On the coupling between moisture and the large-scale circulation

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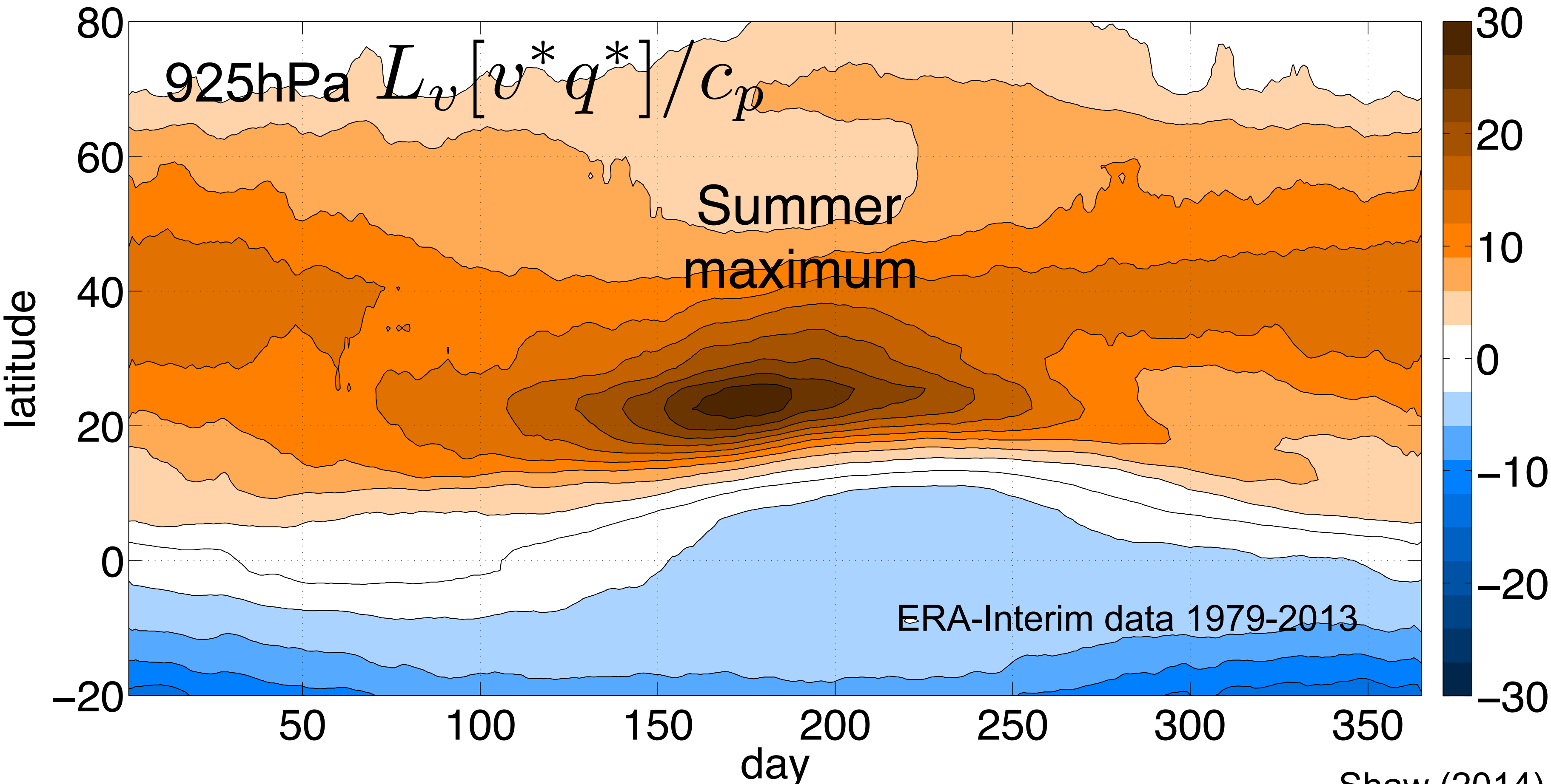
Motivation

- Very successful theories for dry atmospheric dynamics (instabilities, pseudomomentum, EP flux, supercriticality, etc., see Vallis 2006).
- Open questions involve consideration of the effects of moisture.
- As a first step focus on moisture transport: Understand role of horizontal eddy transport in the large scale circulation.
- Vertical transport (convection), clouds and water vapor also important.

Outline

1) Dominance of summertime eddy moisture transport
2) Eddy transport in idealized aquaplanet simulations (QG scaling, abrupt circulation transition)
3) Response to climate change

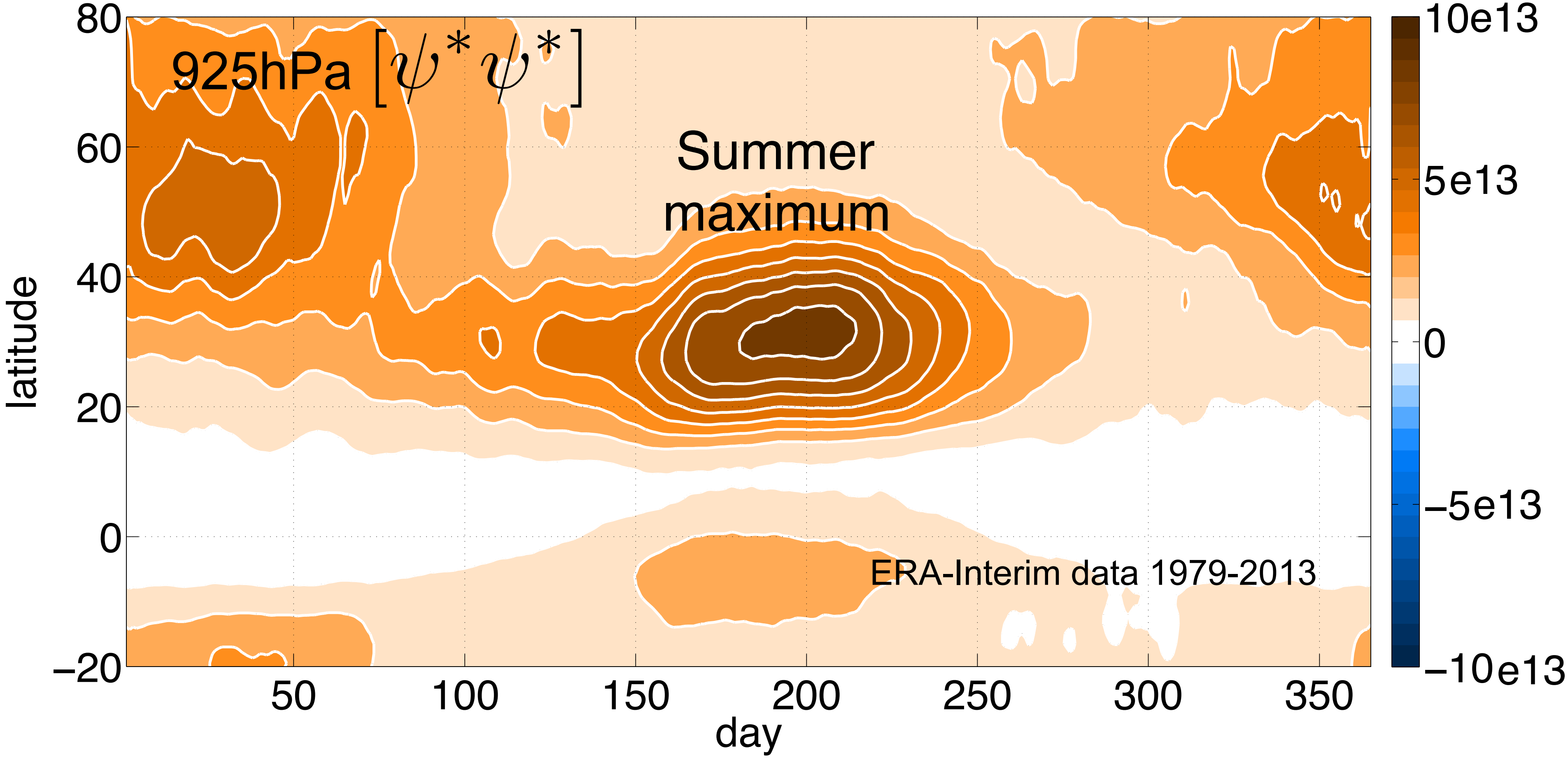
Seasonal cycle of eddy moisture transport



Shaw (2014)

