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

\[ u_s^* = -\frac{gH_0}{2\Omega \sin \phi} \left( 1 - \frac{\gamma}{2} \right) k \times \nabla (T_s^*) \]

See also Emanuel et al. (1994), Pauluis (2004), Prive and Plumb (2007)
Dynamical Implications of thermal contrasts

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

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

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): \[ \delta = -\frac{F_{net}}{\Delta m} \]

Nie et al. (2010)
Convergence drives global circulation: Monsoon-Desert relationship

\[ \beta v_\psi = -f\delta \]

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

Thermal contrast $T$ or $s_b$

Low-level convergence, Upper level divergence

Rossby wave rotational flow, QG moisture & momentum transport (ITCZ, jet stream)
July – May

925hPa $\Delta \psi^*$

Land Cyclone

Oceanic Anticyclones

Dynamical moisture transport dominates

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

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

925hPa $\Delta \psi^*$

- Warmer
- Westward shift
- Similar to July - May

$\Delta \partial_{\phi} s_b > 0$
$\Delta u_s > 0$
Response to Asian warming

$925\text{hPa } \Delta \psi^*$

$\Delta \partial_{\phi} s_b > 0 \rightarrow \Delta \delta_s < 0 \rightarrow \Delta |\psi^*| > 0$

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)

Similar to July - May
Response to Asian cooling

925hPa $\Delta \psi^*$

Colder

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

$\Delta u_s < 0$

Similar to September - August
Opposite responses to seasonal solar insolation

<table>
<thead>
<tr>
<th>July - May</th>
<th>September - August</th>
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<tbody>
<tr>
<td>$\Delta s_b$ maximum over Asia</td>
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<td>Convergence toward land</td>
<td>Divergence from land</td>
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<td>Strengthened monsoon cyclone – oceanic anticyclone circulation</td>
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<td>Poleward jet shift</td>
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Response to CO$_2$ increase: Thermal contrasts around Asia

If land warms (fast adjustment)
- $\Delta s_b$ maximum over land
- $\Delta \partial_\phi s_b > 0$
- Convergence toward land
- Strengthened monsoon
  cyclone – oceanic
  anticyclone circulation
- Poleward jet shift
Response to CO\textsubscript{2} increase: Thermal contrasts around Asia

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Modern analogs: July – May versus September – August
Except CO\textsubscript{2} is well mixed $\Rightarrow$ 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)
**Response to Asian warming**

Stronger monsoon-anticyclone circulation, Poleward jet shift

**Response to Asian cooling**

Weaker monsoon-anticyclone circulation, Equatorward jet shift

925hPa $\Delta \psi^*$
Response to Asian warming

Stronger monsoon-anticyclone circulation, Poleward jet shift

Response to Asian cooling

Weaker monsoon-anticyclone circulation, Equatorward jet shift

Response to ocean warming

Similar circulation responses consistent with $\Delta \varphi_s b < 0$
Response to Asian warming

Stronger monsoon-anticyclone circulation, Poleward jet shift

Response to Asian cooling

Weaker monsoon-anticyclone circulation, Equatorward jet shift

Response to ocean warming

925hPa $\Delta \psi^*$

Response to global $\theta_e$ warming

Similar response to 4xCO$_2$

Shaw & Voigt (2015)
Non robust Asia-Pacific circulation response to increased CO$_2$

Data source: CMIP5 models


$\Delta \psi^*$ 925hPa JJA

Stippling = > 80% model agreement
Tug of war between radiative forcing and SST warming in CMIP5 models

Increased CO2 fixed SSTs (AMIP4xCO2)

Modern analog: July-May

925hPa $\Delta \psi^*$

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

Increased CO2 fixed SSTs (AMIP4xCO2)

Modern analog: July

Increased SSTs fixed CO2 (AMIP4K)

Modern analog: Sept. – Aug.

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

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

Radiative forcing

Poleward shift

Equatorward shift

\( \Delta \text{jet lat. Pacific 700hPa} \)

RCP85  |  AMIP4K  |  AMIPFuture  |  AMIP4xCO2

SST warming

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