AGU PUBLICATIONS

Earth's Future

RESEARCH ARTICLE

10.1002/2013EF000165

Key Points:

- There is a hiatus in the rise in global mean surface temperatures over the past decade
- Global warming continues but manifested in different ways
- Natural variability is playing the major role in the hiatus, through the PDO

Corresponding author:
K. Trenberth, trenbert@ucar.edu

Citation:
Trenberth, K. E., and J. T. Fasullo (2013), An apparent hiatus in global warming? *Earth's Future*, *1*, 19–32, doi:10.1002/2013EF000165.

Received 23 AUG 2013
Accepted 26 OCT 2013
Published online 5 DEC 2013

An apparent hiatus in global warming?

Kevin E. Trenberth[1] and John T. Fasullo[1]

[1]National Center for Atmospheric Research, Boulder, Colorado, USA

Abstract Global warming first became evident beyond the bounds of natural variability in the 1970s, but increases in global mean surface temperatures have stalled in the 2000s. Increases in atmospheric greenhouse gases, notably carbon dioxide, create an energy imbalance at the top-of-atmosphere (TOA) even as the planet warms to adjust to this imbalance, which is estimated to be 0.5–1 W m^{-2} over the 2000s. Annual global fluctuations in TOA energy of up to 0.2 W m^{-2} occur from natural variations in clouds, aerosols, and changes in the Sun. At times of major volcanic eruptions the effects can be much larger. Yet global mean surface temperatures fluctuate much more than these can account for. An energy imbalance is manifested not just as surface atmospheric or ground warming but also as melting sea and land ice, and heating of the oceans. More than 90% of the heat goes into the oceans and, with melting land ice, causes sea level to rise. For the past decade, more than 30% of the heat has apparently penetrated below 700 m depth that is traceable to changes in surface winds mainly over the Pacific in association with a switch to a negative phase of the Pacific Decadal Oscillation (PDO) in 1999. Surface warming was much more in evidence during the 1976–1998 positive phase of the PDO, suggesting that natural decadal variability modulates the rate of change of global surface temperatures while sea-level rise is more relentless. Global warming has not stopped; it is merely manifested in different ways.

1. Introduction

How often have we heard "Wow it's cold, where is global warming?" How can we get a cold and snowy winter with anthropogenic climate change? Most people recognize from their own experience that we have weather in all its infinite and wonderful variety, so that there are large variations in temperature and precipitation from day-to-day and week-to-week. The biggest climate change we experience is the one from summer to winter, or from winter to summer, or in the tropics from the wet monsoon season to the dry "winter monsoon." We expect these changes and even look forward to them. Our planting and harvesting of crops depend on them. Yet every summer is different, and so is every winter. There are "regimes" of climate where one summer may be sunny, dry, and hot, whereas another may be cool, cloudy, and wet. Globally, the biggest cause of such regimes that last several seasons is the El Niño-Southern Oscillation (ENSO) phenomenon. Since the major 1997/1998 El Niño event that affected weather patterns around the world, the term "El Niño" has become part of the public vernacular and not just a scientific term. Yet somehow, when talking about human-induced climate change, often referred to as "global warming," the idea that it is not relentless but rather occurs along with natural fluctuations from ENSO, weather, and other modes of variability has often been lost.

The 2000s are by far the warmest decade on record (Figure 1). Before then the 1990s were the warmest decade on record. Since global warming really reared its head in the 1970s in the sense that the global warming signal emerged from the noise of natural variability, every decade has been warmer than the previous ones and increasing evidence suggests that the past few decades are warmer than any others in the past 2000 years [*IPCC*, 2007]. However, there has been a slowing in the rise of global mean temperature over the past decade, often referred to as a hiatus or plateau. Has global warming stalled? Or is it entirely expected that natural variability rears its head and can offset warming for a decade or two?

In part the answer depends on what we mean by "global warming." For many it means the global mean temperature increases. But for anthropogenic climate change, it means the climate change resulting from all kinds of human activities, and it is now well established that by far the biggest influence occurs from changes in atmospheric composition, which interfere with the natural flow of energy through the climate

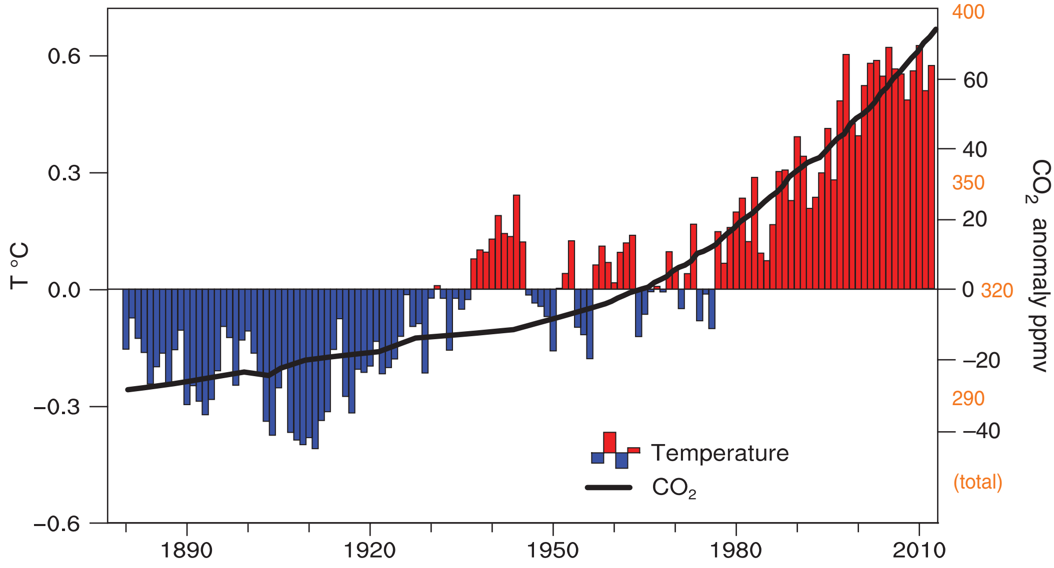

Figure 1. Estimated changes in annual global mean surface temperatures (°C, color bars) and CO_2 concentrations (thick black line) since 1880. The changes are shown as differences (anomalies) from the 1901 to 2000 average values. Carbon dioxide concentrations since 1957 are from direct measurements at Mauna Loa, Hawaii, whereas earlier estimates are derived from ice core records. The scale for CO_2 concentrations is in parts per million (ppm) by volume, relative to a mean of 320 ppm, whereas the temperature anomalies are relative to a mean of 13.9°C (57°F).

system [*IPCC*, 2007]. Referred to as "radiative forcing" by scientists, the biggest effect comes from increasing carbon dioxide in the atmosphere because carbon dioxide is a greenhouse gas (GHG) (Figure 1) [*IPCC*, 2007]. Preindustrial values are estimated to average about 280 ppmv (parts per million by volume) but values in 2013 have exceeded 400 ppmv, a 43% increase, mainly from the burning of fossil fuels. Several other GHGs (methane, nitrous oxide, and chlorofluorocarbons) have also increased from various human activities, while tiny particulates (aerosols) in the atmosphere can cause both warming by absorbing radiation or cooling by scattering and reflecting radiation back to space. The result is a positive (down) energy imbalance at the top-of-atmosphere (TOA). In that sense "global warming" really means global heating. Increasing global mean temperature is but one manifestation of the effects [*Trenberth et al*., 2009] (K. E. Trenberth et al., Earth's energy imbalance, submitted to *Journal of Climate*, 2013, hereinafter referred to as Trenberth et al., submitted manuscript, 2013).

There are numerous other human effects that contribute to climate change, but most of the others are of importance only regionally: building "concrete jungles" known as cities which have an urban heat island effect, other changes in land use and land cover, irrigation, space heating, and so on. Humans also contribute substantially to regional changes in aerosols, which in turn influence clouds (the indirect effect), and these aerosols vary rapidly in time as they are washed out and interact with weather systems. Hence, they have a short lifetime in the atmosphere and their influence is mainly near their source. Their variations over the past few decades are not well known and they are not considered further here. There are also natural radiative forcings of the climate system, especially those related to Sun-Earth geometry and the Earth's orbit. But on century or less time scales the main ones of importance are changes in the Sun and natural aerosols, especially those resulting from explosive volcanic eruptions, which have a lifetime of a few years in the stratosphere.

