Hemispheric (a)symmetries and tropical climate

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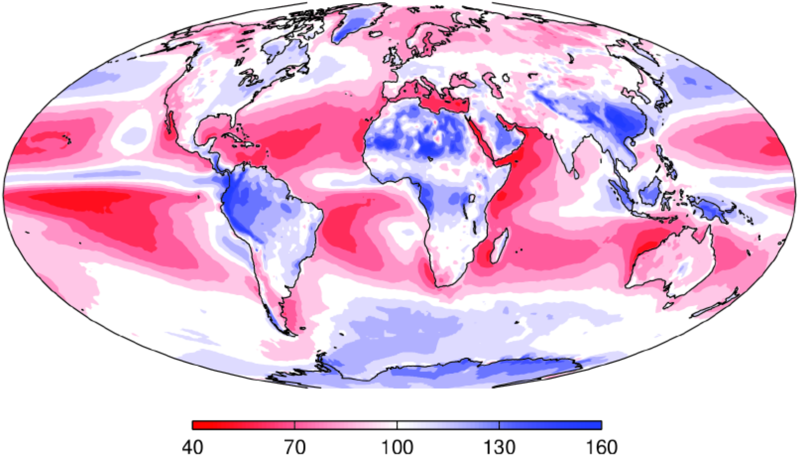
CERES-GERB-SCaRaB Workshop on Earth Radiation Budget, Toulouse, October 2014

Hemispheric symmetry of observed TOA reflected shortwave irradiance

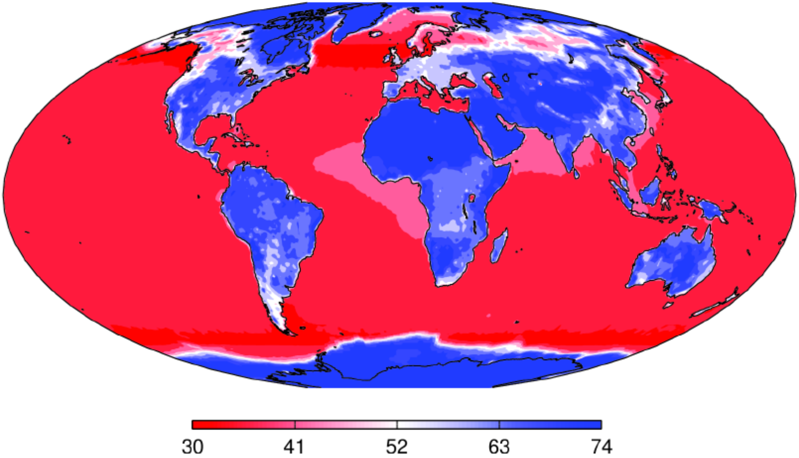


Ceres Ebaf Ed2.6r, 2000-2010, in Wm^{-2}

The all-sky reflection is hemispherically symmetric (asymmetry $< 0.1\,Wm^{-2}$).

Voigt et al., J. Clim., 2013

The symmetry is remarkable given the large clear-sky asymmetry



Ceres Ebaf Ed2.6r, 2000-2010, in Wm^{-2}

The clear-sky reflection is very asymmetric (asymmetry of $6\,Wm^{-2}$).

Hemispheric (a)symmetries in Earth Radiation Budget

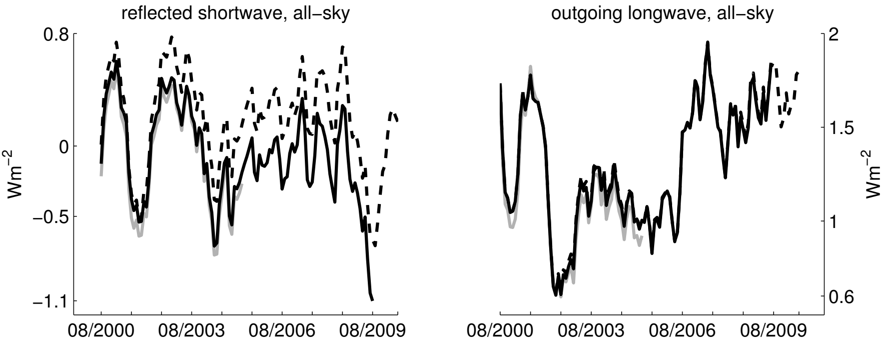
	Northern hemisphere	Southern hemisphere	Difference
SW in	340.1	340.1	0.0*
SW up	99.7	99.5	0.2
SW up clear-sky	55.6	49.4	6.2
OLR	240.4	239.0	1.4
OLR clear-sky	266.8	264.6	2.2

