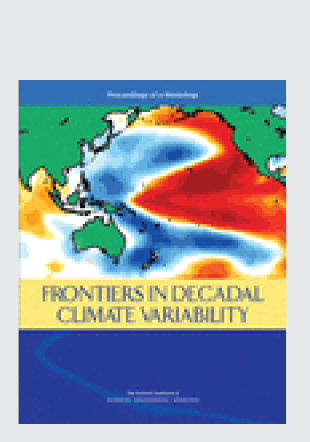

Frontiers in Decadal Climate Variability: Proceedings of a Workshop

DETAILS

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FRONTIERS IN DECADAL CLIMATE VARIABILITY

Proceedings of a Workshop

Amanda Purcell and Nancy Huddleston, Rapporteurs

Board on Atmospheric Sciences and Climate

Ocean Studies Board

Division on Earth and Life Studies

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Cover: A regression map of Pacific sea surface temperature variability. Figure modified after Di Lorenzo et al. (2015).

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This Proceedings of a Workshop has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published proceedings as sound as possible and to ensure that the proceedings meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the process. We wish to thank the following individuals for their review of this proceedings:

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Contents

Overview

Many factors contribute to variability in Earth's climate on a range of timescales, from seasons to decades. Natural climate variability arises from two different sources: (1) internal variability from interactions among components of the climate system, for example, between the ocean and the atmosphere, and (2) natural external forcings, such as variations in the amount of radiation from the Sun. External forcings on the climate system also arise from some human activities, such as the emission of greenhouse gases (GHGs) and aerosols. The climate that we experience is a combination of all of these factors.

Understanding climate variability on the decadal timescale is important to decision-making. Planners and policy makers want information about decadal variability in order to make decisions in a range of sectors, including for infrastructure, water resources, agriculture, and energy.

In September 2015, the Board on Atmospheric Sciences and Climate and the Ocean Studies Board of the National Academies of Sciences, Engineering, and Medicine convened a workshop[1] (Statement of Task in Appendix A) to examine variability in Earth's climate on decadal timescales, defined as 10 to 30 years. During the workshop, ocean and climate scientists reviewed the state of the science of decadal climate variability and its relationship to rates of human-caused global warming, and they explored opportunities for improvement in modeling and observations and assessing knowledge gaps. This report summarizes the workshop presentations and discussions. As such, it is a snapshot of how leading U. S. scientists were approaching the topic at the time. This report does not attempt to provide a complete overview of this rapidly advancing field or present any work not discussed at the workshop or any new work published since the workshop.

The scientific community broadly agrees that the planet as a whole is warming steadily through time (IPCC, 2014). Many workshop participants acknowledged that climate variability can cause the rate of warming to shift over periods lasting from years to a few decades. Internal climate variability can result from shifts in the absorption and transport of heat into the ocean, leading to periods when Earth's surface warms more slowly or more rapidly. Key points from workshop participants for framing the discussions ahead are highlighted in Box 1.

Since 1880, the average temperature at Earth's surface has increased by about 0.85 C. Most of this increase (about 0.72 C) has occurred since 1951 (Hartmann et al., 2013). A number of recent studies indicate that the global mean surface warming trend slowed to near zero (0.07±0.08 C per decade) in the first to second decades of the 21st century (Easterling and Wehner, 2009; Hartmann et al., 2013; Kosaka and Xie, 2013) in relation to the trend during the latter half of the 20th century (i. e., 1950-2012). This slowdown in GMST rise has spurred much research aimed at examining recent and past climate variability in order to understand and better predict decadal climate trends. This period, typically defined as a range between 1998 to 2014, is referred to throughout this report as the "slowdown." The scientific community, the media, and some workshop participants have also broadly used

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[1] This report has been prepared by the workshop rapporteur as a factual summary of what occurred at the workshop. The planning committee's role was limited to planning and convening the workshop. The views contained in the report are those of individual workshop participants and do not necessarily represent the views of all workshop participants, the planning committee, or the National Academies of Sciences, Engineering, and Medicine.

BOX 1

Key Points

During the workshop, participants identified the following points as a foundation for discussions of decadal climate variability:

- The Earth system (land, atmosphere, and ocean) continues to steadily warm through time in response to increasing greenhouse gases (GHGs) in the atmosphere from human activities.
- Global mean surface temperature (GMST) is increasing as the Earth warms, but the rate of surface warming fluctuates because of variability in the internal dynamics of the climate system and in contributions of external forcings.
- Internal climate variability arises from changes in the transport of heat in the climate system (e. g., in the ocean, or from the atmosphere into the ocean), leading to periods when the surface warms more slowly or more rapidly.
- A slowdown in the rise of GMST is not equivalent to a slowdown in global warming. Viewed over long time periods (50+ years), there is a persistent increase in GMST. However, it remains important to understand the decadal variability in GMST that is observed over shorter time periods.

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the terms “hiatus” and “warming pause,” but through the discussions, many participants agreed that “slowdown” is a more accurate term because it does not suggest that something, specifically human-caused climate change, halted during this period (see Box 1, bullet 4).

A major line of inquiry discussed at the workshop is the degree to which natural variability modulated human-caused climate change during the recent warming slowdown, as well as during past periods of increased or accelerated warming, such as from 1970 to 1998. Also discussed was the extent to which previous results are a function of data coverage or remaining biases in sea surface temperature (SST) reconstructions. Some research has indicated that the early-2000s warming slowdown does not appear to be as pronounced if incomplete observed data coverage over the Arctic or errors in calibration of SST observations are taken into account (e. g., Cowtan and Way, 2014; Karl et al., 2015).