With a global energy imbalance due to increased trapping of outgoing longwave radiation by GHGs, which is estimated to be 0.5–1 W m^{-2} in the 2000s [*Trenberth et al*., 2009; *Hansen et al*., 2011] (Trenberth et al., submitted manuscript, 2013), the energy can go various places [*Trenberth and Stepaniak*, 2004]. The incoming energy is radiant energy and it can be transformed into internal energy (related to temperature), potential energy (related to gravity and altitude), kinetic energy (related to motion), latent energy (related to changes in phase of especially water), and even chemical energy and formation of "fuel." Indeed, some energy goes into melting Arctic sea ice, which has decreased by more than 40% in late summer since the 1970s, melting of glaciers and ice sheets such as Greenland, heating the land

10.1002/2013EF000165

and the atmosphere, heating the oceans, and in driving changes in the hydrological cycle. The warming oceans expand and, along with the extra water from melting land ice, lead to rising sea levels at a global rate of 3.2 mm/yr from 1992 to 2012 [updated from *Nerem et al*., 2010]. Increases in evaporation and associated increases in atmospheric humidity in the warmer atmosphere can change storms and clouds and thus the albedo, and therefore feedback and change both the incoming and outgoing radiation because water vapor is a powerful GHG. More than 90% of the associated energy imbalance goes into the oceans [*IPCC*, 2007; *Trenberth*, 2009; *Trenberth and Fasullo*, 2010] (Trenberth et al., submitted manuscript, 2013).

Carbon dioxide concentrations continue to increase (Figure 1) and along with them there is a steady increase in radiative forcing on the order of 0.3 W m^{-2} per decade [*IPCC*, 2007]. In the past decade, this rise is offset somewhat between 2005 and 2010 by reduced solar irradiance during a period of low sunspot activity on the order of 0.1 W m^{-2} [*Trenberth*, 2009] (Trenberth et al., submitted manuscript, 2013), and perhaps by changes in atmospheric aerosols and stratospheric water vapor [*Solomon et al*., 2010, 2011] also on the order of 0.1 W m^{-2}. Nevertheless, one issue is how the radiative forcing is changing and what the expectations should be for our changing climate.

In this article, we explore surface temperature variations and the cause of the apparent hiatus in warming, such as it is, in more detail and the relationship with ENSO and decadal variability. We further explore the recent changes in the ocean.

2. Global Mean Surface Temperatures

Global mean temperatures have been reconstructed by several groups over the past century or longer (Figure 2). They also result from global analyses of all variables, such as the ECMWF (European Centre for Medium-Range Weather Forecasts, Reading, England) reanalysis called ERA-Interim (ERA-I) [*Simmons et al*., 2010]. In spite of the agreement globally, there are some differences among global land and global ocean values. *Simmons et al*. [2010] show, using ERA-I, how missing data over land, and especially the Arctic, lead to underestimates of recent trends in the HADCRU dataset. However, ERA-I has an inhomogeneity in the sea surface temperature (SST) record owing to a switch in sources of information, leading to spuriously cooler values after about 2000, whereas the HADCRU4 data [*Morice et al*., 2012] have larger SST trends [*Simmons et al*., 2010]. The Goddard Institute for Space Studies (GISS) [*Hansen et al*., 2010] values lie in between ERA-I and HADCRU4 estimates in both domains. The NOAA National Climatic Data Center (NCDC) analysis is a blend of land data from the Global Historical Climate Network (GHCN) [*Lawrimore et al*., 2011] with the ERSST3b [*Smith et al*., 2008].

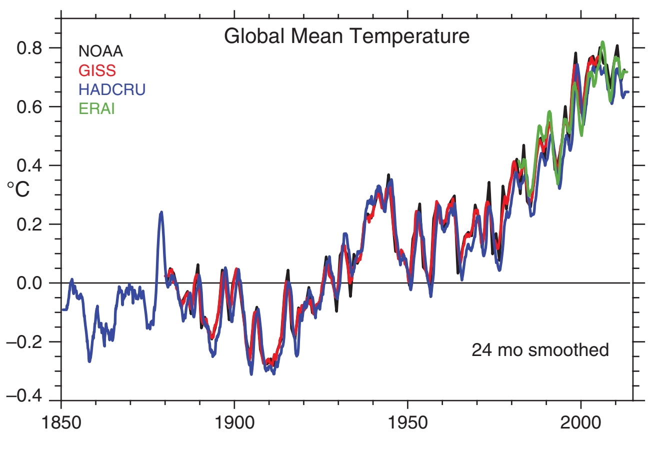

Figure 2. Global mean temperature time series as 24 month running means from several sources: NOAA NCDC, GISS, HADCRU3, and ERA-I. ERA-I was offset by 0.54°C. Here the base period is 1900–1949.

We use the NOAA time series in Figure 1 and explore the seasonality of the trends in Figure 3. In Figures 1 and 2, we note the overall rising global mean temperatures after the 1960s but with a slowing rate in the 2000s. Figure 1 also shows the annual anomalies in carbon dioxide from NOAA scaled to suggest a relationship with global mean temperature, because it is readily demonstrated using climate models that such a relationship exists [*IPCC*, 2007]. However, carbon dioxide has continued to rise, along with other GHGs, and the radiative forcing is increasing steadily. While the lack of agreement between the two time series in Figure 1 is readily apparent from year to year and even from decade to decade, it is desirable to understand why and how the two deviate from each other.

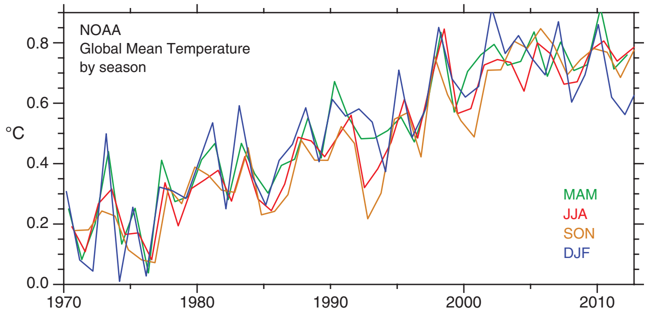

Figure 3. NOAA global mean temperature anomalies after 1970 for the four seasons: DJF, MAM, JJA, and SON.

Examining the seasonality of the global mean temperatures (Figure 3) reveals that the biggest hiatus in warming is in the northern winter season (December-January-February, DJF) owing to a few quite cold winters, especially 2008 and 2012 [*Cohen et al*., 2012]. Yet such winters were not that cold in the overall longer-term context, although very cold spots occurred locally such as in Europe. Some rather unusual atmospheric circulation patterns were responsible in Europe: strong negative values of the North Atlantic Oscillation (NAO) (discussed more later; Figure 7) especially in the northern winter of 2009–2010, which featured exceptionally low values of the NAO over an extended period. *Cohen et al*. [2012] instead refer to the "Arctic Oscillation" as the atmospheric mode associated with the cooling in Eurasia, but this is strongly correlated with the NAO [*Trenberth et al*., 2007].

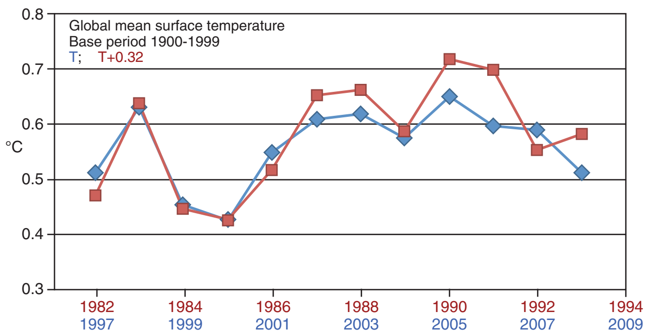

Figure 4. NOAA annual global mean temperature anomalies for 1982–1994 increased by 0.32°C (red) and from 1997 to 2009 (blue).

