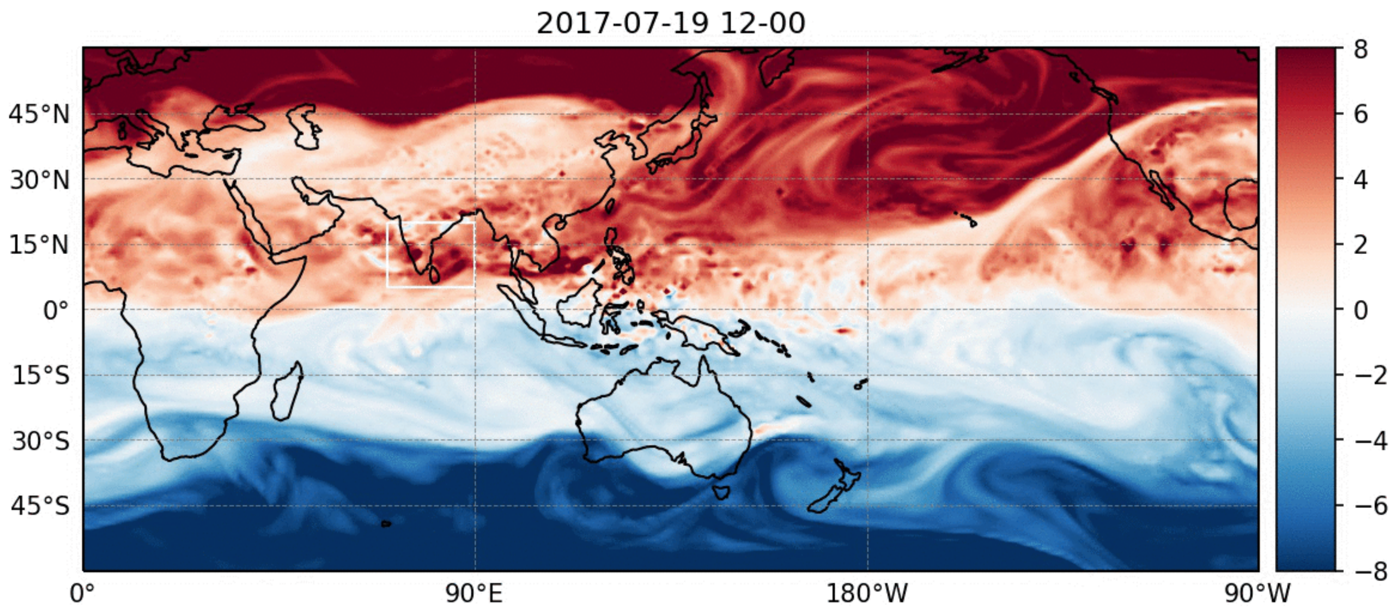
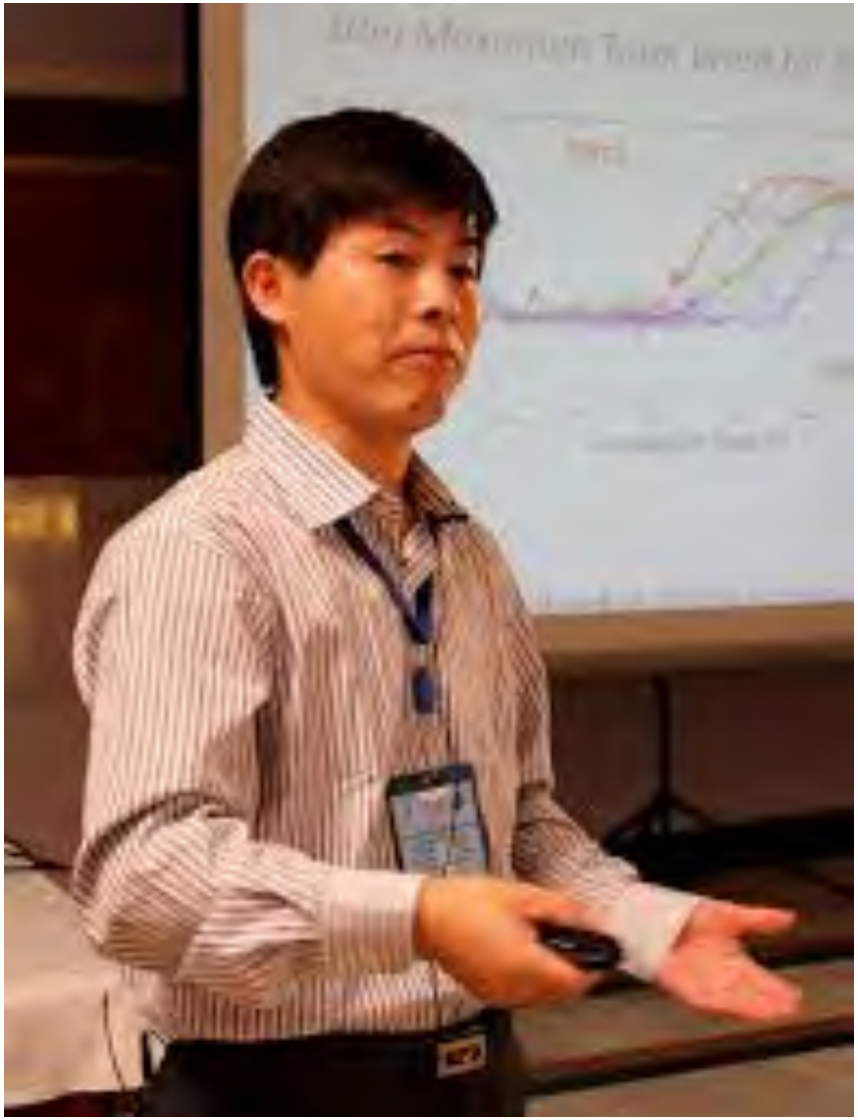
Impermeability: Constraints on communication between tropics & extratropics and the hemispheres



Peter J. Webster,

V. Toma, S. Ortega, C. D. Hoyas, G. L. Stephens,, and G. N. Kiladis

Earth and Atmospheric Sciences
Georgia Institute of Technology



Dedicated to

Professor Fuqing Zhang

for his friendship, enthusiasm, empathy, and the brilliance of his scientific contributions especially with regards to predictability

Some Thoughts

Perhaps prediction and predictability may be thought of as:

Weather: "….. describing the evolution of a high-frequency phenomenon and determining its impact on other regions and phenomena.."

Climate: "…. determining system equilibration (or evolution) relative to internal and external forcing…."

Q: Are there common constraints or rules that jointly govern the global nature of weather and climate variations?

Hemispheric Equilibration

- Tropics are the heat source of the planet and higher latitudes the sink equilibrated by dynamics.

- Early theories: Communication through thermally direct zonally symmetric Hadley-like circulations. Extratropical weather occurred as instabilities of these cells.

- But, observations in the 1950's suggested that upper tropics/subtropics possessed extratropical-like circulations. Found difficult to explain theoretically

  - Here we attempt to explain the interaction of the tropics and extratropics in a holistic fashion in terms of a latitudinal synergy.

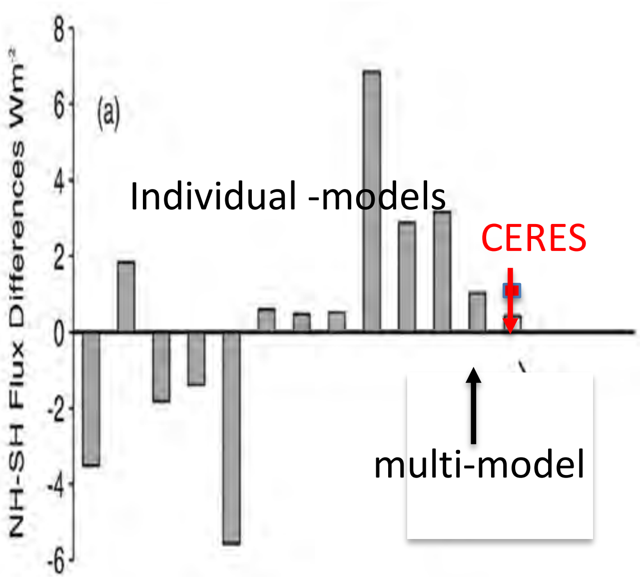
  - Invoke the Haines-McIntyre *Impermeability Theorem* that places strict constraints on latitudinal interactions.

Interhemispheric Equilibration

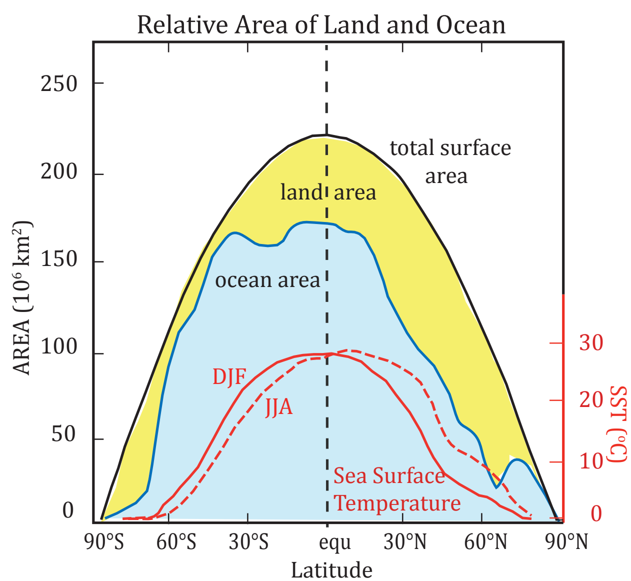
Are there constrains that determine interhemispheric interaction:
Often hemispheres are often considered independent at least relative to position equatorial trough (e.g., Riehl and Malkus 1958). But there are “peculiarities” that suggest otherwise:

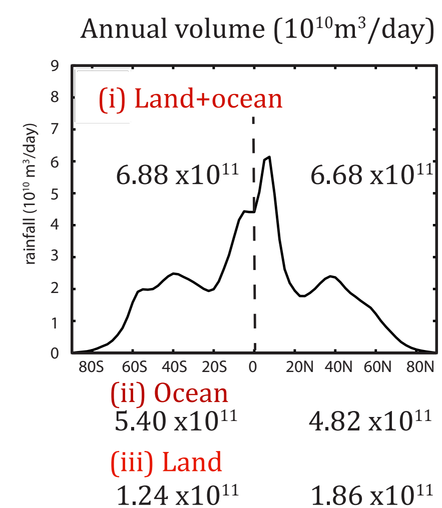
<u>TOA radiation symmetry</u>:
Despite large differences in geography/climatology of NH and SH, annual TOA radiation balance same (Stephens et al. 2015)

<u>Precipitation symmetry</u>:
Despite large differences in geography/climatology of NH and SH, mean annual precipitation (rate or volume) almost same (Webster 2020)



annual NH-SH flux difference W m^{-2}





Early thoughts on extratropical -tropical interaction by Riehl (1954)

- Extremely steady trade winds
- Regions of intermittent upper tropospheric near-equatorial tropical westerlies
- “Trains” of upper tropospheric vortices: greatly disturbed seemingly unattached to lower troposphere

Streamlines 300 m Sept 10, 1945)

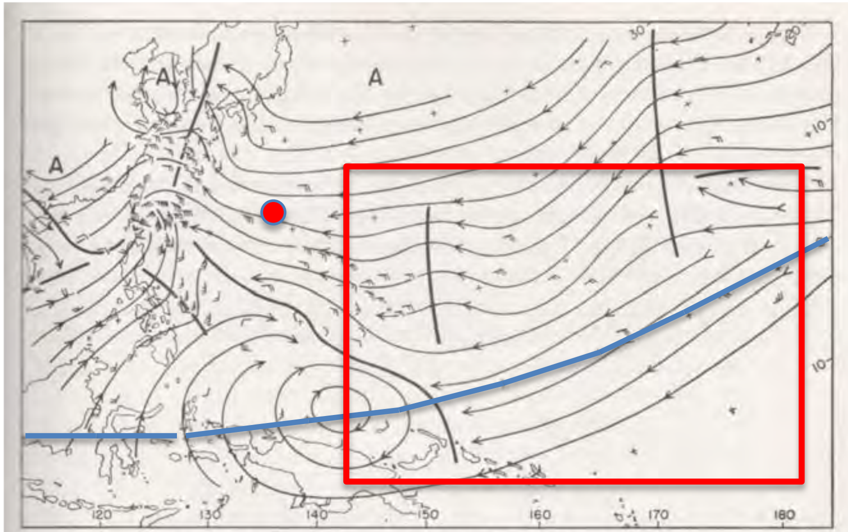


Fig. 10.2. Streamlines at 1,000 feet, Sept. 10, 1945 (40).

Stream lines 200 hPa Sept 10, 1945)

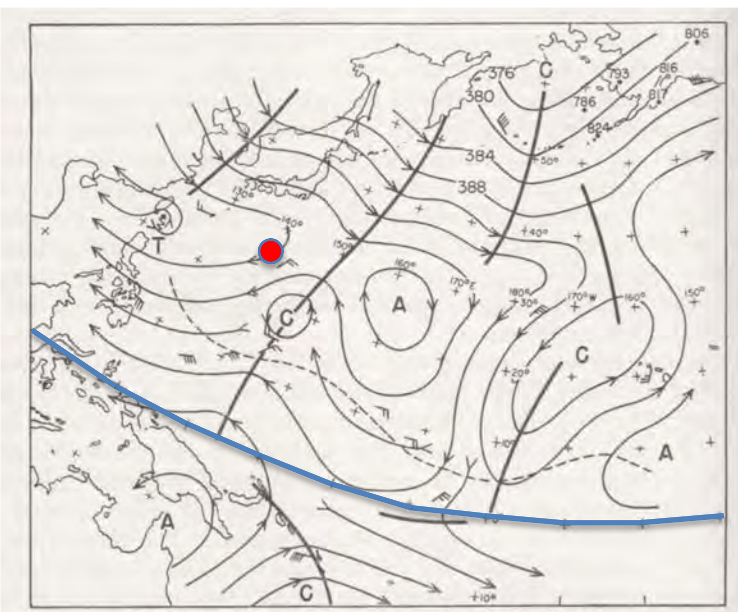


Fig. 10.11. 200-mb streamlines, Sept. 10, 1945 (40).

Cross-section: Iwo Jima Sept 8-13, 1945

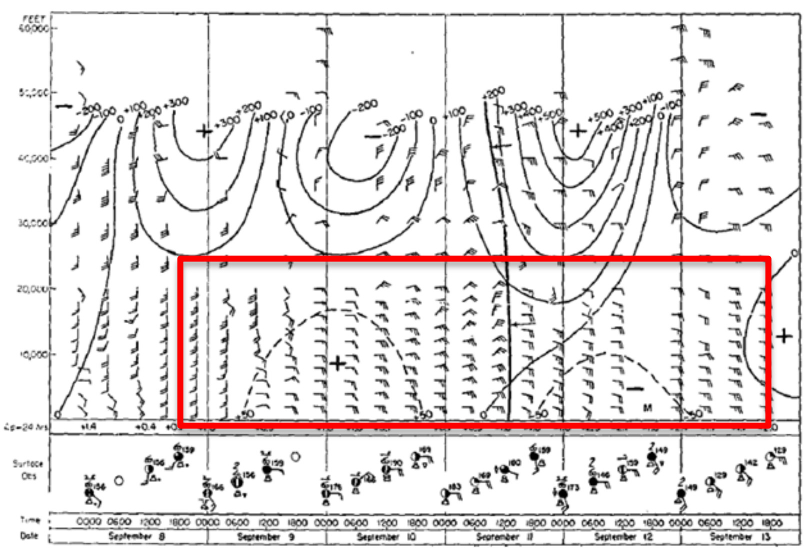


FIG. 4. Vertical time section at Iwo Jima, 8–13 September 1945.

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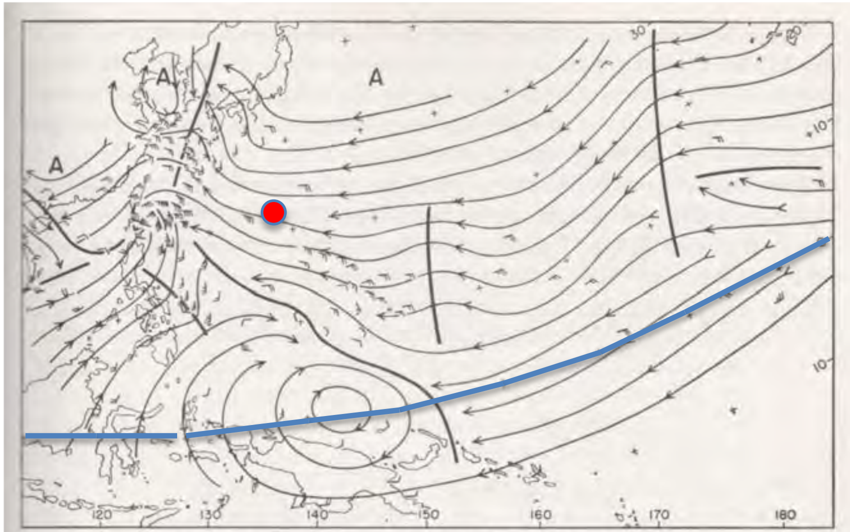

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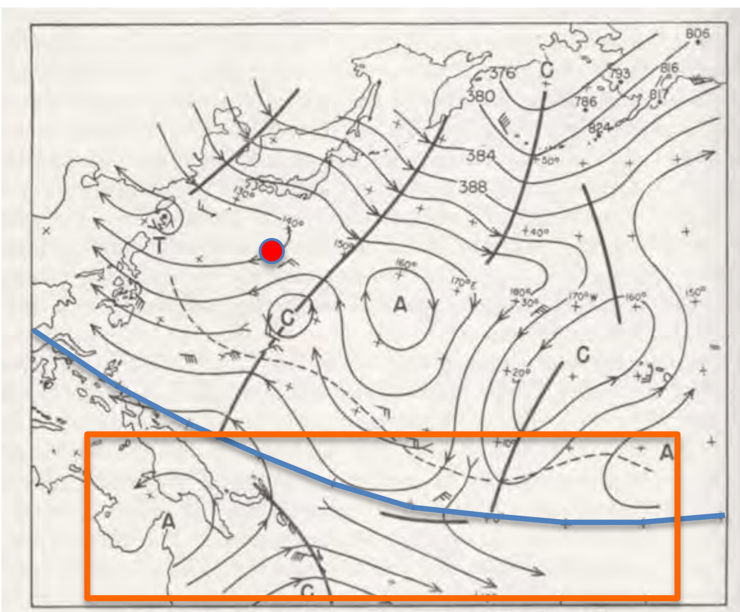

