

Croll Revisited:
Why is the Northern Hemisphere Warmer than
the Southern Hemisphere?

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ABSTRACT

The question of why, in the annual mean, the Northern Hemisphere is warmer than the Southern Hemisphere is addressed, revisiting an 1870 paper by James Croll. We first show that the ocean is warmer than the land in general which, acting alone, would make the Southern Hemisphere warmer because of its greater fraction of ocean. Croll recognized this and thought it was caused by greater humidity and greenhouse trapping over the ocean than over the land. However, for any given temperature, greenhouse trapping is actually greater over the land than the ocean. Instead, oceans are warmer than land because of smaller surface albedo. However, inter-hemispheric differences in total albedo are negligible because the impact of differences in land-sea fraction are offset by Southern Hemisphere ocean and land reflecting more than their Northern Hemisphere counterparts. In agreement with Croll, it is shown that northward cross-equatorial ocean heat transport is critical for the Northern Hemisphere to be warmer. This is examined in a simple box model based on the energy budget of each hemisphere. This inter-hemispheric difference forced by ocean heat transport is enhanced by the positive water vapor-greenhouse feedback, and is partly compensated by the southward atmospheric energy transport, which is accomplished by locating the Intertropical Convergence Zone in the Northern Hemisphere. However, to fully explain the temperature difference in this way requires a northward ocean heat transport at the extreme of observational estimates. A better fit to data is found when a larger basic state greenhouse trapping in the NH, conceived as imposed by continental geometry, is also imposed. Therefore, despite some modifications to his theory, analysis of modern data confirms Croll's 140 year-old theory that the Northern Hemisphere is warmer than the Southern Hemisphere in part because of northward cross-equatorial ocean heat transport.

1. Introduction

One of the most fundamental features of the Earth's climate is that the Northern Hemisphere (NH) is warmer than the Southern Hemisphere (SH) (Fig. 1). There are several possible reasons for this. An informal poll of members of the public and some scientists often produces the answer that it is because the NH has more land and, therefore, heats up more in summer because of the lesser heat capacity. On the other hand, many scientists argue that it is because the ocean transports heat northward across the equator. We have also encountered more subtle arguments such as continental geometry that results in upwelling and equatorward sea ice export in the Antarctic Circumpolar Current (ACC) and Southern Ocean (SO) cooling the SH. Also, it could be argued that the impact of continental geometry on subtropical coastal upwelling preferentially cools the south (Philander et al. 1996). Finally, it could be a transient response to greenhouse gas forcing because the NH has the larger land fraction and heats up faster than the more oceanic SH. While the inter-hemispheric temperature asymmetry is interesting in and of itself, it is also of practical importance because of the influence it exerts on the position of the Intertropical Convergence Zone (ITCZ) (Kang et al. 2008) whose rains are relied upon many tropical societies for their water and food production.

Although it still seems unclear exactly why the NH is warmer than the SH, James Croll, the founder of the astronomical theory of the ice ages, provided an explanation as early as 1870 (Croll 1870). He thought that the hemisphere with more ocean should be warmer than the one with more land because of higher atmospheric humidity, and hence, more greenhouse trapping. Interestingly, we will show that this is in fact incorrect: the greenhouse trapping

in general is greater over land than over ocean at the same temperature. Nonetheless, given that he thought that this mechanism would make the SH warmer than the NH, Croll claimed that the NH was actually warmer because the ocean transports heat northward across the equator:

The lower mean temperature of the southern hemisphere is due to the amount of heat transferred over from that hemisphere to the northern by ocean-currents.

Croll's arguments for how currents accomplish this transport was stated as follows:

Since there is a constant flow of water from the southern hemisphere to the northern in the form of surface currents, it must be compensated by undercurrents of equal magnitude from the northern hemisphere to the southern. The currents, however, which cross the equator are far higher in temperature than their compensating undercurrents; consequently there is constant transference of heat from the southern hemisphere to the northern.

He argues that this idea is supported by the fact that the tropical oceans are cooler than the tropical land as a result of the huge ocean heat flux divergence. While Croll was correct that ocean heat flux divergence does cool some equatorial ocean regions, averaged over longitude it turns out that the tropical oceans are warmer than the tropical land masses. Nevertheless, Croll's northward cross-equatorial ocean heat transport (OHT) explanation is probably the dominant one amongst scientists (e.g. Toggweiler and Bjornsson 2000). It is truly remarkable that in 1870, Croll 1) knew that the NH was warmer than the SH, 2) was able to infer a cross-equatorial OHT and 3) provided a coherent explanation for the temperature asymmetry

that, though largely forgotten, is still invoked 140 years later. As we will show here, Croll appears to have been correct.

2. Data

For temperature, NCEP/NCAR reanalysis data (Kistler and Coauthors 2001) for the period from 1979 to 2009 are used. The annual mean as well as seasonal averages will be analyzed where winter (summer) in the NH is computed as the average of December-to-February (June-to-August) and vice versa in the SH.

To understand the inter-hemispheric differences in temperature, the radiation budget and the meridional energy transport by atmosphere and ocean will be examined. The top-of-atmosphere (TOA) energy budget is determined by satellite data from the Clouds and the Earth's Radiant Energy System (CERES; Wielicki et al. 1996) for March 2000 through October 2005 after some adjustments are made as described in Fasullo and Trenberth (2008a). The atmospheric energy transport – the vertical integral of the meridional transport of the sensible heat, potential energy, kinetic energy, and latent energy – is computed from NCEP/NCAR (Kistler and Coauthors 2001) and ERA40 (Uppala and Coauthors 2005) re-analyses data, and obtained from Fasullo and Trenberth (2008b). For the oceanic energy transport, due to large uncertainties in the ocean data, we consider a range of values as discussed in Section 4a. The total cloud amount in Section 4b is from the International Satellite Cloud Climatology Project (ISCCP) cloud product (Rossow and Schiffer 1991) for the period from July 1983 to June 1991.

3. Temperature Differences

a. Inter-hemispheric Differences

The NH is warmer than the SH by 1.25°C in the annual mean (Fig. 1a). The warmer NH is also found in the multi-model mean of the preindustrial runs of 24 CMIP3 models (Meehl et al. 2007), but with a smaller magnitude of 1.13°C . This suggests that the warmer NH is not a transient adjustment to greenhouse gas forcing with the more-land hemisphere leading, rather it is a basic characteristic of the Earth's climate. This is consistent with Croll identifying the inter-hemispheric temperature difference in 1870 before human impacts on the global scale climate system were appreciable. Interestingly, not all models produce a warmer NH, but the details are beyond the scope of the paper. Furthermore, the inter-hemispheric difference is also present at 700mb with the NH 2.0°C warmer than the SH, excluding the possibility of the surface temperature difference being caused by Antarctica's high elevation.

When divided into seasons, that is, NH summer compared to SH summer and NH winter compared to SH winter, it is clear that the warmer NH in the annual mean results from the inter-hemispheric north minus south difference in summers of 4.2°C being partly offset by a smaller, opposite sign, difference of 1.9°C in winters. There is also a greater seasonal variation of temperature in the NH, 11.4°C , as opposed to 5.2°C in the SH, because the massive NH continents have interiors far from the oceans that warm in summer and cool in winter whereas SH continents are more influenced by ocean temperatures that themselves vary less with season due to large thermal inertia and storage of heat within the wind-driven mixed layer.