Even in the last three decades we can ask whether such slowdowns have occurred before, and Figure 4 shows the 11 years beginning 1982 and 1997 in detail, showing a remarkable resemblance in subsequent evolution. It so happens that 1982–1983 and 1997–1998 were the times of the two biggest El Niños on record, and it is well established that a mini global warming occurs at the latter stages of an El Niño as heat comes out of the upper ocean and contributes to a warmer atmosphere and surface—but resulting in a cooler ocean [*Trenberth et al*., 2002] (Trenberth et al., submitted manuscript, 2013). Even so, the eruptions of El Chichón in March to April 1982 and Mount Pinatubo in June 1991 no doubt also influenced these time series.

Before exploring this aspect further, an examination of meridional profiles (Figure 5) shows the biggest warming in the Arctic where record low sea ice has been reported in several recent years. It is mainly from 20° to 65° latitude in both hemispheres where the slowdown has occurred, although this figure is adversely affected for the ocean by the spurious lower SSTs after about 2000 in the ERA-I analysis. This affects the Southern Hemisphere in particular.

3. Sources of Variability

3.1 ENSO

The biggest fluctuations in global mean surface temperature have been identified with ENSO [e.g., *Trenberth et al*., 2002]. Figure 6 presents the global mean surface temperature as a 12 month running mean of anomalies after 1970 and it reveals that a linear trend is actually a pretty good fit. The huge warming in 1998 from the 1997 to 1998 El Niño is evident, and to emphasize the relationships between the interannual variability and ENSO, the duration of each El Niño and La Niña event, as given by NOAA's Oceanic Niño Index (ONI), is also marked on the figure along with the actual time series of the Niño3.4 SSTs on which the ONI is based. The latter indicates the magnitude of each event. The relationship between ENSO and global mean temperatures is well established [*Trenberth et al*., 2002] and has been used by several studies to linearly "remove" the ENSO effects using linear regression [*Lean and Rind*, 2008, 2009; *Foster and Rahmstorf*, 2011]. These studies show that ENSO accounts for short-term fluctuations in

10.1002/2013EF000165

global surface temperature with a range of up to 0.39°C and a regression of global mean temperature on the Niño3.4 index gives values of 0.1°C per standard deviation with a 3 month lag [*Trenberth et al*., 2002]. Once ENSO is removed, the residual global mean temperature time series is remarkably linear after 1970, with no evidence of a hiatus, highlighting the role of natural variability in the global mean temperatures. These studies have also used simple techniques to remove volcanic and solar signals. There have been no major volcanic eruptions since Mount Pinatubo in 1991 although smaller events may contribute a little (order 0.1 W m^{-2}) to reduced radiative forcing [*Solomon et al*., 2011]. Solar variations occur with the sunspot cycle and are of the order of 0.15 W m^{-2} peak to peak (Trenberth et al., submitted manuscript, 2013). They contribute somewhat to reduced radiative forcing over the past decade especially from 2003 to 2009 but the Sun is now more active again.

Trenberth et al. (submitted manuscript, 2013) examined variations in the TOA energy imbalance in eight ensemble members of the Community Climate System Model version 4 (CCSM4) climate model and found standard deviations of monthly means about an ensemble mean of 0.62 W m^{-2}, reducing to 0.25 W m^{-2} for 12 month running means.

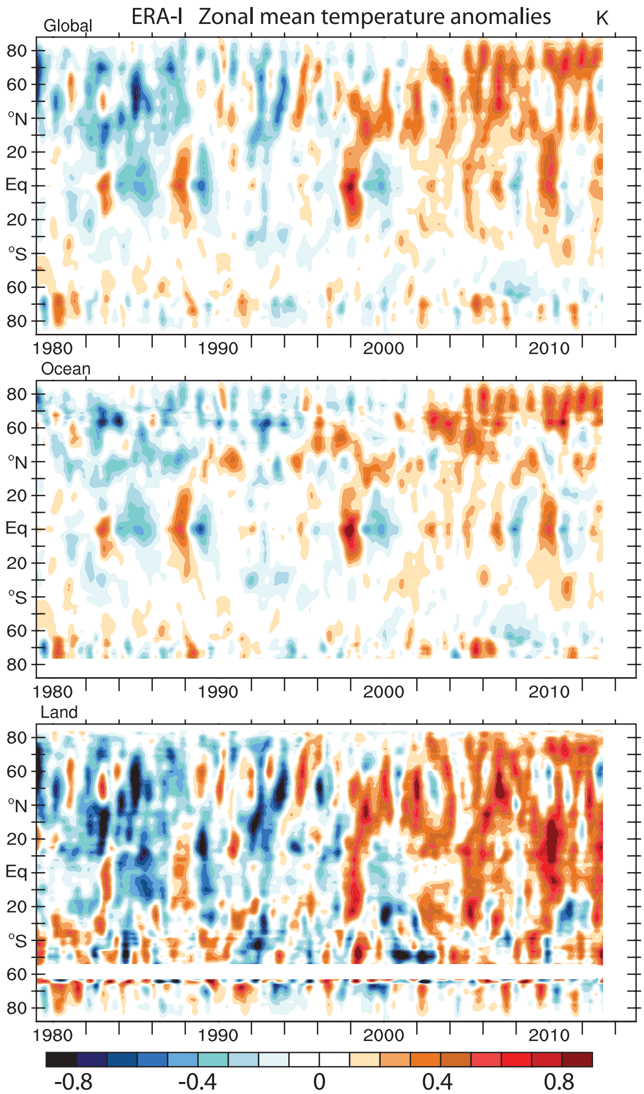

Figure 5. ERA-I zonal mean temperature anomalies weighted by cos(ϕ), where ϕ is latitude, smoothed with a 13-term low-pass filter; top: global; middle: ocean; and bottom: land. The base period is January 1979 to December 2012.

The high level of month-to-month variability is similar to that observed at the TOA by the CERES (Clouds and the Earth's Radiant Energy System) instrument and suggests that cloud fluctuations associated with weather are a nontrivial source of energy imbalance fluctuations. However, they also average out fairly quickly, leaving ENSO and decadal variability as a source of lower-frequency fluctuations.

3.2 Decadal Variability

While the ENSO interannual variations are reasonably well known, the decadal variations are not. Prominent decadal variability occurs in both the Atlantic and Pacific Oceans: the Atlantic Multidecadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO) and associated Interdecadal Pacific Oscillation (IPO) (see *Trenberth et al*. [2007] for reviews and depictions of the associated patterns and time series). The NAO also varies on multiple time scales but is most important in the northern winter months of December through March. *Wu et al*. [2011] used empirical statistical methods to suggest that natural variability has played a significant role in decadal variations in global mean temperatures. Using CMIP3 model simulations of the 20th century, *DelSole et al*. [2011] partitioned the global temperature into an anthropogenic component and a natural component attributed to atmospheric-ocean interactions and, in particular, to