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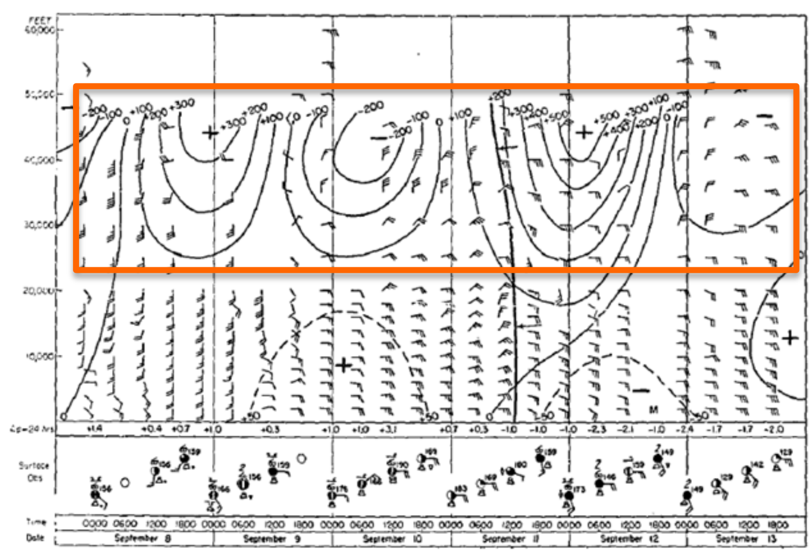

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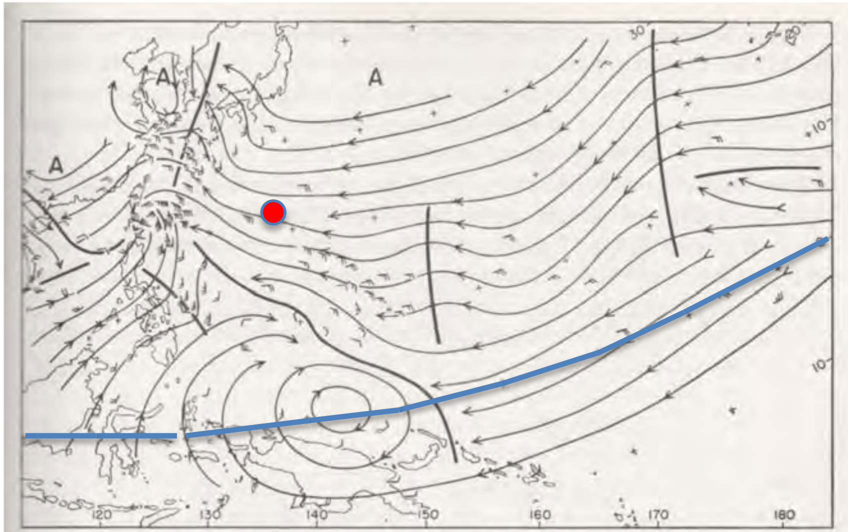
Stream lines 1000 ft (300 m) Sept 10, 1945)



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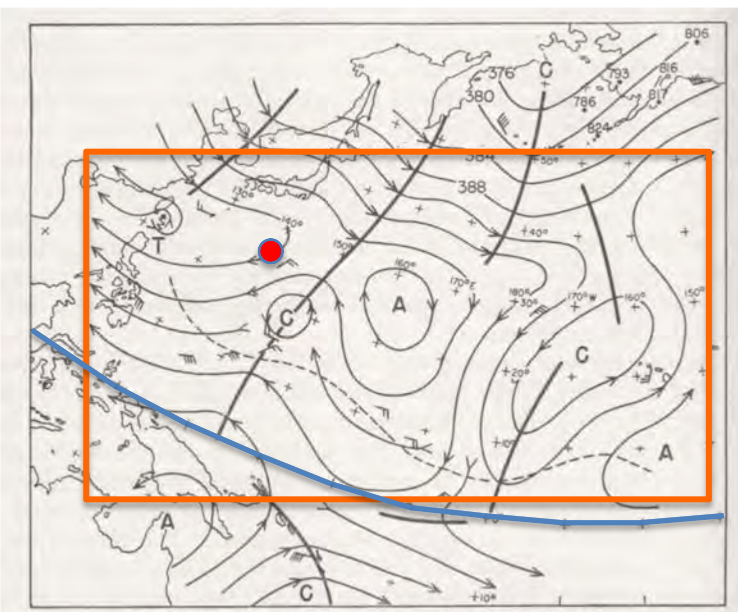

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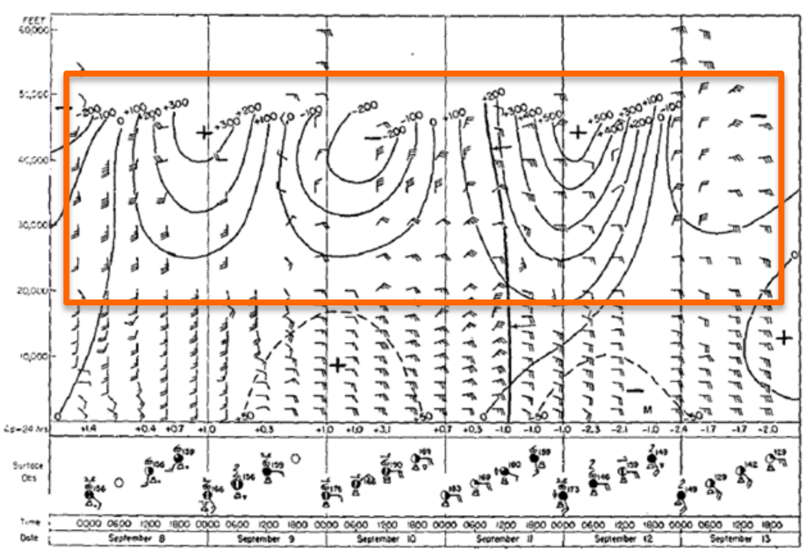


FIG. 4. Vertical time section at Iwo Jima, 8–13 September 1945.

Herbert Riehl (1954) raised important questions

"The intermittent appearance of high tropospheric westerlies on the equator . . . is a foreign thought in classical views of the general circulation. Yet. . . (there is evidence)*. . . that they do occur. . . Since flow in the high levels is so unsteady, coupling at high altitudes between the circulations of the northern and southern hemispheres promises to provide an important link in the understanding of the fluctuations of the general circulation."*

and

". . . an intrusion of extratropical-type disturbances into the heart of the tropics (in the region of the westerlies)….."

Riehl (1954)
"Tropical Meteorology"

Became clear that these characteristics of the tropics and extratropics ***could not*** be explained by zonally symmetric or even zonally averaged arguments!

Noting Riehl, Charney theorized (1963, 1969)

"The picture of the tropical circulation that emerges is quite different from that of the conventional (zonally symmetric Hadley circulation.

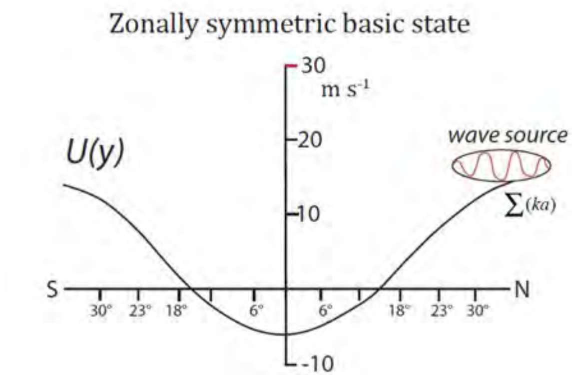
The rising motion is much more concentrated in a narrow band and does not necessarily occur at the equator; the subsiding velocities are small and spread over a large area; and the circulation is not necessarily symmetric.

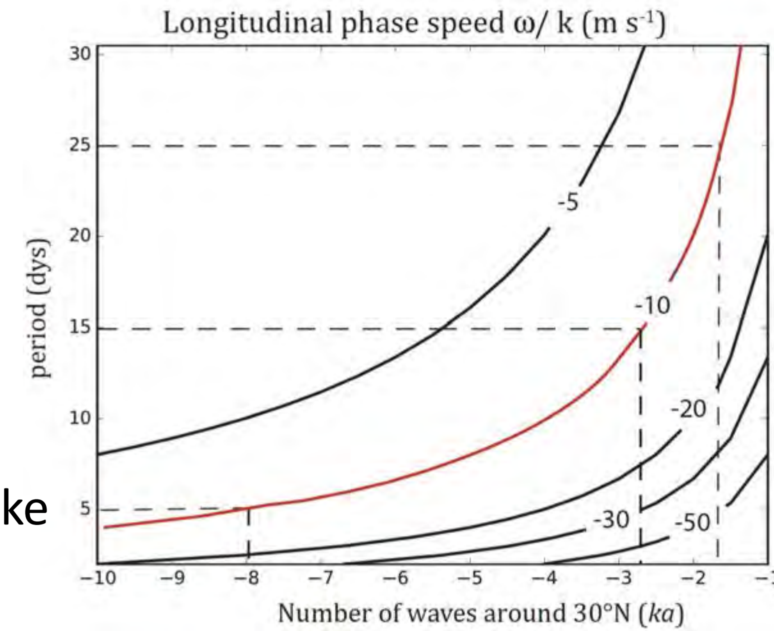
Concluding

The quasi-non-divergent, source-free flow acts to transfer lateral influence from the extratropical circulations to the intertropical convergence zone, so that the position of this zone is determined by the extratropical circulation in both hemispheres." (Charney, 1963)

- Considered only *zonally symmetric basic states* (i.e., U=constant)
- Concluded that only very long waves possessing little energy could propagate to equator
- Tested by Mak (1969), Bennett and Young (1971) who found……

Results of Charney-type calculations






Mankin Mak

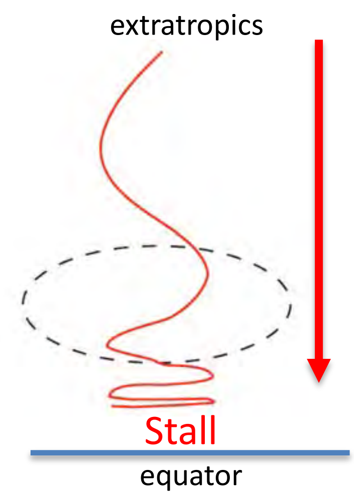

John Young

Which extratropical modes will make it to the equator?

Mak (1969) and Bennett and Young (1971) and using symmetric *U(y)* found:

- Only longest extratropical waves can make it to the equator.
- Waves absorbed/reflected near where *U*=0.

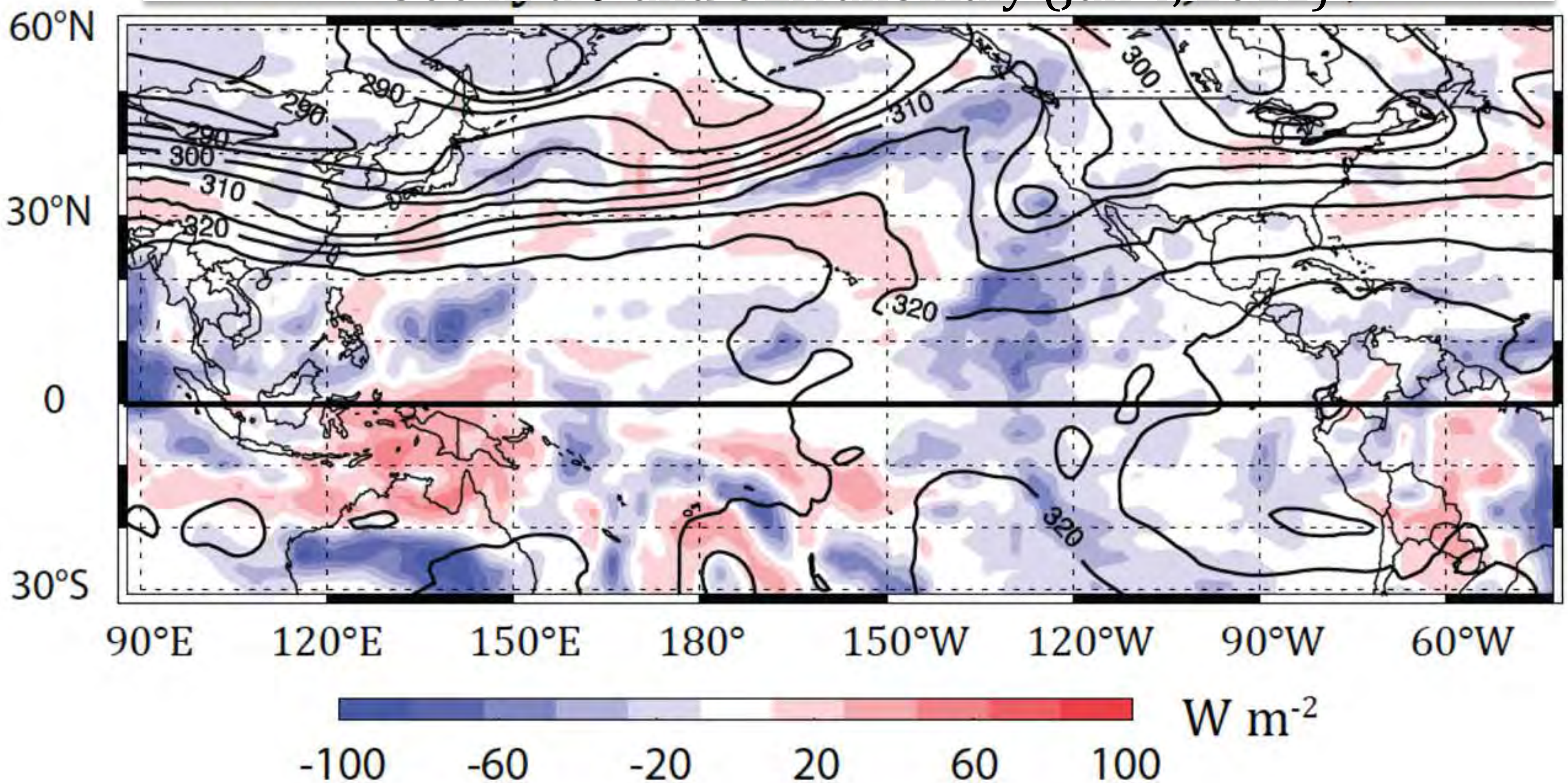
However, Tomas & Webster (1994) concluded that waves propagating through positive shear shrink meridionally and slow down (l $becomes$ $large, cgy -> 0$) and wave stalls



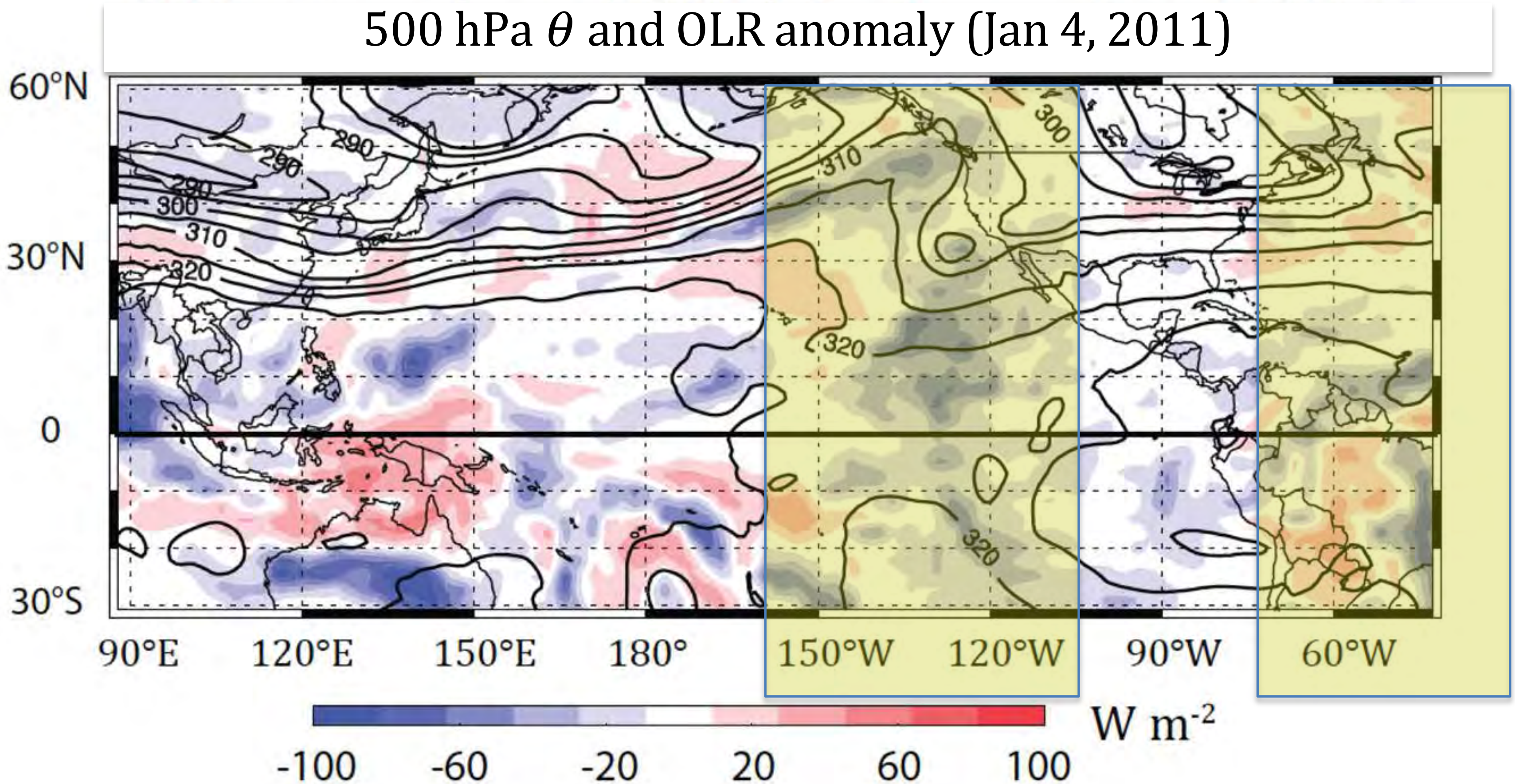
Wave propagation through a zonally symmetric flow does not explain Riehl's observations of energetic wave-trains.

