The role of land-sea contrast in the circulation response to seasonal insolation and global warming

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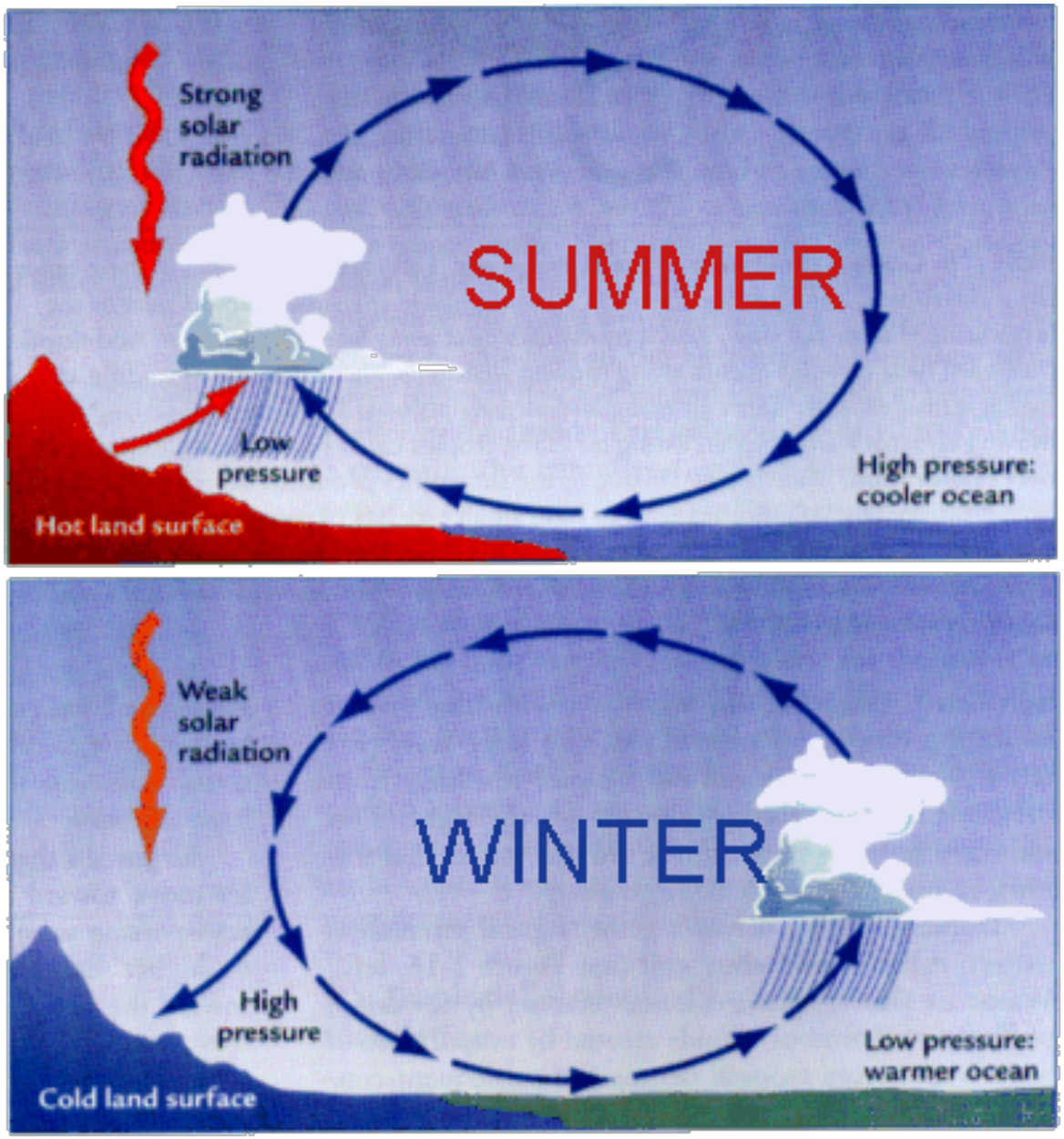
Thanks to A. Voigt, I Simpson, R. Seager



What are the dynamical implications of thermal contrasts?

What is the role of Asian land-sea contrasts in the seasonal circulation evolution?

Why is the summertime circulation response to increased CO_2 not robust?

http://www.geo.arizona.edu/Antevs/ecol438/monsoon.gif

Dynamical Implications of thermal contrasts

1) Sea surface temperature gradients drive low-level flow (Lindzen & Nigam 1987)

$$\mathbf{u}_s^* = -\frac{gH_0}{2\Omega \sin\phi}\left(1 - \frac{\gamma}{2}\right)\mathbf{k} \times \nabla(T_s^*)$$

See also Emanuel et al. (1994), Pauluis (2004), Prive and Plumb (2007)

Dynamical Implications of thermal contrasts

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2) Moist entropy ($s_b = c_p \ln \theta_e^*$) gradients drive flow when moist entropy is supercritical (Emanuel 1995)

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

- Positive north-south thermal gradients imply eastward flow

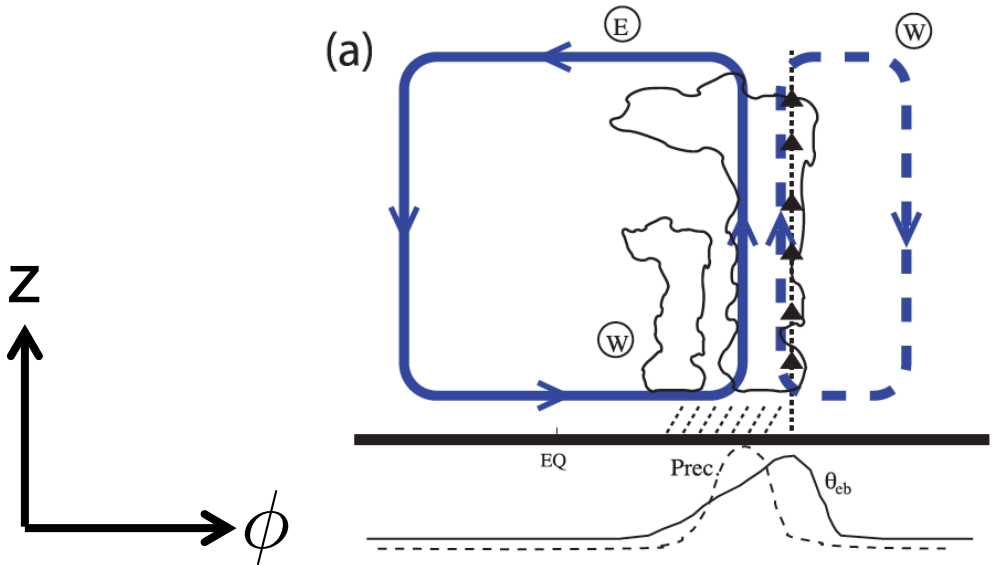
See also Emanuel et al. (1994), Pauluis (2004), Prive and Plumb (2007)

Dynamical Implications of thermal contrasts

- Thermally driven flow + friction = convergence

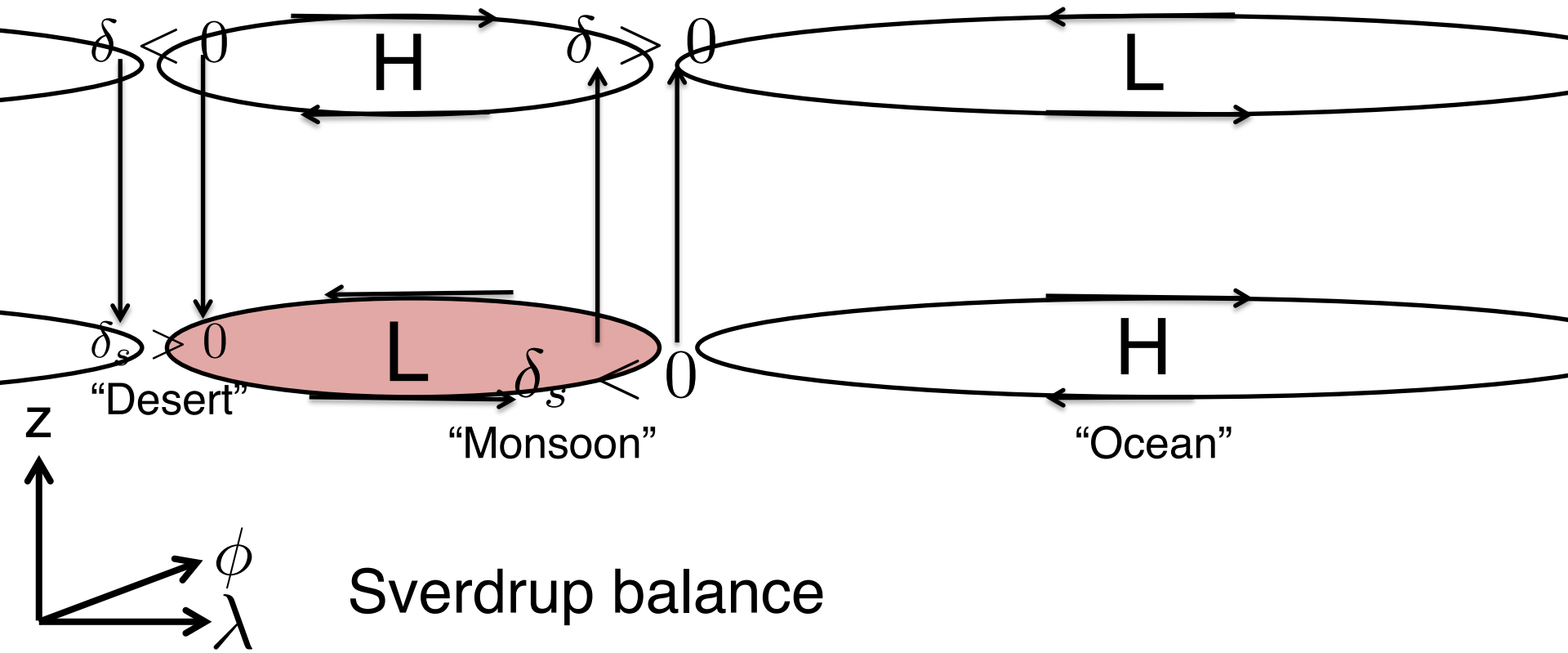
$$\delta_s = \nabla \cdot \mathbf{u}_s \approx -\gamma \zeta_s$$

