Local and Remote Cloud Radiative Effect Impacts onto the Extratropical Atmospheric Circulation

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Response of 850hPa zonal-mean zonal wind to a +4K sea surface temperature anomaly

A poleward shift in all models, but magnitude varies by a factor of 2

Voigt and Shaw [2016]
Models suggest that half or more of the jet response to global warming comes from changes in clouds.

Response to quadrupling CO$_2$ with clouds locked to control climate

Ceppi and Hartmann [2016]
Models suggest that half or more of the jet response to global warming comes from changes in clouds.

\[ u \ (m \ s^{-1}) \]

Response to quadrupling CO\(_2\) with clouds locked to control climate.

Response to clouds being locked to 4x CO\(_2\) simulation but with CO\(_2\) itself held constant.

Ceppi and Hartmann [2016]
Models suggest that half or more of the jet response to global warming comes from changes in clouds.

Similar experiment, but with a specified-SST model, instead of a slab-ocean model.

Voigt and Shaw [2015]
However, the impacts of cloud radiative effects onto the midlatitude jet vary widely across models, even for the present-day climate.

Contours: time-mean zonal mean zonal wind in “clouds-off” simulation

Shading: difference between “clouds-on” and “clouds-off” simulations
Methods

• Use the Clouds On-Off Klimatic Intercomparison Experiment (COOKIE) ensemble [Stevens et al., 2012]
  – A set of specified-SST aquaplanet simulations, in which the radiative transfer scheme is made to ignore the presence of clouds
  – These simulations are compared to control simulations that include cloud radiative effects in order to isolate the impacts of clouds onto the circulation of the atmosphere

• In addition, we perform experiments with the GFDL-AM2.1 and NCAR-CAM5.3 models in which cloud radiative effects are only imposed in certain regions
  – Tropics: equatorward of 30°, extratropics: poleward of 30°
Response of zonal mean zonal wind to cloud radiative effects in tropics vs. extratropics in GFDL-AM2.1
Response of zonal mean zonal wind to cloud radiative effects in tropics vs. extratropics in GFDL-AM2.1 and NCAR-CAM5.3 models
Response of mass streamfunction to cloud radiative effects in tropics vs. extratropics in GFDL-AM2.1 and NCAR-CESM1.2 models.
Why do tropical clouds drive changes in strength of Hadley cell?

\[ ACRE = \frac{c_p}{g} \int_0^{p_s} Q_{cld} \, dp \]

ACRE: Atmospheric Cloud Radiative Effect

Vertical dashed line: latitude of eddy-driven jet for clouds-off simulation
Interactions between subtropical and midlatitude jet

• A strengthened Hadley cell, and thus accelerated subtropical jet, leads to an equatorward shifted eddy-driven jet

• Two theories have been proposed:
  – increased baroclinicity on the poleward flank of the subtropical jet when it is strong [Lee and Kim, 2003]
  – changes in meridional eddy propagation when the subtropical jet strengthens [Ceppi et al., 2013]
What about the extratropical clouds?

- Locally, meridional gradients in ACRE will impact the latitude of maximum baroclinicity of the atmosphere

\[
ACRE_{\phi\phi} = \overline{ACRE}(\phi_{\text{off}} - \alpha) - 2 \cdot \overline{ACRE}(\phi_{\text{off}}) + \overline{ACRE}(\phi_{\text{off}} + \alpha)
\]

\[
\overline{ACRE}(\phi') = \text{mean} \left[ ACRE(\phi) \right]_{|\phi - \phi'| < \frac{\alpha}{2}}
\]

![Diagram of ACRE vs. Latitude](image)
Measure these effects across COOKIE models

• Eddy driven jet position $\phi$: latitude of maximum zonal mean zonal wind at 850hPa
  \[ \Delta \phi = \phi_{on} - \phi_{off} \]

• Hadley cell strength $\psi$: maximum of mass streamfunction
  \[ \Delta \psi = \psi_{on} - \psi_{off} \]

• ACRE gradient: $\text{ACRE}_{\phi\phi}$, approximate measure of second derivative of ACRE about $\phi_{off}$
ΔΦ, Δψ and ACRE_ϕφ across COOKIE models

a) Δψ versus ΔΦ

r = -0.65

ΔΦ [degrees poleward]