Satellites provided a new view of the tropics

500 hPa θ and OLR anomaly (Jan 4, 2011)



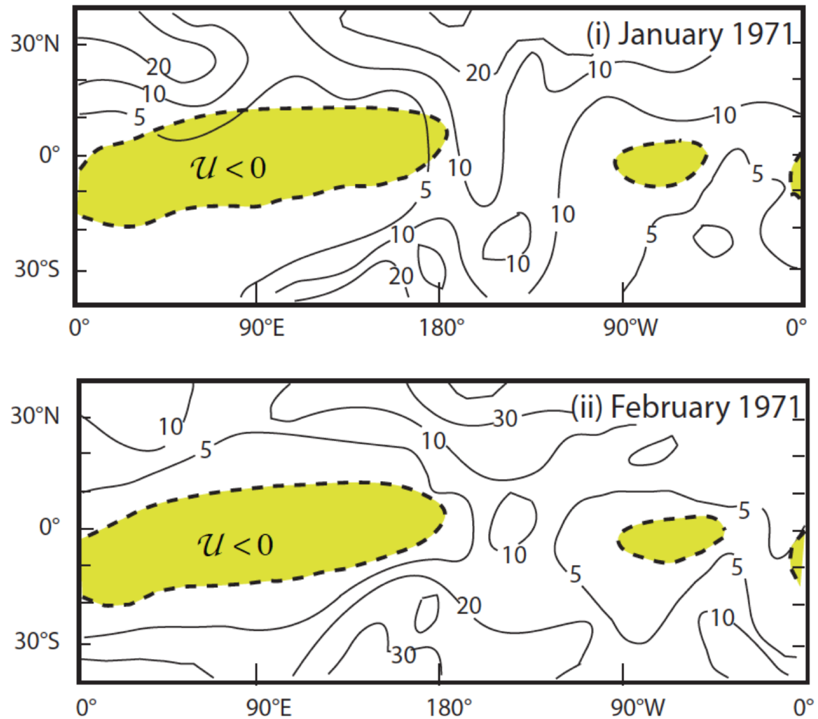
Isentropic perturbation and OLR variation deep in tropics through Riehl's westerlies



Westerly ducts (extratropics to equator) found to possess high variance in each hemisphere both thermodynamically and dynamically

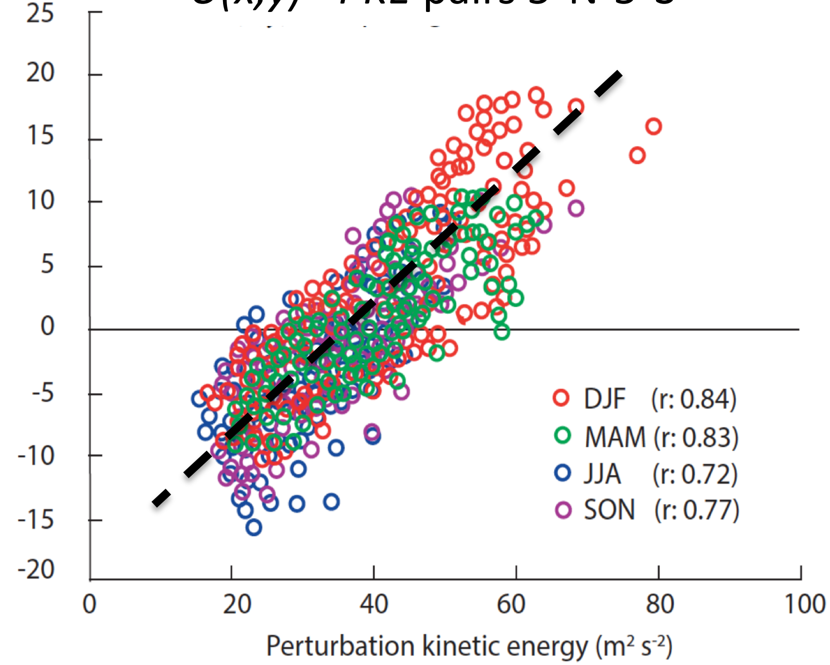
1970-80 data:
Regions of equatorial westerlies are regions of high variance

200 hPa *U* versus *PKE*



Murakami and Unninayer (1972)

U(x,y) –*PKE* pairs 5°N-5°S

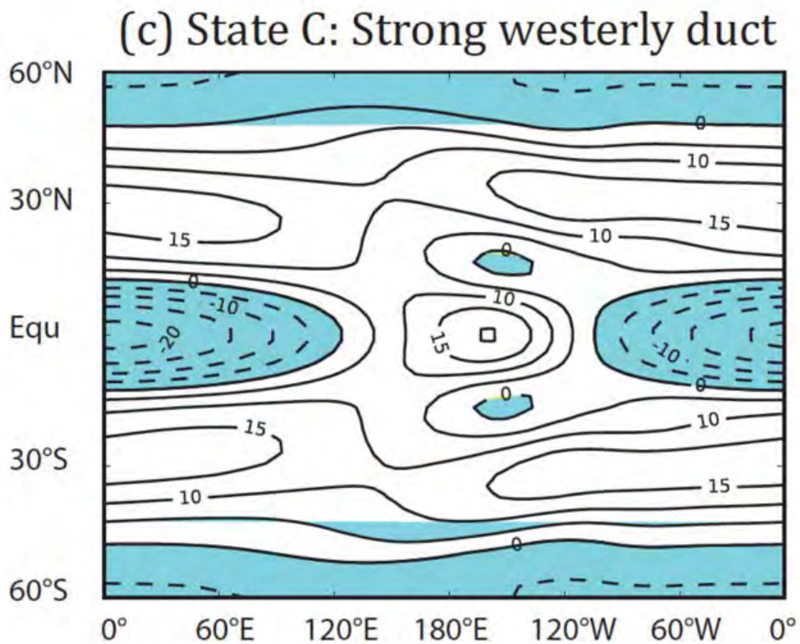


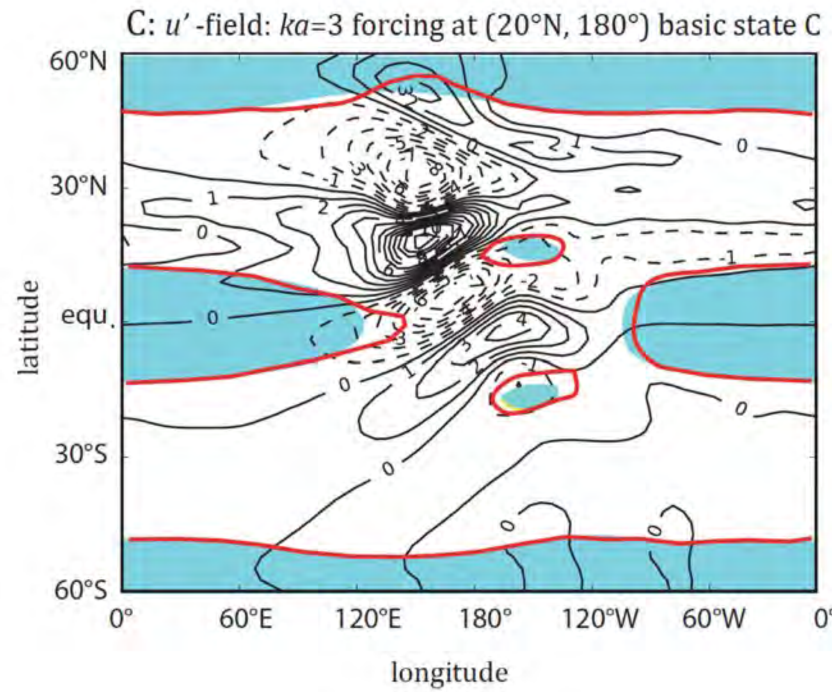
Arkin-Webster 1985

- Strong observational hint of importance of Rossby wave dynamics in duct
- Concept of the “westerly duct” with a basic state *U(x,y)*

Propagation through *U(x,y)* basic state: model results:

Strong equatorial westerlies



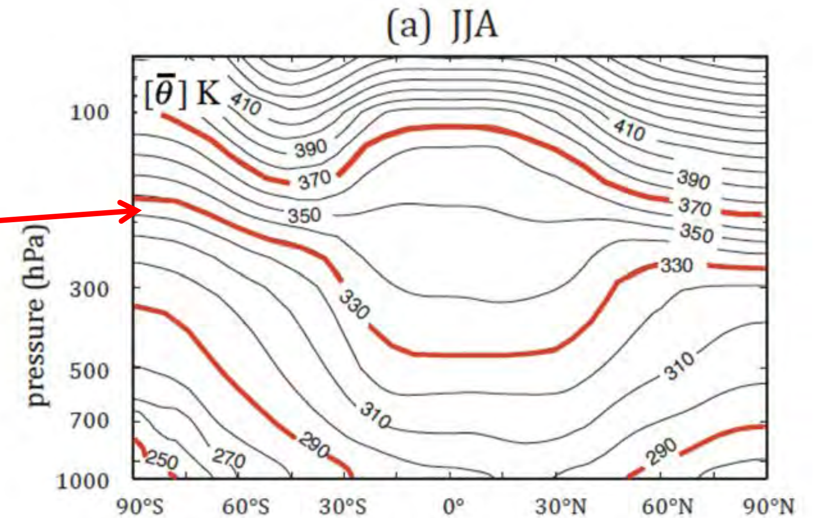


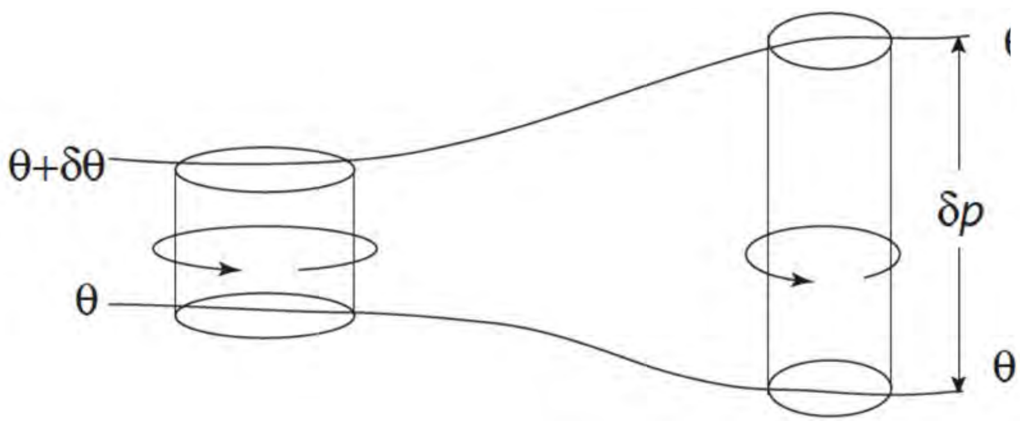
- Moderately equatorial and SH subtropical response.
- Simple model calculations showed propagation to equator only in westerly duct.
- Called a “duct” by Webster and Holton (1982) as it appeared to “duct” Rossby waves towards the equator.

Potential vorticity perspective
Ertel's isentropic potential vorticity (q)

$$q = -g\eta_\theta \frac{\partial\theta}{\partial p} = -g(\zeta_\theta + f)\frac{\partial\theta}{\partial p}$$

defined on isentrope

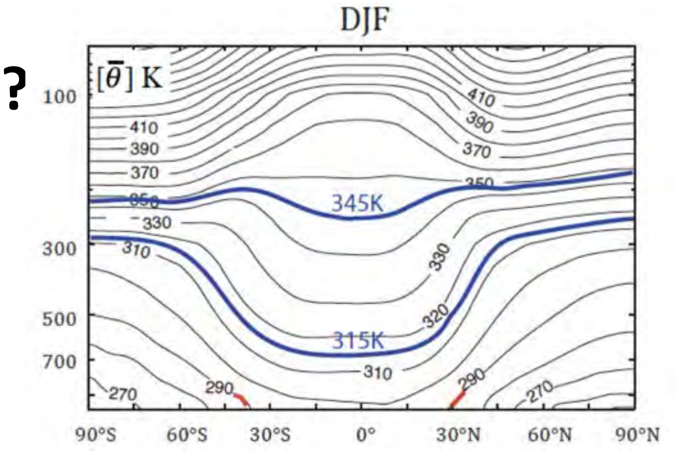


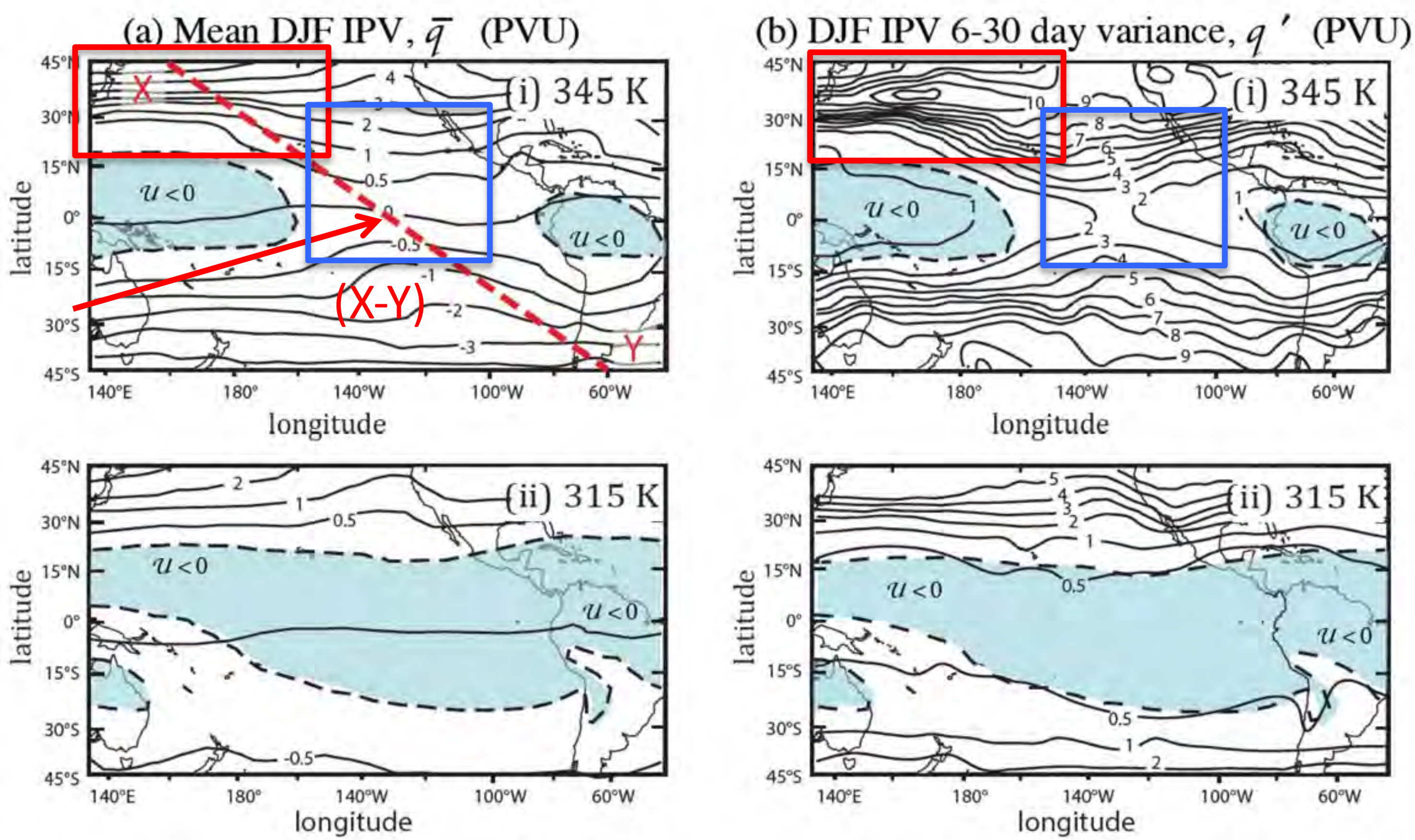


- Potential Vorticity (q) conserved only in adiabatic, frictionless flow, therefore limited

Comparison of upper-lower tropospheric PV ?

- Upper troposphere: high PV variance occurs where $\mathcal{U}$ >0 along equator
- Lower troposphere: $\mathcal{U}$ <0 everywhere. Low values of q' variance.



