Interhemispheric Variability of Earth’s Radiation
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ABSTRACT

The variability of interhemispheric symmetry of Earth's energy serves as an independent indicator of climate change. The analysis of updated data obtained from satellite measurements at the top of the atmosphere (TOA) shows that in accord with Earth's orbital requirements the annually averaged incident solar radiation is the same in the Northern and Southern Hemispheres, the annual mean of the reflected shortwave radiation is almost north–south symmetric, and the annual mean of the outgoing longwave radiation is larger in the Northern Hemisphere by 1.4 W m\(^{-2}\). These mean radiations systematically differ from the mean radiations found from the numerical atmospheric models that participated in the Coupled Model Intercomparison Project phase 5 (CMIP5). The hemispheric differences of the TOA radiations vary on the annual and interannual time scales. The multidecadal variability in Earth’s north–south temperature difference reveals a similarity of trends in both hemispheres. The Atlantic meridional transport (in contrast to the Pacific meridional transport) is found to be coherent with the interhemispheric ocean heat content (OHC) difference on decadal and multidecadal time scales, indicating a critical role of the Atlantic in the interhemispheric energy balance change.

1. Introduction

The increasing of greenhouse gases causes an imbalance between incoming and outgoing radiation at the top of atmosphere (TOA) by trapping a part of Earth’s outgoing radiation. The imbalance can be seen in the surface temperature increase, melting Arctic sea ice, and an increased transport of energy into the ocean (Trenberth et al. 2014). The TOA data for the main components of the radiative balance, the incoming solar radiation (ISR), reflected shortwave radiation (RSW), outgoing longwave radiation (OLR), and the resulting net radiation (NET = ISR − RSW − OLR) are provided by satellite measurements and used in the evaluation of climate variability of the global Earth (Loeb et al. 2012; Stephens et al. 2012; Allan et al. 2014). The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC 2013) concluded that the global surface temperature has shown a much smaller linear trend over the time period 1998–2012 than over the previous 30–60 yr. The apparent stall in the trend inspired a set of possible explanations for the cause of this hiatus, including changes in the ocean heat content (OHC) in the Pacific and Atlantic Oceans (Meehl et al. 2013; Chen and Tung 2014). This slowdown of the global temperature trend is recently disputed by Karl et al. (2015). The study of the hemispheric difference may help to identify the cause of the energy transport leading to the possibility of the hiatus.

The difference in Earth’s energy radiation between the Northern and Southern Hemispheres serves as an additional component that can be useful in studying climate change. Drost and Karoly (2012) showed that the interhemispheric temperature contrast can be used as an index of climate change. Maps of temperature trends over the twentieth century show a conspicuous region of cooling in the northern Atlantic. Rahmstorf et al. (2015) argued that this cooling may be due to a reduction in the Atlantic Ocean overturning circulation (AMOC) over the twentieth century and particularly after 1970. This time evolution is consistently suggested by an AMOC index based on the hemispheric sea surface temperature difference and supported by other proxies and by oceanic measurements. Xu and Ramanathan (2012) have found that the latitudinally asymmetric response of global surface temperature does not depend on the symmetry of forcing and is caused by the hemispheric land–ocean asymmetry weakened by
the asymmetry in the distribution of aerosols. However, Friedman et al. (2013), who studied the temperature contrast between the Northern and Southern Hemispheres [the interhemispheric temperature asymmetry (ITA)] using observations and CMIP5 numerical simulations, have found that ITA depends on forcing. They reported a continued increase in the ITA over the twenty-first century, well outside the twentieth-century range, attributing this increase to the uneven spatial impacts of greenhouse forcing, which result in amplified warming in the Arctic and northern landmasses. In a recent review, Stephens et al. (2015) emphasized that the fraction of the incoming solar energy scattered back to space (the planetary albedo) is almost the same in the Northern and Southern Hemispheres and suggested that this approximate symmetry is achieved by increased reflection from Southern Hemisphere clouds that precisely offsets the greater reflection from the Northern Hemisphere landmasses.

