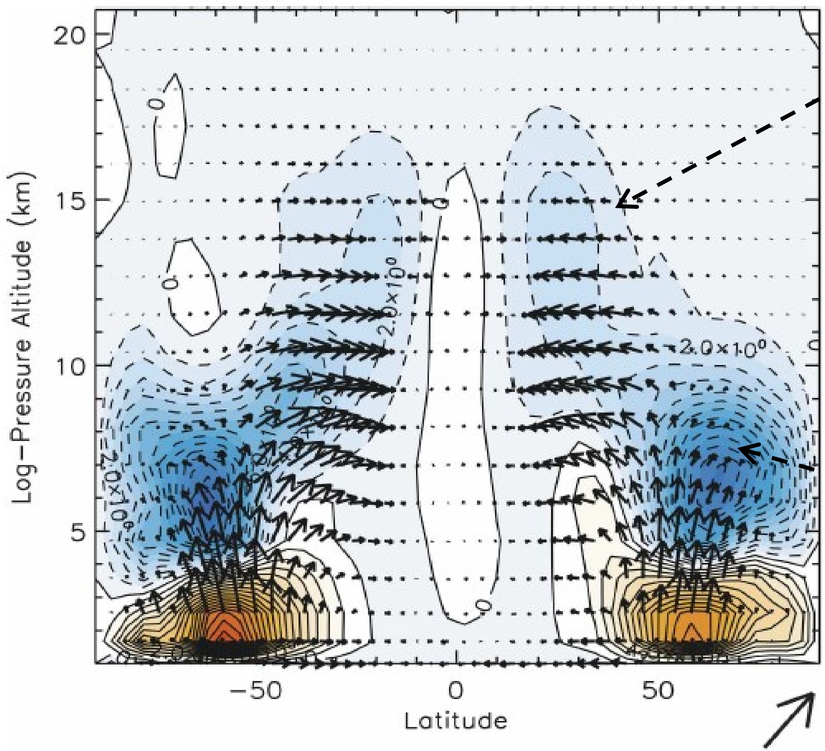


poleward propagation (LC2)



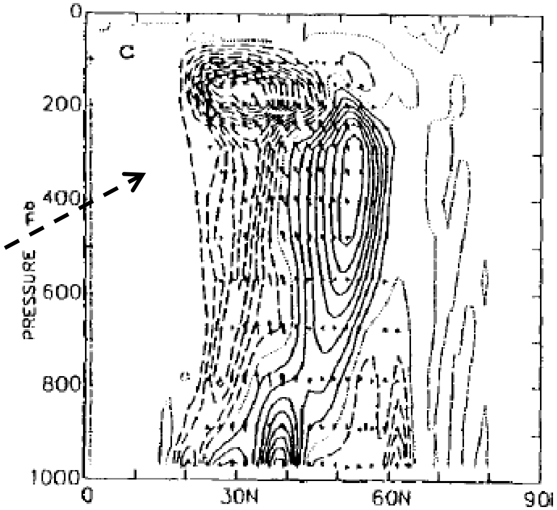
Thorncroft et al., 1993, Q.J.R. Meteorol. Soc.

Climatology

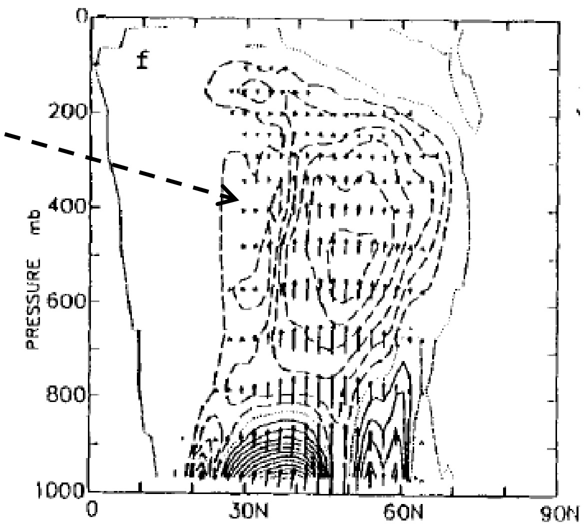


Garcia and Randel, 2008, J. Atmos. Sci.

LC1



LC2



Thorncroft et al., 1993, Q.J.R. Meteorol. Soc.

Using phase speed spectra to diagnose critical layer interactions

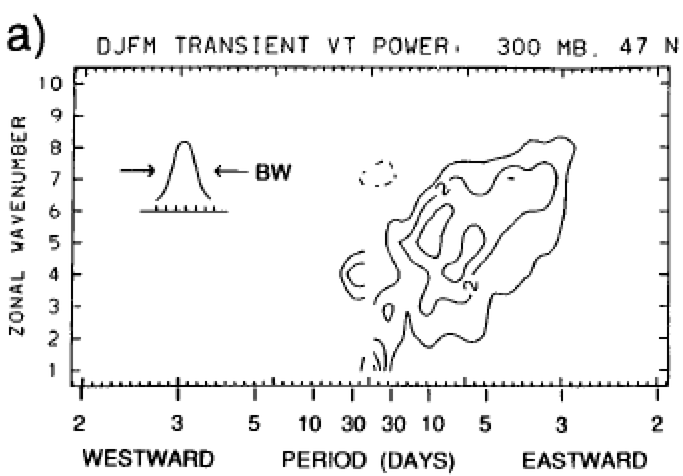
wave flux
co-spectra as a function
of zonal wavenumber
and phase speed

$$K_{n,c} = K_{k,\omega} \cdot \left(\frac{n}{a \cos\phi} \right).$$

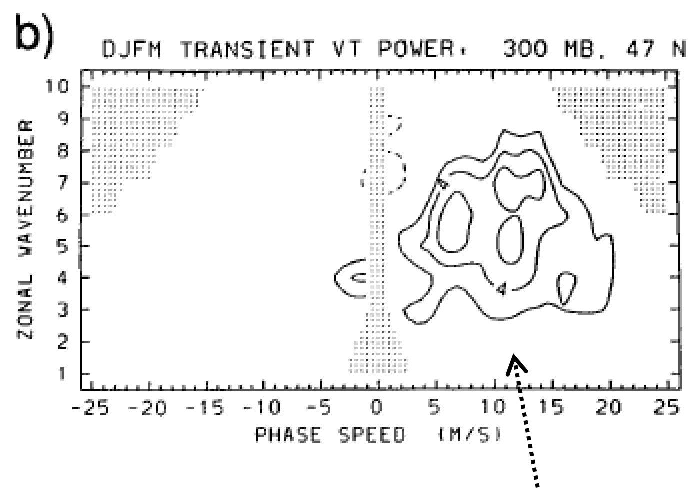
traditional
wavenumber vs.
frequency

Randel and Held 1991

wavenumber vs. frequency



wavenumber vs. phase speed

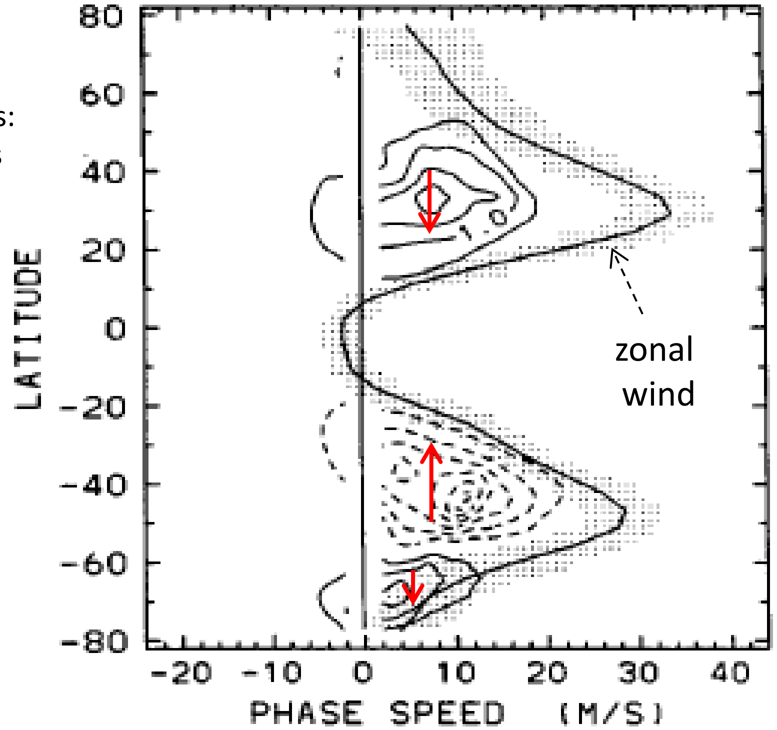


Rossby waves move eastward
at ~5-15 m/s

Integrate over wavenumber to derive eddy flux phase speed spectra

eddy momentum flux u'v' 300 hPa

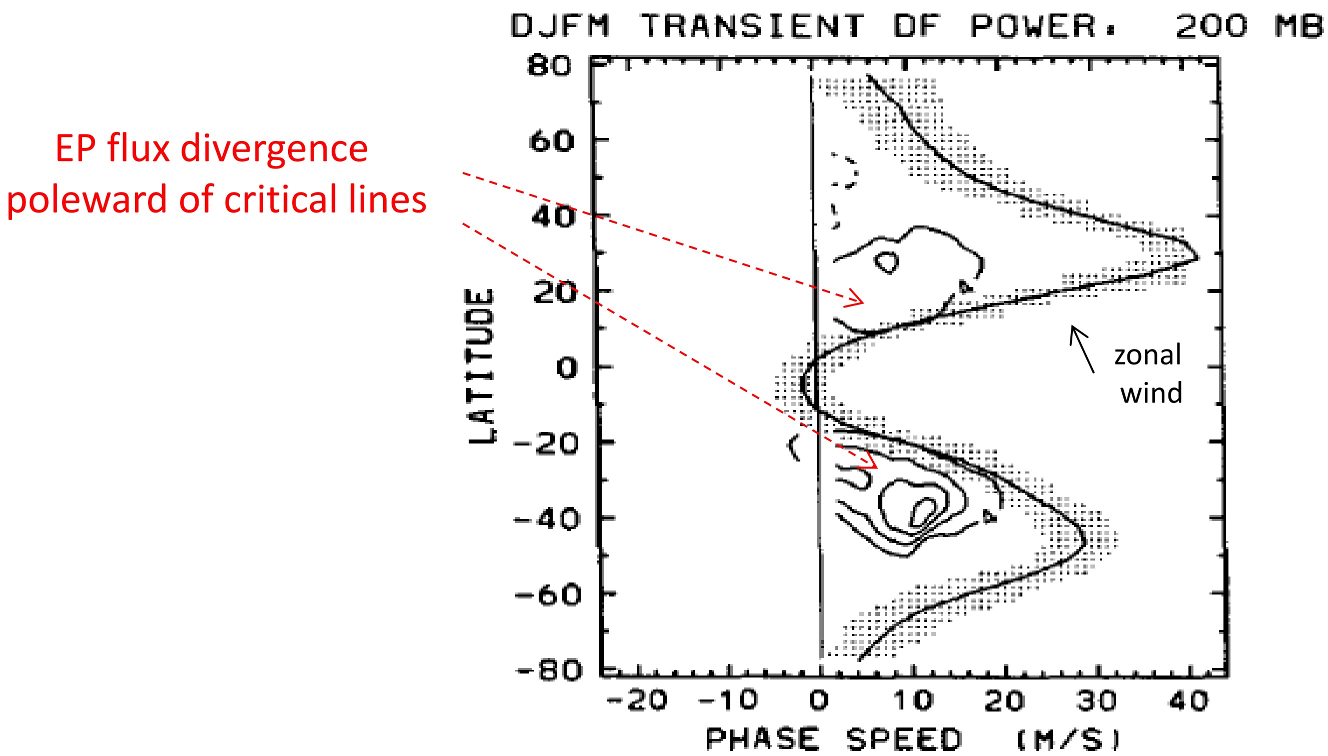
red arrows:
EP fluxes



- EP fluxes: propagation to near critical lines (c = U)
- evidence for critical layer behavior

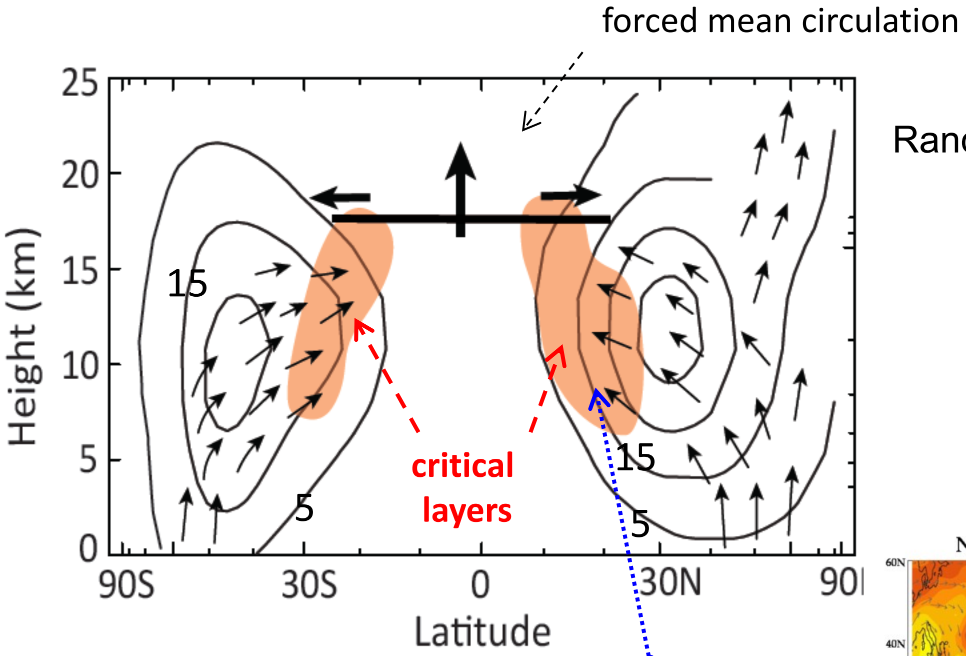
Randel and Held 1991

EP flux divergence phase speed spectra

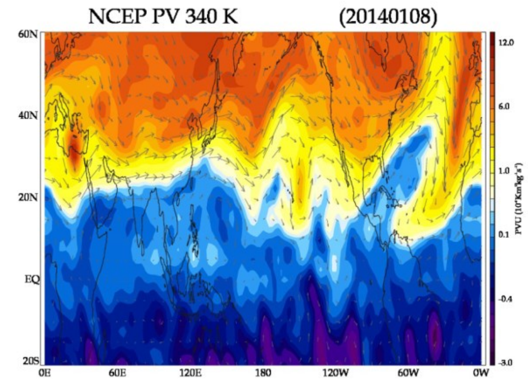


Randel and Held 1991

Subtropical critical layers for Rossby waves with phase speeds ~ 5-15 m/s



Randel and Jensen, 2013, Nat. Geosci.