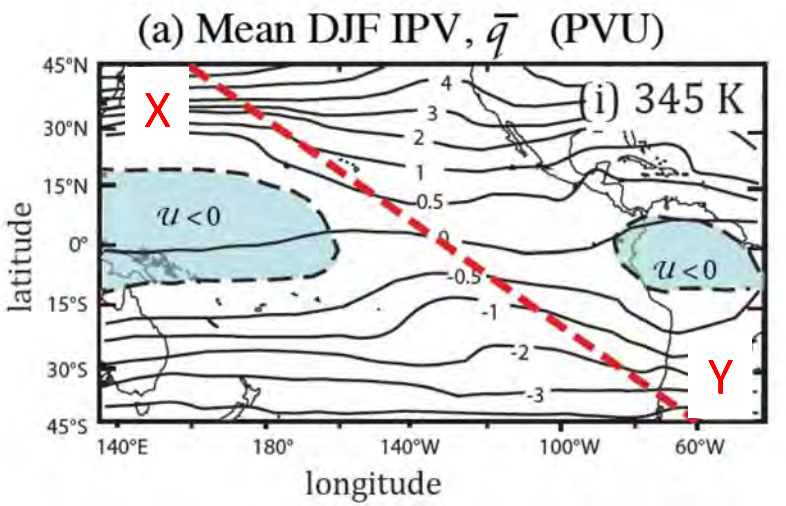


Note

Large gradient of PV in two locations

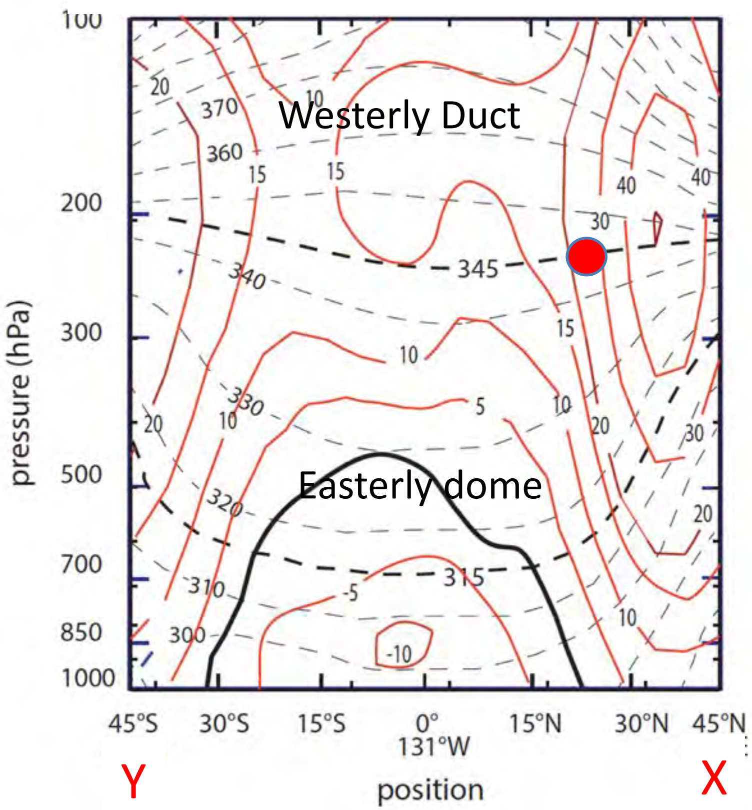
(i) Pacific- low latitudes

(ii) High latitude poleward of easterlies

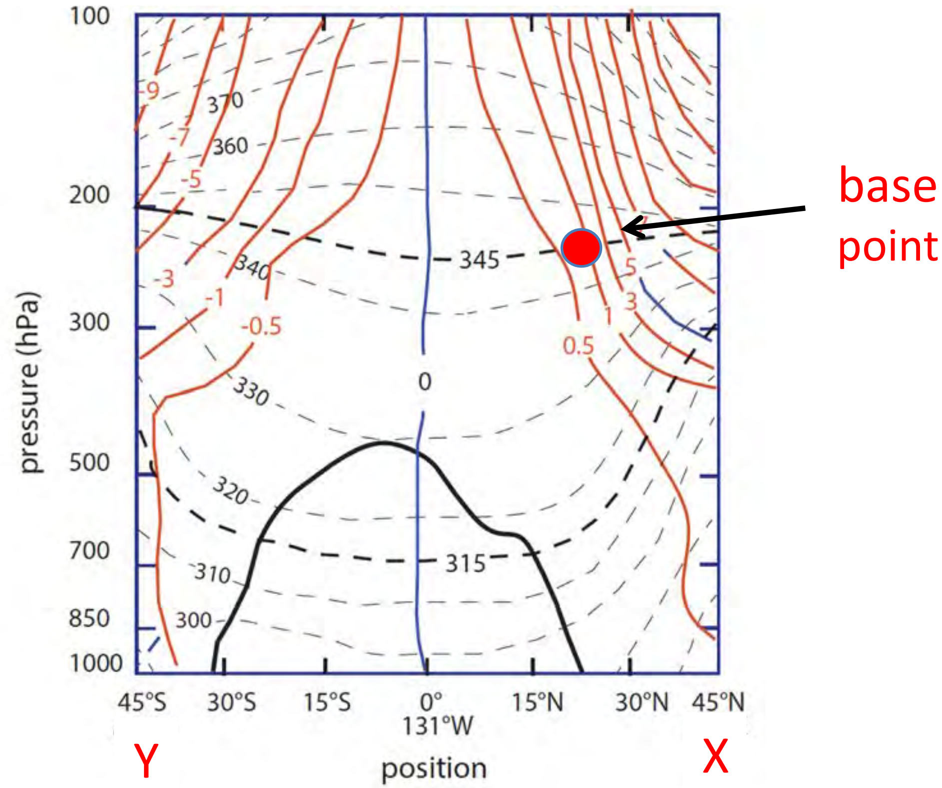


Cross-sections of zonal velocity and potential temperature along diagonal X-Y

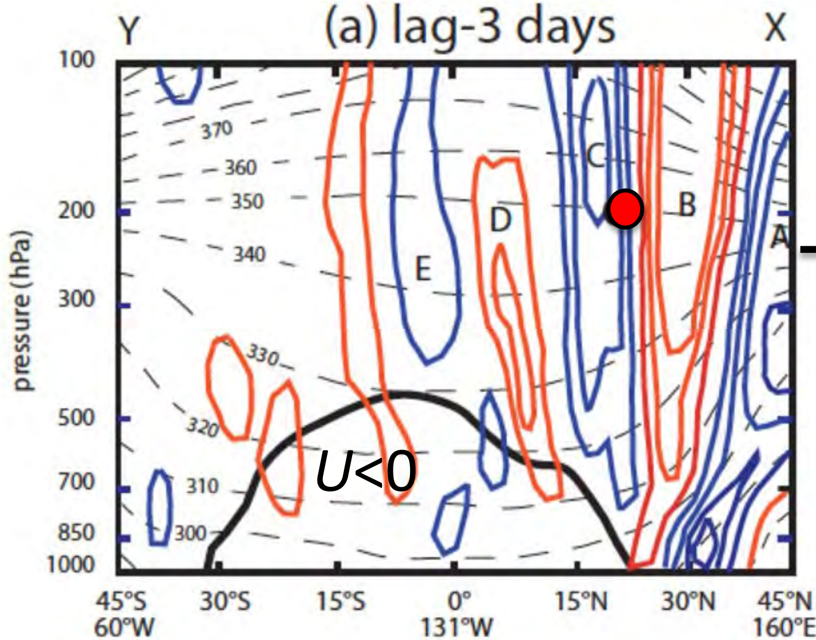
Zonal wind along X-Y

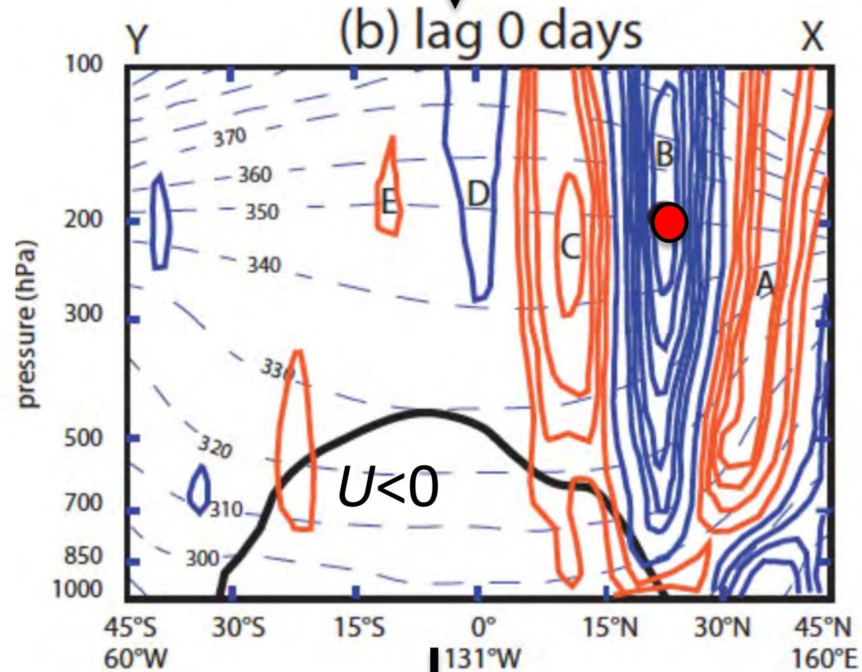


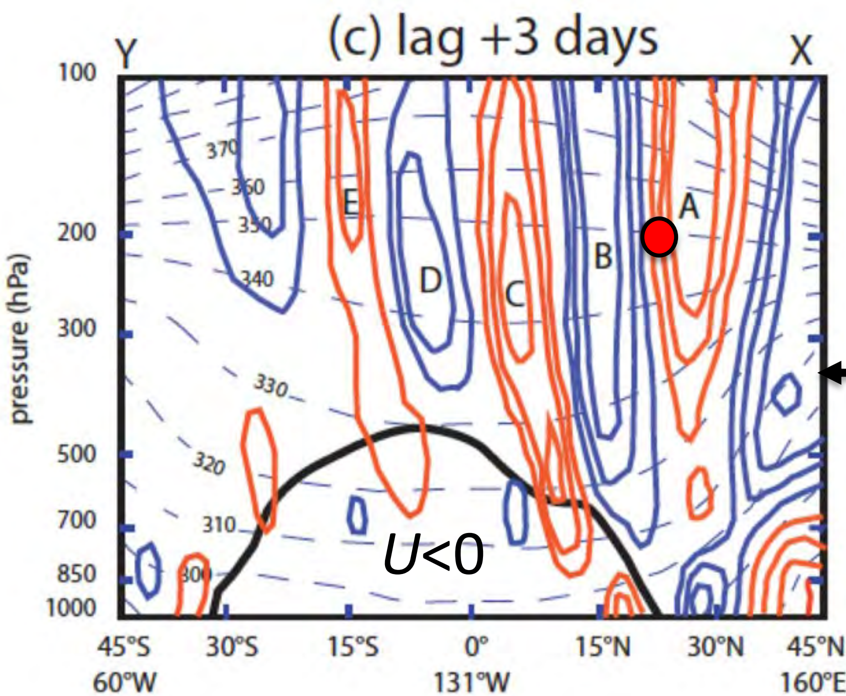
Potential vorticity along X-Y



Lagged-correlations NW-SE diagonal across Pacific through Westerly Duct

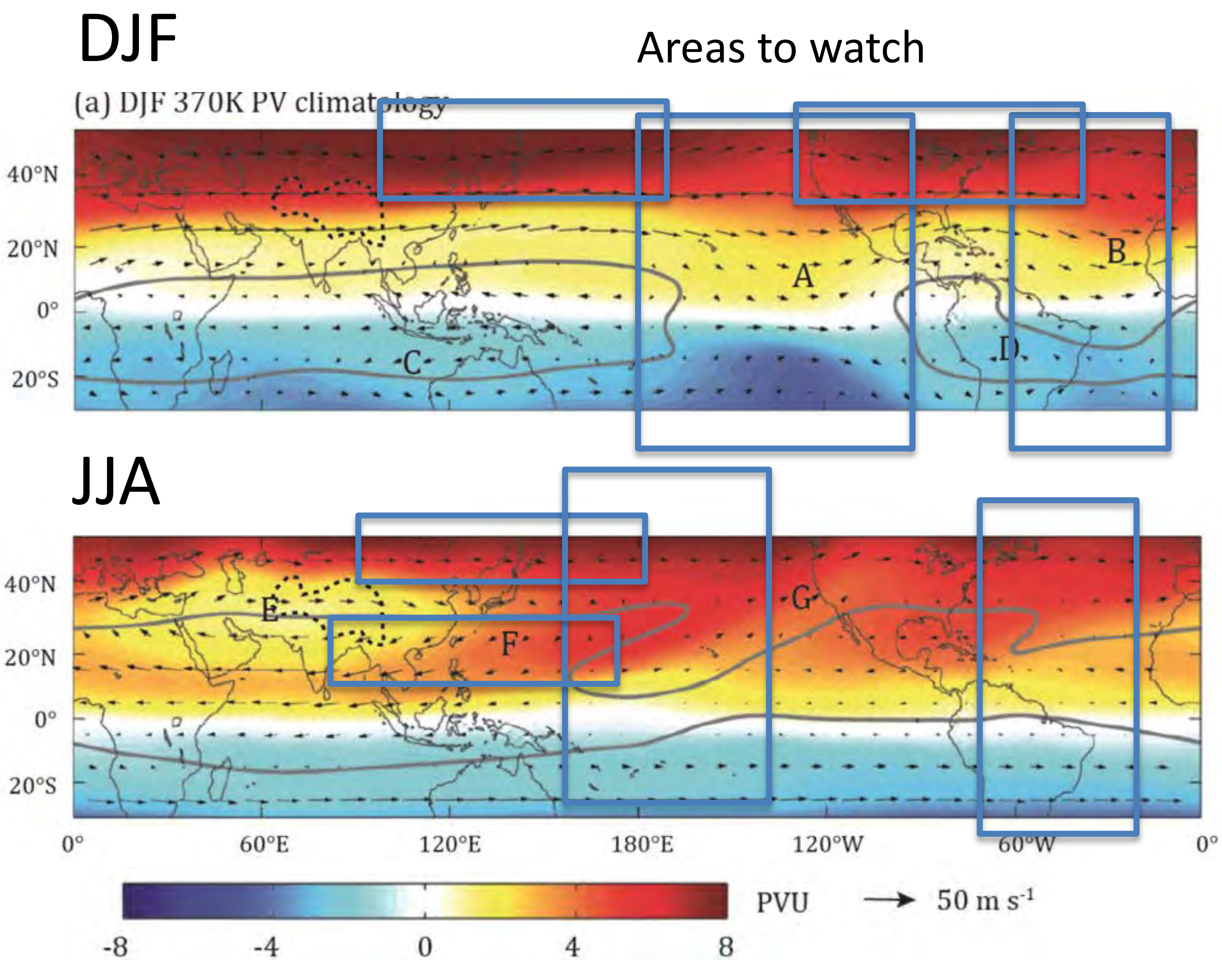






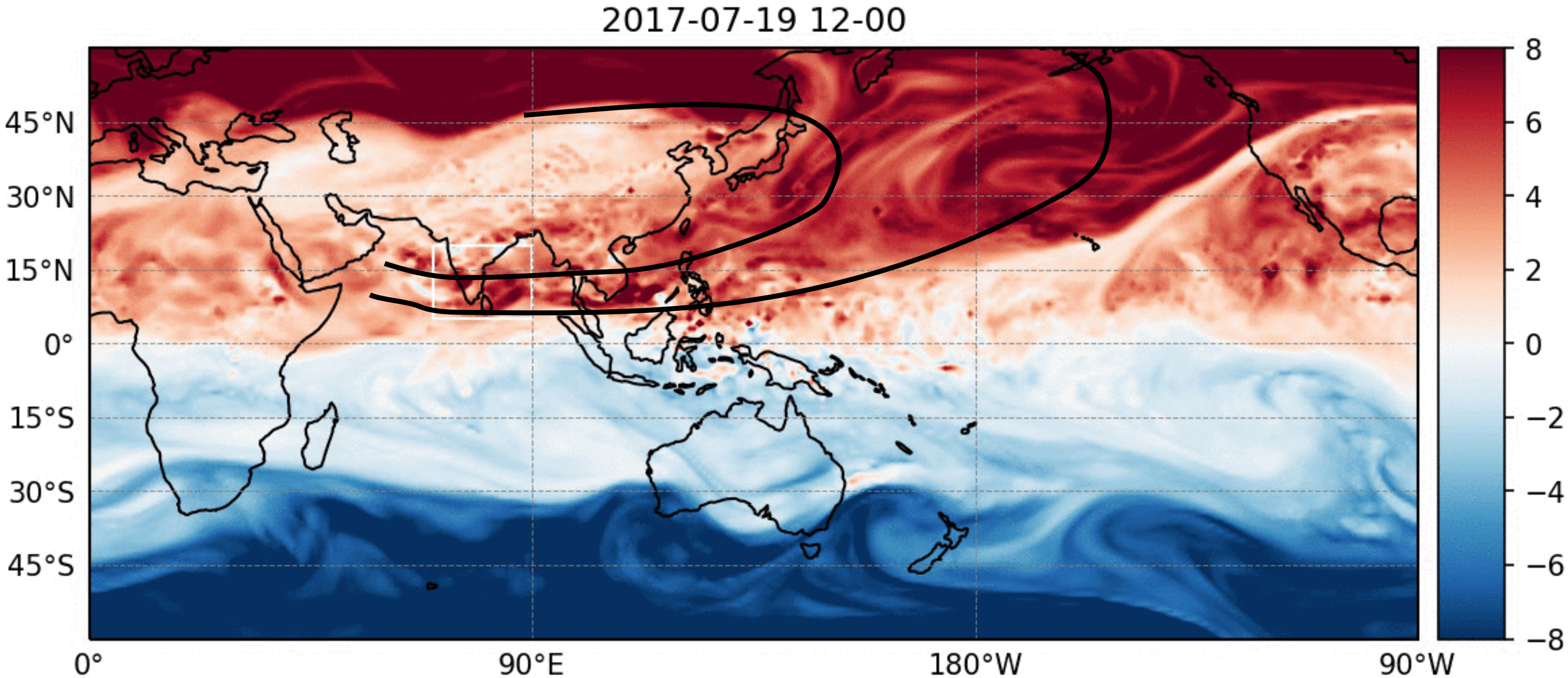
Waves "ride" over the "easterly dome"

Climatology on the 370K isentrope: Potential vorticity q

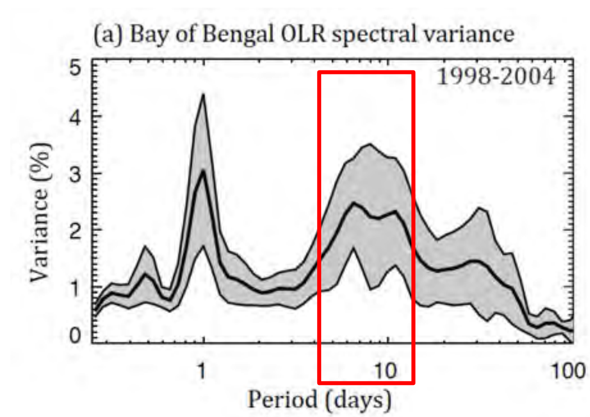


- In winter, high values of PV extend across equator in the westerly ducts (A & B).
- In summer, high PV extends from central western Pacific (F & G), across the equatorial North Indian Ocean towards Africa.

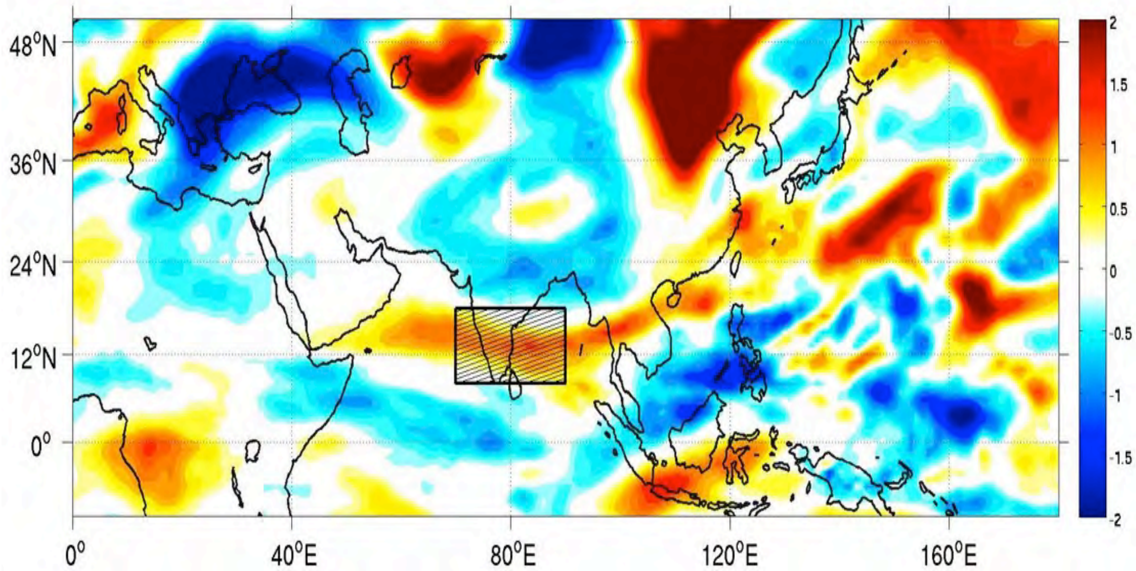
(1) Boreal summer PV evolution 370K: Jul 19 to Sep 13 2014



- Note the breaking of Rossby waves and the migration of filaments to the south Asia and India.