Here we investigate how the radiative imbalance is distributed and evolves in Earth’s two hemispheres at the TOA and how it is related to the ocean energy imbalance. Our study is stimulated by the recently revisited problem of the origin of the 1.25°C surface temperature difference between the Northern and Southern Hemispheres (Croll 1870; Feulner et al. 2013; Kang et al. 2014; Marshall et al. 2014), which can be described in short as follows. It is a need for further investigation of the hemispheric differences, have found that ITA depends on forcing. They reported a continued increase in the ITA over the twenty-first century, well outside the twentieth-century range, attributing this increase to the uneven spatial impacts of greenhouse forcing, which result in amplified warming in the Arctic and northern landmasses. In a recent review, Stephens et al. (2015) emphasized that the fraction of the incoming solar energy scattered back to space (the planetary albedo) is almost the same in the Northern and Southern Hemispheres and suggested that this approximate symmetry is achieved by increased reflection from Southern Hemisphere clouds that precisely offsets the greater reflection from the Northern Hemisphere landmasses.

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where

\[
\overline{X}_{\text{Jan}} = \sum_{i=1}^{31} X_{\text{Jan}}(i), \\
\overline{X}_{\text{Feb}} = \sum_{i=1}^{28} X_{\text{Feb}}(i), \ldots, \overline{X}_{\text{Dec}} = \sum_{i=1}^{31} X_{\text{Dec}}(i)
\]

are the monthly averages, we use a more accurate mean

\[
\frac{1}{365} (31\overline{X}_{\text{Jan}} + 28\overline{X}_{\text{Feb}} + \cdots + 31\overline{X}_{\text{Dec}})
\]

for normal years, with the replacement of the factors 28 and 365 by 29 and 366 for the leap years.

The incoming solar radiances daily data are compiled by the CERES team from total solar irradiance data measurements on the Solar Radiation and Climate Experiments satellite [SORCE Total Irradiance Monitor (TIM) Total Solar Irradiance (TSI) V-15; http://lasp.colorado.edu/home/sorce/data/tsi-data/] for the time period from March 2000 to June 2013 (Kopp and Lean 2011; Kopp and Lean 2011; Kopp 2014), followed by the Royal Meteorological Institute of Belgium (RMIB) dataset (Jounee and Bertrand 2011) from July onward. The CERES solar product is produced accurately by taking into account the actual daily distances of Earth from the SORCE satellite and correcting for the nonsphericity of Earth.

For the OHC, we use the annual data from the National Oceanographic Data Center at https://www.nodc.noaa.gov/OC5/3MHEATCONTENT/ for the 0–700-m depths covering the time period 1955–2014. Another set of data is available at www.esrl.noaa.gov/psd/data/timeseries/ocean/oras4.html. These compiled data have been produced from the operational Ocean Analysis/Reanalysis System (ORAS4) by combining, every 10 days, the output of an ocean model forced by atmospheric reanalysis fluxes and quality controlled ocean observations (Balmaseda et al. 2013, 2014). The OHC data for deeper ocean depths are also available at that website for a shorter period of time (starting from 2005) and are not used here. The quality of the OHC data obtained from different measurements and reanalyses are discussed in Smith et al. (2015).