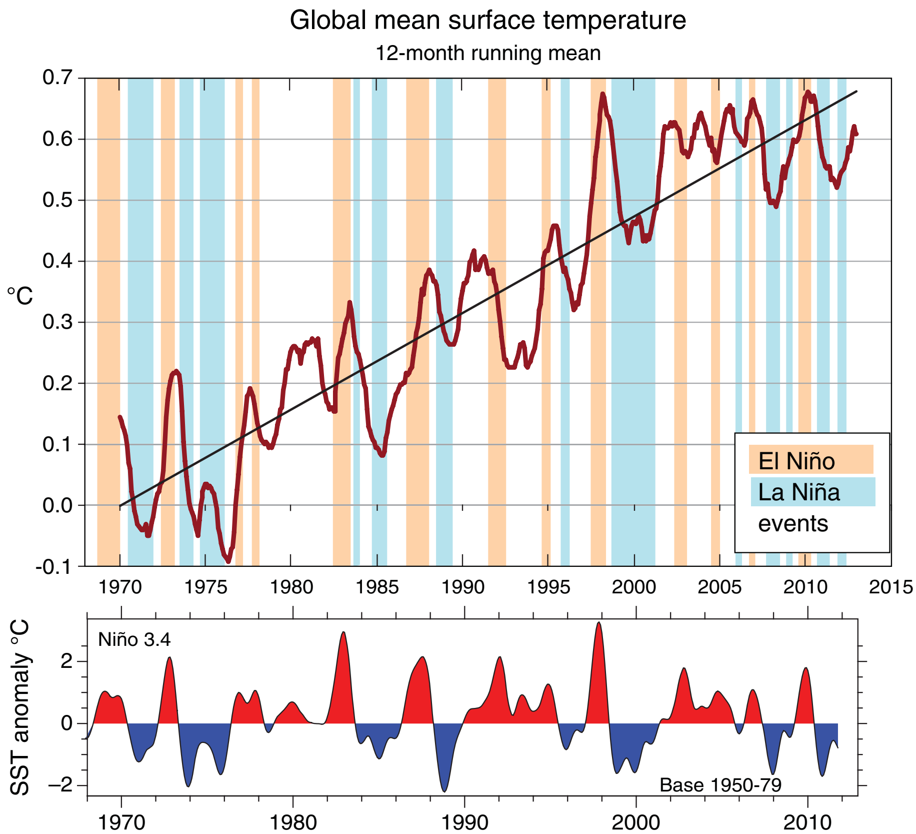

Figure 6. The NOAA global mean 12 month running mean surface temperatures are given relative to 1901–2000 along with a linear trend fit. Marked on the graph are the El Niño (buff) and La Niña (sky blue) periods as defined by NOAA's ONI, based on the Niño 3.4 SST anomalies, as given in the lower panel relative to a base period of 1950–1979.

the AMO. However, these results depend on the fidelity of models and the forcings used, and the latter are not well known, especially for aerosols.

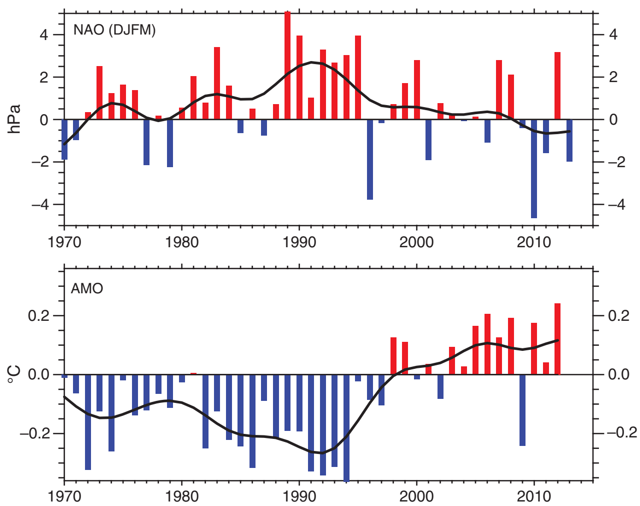

Figure 7. Time series of values of the NAO in northern winter (DJFM) and annual mean AMO along with a low-pass (13-term) decadal filter used in IPCC [*Trenberth et al.*, 2007]. For AMO the units are K and for NAO the units are hPa.

The NAO index (Figure 7) depicts the strength of the westerlies from the North Atlantic into Europe and correlates well with temperatures in Eurasia and inversely with those over Greenland, as well as precipitation as a north-south dipole over Europe: wet in the north and dry in the south in the positive phase. The winter (December through March) station-based index of the NAO [*Hurrell*, 1995] is based on the difference of normalized sea-level pressure (SLP) between Lisbon, Portugal, and Stykkisholmur/Reykjavik, Iceland, since 1864 in hectopascal (hPa); http://climatedataguide.ucar.edu/guidance/hurrell-north-atlantic-oscillation-nao-index-station-based. The NAO is important in the northern extratropics in winter [*Hurrell*, 1996] where it accounted for 31% of the 20°N–90°N surface temperature variance for 1935–1994 for DJFM, but subsequently NAO has not gone hand-in-hand with global temperature and there is no significant correlation overall.

The AMO is a measure of SSTs in the North Atlantic, north of the equator, relative to the global mean [*Trenberth and Shea*, 2006]. The recent post-1970 variations in the AMO and NAO (Figure 7) show indeed that variability is quite large. Note that in terms of global mean temperature, the scale on Figure 7 would be reduced by the ratio of the area of the North Atlantic to the global area, which is 7.3%.

The PDO has been identified with changes in SLP over the North Pacific [*Trenberth and Hurrell*, 1994]. Often it is defined by using SSTs in the Pacific [*Mantua et al*., 1997] using 110°E to 100°W, 20°N to 70°N as a core region, with the global mean SSTs removed, to compute the first empirical orthogonal function (EOF) pattern and associated time series, and then regress the time series with SSTs over the entire globe (Figure 8). This is a new analysis (courtesy of Adam Phillips; cf. *Deser et al*. [2004]) and the EOF accounts for 25% of the monthly anomaly variance of SST for the period 1900 to May 2013, using the HADISST dataset. *Chen et al*. [2008] provide an alternative derivation of Pacific decadal variability that shows how robust it is to different approaches. They also note how similar many aspects of the pattern are to ENSO but that the PDO does not account for changes in global mean surface temperature owing to large regional cancellations.

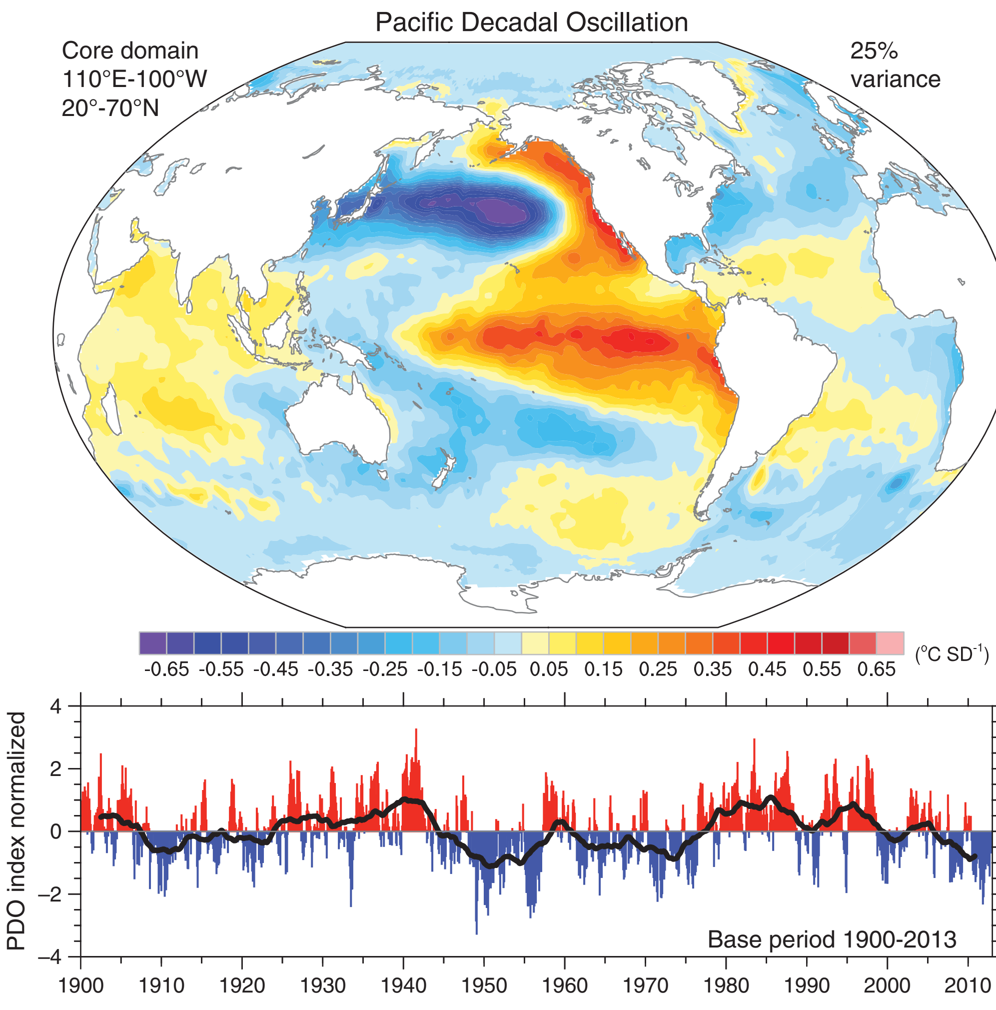

Figure 8. The Pacific Decadal Oscillation based on an EOF analysis of SST anomalies with the global mean removed from 1900 to May 2013 in the 20°N–70°N and 110°E–100°W region of the North Pacific, which explains 25% of the variance. The principal component time series, given below in normalized units, is regressed on global SSTs to give the map above. The black curve is a 61 month running average.