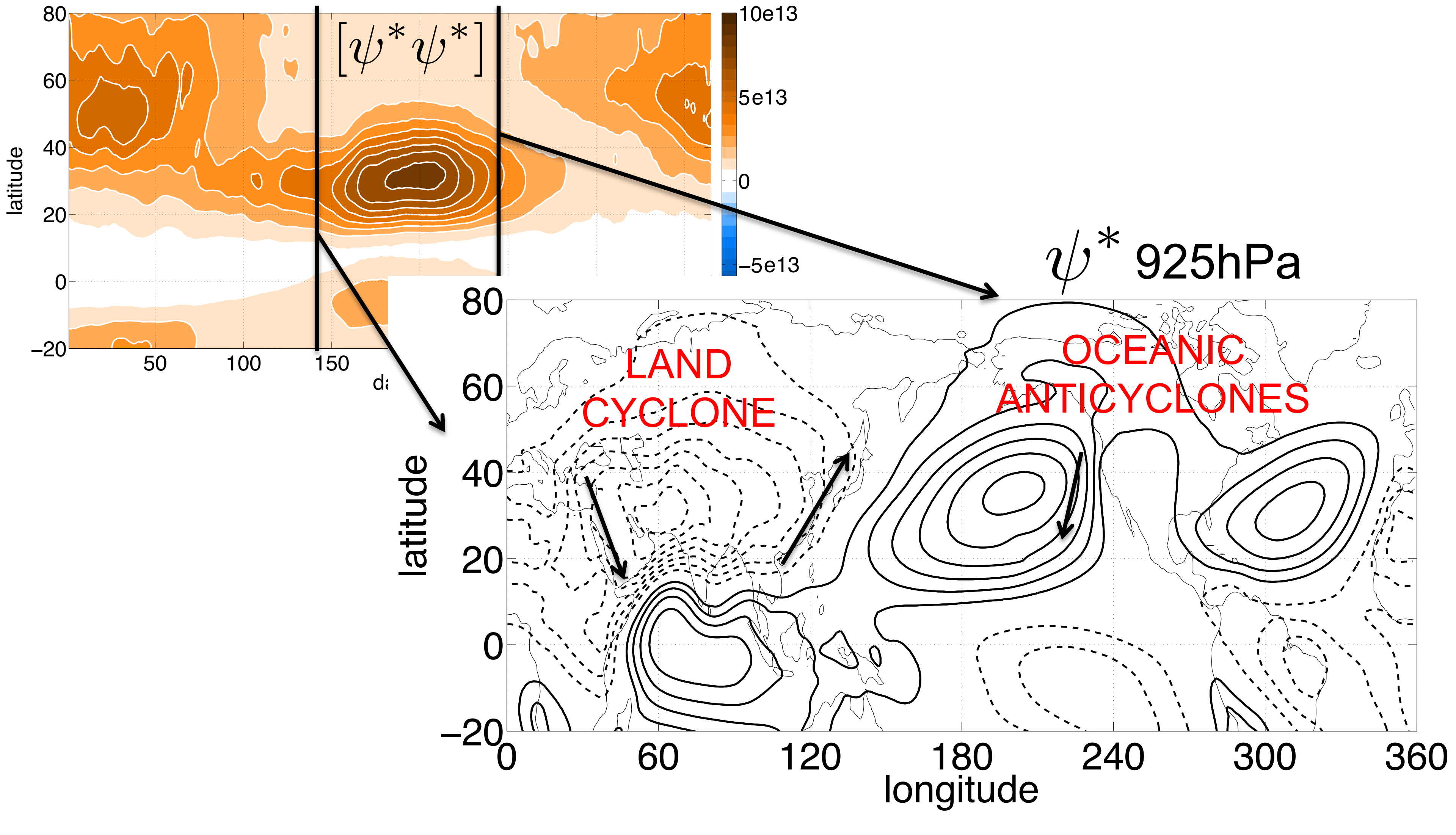
Large momentum transport in the upper troposphere

Reflects growth of planetary-scale rotational flow



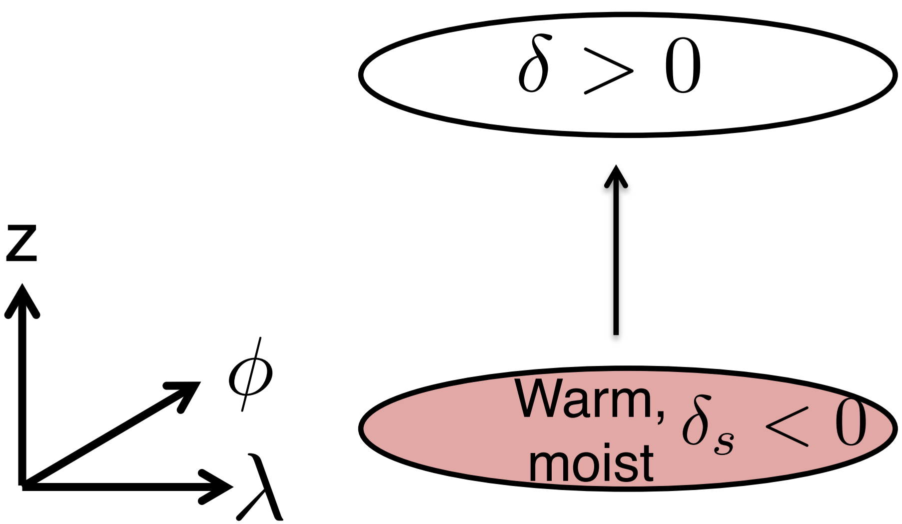
Occurs in conjunction with northward shift of ITCZ and jet stream

Reflects growth of planetary-scale rotational flow



Ingredients of the summertime circulation

- Maximum solar insolation
- Land-sea contrasts in T and moist entropy ($s_b = c_p \ln \theta_e^*$)
- Thermal gradient + friction = low-level convergence, upper level divergence
- Rotational flow & eddy transport



$$\mathbf{v}_s = \frac{(T_s - T_t)}{2\Omega \sin\phi} \mathbf{k} \times \nabla(s_{b_{crit}} - s_b)$$

$$\delta_s \approx -\gamma \zeta_s$$

Emanuel (1995),
Plumb & Hou (1992)

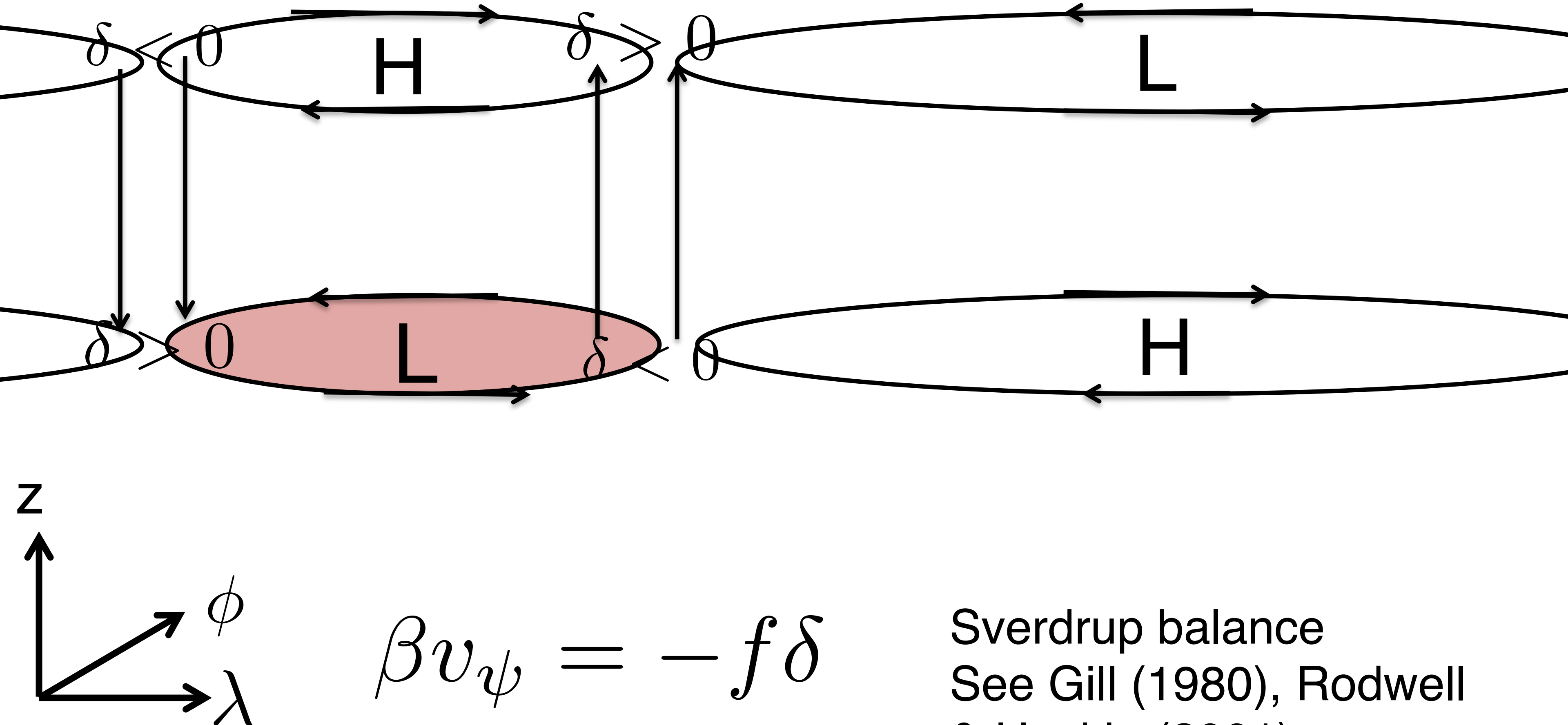
Divergence leads to Rossby wave generation

$$\left(\frac{\partial}{\partial t} + \mathbf{v}_\psi \cdot \nabla\right)\zeta_a = -\mathbf{v}_\chi \cdot \nabla\zeta_a - \zeta_a\delta + F$$