CERES-EBAF Ed2.8, 03/2000-02/2014

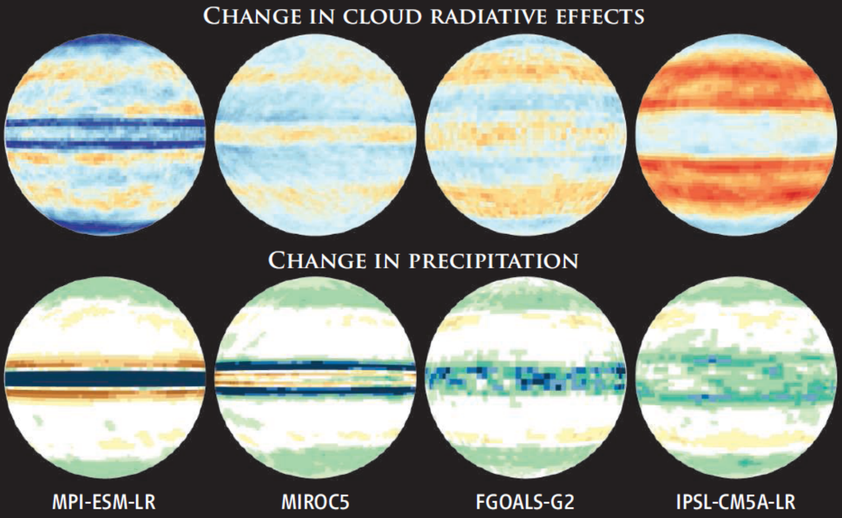
The hemispheric albedo symmetry is seen in all CERES-EBAF editions. Indeed, it has been seen in previous satellite-based observations of Earth Radiation Budget. (Vonder Haar and Suomi (1971), Ramanathan (1987), Zhang and Rossow (1997))

NB: The albedo symmetry and more longwave energy loss in the northern hemisphere implies that the atmosphere+ocean cross-equatorial heat transport is northward.

The symmetry is realized also during individual 12-month running means



Models have trouble representing the coupling of water to the circulation. Much of this trouble is from the radiative coupling.



Stevens and Bony, 2013

Outline

1. Is the hemispheric symmetry of planetary albedo trivial?
2. Is the symmetry a constraint? Is there a compensation mechanism?
3. What determines the efficiency of the compensation mechanism?

Answering these questions is important to better understand the response of the atmospheric circulation to regional radiative forcings and the regional manifestation of global climate change.

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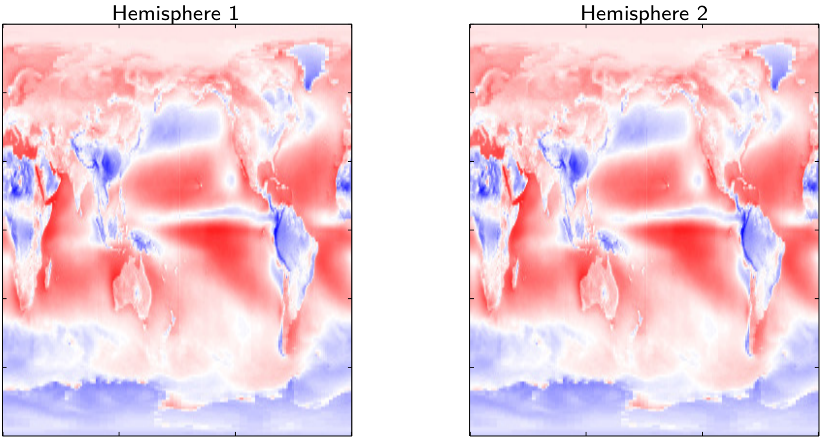
Is the observed symmetry trivial?



1. Partition of Earth into a pair of two random non-overlapping “hemispheres”
2. Compute the hemispheric difference D
3. Repeat 10^4 times to quantify probability to find $D < 0.1\,\mathrm{Wm}^{-2}$

NB: We use several approaches to estimate the zonal and meridional length scales. We find $\Delta\lambda = 36^\circ$, $\Delta\Phi = 10^\circ$.