10.1002/2013EF000165

Deniers of climate change often cherry-pick points on time series and seize on the El Niño warm year of 1998 as the start of the hiatus in global mean temperature rise (Figure 6). This turns out, arguably, to have been the transition time from a positive to a negative phase of the PDO. The monthly time series (Figure 8) readily reveals the multidecadal regimes of the PDO (given by the black line) with positive phases from 1923 to 1942 and 1976 to 1998, and negative phases from 1943 to 1976 and after 1999. While naturally emphasizing the North Pacific, the pattern covers the entire Pacific with a somewhat ENSO-like pattern but one that is broader in the tropics [*Chen et al*., 2008].

If we now examine the hiatus period of 1999–2012 and compare it to the time when global warming really took off from 1976 to 1998 (Figure 9), the negative PDO pattern emerges very strongly throughout the Pacific although warming prevails in the Atlantic and Indian Oceans and on land. In other words, it is the central and eastern Pacific more than anywhere else that has not warmed in the past decade or so. In spite of some cold European winters, Europe does not standout in Figure 9 and instead is a warm region. The AMO is positive (Figure 7) and is revealed in Figure 9 to be part of a wider warming.

One approach to estimating ocean heat content (OHC) changes is by combining the available observations (surface, ocean, and from space) with an ocean model to produce a dynamically consistent ocean analysis. The new ORAS-4 ocean reanalysis from ECMWF has revealed very distinctive climate signatures that are realistic in magnitude and duration in terms of changes in OHC [*Balmaseda et al*., 2013] (Trenberth et al., submitted manuscript, 2013). Figure 10 shows the five ensemble members of the ORAS-4 ocean reanalysis OHC for 0–700 m and full-depth ocean and reveals the increased heating below 700 m depth of 0.21 W m^{-2} globally after 2000. The orange bars show the times of the El Chichón and Pinatubo volcanic eruptions when sharp drops occurred in OHC that quantitatively match estimates of TOA radiative changes (such as in Pinatubo) [*Trenberth and Dai*, 2007], as demonstrated in a new analysis by Trenberth et al. (submitted manuscript, 2013). ORAS-4 also reveals a major cooling of the tropical Pacific Ocean in association with the 1997–1998 El Niño event. Following this, the ocean warmed at a startling rate of over 1.2 W m^{-2} from the 2000s for the global ocean (or 0.84 W m^{-2} for the global area), and the overall heating is estimated to be 0.91 W m^{-2} globally when melting sea ice and other components are included as well [*Balmaseda et al*., 2013] (Trenberth et al., submitted manuscript, 2013). More than 30% of the heat was deposited into the ocean below 700 m in an unprecedented fashion in the post 2000 record from ORAS-4 and was identified mainly with changes in the tropical and subtropical winds in the Pacific.

Figure 11 shows the regime changes for 1999–2012 versus 1979–1998 from the ERA-I reanalysis for SLP and surface winds. Reanalysis winds and surface fluxes, bias corrected, were used to drive the ocean in

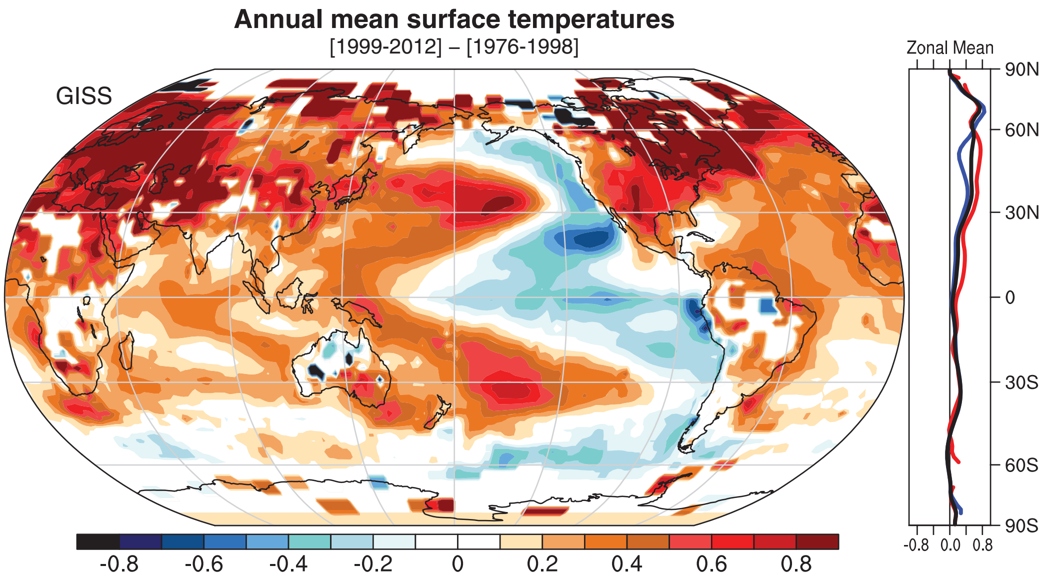

Figure 9. Mean annual surface temperature differences from GISS for 1999–2012 and 1976–1998 in °C, with zonal means at right for ocean (blue), land (red), and zonal mean (black).

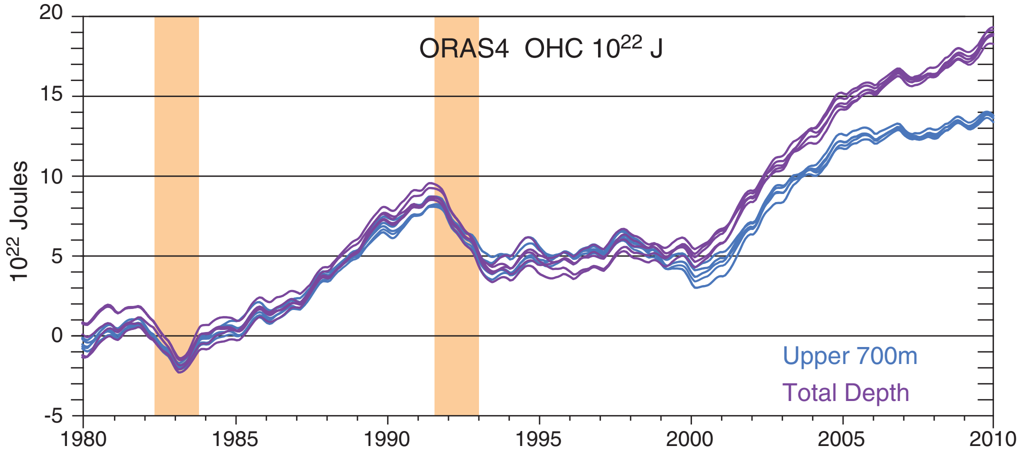

Figure 10. The five ensemble members of the ORAS-4 ocean reanalysis OHC for 0–700 m and full-depth ocean are shown, where they have been aligned for 1980 to 1985, in 10^{22} J. The increased heating below 700 m of about 0.2 W m^{-2} globally is revealed after about 2000. The orange bars show the times of the El Chichón and Pinatubo volcanic eruptions.