As land and ocean temperatures are vastly different due to contrasting thermal inertia and heat storage, it is useful to breakdown the inter-hemispheric temperature difference as following:

$$\Delta T = f_{O,N}T_{O,N} + (1 - f_{O,N})T_{L,N} - f_{O,S}T_{O,S} - (1 - f_{O,S})T_{L,S}. \quad (1)$$

Here, ΔT denotes the difference of temperature between the two hemispheres, f_O is fraction of ocean, T_L is area-weighted average temperature of land and T_O area-weighted ocean temperature. The subscripts N and S denote the northern and the southern hemispheres, respectively. The hemispheric mean temperatures of ocean and land, T_O and T_L , for both hemispheres are compared separately in Figs. 1b and 1c. The NH is warmer than the SH over ocean in both seasons and over land in summer. The latitudinal structure of the NH-SH difference in T_O in Fig. 2b indicates that the NH oceans are warmer than the SH oceans throughout the year at almost all latitudes. NH land is warmer than SH land in summer (Fig. 2c). However, between the latitudes of 28° and 66° where the vast northern continents are, winter T_L is cooler in the north than the south because the southern continental temperatures are more moderated by ocean temperatures. At these latitudes, summer T_L is warmer in the NH by 1.7°C but winter T_L is colder by 2.9°C . This implies the cooling effect of land in winter outweighs its warming effect in summer. Hence, in the annual mean the presence of the NH midlatitude continents tends to actually cool the NH relative to the SH, as evidenced by colder northern extratropics than the southern extratropics (Fig. 2a). However, the tropical land regions equatorward of 28° and the high latitudes poleward of 66° are warmer in the north almost throughout the year.

As depicted in Fig. 3, the differences in land (or ocean) fraction between the two hemi-

spheres complicates the picture of dividing hemispheric mean temperature into contributions from T_L and T_O . Because there is a larger ocean fraction in the south, ocean temperatures are weighted more when computing the hemispheric mean. For example, during winters, although NH oceans are warmer than SH oceans, and the difference in land temperatures is small, the NH is colder than the SH because the land is colder than the ocean and the north has more land. Hence, in addition to temperature differences between land and ocean, both within a hemisphere and between the hemispheres, the inter-hemispheric temperature difference is also attributed to by differences in the fractional coverage of ocean. Therefore, we divide up the inter-hemispheric difference into these three components. Eq. (1) is rewritten as:

$$\Delta T = f_{O,N}(T_{O,N} - T_{O,S}) + (1 - f_{O,S})(T_{L,N} - T_{L,S}) + (f_{O,S} - f_{O,N})(T_{L,N} - T_{O,S}). \quad (2)$$

These three terms can be thought of as, in order, a term due to differences in ocean temperature, second, a term due to differences in land temperature and, third, a term due to differences in land and ocean fractions. Fig. 4 shows the decomposition of inter-hemispheric temperature differences using Eq. (2) for the annual mean and each season. The warmer NH in the annual mean is due to both the ocean and land being warmer in the north than the south while this is partly offset by the larger fraction of land in the north which tends to make the NH cooler. As seen from Fig. 2, the greater land fraction in the NH warms northern summers, but greatly cools winters and hence cools the NH in the annual mean. In all seasons, the warmer ocean in the north contributes the most to preferentially warming the NH.

b. Ocean versus Land Temperatures

It is shown in the last section that land, compared to ocean, gets colder in winter by a larger amount than it gets warmer in summer, suggesting the hemisphere with the larger land fraction should be colder on average: this effect would make the SH warmer than the NH. Here, we examine, and explain why, in general, ocean is warmer than land. Fig. 5a shows the latitudinal distribution of the difference between the ocean and land temperatures. In winter, T_O is significantly warmer than T_L at all latitudes because land with small heat capacity cools more effectively than the ocean. In contrast, in summer, T_L is warmer than T_O in the mid- to high latitudes because the land warms up more than the ocean. This seasonal variation is greater in the north because the northern continents are larger and more shielded from the mitigating ocean effects. As expected, there is little seasonal variation in the tropics, with the ocean always being warmer than the land. Because the degree to which ocean is warmer in winter is much larger than the degree to which ocean is colder in summer, ocean in the annual mean is warmer than land at every latitude. If this was the only process operating then we would expect the SH, with more ocean, to be warmer than the NH. Or, as Croll stated it:

Were there no ocean-currents, it would follow, according to theory, that the southern hemisphere should be warmer than the northern, because the proportion of sea to land is greater on that hemisphere than on the northern; but we find that the reverse is the case.

Then, why is ocean warmer than land in general? Croll (1870) thought that the ocean will be warmer because of the greater amount of water vapor above and larger greenhouse trapping,

(although he did not use that term). Croll argued that:

The aqueous vapour of the air acts as a screen to prevent the loss by radiation from water, while it allows radiation from the ground to pass more freely into space; the atmosphere over the ocean consequently throws back a greater amount of heat than is thrown back by the atmosphere over land.

To check this, the greenhouse trapping, G , is computed as the difference between the upward longwave radiation at the surface and the outgoing longwave radiation (OLR). The latitudinal difference of G over ocean and land in Fig. 5b indeed indicates that, at a given latitude, the greenhouse trapping is generally larger over the ocean in the annual mean. The exception is over the lower latitudes in the SH and arises from a contrast between large greenhouse trapping over the Amazon and Congo and weak trapping over the cool southeast tropical Pacific and Atlantic Oceans (refer to Fig. 12). However, G_O could be larger than G_L solely because T_O is warmer than T_L . Hence it is more informative to compare G over ocean and land at the same temperature. To do so, the global temperature data is binned in intervals of 2°C , and G , multiplied by the grid area, is summed within the bin. Fig. 6 indicates that the greenhouse trapping is in fact larger for any given temperature over the land than over the ocean. The exceptions are at very high temperatures where there is very high greenhouse trapping over the Indo-Pacific warm pool and at very low temperatures where there is very weak trapping over very cold and dry continents. Over land, the atmospheric humidity can get very high within summer monsoons, especially over Asia and North America. In contrast, over oceans, the atmospheric humidity can get very low in the descending, eastern, branches of the subtropical anticyclones, which partly owe their existence to monsoonal

heating during summer over land (Rodwell and Hoskins 2001; Seager et al. 2003). Hence, greater greenhouse trapping over the ocean cannot be the reason why the ocean is warmer than the land. The reason for the ocean being warmer than land is instead because of the smaller ocean albedo (Fig. 5c).

Do inter-hemispheric albedo differences then contribute to the inter-hemispheric temperature difference with the Southern Hemisphere having a lower albedo? Following Eq. (2), the north-south difference of shortwave reflection at TOA (S^\uparrow) can be decomposed as:

$$\Delta S^\uparrow = f_{O,N}(S_{O,N}^\uparrow - S_{O,S}^\uparrow) + (1 - f_{O,S})(S_{L,N}^\uparrow - S_{L,S}^\uparrow) + (f_{O,S} - f_{O,N})(S_{L,N}^\uparrow - S_{O,S}^\uparrow).$$

The inter-hemispheric difference of S^\uparrow resulting from its differences over ocean, those over land, and land-ocean fraction difference is plotted in Fig. 7. More ocean cover in the SH indeed acts to decrease S^\uparrow in the SH compared to the NH. However this difference is offset by the fact that the Southern Hemisphere ocean and land reflect more than their Northern Hemisphere counterparts, partly because of more clouds in the SH (refer to Fig. 11) due to both extensive subtropical stratus decks and cloud cover over the Southern Ocean. Hence, the hemispheric mean difference in shortwave reflection is only 0.2 Wm^{-2} , suggesting little impact of ΔS^\uparrow on the inter-hemispheric temperature difference.