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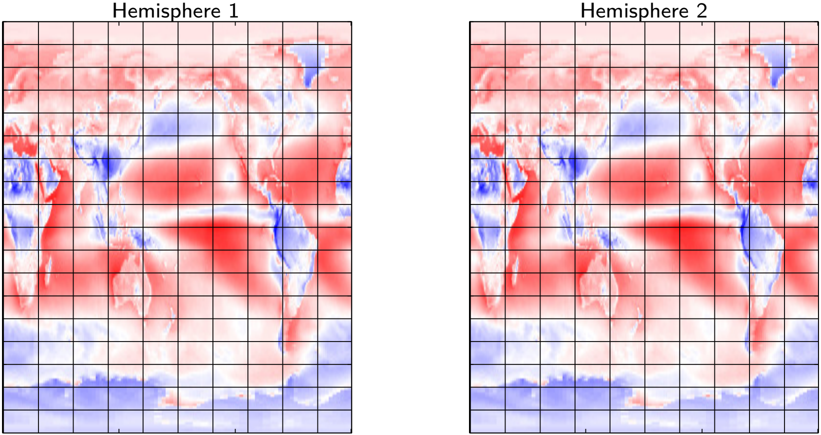

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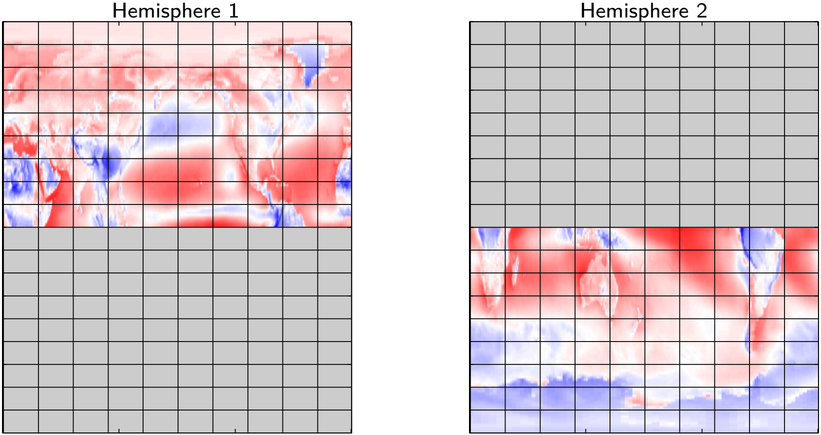

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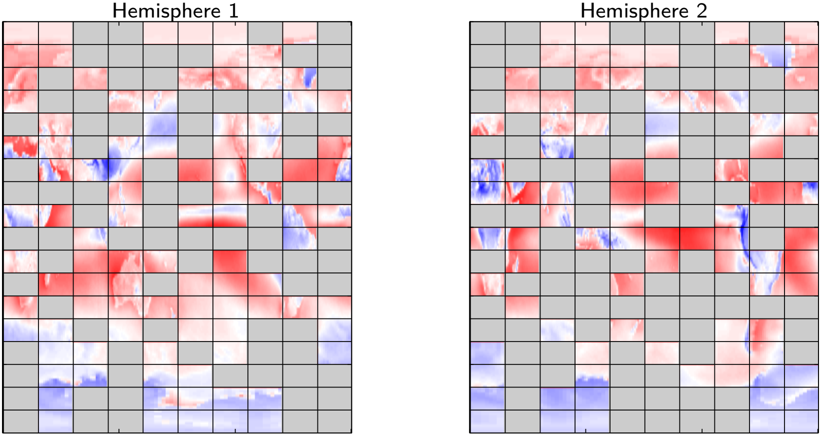