Rossby-wave source
Sardeshmukh & Hoskins (1988)

$$\mathbf{v} = \mathbf{v}_\psi + \mathbf{v}_\chi$$
$$\delta = \nabla \cdot \mathbf{v}_\chi = \nabla^2\chi$$
$$\zeta = \nabla \times \mathbf{v}_\psi = \nabla^2\psi$$
$$\zeta_a = f + \zeta$$

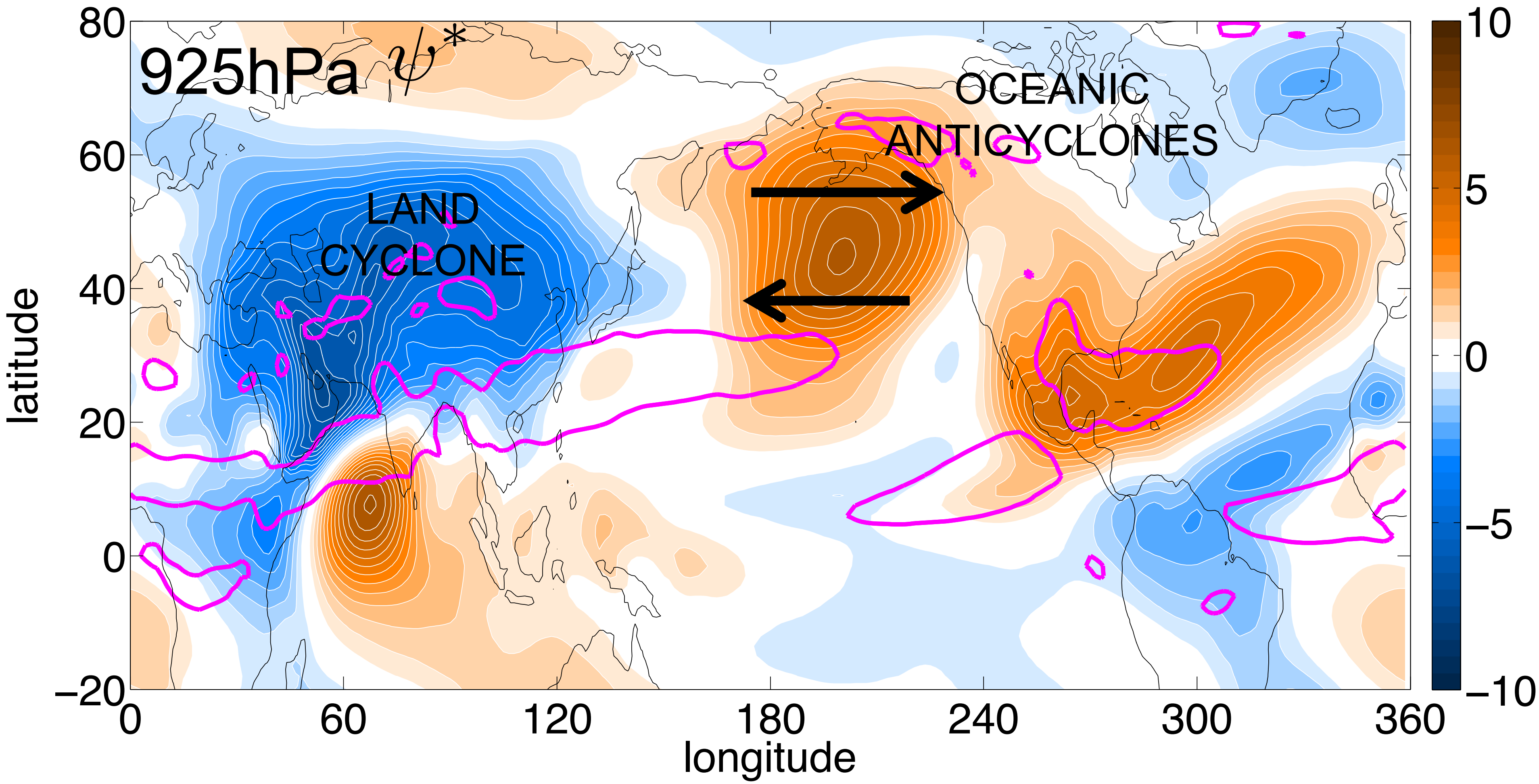
Stationary wave circulation



$$\beta v_{\psi} = -f\delta$$

Sverdrup balance
See Gill (1980), Rodwell & Hoskin (2001)