- Convergence due to energy input and gross moist stability (Neelin & Held 1987): $\delta = -F_{net}/\Delta m$



Nie et al. (2010)

Convergence drives global circulation: Monsoon-Desert relationship

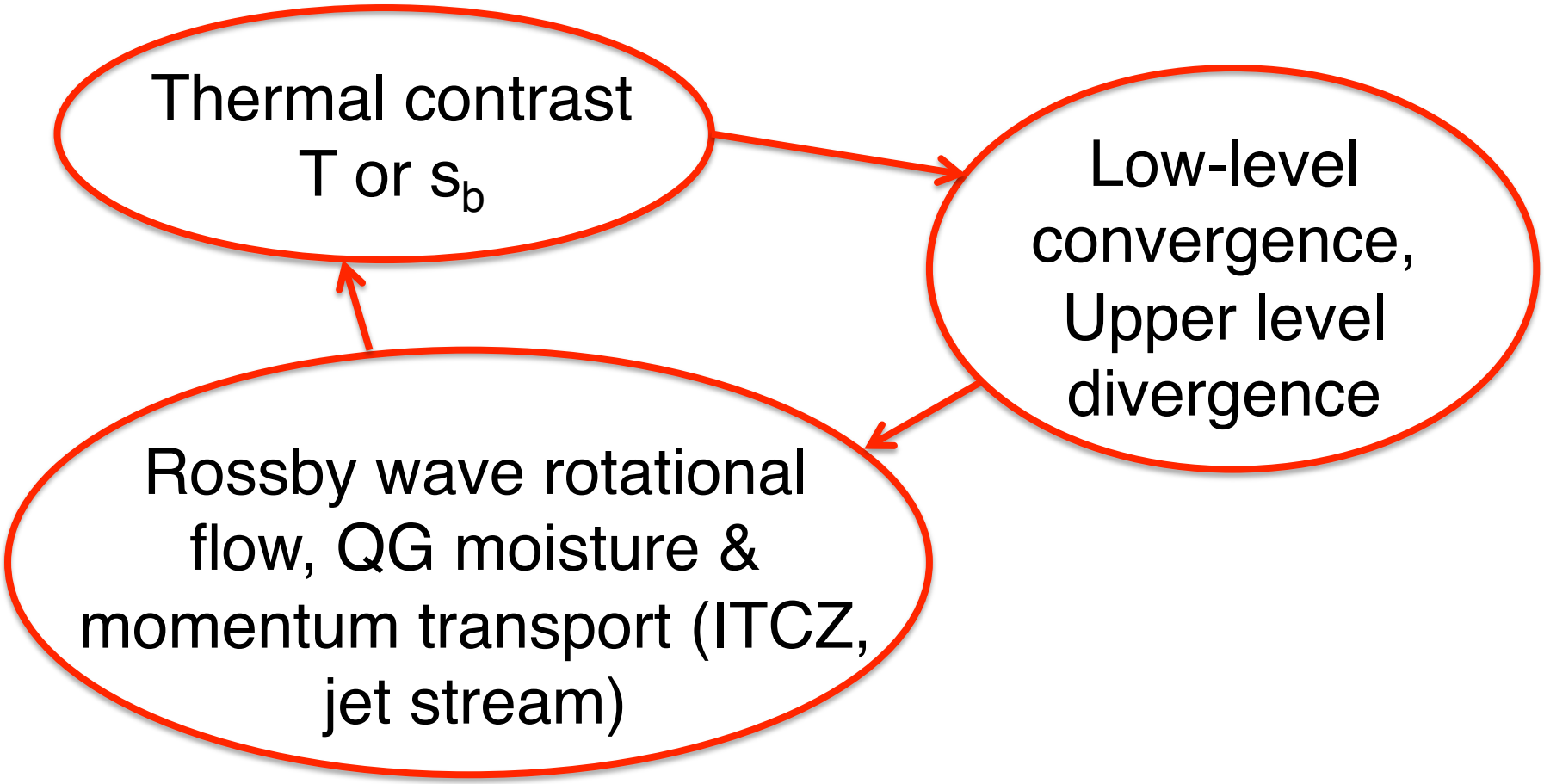


Sverdrup balance

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

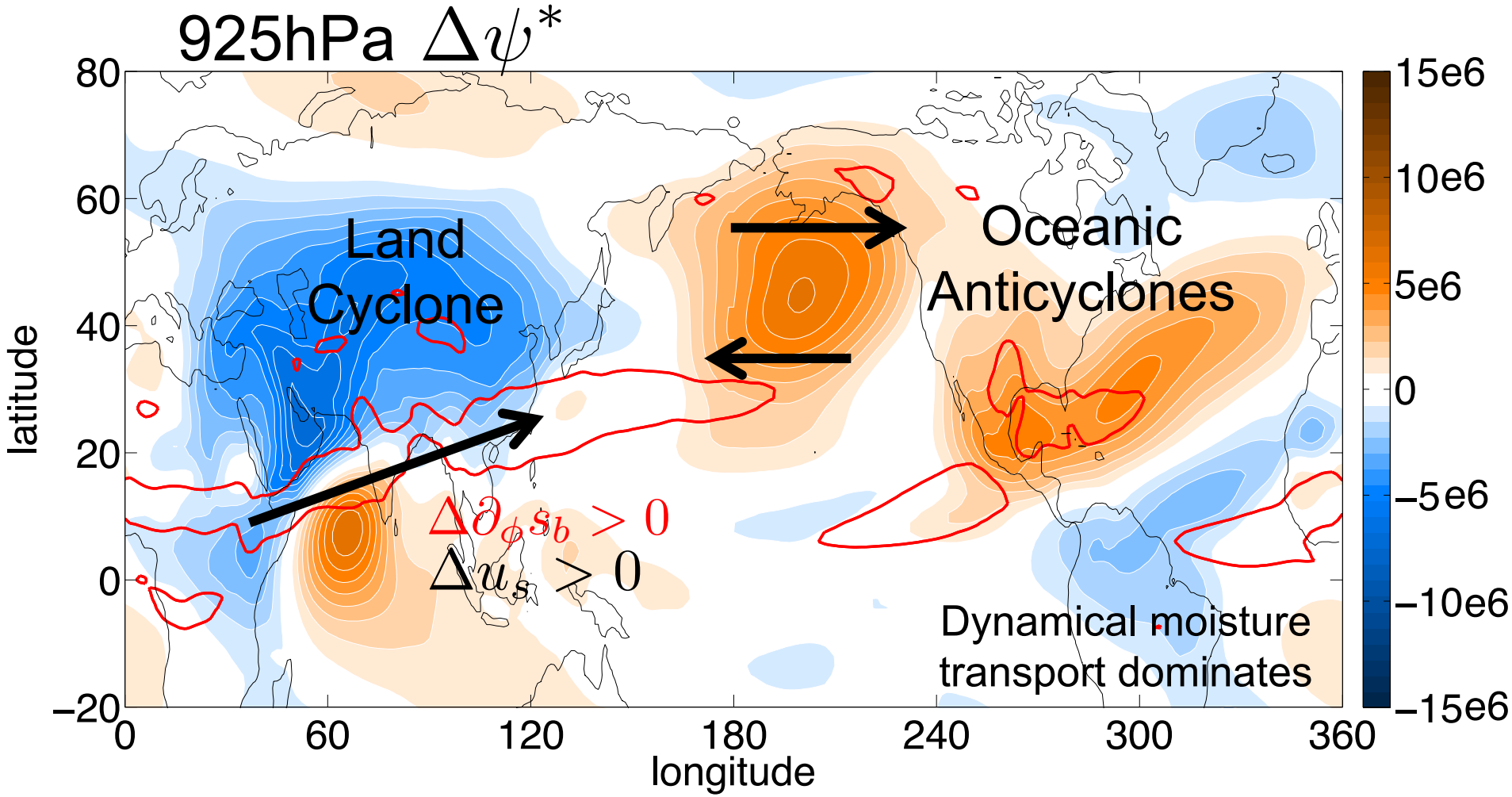
See Gill (1980), Sardeskmuhk & Hoskins (1988), Wang & Ting (1999), Rodwell & Hoskins (2001)

Thermodynamic & Dynamic Links



Poleward extent of Asian & N. American monsoons set by dynamical factors (Chou & Neelin 2003)