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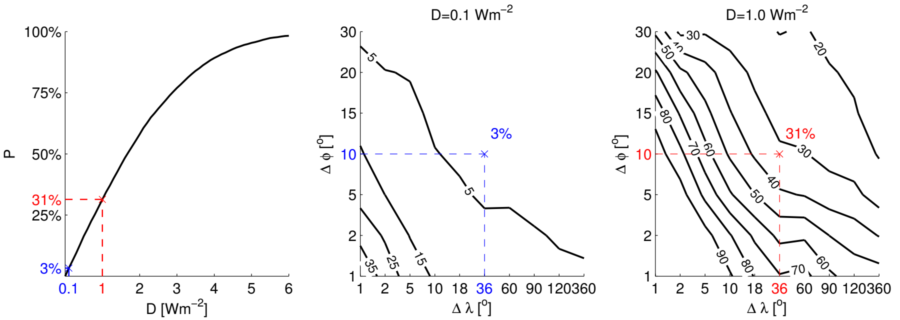
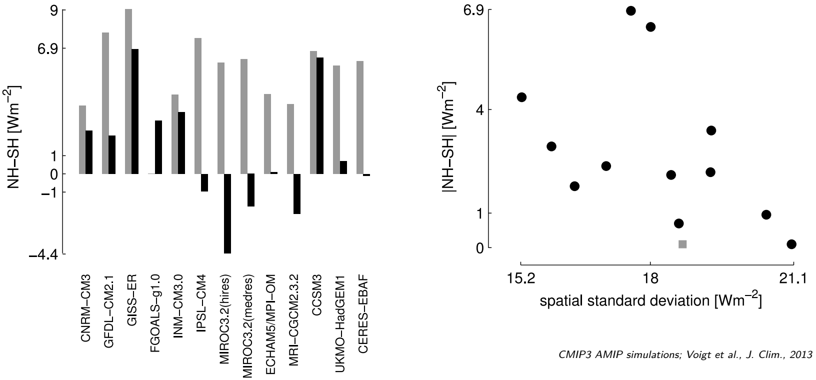
The probability to find the symmetry by chance is only 3%



Voigt et al., J. Clim., 2013

Models have trouble reproducing the albedo symmetry



CMIP3 AMIP simulations; Voigt et al., J. Clim., 2013

No improvement from CMIP3 to CMIP5 (see Stephens et al., 2014, in review).
Note the enormous spread in the the clear-sky difference.

Outline

1. The hemispheric symmetry of planetary albedo is non-trivial.

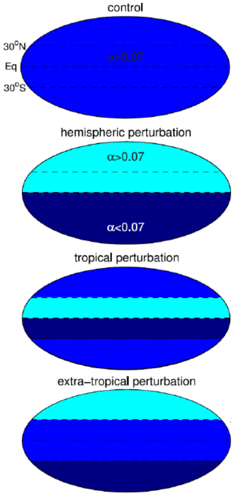
2. Is the symmetry a constraint? Is there a compensation mechanism?

3. What determines the efficiency of the compensation mechanism?

Answering these questions is important to better understand the response of the atmospheric circulation to regional radiative forcings and the regional manifestation of global climate change.

Simulation framework: Comprehensive climate models in idealized setup

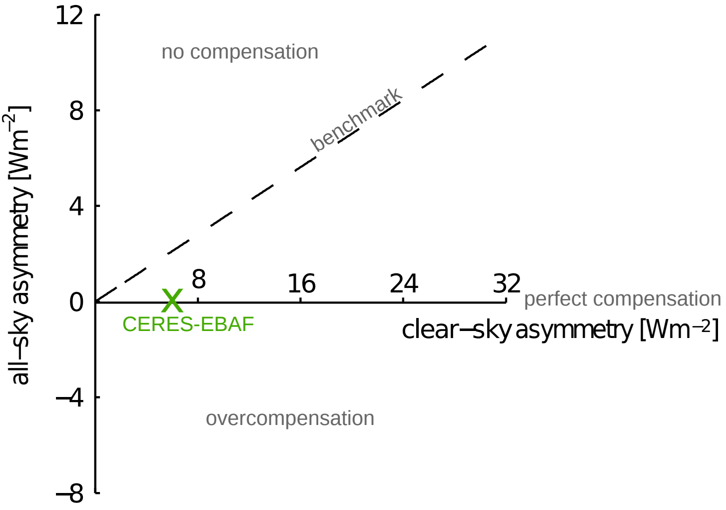
- ECHAM6 atmosphere model
- Aquaplanet setup: no continents, zonally-symmetric, no sea ice
- Interactive sea-surface temperatures by coupling to slab ocean
- Introduce hemispheric asymmetries in clear-sky albedo by perturbing the surface albedo
- Monitor the hemispheric difference in all-sky reflection as a function of clear-sky reflection difference



Voigt et al., 2014, J. Clim.