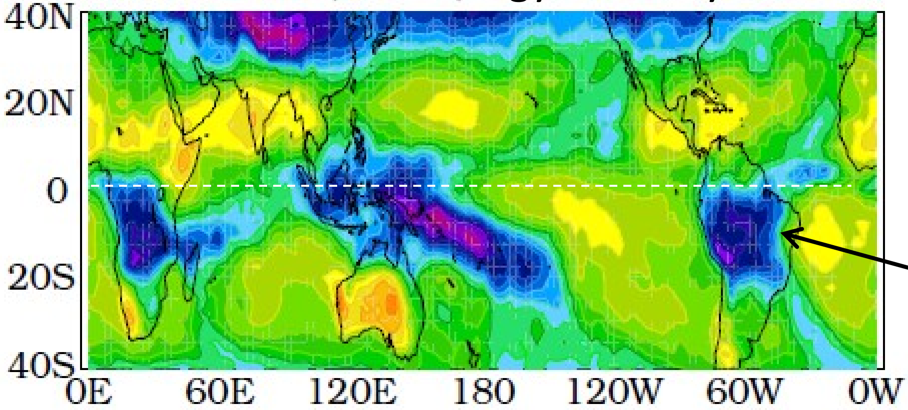
Key points:

- Baroclinic wave life cycles: baroclinic growth and barotropic decay
- Two idealized types of life cycles: equatorward and poleward wave breaking
  (LC1 and LC2)
- Consistent with tropospheric EP flux circulation statistics
- Phase speed spectra: clear evidence for critical layers in subtropics
  (important influence of extratropical waves on tropical circulations)

Large-scale tropical circulations are forced by latent heating from deep convection

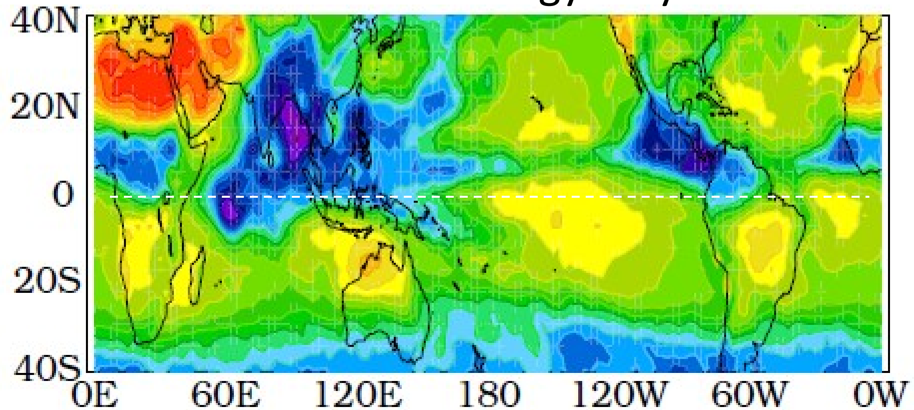
Outgoing Longwave Radiation (OLR) is a useful proxy for deep convection

OLR climatology January

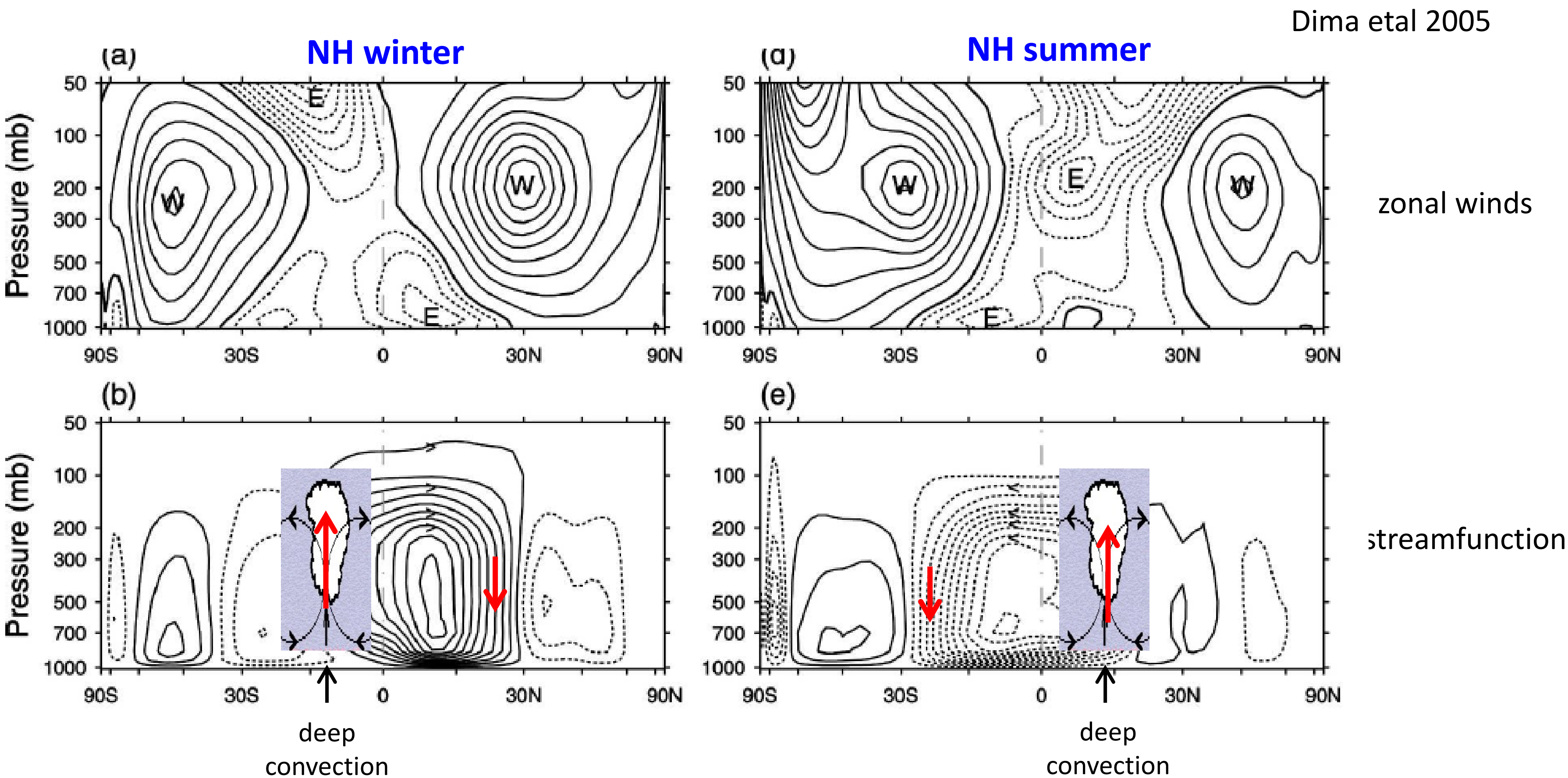


high clouds ~ deep convection

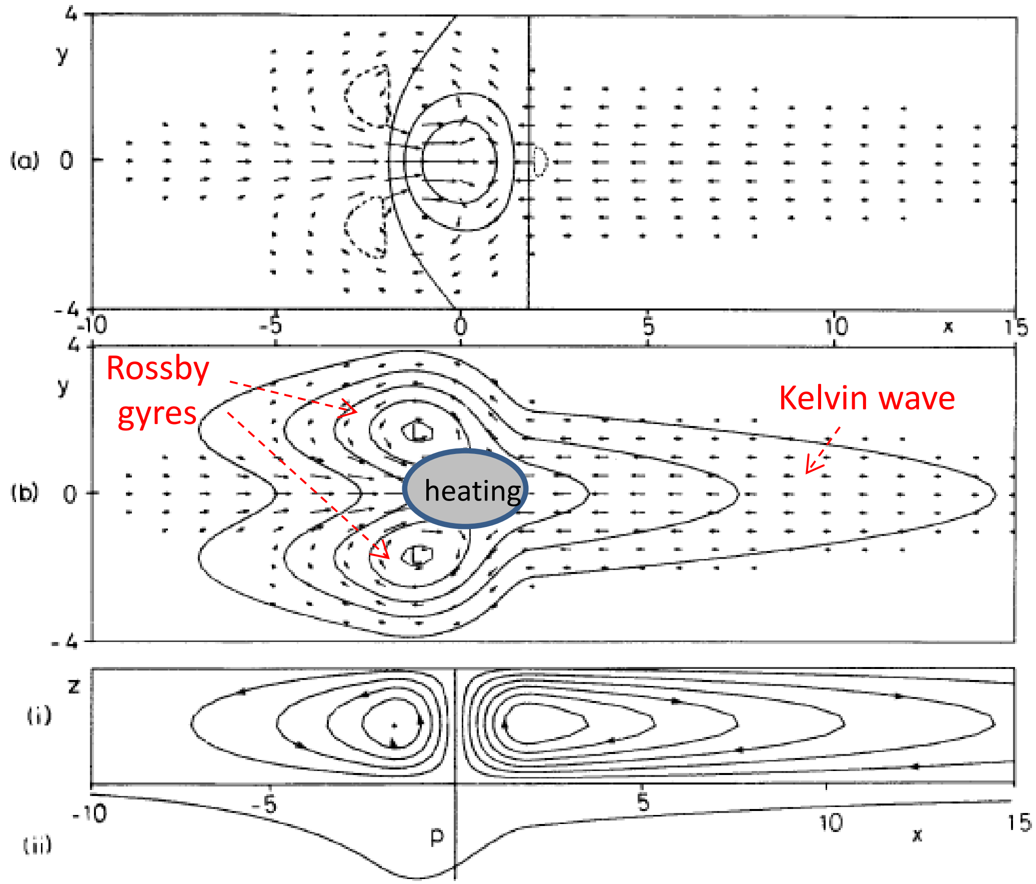
OLR climatology July



Seasonal variations in tropical overturning circulation (Hadley cell)



Dynamical response to low frequency convective forcing



low level convergence

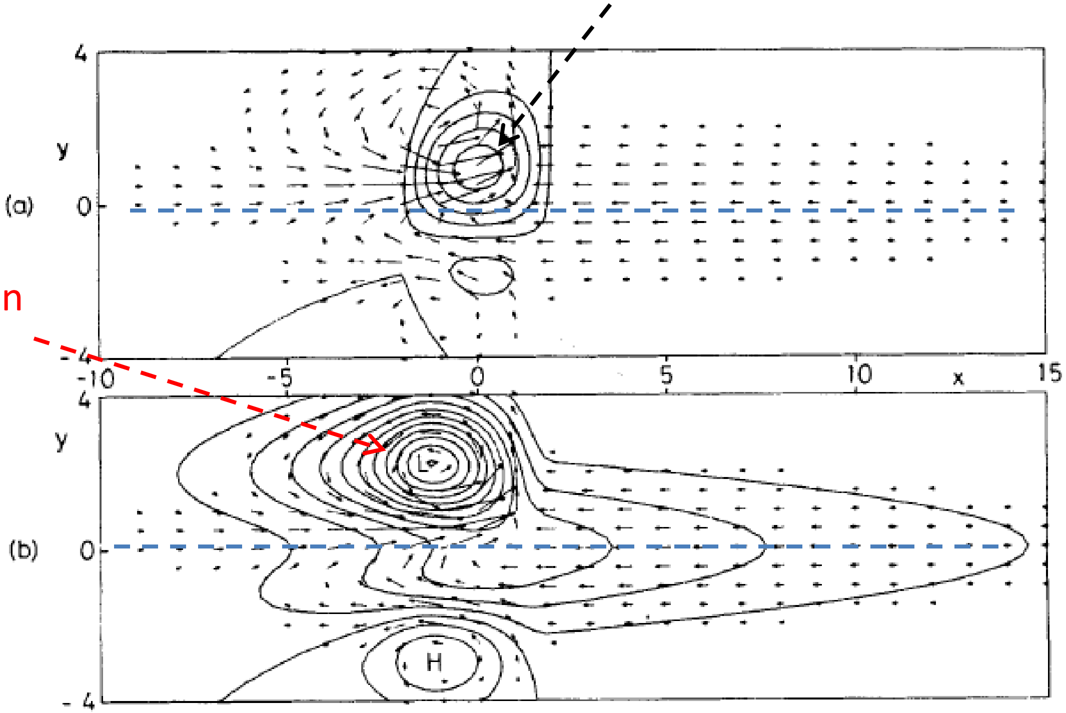
low level circulation

vertical structure

Gill, 1980

Dynamical response to heating centered north of equator

heating north of equator



stronger circulation close to heating

low level convergence

low level circulation

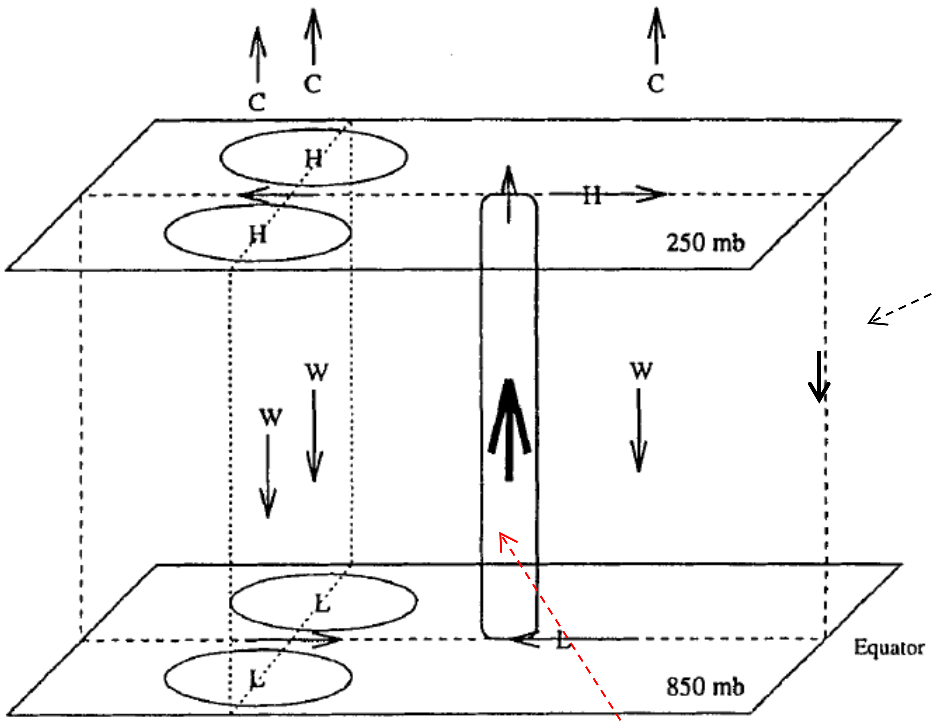
Gill, 1980

The tropical tropopause

By E. J. HIGHWOOD* and B. J. HOSKINS
University of Reading, UK

QJRMS 1998

<u>vertical structure</u>: out of phase between lower troposphere and upper troposphere