Much of the workshop discussion focused on the mechanisms governing decadal variability. Several participants presented evidence that the recent slowdown is driven in large part by well-documented swings in Pacific SSTs and sea level pressure known as the Interdecadal Pacific Oscillation (IPO). Other research has made the case that external forcing also played a role; for example, multiple small- to moderate- sized volcanoes have produced an accumulation of aerosols in the stratosphere that contribute to cooling (e. g., Ridley et al., 2014; Santer et al., 2014).

The specific mechanisms driving decadal variability, not only in the Pacific but also in all of the ocean basins, are subjects of intense scientific inquiry. Workshop participants shared research into potential mechanisms driving Pacific temperature swings, including storage of excess heat in the deeper ocean, movement of heat to the Indian Ocean, wind-driven changes, and teleconnections with the Atlantic Ocean. Proposed mechanisms of Atlantic variability include changes induced by the ocean’s major current (the Atlantic Meridional Overturning Circulation, or AMOC) and its relationship to the North Atlantic Oscillation (NAO). Also discussed was variability in the Indian Ocean and polar regions.

Because the storage of heat in the ocean has been implicated in the recent warming slowdown as measured by GMST, participants discussed the limitations of using GMST as the primary metric of global climate change. Many participants supported the notion that, because 93 percent of the excess heat from GHGs is stored in the ocean, sea-level rise, or sea-level rise together with GMST, may be a more appropriate metric of global climate change.

Variability at decadal timescales is a well-known feature of the climate system. Climate models produce periods of slower and more accelerated warming, although a specific slowdown in the GMST warming trend in the early 2000s was not directly projected by climate models (the warming trend during this period was near the lower edge of the 5-95 percent range of projections from the Coupled Model Intercomparison Project Phase 5; Schmidt et al., 2014). Many participants agreed that being able to predict decadal variability would be important given its implications, for example, its link to important regional phenomenon such as drought. Much remains to be learned before scientists will be able to make skillful predictions of variability on these timescales, however.

Workshop participants discussed the importance of advancing understanding of how all of the physical mechanisms in the ocean and atmosphere work in concert to produce decadal variability in the GMST and of improving observations and modeling capabilities in order to make predictions. Participants identified the continuation and improvement of ocean and atmospheric monitoring as well as more creative ways to use existing data, including paleoclimate data and synthesis products from models, as possible opportunities to improve predictions.

The study of Earth's climate system involves a large and diverse group of experts. Participants commented on the great value provided by bringing together a diversity of researchers to discuss key challenges and opportunities in the field of decadal climate variability.

Introduction

Studies of historic and paleoclimate data (e. g., NRC, 1998), as well as climate model simulations (e. g., Easterling and Wehner, 2009), demonstrate that Earth's climate system exhibits natural variability at a wide range of timescales because of both internal and external factors (see Box 2). Decadal climate variability refers to variability of regional and global climate on timescales of 10 to 30 years. [1] Longer trends (50 years or more) in observed global mean surface temperature (GMST) in the recent century largely reflect increases in anthropogenic greenhouse gases (GHGs; e. g., Bindoff et al., 2013). Decadal variability can be described as the ups and downs of the climate, which are superimposed on that trend (see Figure 1). In this way, decadal variability can accelerate or decelerate the rate of warming on shorter timescales, whereas climate change is dominated by the steady warming from increasing GHGs over the long term.

The slowdown in the GMST warming trend during the early 2000s spurred a lot of research aimed at identifying variability in observations and models, as well as attributing its mechanisms. What physical mechanisms can explain recent as well as past decadal variability? How much of the variability in recent trends in surface warming is due to internal, natural variability versus external forcing, and how does this attribution vary as a function of timescale? Given what is known today about the controls on decadal variability, what can be said about the future? Are such accelerations and slowdowns predictable? What observations, data synthesis, and improvements in climate models might be needed to provide comprehensive answers to such questions? Finally, what is the best way to measure the influence of human-emitted GHGs on the global climate? Is GMST the best

BOX 2

Definitions of Climate Variability and Climate Change

The following definitions are taken from the Intergovernmental Panel on Climate Change 5th Assessment Report (IPCC, 2014) and are provided as background to the discussions summarized below.

Climate change refers to a change in the state of the climate that can be identified (e. g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the atmosphere's composition or land use.

The **climate system** is the highly complex system consisting of five major components: atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere and the interactions among them. The climate system evolves in time in response to internal dynamics and external forcings such as volcanic eruptions, solar variations, and anthropogenic changes in the atmosphere's composition or land use.

External forcing refers to an external agent that causes a change in the climate system. Volcanic eruptions, solar variations, and anthropogenic changes in the atmosphere's composition and land use are external forcings. Orbital forcing is also an external forcing because the insolation changes with orbital parameters such as eccentricity, tilt, and precession of the equinox.

Climate variability refers to variations in the mean state and other statistics (e. g., standard deviations, occurrence of extremes) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural processes internal to the climate system or to natural or anthropogenic external forcing. Variability of the climate occurs on a variety of timescales—from seasons to decades to millennia.

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[1] Participants noted that while the timescale of decadal climate variability is approximately 10-30 years, the mechanisms and drivers of this variability occur at a variety of timescales, for example, ENSO (see Box 3).