Clouds compensate albedo asymmetries

(although not perfectly)



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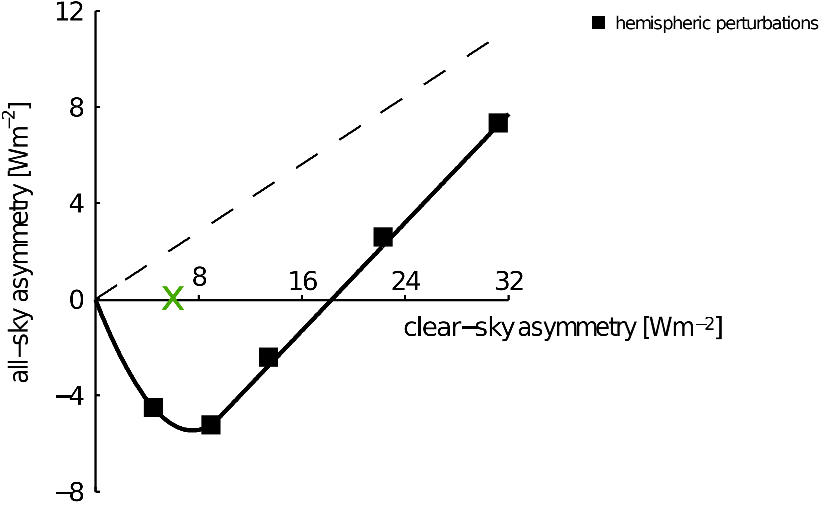

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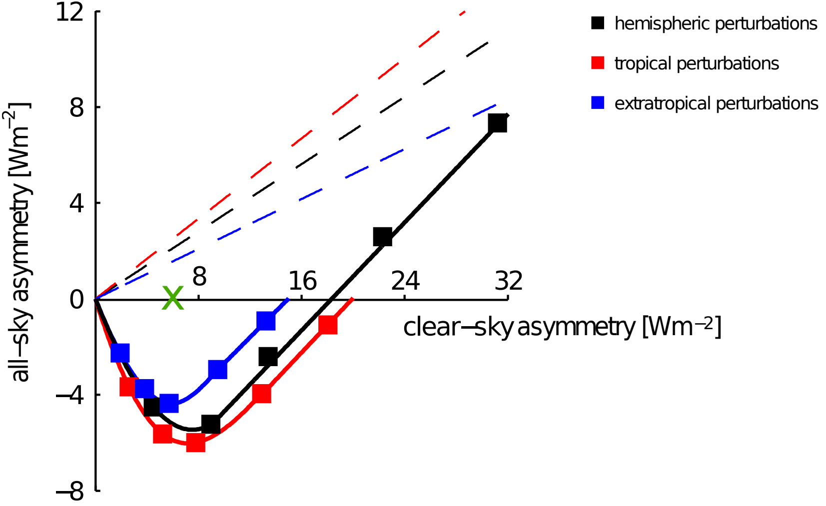
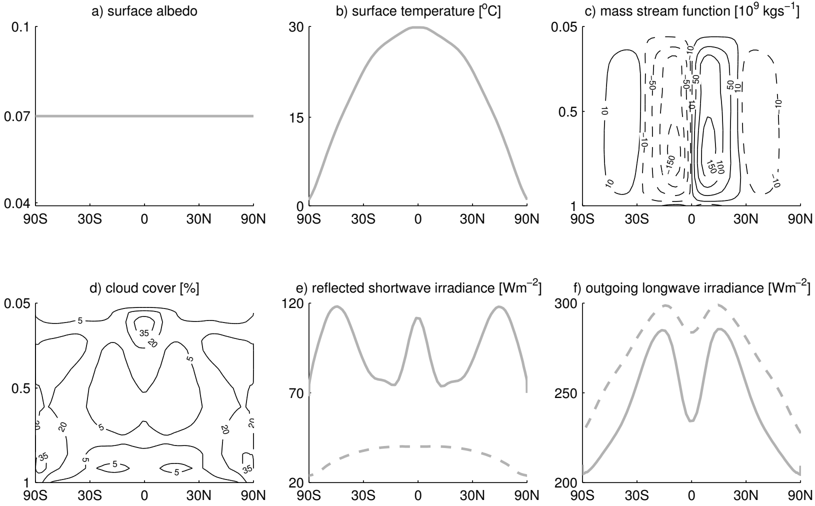
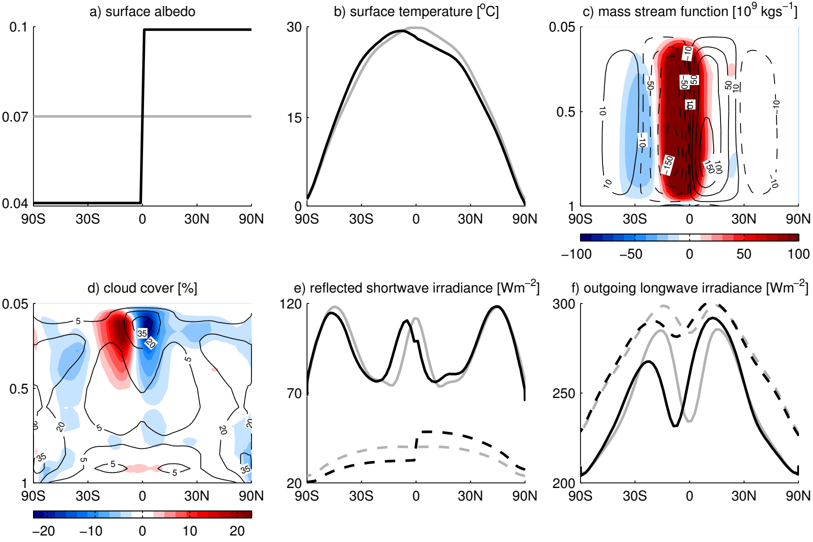