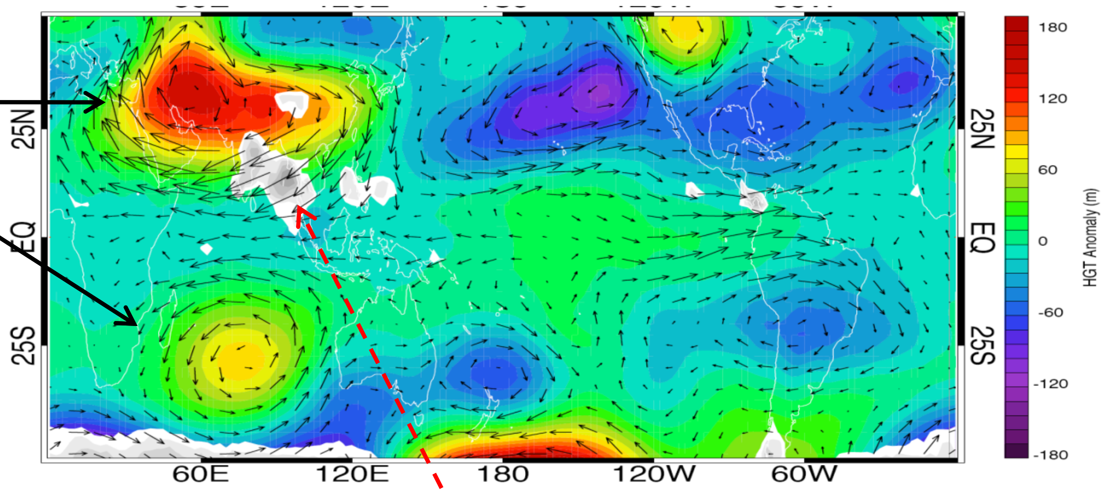
Walker circulation (east-west)

deep convection / heating

Tropical heating produces subtropical anticyclones in the UTLS

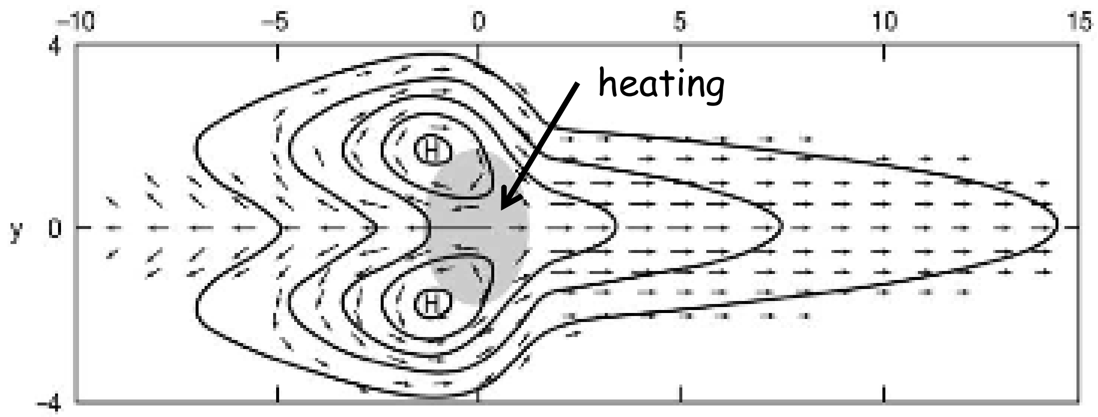
JJA geopotential height and winds 100 hPa

anticyclones



Convection (heating)

Park et al 2007



Matsuno-Gill Solution

Key points:

- Organized deep convection (latent heating) drives large-scale tropical circulations
- Seasonal movement between solstices (SH – NH subtropics)
- Hadley and Walker overturning circulations
- Matsuno-Gill dynamical response to local heating: subtropical Rossby waves and equatorial Kelvin waves
- Subtropical anticyclones in UTLS (especially Asian monsoon during NH summer)

The Quasi-Biennial Oscillation (QBO) and El Nino Southern Oscillation (ENSO) are important modes of circulation in the stratosphere, troposphere and UTLS

- QBO: approximate 28-month oscillation in tropical stratosphere, forced by vertically propagating waves interacting with mean flow

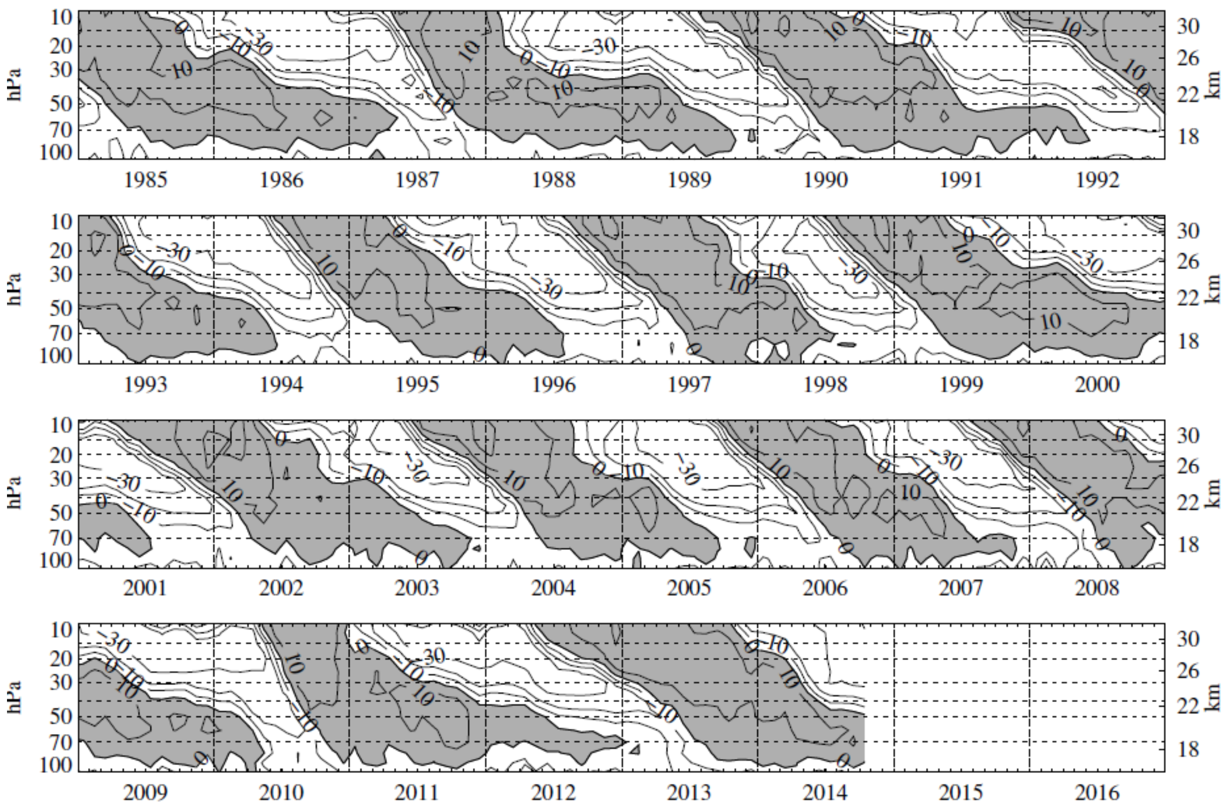
- ENSO: ~2-6 year time scale oscillations of convection, oceanic and atmospheric circulations. Wave effects extend into high latitudes and into tropical lower stratosphere.

- Both QBO and ENSO influence temperature, circulation and transport in UTLS

Brief observational characteristics of QBO

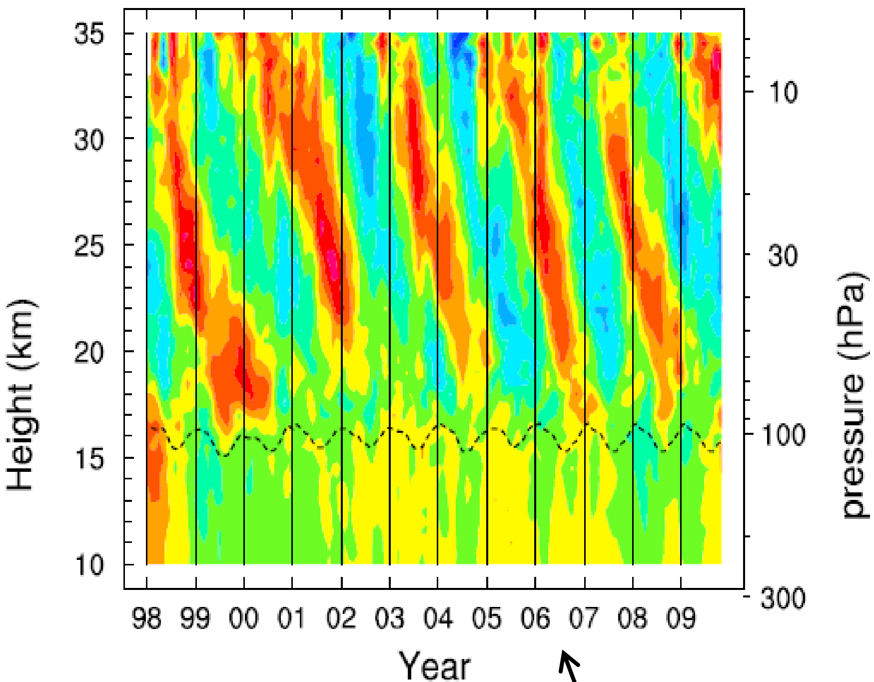
easterly descent is regular;
sometimes the westerly phase 'stalls'

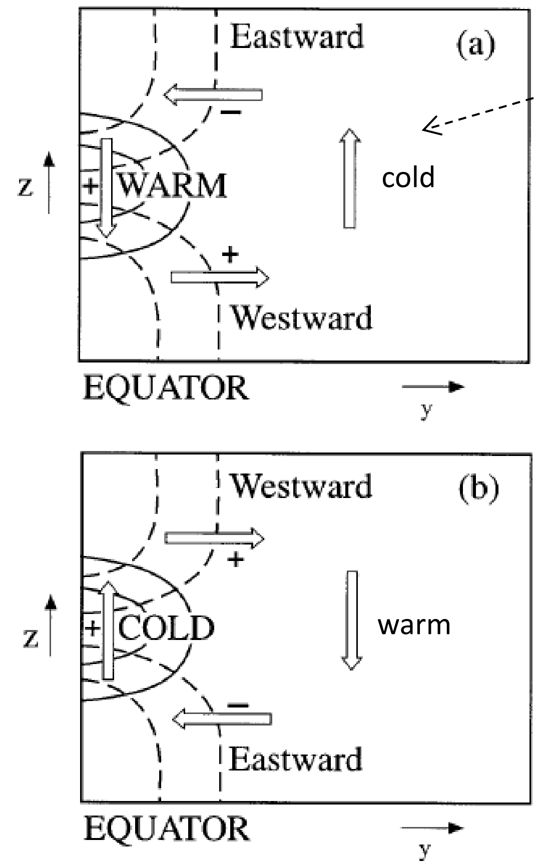
Zonal winds at Singapore (1° N) - standard QBO reference



Meridional circulations and temperatures linked with the QBO

equatorial temp anomalies





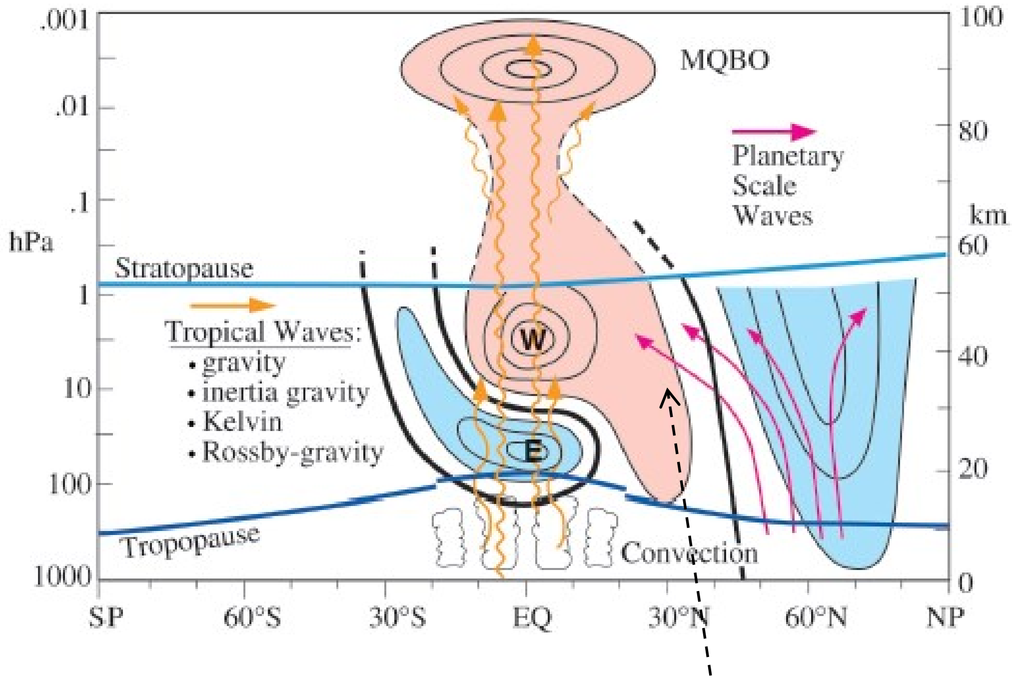
extension to middle latitudes

- temp anomalies at equator up to +/- 4 K
- extend downward to near tropopause

Plumb and Bell, 1982b, Q.J.R. Meteorol. Soc.

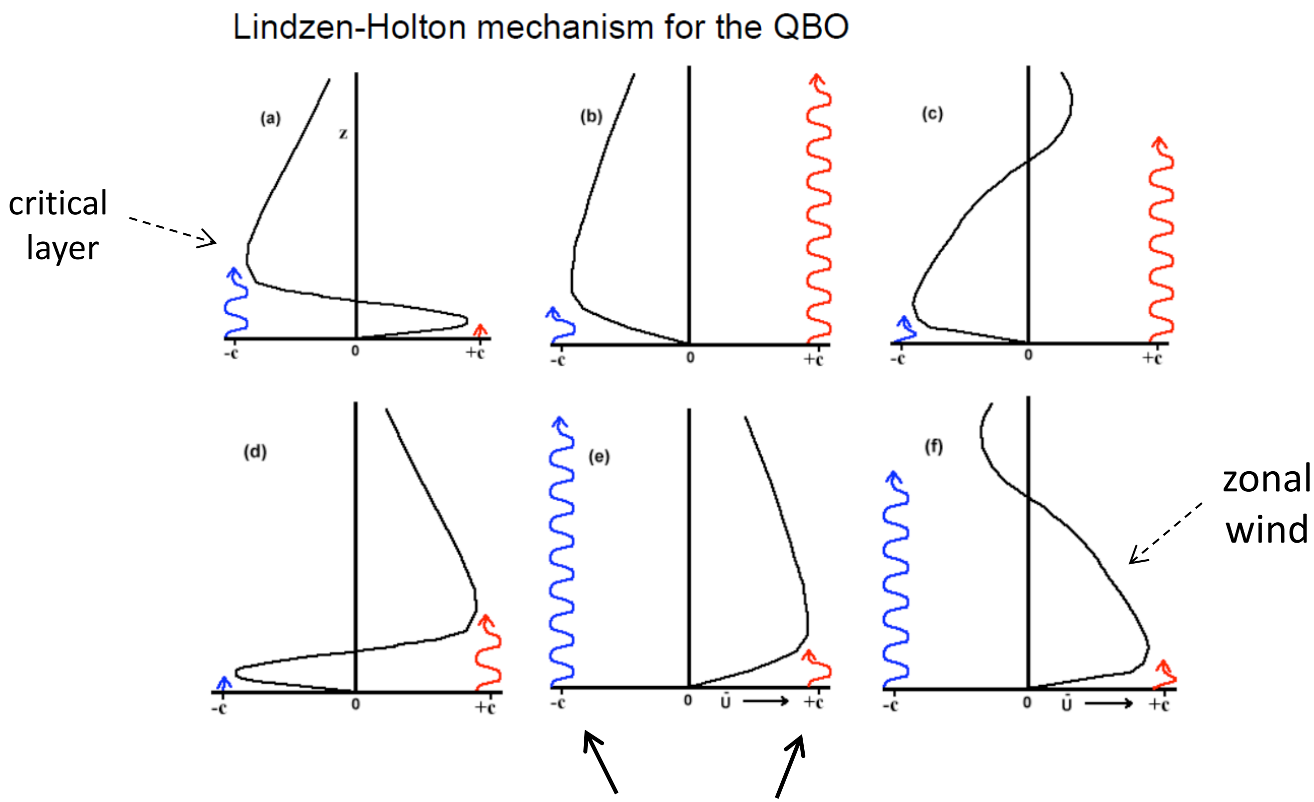
Meridional structure and global influences of the QBO