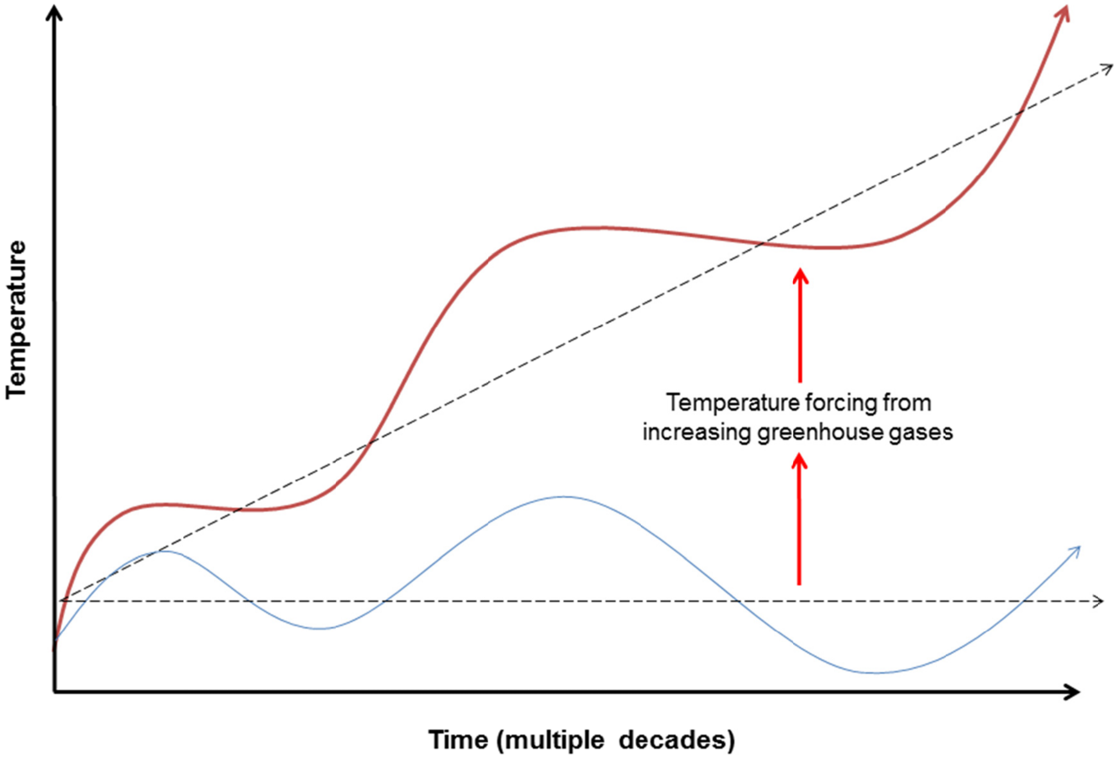

FIGURE 1 This schematic illustrates natural decadal climate variability in GMST (blue), which is superimposed on the long-term forcing from GHGs (change in dotted baseline indicated with red arrows). NOTE: The normal ups and downs of natural variability are then accelerated or decelerated by the long-term warming, producing a new curve that represents the combination of natural variability and human-caused warming (maroon). SOURCE: Adapted from Gerald Meehl presentation, September 3, 2015.

metric? Regardless of the measure, what methods can best evaluate inflections in the rate of climate change?

The importance of answering these and related questions extends beyond explaining the recent slowdown in surface warming: The ability to anticipate, and eventually predict, such changes is important to decision-making. Planners and policy makers want information about decadal variability to make decisions in a range of sectors, including for infrastructure, water resources, agriculture, and energy. Furthermore, like the well-studied El Niño and La Niña interannual variations, decadal climate variability is associated with specific regional patterns of temperature and precipitation, such as heat waves, cold spells, and droughts. For example, some of the same mechanisms responsible for the recent warming slowdown may have played a role in the extended drought in the U. S. western states (e. g., Delworth et al., 2015). Clarifying the processes behind the recent slowdown in GMST rise can improve understanding and prediction of regional climate, which in turn can inform decisions that affect our society (e. g., Murphy et al., 2010).

In September 2015, the Board on Atmospheric Sciences and Climate and the Ocean Studies Board of the National Academies of Sciences, Engineering, and Medicine convened a workshop to examine these questions (see Statement of Task in Appendix A). The workshop included a number of panels followed by open discussions, as well as breakout groups focused on specific modeling and observational challenges, and concluded with reflections on the workshop's key messages and lessons on communicating these messages (see workshop agenda in Appendix B).

Challenges in Examining Climate Trends

Many participants noted that conversations about climate trends should clearly specify which time periods defined the trend, which period served as the baseline for determining the trend, and how the trend was quantified. However, not every workshop presented provided these specifications when discussing the slowdown. The presentations spurred discussion about whether the global mean surface temperature (GMST) warming trend did indeed slow down during the early 2000s—the answer to which depended on the timescale chosen and the quantification method used.

The discussion about ways to frame climate trends was motivated in part by a paper released by Karl et al. (2015) prior to the workshop, which suggested that the slowdown during the early 2000s was an artifact of residual data biases in the calculation of GMST from an early version of a global surface temperature dataset.[1] Karl et al. based their paper on recent updates to the National Oceanic and Atmospheric Administration (NOAA) GMST dataset, which revealed that the surface ocean has warmed nearly twice as fast in recent years as previously thought. When combined with updated land surface temperature data, which show a slight increase in the rate of land surface warming, the GMST data show a small but significant positive trend (at the 0.10 level) in GMST from 1998 to 2012.

Huai-Min Zhang, a scientist from the NOAA National Centers for Environmental Information (NCEI), said that with these corrections the trend for 1998-2012 is not statistically significantly different from the estimates for the trend for 1951-2012. Zhang suggested that the years used in the Intergovernmental Panel on Climate Change analysis of GMST (IPCC, 2014) do not provide a very good picture of decadal warming trends, because the analysis period is short and started with 1998 (one of the warmest years on record because of a large El Niño event). With the updated dataset and an extended analysis period (1998-2014 or 2000-2014), recent warming rates are even higher and, for the latter period, comparable to warming rates of the second half of the 20th century.