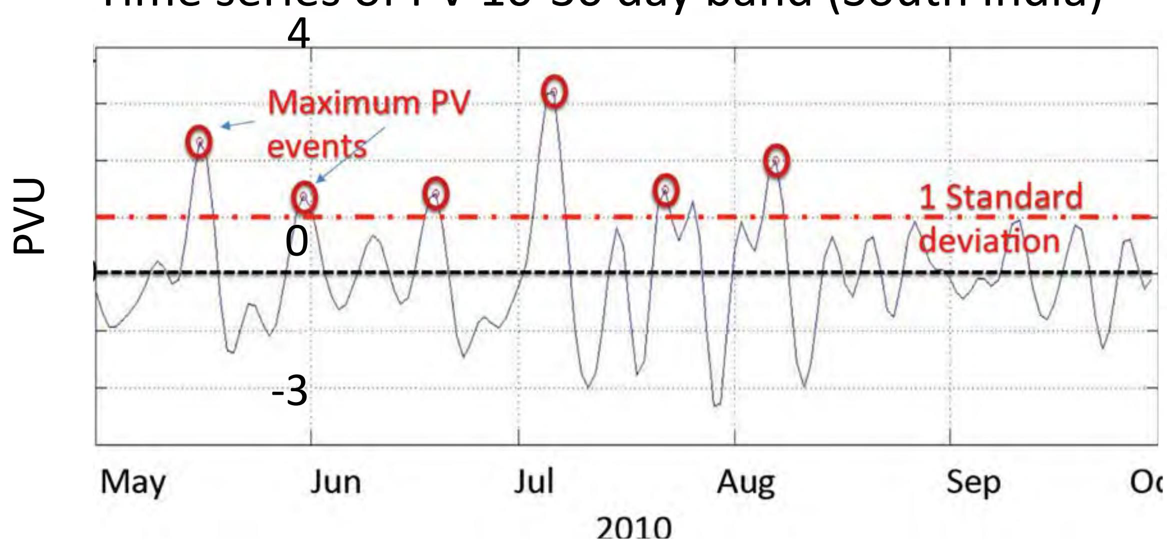


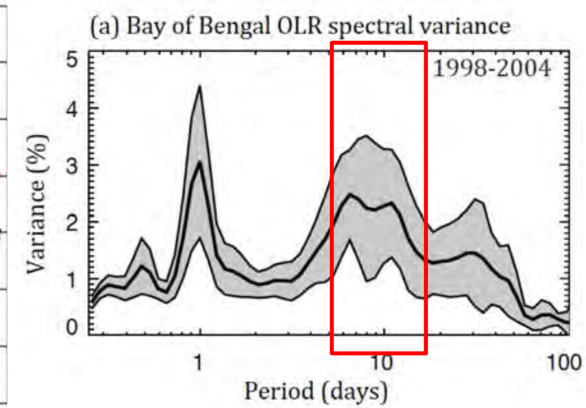
q-variance 10-30 day band: Recursive Rossby wave impact



Underutilized predictability??

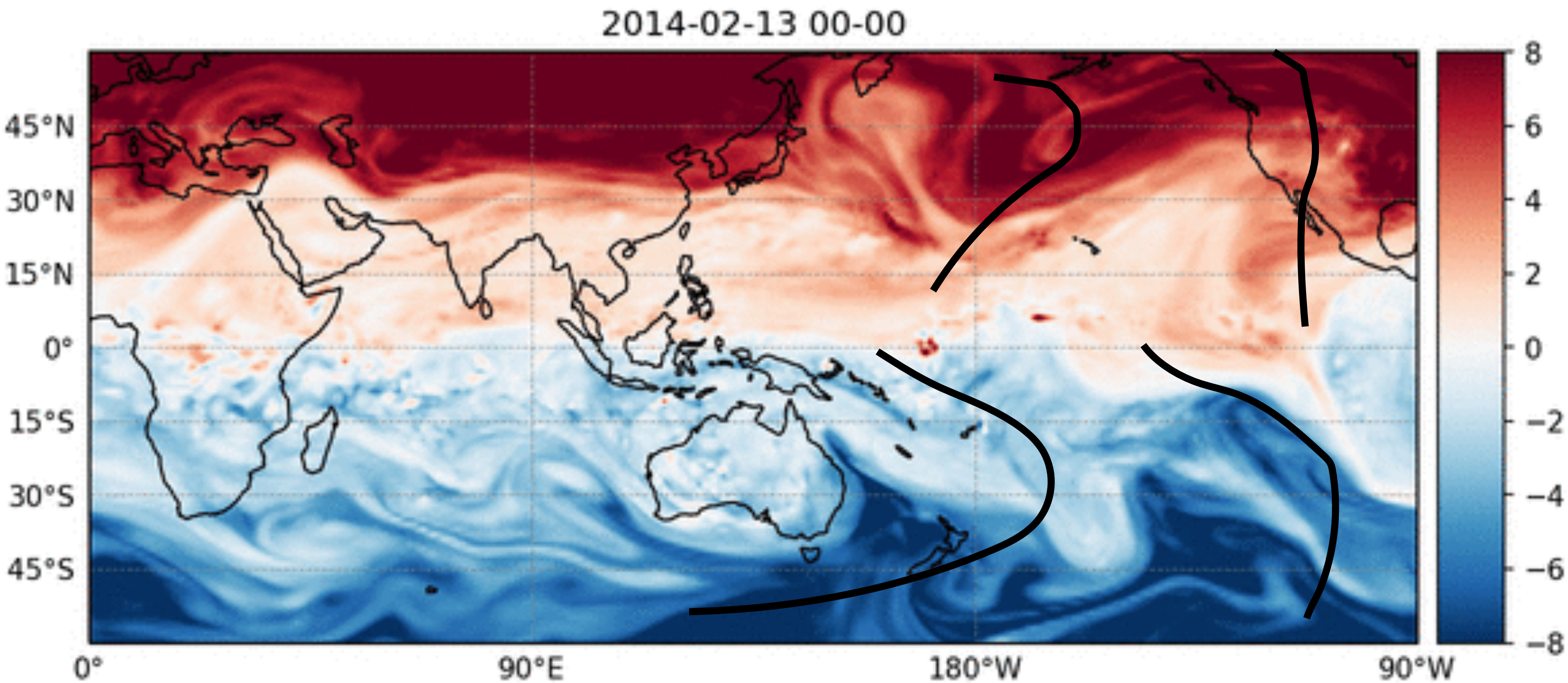
Time series of PV 10-30 day band (South India)





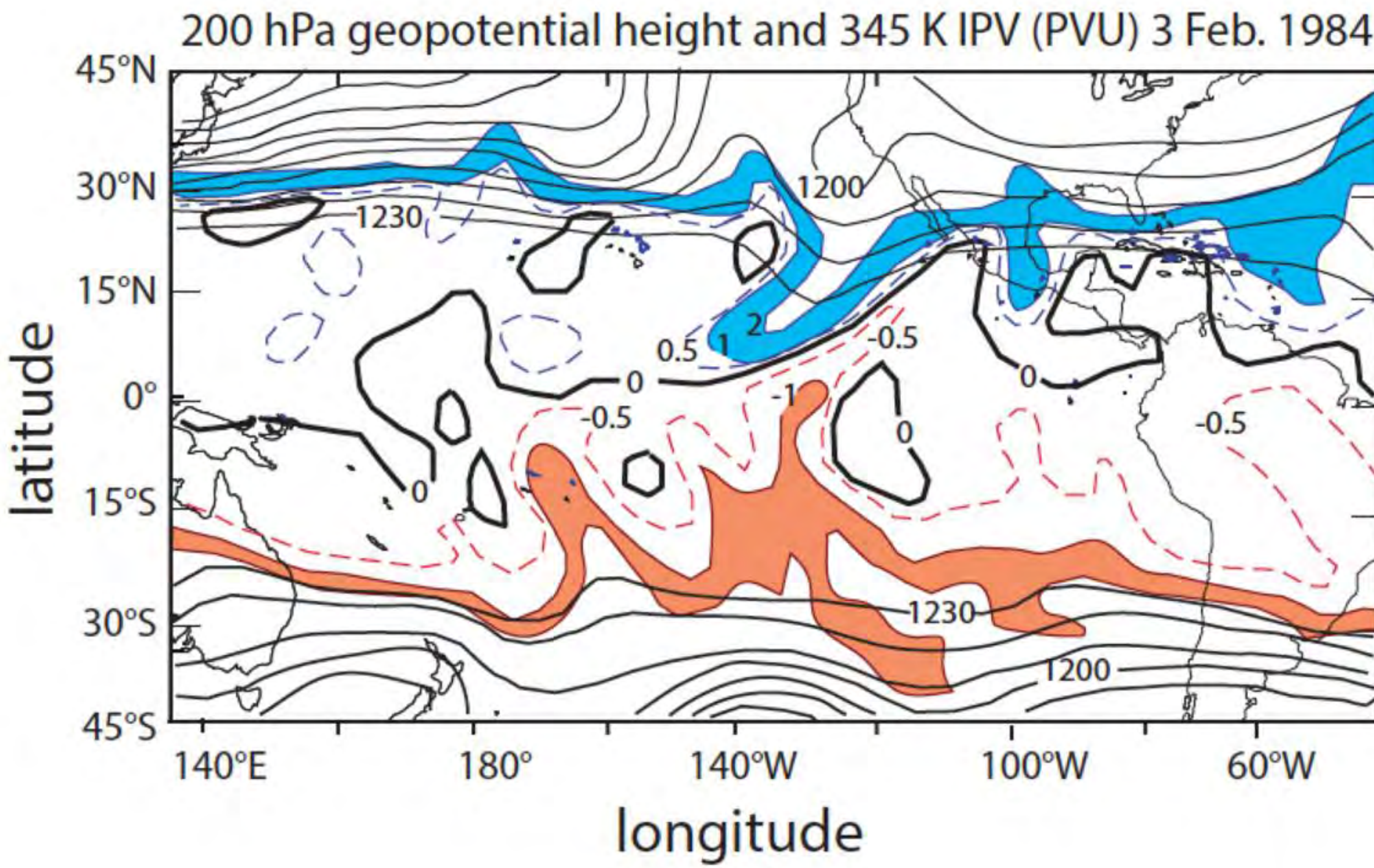
Ortega et al. (2017)

(2) Boreal winter PV evolution: Feb. 12 to Apr. 13, 2014



- Continual eastward propagation of waves out of the jet-stream region of Central Asia (characterized by large PV gradients)
- Continual breaking of Rossby waves in both NH and SH with high amplitude filaments of PV moving to west.
- Recursive Rossby wave penetration

Boreal Winter Rossby Waves in Eastern Pacific

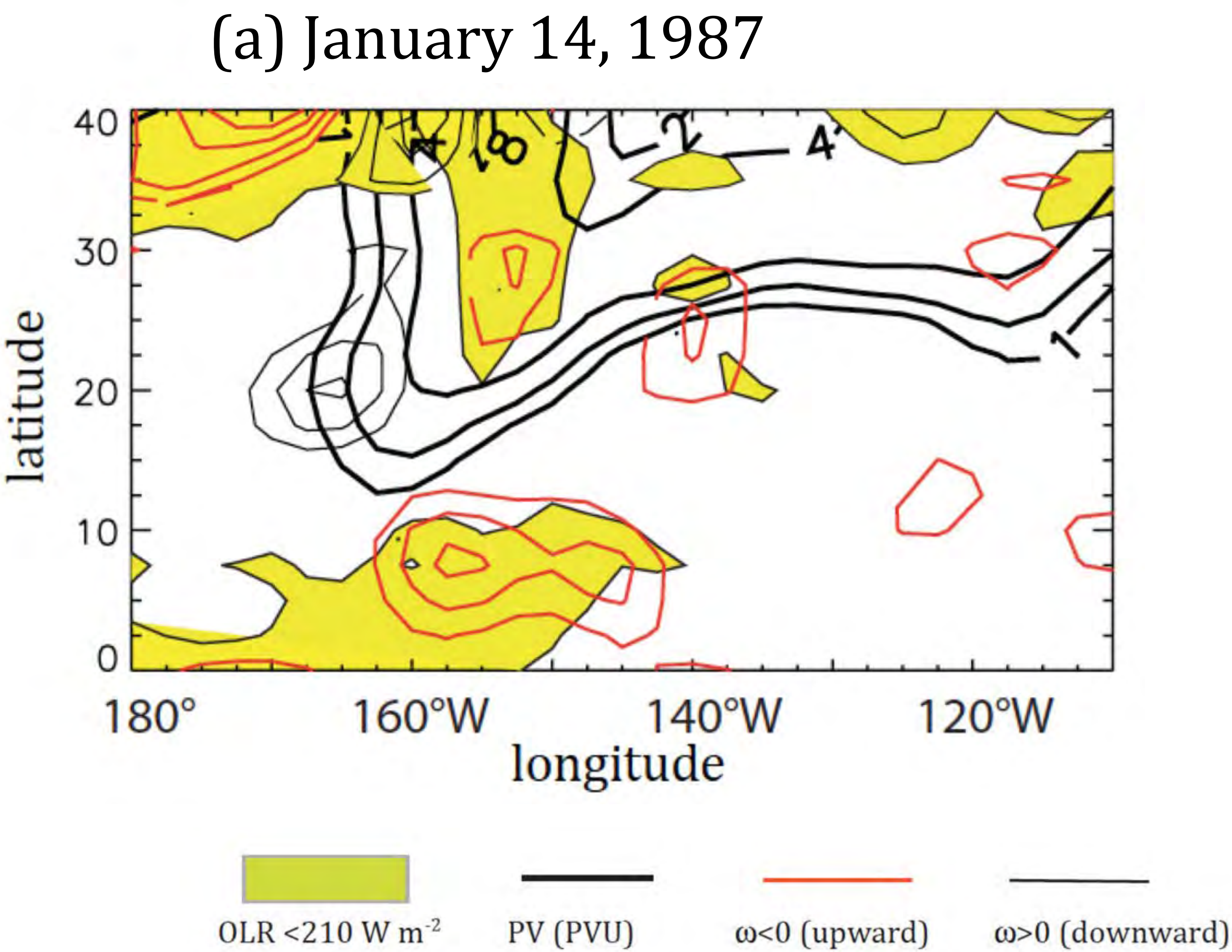


- Within the Westerly Duct, Rossby waves continually break in both NH and SH

Based on Funatsu and Waugh (2008)

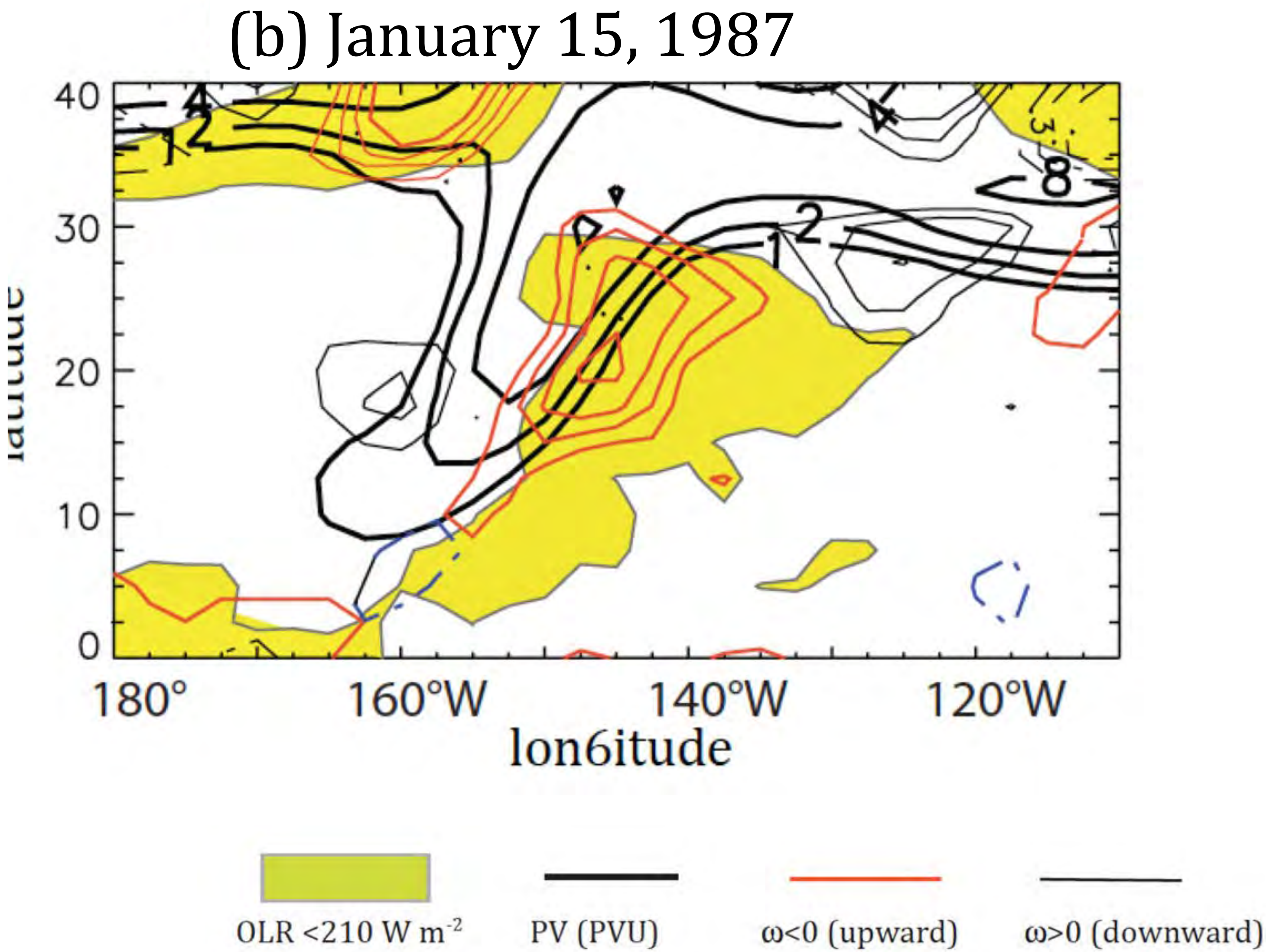
Impact of Breaking Ro-Wave into East Pacific

Funatsu and Waugh (2008)



Impact of Breaking Ro-Wave (PV intrusion) into East Pacific

Funatsu and Waugh (2008)