Baldwin et al 1998



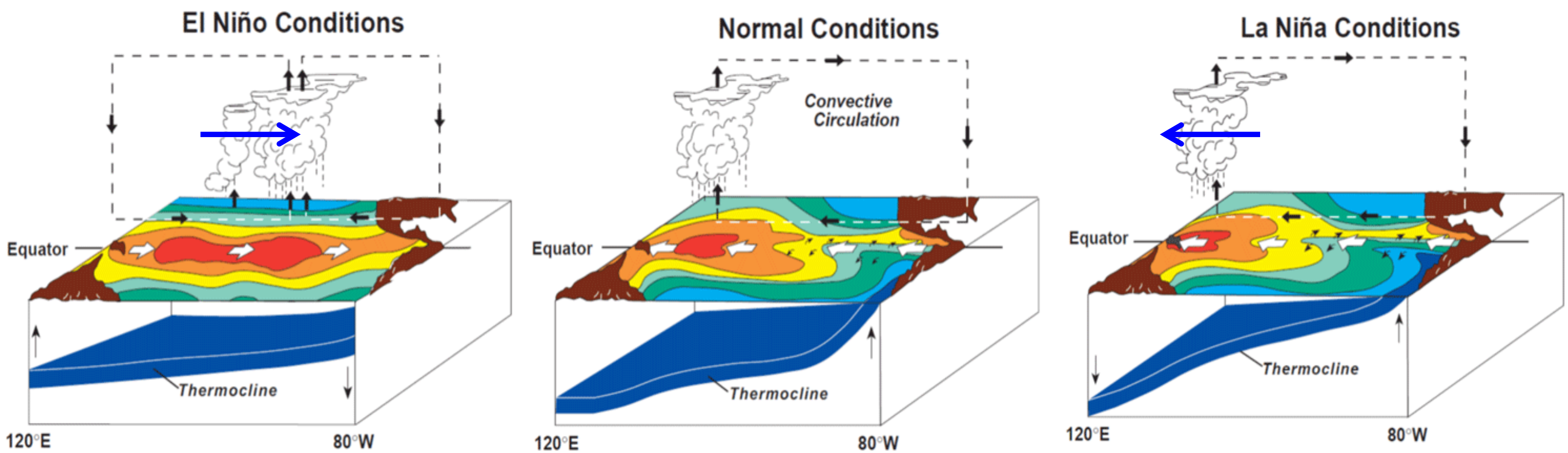
influence on high latitudes
via subtropical critical lines

- waves propagate vertically until reaching critical level (U=c)
- wave absorption produces zonal acceleration (towards phase speed of wave)

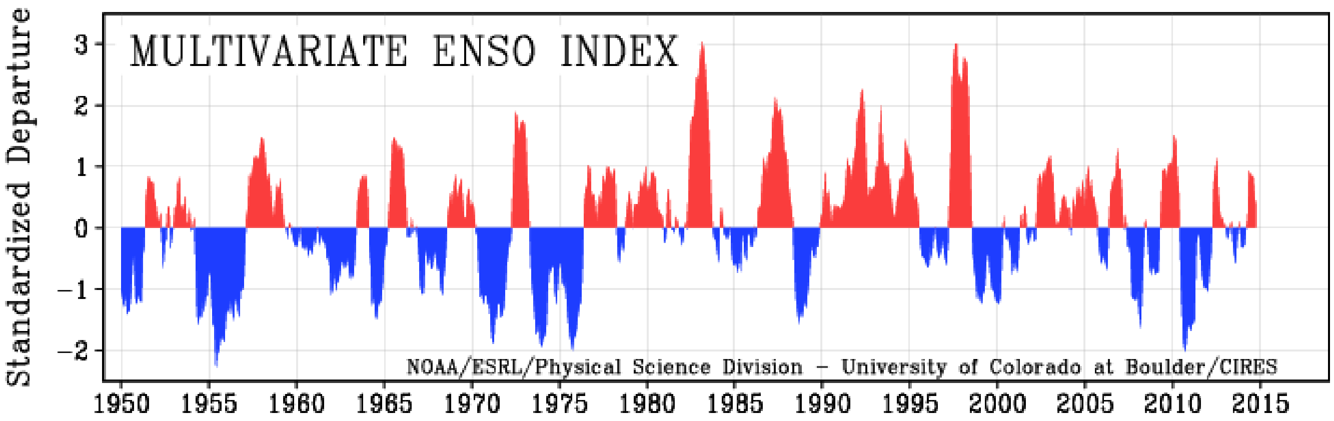


eastward and westward propagating waves forced from troposphere

ENSO – large-scale shifts in tropical convection, winds, temperatures



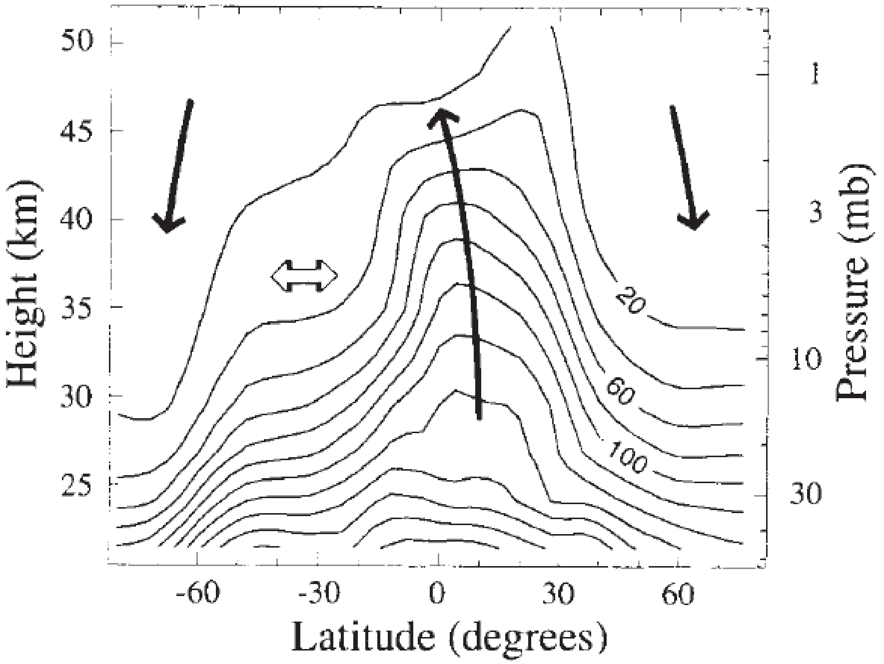
Standard time series for ENSO



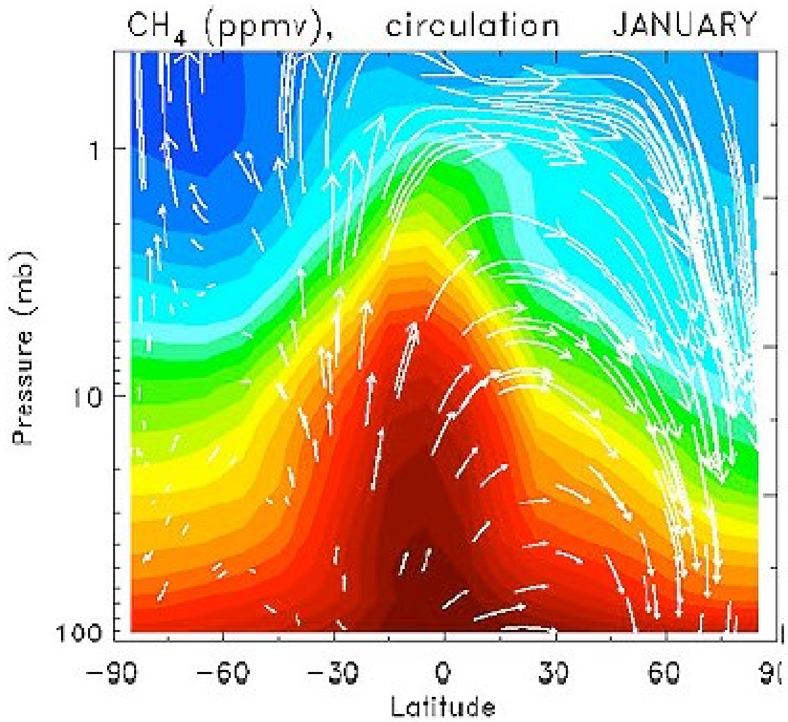
Stratospheric tracer transport: evidence from satellite observations

- N_2O is a 'tropospheric source gas'
- destroyed by photolysis (radiation) in upper stratosphere
- Source of reactive nitrogen (NO, NO2) in upper stratosphere; important for stratospheric ozone
- Behavior reflects Brewer-Dobson circulation and eddy mixing

N_2O mixing ratio



Methane CH_4 is another tropospheric source gas, oxidized to H_2O in upper stratosphere

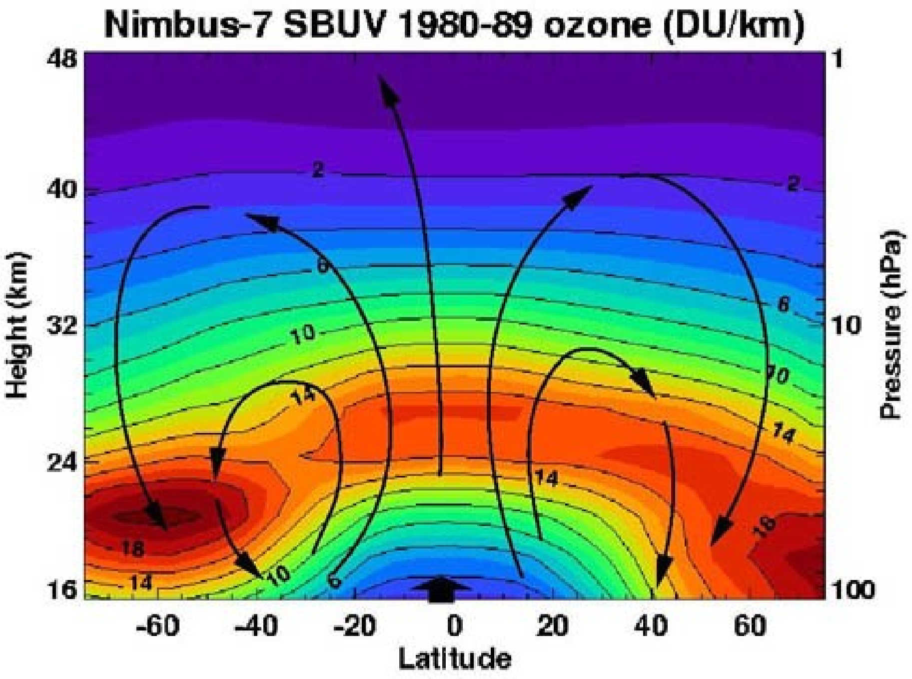


Observed ozone and Brewer-Dobson circulation

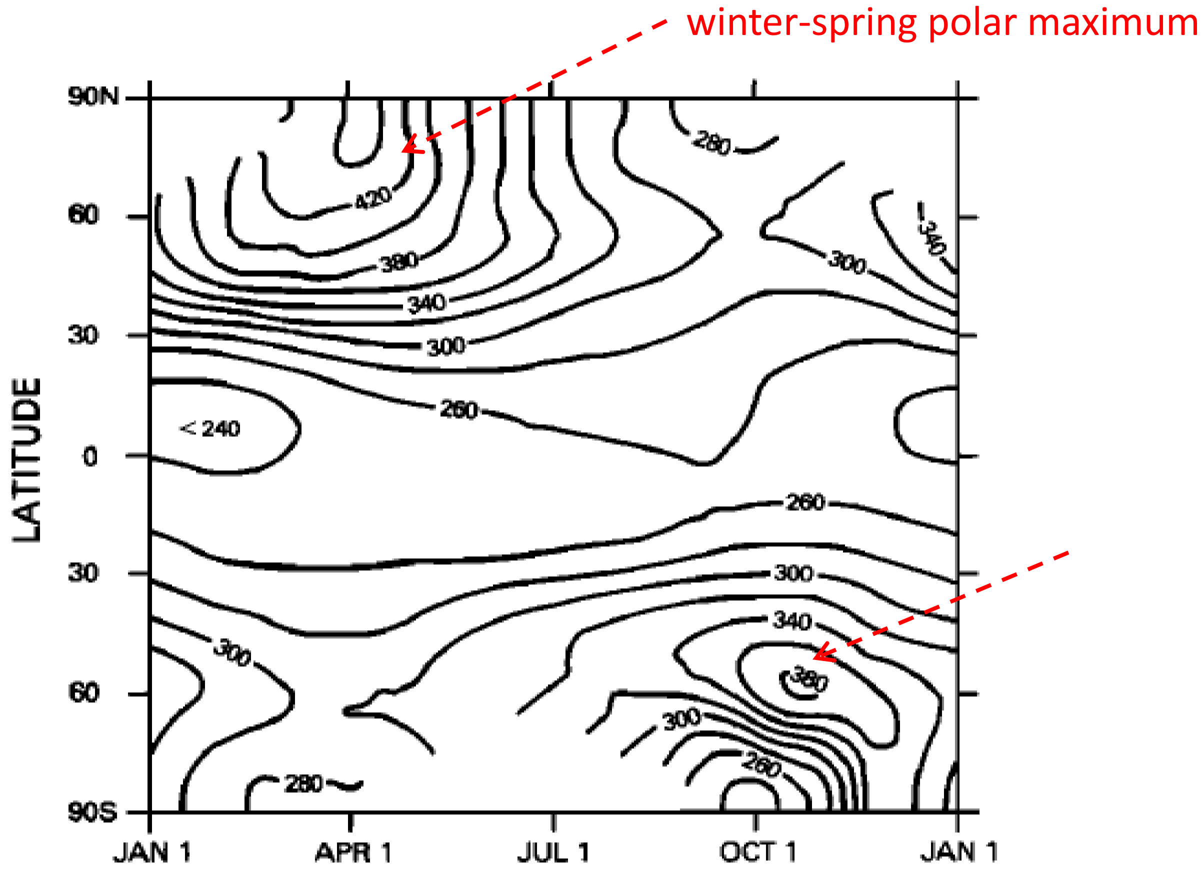
- ozone is made in the tropical stratosphere

- Short lifetime in upper stratosphere
- Long lifetime in lower stratosphere

- transport causes high latitude maximum
  during winter / spring



Seasonal cycle of column ozone reflects Brewer-Dobson circulation



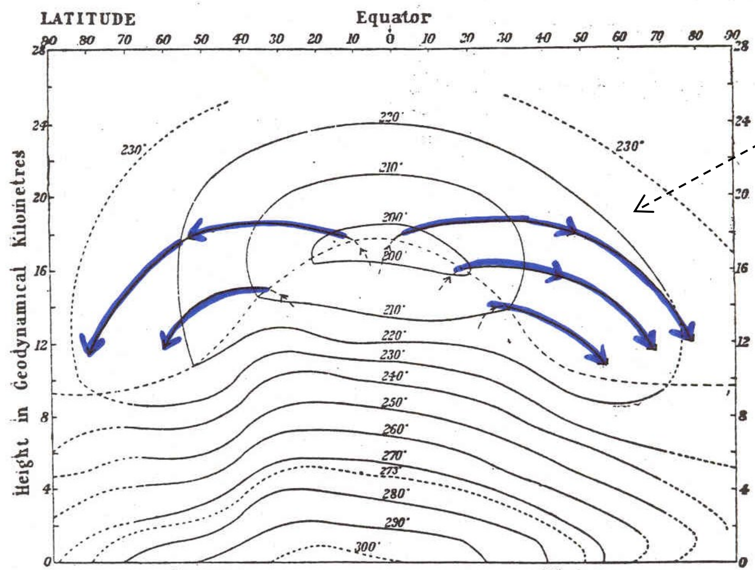
Bowman and Krueger, 1982

QJRMS, 1949

EVIDENCE FOR A WORLD CIRCULATION PROVIDED BY MEASUREMENTS OF HELIUM AND WATER VAPOUR DISTRIBUTION IN THE STRATOSPHERE

By A. W. BREWER, M.Sc., A.Inst.P.