The OHC is defined as the integral over the temperature profile along the ocean layer and usually is expressed in the energy units \(10^{22}\) J. For a thin layer, it is expected to evolve closely to the sea surface temperature. We compare the records of the OHC with the hemispheric land–ocean surface temperatures from http://data.giss.nasa.gov/gistemp/ and with the indices of the ocean meridional modes in Atlantic and Pacific (AMM and PMM; www.esrl.noaa.gov/psd/data/timeseries/monthly/). The AMM and PMM spatial patterns are defined applying maximum covariance analysis to sea surface temperature (SST) over the time period from 1950 to present from the NCEP–NCAR reanalysis. The SST data are taken over the latitudinal region 21°S–32°N and spatially smoothed (three longitude by two latitude points). The seasonal cycle is removed, data are detrended, a 3-month running mean is applied to the data, and the linear fit to the cold tongue index (a measure of ENSO variability) is subtracted from each spatial point. Spatial patterns are defined as the first empirical orthogonal functions (EOFs) of the SST via the singular value decomposition of the covariance matrix. The AMM and PMM indices (time series) are calculated as the principal components of these EOFs. The physical interpretation of the meridional modes and additional references can be found in Chiang and Vimont (2004).

For comparison with modeling, we look at the solar inputs and radiation outputs available for the time period from 2002 to 2008 from seven climate models (Table 1). All these models participated in the Coupled Model Intercomparison Project phase 5 (CMIP5) numerical experiments and are validated by recent observations [e.g., Jiang et al. (2012)]. 1) The CanAM4 model is the fourth Canadian Atmospheric Model, developed by the Canadian Centre for Climate Modelling and Analysis (CCCma). Details about the CanAM4 physical parameterizations are given in von Salzen et al. (2013). 2) The GFDL AM3 model is developed by the Geophysical Fluid Dynamics Laboratory (GFDL) and documented in Donner et al. (2011). The model is the atmospheric component of the GFDL coupled model CM3. 3) The IPSL-CM5A-LR model is developed by the L’Institut Pierre-Simon Laplace (IPSL) and described in Dufresne et al. (2013) and Hourdin et al. (2013). 4) The MIROC5 model, described by Watanabe et al. (2010), is developed by Japan’s Model for Interdisciplinary Research on Climate project. 5) The HadGEM2-A is an atmospheric model described in Collins et al. (2008). The model is developed by the U.K.’s Met Office Hadley Center (MOHC). 6) The Atmospheric Model Intercomparison Project (AMIP) experiment output of the Max Planck

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<tr>
<th>No.</th>
<th>Model</th>
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<td>7</td>
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<td>CGCM3</td>
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Institute (MPI) MPI-ESM-LR model is described by Block and Mauritsen (2013). The atmospheric part of the Meteorological Research Institute, Japan (MRI)’s MRI-CGCM3 model used for this study is described in Yukimoto et al. (2012). The simulations conducted by these atmospheric GCMs are forced with the same observed SST, sea ice fractions, CO2 concentrations, and other external forcings as defined in the AMIP framework (Taylor et al. 2012). To better match the observational data and keep track with the orbital year, we use the daily model inputs and outputs to avoid extra differences used by models for producing the monthly averaged data. Thus, CanAM4, IPSL-CM5A-LR, and MIROC5 use 365 days as a calendar year, MPI-ESM-LR uses a “proleptic Gregorian calendar,” MRI-CGCM3 uses a “standard calendar,” and HadGEM2-A counts 360 days in a year (i.e., averaging over 30 days for monthly outputs).

3. Observed and modeled solar radiances

Incoming solar radiances provide a radiative input to Earth’s atmosphere. All other components of the radiative budget must be calibrated against ISR. As noted in the introduction, in accord with Earth’s orbital movement, the annual ISR is expected to be equal for both hemispheres.

Incoming global solar radiation from the SORCE TSI is $1360.2 \pm 0.13 \text{ W m}^{-2}$ at 1 astronomical unit (AU; Kopp 2014). The error expected as a result of inaccuracy of the SORCE measurements is small: $0.13/4 = 0.03 \text{ W m}^{-2}$. The TSI mean value at Earth obtained simply as TSI/4 of the SORCE value at 1 AU is $340.3 \text{ W m}^{-2}$. The CERES global annual mean ISR at Earth (relative to Earth’s center), which is used here, is additionally corrected for the actual orbital position of Earth and Earth’s nonsphericity and equal to $339.8 \text{ W m}^{-2}$ (i.e., lower by $0.5 \text{ W m}^{-2}$ relative to the TSI/4 value).