4. Meridional Energy Transport and Radiation Budget

Regional temperatures are determined by the radiation budget and the energy transports by the atmosphere and ocean. One may expect warmer temperature where there is more greenhouse trapping, less shortwave reflection, and more energy convergence by atmosphere

and ocean. Hence, in this section, the top-of-atmosphere (TOA) radiation budget and meridional energy transports by ocean and atmosphere are examined to study what leads to the warmer NH.

a. Cross-equatorial Oceanic Energy Transports

The oceanic energy transport divergence is balanced by the ocean heat content tendency and the downward surface fluxes over the ocean, which in turn is determined by the atmospheric energy transport divergence and tendency and the net TOA radiative flux. In Trenberth and Fasullo (2008), TOA flux is determined by satellite retrievals from ERBE and CERES and atmospheric energy transport divergence is computed from reanalyses. Trenberth and Fasullo (2008) used three different ocean data sets to estimate the ocean heat content tendency. By combining the ERBE and CERES data with atmospheric heat transports calculated with different reanalysis, and the three different estimates of ocean heat tendency, Trenberth and Fasullo (2008) were able to create nine estimates of the ocean heat transport providing for a median estimate with two standard deviation error bars.

In the Atlantic, they found the median gave a large northward cross-equatorial ocean transport of 0.56 ± 0.09 PW in the annual mean (Trenberth and Fasullo 2008). The yearlong northward transport corresponds to a warmer northern sector than the southern sector in all seasons (Fig. 8). In the Pacific, the median gave little cross-equatorial transport regardless of season, with -0.01 ± 0.19 PW in the annual mean (Trenberth and Fasullo 2008), but the coastal upwelling in the southern subtropics, west of Chile (Philander et al. 1996) can contribute to the warmer northern Pacific sector. In the Indian Ocean, there is a large sea-

sonal cycle in the cross-equatorial ocean transport, with the median of the estimates having 1.4PW to the north in boreal winter (December through February) and 1.8PW to the south in austral winter (June through September) (Loschnigg and Webster 2000). Hence, when comparing NH winter with SH winter, and vice versa, Indian OHT has little impact on the inter-hemispheric temperature contrast.

Because of the large seasonality in the Indian sector, the total energy transport by the ocean also exhibits a pronounced seasonal variability with a northward transport in boreal winter and a southward transport in boreal summer (Fig. 9a in Trenberth and Fasullo 2008). However, in the annual mean, the total cross-equatorial ocean transport is small with the median estimate providing $0.1PW$ with a two standard deviation spread of 0.6PW. However, the fact that warmer ocean temperatures in the north are most responsible for the warmer NH (Fig. 4), and that the Atlantic sector exhibits the largest inter-hemispheric contrast (Fig. 8) clearly do hint at the important role of cross-equatorial ocean transport although, clearly, the quality of ocean data is insufficient to support this assertion. Nonetheless, the simple box model calculation in Section 5 suggests that the OHT must be northward across the equator and within the error bars of the estimates of Trenberth and Fasullo (2008).

b. TOA Radiation Budget

The inter-hemispheric differences of downward and upward shortwave radiation at TOA, and greenhouse trapping are shown in Fig. 9. The SH receives 0.67 Wm^{-2} more incoming solar radiation than the NH because the Earth is closest to the Sun in SH summer. This is partly offset by 0.20 Wm^{-2} more shortwave reflection in the SH than the NH in the

annual mean. Hence, the TOA solar radiation would tend to make the SH the warmer hemisphere but this effect is small. In contrast, there is a significantly larger amount, 5.67 Wm^{-2} , of longwave radiation trapped within the atmosphere in the NH in the annual mean. The seasonal variation of the NH minus SH difference in the greenhouse effect, positive in summer and negative in winter, is proportional to the inter-hemispheric temperature difference indicating the expected coupling between temperature and greenhouse trapping.

The latitudinal structures of the inter-hemispheric differences in upward TOA shortwave radiation and greenhouse trapping are shown in Fig. 10 and that of cloud cover in Fig. 11. In summer seasons, the NH reflects less SW than the SH in the mid- to high latitudes, despite ice-free land albedo being larger than ocean albedo, due to less cloud cover (Fig. 11) and the high albedo Antarctic ice sheet. In winter seasons, the NH reflects more partly due to snow cover over land poleward of 40° . However there is also more SW reflection in the NH between 15° and 40° even though cloud cover is less in the NH all year long (Fig. 11). The SW reflection is larger in the NH equatorward of 15° because of clouds associated with the NH ITCZ.

The gross features of the latitudinal structure in the inter-hemispheric difference in greenhouse trapping (Fig. 10) are well correlated with those in surface temperatures (Fig. 2a), except the local maxima in the deep tropics where there is little temperature differences. The peak in greenhouse trapping in the tropics is due to a super greenhouse effect, whereby greenhouse trapping increases with surface temperature so strongly that OLR actually decreases as the surface warms (Raval and Ramanathan 1989). During winter seasons the smaller greenhouse trapping in the NH in the mid- to high latitudes is due to drying and cooling of the continents. The opposite occurs in summer seasons. The map of annual mean

greenhouse trapping overlain with surface temperature (Fig. 12) clearly indicates that these are well correlated. However, it is not clear which is the cause and which is the effect.

On the face of it then the NH is warmer than the SH because of the greater greenhouse trapping in the NH. This is in contrast with Croll's expectation that the hemisphere with more ocean would have the greater trapping and be warmer were it not for ocean heat export from the SH to the NH. However it could be that the greater greenhouse trapping in the NH is not the cause of that hemisphere being warmer but a consequence, via the positive water vapor-greenhouse feedback, of the ocean heat export warming the NH relative to the SH.

5. A Simple Model of Inter-hemispheric Temperature

Asymmetry

To examine whether inter-hemispheric differences in G are causes or effects of inter-hemispheric differences in T , a simple box model is used that solves for ΔT from the energy budget, as depicted in Fig. 13. The model conceptually follows those in Ramanathan and Collins (1991) and Sun and Liu (1996). Two boxes with temperatures T_S and T_N respectively represent the SH and the NH. At TOA, there is net shortwave radiation S and outgoing longwave radiation F . For simplicity, the net shortwave radiation S is considered to be the same for the two hemispheres by taking the global mean of $S_0=239.5 \text{ Wm}^{-2}$. Since differences in S are small, taking the actual values for the respective hemisphere, S_S and S_N makes little difference. The OLR is given by $F = \sigma T^4 - G$ where $\sigma=5.67 \times 10^{-8} \text{ Wm}^{-2}\text{K}^{-1}$ and G is the greenhouse trapping. The northward oceanic transport F_O is prescribed, but due to its

uncertainties a range of values from 0 to 1.10 PW is used (Section 4a). The atmospheric transport F_A is thermally direct and parameterized as a function of $\Delta T = T_N - T_S$, i.e. $F_A = \frac{\partial F_A}{\partial \Delta T} \Delta T$. The annual mean values of F_A and ΔT at the equator from NCEP/NCAR reanalysis between 1979 and 2007 are used to compute the coefficient, $\frac{\partial F_A}{\partial \Delta T}$, referred to as the strength of atmospheric transport, by regressing F_A onto ΔT , yielding the value of -0.20 PW K⁻¹. To express atmospheric and oceanic energy transport in a flux form in Wm⁻², F_A and F_O are divided by the hemispheric mean area, A_0 . The energy budget for the two boxes can be written as:

$$S_0 - \sigma T_S^4 + G_S - F_O/A_0 + \left| \frac{\partial F_A/A_0}{\partial \Delta T} \right| \Delta T = 0 \quad (3)$$

$$S_0 - \sigma T_N^4 + G_N + F_O/A_0 - \left| \frac{\partial F_A/A_0}{\partial \Delta T} \right| \Delta T = 0 \quad (4)$$

The above equations can be linearized by applying the first-order Taylor expansion around global mean values denoted by the subscript 0 as:

$$S_0 - \{\sigma T_0^4 + 4\sigma T_0^3(T_S - T_0)\} + \{G_{0,S} + \frac{\partial G}{\partial T}(T_S - T_0)\} - F_O/A_0 + \left| \frac{\partial F_A/A_0}{\partial \Delta T} \right| \Delta T = 0 \quad (5)$$

$$S_0 - \{\sigma T_0^4 + 4\sigma T_0^3(T_N - T_0)\} + \{G_{0,N} + \frac{\partial G}{\partial T}(T_N - T_0)\} + F_O/A_0 - \left| \frac{\partial F_A/A_0}{\partial \Delta T} \right| \Delta T = 0 \quad (6)$$

Note that G is linearized at different basic states in each hemisphere ($G_{0,S}$ and $G_{0,N}$), in recognition of potential differences in thermal characteristics between the two hemispheres not caused by the temperature difference but imposed by differences in fractional coverage of ocean, continental arrangements, etc. For example, $G_{0,N}$ could be larger than $G_{0,S}$, despite greater ocean fraction in the south, because subtropical dry regions over the ocean are more developed in the SH than the NH and due to massive humidity in Asia associated with the summer monsoon.