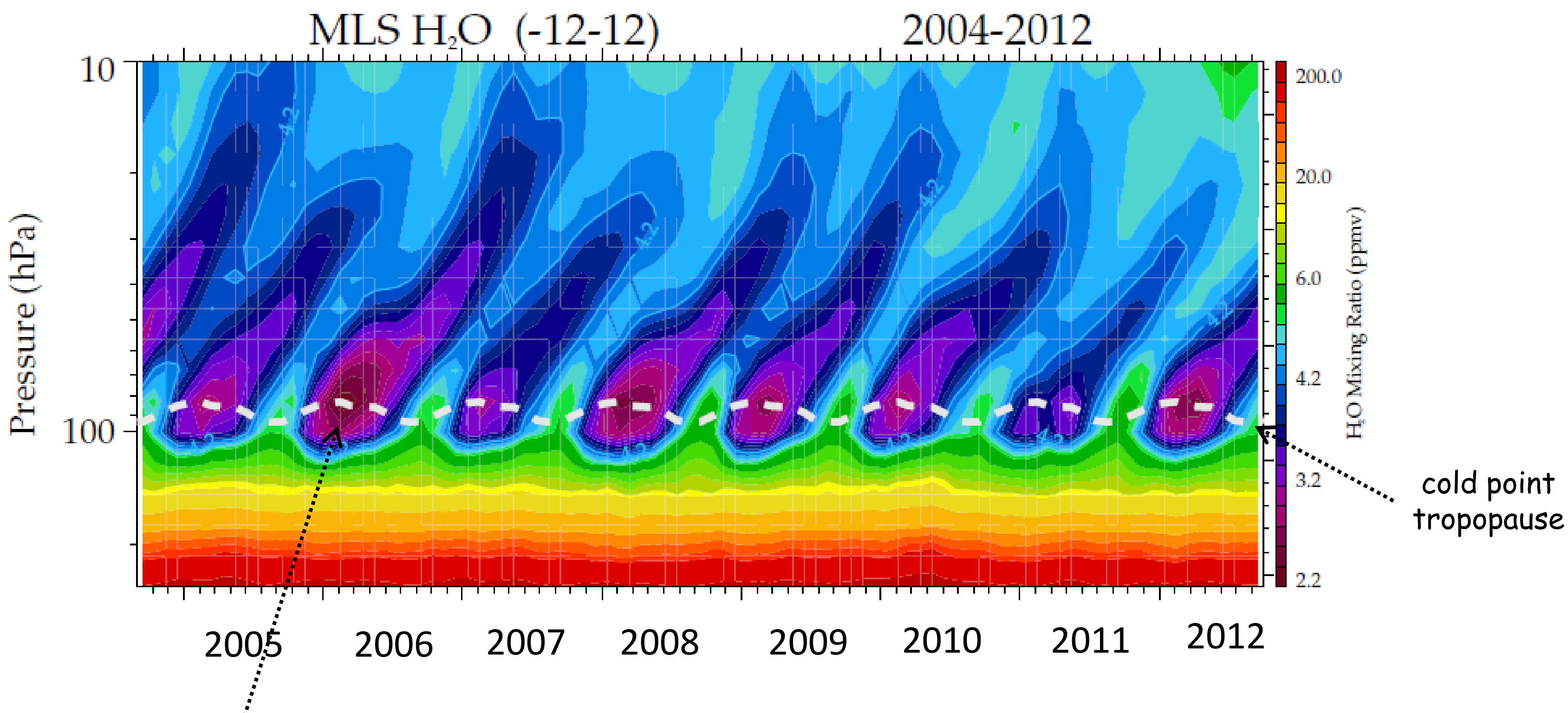
The stratosphere is extremely dry because air is dehydrated passing the cold tropical tropopause



Isotherms over the Globe

FIG. 5. A supply of dry air is maintained by a slow mean circulation from the equatorial tropopause.

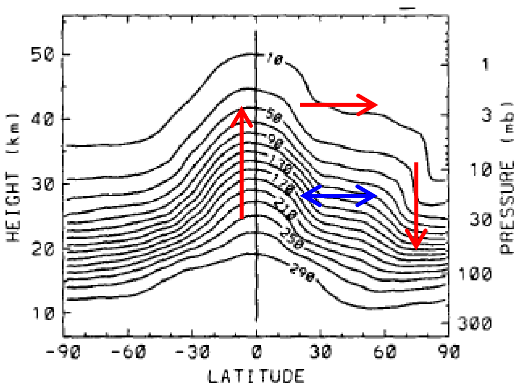
Tropical tape recorder observed by MLS 2004-2012



- annual cycle in tropopause temperature imparts annual cycle in H_2O
- upward propagation with Brewer-Dobson circulation

tracer zonal mean transport budget

model N_2O (ppbv)



mean advection — eddy transport

$$\frac{\partial \overline{\chi}}{\partial t} = -\overline{v}^{*}\frac{1}{a}\frac{\partial \overline{\chi}}{\partial \phi} - \overline{w}^{*}\frac{\partial \overline{\chi}}{\partial z} + \nabla \cdot M + P - L$$

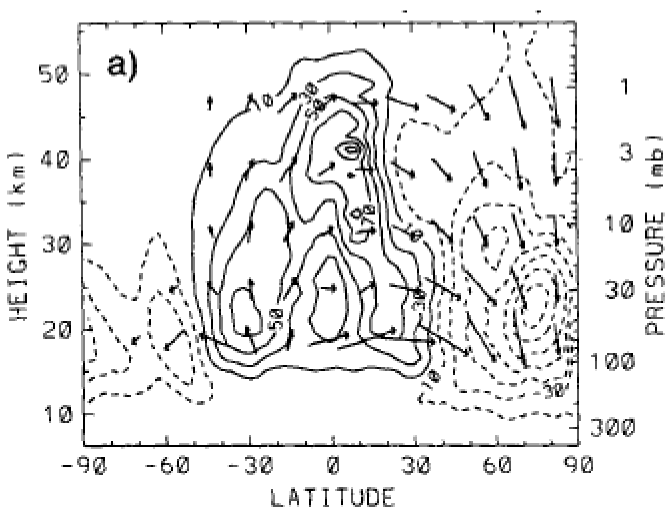
$$M_y = -e^{-z/H}\left(\overline{v'\chi'} - \frac{\overline{v'T'}}{S}\bar{\chi}_z\right)$$

$$M_z = -e^{-z/H}\left(\overline{w'\chi'} + \frac{\overline{v'T'}}{S}\bar{\chi}_y\right)$$

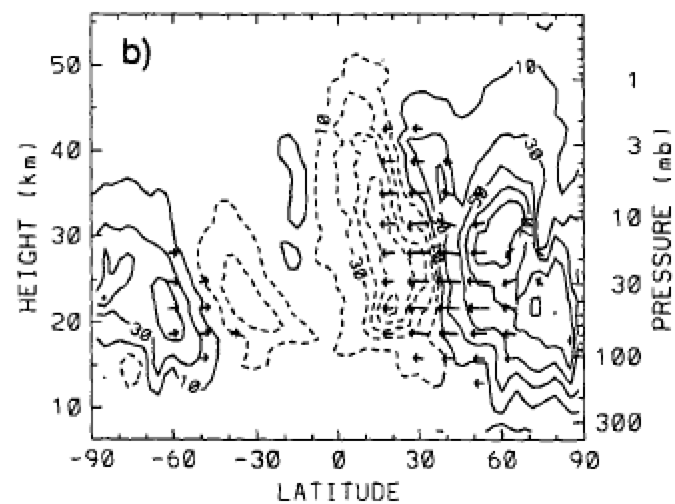
these terms generally balance each other

contours: N_2O tendency (ppbv/100 days)

mean advection



eddy transport



Randel et al 1994

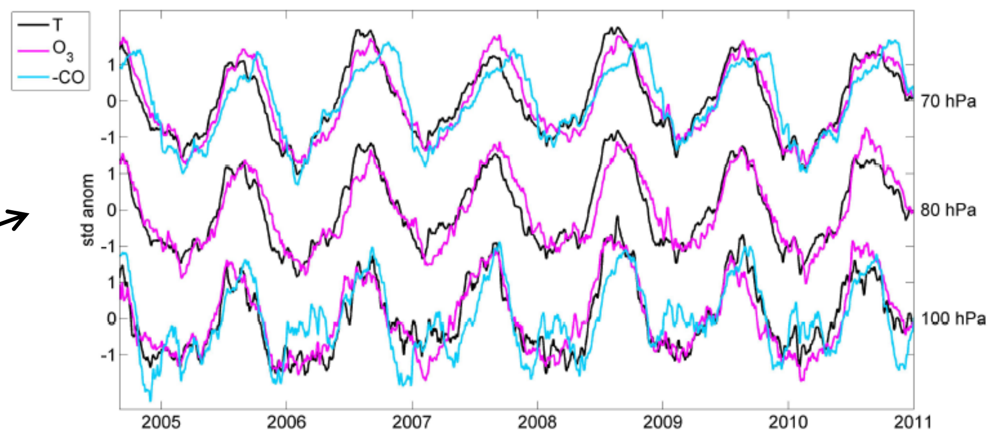
Tracer transport equation similar to thermodynamic equation:

tracer
$$\frac{\partial \overline{\chi}}{\partial t} = -\overline{v}^* \frac{1}{a} \frac{\partial \overline{\chi}}{\partial \phi} - \overline{w}^* \frac{\partial \overline{\chi}}{\partial z} + \nabla \cdot M + P - L$$

temperature
$$\frac{\partial \overline{T}}{\partial t} + \overline{v}^* \frac{1}{a} \frac{\partial \overline{T}}{\partial \phi} + \overline{w}^* S = \overline{Q},$$

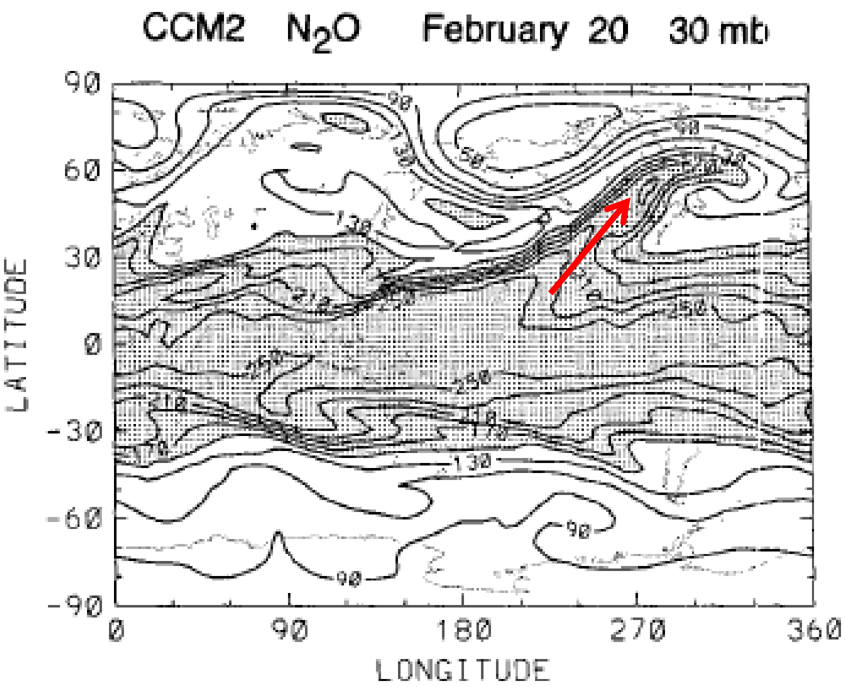
This is why temperature and tracers are sometimes highly correlated:

for example, T, O_3 and CO in tropical stratosphere (Abalos et al 2012)