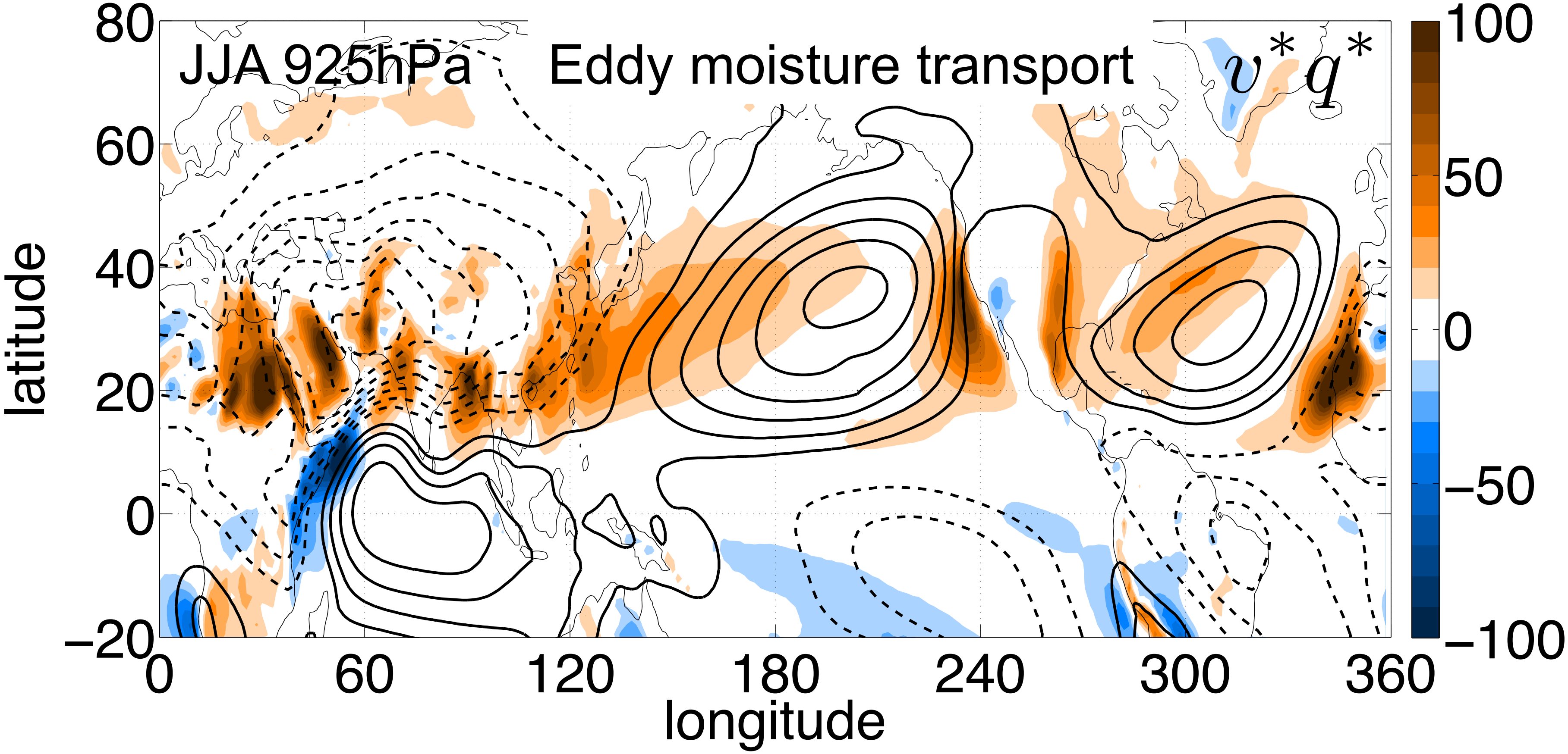
July - May



Magenta = $|\nabla \theta_e^*| > 0$

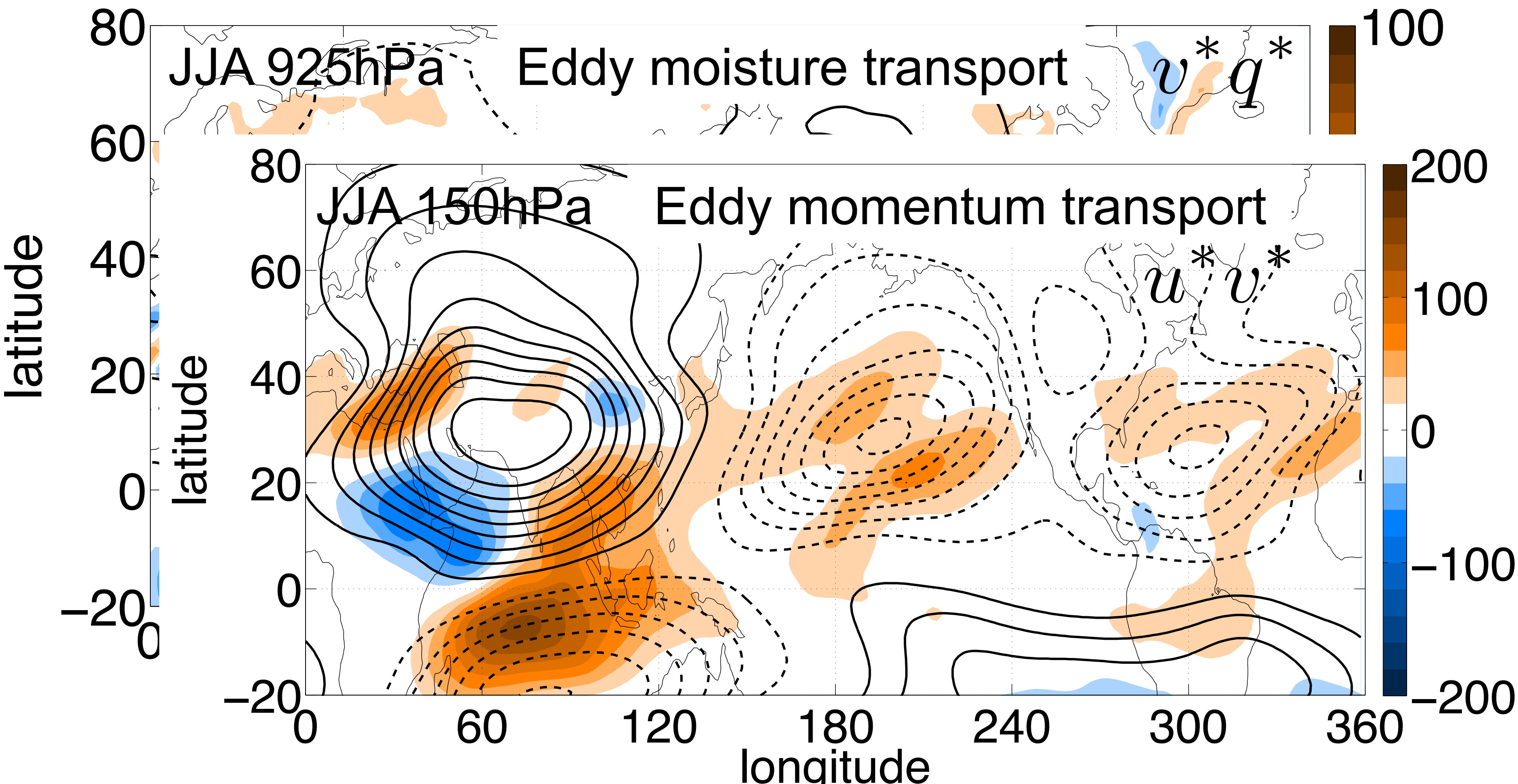
Opposite pattern for Sept-Aug

Rotational flow leads to transport



Eddy moisture transport dominates over zonal mean transport (Shaw 2014, Chou and Neelin 2003)

Rotational flow leads to transport



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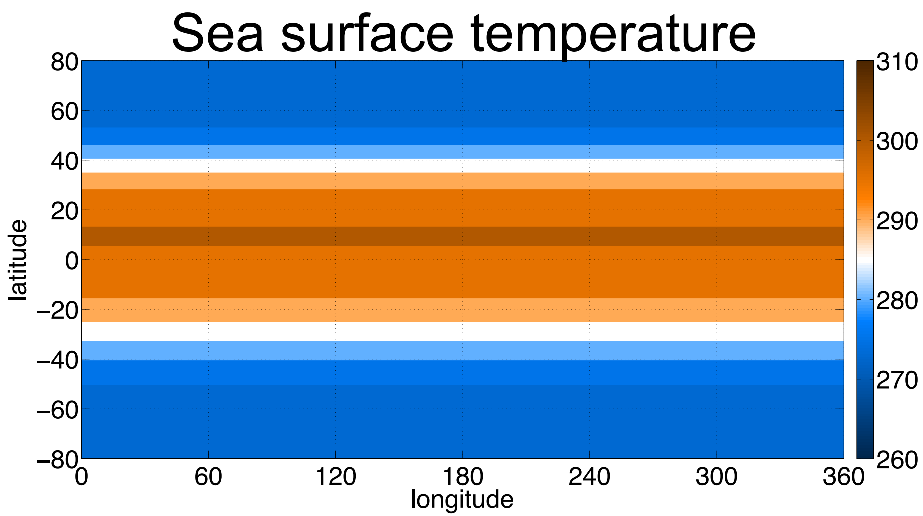
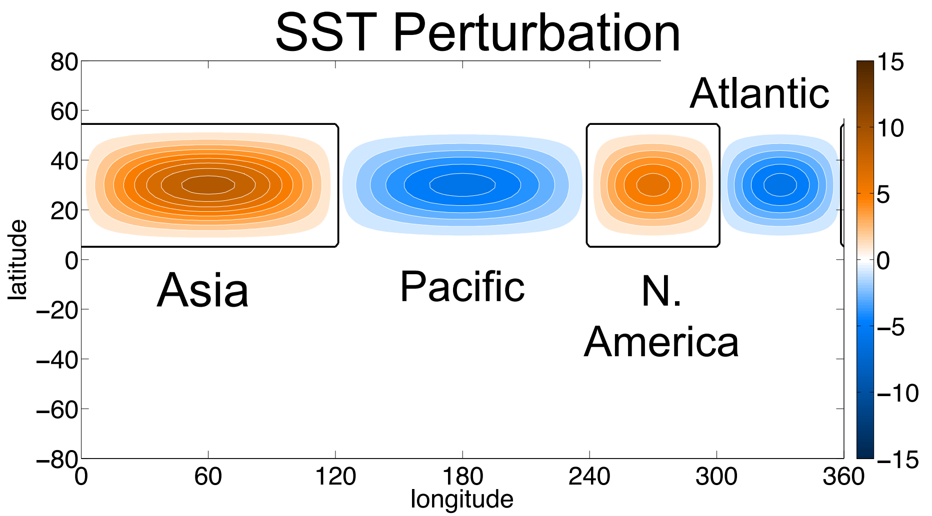
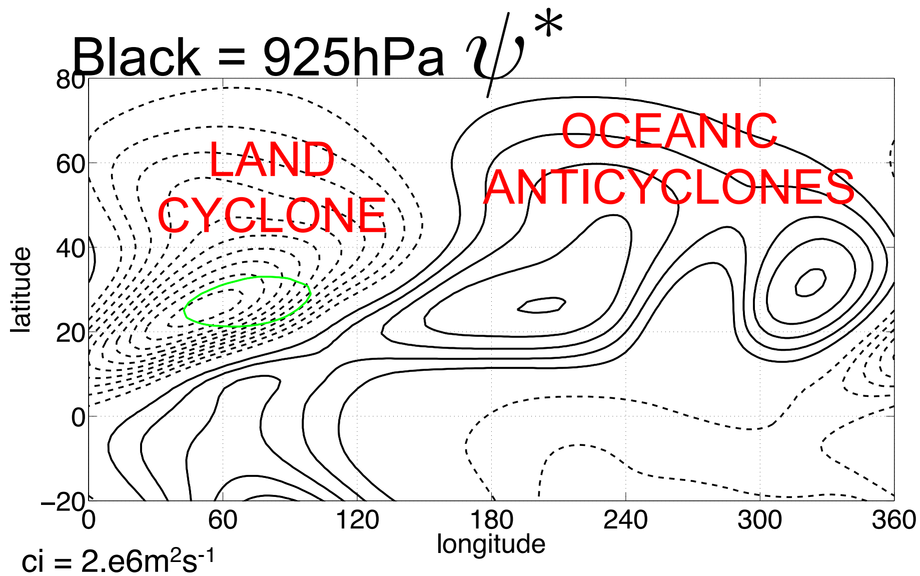
Aquaplanet simulations