ORAS-4 during the assimilation to result in the OHC fields in Figure 12. Figure 11a reveals the very strong changes toward higher pressures over the cool central and eastern Pacific especially in the subtropics and the much stronger than normal tradewinds by more than 1 m s^{-1} in the vicinity of the equator from 15°N to 15°S, 150°E to 150°W, and in the subtropics farther east (160°W to 110°W). The SST pattern of change is reflected in the OHC changes down to 700 m (Figure 12) signifying the extra heat storage in the tropical western Pacific and deeper thermocline, but with much cooler conditions throughout the eastern Pacific from 30°N to 30°S. Variability in the surface wind field is independently corroborated by changes in sea level based on both the altimetry and gauge records as the easterly anomalous winds have driven a “piling up” of water in the western Pacific Ocean. Because of this effect, some regions in the western Pacific have experienced sea-level rise at three times the rate of the global ocean in recent decades. The length of the gauge record provides an extended record over which this regional increase can be linked to the PDO [*Merrifield et al*., 2012].

Figure 11b presents the northern polar view of the same changes in Figure 11a to highlight the relationships of the apparent wavelike structure extending northward from the Pacific, across the pole into Europe. This aspect is likely better seen in the upper troposphere as a quasi-stationary Rossby wave [*Ineson and Scaife*, 2009], an aspect to be pursued elsewhere. Nonetheless, it is very suggestive of a relationship with the NAO in its negative phase. This also highlights the influence of the changes in the Pacific with the high latitudes of both hemispheres, the extension to the North Atlantic in the Northern Hemisphere and to the Southern Oceans in the Southern Hemisphere (Figure 11a), where the wave structure relates to changes in Antarctic sea ice.

These kinds of changes have been independently simulated in hiatus periods in warming scenarios of the 21st century in the CCSM4 [*Meehl et al*., 2011, 2013] in association also with negative PDO (or IPO) periods and more frequent La Niña events. They are identified with a stronger wind-driven overturning in the Pacific, with upwelling near the equator and subsiding waters in the subtropics, leading to the buildup in heat off the equator in the western and central Pacific.

So what about the cold northern winters in the 2000s that have been associated with the strong negative phase of the NAO? In Figure 7 the NAO reveals some low-frequency variability that appears to be in phase with the PDO variations (Figures 11b and 13). Given the global nature of the atmosphere it is not surprising that links between the Pacific and Atlantic Oceans form at times, but these modes are not inherently coupled. Low-frequency variability in NAO and links to ENSO are discussed by *Ineson and Scaife* [2009] who note the important role of the global teleconnection pathway from the Pacific region via the stratosphere. Moreover, small effects from the Sun in the ultraviolet from the lower stratosphere can be amplified [*Ineson et al*., 2011]. Together, the PDO, AMO, and NAO account for a lot of the regional and seasonal climate changes going on. While these are the predominant natural modes of variability, it is quite

10.1002/2013EF000165

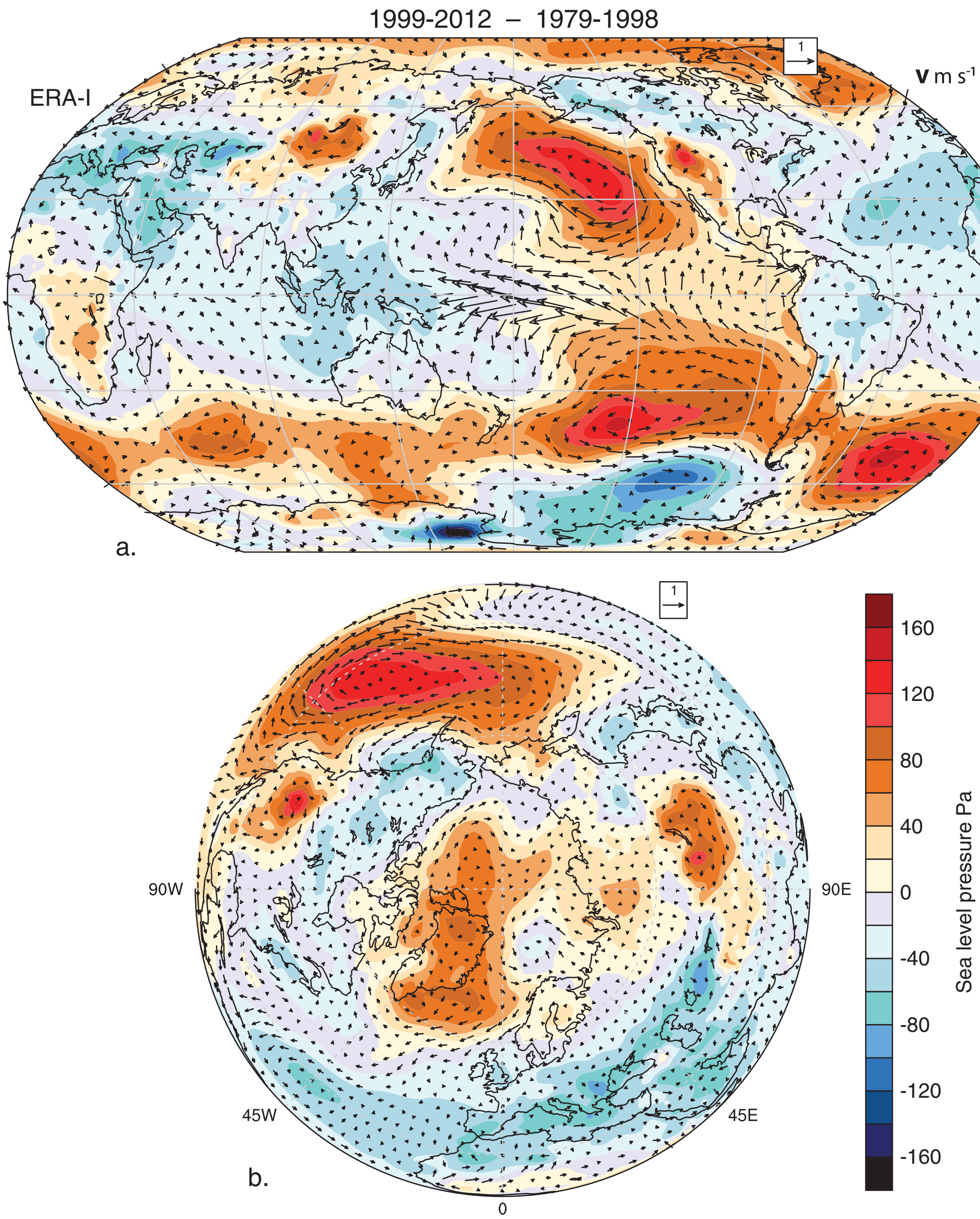

Figure 11. Mean annual sea-level pressure differences from ERA-I for 1999–2012 and 1979–1998 in Pa (colors) and for surface wind vectors (arrows) in m s^{-1} with the key at top right. (a) Map projection centered on the Pacific and (b) polar stereographic projection of the Northern Hemisphere.

possible, if not likely, that aspects of global climate change are manifested through changes in frequency of such modes [*Palmer*, 1999].