Figure 1a shows the incoming solar radiation for the Northern and Southern Hemispheres plotted using the daily values in the time period from 1 March 2000 to 28 February 2014 (i.e., for a 14-yr time period). As expected, the solar insolations in the Northern and Southern Hemispheres are phase shifted by 6 months. The mean value for the Northern Hemisphere is $339.85 \text{ W m}^{-2}$ with a maximum value of $460.43 \text{ W m}^{-2}$. The mean value is

![Figure 1a](http://lasp.colorado.edu/home/sorce/data/tsi-data/)

**Fig. 1.** (a) Daily ISR in the Northern Hemisphere (solid curve) and in the Southern Hemisphere (dashed curve) for the 14-yr time period from 1 Mar 2000 to 28 Feb 2014. The maximal and annual mean values are shown on the bottom of the graph. The hemispheric difference (north minus south) of the mean values is negligibly small: $0.04 \text{ W m}^{-2}$. (b) Low-frequency change in the global solar irradiance caused by solar variability. The curve was obtained by low-frequency filtering of the global ISR from the SORCE data (http://lasp.colorado.edu/home/sorce/data/tsi-data/).
339.81 W m$^{-2}$ for the Southern Hemisphere, which has much higher maximal value 491.15 W m$^{-2}$ owing to the orbital features discussed in the introduction. However, the annual orbital mean difference between the Northern and Southern Hemisphere is negligibly small (0.04 W m$^{-2}$). Hence, the observed ISR annual orbital means for both hemispheres are proven to be equal. The more accurate averaging of the monthly solar input data [see Eq. (1)] gives a close result. The incoming radiance is modulated by 11-yr solar variability; see Fig. 1b.

The incoming solar radiances used in the seven models listed in Table 1 have different global inputs: 341.3, 340.3, 341.8, 341.5, 341.5, 340.4, and 341.6 W m$^{-2}$, respectively. Thus, all model global ISR inputs are higher than the observed one by 0.6 to 2 W m$^{-2}$. However, we find that the annual mean differences of the ISR on the Northern and Southern Hemispheres used in the models are small: 0.00, −0.03, 0.08, −0.00, 0.00, −0.04, and −0.22 W m$^{-2}$, respectively. Thus, in spite of different global inputs, the hemispheric annual mean differences for these models have almost equal ISR in the Northern and Southern Hemispheres, as required by the orbital studies and supported by the satellite observations.

4. The TOA radiation: Means and variability

The time series of the OLR, RSW, and NET radiation averaged over Earth’s two hemispheres are shown in Fig. 2. We see that all radiative components are shifted by 6 months relative to their values in the opposite
hemisphere. The OLR mean value in the Northern Hemisphere is larger by 1.45 W m\(^{-2}\) compared with the OLR in the Southern Hemisphere. The seasonal variability of the OLR is noisy in the Southern Hemisphere. The mean values of the RSW radiations are almost equal in Northern and Southern Hemispheres. They differ only by 0.1 W m\(^{-2}\), which is within the error budget and agrees with the estimate made by Voigt et al. (2013), who used the earlier versions of the CERES monthly data (EBAF 2.5A and 2.6r) for the time period 2000–10. The NET radiation difference between the hemispheres (i.e., the algebraic sum of the solar, OLR, and RSW radiation) shows the averaged north–south imbalance of \(-1.5 \pm 0.1\) W m\(^{-2}\).

The model outputs for annual mean values of the solar inputs, the OLR, the absorbed shortwave radiation (ASW = solar – RSW), and the NET radiation for the global Earth and for the Northern and Southern Hemispheres are shown by asterisks in Fig. 3 and Fig. 4 relative to the observed mean values shown by the solid lines. The numerical values of all means are listed in the figure captions. There are significant deviations in the observed and modeled NET radiation. Thus all models have higher NET than observed; that is, the models overestimate the warming of the Northern Hemisphere (see in particular Fig. 4g).