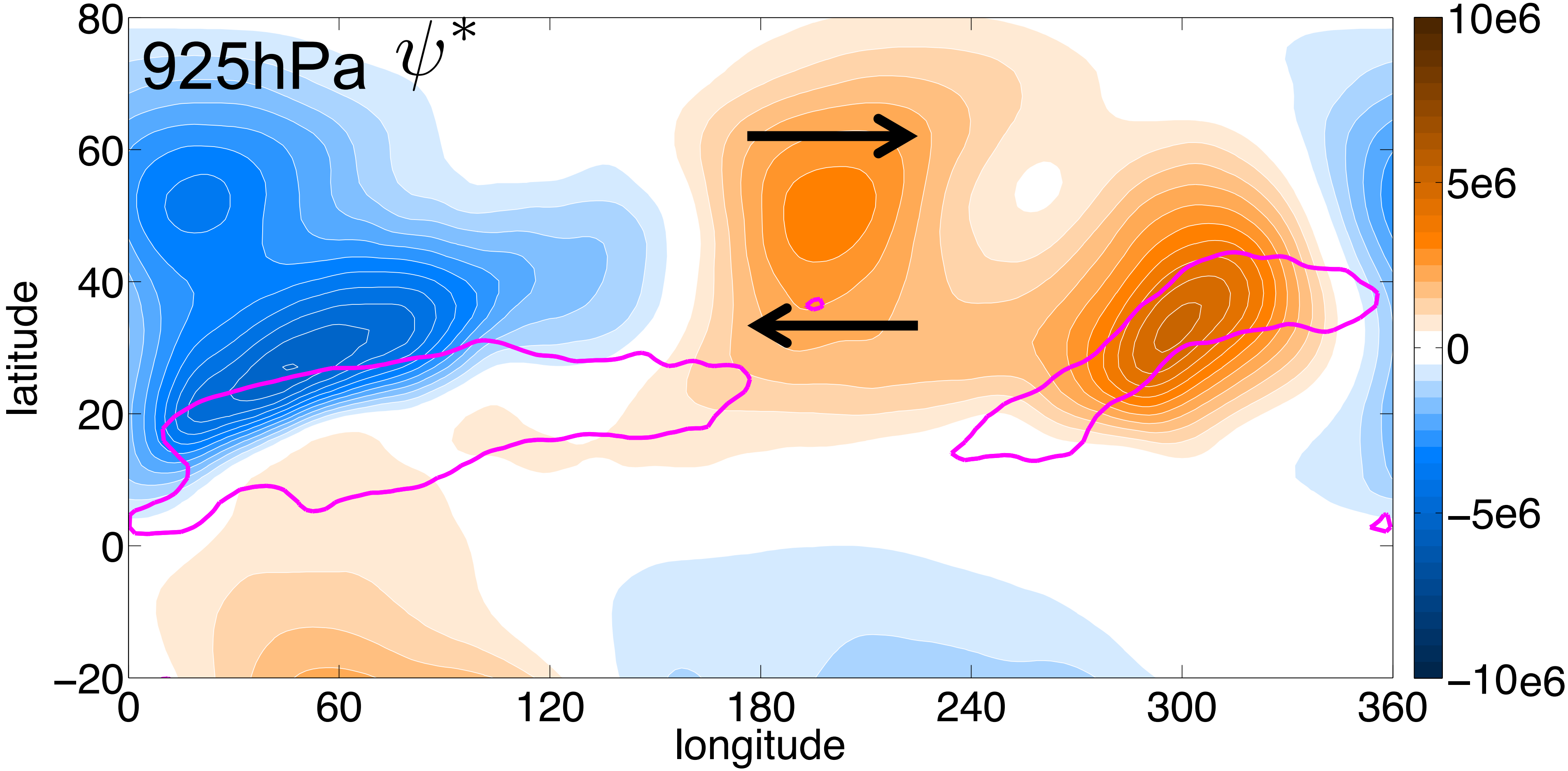




Neale & Hoskins (2001)



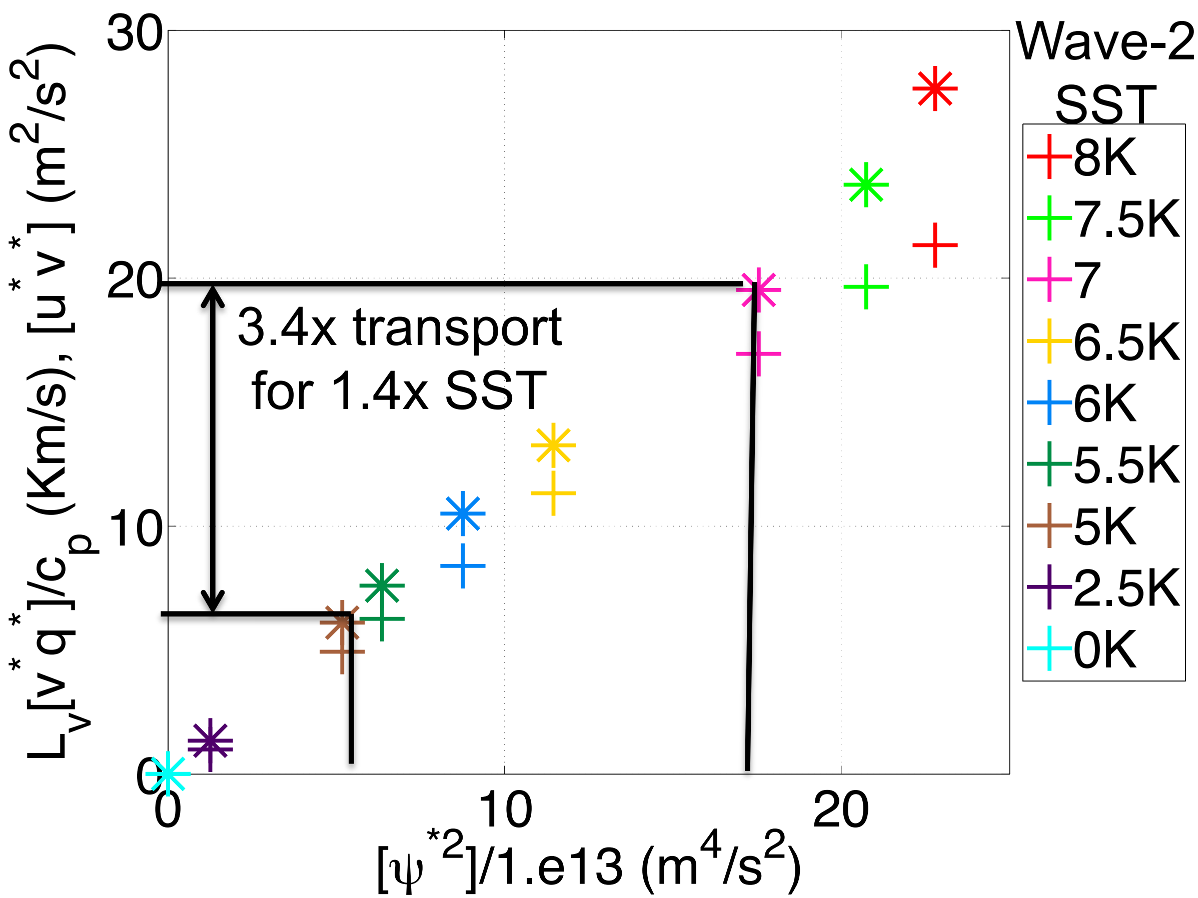
Warm Asia



Opposite pattern when Asia is cooled

Wave transport grows quadratically with surface forcing consistent with QG theory

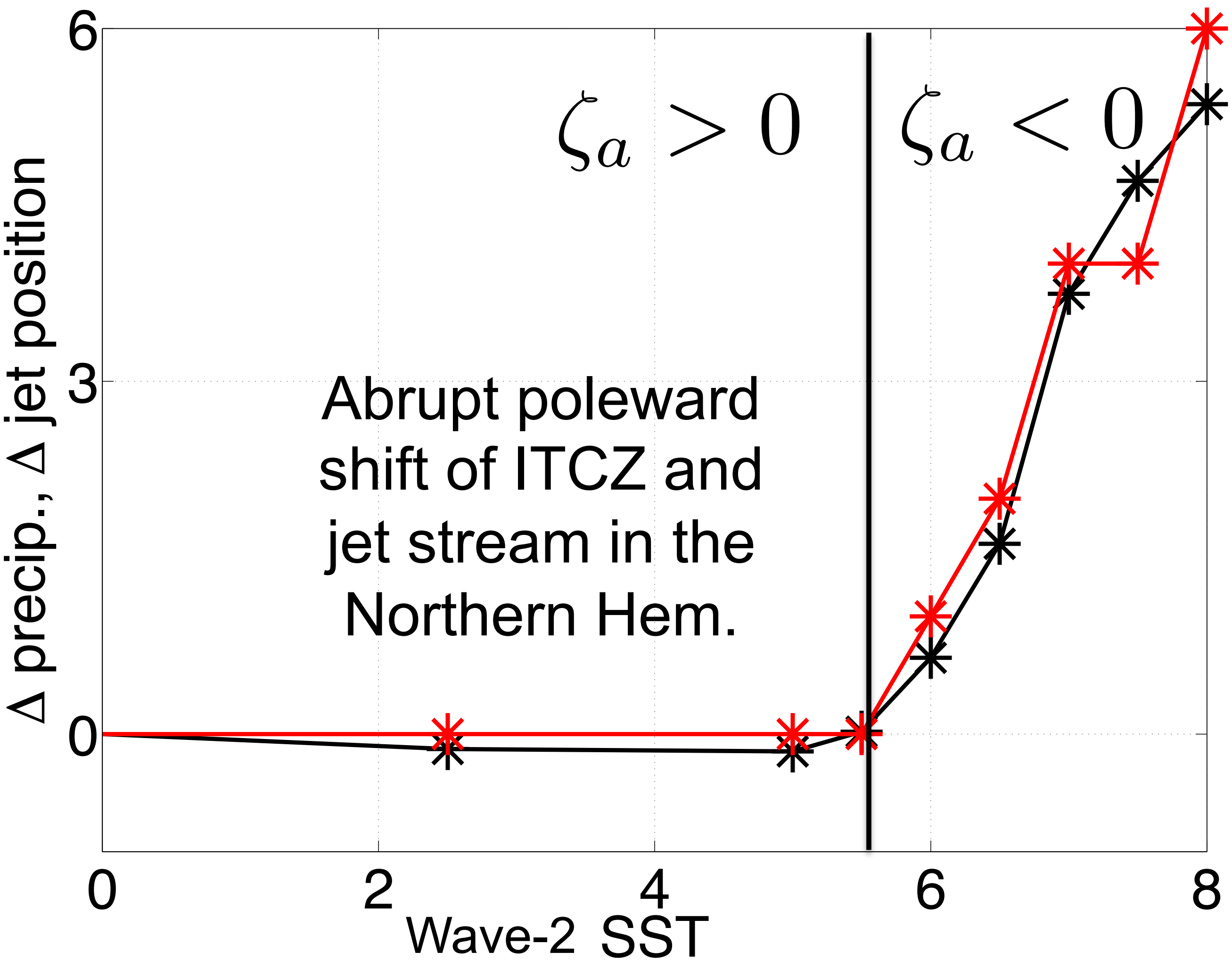
$$\psi^* \sim O(SST) \qquad \psi \sim g(T_s - T_t)(s_{b_{crit}} - s_b)/f$$