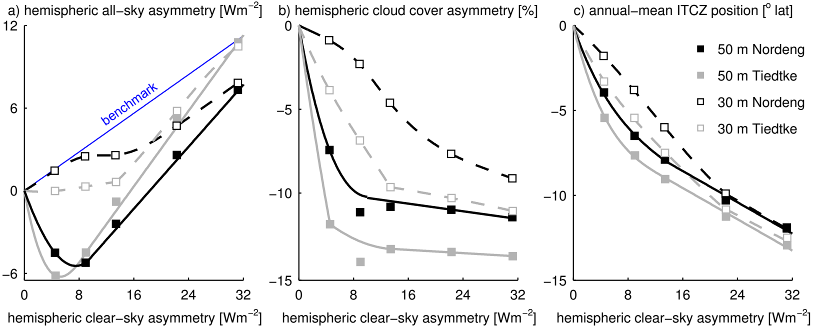
Tropical compensation mechanism: control climate



Tropical compensation mechanism: ITCZ and high tropical clouds shift into dark-surface hemisphere

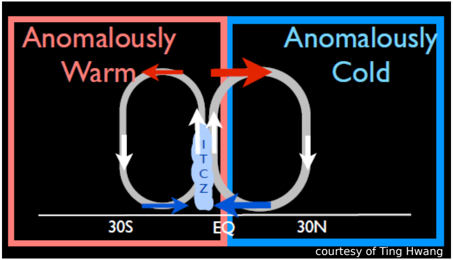


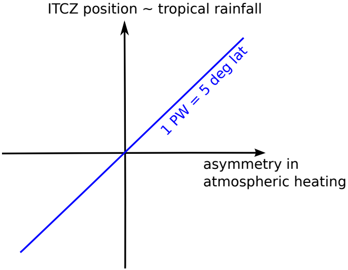
Rich behavior, and degree of compensation scales with magnitude of ITCZ shift



The symmetry does not seem to be a constraint, but the real Earth might be on a plateau like the one simulated by one model version.

An emerging picture: ITCZ and tropical rainfall shift towards heated hemisphere/away from cooled hemisphere





- Cross-equatorial northward ocean heat transport "explains" why ITCZ is in the Northern hemisphere (Frierson et al., Nat. Geosci., 2013; Marshall et al., Clim. Dyn., 2013)
- Models with too little reflection from Southern ocean clouds tends to have double ITCZ in East Pacific (Hwang & Frierson, PNAS, 2013)
- In the future, stronger land warming will shift ITCZ north (Friedman et al., J. Climate, 2013)
- In the past, NH cooling from aerosols shifted ITCZ south, leading to Sahel drought (Hwang et al., GRL, 2013; Haywood et al, Nat. Clim. Change, 2013)
- Mid-latitude afforestation expected to shift ITCZ north (Swann et al., PNAS, 2012)

Outline

1. The hemispheric symmetry of planetary albedo is non-trivial.

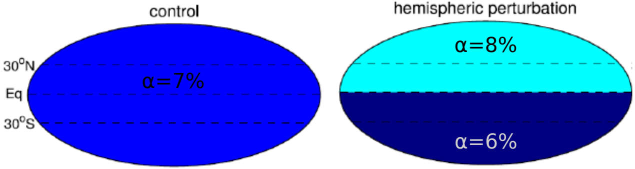
2. ITCZ shifts towards darker hemisphere, or more generally towards warmed hemisphere.