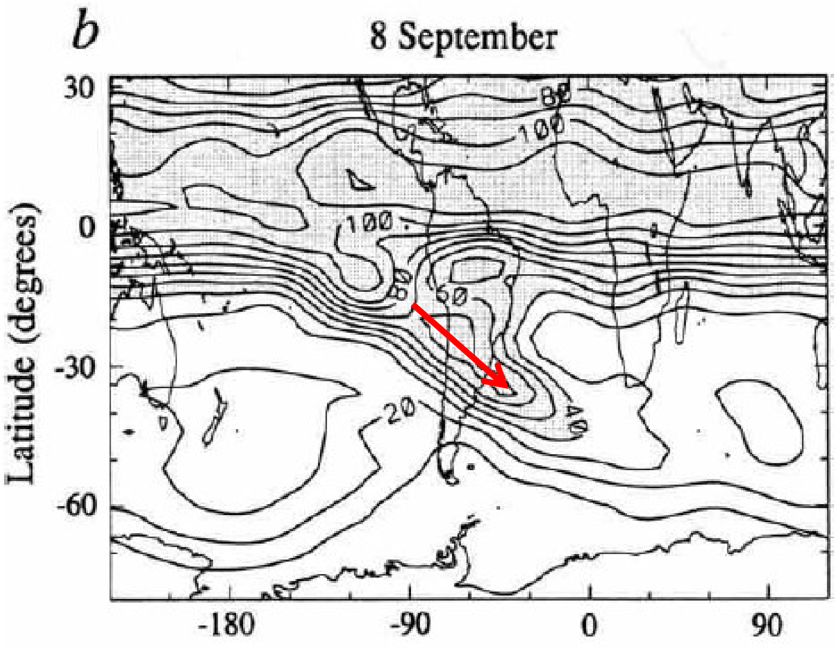
Examples of stratospheric wave mixing

model



N_2O near 35 km from CLAES instrument on UARS

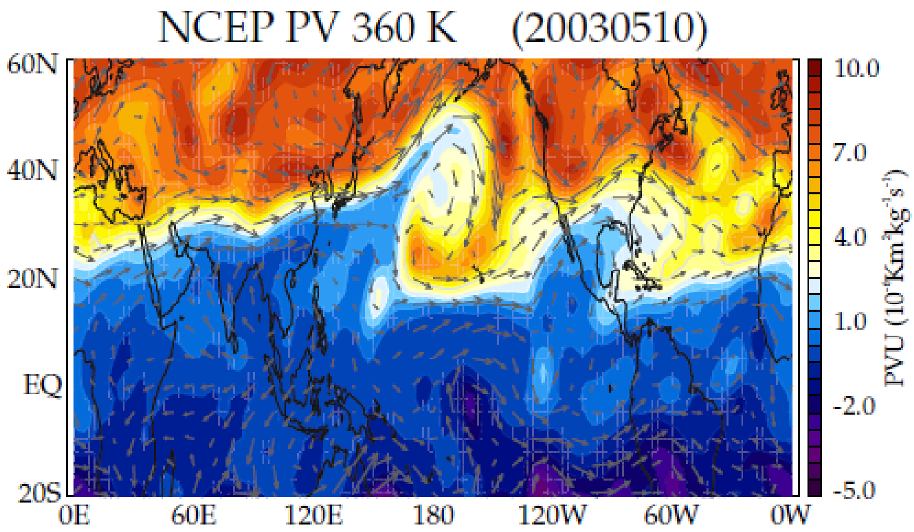
observations



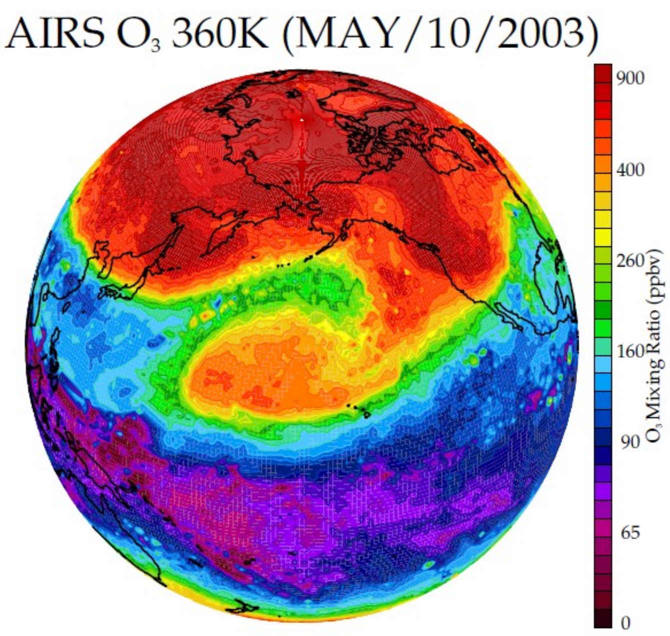
Randel et al 1993

Mixing across tropopause linked to Rossby wave breaking

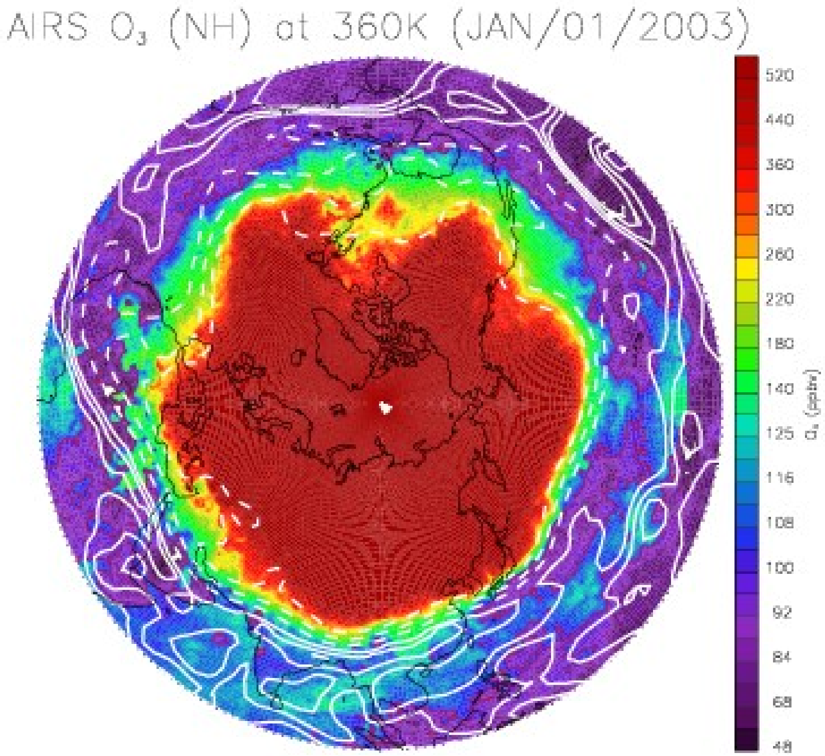
potential vorticity



ozone derived from AIRS



Rossby wave variability reflected in ozone near tropopause

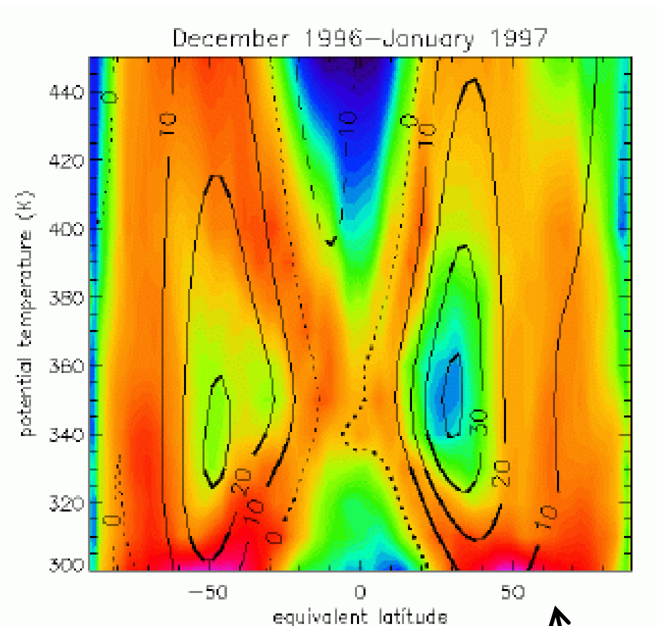


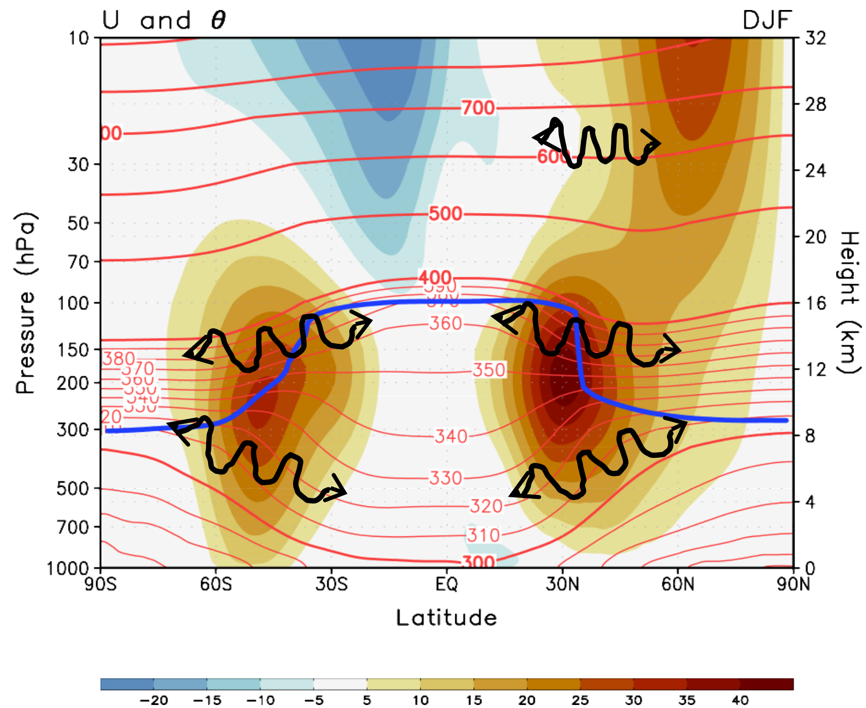
Effective diffusivity as a diagnostic of atmospheric transport
2. Troposphere and lower stratosphere

JGR 2000

Peter Haynes and Emily Shuckburgh

Estimates of mixing based on stretching of PV contours in trajectory calculations





important points:

- mixing on flanks of jet (near critical lines for c ~10 m/s)
- small mixing across jet core (jet cores are mixing barriers)

Key points:

- Stratospheric transport: Brewer-Dobson circulation and wave mixing
  (clear behavior for tropospheric source gases)

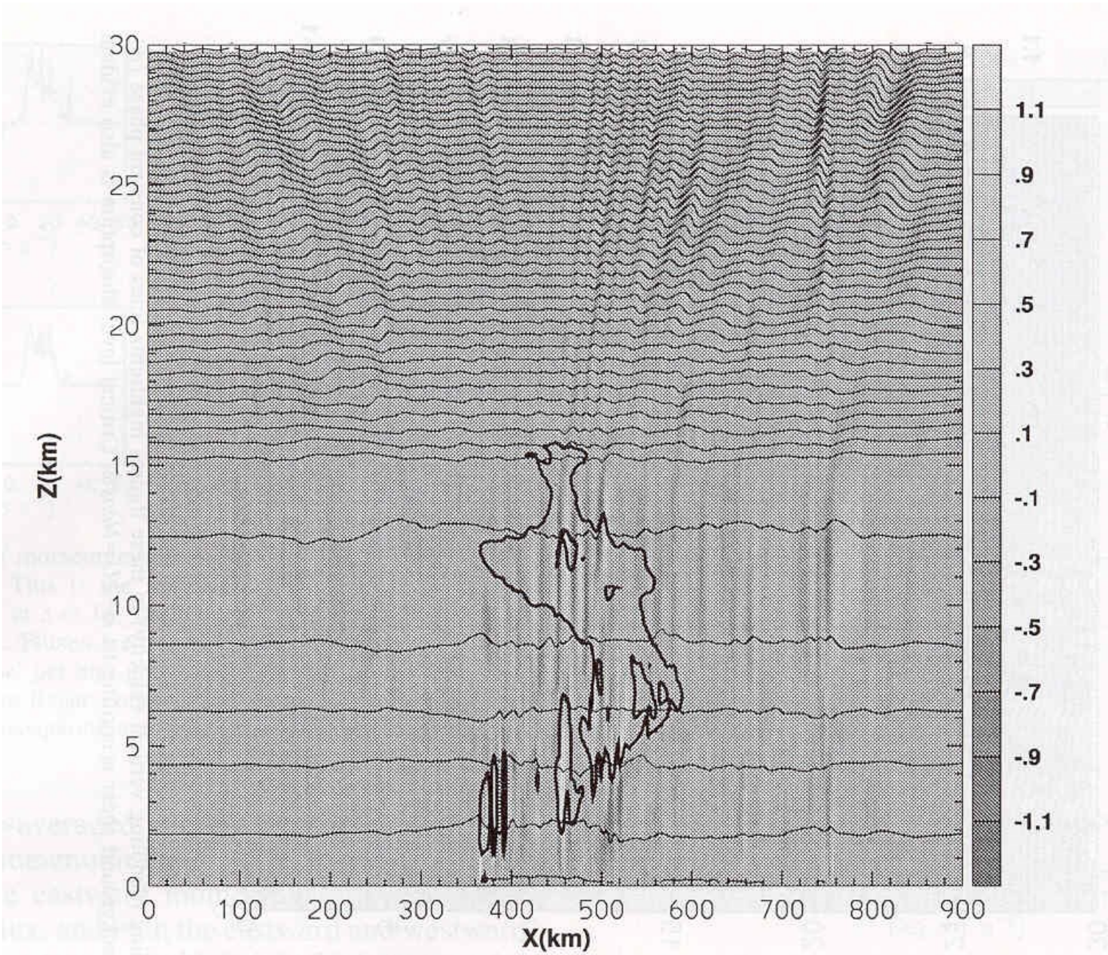
- Stratrospheric ozone: produced in tropical stratosphere, transported to
  high latitudes (reflects seasonal Brewer-Dobson circulation)

- Stratospheric water vapor: dehydration near tropical cold point,
  strong seasonal cycle (‘tape recorder’)

- Tracer budgets: mean advection and eddy transports (tied to Rossby waves
  and critical layers)