$$[u^* v^*] = -k\ell|\psi^* \psi^{*\dagger}|$$

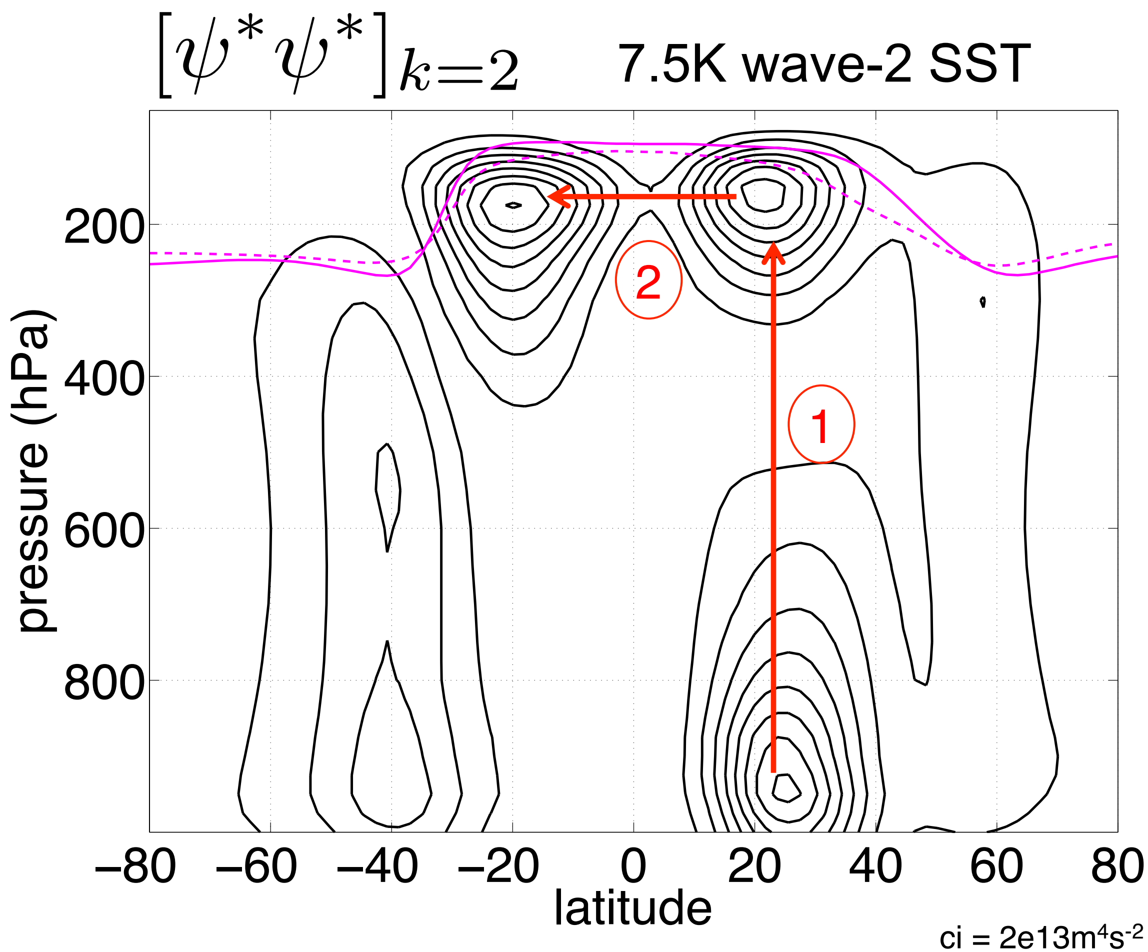
$$[v^* q^*] = k\gamma|\psi^* \psi^{*\dagger}|$$

Aquaplanet exhibits regime transition



Criticality occurs via stationary wave growth and meridional wave propagation in the upper troposphere (Shaw 2014)

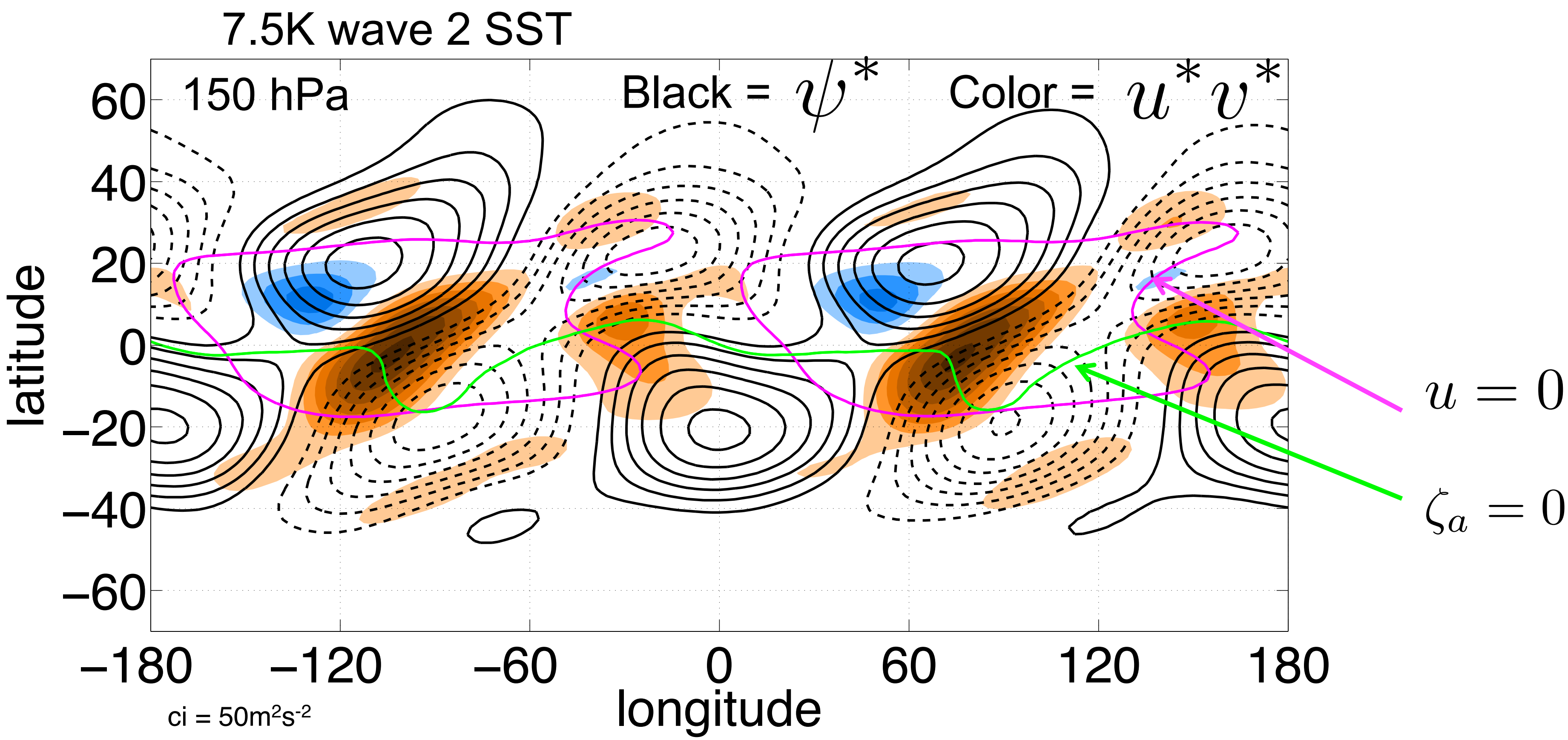
Stationary wave dynamics couple lower and upper troposphere