3. What determines the magnitude of the ITCZ shift in response to a given forcing?

Answering this questions is crucial for the tropical rainfall response during past and future climate changes.

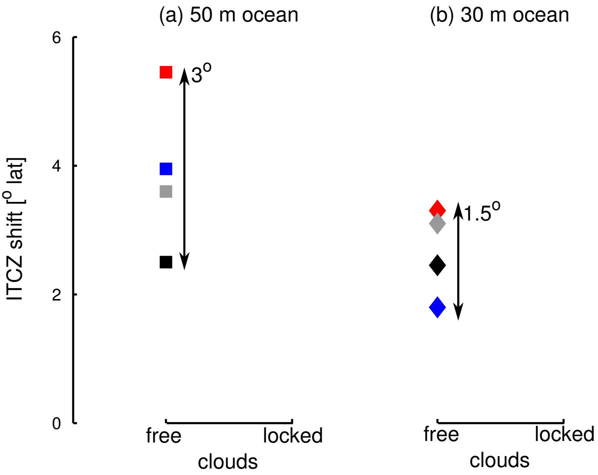
Simulation framework: Comprehensive climate models in idealized setup

- Four models: ECHAM6-TNT, ECHAM-TTT, LMDz5A, LMDz5B atmosphere model
- Aquaplanet setup: no continents, zonally-symmetric, no sea ice
- Interactive sea-surface temperatures by coupling to slab ocean
- Introduce hemispheric asymmetries in clear-sky albedo by perturbing the surface albedo
- Investigate impact of cloud-radiative changes on ITCZ shift

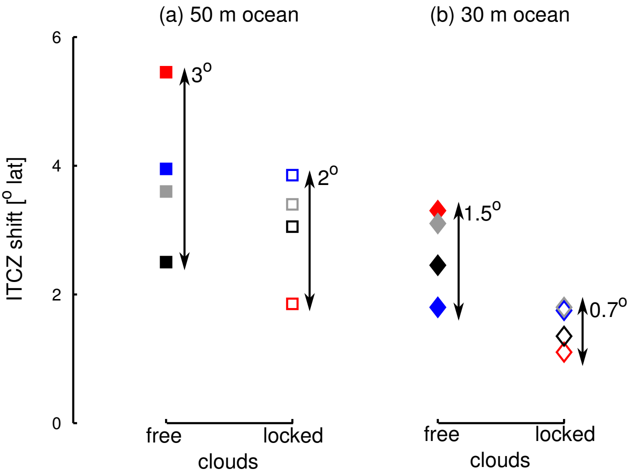


Voigt et al., GRL, 2014

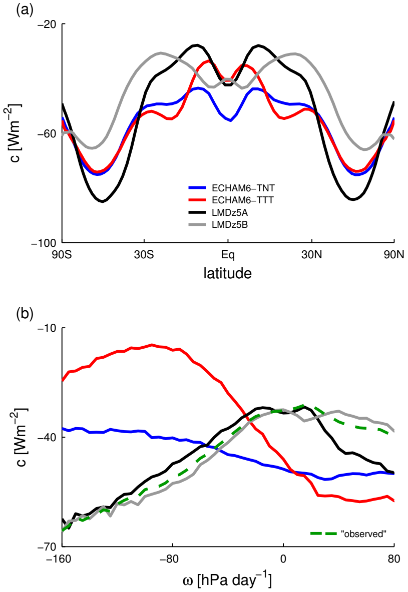
Magnitude and model-spread in simulated ITCZ shift



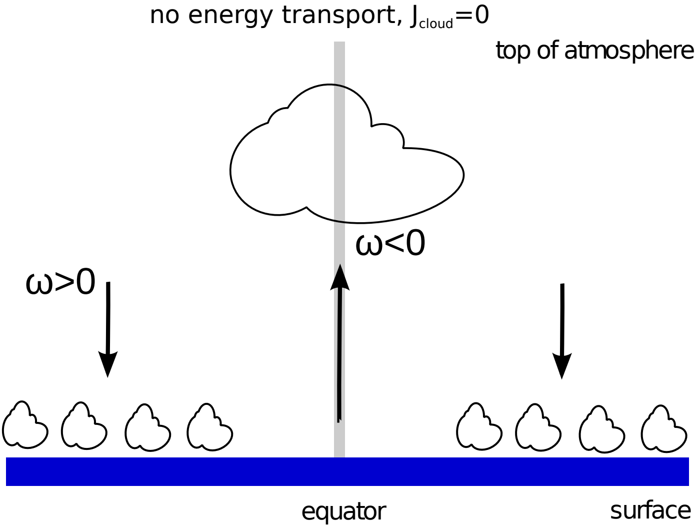
Cloud-radiative feedback is responsible for half of the model-spread



Exploit coupling between radiative effect of tropical clouds and vertical motion



Is the feedback mainly due to the radiative contrast between upsidence and subsidence clouds?