By adding the two equations, we get a constraint on the global mean greenhouse effect, $(G_{0,S}+G_{0,N})/2 = \sigma T_0^4 - S_0$ ($=288.8 \text{ Wm}^{-2}$) where T_0 is the global-mean annual-mean surface temperature of 14.8°C . Eqs. (5) and (6) can be expressed in terms of one unknown, ΔT :

$$\left(2\sigma T_0^3 - \frac{1}{2} \frac{\partial G}{\partial T} + \left| \frac{\partial F_A/A_0}{\partial \Delta T} \right| \right) \Delta T = F_O/A_0 + \Delta G_0/2. \quad (7)$$

$\Delta G_0 \equiv G_{0,N} - G_{0,S}$ is the basic state G difference between the hemispheres. $\frac{\partial G}{\partial T}$ ($=4.0 \text{ Wm}^{-2}\text{K}^{-1}$), referred to as the greenhouse trapping efficiency, is estimated as $4\sigma T_0^3 - \frac{\partial F}{\partial T}$ where $\frac{\partial F}{\partial T}$ ($=1.5 \text{ Wm}^{-2}\text{K}^{-1}$) is the regression coefficient relating the monthly anomaly of global mean OLR to that of T using surface temperature from NCEP/NCAR reanalysis and OLR from CERES data between 2001 and 2004.

The model results for ΔT from Eq. (7) as a function of F_O for the case with $\Delta G_0=0$ are plotted in Fig. 14a. The shading indicates the one standard deviation of observed ΔT from its global mean. The realistic solutions are those that fall within the shaded area. The reference state with the most reasonable estimates of parameters, $\frac{\partial G}{\partial T}=4.0 \text{ Wm}^{-2}\text{K}^{-1}$ and $\frac{\partial F_A}{\partial \Delta T}=0.20 \text{ Wm}^{-2}\text{K}^{-1}$, is plotted in black and requires large northward F_O of about 0.57 PW to fall in the realistic range of ΔT . When there is no cross-equatorial transport by the atmosphere (blue), ΔT increases and deviates from the realistic range for a cross-equatorial F_O greater than 0.2PW, suggesting that the atmosphere acts to reduce the inter-hemispheric contrast. When the greenhouse trapping efficiency increases (red), the inter-hemispheric difference gets larger via positive water vapor feedback for a given F_O as the warmer NH gets even warmer and the cooler SH cools more. The resulting inter-hemispheric difference of greenhouse trapping, ΔG for a given ΔT is displayed in Fig. 14b. Here the horizontal shading shows the range of the observed ΔG . Because ΔG is determined by $\frac{\partial G}{\partial T}$ and ΔT , it

changes only when the efficiency $\frac{\partial G}{\partial T}$ varies for a given ΔT , hence, the lines representing cases with (black) and without (blue) atmosphere heat transport are overlapped. The greenhouse trapping contrast increases with larger ΔT or as its efficiency gets larger. In the cases with a realistic range of ΔT , the reference state including atmospheric energy transport yields ΔG that is at the margin of the observed range.

In the box model with the same basic state G in each hemisphere, the northward oceanic transport is the only mechanism that can produce a warmer NH. However, the magnitude of northward OHT needed for realistic solutions appears larger than the data supports (Section 4a). Hence, we consider the case with nonzero ΔG_0 , since not all of ΔG in Fig. 9 need be a result of ΔT , but could be in part due to basic state differences as suggested in Fig. 6 and discussed above. The model solutions for $F_O=0$ as a function of ΔG_0 are shown in Figs. 14c and 14d. For the reference solution (black) to be in the realistic ΔT range, it requires $\Delta G_0 \approx 4 \text{ Wm}^{-2}$, which then yields $\Delta G \approx 9 \text{ Wm}^{-2}$, much larger than the real value of 5.67 Wm^{-2} . *That is, with no ocean heat transport, too large of an inter-hemispheric difference of G is needed to obtain the right magnitude of ΔT .* We therefore consider a combination of the first two models that takes into account both F_O and ΔG_0 . Figs. 14e and 14f show the solutions for $F_O=0.3 \text{ PW}$, which is within the range in Fasullo and Trenberth (2008b), as a function of ΔG_0 . The realistic ΔT is obtained for $\Delta G_0 \approx 1.5 \text{ Wm}^{-2}$, which then yields ΔG within the realistic range of about 6.0 Wm^{-2} .

For plausible magnitudes of northward OHT, positive ΔG_0 , greenhouse trapping efficiency and atmospheric heat transport strength, the box model does predict values of ΔT and ΔG that are consistent with those observed. Therefore the model supports the idea that a northward cross-equatorial OHT is required for the inter-hemispheric temperature

difference on Earth, as Croll suggested.

6. Discussion

The box model based on the TOA energy budget suggests that the necessary factors for the warmer NH than the SH are:

- a northward cross-equatorial ocean heat transport
- a larger basic state greenhouse effect in the north

The larger annual-mean inter-hemispheric difference in the Atlantic sector (5.2°C) than in the Pacific sector (2.5°C) (Fig. 8) supports this idea because the northward cross-equatorial OHT occurs in the Atlantic Ocean (e.g. see Fig. 9 in Trenberth and Fasullo 2008). That is, the ocean transports energy northward, the NH gets warmer and this inter-hemispheric difference is enhanced by greenhouse trapping. Since the tropical mean atmospheric circulation is thermally direct, the inter-hemispheric temperature difference is partly compensated by the atmospheric energy transport from the north to the south which is associated with the mean ITCZ being in the north (Kang et al. 2008, 2009).

However, the quality of ocean data is insufficient for deriving not only the magnitude but also the direction of cross-equatorial OHT. For the inter-hemispheric temperature difference to be entirely caused by northward cross-equatorial OHT a value ($\sim 0.6\text{PW}$) at the very upper limit of the observational range is required. A more reasonable OHT is inferred if some portion of the inter-hemispheric temperature difference arises from a difference in the basic state greenhouse trapping, i.e. some aspect of the atmospheric circulation and humidity

distribution that creates more greenhouse trapping in the NH than the SH independent of the temperature difference. However, since the greenhouse effect incorporates efficient positive feedback, it is difficult to extract this postulated basic state difference between the two hemispheres.

Only much more accurate OHT data, presumably obtained through combinations of in-situ data, atmospheric and oceanic Reanalyses, satellite data and adjoint methods, will be able to settle the contribution of cross-equatorial OHT to the inter-hemispheric temperature difference. The issue of a postulated inter-hemispheric difference in basic state greenhouse trapping would most likely be best addressed with idealized climate modeling.

7. Conclusions

We have discussed why the NH is warmer than the SH in the annual mean and pursued the idea, put forth by Croll (1870), that it is caused by northward cross-equatorial OHT. Croll (1870) claimed that the hemisphere with the larger ocean fraction would be warmer because of higher humidity, and hence, more greenhouse trapping. It is true that the ocean is warmer than land at every latitude in the annual mean. However, we find that the greenhouse trapping is in fact larger over land than ocean at the same temperature. The reason for the warmer ocean is, instead, the smaller surface albedo of the ocean. Therefore the larger land fraction in the north acts to cool the NH relative to the SH. This effect is offset by the fact that both the NH land masses and the NH oceans are warmer than their SH counterparts.