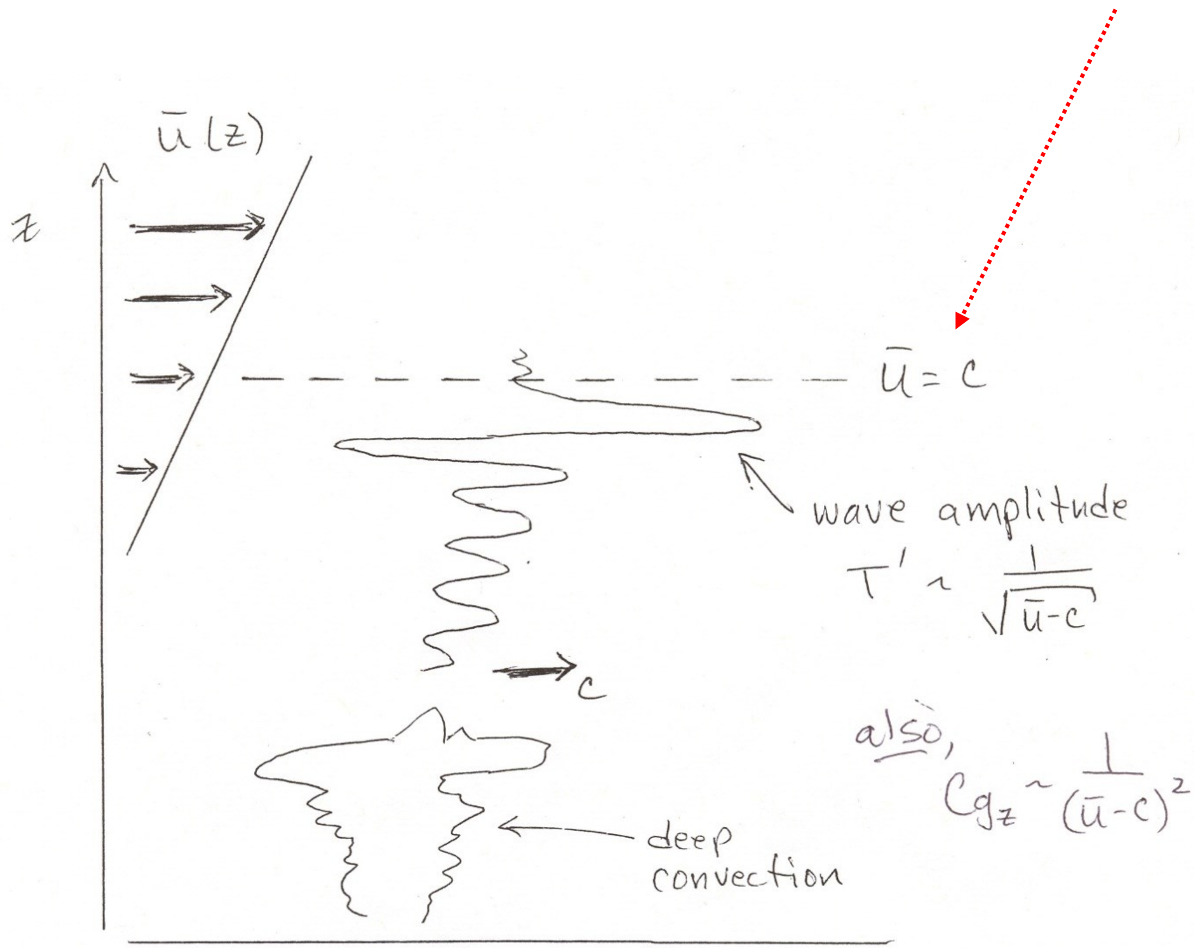
Extra slides

Model simulation of gravity waves forced by deep convection

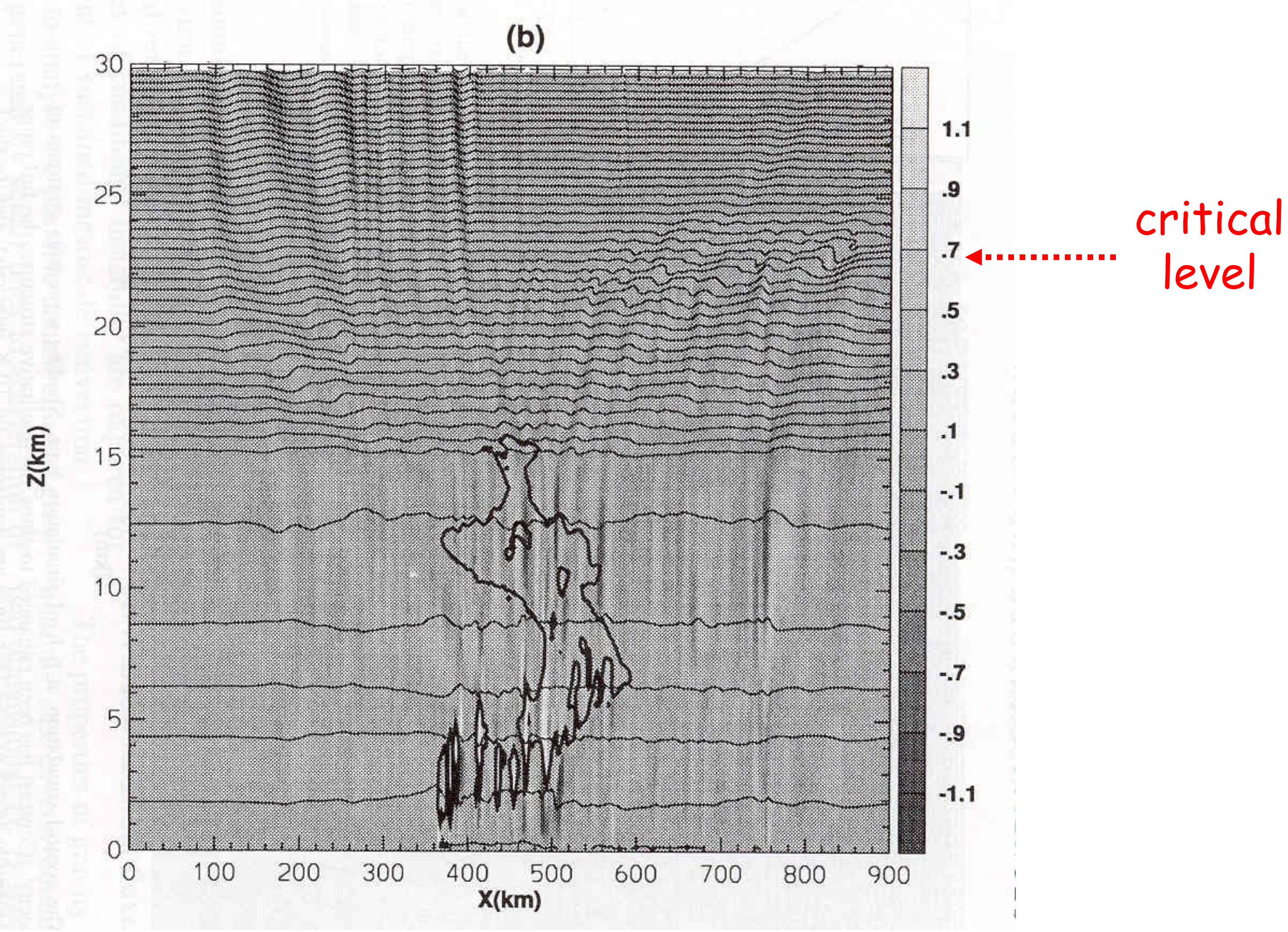


Alexander and Holton, 2000

Gravity waves interacting with a critical level



Gravity waves interacting with a critical level



Alexander and Holton, 2000, J. Atmos. Sci.

Climatology of Intrusions into the Tropical Upper Troposphere

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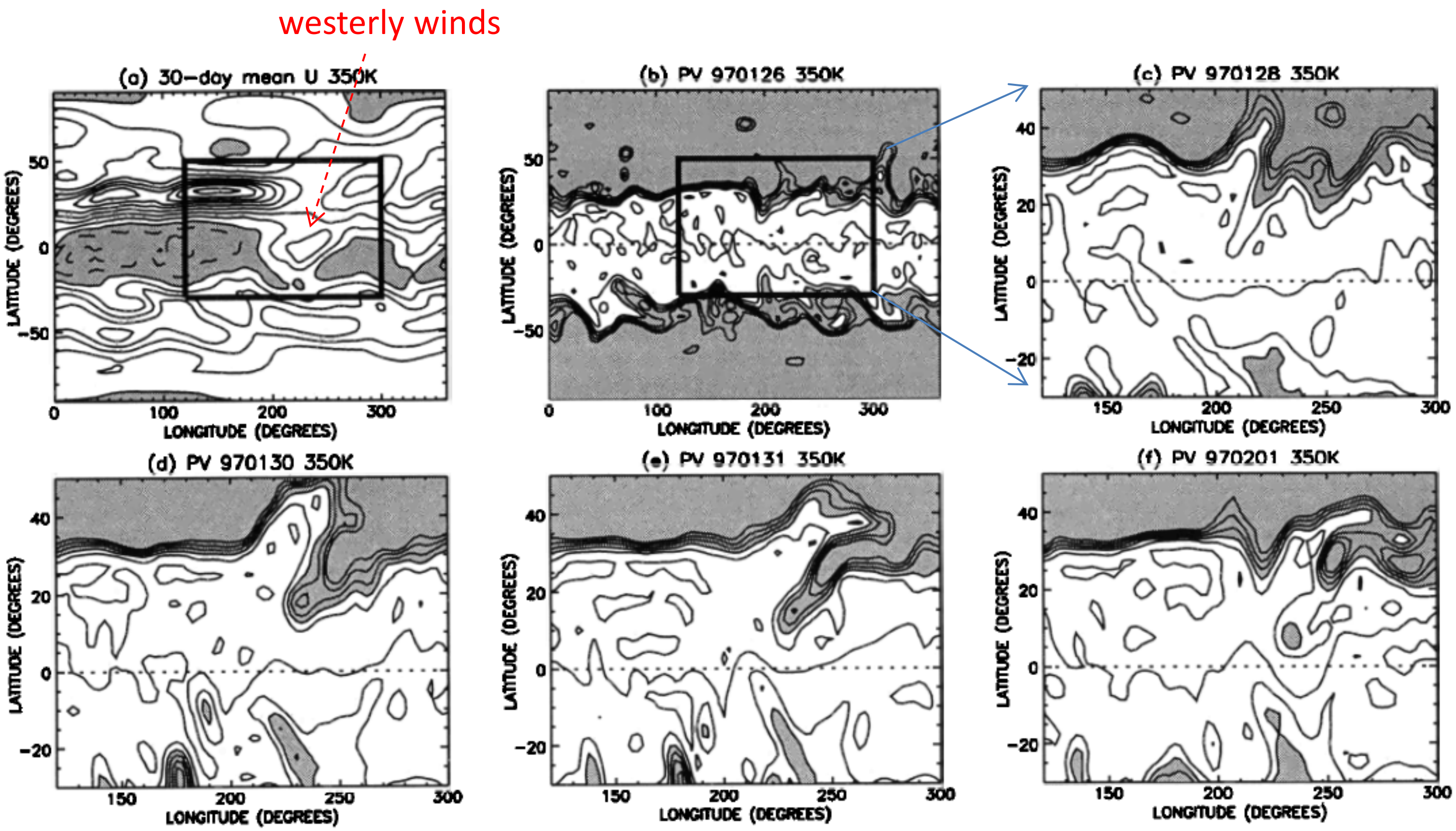
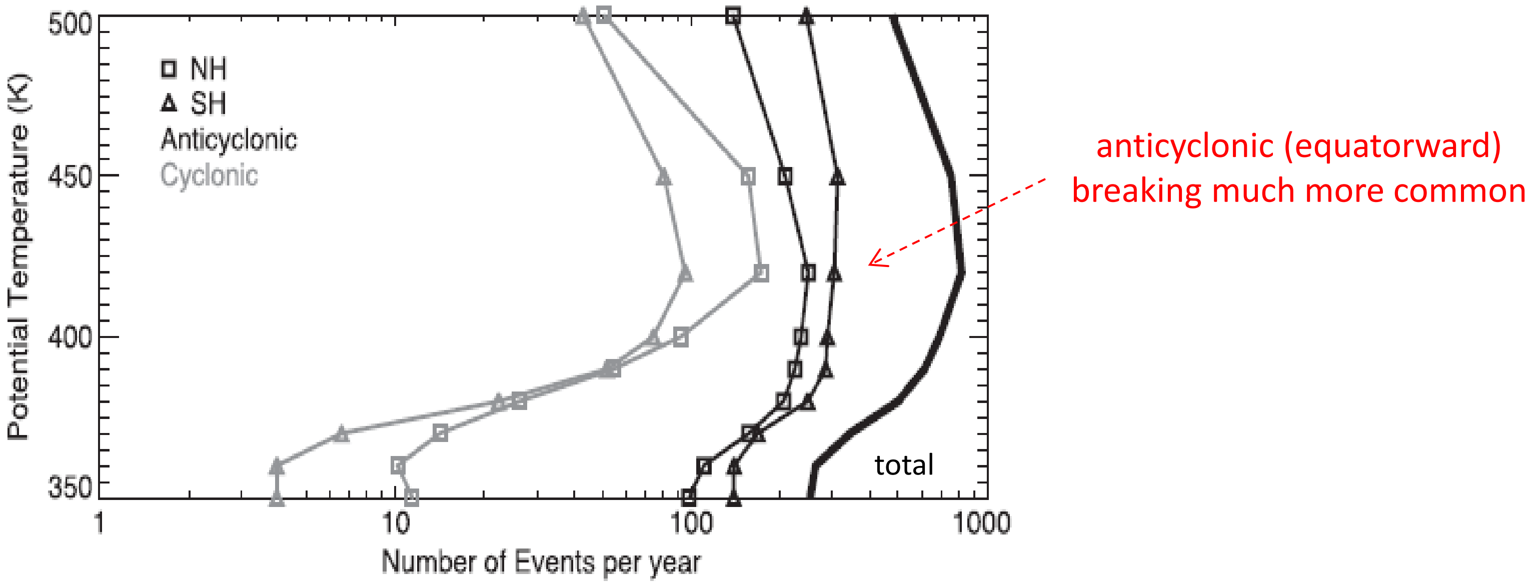
Latitudinal propagation depends on background zonal winds:

- Rossby wave propagation through westerly wind 'ducts'



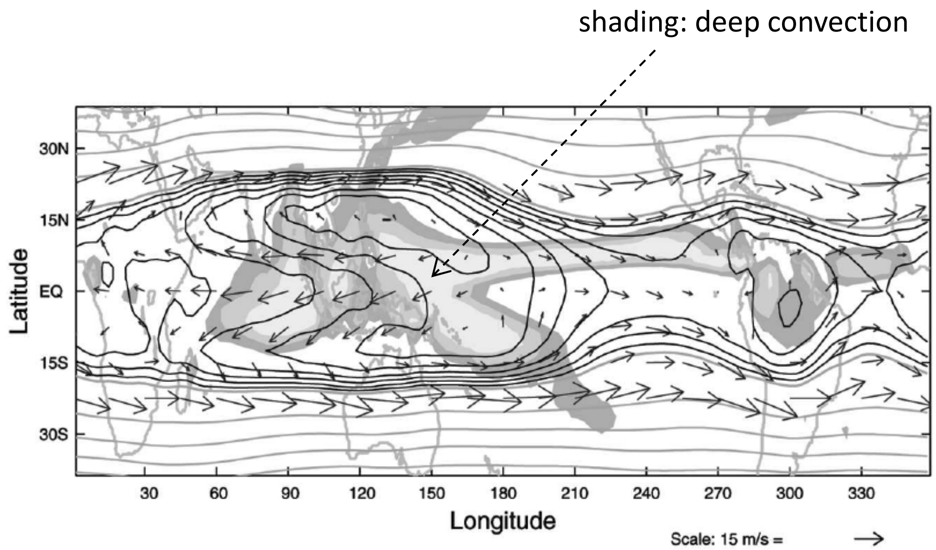
climatology of Rossby wave breaking events