Δψ [10^9 kg/s]

-6 -5 -4 -3 -2 -1 0 1 2 3 4

-25 0 25 50 75

CNRM-CM5
NCAR-CAM5.3
MPI-ECHAM6
GFDL-AM2.1
HadGEM2-A
IPSL-CM5B-LR
IPSL-CM5A-LR
MRI-CGCM3

GFDL-AM2.1, extratrop on
GFDL-AM2.1, tropical on
GFDL-AM2.1, deep trop on
GFDL-AM2.1, subtrop on
NCAR-CAM5.3, extratrop on
NCAR-CAM5.3, tropical on
\(\Delta \phi, \Delta \psi\) and ACRE\(\phi\phi\) across COOKIE models

a) \(\Delta \psi\) versus \(\Delta \phi\)

\[ r = -0.65 \]

b) ACRE\(\phi\phi\) versus \(\Delta \phi\)

\[ r = -0.41 \]
∆φ, ∆ψ and ACRE_{φφ} across COOKIE models

a) ∆ψ versus ∆φ

b) ACRE_{φφ} versus ∆φ

c) ∆ψ versus ACRE_{φφ}

Blue: equatorward shift
Red: poleward shift
Black lines show least-squares best fit to:

\[ \Delta \phi = A \cdot \Delta \psi + B \cdot ACRE_{\phi\phi} + C \]
$\Delta \phi, \Delta \psi$ and $\text{ACRE}_{\phi\phi}$ across COOKIE models

a) ACRE influence regressed out

$r = -0.71$

b) Hadley influence regressed out

$r = -0.53$

c) true versus best fit $\Delta \phi$

$r = 0.76$

- CNRM-CM5
- NCAR-CAM5.3
- IPSL-CM5B-LR
- MPI-ECHAM6
- GFDL-AM2.1
- HadGEM2-A
- IPSL-CM5A-LR
- GFDL-AM2.1, extratrop on
- GFDL-AM2.1, tropical on
- GFDL-AM2.1, deep trop on
- GFDL-AM2.1, subtrop on
- GFDL-AM2.1, LW on
- GFDL-AM2.1, SW on
- NCAR-CAM5.3, extratrop on
- NCAR-CAM5.3, tropical on
What about the global warming response of the jet?

Response of 850hPa zonal wind to +4K SST perturbation
What about the global warming response of the jet?

Response of 850hPa zonal wind to +4K SST perturbation

Clouds off

Clouds on
Summary

• Across models, the impact of cloud radiative effects onto the position of the midlatitude jet varies widely in sign and magnitude
• This is primarily controlled by how much cloud radiative effects strengthen the Hadley cell, and thus accelerate the subtropical jet
• An important secondary control is the local impact of cloud radiative effects onto meridional temperature gradients in the midlatitudes
• Work to be done:
  – Implications for global warming response of jets?
  – What would the impact of including an interactive ocean be? (greater role for low clouds)
• Paper out in *GRL*: “Local and Remote Impacts of Atmospheric Cloud Radiative Effects Onto the Eddy-Driven Jet”

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Extra slides
Black: ACRE in clouds-on simulation. Red: ACRE in clouds-off simulation (where available)
Black: ACRE in clouds-on simulation. Red: ACRE in clouds-off simulation (where available)
$\Delta \phi, \Delta \psi$ and ACRE$_{\phi\phi}$ across COOKIE models

(a) ACRE influence regressed out

(b) Hadley influence regressed out

(c) true versus best fit $\Delta \phi$
$\Delta \phi$, $\Delta \psi$ and ACRE$\phi\phi$ across COOKIE models

a) ACRE influence regressed out

$\Delta \phi [\text{degrees poleward}]$

$\Delta \psi [10^9 \text{ kg/s}]$

r = -0.71

b) Hadley influence regressed out

$\Delta \phi [\text{degrees poleward}]$

r = -0.53

c) true versus best fit $\Delta \phi$

r = 0.76

g) IPSL-CM5A-LR

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