4. Conclusions

The picture emerging is one where the positive phase of the PDO from 1976 to 1998 enhanced the surface warming somewhat by reducing the amount of heat sequestered by the deep ocean, while the negative phase of the PDO is one where more heat gets deposited at greater depths, contributing to the overall warming of the oceans but cooling the surface somewhat. The Pacific Ocean appears to account for the majority of the decadal variability [*Chen et al*., 2008]. Nevertheless, the events in the Pacific undoubtedly

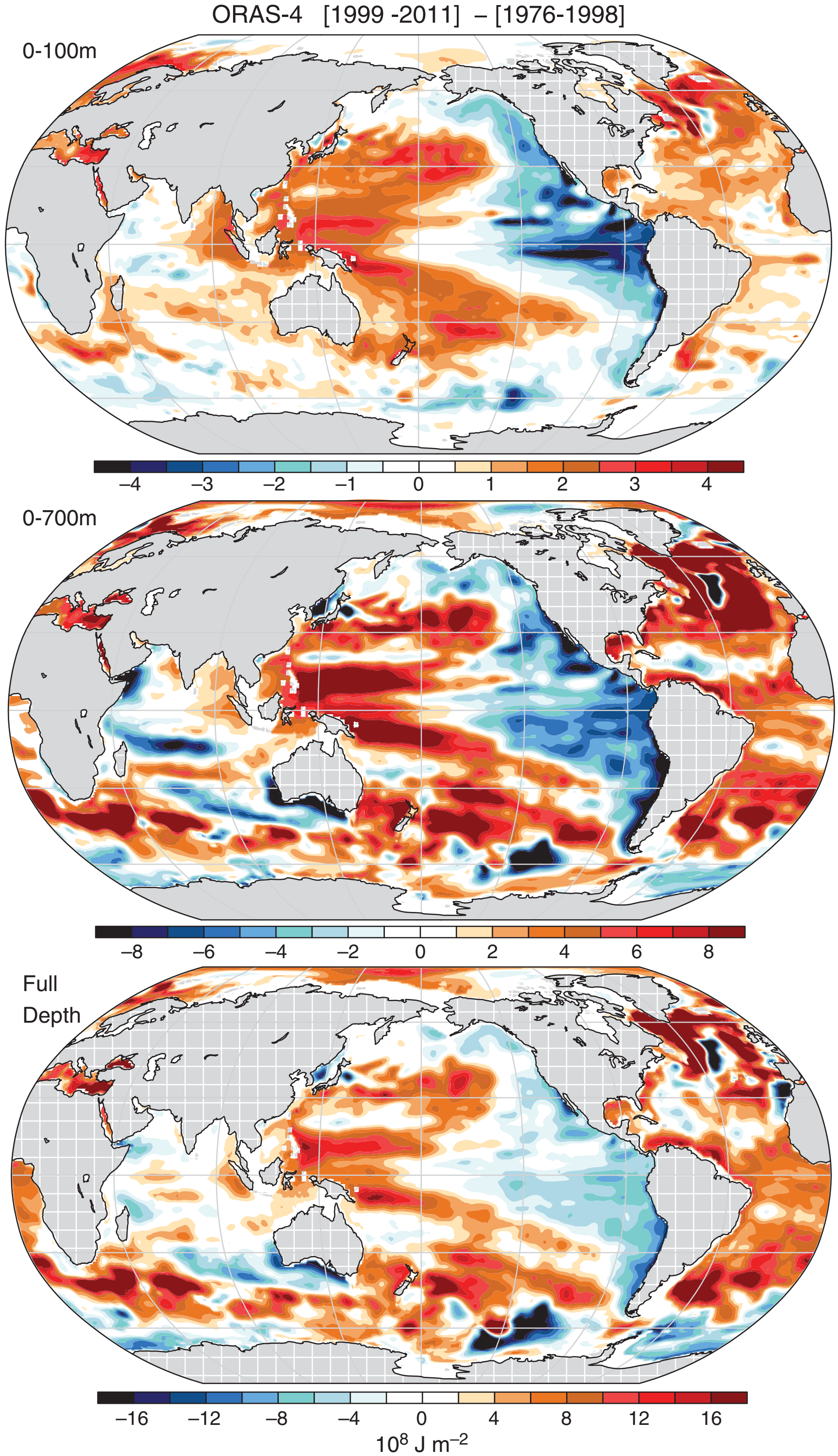

Figure 12. From ORAS-4 OHC differences for 1999–2012 and 1976–1998 in 10^8 J m^{-2} for the (top) 100 m, (middle) 0–700 m, and (bottom) full ocean depth. Note the different color keys for each figure.

also affect the Atlantic, Indian, and Southern Oceans as the system acts collectively to equilibrate to these changes in the flow of energy.

Kosaka and Xie [2013] have very recently performed some novel experiments that highlight the important role of the PDO in the apparent hiatus in global mean surface temperatures. They used a climate model with radiative forcing and prescribed SSTs over the central and eastern Pacific Ocean. Yet they were able to reproduce many aspects of the observed changes from 1970 to 2012, including the changes in global mean temperature and the recent pause in warming, and several regional and seasonal aspects. Accordingly, the key indeed seems to lie in the Pacific and the decadal tendency for more La Niña events (associated with Pacific decadal variability), as suggested by *Meehl et al*. [2011, 2013]. However, *Kosaka and Xie* [2013] did not deal with why the SSTs have changed as observed.

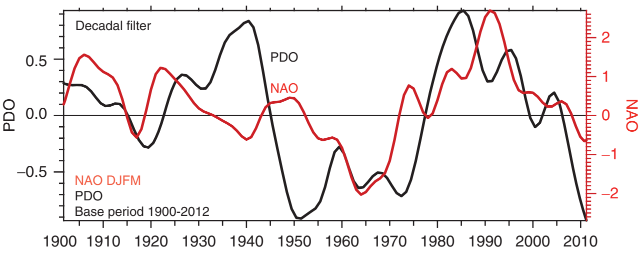

Figure 13. The decadal filtered PDO and NAO (DJFM).

We can speculate that the huge 1997–1998 El Niño event was a trigger for the change in the PDO; certainly, it led to a large loss of heat in the Pacific [*Balmaseda et al*., 2013] that has taken years to recover from, if the recovery is even complete. Past behavior of the PDO (Figure 8) suggests that regimes can last for 25 years. The CCSM4 model has hiatus periods up to about 15 years in duration, projected during the 21st century when there is a positive TOA energy imbalance [*Meehl et al*., 2013]. Accordingly, it becomes very important for climate models to be able to simulate ENSO and Pacific decadal variability realistically, with the correct amplitude and duration as a form of natural climate noise in which any external signals are embedded.

Variations in climate forcings are important, especially when major volcanic eruptions occur and reverberations are felt for years. Natural variations in clouds, changes in the Sun, and increases in minor volcanic eruptions may have accounted for up to a 20% reduction in radiative forcing and TOA energy imbalance in part of the 2000s but the Sun has now recovered and is now a factor in increased warming (Trenberth et al., submitted manuscript, 2013). The changes in external forcings are not obvious in the CERES TOA observations (Trenberth et al., submitted manuscript, 2013). Hence, although important, the variations in natural external forcings are not an explanation of the hiatus, but rather internal variations within the climate system are keys.

Expectations for the response from an energy imbalance come from climate models, and rely on realistic simulations of variability on all time scales. Many models have difficulty in simulating ENSO, although ENSO amplitude is actually too large in the CCSM4 model. But the veracity of decadal variability in models is an issue. Climate sensitivity estimates are greatly impacted by such variability especially when the observed record is used to try to place limits on equilibrium climate sensitivity [*Otto et al*., 2013], and simply using the ORAS-4 estimates of OHC changes in the 2000s instead of those used by Otto et al., so that the entire system uptake changes from 0.65 to 0.91 W m^{-2}, changes their computed equilibrium climate sensitivity from 2.0°C to 2.5°C, for instance. Using short records with uncertain forcings of the Earth system that is not in equilibrium does not (yet) produce reliable estimates of climate sensitivity.

The PDO is essentially a natural mode of variability, although there are questions about how it is affected by the warming climate, and so the plateau in warming is not because global warming has ceased. The evidence supports continued heating of the climate system as manifested by melting of Arctic sea ice and glaciers, as well as Greenland, but most of the heat is going into the oceans and increasingly into the deep ocean, and thus contributes to sea-level rise. The analysis in this article does not suggest that global warming has disappeared; on the contrary, it is very much alive but being manifested in somewhat different ways than a simple increase in global mean surface temperature.

Acknowledgments
This research is partially sponsored by NASA under grant NNX09AH89G. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

References

Balmaseda, M. A., K. E. Trenberth, and E. Källén (2013), Distinctive climate signals in reanalysis of global ocean heat content, *Geophys. Res. Lett.*, *40*, 1754–1759, doi:10.1002/grl.50382.