To investigate the time evolution of the hemispheric differences in TOA radiation we decompose the difference of the time series shown in Fig. 2c into spectral
components using the data adaptive ensemble empirical mode decomposition technique (EEMD) (Wu and Huang 2009). The modes, which we display in Fig. 5 for the NET radiation, are statistically significant relative to the white noise. The figure shows the noise, annual variability, and low-frequency modes characterizing the interannual variability of the NET on 2–6-yr time scales. The residual (a difference between the data and the sum of all oscillating components) shown in the last panel presents a decadal trend. Although the mean value of the NET interhemispheric difference is small (−1.5 W m\(^{-2}\)), we see a substantial nonlinear negative trend in the time period 2000–14 under consideration.
5. The interhemispheric difference in the ocean heat content

The atmosphere and ocean are thermodynamically connected via the surface heat flux, which is balanced by changes in the OHC. Time series of the hemispheric difference for Earth’s surface temperature anomalies $\delta T$ and for the OHC in the 0–700-m column are presented in Fig. 6. Figures 6b and 6c show the low-frequency EEMD modes of their hemispheric differences. The noise and annual modes are not shown. Figure 6b displays the interannual variability of the quasi-decadal modes for both the temperature and OHC. Figure 6c shows the residuals (trends) for both variables. We see a
strong, nonlinear coherent behavior of $\delta T$ and OHC on these time scales with a phase delay of the temperature. This phase shift indicates that the long-term changes in the surface temperature are driven by the ocean variability. This supports the results by Rahmstorf et al. (2015), who argued that cooling in the northern Atlantic in the last century may be due to a reduction in the AMOC over the twentieth century and particularly after 1970. This time evolution is consistently suggested by an AMOC index based on the hemispheric sea surface temperature difference, by the hemispheric temperature difference itself, and by coral-based proxies and oceanic measurements. The flattening of the interhemispheric temperature difference during the apparent hiatus period indicates that there is a stall in the trend not only for the global temperature but also for the temperatures in both hemispheres. Since the Northern Hemisphere is land dominated it means that the air temperature trends over the land and over the ocean are not substantially different, and a higher trend in the Northern Hemisphere may be compensated by the higher concentration of aerosols in the Northern Hemisphere as suggested by Xu and Ramanathan (2012), although these authors considered a different time period. The land–ocean coupling is also provided by a relatively fast (monthly scales) cold land–warm ocean mode of the land–ocean air exchange (Wallace et al. 1995).

The net radiative flux at the top of the atmosphere on longer-than-annual time scales is mostly balanced by the upward surface energy flux from the ocean to the atmosphere. This flux is determined by the rate (time derivative) of the ocean heat content (Trenberth and Fasulo 2008). We see from our Fig. 6c a noticeable difference in $T$ and OCH gradients in the end of the time period under consideration when the temperature gradient flattens but the OHC decreases. This decrease in the rate of the OHC is roughly matched by the sign of the north–south NET radiation difference seen in the

**Fig. 6.** Comparison of the interhemispheric differences (NH minus SH) of Earth’s temperature (°C) with the OHC (10^{22} J). (a) The differences of the temperature anomalies (solid curve) and difference of the OHC for the ocean depths 0–700 m in 1955–2014 (dashed curves). (b),(c) The interannual modes for the temperature (solid) and OHC (dashed) differences.
The rate is positive before its maximum (NET positive on average) and negative after the maximum (NET negative on average). The general NET decrease (negative trend) in 2000–14 agrees with the negative second derivative (negative trend in the ocean to atmosphere flux) around the maximum of the OHC in Fig. 6c.