① Vertical coupling in the subtropics

② Cross equatorial wave propagation

Meridional wave propagation accounts for reversal of absolute vorticity

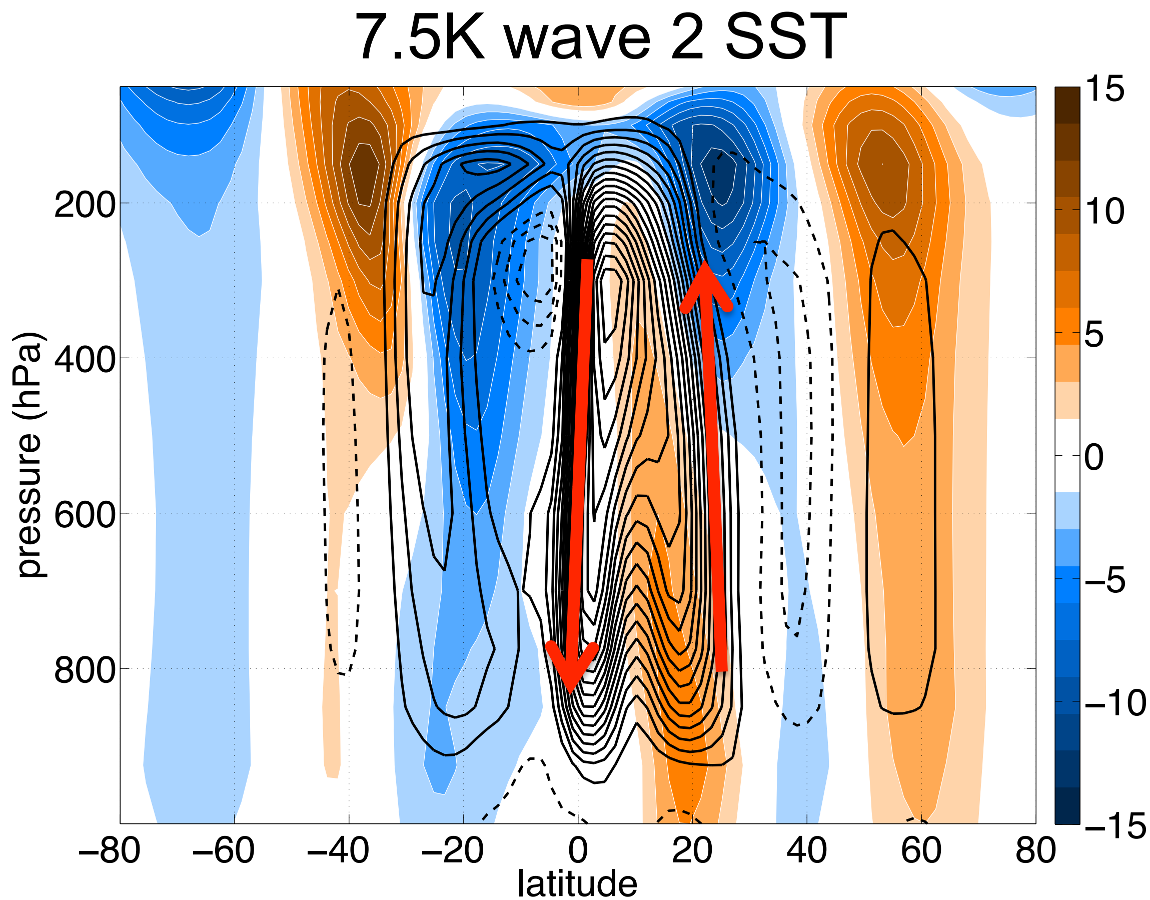


$$c_{gy} = [v] + \frac{2\beta^* k\ell}{(k^2 + \ell^2)^2}$$

See Schneider & Watterson (1984)

Northward ITCZ shift
Poleward jet shift

Large change in GMS



$$[P] - [E] = -\nabla \cdot (\widehat{[v^* q^*]}) = -\mathcal{Q}$$

$$r[u] = -\nabla \cdot (\widehat{[u^* v^*]}) = -\mathcal{F}$$

N.B. Different response with slab ocean

Response to global warming: Importance of thermal contrasts around Asia

If $|\nabla\theta_e^*| > 0$ (land warming)

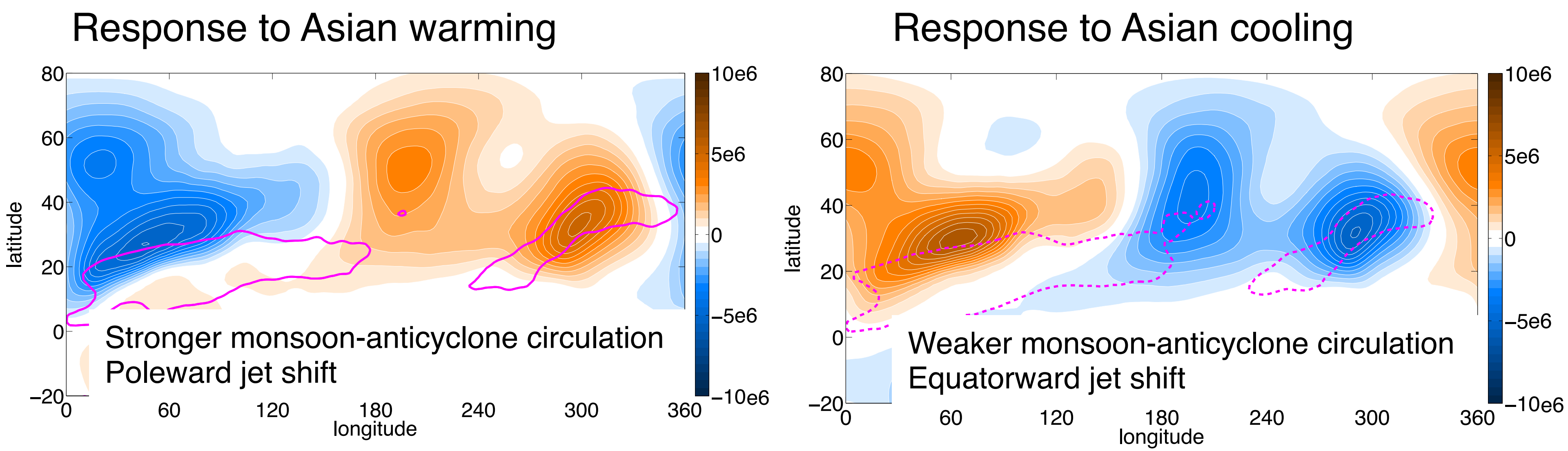
- θ_e maximum over land
- Strengthened monsoon-anticyclone circulation
- Poleward jet shift

If $|\nabla\theta_e^*| < 0$ (SST warming)

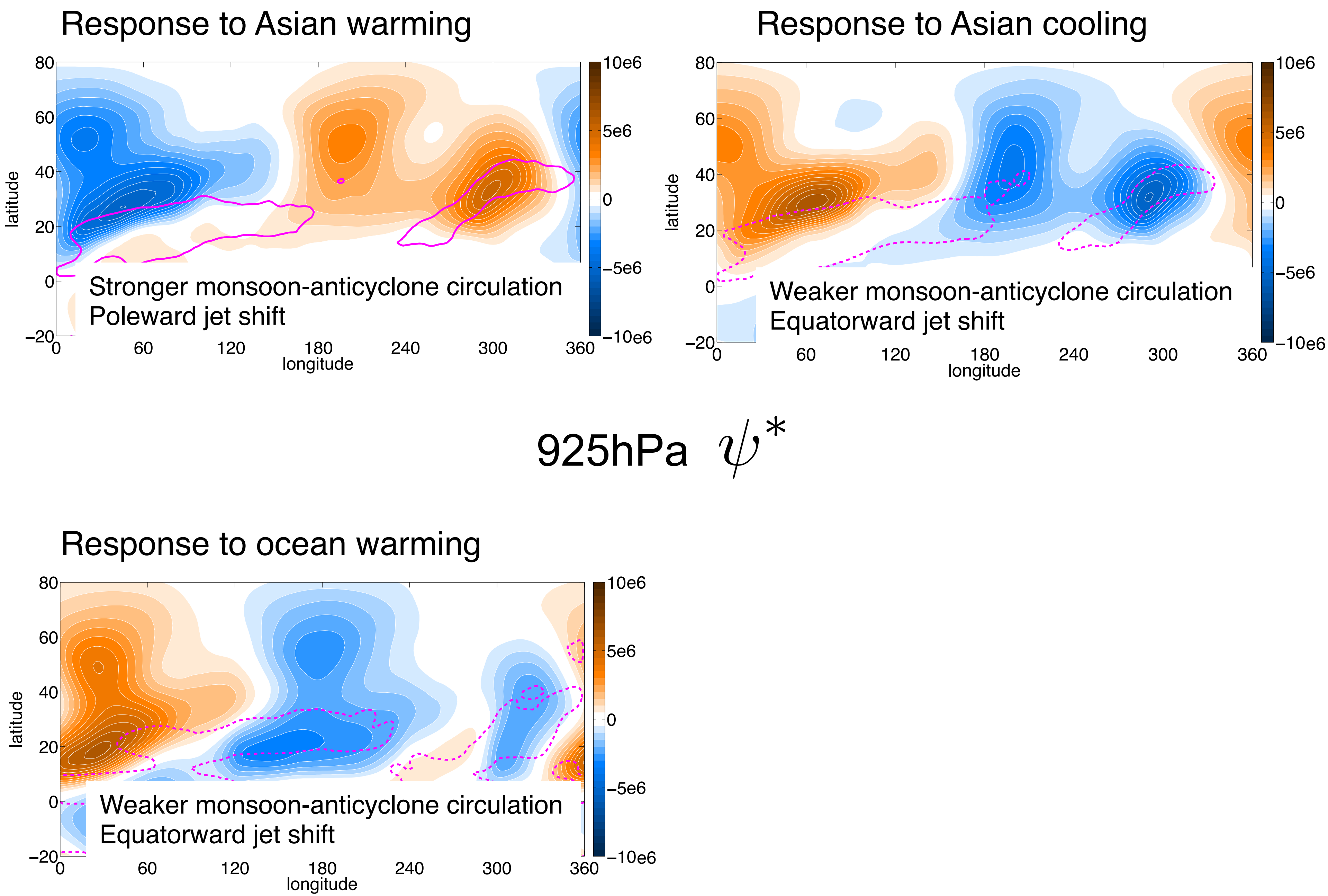
- θ_e maximum over ocean
- Weakened monsoon-anticyclone circulation
- Equatorward jet shift