Gerald Meehl, chair of the workshop organizing committee and senior scientist at the National Center for Atmospheric Research,

Explanation of NOAA's Improved Operational Dataset

Karl et al. (2015) explains the changes to NOAA's dataset:

> The data used in our long-term global temperature analysis primarily involve surface air temperature observations taken at thousands of weather-observing stations over land, and for coverage across oceans, the data are sea surface temperature (SST) observations taken primarily by thousands of commercial ships and drifting surface buoys. These networks of observations are always undergoing change. Changes of particular importance include (i) an increasing amount of ocean data from buoys, which are slightly different than data from ships; (ii) an increasing amount of ship data from engine intake thermometers, which are slightly different than data from bucket seawater temperatures; and (iii) a large increase in land-station data, which enables better analysis of key regions that may be warming faster or slower than the global average. We address all three of these, none of which were included in our previous analysis used in the IPCC report. (p.1470)

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[1] HadSST3 (the Met Office Hadley Centre gridded SST dataset) made the SST adjustments made by Karl et al. (2015) several years earlier prior; see Kennedy et al. (2011).

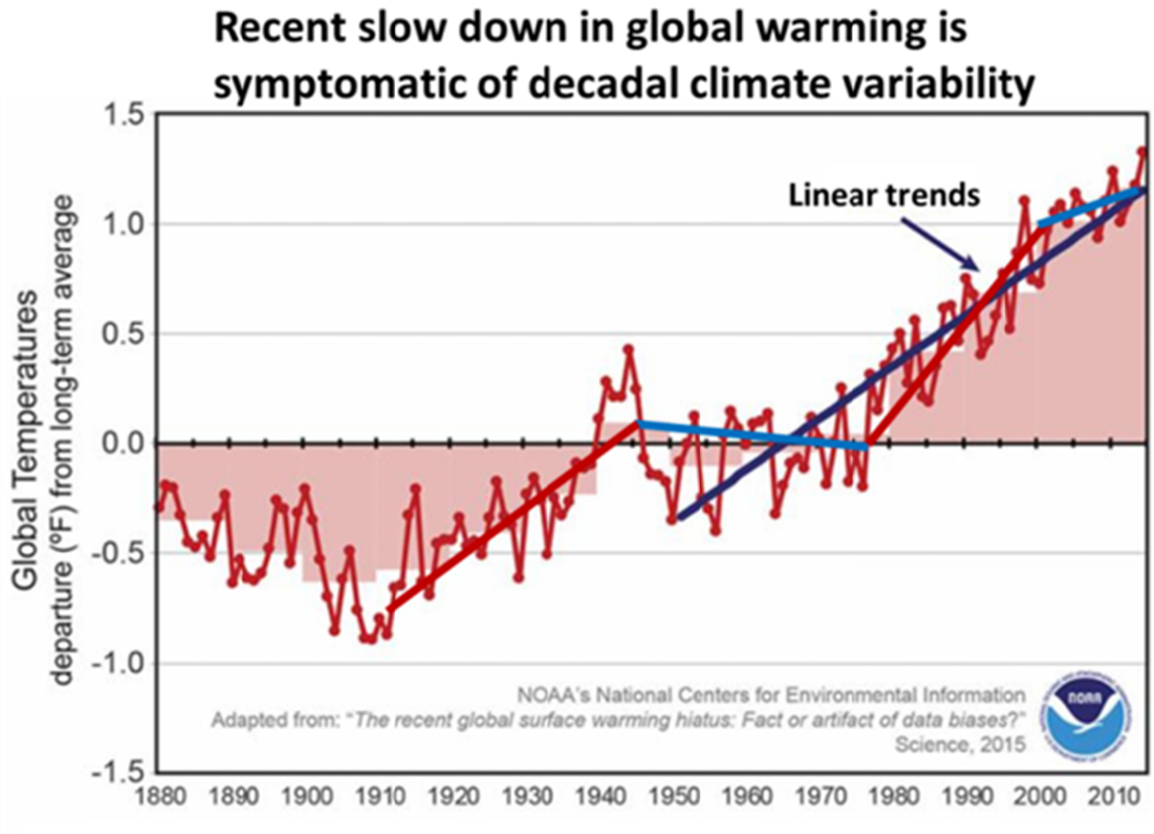

FIGURE 2 Time series of annual GMST anomalies in Fahrenheit (dots) based on data from Karl et al. (2015). NOTEs: Black line is linear trend computed from 1950 to 2014 showing long-term trend forced mainly by increasing GHGs. Red and blue lines show that the linear trend is dependent on time period chosen (in this case, positive and negative phases of the Interdecadal Pacific Oscillation (IPO), respectively). SOURCE: Meehl (2015).

presented a graph of the GMST rise since the late 1800s (Figure 2) to demonstrate that warming rates are sensitive to the years chosen to fit a linear trend. For example, from about 1945 to 1975, the period of low or negative trends in GMST was pronounced (see light blue line in Figure 2). However, over the longer term, the general warming trend is pronounced and clearly evident. He described the global warming trend as an uneven staircase: there are steeper and less steep periods, but the trend over longer timescales has been increasing, consistent with human-caused global warming, regardless of whether some shorter periods exhibit statistically significant positive (or negative) trends.