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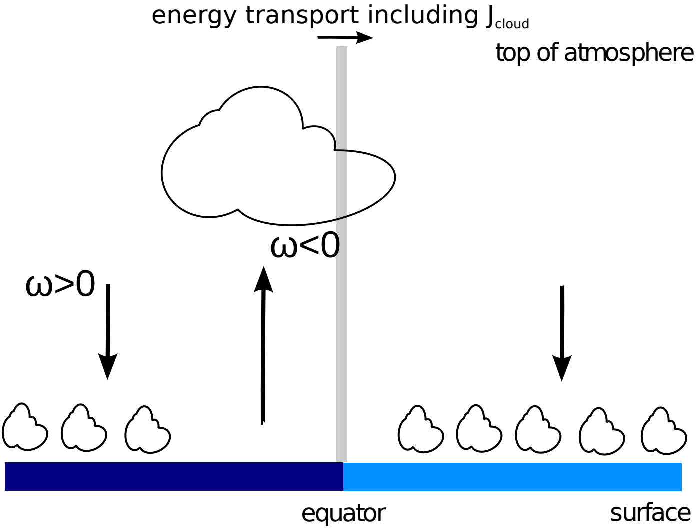


Calculate dynamical ("fixed ω-cloud relation") component of J_{cloud}

Cloud effect on TOA energy budget over entire, northern, and southern tropics:

$$\begin{aligned} C &= \int c(\omega)p(\omega)d\omega, \\ C_N &= \int c_N(\omega)p_N(\omega)d\omega, \\ C_S &= \int c_S(\omega)p_S(\omega)d\omega, \end{aligned}$$

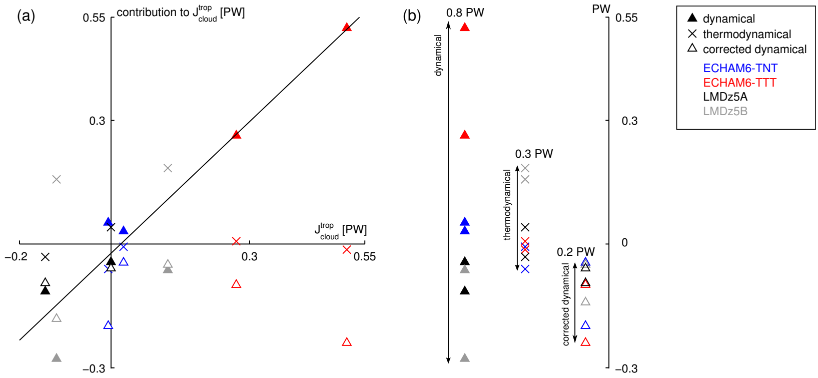
Cloud-contribution to cross-equatorial energy transport:

$$J_{cloud} \propto C'_N - C'_S \propto \int c'_N p'_N - c'_S p'_S \, d\omega. \tag{1}$$

Dynamical component of the cloud-contribution:

$$J_{cloud} \propto \underbrace{\int c(p'_N - p'_S)d\omega}_{dynamical} + \underbrace{\int (c'_N - c)p'_N - (c'_S - c)p'_S d\omega}_{residual}. \tag{2}$$

Dynamical component explains model spread in J_{cloud}: Tuning the models' relationship between tropical CRE and vertical motion would half model spread in ITCZ shift



Summary

- The Northern and Southern hemisphere reflect the same amount of shortwave irradiance. This property is surprising given the large clear-sky asymmetry and it is non-trivial.
- The ITCZ shifts into the darker hemisphere to compensate for clear-sky albedo asymmetries, yet there seems to be no fundamental reason why the compensation needs to be perfect.
- In general, the ITCZ shifts into the hemisphere that receives anomalous heating.
- Tropical clouds strongly affect the magnitude of the ITCZ. Correctly modelling their radiative effects as a function of the tropical circulation is crucial to predict the magnitude of ITCZ shifts.