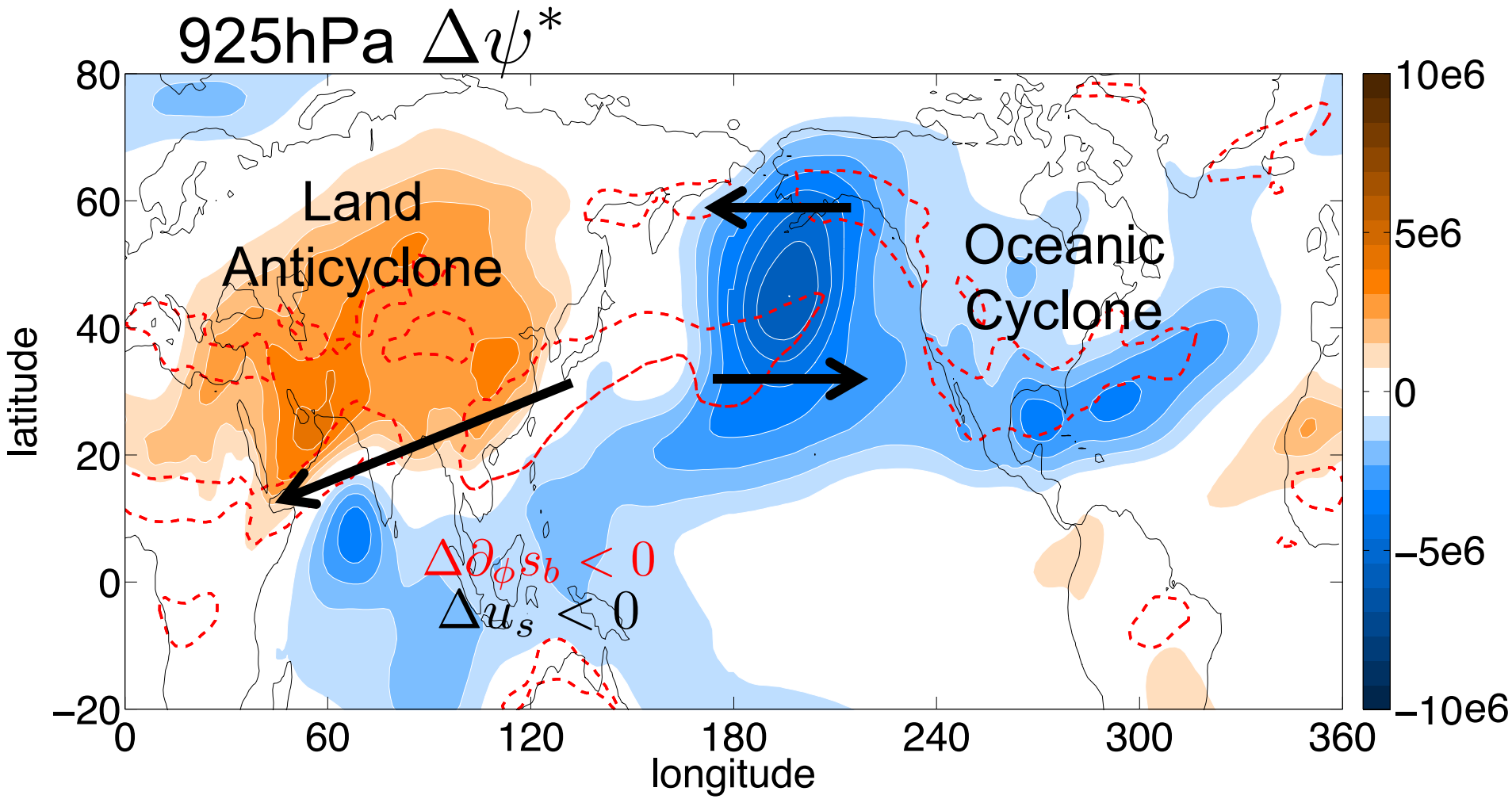
July – May



Opposite pattern aloft

Data source: ERA-Interim

September - August

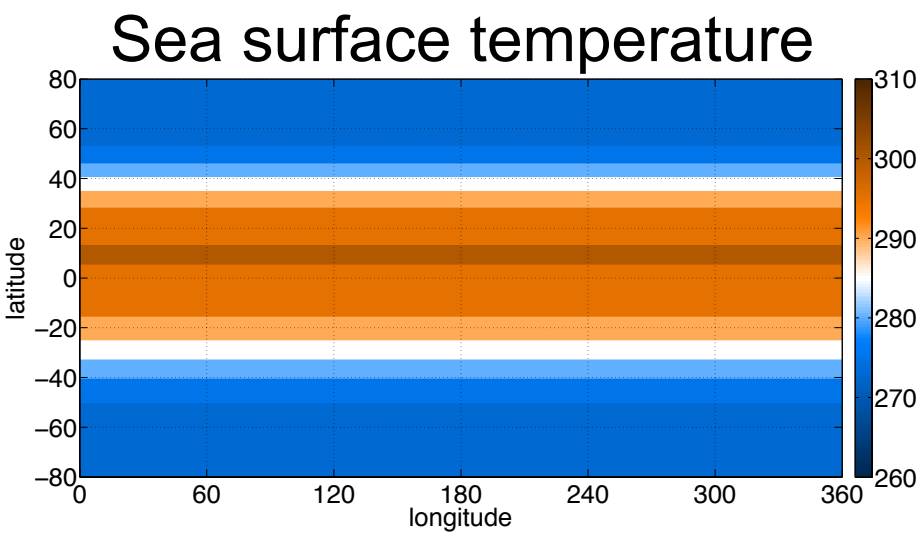


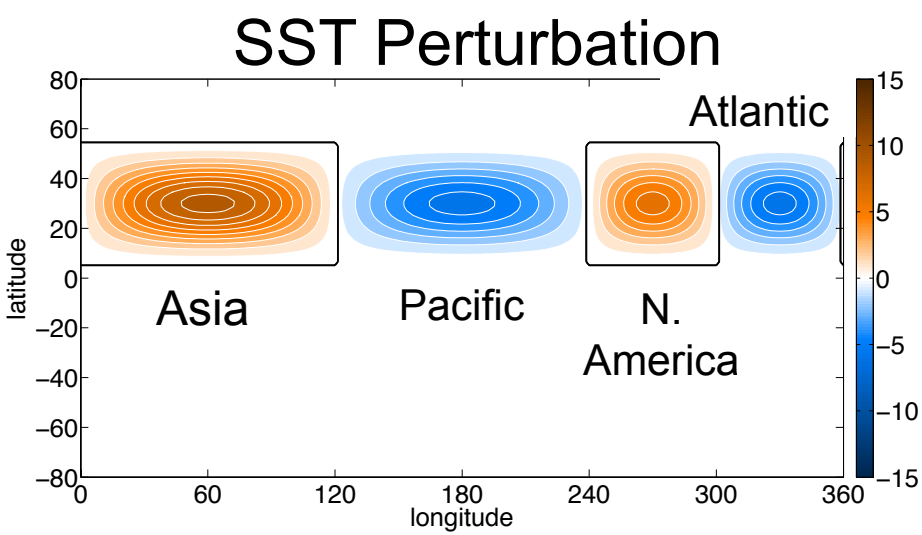
Opposite pattern aloft

Data source: ERA-Interim

Aquaplanet model simulations of the summertime circulation

- MPI-ESM model
- Fixed sea surface temperature (SST)
- Background SST follows Neale & Hoskins (2001)
- Add SST perturbation to mimic land-ocean asymmetries



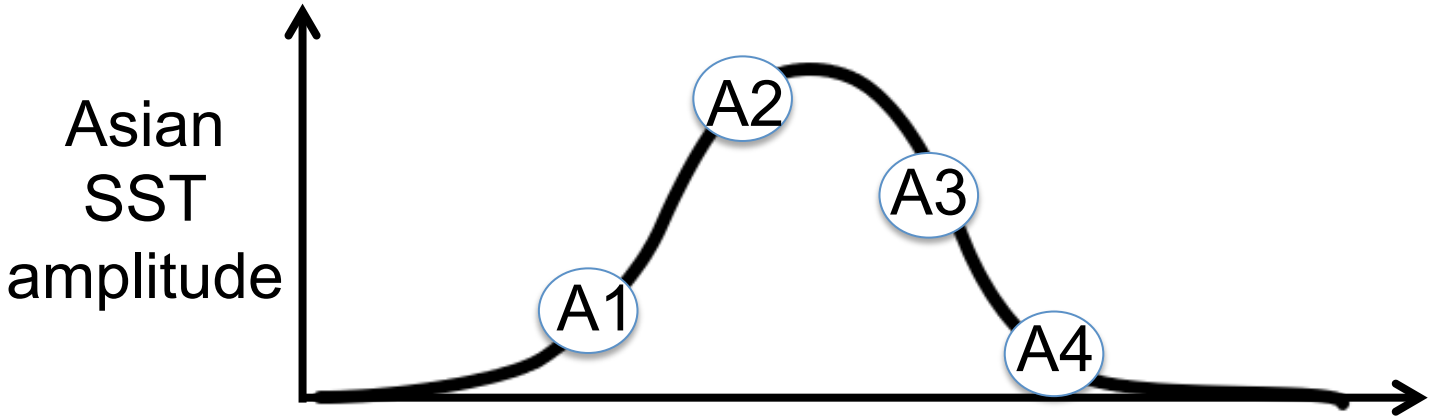


See Shaw (2014), Shaw & Voigt (2015)