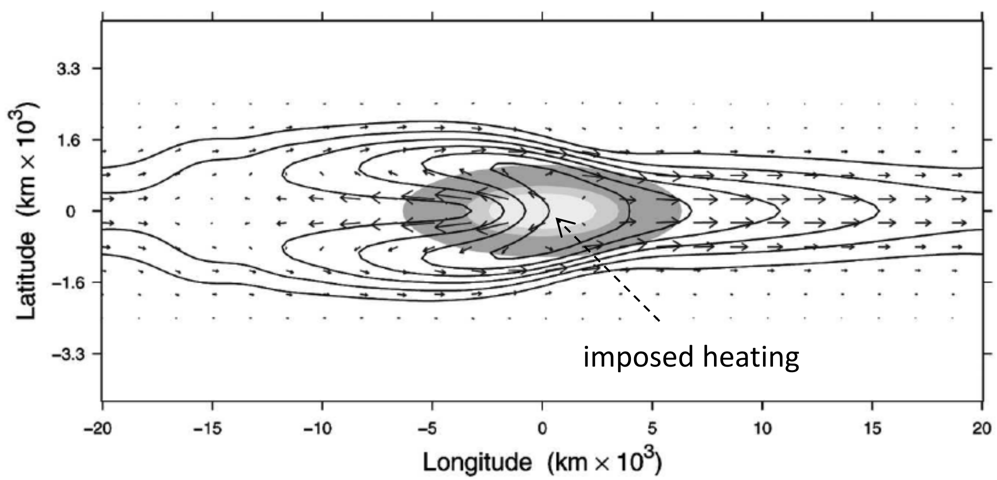
Homeyer and Bowman 2013

observations vs. model

upper troposphere geopotential height and winds



annual mean observations



nonlinear shallow water model

Dima et al 2005

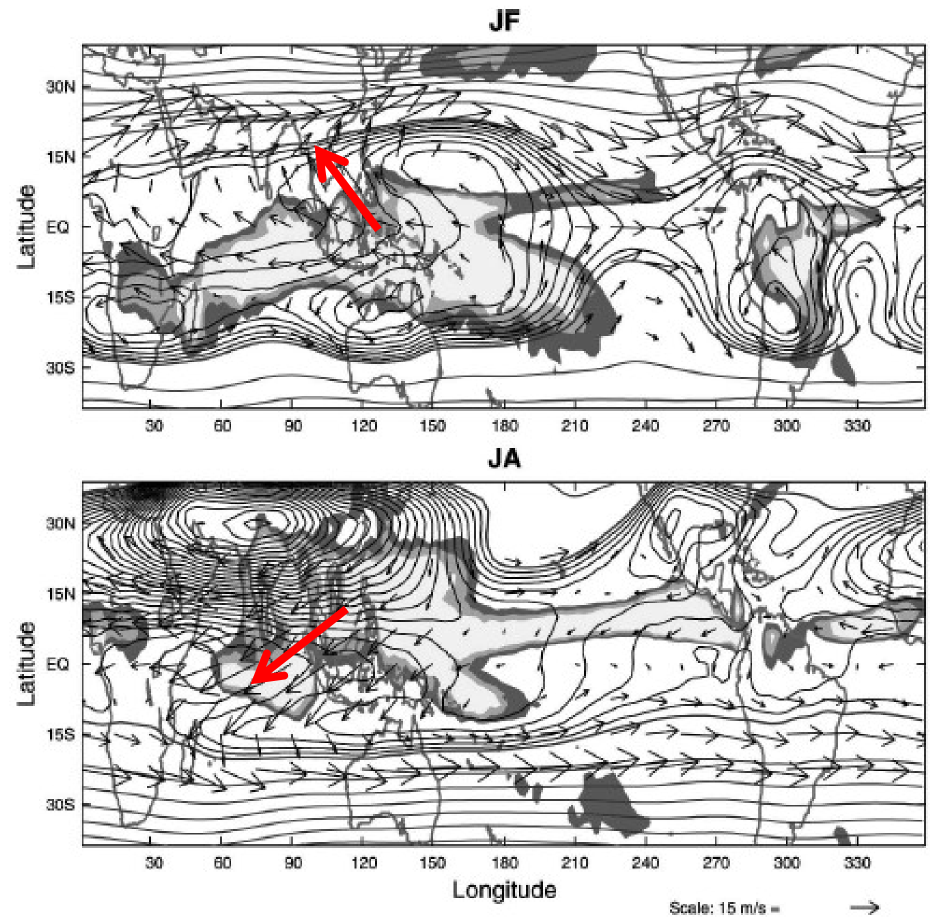
Seasonal variation of tropical waves

tropical zonal mean
momentum balance:

$$\frac{\partial[u]}{\partial t} \cong [v]\left(f - \frac{1}{\cos\phi}\frac{\partial[u]\cos\phi}{\partial y}\right) - [\omega]\frac{\partial[u]}{\partial p}$$

$$-\frac{1}{\cos^2\phi}\frac{\partial[u^*v^*]\cos^2\phi}{\partial y} - \frac{\partial[u^*\omega^*]}{\partial p} - [F_x].$$

eddy momentum
fluxes balance
Hadley flow

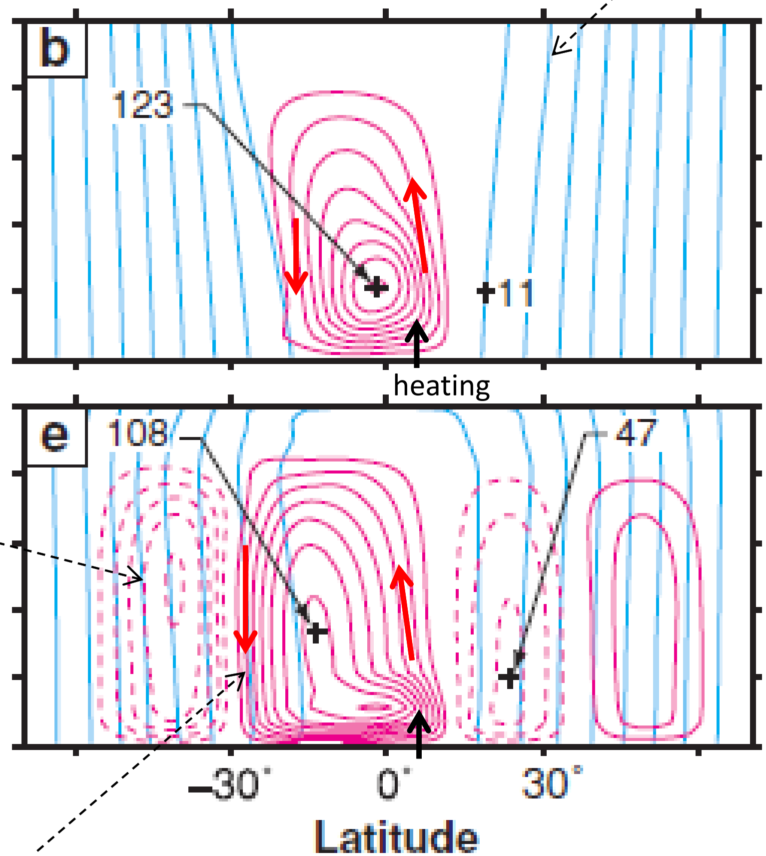


Dima et al 2005

Hadley cell interactions with extratropical eddies: (a complicated subject)

Idealized model simulations:

angular momentum contours



zonally symmetric dynamics

include extratropical eddies

midlatitude 'Ferrel cell' linked to midlatitude eddies

extension of Hadley cell to higher latitudes

Schneider 2006

tracer zonal mean transport budget

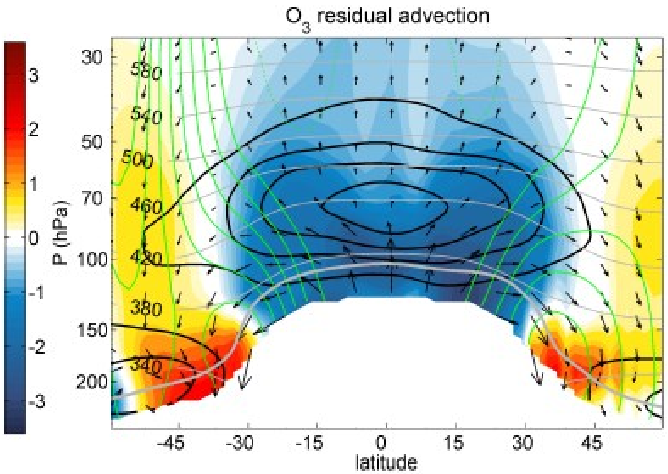
eddy transport

$$\frac{\partial \overline{\chi}}{\partial t} = -\overline{v}^* \frac{1}{a}\frac{\partial \overline{\chi}}{\partial \phi} - \overline{w}^* \frac{\partial \overline{\chi}}{\partial z} + \nabla \cdot \boldsymbol{M} + P - L$$

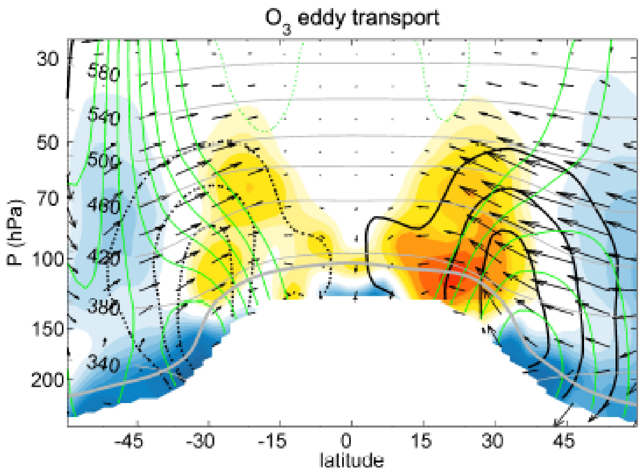
$$M_y = -e^{-z/H}\left(\overline{v'\chi'} - \frac{\overline{v'T'}}{S}\bar{\chi}_z\right)$$
$$M_z = -e^{-z/H}\left(\overline{w'\chi'} + \frac{\overline{v'T'}}{S}\bar{\chi}_y\right)$$

tropical ozone budget
from WACCM

mean advection



eddy transport



ozone
tendency
in % per day

Abalos et al 2013

Reference1

- Abalos, M., Randel, W.J. and Serrano, E., 2012: Variability in upwelling across the tropical tropopause and correlations with tracers in the lower stratosphere, Atmos. Chem. Phys., 12, 11505-11517.
- Abalos, M., Randel, W.J. and Serrano, E., 2014: Dynamical forcing of sub-seasonal variability in the tropical Brewer-Dobson circulation, J. Atmos. Sci., 71, 3439-3453.
- Abalos, M., Randel, W.J., Kinnison, D.E. and Serrano, E., 2013: Quantifying tracer transport in the tropical lower stratosphere using WACCM, Atmos. Chem. Phys., 13, 10591-10607.
- Alexander, M.J. and Holton, J.R., 1997: A model study of zonal forcing in the equatorial stratosphere by convectively induced gravity waves, J. Atmos. Sci., 54, 408-419.
- Andrews, D.G., Holton, J.R. and Leovy, C.B., 1987: Middle atmosphere dynamics, Academic press, pp.489.
- Baldwin, M.P., Gray, L.J., Dunkerton, T.J., Hamilton, K., Haynes, P.H., Randel, W.J., Holton, J.R., Alexander, M.J., Hirota, I., Horinouchi, T., Jones, D.B.A., Kinnersley, J.S., Marquardt, C., Sato, K., Takahashi, M., 2001: The quasi-biennial oscillation, Rev. Geophys., 39, 179-229.
- Birner, T. and Bönisch, H., 2011: Residual circulation trajectories and transit times into the extratropical lowermost stratosphere, Atmos. Chem. Phys., 11, 817-827.
- Bowman, K.P. and Krueger, A.J., 1985: A global climatology of total ozone from the Nimbus 7 total ozone mapping spectrometer, J. Geophys. Res., 90, 7967-7976.

Reference2

- Brewer, A.W., 1949: Evidence for a world circulation provided by the measurements of helium and water vapour distribution in the stratosphere, Q.J.R. Meteorol. Soc., 75, 351-363.
- Butchart, N., 2014: The Brewer-Dobson circulation, Rev. Geophys., 52, 157-184.
- Charney, J.G. and Drazin, P.G., 1961: Propagation of planetary-scale disturbances from the lower into the upper atmosphere, J. Geophys. Res., 66, 83-109.
- Dima, I.M., Wallace, J.M. and Kraucunas, I., 2005: Tropical zonal momentum balance in the NCEP Reanalyses, J. Atmos. Sci., 62, 2499-2513.
- Dobson, G.M.B., 1956: Origin and distribution of the polyatomic molecules in the atmosphere, Proc. R. Soc. Lond. A, 236, 187-193.
- Dunkerton, T., 1980: A Lagrangian mean theory of wave, mean-Flow interaction with applications to nonacceleration and its breakdown, Rev. Geophys., 2, 387-400.
- Edmon Jr., H.J., Hoskins, B.J. and McIntyre, M.E., 1980: Eliassen-Palm cross sections for the troposphere, J. Atmos. Sci., 37, 2600-2616.
- Gabriel, A. and Peters, D., 2008: A diagnostic study of different types of Rossby wave breaking events in the northern extra-tropics, J. Meteor. Soc. Japan, 86, 613-631.
- Garcia, R.R. and Randel, W.J., 2008: Acceleration of the Brewer-Dobson circulation due to Increases in greenhouse gases, J. Atmos. Sci., 65, 2731-2739.
- Gill, A.E., 1980: Some simple solutions for heat-induced tropical circulation, Q.J.R. Meteorol. Soc., 106, 447-462.

Reference3

- Harada, Y., Goto, A., Hasegawa, H., Fujikawa, N., Naoe, H. and Hirooka, T., 2010: A major stratospheric sudden warming event in January 2009, J. Atmos. Sci., 67, 2052-2069.
- Haynes, P.H., McIntyre, M.E., Shepherd, T.G., Marks, C.J. and Shine, K.P., 1991: On the “Downward Control” of extratropical diabatic circulations by eddy-induced mean zonal forces, J. Atmos. Sci., 48, 651-678.
- Highwood, E.J. and Hoskins, B.J., 1998: The tropical tropopause, Q.J.R. Meteorol. Soc., 124, 1579-1604.
- Holton, J.R., Haynes, P.H., McIntyre, M.H., Douglass, A.R., Rood, R.B. and Pfister, L., 1995: Stratosphere-troposphere exchange, Rev. Geophys., 33, 403-439.
- Homeyer, C.R. and Bowman, K.P., 2013: Rossby wave breaking and transport between the tropics and extratropics above the subtropical jet, J. Atmos. Sci., 70, 607-626.
- Matsuno, T., 1970: Vertical propagation of stationary planetary waves in the winter Northern Hemisphere, J. Atmos. Sci., 27, 871-883.
- Matsuno, T., 1971: A dynamical model of the stratospheric sudden warming, J. Atmos. Sci., 28, 1479-1494.
- Park, M., Randel, W.J., Gettelman, A., Massie, S. and Jiang, J., 2007: Transport above the Asian summer monsoon anticyclone inferred from Aura MLS tracers, J. Geophys. Res., 112, D16309.
- Plumb, R.A, 2002: Stratospheric transport, J. Meteorol. Soc. Japan, 80, 793-801.

Reference4

- Plumb, R.A. and Bell, R.C., 1982: A model of the quasi-biennial oscillation on an equatorial beta-plane, Q.J.R. Meteorol. Soc., 108, 335-352.
- Postel, G.A. and Hitchman, M.H., 1999: A climatology of rossby wave breaking along the subtropical tropopause, J. Atmos. Sci., 56, 359-373.
- Randel, W.J., Boville, B.A., Gille, J.C., Bailey, P.L., Massie, S.T., Kumer, J., Mergenthaler, J. and Roche, A., 1994: Simulation of stratospheric N2O in the NCAR CCM2: Comparisons with CLAES data and global budget analyses, J. Atmos. Sci., 51, 2834-2845.
- Randel, W.J., Gille, J.C., Roche, A.E., Kumer, J.B., Mergenthaler, J.L., Waters, J.W., Fishbein, E.F. and Lahoz, W.A., 1993: Stratospheric transport from tropics to middle latitudes by planetary wave mixing, Nature, 365, 533-535.
- Randel, W.J. and Held, I.M., 1991: Phase speed spectra of transient eddy fluxes and critical layer absorption, J. Atmos. Sci., 48, 688-697.
- Randel, W.J. and Jensen, E.J., 2013: Physical processes in the tropical tropopause layer and their role in a changing climate, Nature Geoscience, 6, 169-176.
- Schneider, T., 2006: The general circulation of the atmosphere, Annu. Rev. Earth Planet. Sci., 34, 655-688.
- Simmons, A.J. and Hoskins, B.J., 1980: Barotropic influences on the growth and decay of nonlinear baroclinic waves, J. Atmos. Sci., 37, 1679-1684.
- Thorncroft, C.D., Hoskins, B.J. and McIntyre, M.E., 1993: Two paradigms of baroclinic-wave life-cycle behaviour, Q.J.R. Meteorol. Soc., 119, 17-55.

Reference5

- Vallis, G.K., 2006: Atmospheric and oceanic fluid dynamics, Cambridge University Press, pp.770.
- Warn, T. and Warn, H., 1978: The evolution of a nonlinear critical level, Stud. Appl. Math., 59, 27-71.
- Waugh, D.W. and Polvani, L.M., 2000: Climatology of intrusions into the tropical upper troposphere, Geophys. Res. Lett., 27, 3857-3860.