Of these it is the warmer ocean in the north that contributes most to preferentially warming the NH. A simple box model based on the energy budget shows that in order to

obtain an inter-hemispheric temperature difference within the observed range an unrealistically large greenhouse trapping difference is needed if there is no ocean transport across the equator. On the other hand, unrealistically large northward cross-equatorial ocean transport is needed for the case with no basic static greenhouse trapping difference between the two hemispheres. The most reasonable solution combines a modest northward OHT and an inter-hemispheric difference in the basic state greenhouse trapping. Hence, the greater greenhouse trapping in the NH (by 5.7 Wm^{-2}) is not the main cause of the warmer north but more of a consequence, and the northward oceanic heat transport is critical to producing a warmer NH, consistent with Croll (1870). We also suggest that the inter-hemispheric temperature difference is contributed to by an inter-hemispheric difference in the basic state greenhouse trapping. This inter-hemispheric temperature difference created by these mechanisms is enhanced by the positive water vapor-greenhouse feedback. The thermally direct tropical mean atmospheric circulation then partly compensates for this inter-hemispheric contrast by transporting energy southward in association with the ITCZ in the NH.

It is normally assumed that the northward oceanic heat transport, which occurs in the Atlantic Ocean, is a result of the deep Atlantic meridional overturning circulation with northward surface flow, sinking in the North Atlantic and southward flow at depth and upwelling around Antarctica and it can be reproduced in this way easily in idealized models (Toggweiler and Bjornsson 2000). As such, it is a consequence of the arrangement of continents and oceans on the planet that enable the Atlantic Ocean to be saltier than the Pacific Ocean (Emile-Geay et al. 2003). On the other hand it has not to our knowledge been demonstrated that Atlantic cross-equatorial OHT could not exist in the absence of the deep overturning circulation just as it does (to the south) in the Indian Ocean. Consequently a definitive

account of why the NH is warmer than the SH requires a thorough accounting for the causes of the cross-equatorial OHT because, as shown here, this is a fundamental cause of the asymmetry.

However, unless estimates of cross-equatorial OHT are highly inaccurate, it is unlikely that this is the sole cause of the inter-hemispheric temperature difference. An inter-hemispheric difference in greenhouse trapping appears to be a probable additional cause. This would likely be a result of how the arrangement of continents, and its impact on atmosphere-ocean circulation features such as monsoons, subtropical anticyclones and ocean upwelling regions, determines the distribution of atmospheric water vapor. To assess if this is so will require much more research including the use of idealized and comprehensive climate models.

The fact that the NH is warmer than the SH is potentially linked to the fact that the ITCZ is in the NH (Kang et al. 2008). The mechanisms for the inter-hemispheric temperature difference are such that we would expect the difference to change as a result of radiatively-forced climate change and, hence, influence the ITCZ position. Millions of the world's population depend on ITCZ rains for their water and food making the problem of how ITCZ location is determined one of great social relevance. It is sobering that the current state of observations of the Earth's climate system is inadequate to fully answer such a fundamental question as why the NH is warmer than the SH and, hence provide a full account of why tropical rain belts are where they are.

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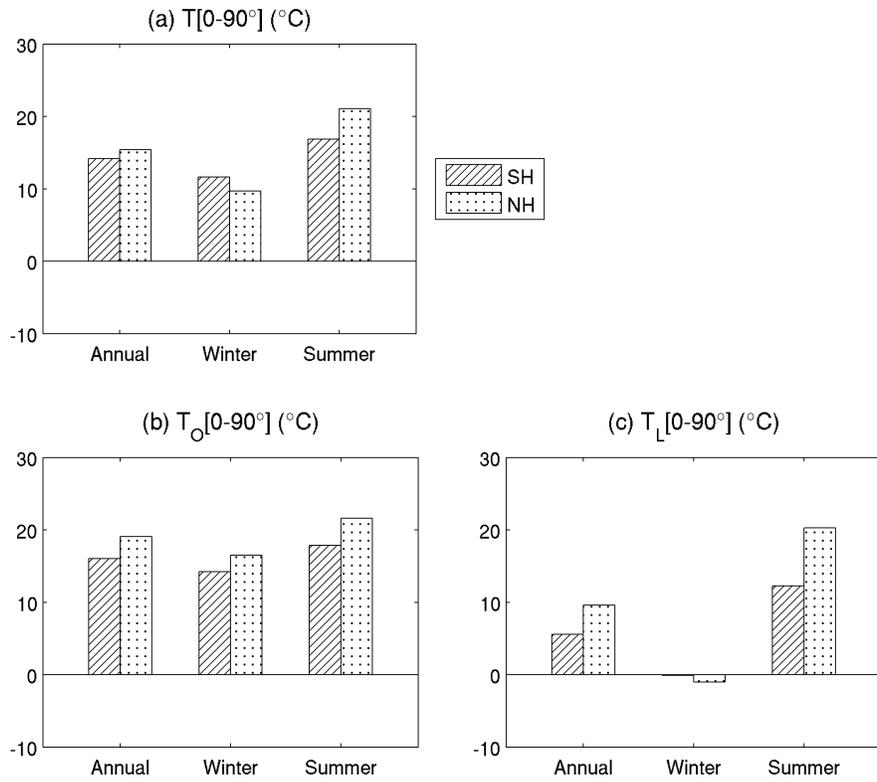


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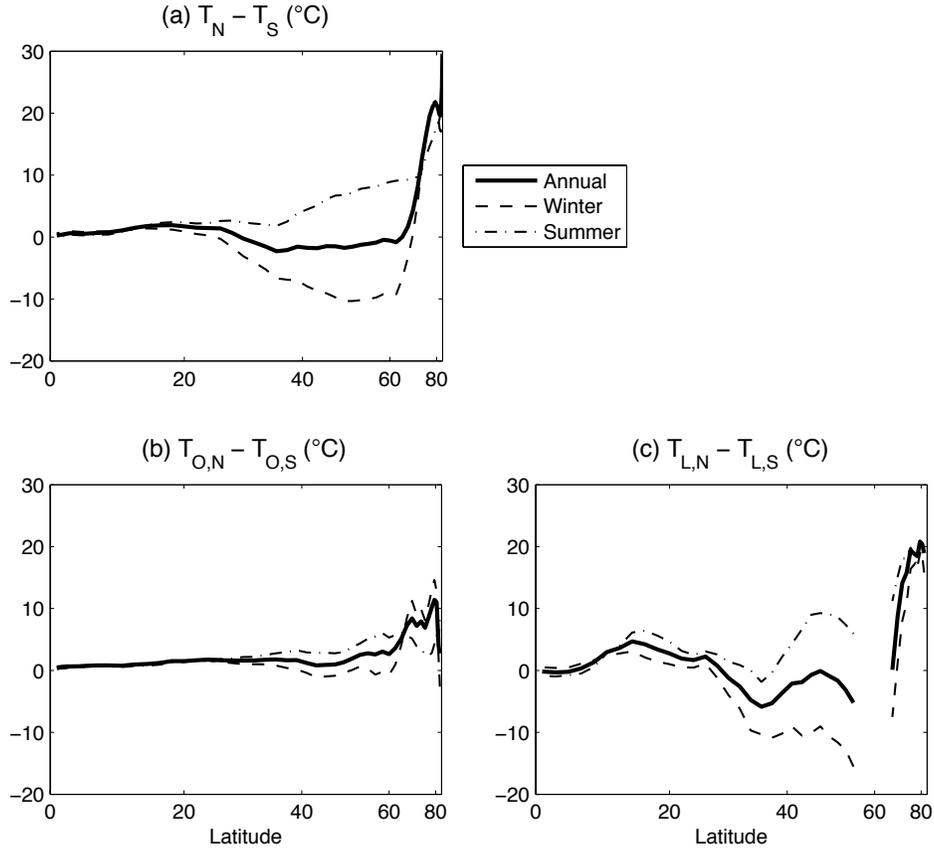