John Fyfe from the Canadian Centre for Climate Modelling and Analysis (CCCma) and his colleagues disagree with the argument by Karl et al. (2015) that the slowdown during the early 2000s is not apparent after correcting observations of global sea surface temperature. Fyfe pointed out that the baseline period used by Karl et al. (2015) for comparison includes the so-called "big hiatus" (a period of near-zero trend in the mid-20th century, shown in Figure 3); therefore the trend computed for the baseline period is low and not dissimilar from recent trends.

Fyfe suggested that the baseline period should be physically based to reflect natural variability. Using a baseline period of 1972-2001, which excludes the "big hiatus," Fyfe concluded that a warming slowdown did indeed occur, relative to 1972-2001 (see Fyfe at al., 2016).

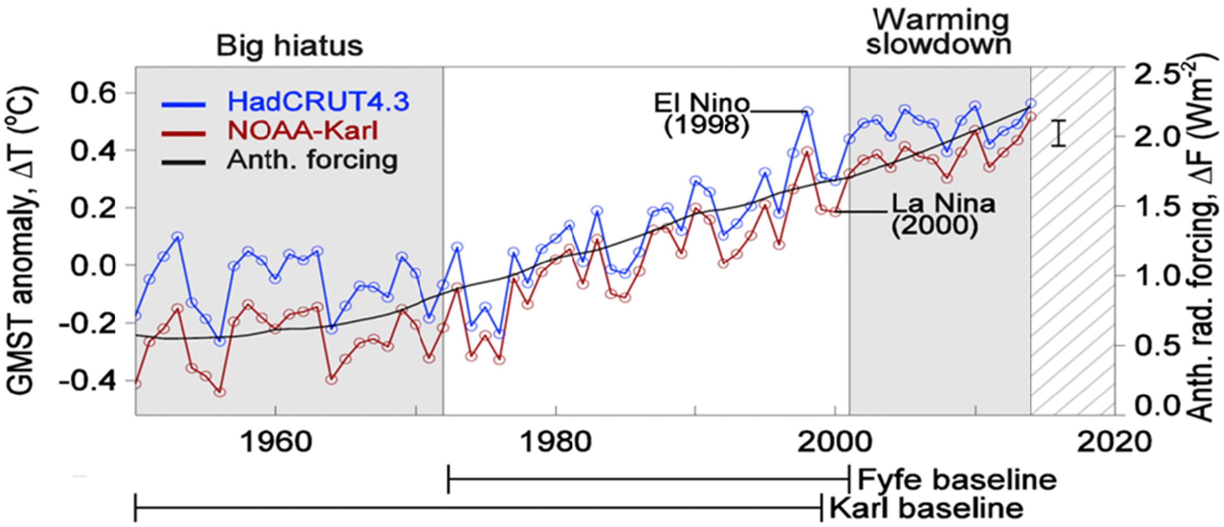

FIGURE 3 GMST anomalies based on HadCRUT4.3[2] data (blue), Karl et al. (2015) updated dataset (red), and estimated anthropogenic forcing (black, using RCP; Meinshausen et al., 2011) from 1950 to 2014. NOTES: Karl et al. anomalies are relative to 1971-2000 climatology, and HadCRUT4.3 anomalies are relative to 1961-1990 climatology. The Karl et al. baseline includes the "big hiatus" (shaded gray), whereas the Fyfe et al. baseline does not. SOURCE: John Fyfe presentation, September 3, 2015. © Her Majesty the Queen in Right of Canada, as represented by the Minister of Environment, 2016.

Workshop participants highlighted the fact that GMST variations are expected in the globally integrated Earth system. Challenges to quantifying exact rates and identifying the multitude of processes related to the differing rates largely result from gaps in observations and the ability to measure global energy changes in components of Earth's climate system. Nonetheless, participants agreed that human-caused changes to Earth's energy balance have not been on "hiatus" and are causing the planet to warm on average over longer timescales.

Many participants also agreed that, regardless of whether a temporary slowdown in GMST rise occurred between 1998 and 2014, natural variations are expected in the long-term temperature record for periods on the decadal timescale. Understanding of this climate variability will in turn inform understanding of the physical climate system as well as advance prediction and attribution capabilities. Some participants noted that framing the discussion around whether or not there was a recent slowdown period obscures the importance of understanding decadal variability and its many climate impacts. Much of the remainder of the workshop discussions delved into research to uncover the contributions by various internal mechanisms and external forcing, how they interact to produce global and regional decadal climate variability, and the potential for increased knowledge to lead to predictions of transitions between periods of slower and faster warming of GMST in response to GHG forcing.

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[2] HadCRUT4.3 is a gridded dataset of global historical surface temperature anomalies relative to a 1961-1990 reference period. Data are available for each month since January 1850, on a 5 degree grid. The dataset is a collaborative product of the Met Office Hadley Centre and the Climatic Research Unit at the University of East Anglia. At the time of this writing, HadCRUT4.3 had been updated to version HadCRUT4.4. Available at http://www.metoffice.gov.uk/hadobs/hadcrut4/.

Modes and Mechanisms of Internal Variability

A combination of internal variability and external forcing causes variability in global mean surface temperature (GMST) trends. Much of the workshop focused on examining how known modes and patterns of internal variability contribute to variability of observed decadal global surface temperature. Broadly speaking, internal variability results when interaction of climate components, including the atmosphere, ocean and sea ice, cause heat to move within the climate system (IPCC, 2013). Often, this transport takes the form of observable patterns, such as sea surface temperature anomalies in the Pacific Ocean (Christensen et al., 2013). Box 3 provides a brief overview of dominant modes and patterns of internal (interannual to decadal) climate variability.