To better understand which ocean basin is responsible for the OHC hemispheric difference, we compare it with the meridional ocean indices for the Atlantic and Pacific Oceans (Figs. 7 and 8). The upper panels of these figures display the monthly data for the indices (smoothed by 12 data points for better comparison with the yearly OHC data). Figures 7b, 7c, 8b, and 8c show the interannual modes. We see that the Atlantic meridional mode is much better correlated with the OHC hemispheric differences compared with the Pacific meridional mode. The AMM also clearly displays a plateau in the hiatus time period (after 2000) for both low-frequency modes (Fig. 7b,c).

6. Discussion

Using accurate averaging of the satellite data at the top of the atmosphere (TOA), we find that Earth gets equal amounts of annual solar insolation in the Northern and Southern Hemispheres in agreement with the expectation from orbital studies. This result resolves a confusion of possible disagreement between the TOA flux measurements and the orbital requirement (Feulner et al. 2013). The model solar radiation inputs for the Northern and Southern Hemispheres are also in agreement with this symmetry, although the values of the hemispheric solar inputs are different for different models and different from the observed solar inputs.

The orbital year mean of the all-sky outgoing long-wave radiation difference in the two hemispheres is found to be 1.4 W m\(^{-2}\), confirming the independently established fact that Northern Hemisphere is warmer than the Southern Hemisphere (Croll 1870; Feulner et al. 2013; Kang et al. 2014; Marshall et al. 2014). The
Southern Hemisphere OLR is phase shifted by 6 months relative to the Northern Hemisphere OLR. The mean interhemispheric difference of the cloud clear OLR is higher by 2.25 W m\(^{-2}\). Since the OLR sensitivity to the surface temperature is positive, the value of the OLR hemispheric difference confirms the fact that the Northern Hemisphere is warmer than the Southern Hemisphere. However, OLR also depends on other parameters, such as the relative humidity and temperature of the atmosphere, making the quantitative comparison of the interhemispheric \(\delta\)OLR with the 1.25°C difference in the north–south temperature model dependent. The OLR differences found here can be used for calibrating such model estimates.

In contrast to the OLR, the orbital year mean of the reflected shortwave radiation (RSW) and, hence, the hemispheric albedo in both hemispheres differs by only 0.1 W m\(^{-2}\), which is within observational and model errors. This result confirms the test study made by Voigt et al. (2013), who carried out a statistical analysis partitioning Earth into pairs of random halves and showed that the hemispheric symmetry in reflected shortwave irradiance is not a random artifact but a nontrivial property of the earth system. Voigt et al. (2013) found a hemispheric difference in the clear-sky RSW radiation caused by hemispheric asymmetries in landmasses and aerosol load. They suggested that a possible compensating mechanism should take into consideration the location of the Hadley circulation closely related to the intertropical conversion zone (ITCZ), which is influenced by the ocean heat transport (Marshall et al. 2014).

In the absence of the hemispheric asymmetry in the OLR, the ITCZ would follow the seasonal solar input and be centered at the equator in its annual mean. Since the ITCZ is associated with the warm surface and closely

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**Fig. 8.** The index of PMM (solid curve) and OHC (dashed curve). (a) The PMM (°C) and interhemispheric difference of the OHC for the ocean depths 0–700 m in 1955–2014 (10\(^{22}\) J). (b),(c) The interannual modes for PMM and the global OHC NS hemispheric differences.
collocated with the ascending branch of the meridional Hadley circulation, its northward position drives the atmospheric heat transport southward. The atmospheric transport compensates about a half of the cross-equatorial northward transport of heat (Marshall et al. 2014). The association of the interhemispheric transport with the ITCZ may explain why the hemispheric difference obtained from climate models do not agree with the observations since most models have problems reproducing the correct form and location of the ITCZ (Hwang and Frierson 2013). The ITCZ is positioned north of the equator owing to the interaction between the ocean and atmosphere (Waliser and Somerville 1994) and the geometries of the continents that determine which hemisphere has the warmest water to locate the ITCZ (Philander et al. 1996). Philander et al. (1996) emphasized the critical role of highly reflective low-level stratus clouds feedback in maintaining the hemispheric asymmetry.