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	$f_{L,N}=39\%$	$f_{O,N}=61\%$
Annual	10°C	19°C
Winter	-1°C	17°C
Summer	20°C	22°C
Annual	6°C	16°C
Winter	0°C	14°C
Summer	12°C	18°C
	$f_{L,S}=18\%$	$f_{O,S}=82\%$

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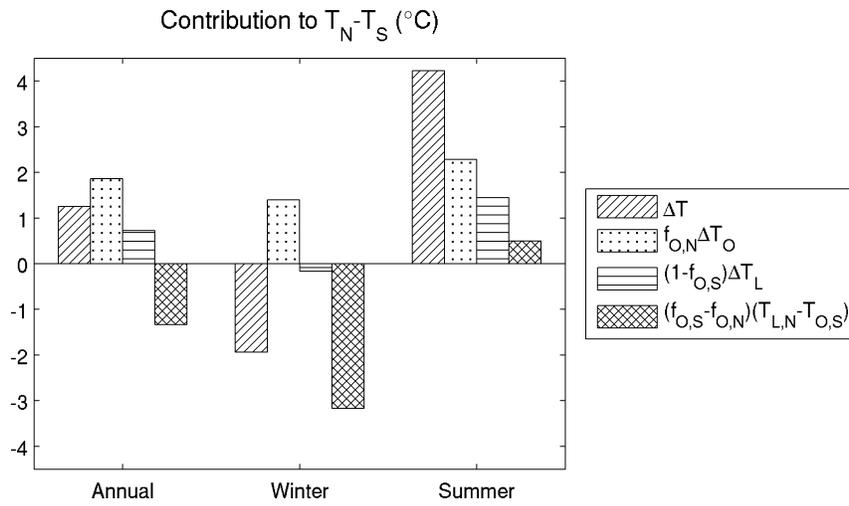


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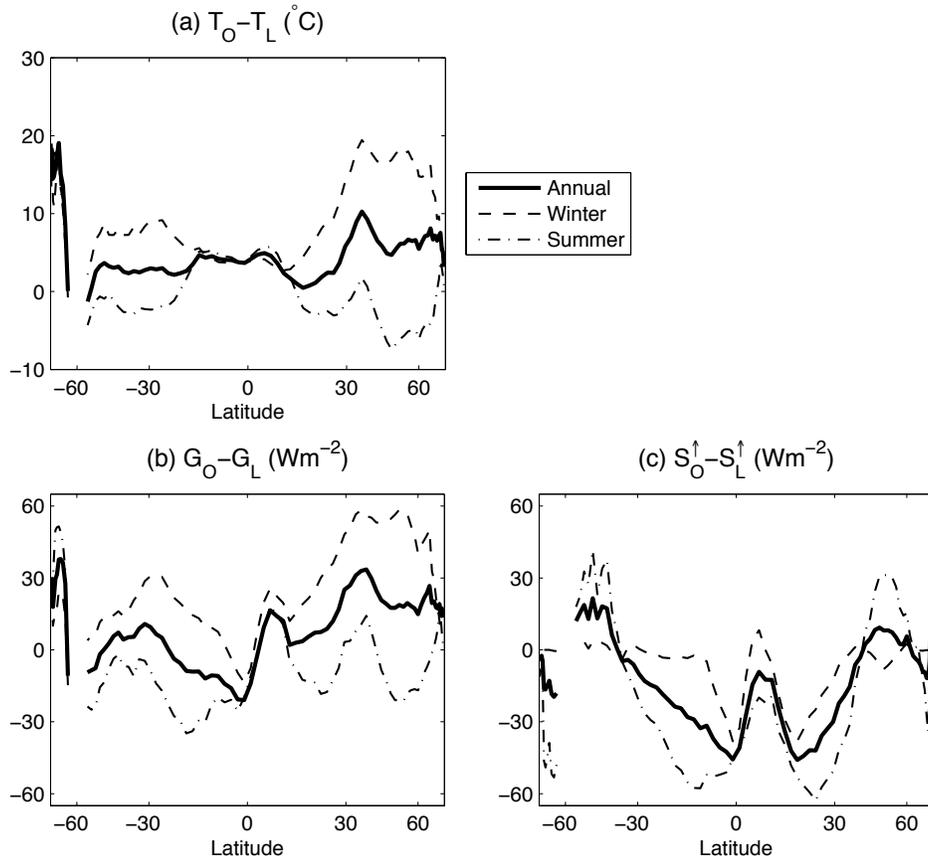


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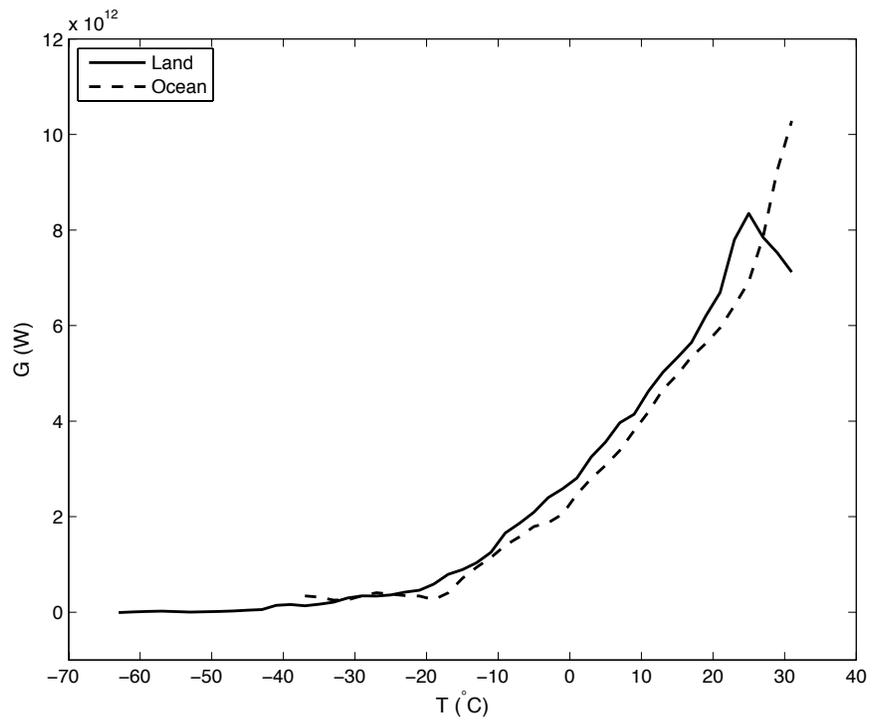


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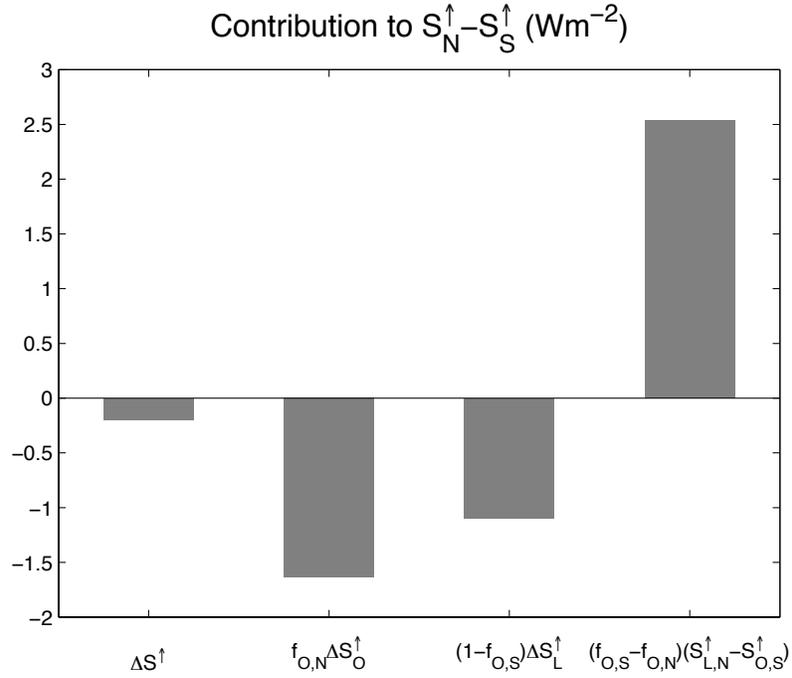