Scientists study these modes of climate variability in part by looking for patterns in long-running observations of air and sea surface temperatures (SSTs), air pressure, and precipitation (Christensen et al., 2013). They use a variety of statistical techniques, such as empirical orthogonal function (EOF) analysis,[1] to identify and define preferred states or leading patterns of variability over different time periods. Although often prominent features in the climate system, these patterns or modes are not sufficiently understood to enable prediction of future conditions. What controls the strength of variability in the patterns, and the transition between different phases of such modes, is in many cases far from clear (Christensen et al., 2013). Improved knowledge of how these modes interact to produce the current climate could lead to improved prediction of decadal climate variability.

Understanding the various mechanisms involved in the transfer of heat within the climate system was a major focus of the workshop. As much as 93 percent of the heat trapped by greenhouse gases (GHGs) goes into the ocean; the lower atmosphere—where global surface temperature is measured—is a very small heat reservoir in comparison (Rhein et al., 2013). Veronica Nieves of the NASA Jet Propulsion Laboratory presented evidence that during the recent slowdown in GMST rise (in this case, using 2003 as the period start), excess heat was sequestered in the subsurface tropical Pacific waters, which is a "symptom" of decadal variability. In the early 2000s, Pacific surface temperatures were cooler, and unusually strong winds caused the heat to travel to the subsurface (100-300 m) depth layer in the eastern Pacific Ocean to the central/western Pacific Ocean and Indian Ocean. Therefore, as Nieves explained, there was no slowdown in terms of depth-integrated temperature, because when the Pacific Ocean surface gets cold there can be warming beneath and vice versa (global trends shown in Figure 4).

Because water expands as it warms and contracts when it cools, Nieves suggested that global mean sea level may be a more appropriate measure for climate change than GMST because it reflects the depth-integrated temperature.

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[1] Empirical Orthogonal Function (EOF) analysis is a method used in statistics and signal processing to decompose a signal or data set in terms of orthogonal (or perpendicular) basis functions that are determined from the data. The EOF method finds patterns in both space and time, although otherwise is the same as performing a principal components analysis on the data. EOF analysis is often used to study possible spatial modes (i. e., patterns) of variability and how they change with time. It is not based on physical processes; rather a field is partitioned into mathematically orthogonal (independent) modes, which sometimes may be interpreted as atmospheric and oceanographic modes ("structures").