Chen, J., A. D. Del Genio, B. E. Carlson, and M. G. Bosilovich (2008), The spatiotemporal structure of twentieth-century climate variations in observations and reanalyses. Part II: Pacific pan-decadal variability, *J. Clim.*, *21*, 2634–2650.

Cohen, J. L., J. C. Furtado, M. Barlow, V. A. Alexeev, and J. E. Cherry (2012), Asymmetric seasonal temperature trends, *Geophys. Res. Lett.*, *39*, L04705, doi:10.1029/2011GL050582.

DelSole, T., M. K. Tippett, and J. Shukla (2011), A significant component of unforced multidecadal variability in the recent acceleration of global warming, *J. Clim.*, *24*, 909–926, doi:10.1175/2010JCLI3659.1.

Deser, C., A. S. Phillips, and J. W. Hurrell (2004), Pacific interdecadal climate variability: Linkages between the Tropics and the North Pacific during boreal winter since 1900, *J. Clim.*, *17*, 3109–3124.

Foster, G., and S. Rahmstorf (2011), Global temperature evolution 1979–2010, *Environ. Res. Lett.*, *6*, doi:10.1088/1748-9326/6/4/044022.

Hansen, J., R. Ruedy, M. Sato, and K. Lo (2010), Global surface temperature change, *Rev. Geophys.*, *48*, RG4004, doi:10.1029/2010RG000345.

Hansen, J., M. Sato, P. Kharecha, and K. von Schuckmann (2011), Earth's energy imbalance and implications, *Atmos. Chem. Phys.*, *11*, 13421–13449, doi:10.5194/acp-11-13421-2011.

Hurrell, J. W. (1995), Decadal trends in the North Atlantic Oscillation and relationships to regional temperature and precipitation, *Science*, *269*, 676–679.

Hurrell, J. W. (1996), Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperatures, *Geophys. Res. Lett.*, *23*, 665–668.

Ineson, S., and A. A. Scaife (2009), The role of the stratosphere in the European climate response to El Niño, *Nat. Geosci.*, *2*, 32–36, doi:10.1038/ngeo381.

Ineson, S., A. A. Scaife, J. R. Knight, J. C. Manners, N. J. Dunstone, L. J. Gray, and J. D. Haigh (2011), Solar forcing of winter climate variability in the Northern Hemisphere, *Nat. Geosci.*, *4*, 753–757, doi:10.1038/ngeo1282.

IPCC (2007), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon et al., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kosaka, Y., and S.-P. Xie (2013), Recent global-warming hiatus tied to equatorial Pacific surface cooling, *Nature*, *501*, 403–407, doi:10.1038/nature12534.

Lawrimore, J. H., M. J. Menne, B. E. Gleason, C. N. Williams, D. B. Wuertz, R. S. Vose, and J. Rennie (2011), An overview of the Global Historical Climatology Network monthly mean temperature data set, version 3, *J. Geophys. Res.*, *116*, D19121, doi:10.1029/2011JD016187.

Lean, J. L., and D. H. Rind (2008), How natural and anthropogenic influences alter global and regional surface temperatures: 1889 to 2006, *Geophys. Res. Lett.*, *35*, L18701, doi:10.1029/2008GL034864.

Lean, J. L., and D. H. Rind (2009), How will Earth's surface temperature change in future decades?, *Geophys. Res. Lett.*, *36*, L15708, doi:10.1029/2009GL038932.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis (1997), A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Am. Meteorol. Soc.*, *78*, 1069–1079.

Meehl, G. A., J. M. Arblaster, J. T. Fasullo, A. Hu, and K. E. Trenberth (2011), Model-based evidence of deep-ocean heat uptake during surface-temperature hiatus periods, *Nat. Clim. Change*, *1*, 360–364, doi:10.1038/NCLIMATE1229.

Meehl, G. A., A. Hu, J. Arblaster, J. T. Fasullo, and K. E. Trenberth (2013), Externally forced and internally generated decadal climate variability in the Pacific, *J. Clim.*, *26*, 7298–7310, doi:10.1175/JCLI-D-12-00548.1.

Merrifield, M. A., P. R. Thompson, and M. Lander (2012), Multidecadal sea level anomalies and trends in the western tropical Pacific, *Geophys. Res. Lett.*, *39*, L13602, doi:10.1029/2012GL052032.

Morice, C. P., J. J. Kennedy, N. A. Rayner, and P. D. Jones (2012), Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set, *J. Geophys. Res.*, *117*, D08101, doi:10.1029/2011JD017187.

Nerem, R. S., D. P. Chambers, C. Choe, and G. T. Mitchum (2010), Estimating mean sea level change from the TOPEX and Jason altimeter missions, *Mar. Geod.*, *33*, 435–446, doi:10.1080/01490419.2010.491031.

Otto, A., et al. (2013), Energy budget constraints on climate response, *Nat. Geosci.*, *6*, 415–416.

Palmer, T. N. (1999), A nonlinear dynamical perspective on climate prediction, *J. Clim.*, *12*, 575–591.

Simmons, A. J., K. M. Willet, P. D. Jones, P. W. Thorne, and D. P. Dee (2010), Low frequency variations in surface atmospheric humidity, temperature, and precipitation: Inferences from reanalyses and monthly gridded observational data sets. *J. Geophys. Res.*, *115*, D01110, doi:10.1029/2009JD012442.

Smith, T. M., R. Reynolds, T. C. Peterson, and J. Lawrimore (2008), Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880–2006), *J. Clim.*, *21*, 2283–2296, doi:10.1175/2007JCLI2100.1.

Solomon, S., K. Rosenlof, R. Portmann, J. Daniel, S. Davis, T. Sanford, and G.-K. Plattner (2010), Contributions of stratospheric water vapor to decadal changes in the rate of global warming, *Science*, *327*, 1219–1223.

Solomon, S., J. S. Daniel, R. R. Neely III, J.-P. Vernier, E. G. Dutton, and L. W. Thomason (2011), The persistently variable ''background'' stratospheric aerosol layer and global climate change, *Science*, *333*, 866–870, doi:10.1126/science.1206027.

Trenberth, K. E. (2009), An imperative for adapting to climate change: Tracking Earth's global energy, *Curr. Opin. Environ. Sustain.*, *1*, 19–27.

Trenberth, K. E., and A. Dai (2007), Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering, *Geophys. Res. Lett.*, *34*, L15702, doi:10.1029/2007GL030524.

Trenberth, K. E., and J. T. Fasullo (2010), Tracking Earth's energy, *Science*, *328*, 316–317.

Trenberth, K. E., and J. W. Hurrell (1994), Decadal atmosphere–ocean variations in the Pacific, *Clim. Dyn.*, *9*, 303–319.

Trenberth, K. E., and D. J. Shea (2006), Atlantic hurricanes and natural variability in 2005, *Geophys. Res. Lett.*, *33*, L12704, doi:10.1029/2006GL026894.

Trenberth, K. E., and D. P. Stepaniak (2004), The flow of energy through the Earth's climate system, *Q. J. R. Meteorol. Soc.*, *130*, 2677–2701.

Trenberth, K. E., J. M. Caron, D. P. Stepaniak, and S. Worley (2002), The evolution of ENSO and global atmospheric surface temperatures, *J. Geophys. Res.*, *107*(4065), D8, doi:10.1029/2000JD000298.
Trenberth, K. E., et al. (2007), Observations: Surface and atmospheric climate change, in *Climate Change 2007. The Physical Science Basis*, edited by S. Solomon et al. , pp. 235–336, Cambridge Univ. Press, Cambridge, U. K.
Trenberth, K. E., J. T. Fasullo, and J. Kiehl (2009), Earth's global energy budget, *Bull. Am. Meteorol. Soc.*, *90*, 311–323.
Wu, Z., N. E. Huang, J. M. Wallace, B. V. Smoliak, and X. Chen (2011), On the time-varying trend in global-mean surface temperature, *Clim. Dyn.*, *37*, 759–773, doi:10.1007/s00382-011-1128-8.