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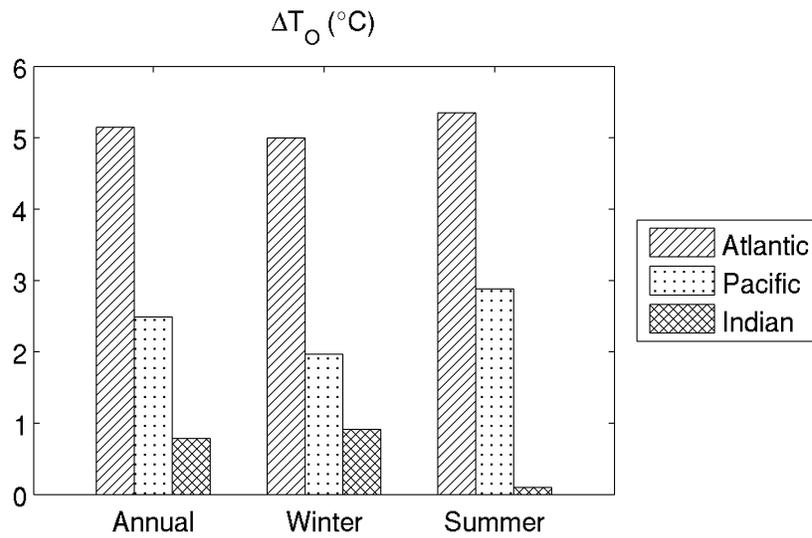


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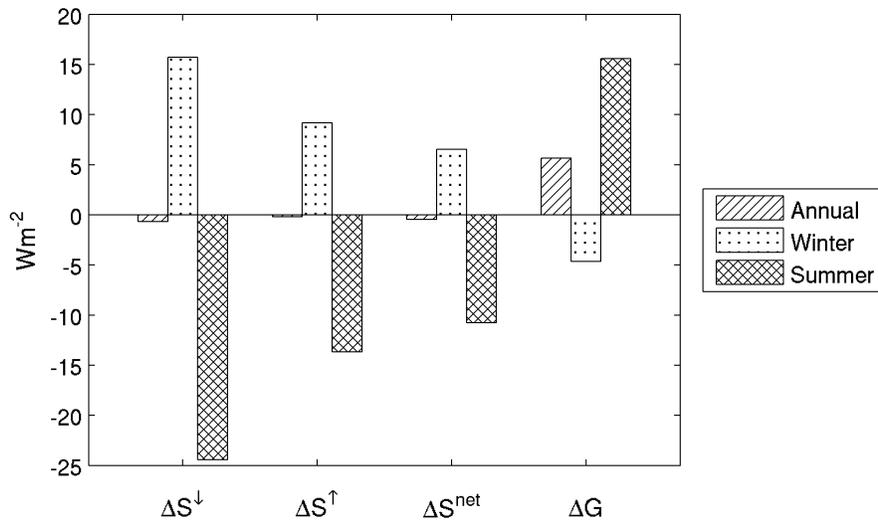


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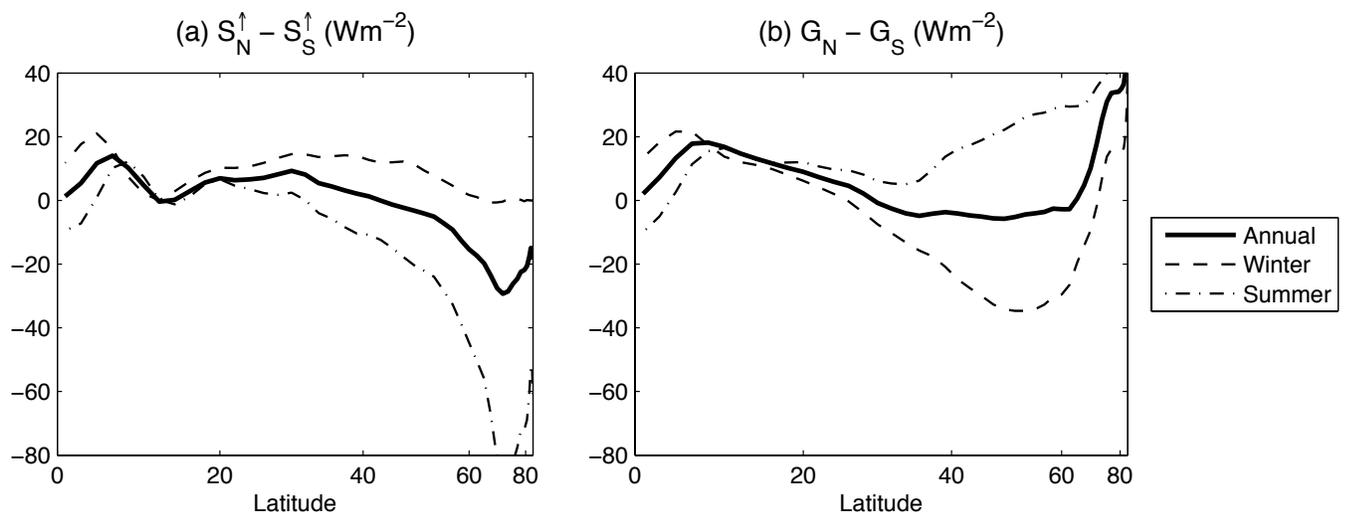


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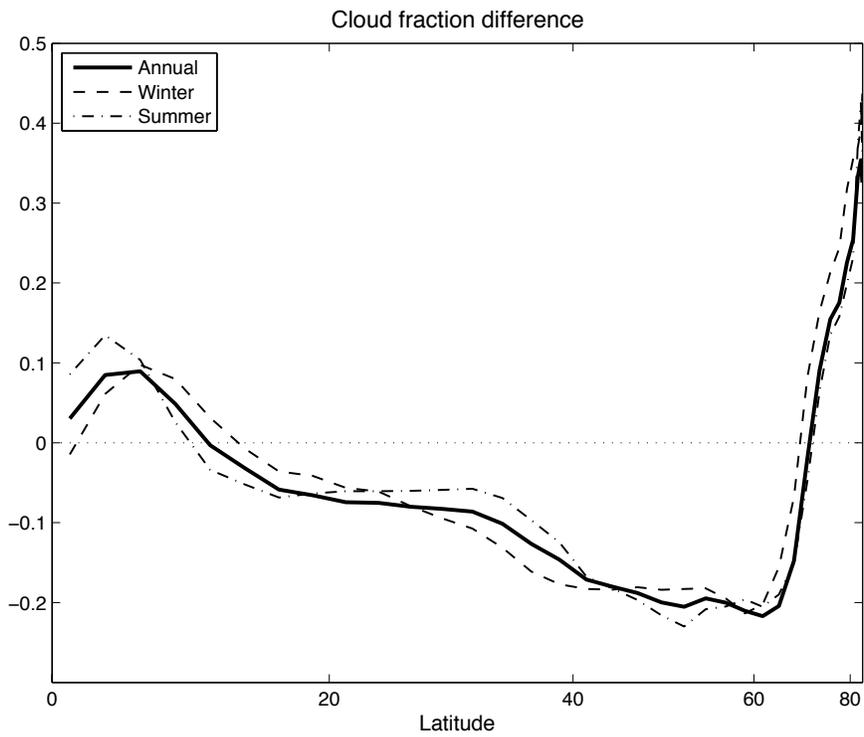