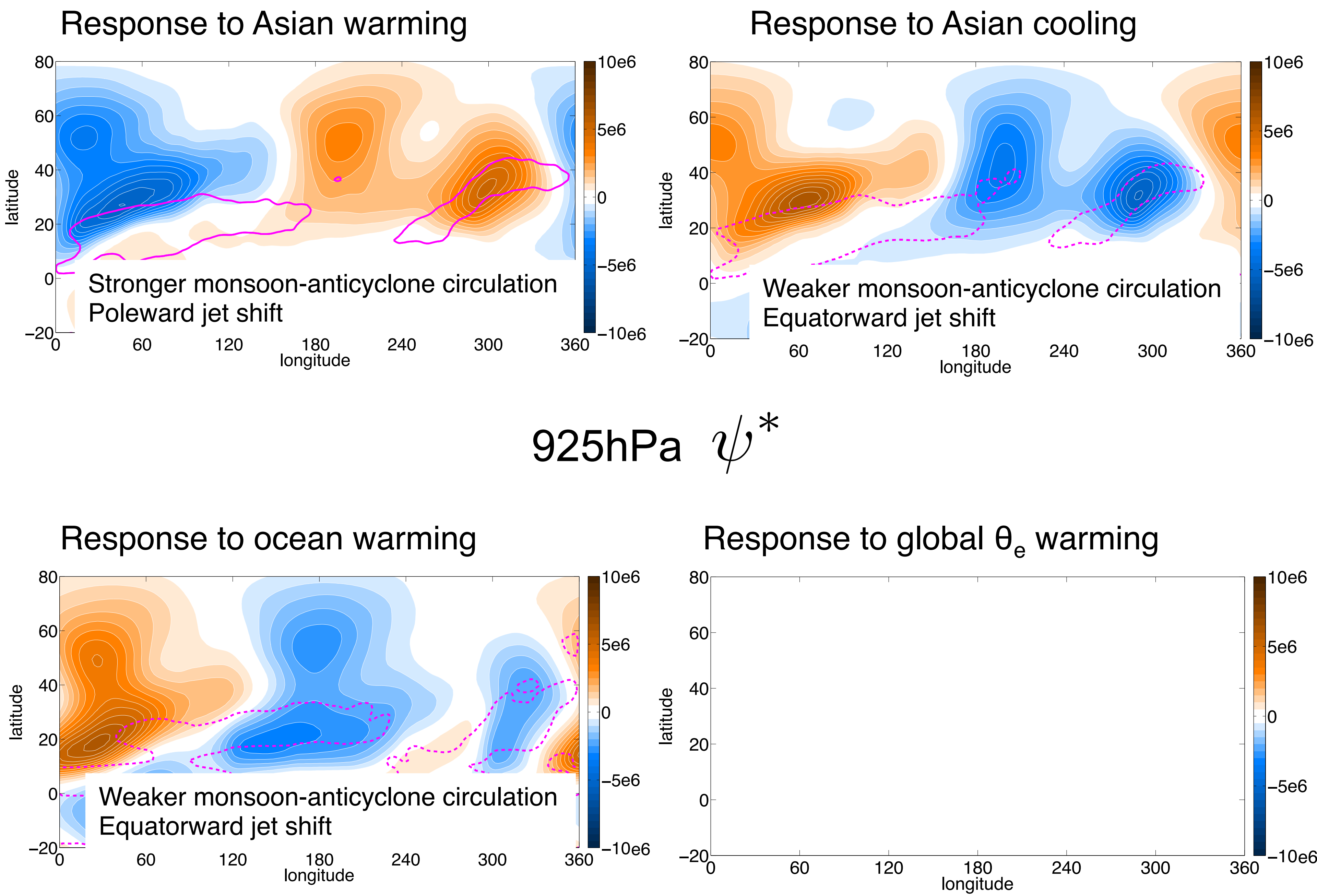
Analogous to seasonal tug of war:

July – May versus September – August


Response to Asian warming
80
60
40
20
0
−20
latitude
0
60
120
180
240
300
360
longitude
10e6
5e6
0
−5e6
−10e6
Stronger monsoon-anticyclone circulation
Poleward jet shift
Response to Asian cooling
Weaker monsoon-anticyclone circulation
Equatorward jet shift

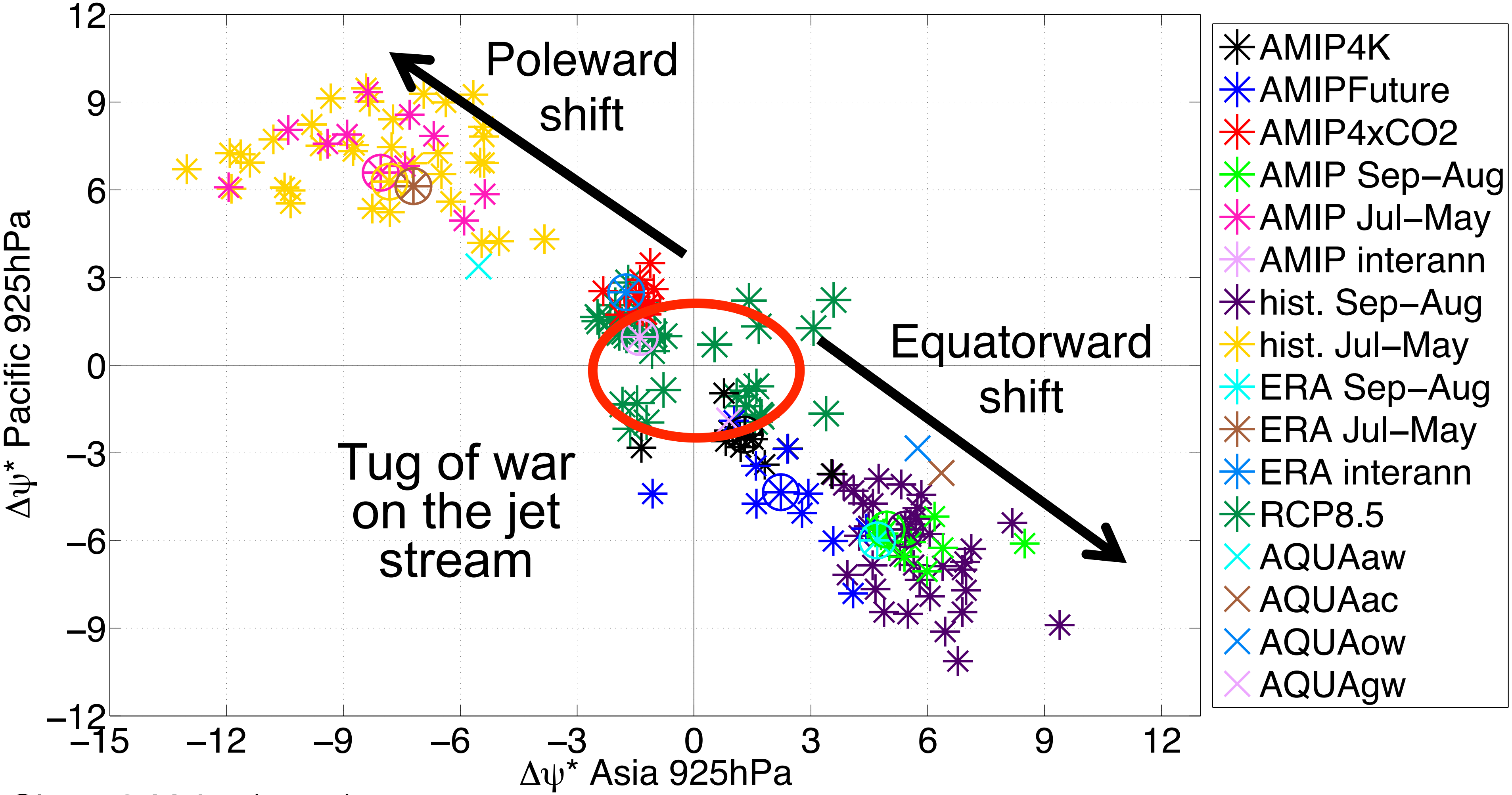
925hPa ψ^*


Response to Asian warming
Stronger monsoon-anticyclone circulation
Poleward jet shift
Response to Asian cooling
Weaker monsoon-anticyclone circulation
Equatorward jet shift
925hPa ψ^*
Response to ocean warming
Weaker monsoon-anticyclone circulation
Equatorward jet shift
latitude
longitude
80
60
40
20
0
−20
0
60
120
180
240
300
360
10e6
5e6
−5e6
−10e6



Shaw & Voigt (2015)

Thermal contrasts around Asia control Pacific circulation and jet response



Shaw & Voigt (2015)

Summary

- Summertime rotational flow, which is connected to land-sea moist entropy contrasts and divergent flow, dominates the seasonal cycle of eddy moisture transport

- Aquaplanet simulations show moisture transport exhibits a QG scaling.
  - Quadratic dependence on surface forcing can produce abrupt transition
  - Stationary wave moisture and momentum transports determine Hadley circulation width and jet stream position

- Tug of war on summertime circulation response to global warming due to opposing thermal (moist entropy) land-sea contrast
  - Consistent with tug of war during seasonal cycle
  - Leaves Pacific jet stream in a stand still