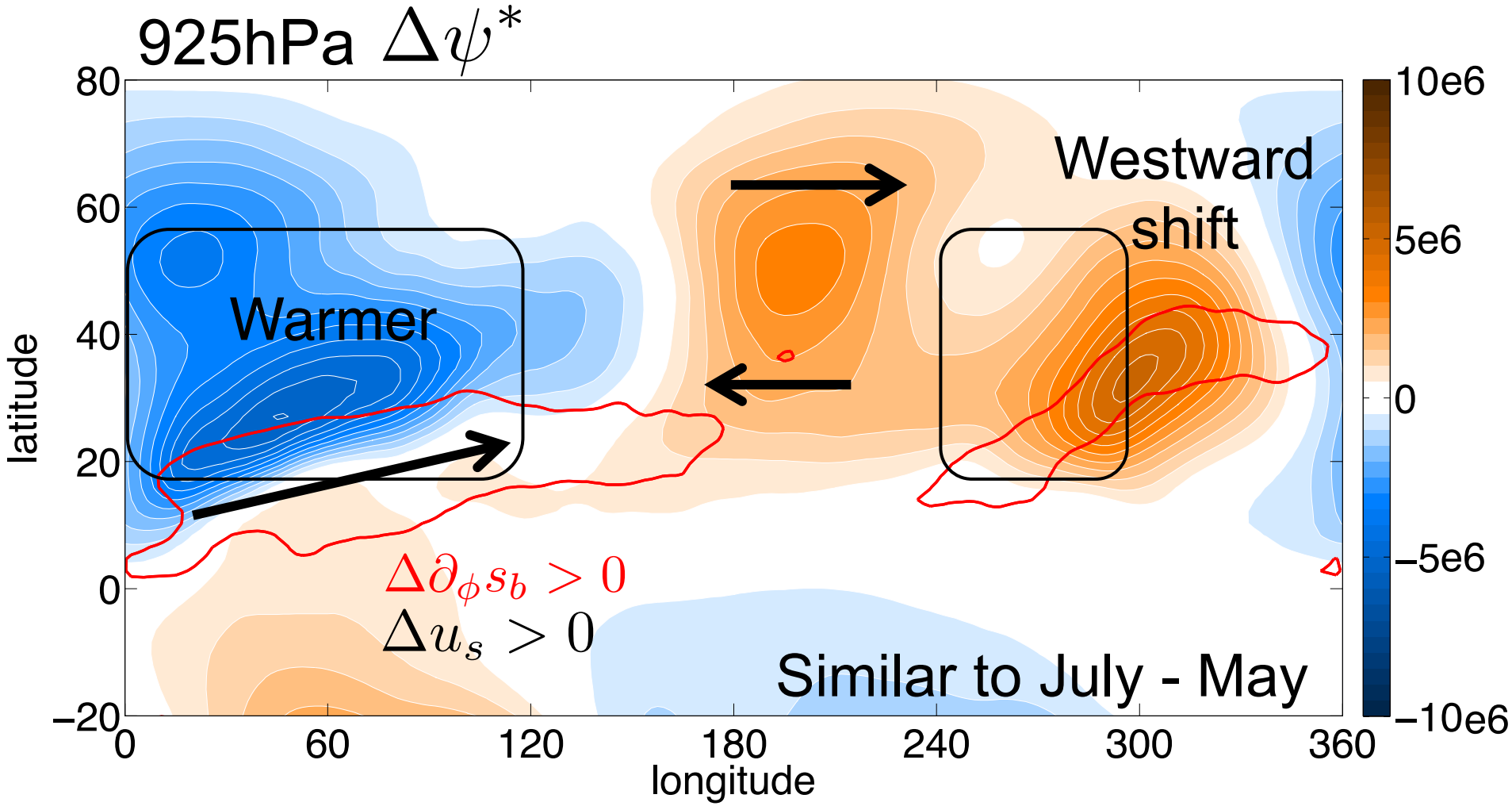
Test hypothesis that Asian land-sea contrasts influence Pacific and Atlantic circulations

Starting from a zonally-asymmetric aquaplanet control state:

- Mimic increased solar insolation by warming Asia relative to control (A2-A1)
- Mimic decreased solar insolation by cooling Asia (A4-A3)



Response to Asian warming



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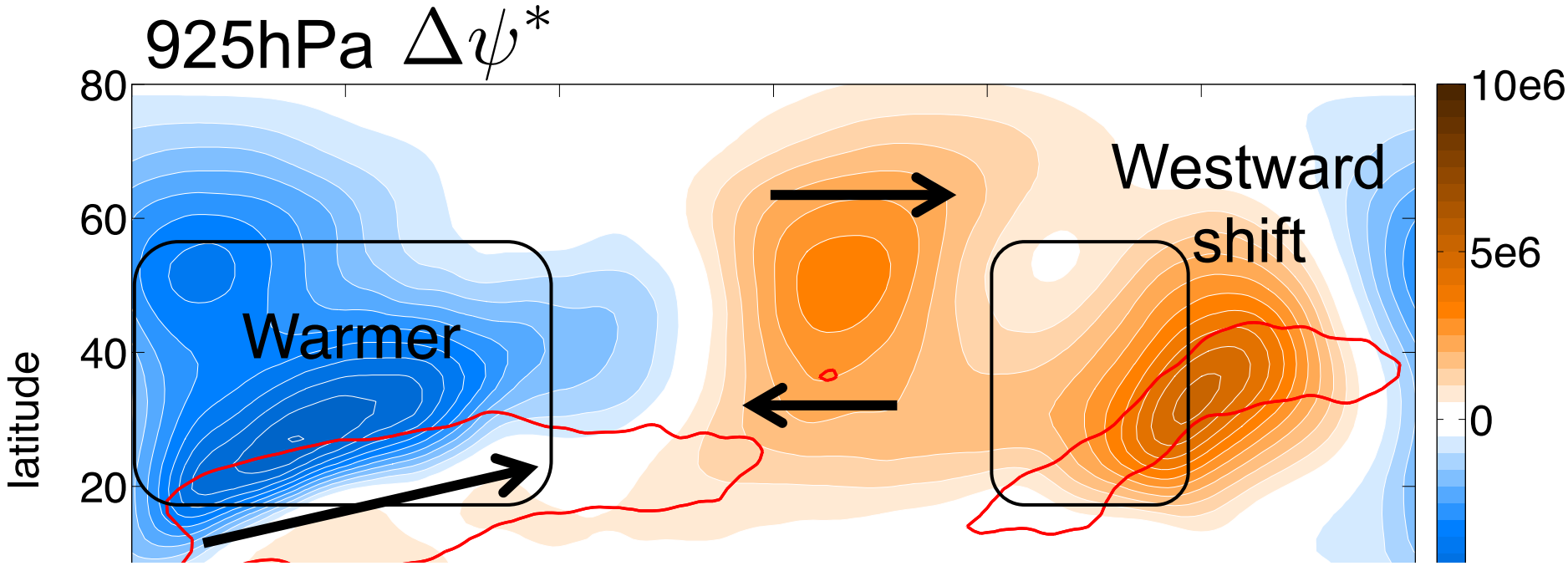


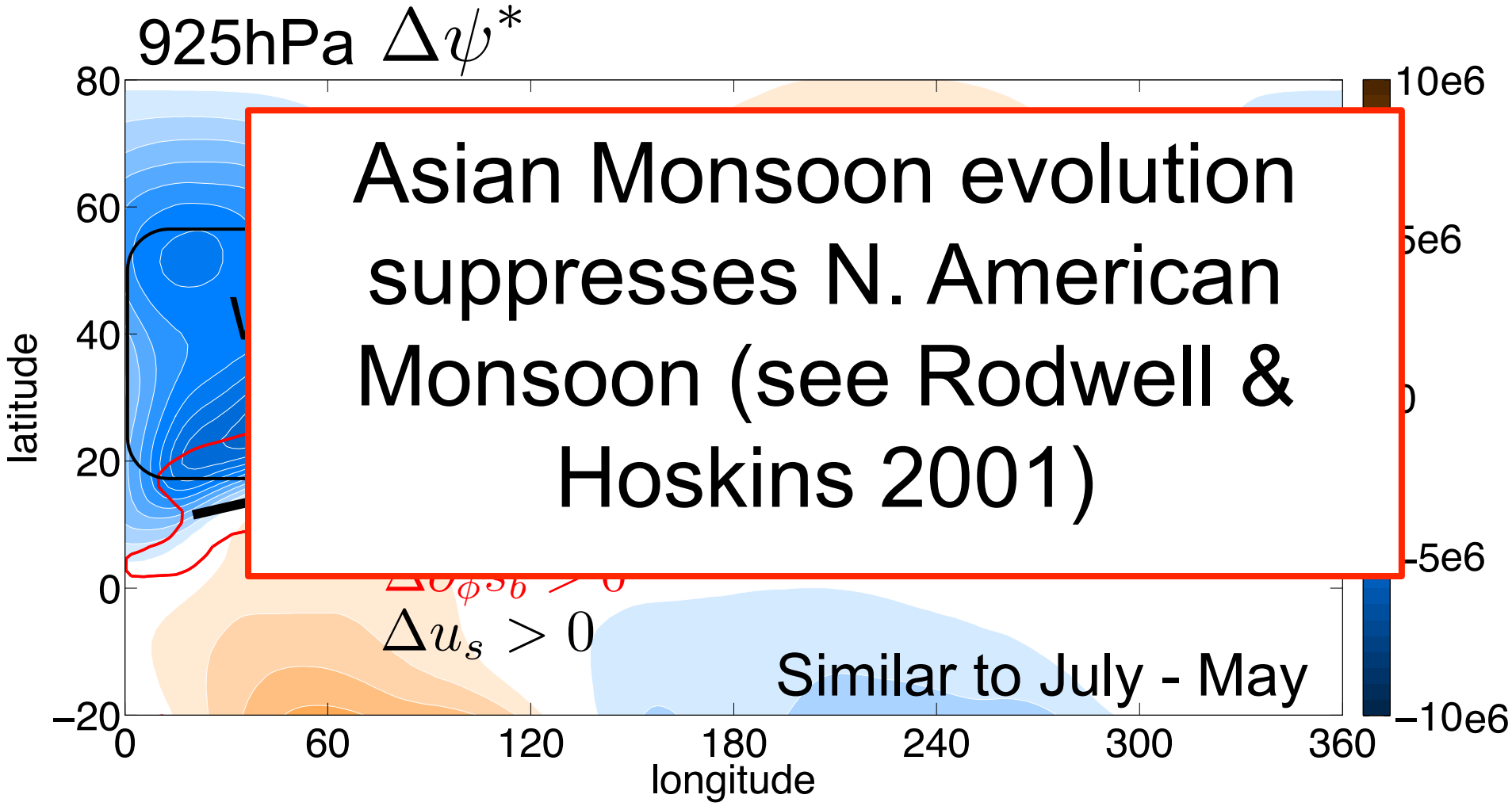
$\Delta\partial_\phi s_b > 0$ → $\Delta\delta_s < 0$ → $\Delta|\psi^*| > 0$