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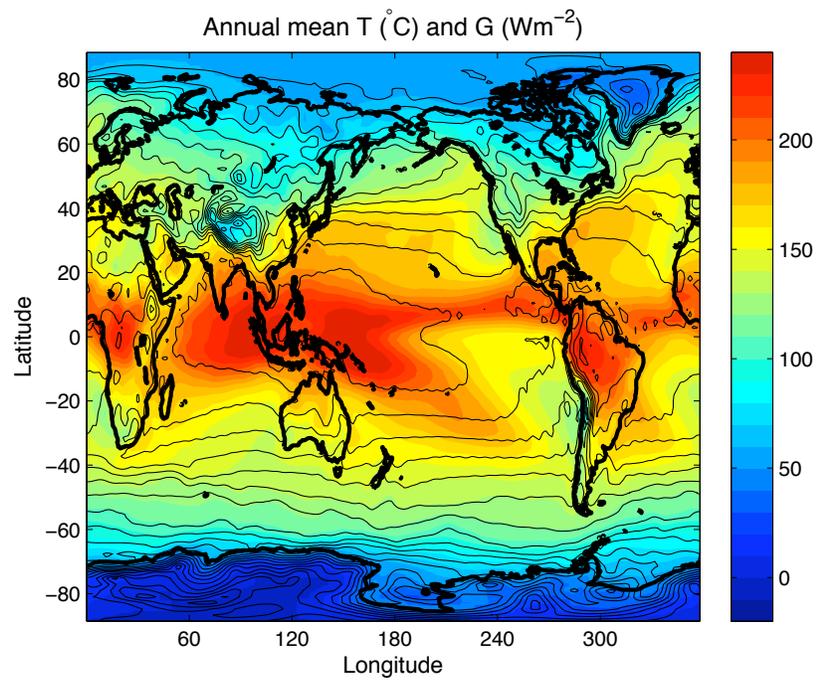


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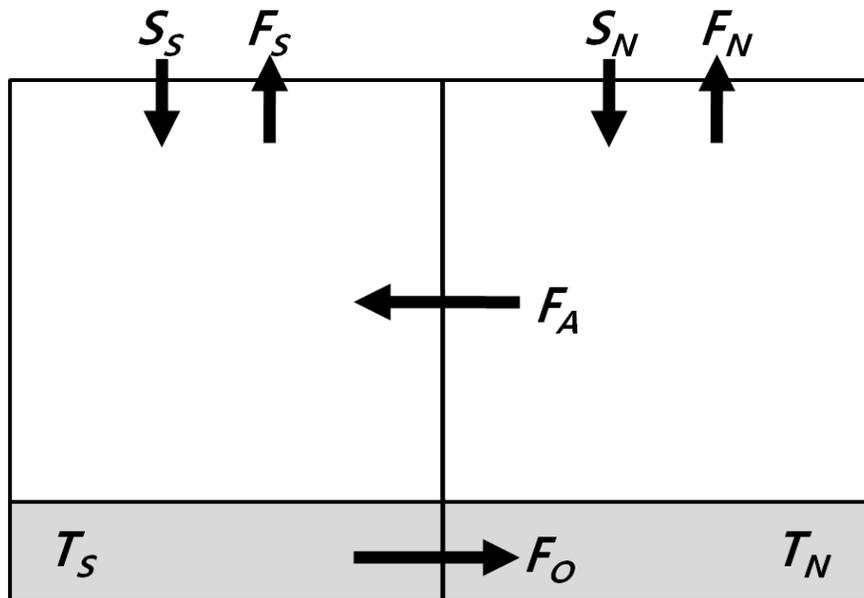


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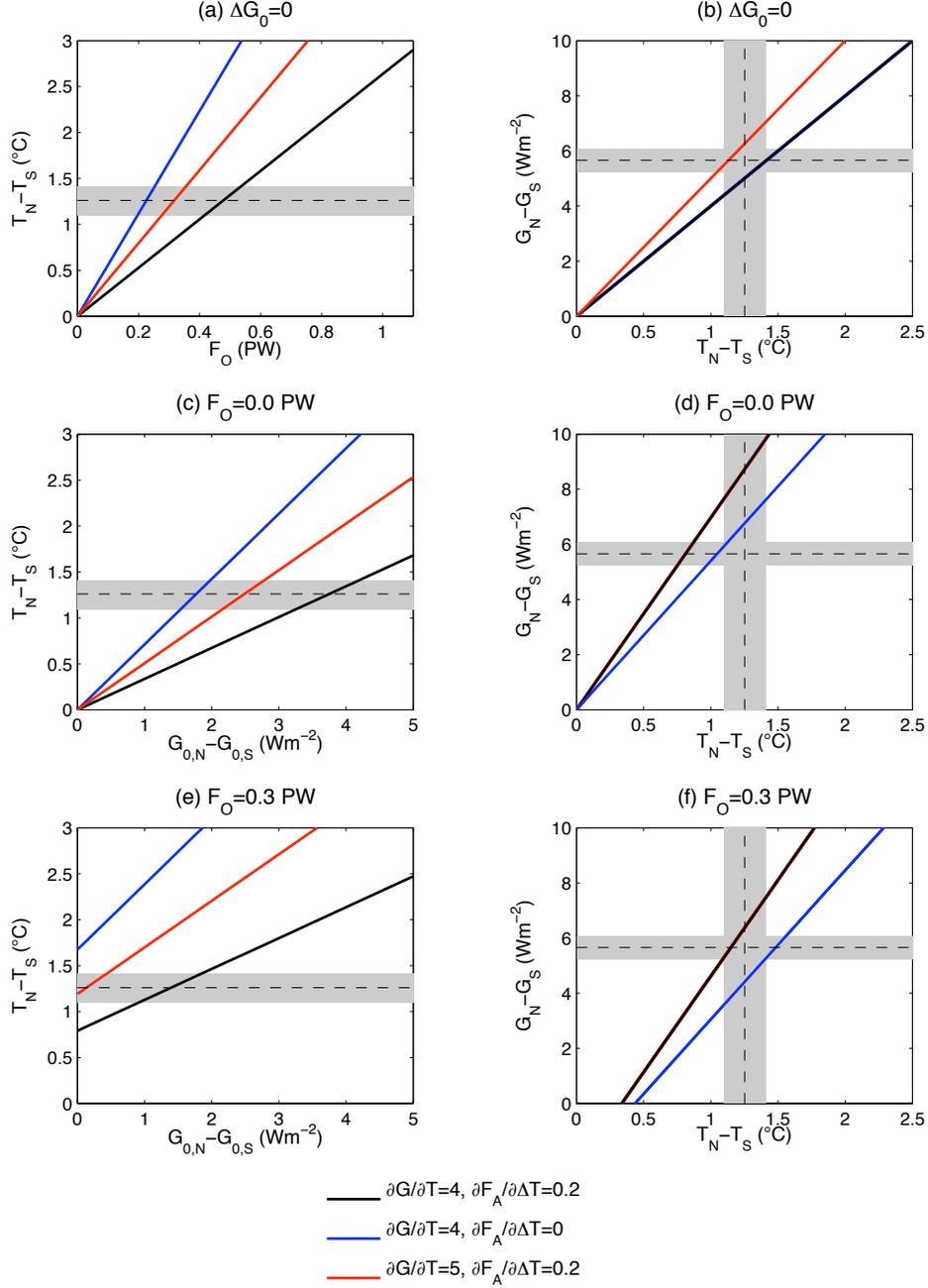


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