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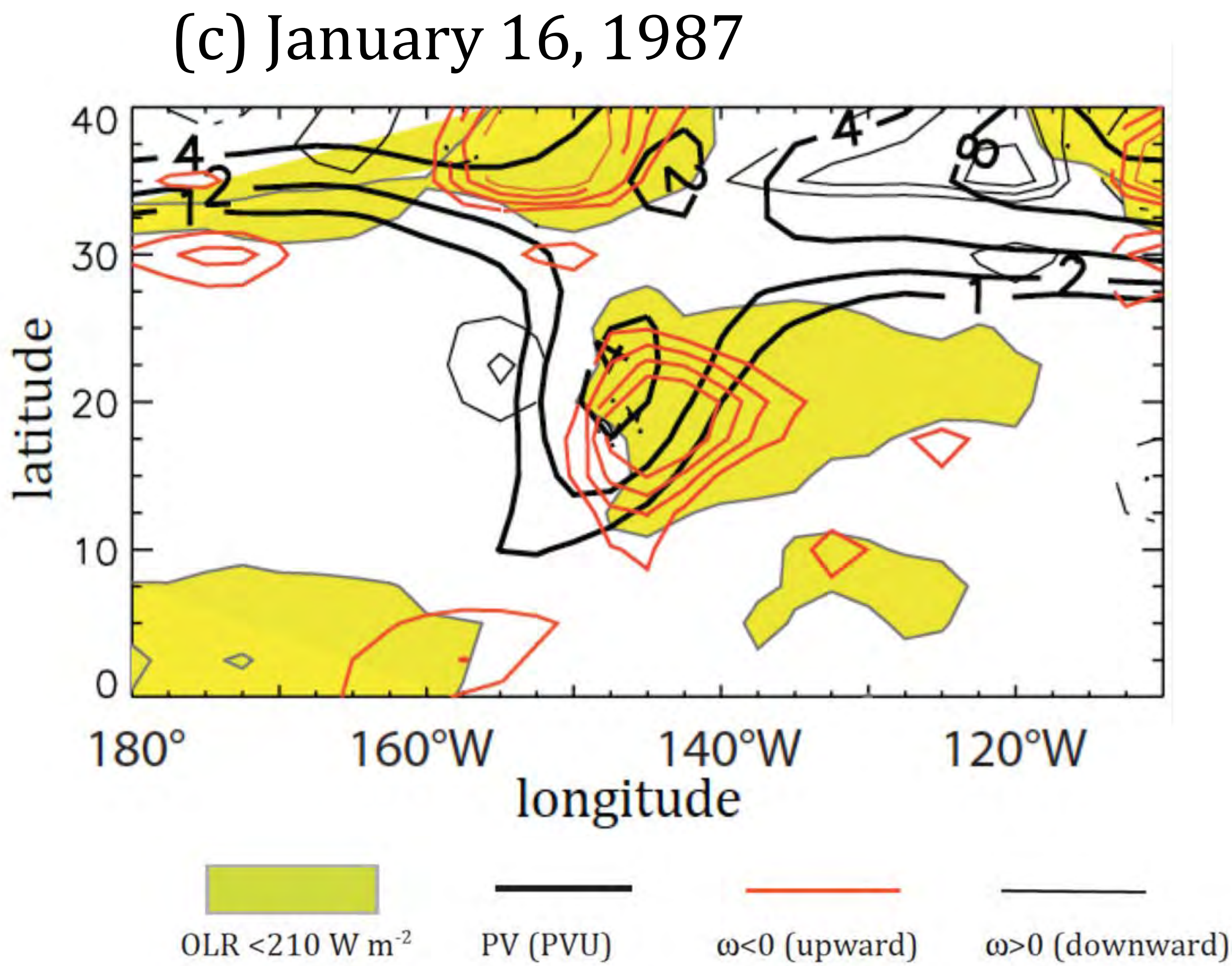
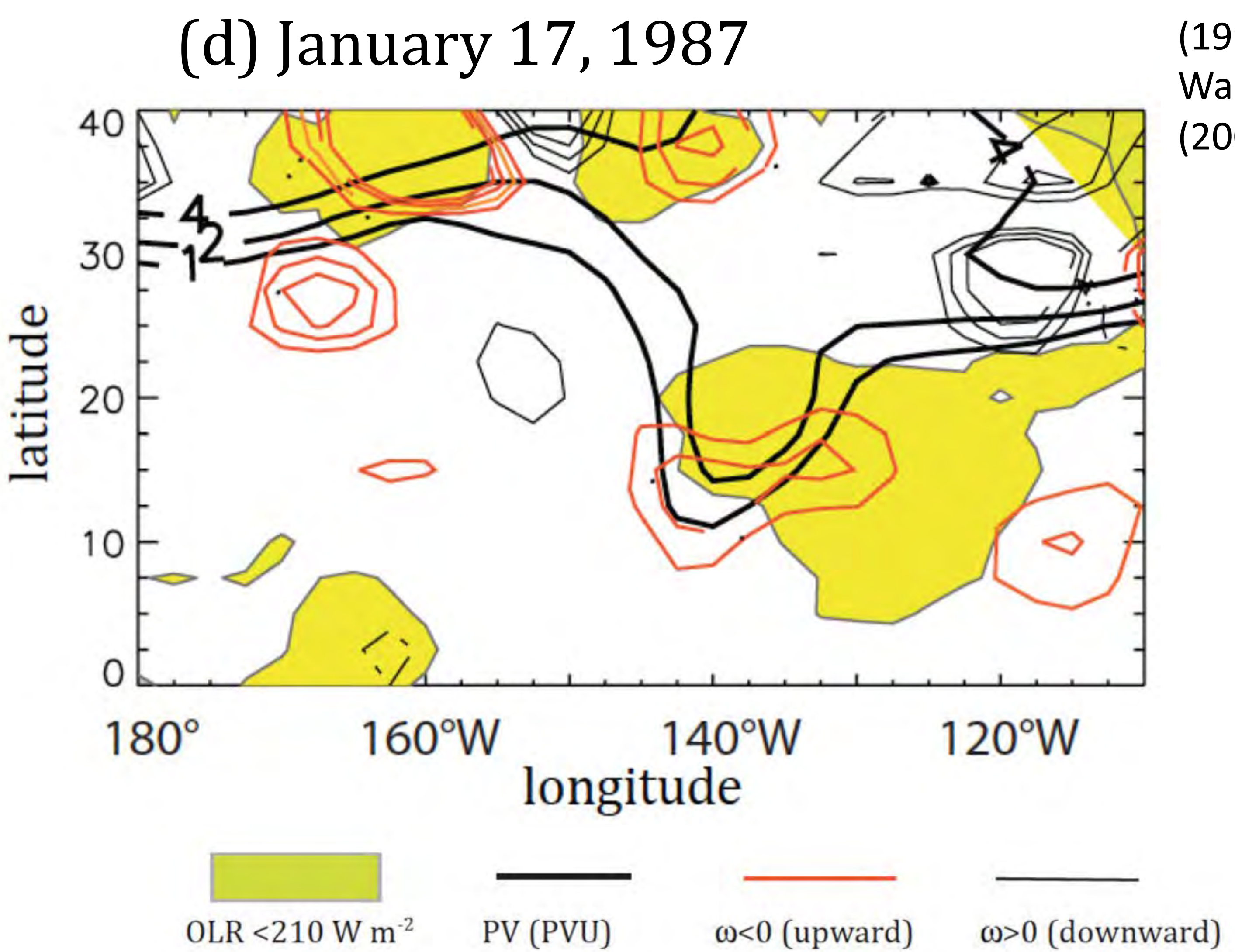


Impact of Breaking Ro-Wave (PV intrusion) into East Pacific

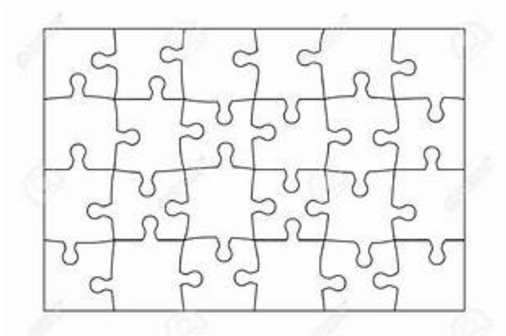
Funatsun and Waugh (2008) also Kiladis and Weikmann (1992), Kiladis (1998), Waugh and Funatsu (2003)



McIntyre (2008) described polar vortex as a wave-turbulence 'jigsaw picture' made up of:

- Regions of strong PV gradients where oscillatory modes dominate (e.g., waves on jet streams)
- Regions where Rossby waves break

Can we sought out McIntyre's (2008) jig saw picture



- Rossby wave breaking in WDs leading to advective equatorward PV fluxes

and:

- Divergent circulations (e.g., local Hadley overturning, monsoon heating), leads to advective PV fluxes poleward forcing of jets.

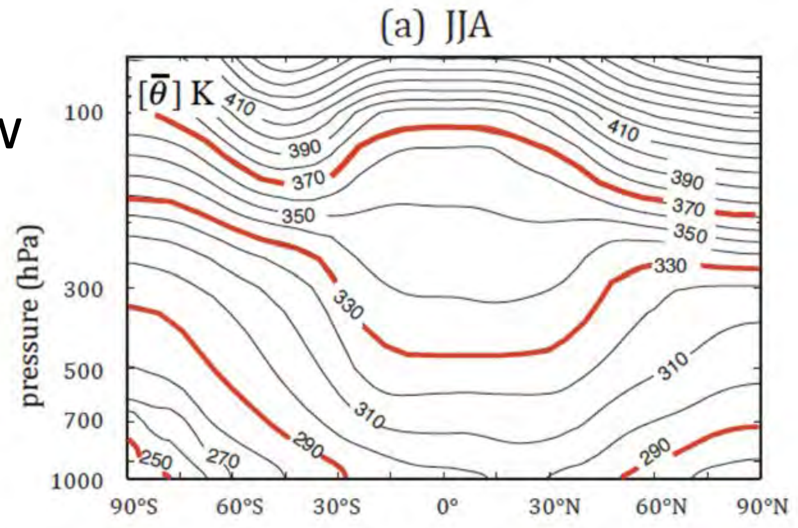
These regimes are related

An alternative potential vorticity perspective: *Potential vorticity substance*

Potential Vorticity (q) conserved

Only in adiabatic, frictionless flow

We require a quantity that is conserved even when there is dissipation and heating:



$$q_s = \sigma q$$ Potential Vorticity Substance

$$\sigma = -\partial p / \partial \theta / g$$ Isentropic Mass Density

Derivation of the Conservation of Potential Vorticity Substance Equation

$$\left(\frac{\partial}{\partial t}+\tilde{V}+\nabla_{\theta}\right)q \;=\frac{q}{\sigma}\frac{\partial}{\partial\theta}\left(\sigma\dot{\theta}\right)-\frac{1}{\sigma}\tilde{k}\bullet\nabla_{\theta}\times\left(\dot{\theta}\frac{\partial\tilde{V}}{\partial\theta}-\tilde{\mathcal{F}}\right)$$

Potential vorticity equation

$$\frac{\partial\sigma}{\partial t}+\nabla_{\theta}\bullet\left(\sigma\tilde{V}\right)+\frac{\partial}{\partial\theta}\left(\sigma\dot{\theta}\right)=0$$

Mass conservation

Combining gives

$$\boxed{\frac{\partial\left(\sigma\,q\,\right)}{\partial t}+\nabla\bullet\mathcal{J}_{T}=0 \qquad \text{or} \qquad \frac{\partial\left(q_{\;s}\right)}{\partial t}+\nabla\bullet\mathcal{J}_{T}=0}$$

Impermeability theorem

$$\mathcal{J}_{T}=\mathcal{J}_{A}+\mathcal{J}_{\dot{\theta}}+\mathcal{J}_{\tilde{\mathbb{F}}}$$

Total PVS flux: advective + heat + dissipative processes.

Allows an understanding of communication between latitudes through the *impermeability theorem (IT)* of Haynes and McIntyre (1987, 1990).

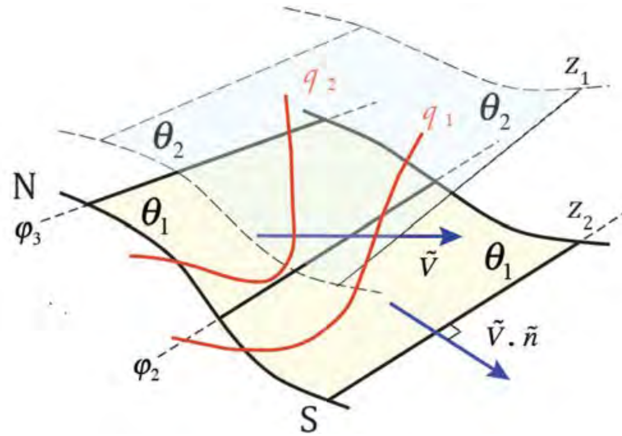
McIntyre

Haynes

Theorem states:

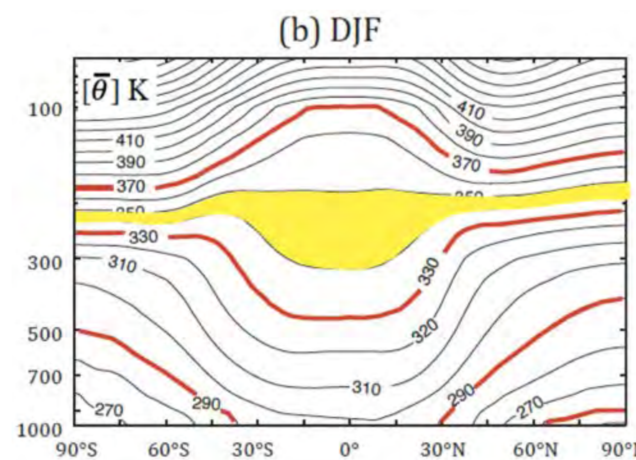
(i) There are no sources or sinks of PVS between isentropes that don't intercept the ground.

(ii) PVS flux across isentropes cannot occur



IT theorem states that integrated flux across latitude circle is zero even diabatic heating and dissipation:

$$\iint \nabla \cdot \left(\sigma\, q\, \tilde{V}\right) dA = \oint \left(\sigma\, q\, \tilde{V}\right) \cdot \tilde{n}\, dl = \boxed{2\pi a \cos\phi_0 [\sigma\, q\, \tilde{V}] = 0}$$



I.e., $\boxed{\left[q_s \tilde{V}\right] = 0}$

See Ortega et al. (2018) and Webster (2020) for details

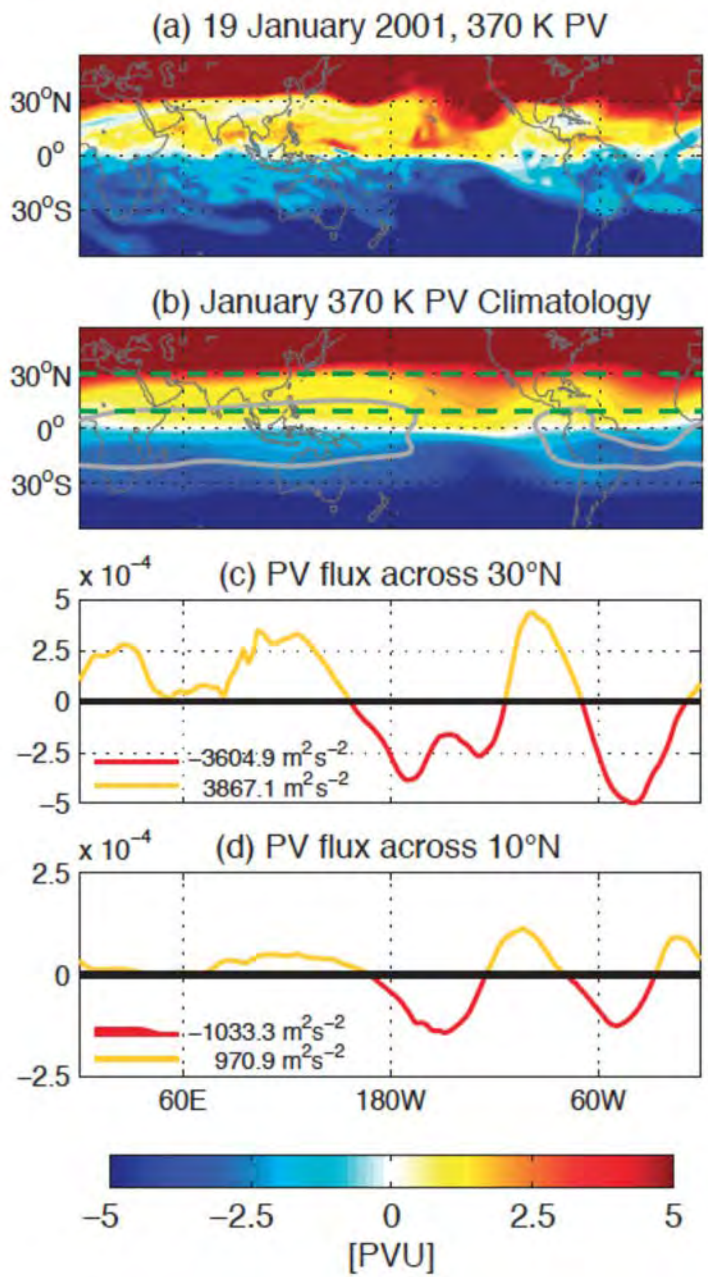
Observed mean PVS fluxes (January)

Snapshot
Jan, 21, 2001

Mean January
2001

Mean Flux
across 30°N

Mean Flux
across 10°N



- Zonally averaged PV fluxes across 30°N near zero.
- Similarly at 10°N.
- Maximum equatorial PV fluxes occur in westerly duct with recursive Rossby waves.
- Poleward flux of PV balanced by equatorward flux.