Increased Asian thermal contrast

Increased Asian convergence

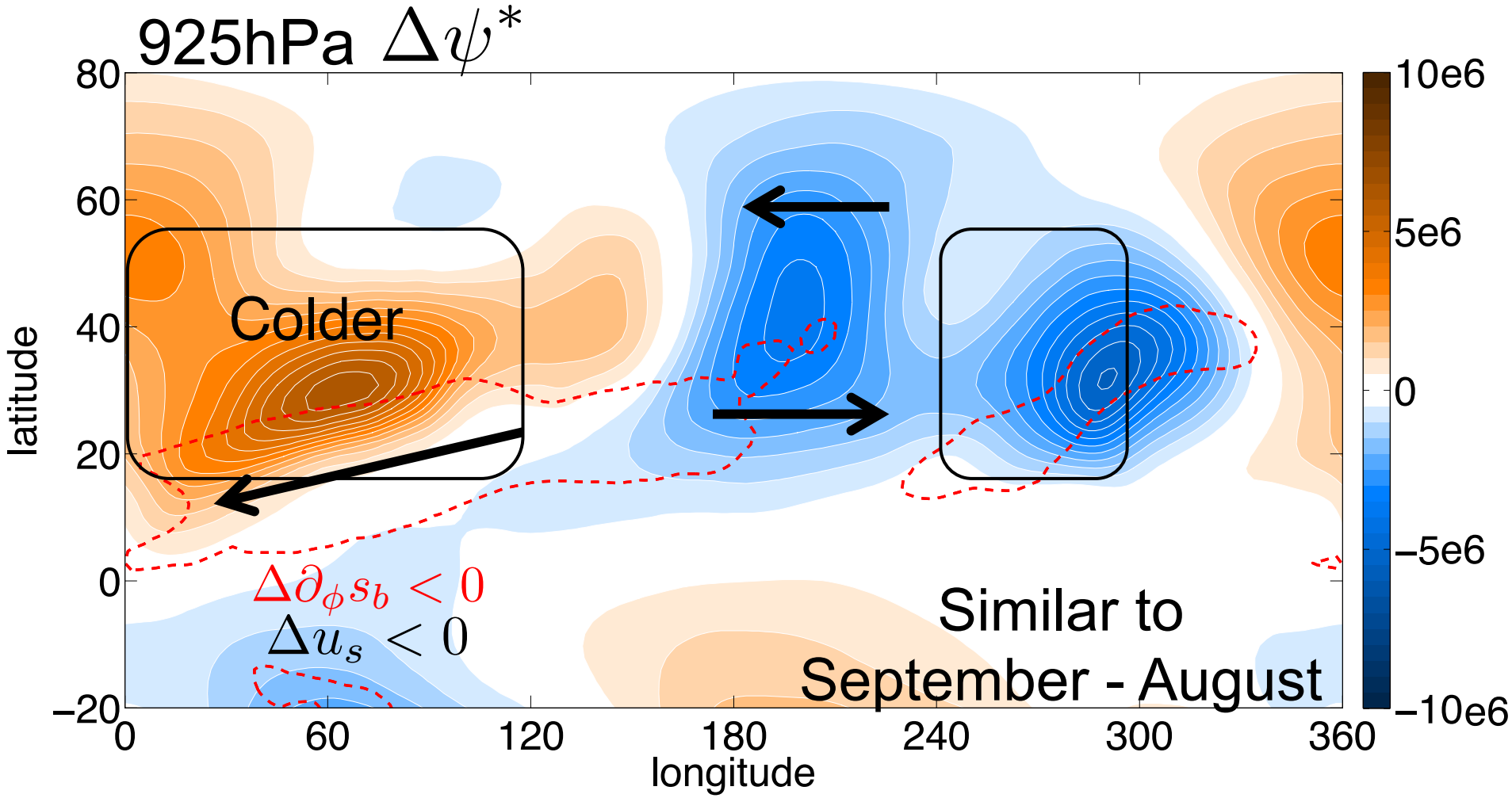
Amplified cyclone-anticyclone, poleward jet shift

Response to Asian warming



Asian Monsoon evolution suppresses N. American Monsoon (see Rodwell & Hoskins 2001)

Response to Asian cooling



Opposite responses to seasonal solar insolation

<u>July - May</u>

- Δs_b maximum over Asia
- $\Delta \partial_\phi s_b > 0$
- Convergence toward land
- Strengthened monsoon cyclone – oceanic anticyclone circulation
- Poleward jet shift

<u>September - August</u>

- Δs_b minimum over Asia
- $\Delta \partial_\phi s_b < 0$
- Divergence from land
- Weakened monsoon cyclone – oceanic anticyclone circulation
- Equatorward jet shift

Response to CO_2 increase: Thermal contrasts around Asia

<u>If land warms (fast adjustment)</u>

- Δs_b maximum over land
- $\Delta \partial_\phi s_b > 0$
- Convergence toward land
- Strengthened monsoon cyclone – oceanic anticyclone circulation
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Response to CO_2 increase: Thermal contrasts around Asia

<u>If land warms (fast adjustment)</u>

- Δs_b maximum over land
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- Convergence toward land
- Strengthened monsoon cyclone – oceanic anticyclone circulation
- Poleward jet shift

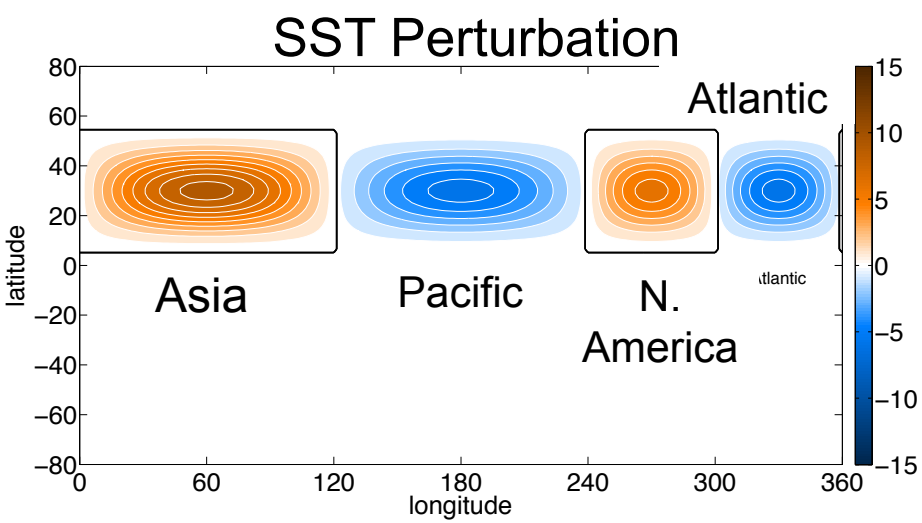
<u>If ocean warms</u>

- Δs_b maximum over ocean
- $\Delta \partial_\phi s_b < 0$
- Divergence from land
- Weakened monsoon cyclone – oceanic anticyclone circulation
- Equatorward jet shift

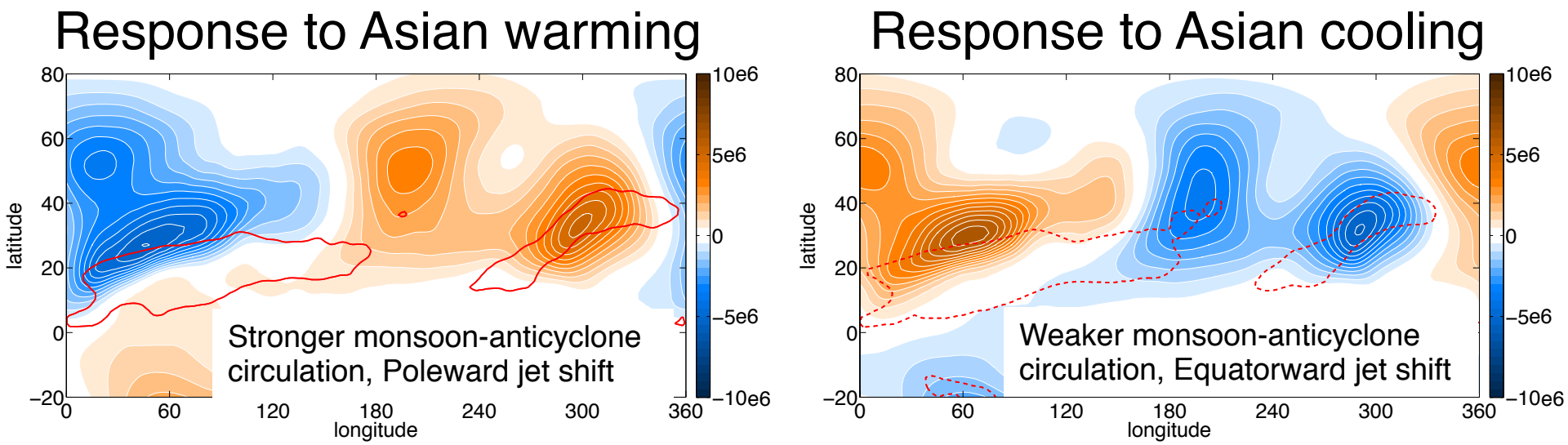
Modern analogs: July – May versus September – August

Except CO_2 is well mixed ➔ competition

Idealized climate change with aquaplanet & CMIP5 models

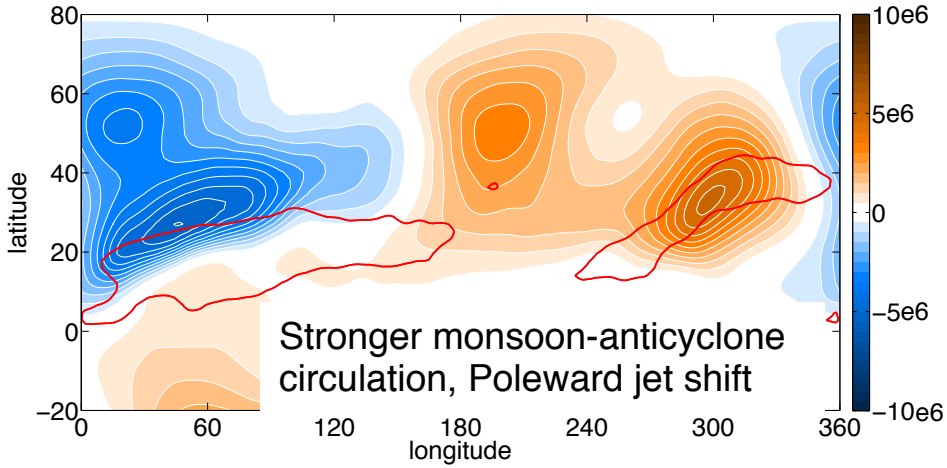


- Increased solar insolation (warm Asia)
- Decreased solar insolation (cool Asia)
- Land warming response to CO_2 increase (warm Asia)
- Ocean warming response to CO_2 increase (warm outside black “land” boxes)
- Global warming (warm everywhere)