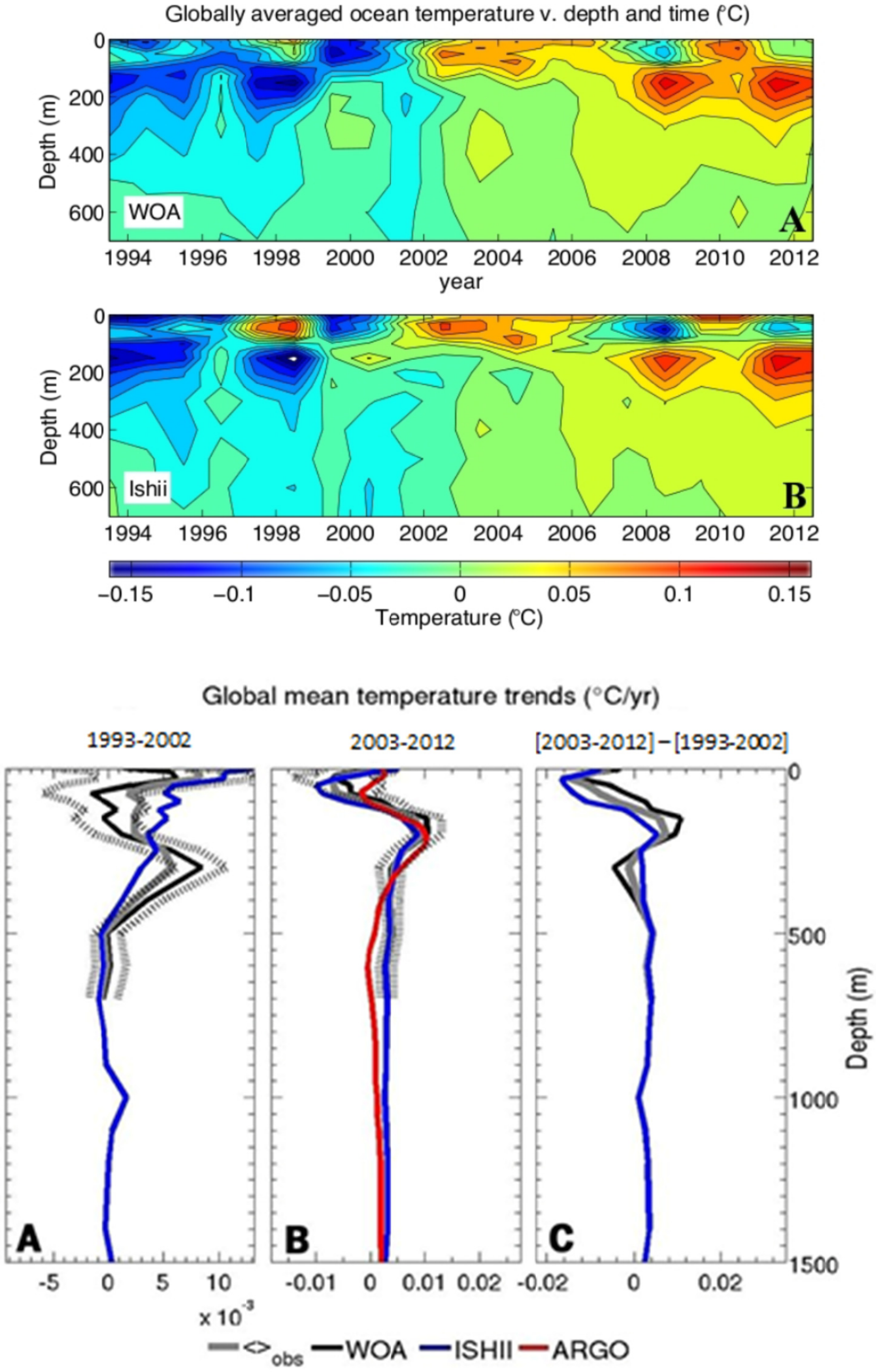

FIGURE 4 (Top) Globally averaged ocean temperature as a function of depth (top 700 m) and year for the World Ocean Atlas (WOA; A) and Ishii (B), two ocean observational products. (Bottom) Global mean temperature trends as a function of depth using observational products for the 90s (A), 00s (B), and 00s-90s (C). NOTES: The gray line corresponds to the average of WOA (black) and Ishii (blue) estimates.90s and 00s stands for the periods from 1993 to 2002 and from 2003 onwards, respectively. Cooling trends in the top 100 m are correlated with warming in the 100-300 m layer during the slowdown period. SOURCE: Nieves et al. (2015).

BOX 3

Patterns of Internal Variability

The **El Niño–Southern Oscillation (ENSO)** is an interannual variability phenomenon that combines the tropical Pacific Ocean surface water temperature over the eastern equatorial Pacific Ocean with air pressure difference across the tropical western Pacific Ocean basin (the Southern Oscillation). ENSO has two coupled phases: El Niño (warm phase) and La Niña (a cool phase). ENSO has a well-understood relationship to the Walker Circulation. When the Walker Circulation is weak or reverses, there is very little upwelling of cold water, resulting in an El Niño with warmer than average ocean temperatures in the eastern equatorial Pacific Ocean. When the Walker Circulation is very strong, upwelling increases, resulting in a La Niña with cooler ocean temperatures there. ENSO “events” (phases) persist for 6 to 18 months. ENSO variability is mostly interannual (in the 3- to 7-year range), although analyses also suggest decadal-scale shifts in its variability (NRC, 1995).

Pacific Decadal Variability (PDV) is dominated by the Pacific Decadal Oscillation (PDO) and Interdecadal Pacific Oscillation (IPO), two indices described below. The terms can sometimes be used interchangeably, although PDV is preferred—as noted by some workshop participants—because the changes in the PDO and IPO may not be true oscillations. Recent work (Newman et al., 2016) suggests that the PDV is not one single mode, as discussed later in this section, indicating a need to distinguish the terms.

- The **PDO** describes an ENSO-like decadal pattern of variability in sea surface temperature (SST) of the North Pacific Ocean (poleward of 20 N). This pattern was identified when contrasting climate variability in the North Pacific Ocean with the strong interannual variability in the tropics (i. e., ENSO). During the positive (or “warm") phase, the west Pacific Ocean becomes cooler and part of the eastern ocean warms; during the negative (or “cool”) phase, the opposite pattern occurs. The PDO is empirically defined as the largest amplitude variability of wintertime SSTs in the North Pacific Ocean (i. e., the first leading Empirical Orthogonal Function [EOF] on the SSTs; Mantua and Hare [2002] and Mantua et al. [1997]). The PDO phases persist for 20 to 30 years.
- The **IPO** is a variability pattern of SST fluctuations and sea level pressure changes in the entire Pacific basin; the IPO can be thought of as the Pacific-wide expression of the PDO. During the positive (or “warm”) phase of the IPO, SSTs in the tropical Pacific Ocean are warmer than average and those in the Northwest and Southwest Pacific Ocean are cooler; during the negative (or “cool”) phase, the opposite pattern occurs. The IPO can be defined as the second largest amplitude variability component of the Pacific-wide SSTs (i. e., the second leading empirical EOF).

The **North Atlantic Oscillation (NAO)** is the Atlantic expression of the Northern Annular Mode (NAM) or the Arctic Oscillation (AO), which is the dominant mode of atmospheric variability in the extratropical Northern Hemisphere (Thompson and Wallace, 2000). The NAO is a phenomenon identified by variations in atmospheric pressure (variations of the strength of high and lower pressure systems) that control the strength and direction of east-west winds over the North Atlantic Ocean, and is calculated using leading EOF of the sea level pressure anomalies over the Atlantic sector: 20 -80 N, 90 W-40 E. It has a large impact on storm tracks. NAO phases are related to the strength and positions of a persistent low-pressure system over Iceland (the Icelandic Low) and a persistent high-pressure system over the Azores (the Azores High). When there is a large difference in the pressure at the two systems, the NAO is positive, producing above-normal temperatures in the eastern United States and across northern Europe and below-normal temperatures in Greenland and oftentimes across southern Europe and the Middle East. When there is a small difference in the pressure of the systems, the NAO is negative (also referred to as “blocked”) and is associated with strong snowstorms in the eastern United States and very cold winters and increased storm activity in southern Europe and North Africa. The NAO varies on all timescales from days to years.

The **Atlantic Multidecadal Oscillation (AMO)** pattern describes variability in SSTs averaged over the entire North Atlantic Ocean. The AMO index is usually calculated as the average of north Atlantic SST temperature anomalies after removing any linear trend (Enfield et al., 2001). Plotting such an index reveals warmer and cooler periods spanning several decades (20-40 years). Although not completely understood, the drivers of these variations may be related to changes in the Atlantic Meridional Overturning Circulation (AMOC; Zhang, 2007), or may be largely a result of climate change influence on SSTs (Mann et al., 2014). Warmer and cooler phases of the AMO have been linked to changes in weather and climate variability throughout the world, including more or less drought periods in North America, and changes in Atlantic hurricane activity (Goldenberg et al., 2001).