Ortega et al., 2018

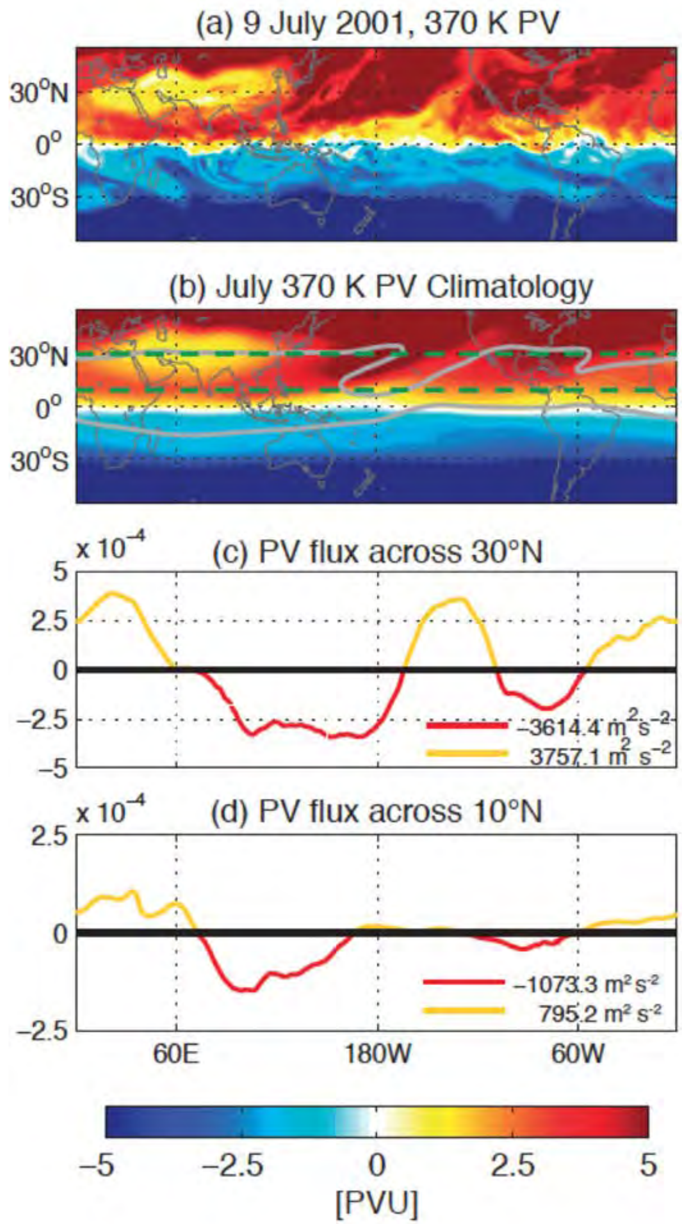
Observed PV fluxes (July)

Snapshot
Jul 9, 2001

Mean July
2001

Mean Flux
across 30°N

Mean Flux
across 10°N

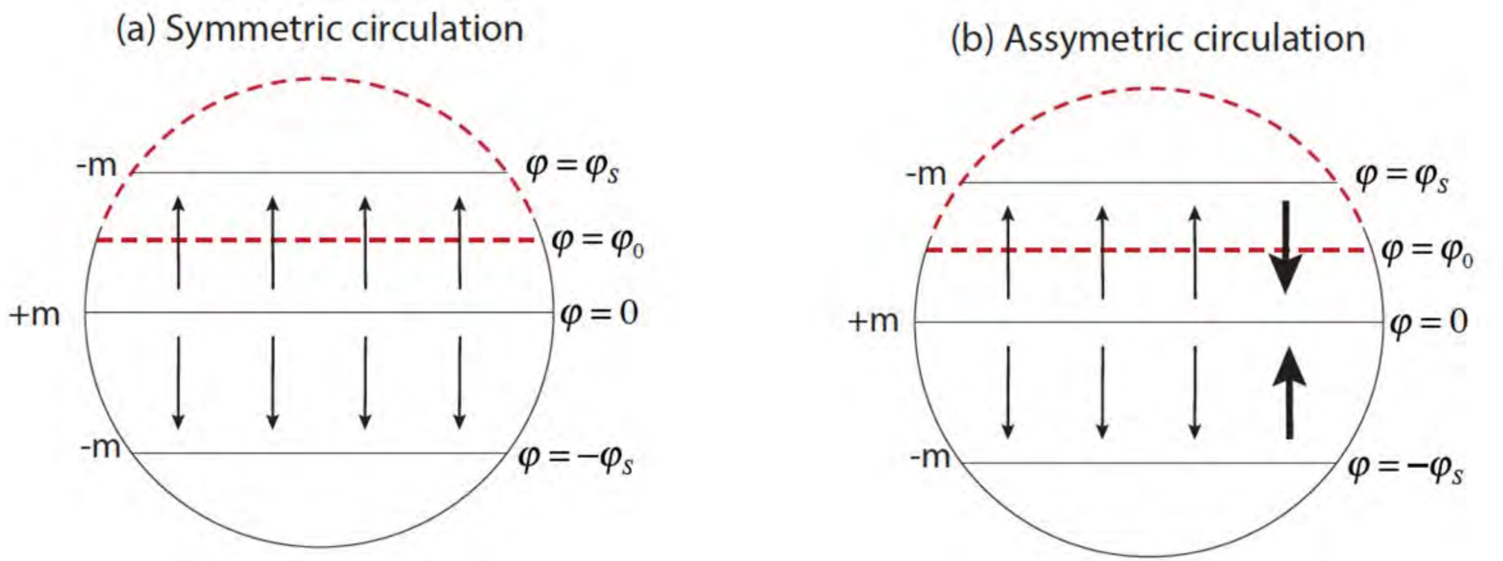


- PV fluxes across 30°N and 10°N are almost balanced as in the winter case.
- Maximum equatorial PV fluxes associated with the Tropical Upper-Tropospheric Trough (TUTT)
- Recursive Rossby waves break in N. Pacific and cycle around the Asian Monsoon Gyre
- Overall, poleward flux of PV balanced by equatorward flux.

Ortega et al., 2018

Now consider two situations:

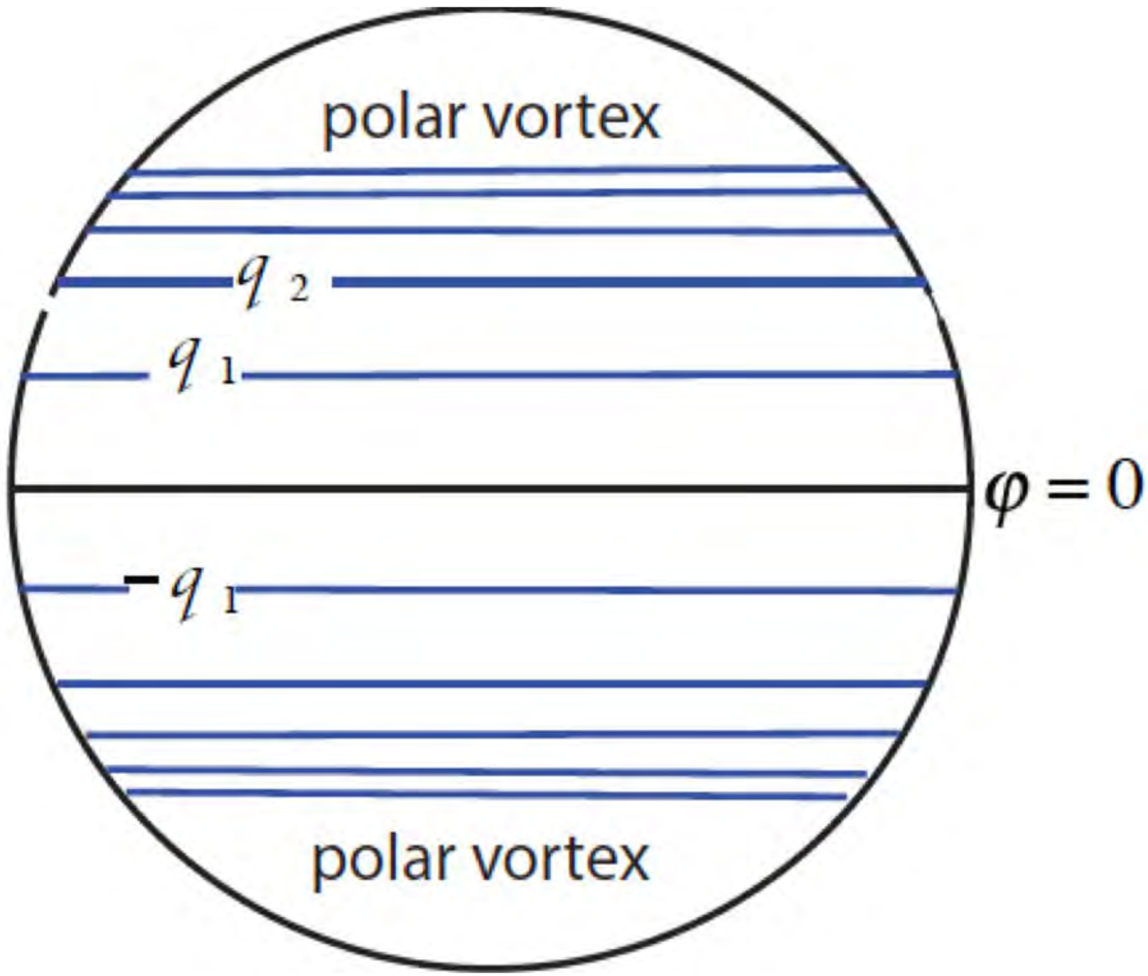
- zonally symmetric model (e.g., Held and Hou 1980) and,
- zonally asymmetric model.



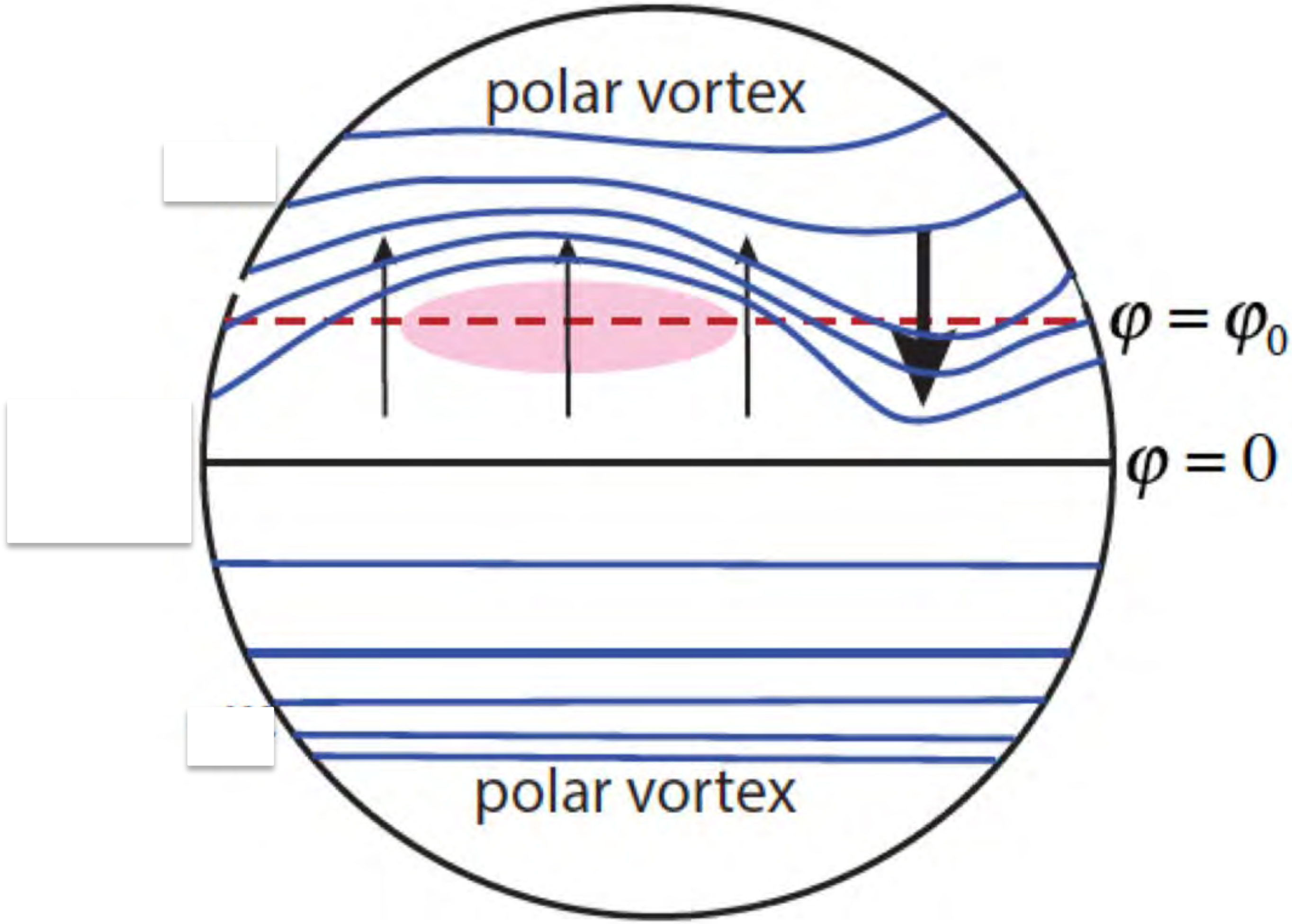
(a) Zonally symmetric solution (pure Hadley): $V > 0$ in (e.g.) NH then for conservation, PVS flux =0 everywhere!

(b) If V has a poleward component then an equatorward PV flux must exist somewhere to compensate for poleward flux

System with no heating



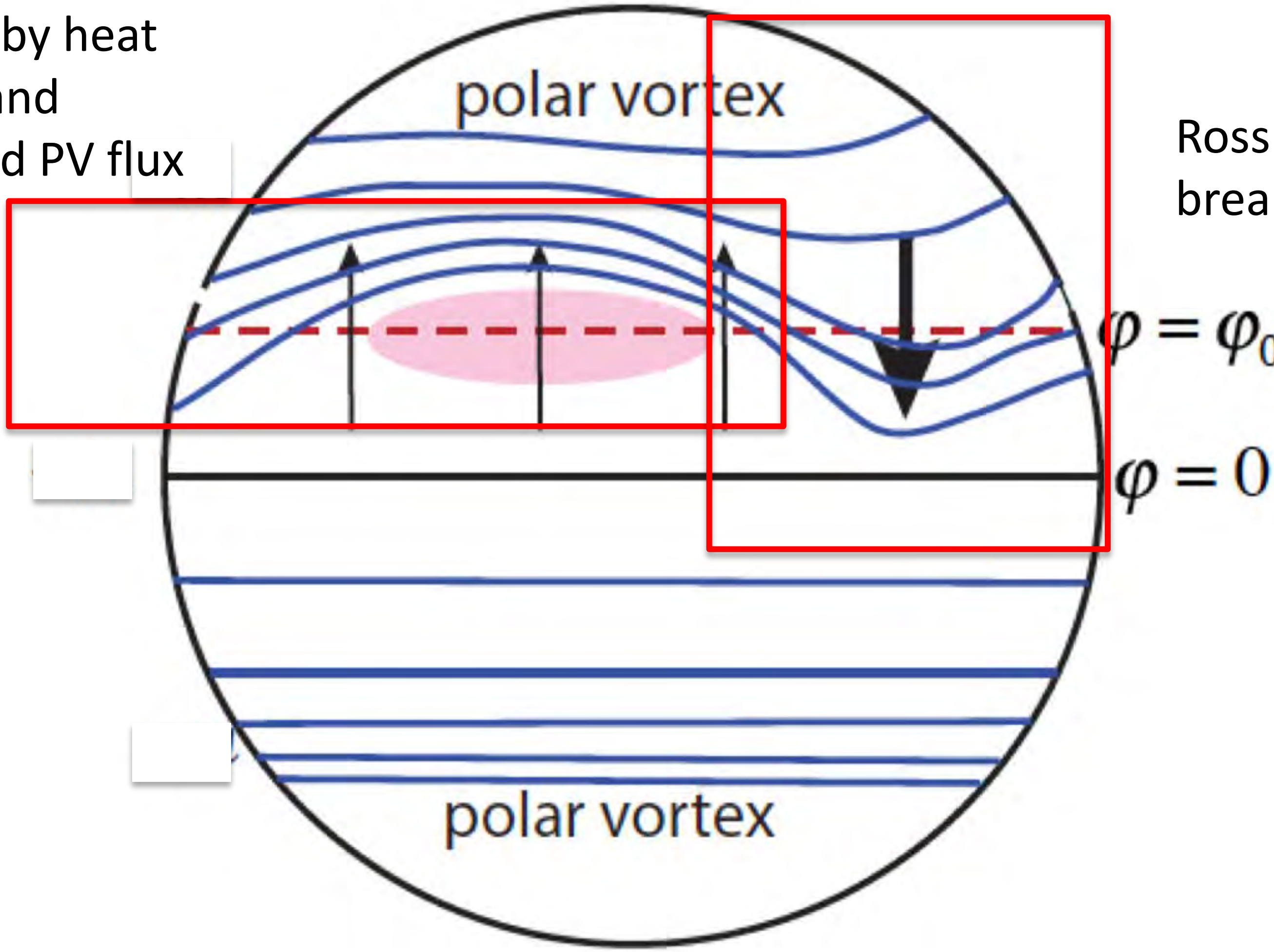
Introduction of heat source



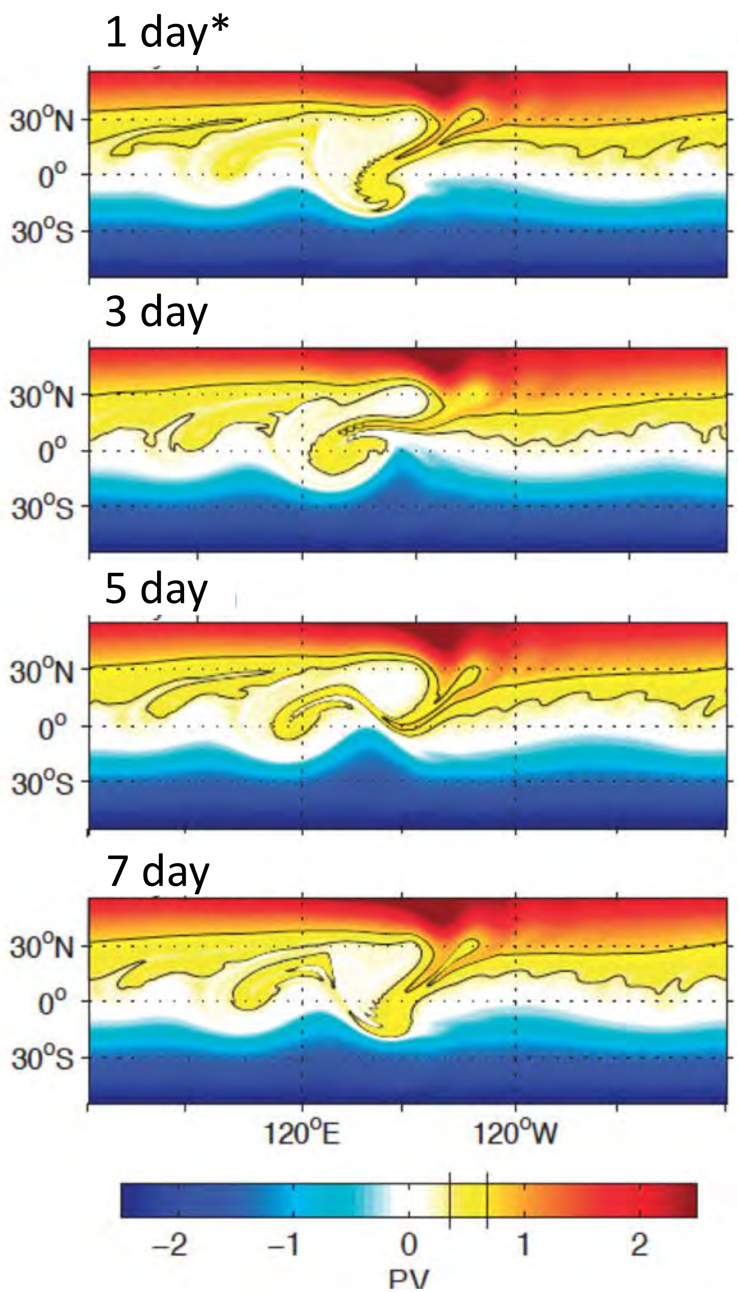
Westerly maximum created by heat source and poleward PV flux

Waves in Westerly Duct or integrated WD returns PV to equator

Rossby wave breaking zone



Westerly Duct serves to return PVS to the equator (thus satisfying the impermeability theorem) and is anchored downstream of westerly jet location of breaking Ro-waves

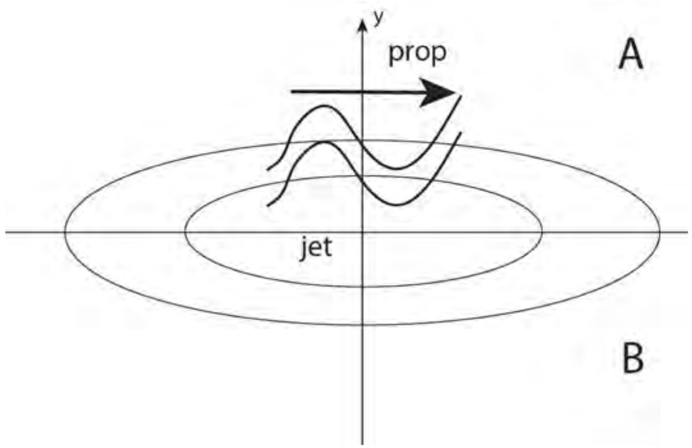


(*scaled)

Breaking Rossby Waves appear to be important but why do they break?