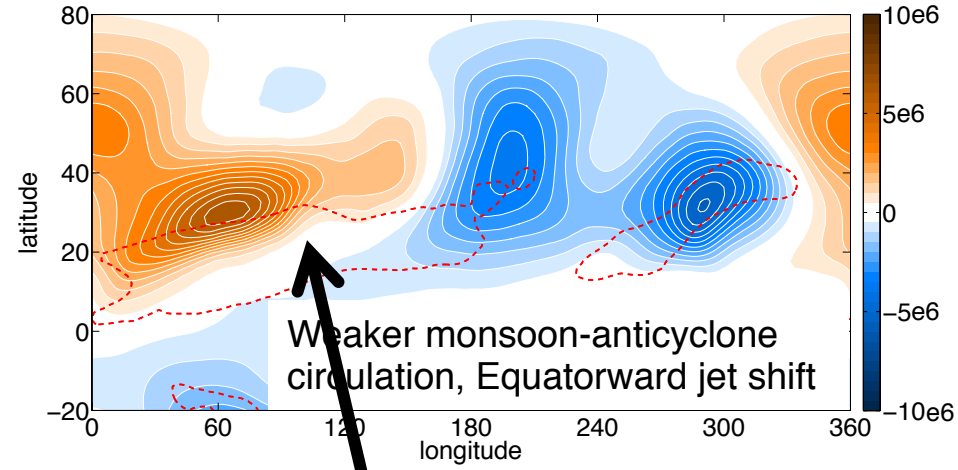


925hPa $\Delta\psi^*$

Response to Asian warming

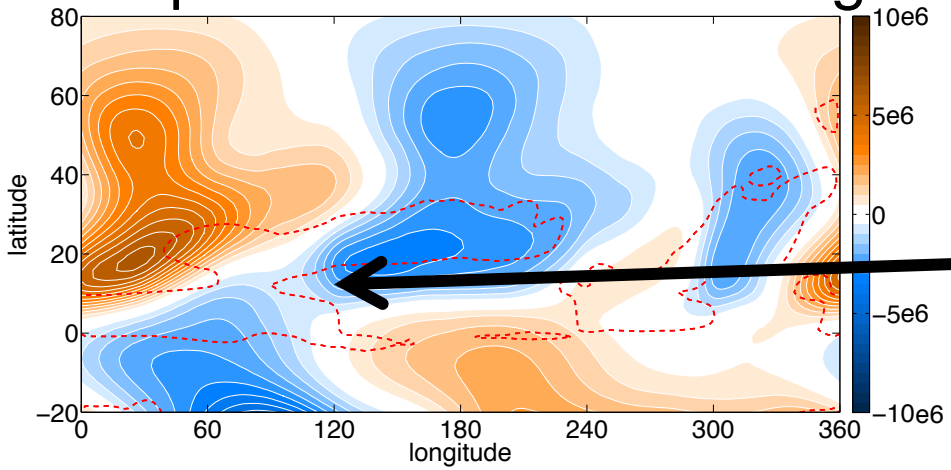


Response to Asian cooling



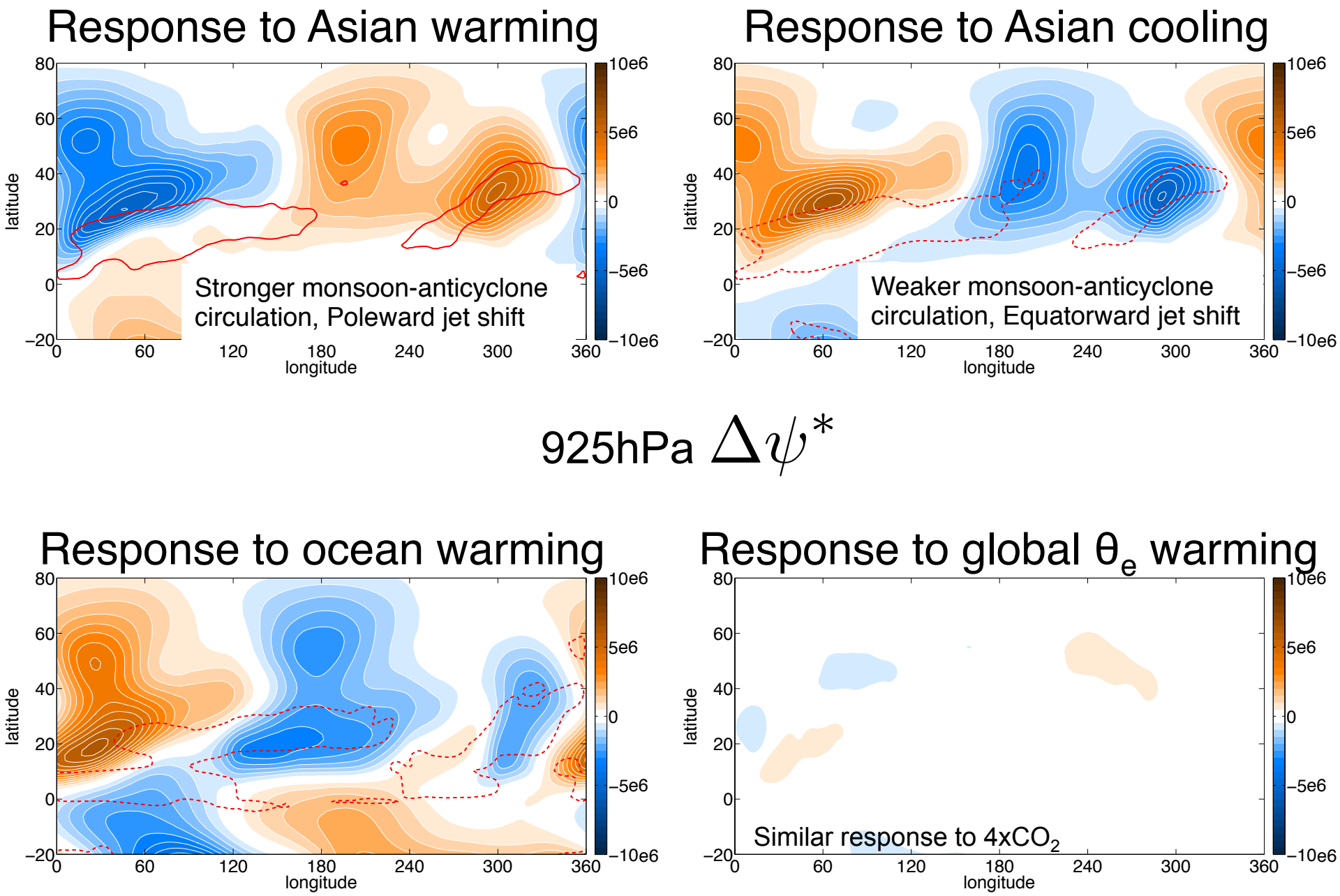
925hPa $\Delta\psi^*$

Response to ocean warming



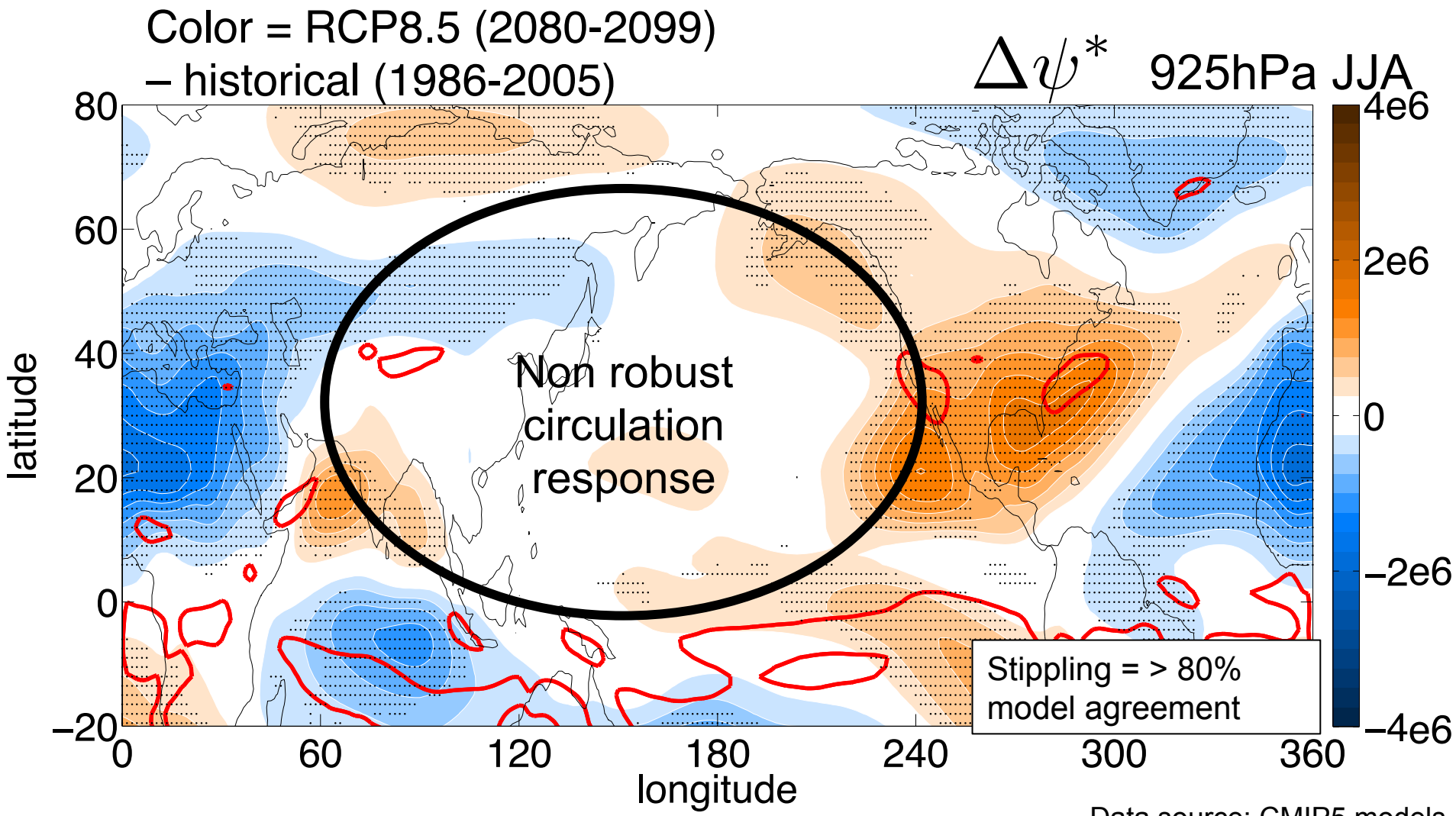
Similar circulation responses consistent with