Some details of the hemispheric distribution of RSW can be seen in the time averaged all-sky and clear-sky latitudinal distribution of RSW found from the CERES data (Fig. 9). The clear-sky RSW is larger in the land- and aerosols-dominated Northern Hemisphere. A large contribution to the Northern Hemisphere excess of the clear-sky RSW is due to desert areas in the Northern Hemisphere, whereas the Southern Ocean at about 55°S is strongly absorbing shortwave radiation. The all-sky RSW has a peak at the location of the ITCZ.

We can add a quantitative estimate of the cloud cover using the clear-sky CERES data for the 14 yr between 2001 and 2014. The mean hemispheric difference (north minus south) between the all-sky and the clear-sky RSW radiation is −6.0 W m⁻². For a rough estimate of the hemispheric difference in reflective clouds we assume that a change in the reflected shortwave radiation relative to the incoming solar radiation is \( \delta(RSW) = ISR \delta \alpha \), where \( \delta \alpha \) is a change in the cloud albedo; that is, \( \delta \alpha = \alpha_{\text{cloud}} \delta(CF) \), with CF as the cloud fraction and \( \alpha_{\text{cloud}} \approx 0.4 \). Using the observed difference between the all-sky and clear-sky RSW \([\delta(RSW)] = 6 \text{ W m}^{-2}\) and ISR = 339.8 W m⁻² (see section 3 and Fig. 1), we obtain \( \delta(CF) \approx 4.4\% \). This estimate indicates that, in order to provide the hemispheric symmetry of the reflected shortwave radiation, the Southern Hemisphere should have on average about 4% more reflective clouds than the Northern Hemisphere.

The hemispherical difference in Earth’s surface temperature follows the OHC in the 0–700-m ocean layer for about 60 yr (Fig. 6). However, these climate indicators deviate from each other at the time of the climate hiatus when the hemispheric temperature difference trend flattens and the OHC difference declines.
The energy decline in the OHC is reflected in the TOA NET radiation (Fig. 5f). The comparison of the Atlantic and Pacific meridional modes with the OHC hemispheric differences modes indicates that Atlantic meridional transport (in contrast to the Pacific meridional transport) has a coherent behavior with the OHC on decadal and multidecadal time scales with some phase delay, as seen in Fig. 7b of the multidecadal modes. On the one hand, the Pacific and Atlantic modes are analogous, both being governed by physics intrinsic to the ITCZ (Chiang and Vimont 2004). The AMM and PMM are characterized by an anomalous SST gradient across the mean latitude of the ITCZ coupled to an anomalous displacement of the ITCZ toward the warmer hemisphere. Both are forced by trade wind variations in their respective northern subtropical oceans. On the other hand, the decay in the subtropical SST anomaly (around 20°N) in the Atlantic is coincident with increased fluxes out of the ocean. However, the increased flux out of the ocean is not as clear in the Pacific. The coherent behavior of the AMM and OHC interhemispheric differences found here suggests a stronger role of the Atlantic transport in support of the energy imbalance between the Northern and Southern Hemispheres. The modes displayed in the last panels of Figs. 6 and 7 reflect the multidecadal (65 yr) variability inferred from the analysis of the global temperature (Wu et al. 2011) and analysis of the Atlantic Ocean variability (Chen and Tung 2014). The Pacific variability has a different structure of this residual mode; see Fig. 8. The Atlantic and Pacific meridional variability also differ in shorter (15–20 yr) low-frequency modes (Figs. 7b and 8b). These results indicate a multidecadal variability of the north–south asymmetry and suggest that the Atlantic Ocean plays a major role in this variability. The change of the OHC regime in the last decade (see Figs. 6c and 7c), which is also evident in the change of the sign of the NET at the TOA (the bottom panel in Fig. 5), indicates a nonmonotonic behavior of Earth’s energy balance during the hiatus period.

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