- A Rossby wave is said to *break* when potential vorticity contours are irreversibly deformed, leading to the mixing of the potential vorticity field instead of the propagation of the wave.
- Why does this "irreversible distortion" occur downstream of the westerly jet?

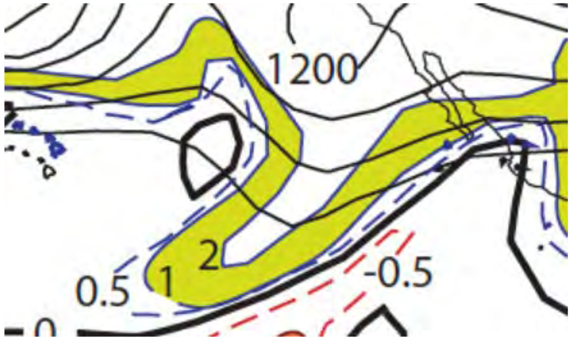
Breaking Rossby waves:



$$d\mathcal{U}/dx<0$$
$$d\mathcal{U}/dy<0$$

$$d\mathcal{U}/dx<0$$
$$d\mathcal{U}/dy>0$$

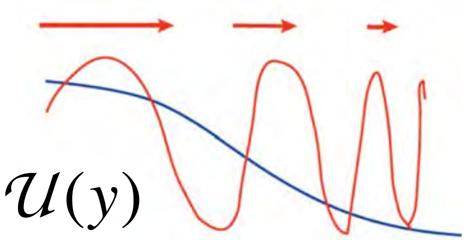
- Wave propagates into a strong, spatially varying basic state



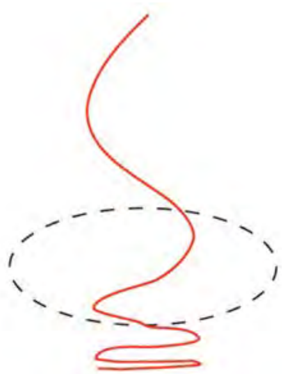
Along a ray path assuming constant frequency:

$$dk/dt=-kd\mathcal{U}/dx$$
$$dl/dt=-kd\mathcal{U}/dy$$

- Severe distortion in exit zone of the jet.
- Compressed zonally.
- Extended poleward.
- Compressed equatorward.



A, B

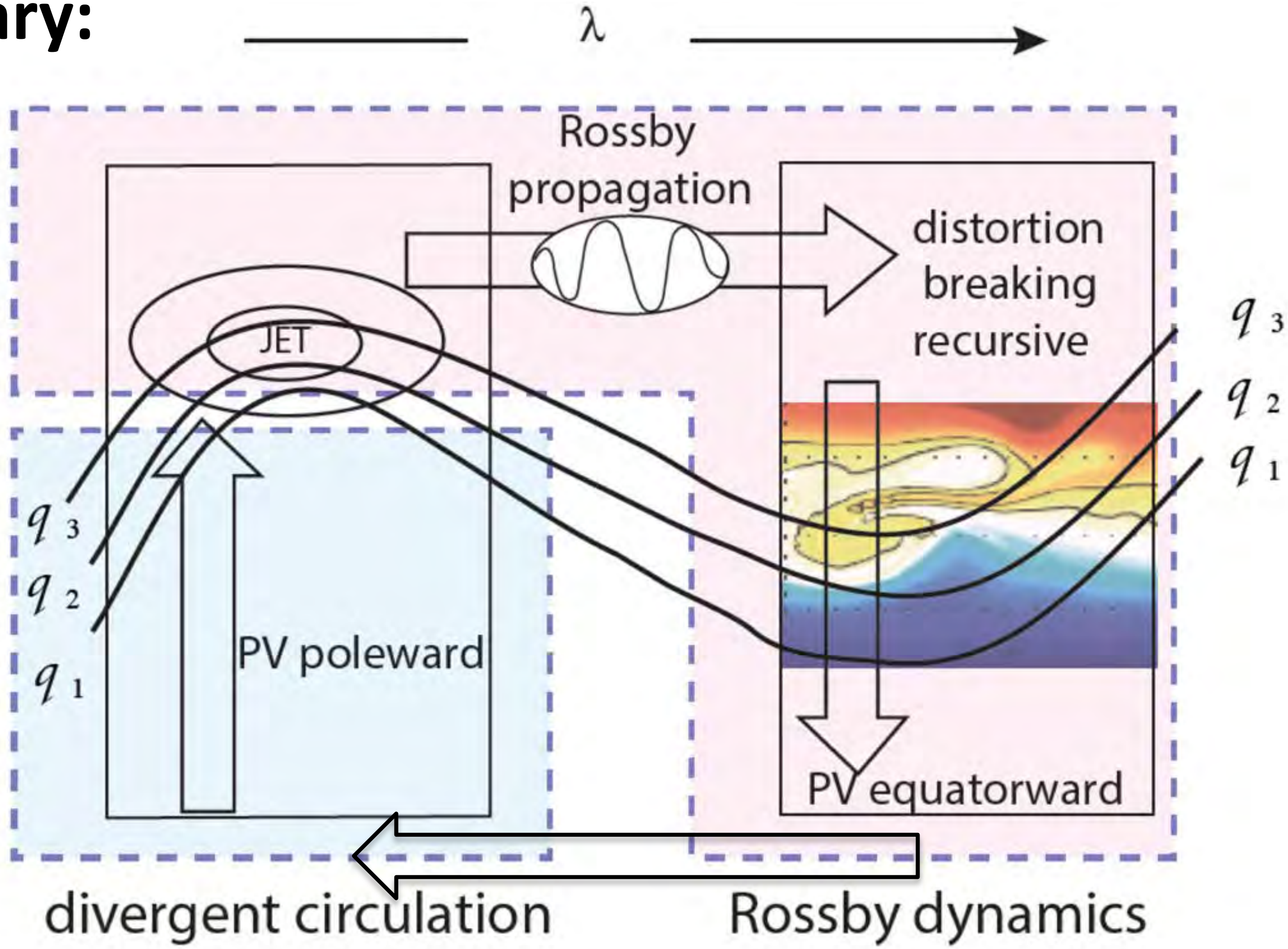


A

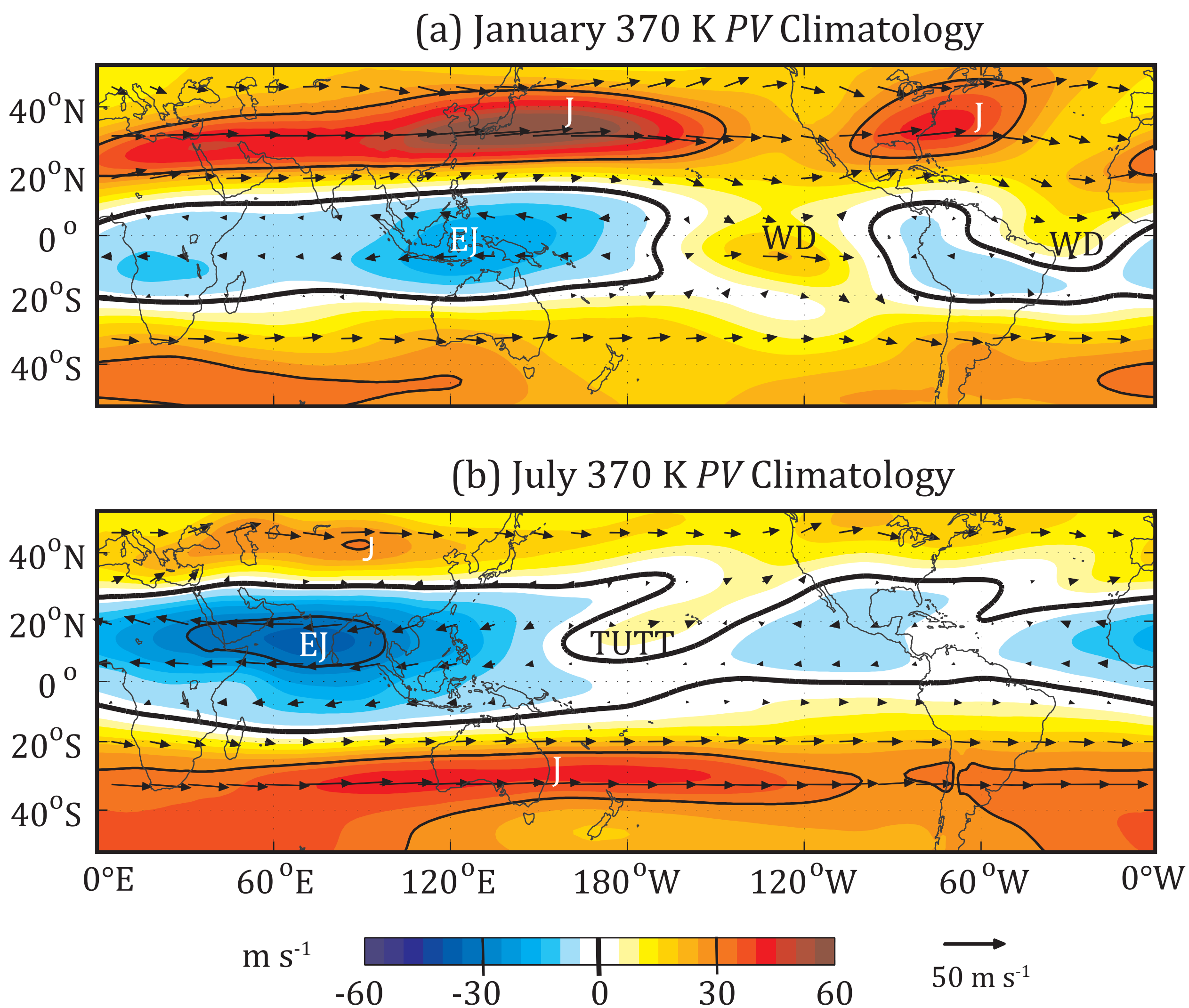
B

Bretherton and Garratt (1968), Bretherton (1978), Webster and Chang (1987)

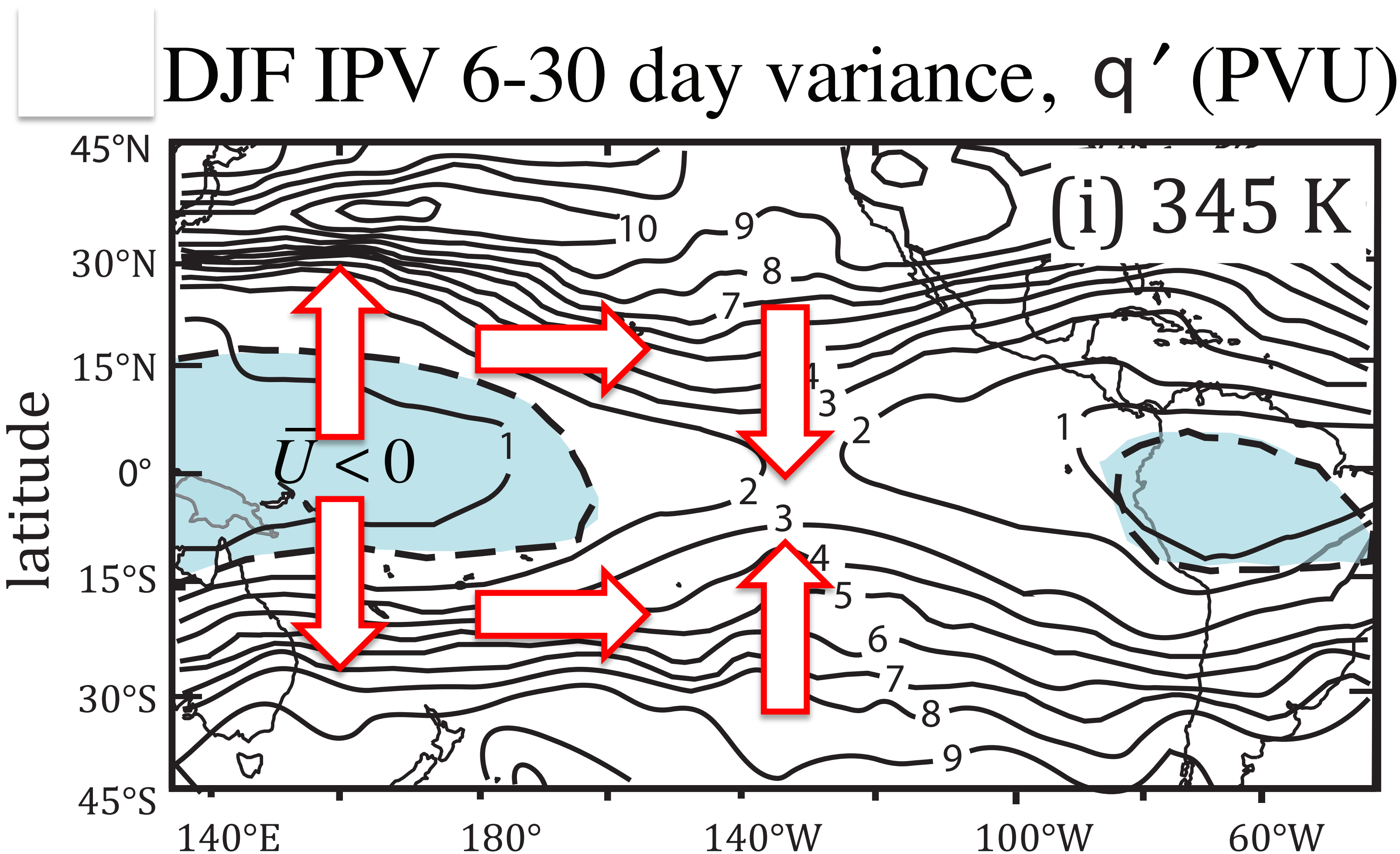
Summary:



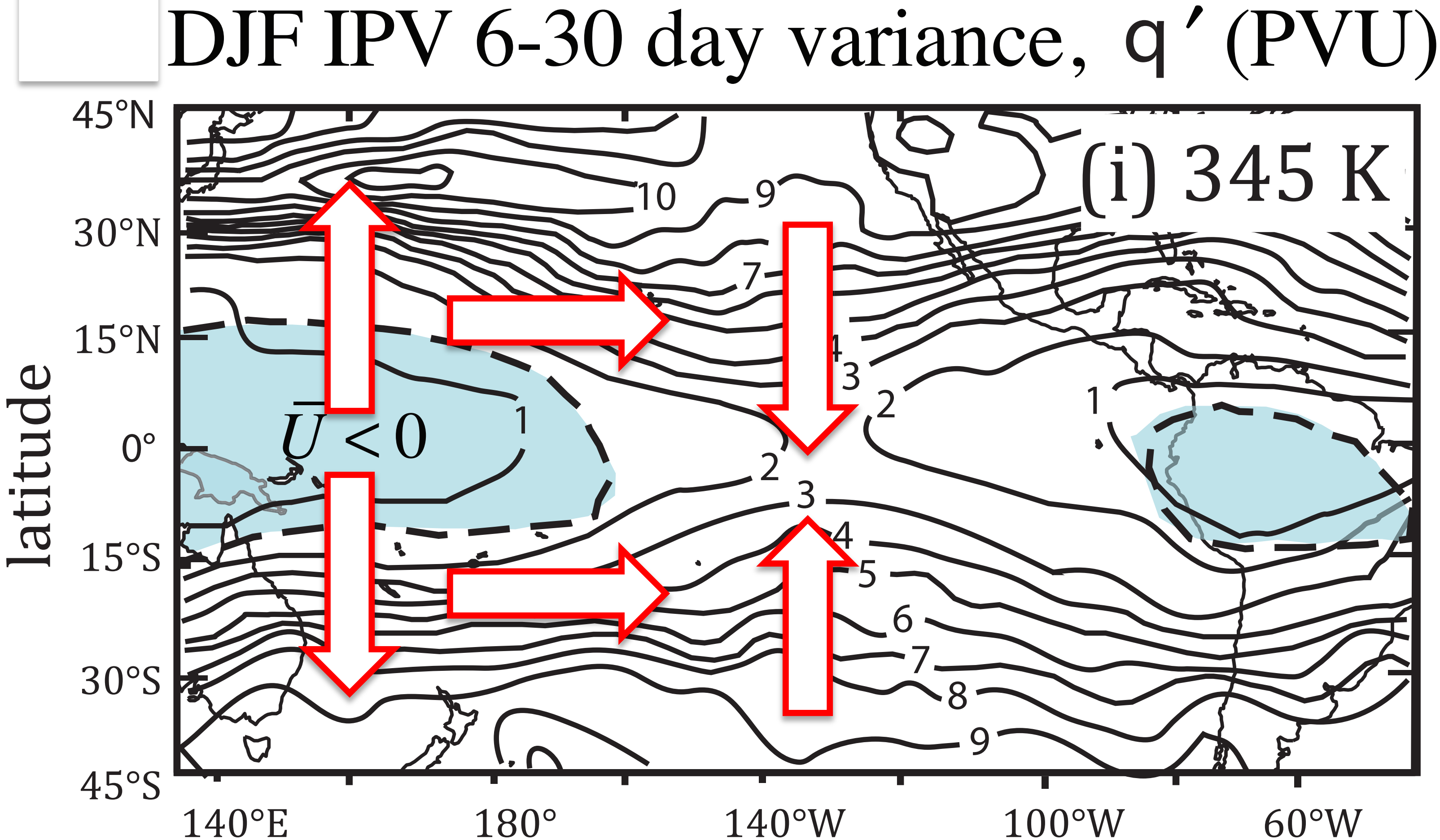
- Divergent circulations and Rossby wave dynamics collaborate in the interaction of the tropics and extratropics
- Westerly ducts and TUTTS serve as conduits of PV providing a global balance as per the impermeability concept


(a) January 370 K *PV* Climatology
(b) July 370 K *PV* Climatology
40°N
20°N
0°
20°S
40°S
J
EJ
WD
TUTT
0°E
60°E
120°E
180°W
120°W
60°W
0°W
m s⁻¹
-60
-30
0
30
60
50 m s⁻¹

PVS conservation is a global concept



PVS conservation is a global concept



Increased heating in Western Pacific will change fluxes will influence both hemipheres

Some tentative conclusions

Weather: "….. describing the evolution of a high-frequency phenomenon and determining its impact on other regions and phenomena.."

Climate: "…. determining system equilibration (or evolution) relative to internal and external forcing…."

This is work in progress but it does seem that common constraints do exist for weather and climate both regionally and globally and that these exist within the framework developed by Haines and McIntyre

(expanded on in Webster 2020)