$$\Delta\partial_\phi s_b < 0$$



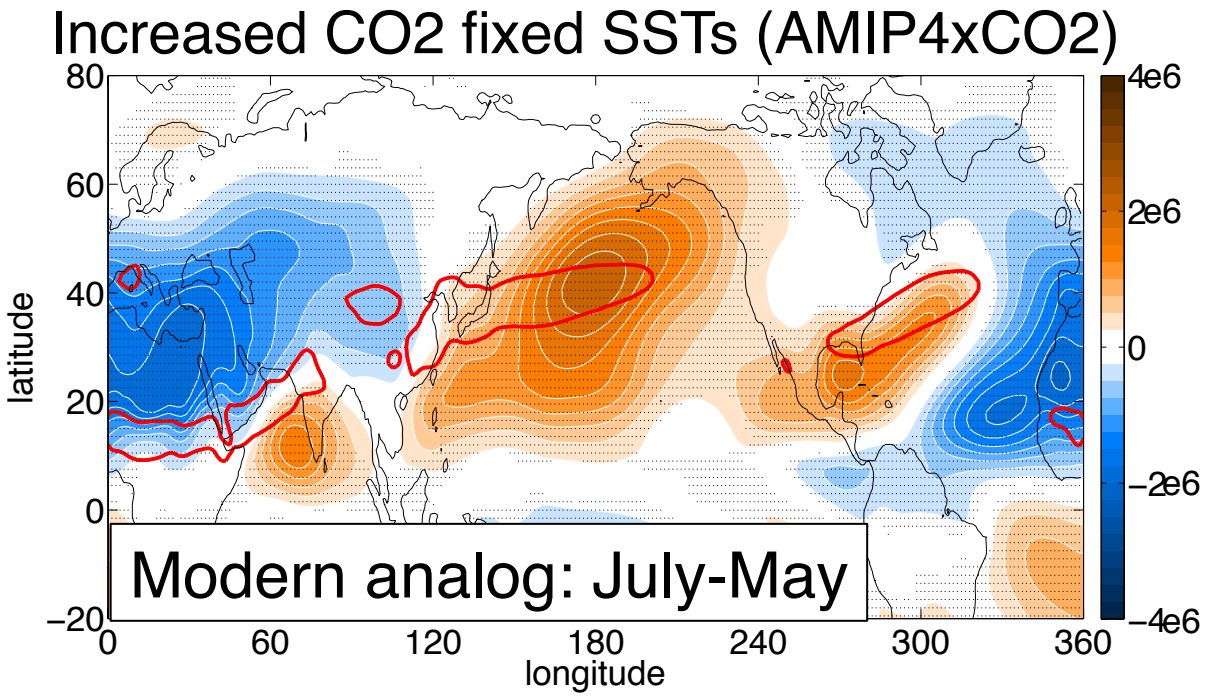
Shaw & Voigt (2015)

Non robust Asia-Pacific circulation response to increased CO_2



Data source: CMIP5 models

Tug of war between radiative forcing and SST warming in CMIP5 models

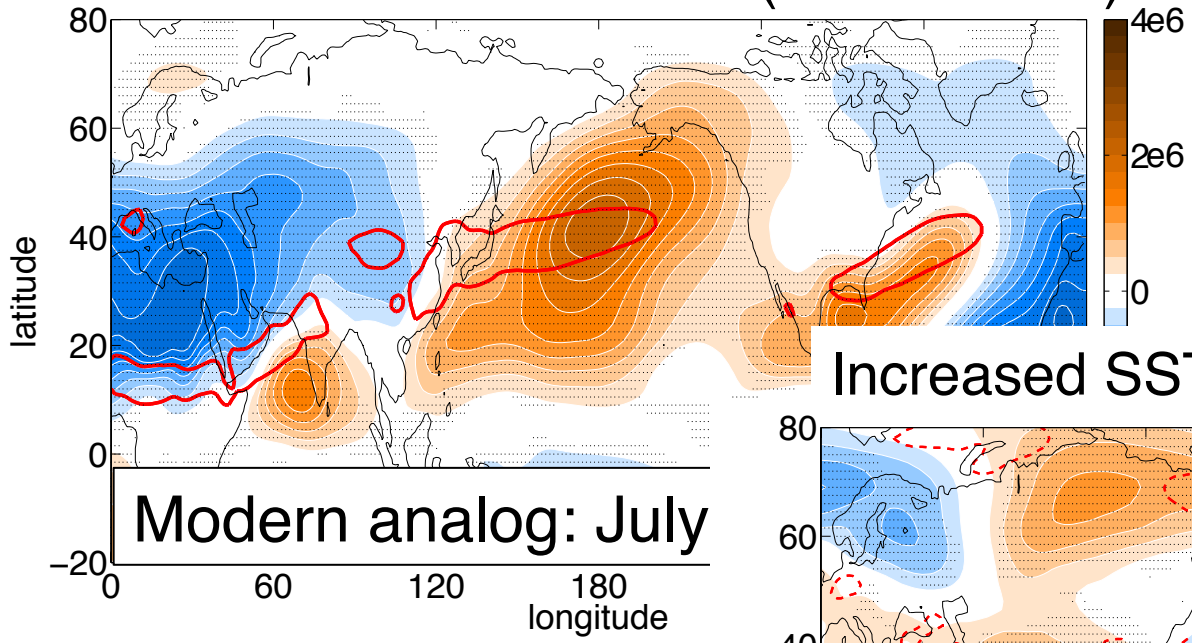


925hPa $\Delta\psi^*$

JJA

Tug of war between radiative forcing and SST warming in CMIP5 models

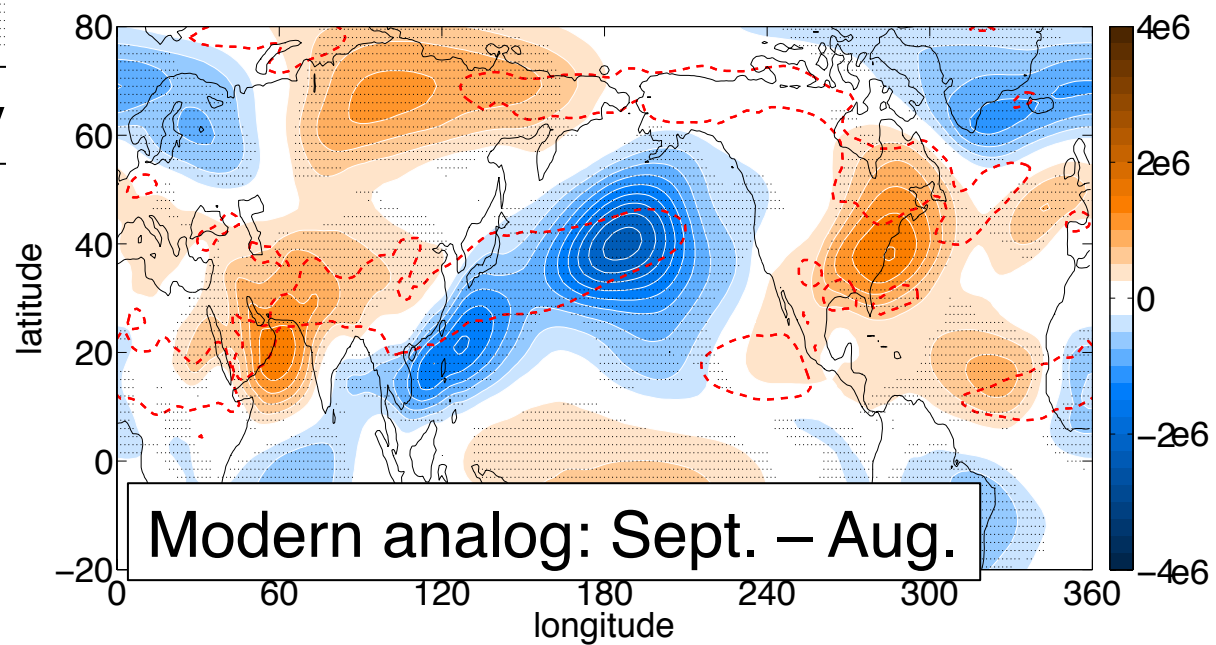
Increased CO2 fixed SSTs (AMIP4xCO2)



925hPa $\Delta\psi^*$

JJA

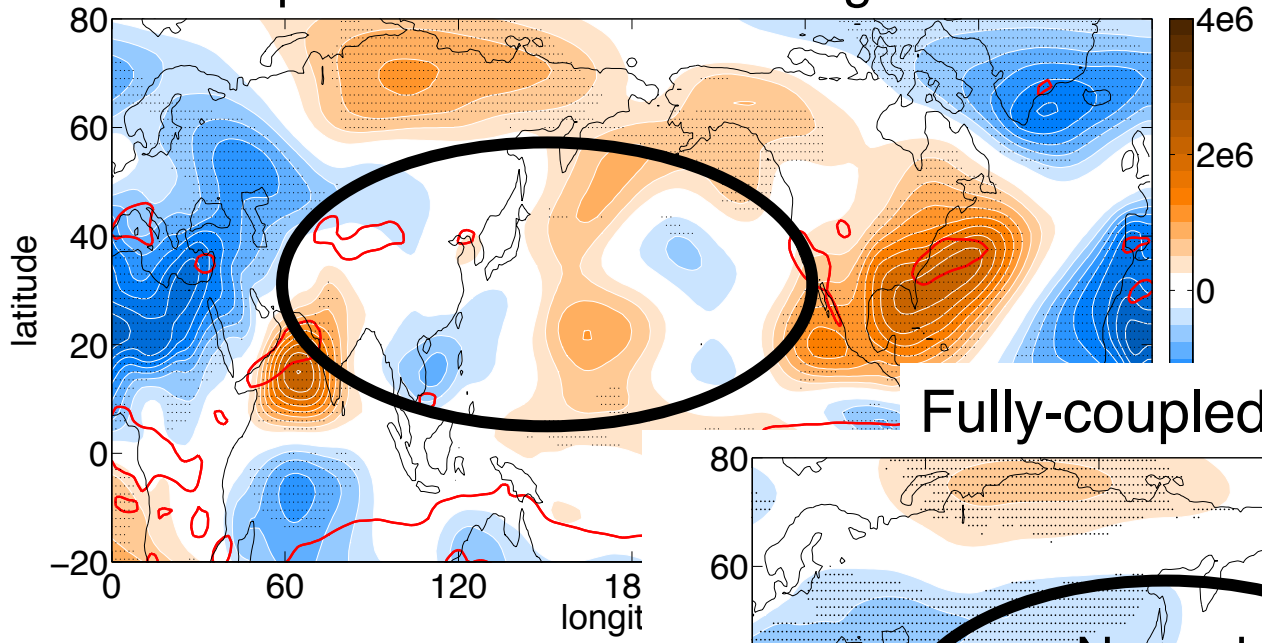
Increased SSTs fixed CO2 (AMIP4K)



Shaw & Voigt (2015)

Tug of war between radiative forcing and SST warming in CMIP5 models

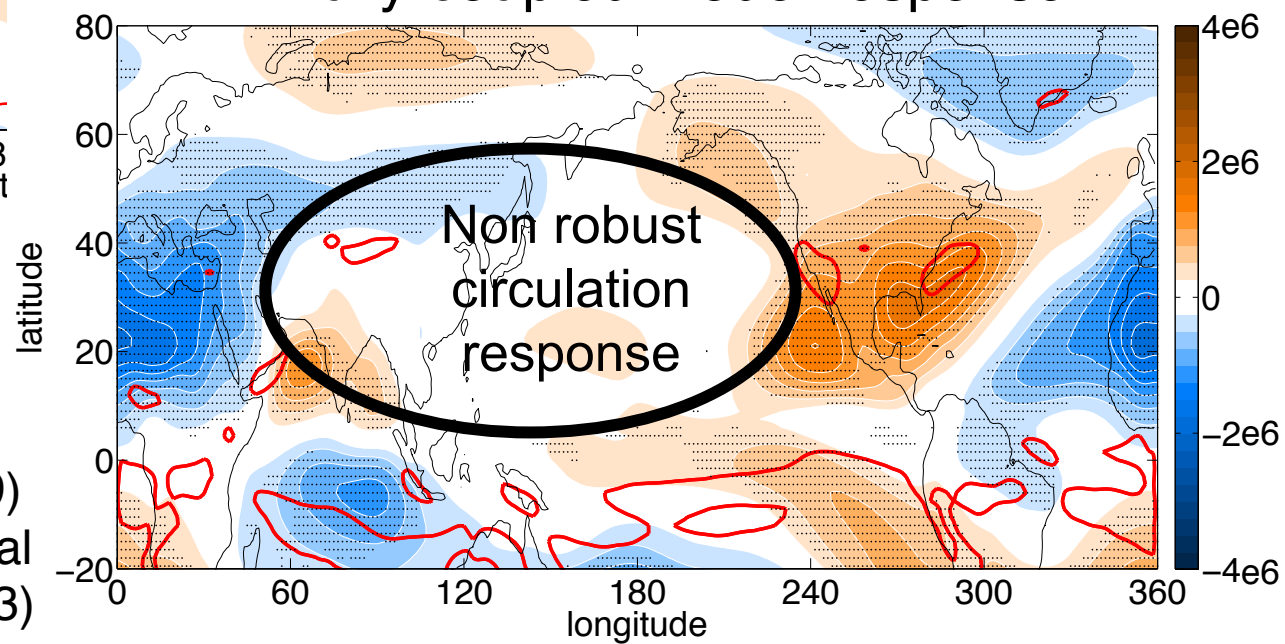
Sum of response to radiative forcing and SST warming



925hPa $\Delta\psi^*$

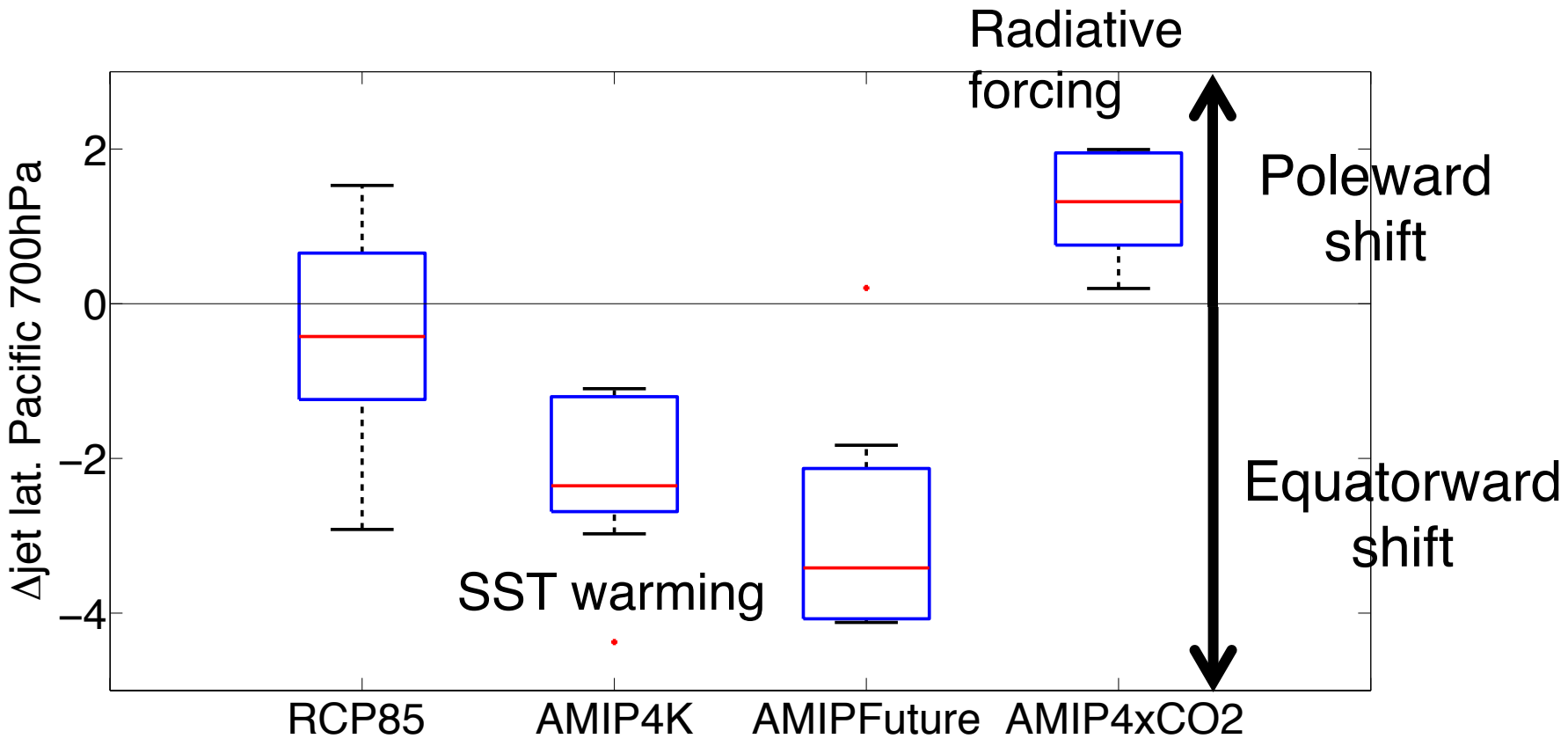
JJA

Fully-coupled model response



See decomposition of recent trends (Deser & Phillips 2009) and future response of tropical precipitation (Bony et al. 2013)

Tug of war on the Pacific jet stream



Shaw & Voigt (2015)

Summary

- What are the dynamical implications of land-sea moist entropy contrasts?
  - Land-sea moist entropy contrasts drive rotational flow and convergence in the presence of friction
- What is the role of Asian land-sea thermal contrasts in the seasonal circulation evolution?
  - Asian land-sea moist entropy contrasts control the seasonal cycle of circulation globally (see Rodwell & Hoskins 2001)
- Why is the Asia-Pacific summertime circulation response to climate change not robust?
  - Tug of war on circulation between radiative forcing and sea surface warming due to opposite land-sea moist entropy contrast, analogous to seasonal evolution