The heat storage of the ocean is much larger than that of the surface layer. Therefore, many participants stressed the importance of understanding the various mechanisms that transport this heat in order to better understand the current state of Earth's climate and how it changes. This section summarizes the workshop presentations about several of the proposed contributors to and patterns of this heat transport.

Processes and Patterns in the Pacific Ocean

The El Niño–Southern Oscillation (ENSO, see Box 3) is the dominant mode of interannual variability in the Pacific Ocean, with well-known connections worldwide, including to U. S. climate. For example, El Niño (the warm phase of the ENSO) is associated with strong winter effects in the Northern hemisphere that result in more precipitation across the southern United States and cooler than normal temperatures in the southeast, as well as fewer hurricanes (in June to November; Goldenberg et al., 2001). Although the mechanisms surrounding ENSO phases are well studied and understood (see Box 3), the drivers of Pacific Decadal Variability (PDV) patterns are less so, although studies have implicated ENSO as one driver.

Gerald Meehl, National Center for Atmospheric Research (NCAR), emphasized that the precise mechanisms that control decadal variability in the Pacific Ocean and trade winds, including the mechanisms that control phase changes in PDV (i. e., the Pacific Decadal Oscillation [PDO] or the Interdecadal Pacific Oscillation [IPO]), are still a topic of debate. Such phase changes could involve coupled air-sea tropical-mid-latitude processes (Meehl and Hu, 2006) or chaotic (stochastic) amplitude modulation of ENSO (e. g., Jin, 2001), or might be triggered by variability in the Atlantic Ocean (e. g. McGregor et al., 2014; Li et al., 2016).

Importance of the Pacific Ocean to Global Trends

Several participants noted that decadal variability in the Pacific Ocean is a major driver of global variability, which is superimposed on long-term warming trends (Kosaka and Xie, 2013; England et al., 2014; Nieves et al., 2015; Meehl, 2015; Newman et al., 2016). Meehl presented evidence linking phases of the IPO, observed as decadal variability in SSTs across the Pacific Ocean, to decadal variability in GMST. Meehl said the slowdown in GMST in the early 2000s occurred when the IPO was in its negative phase (2000-2013), whereas the IPO was in its positive phase during a previous period of faster warming (late 1970s to late 1990s; see Figure 5). There is also evidence of the influence of PDV in other slowdown periods in the past (e. g., mid-1940s to late 1970s).

The GMST slowdown and the recent negative IPO phase are likely related to the presence of stronger trade winds during the negative phase of the IPO. Stronger trade winds cause a La Niña–like pattern of increased upwelling of cooler waters in the eastern tropical Pacific Ocean and intensified subtropical cell circulation in the atmosphere, which promotes enhanced mixing of warmer water into the subsurface of the ocean. Such enhanced mixing could account for about 50 percent of energy represented in the slowdown in GMST rise (England et al., 2014; Delworth et al., 2015).

Shang-Ping Xie from the Scripps Institution of Oceanography also presented evidence that the tropical Pacific SST affects timing and magnitude of the warming acceleration and slowdown in GMST, including the recent slowdown period. He presented results from a

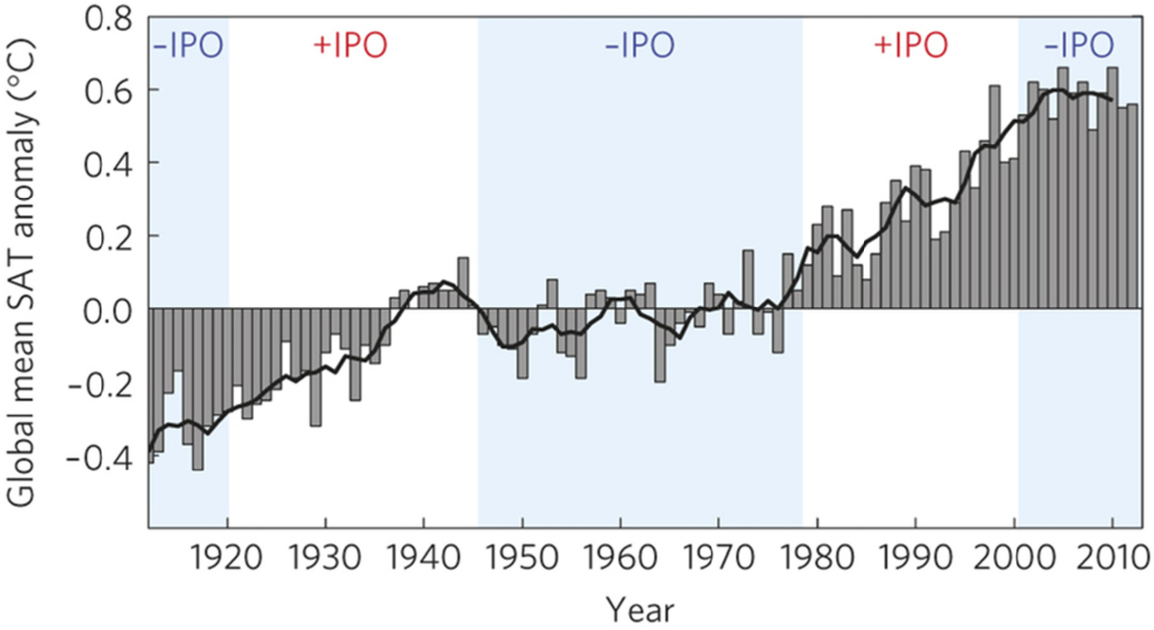

FIGURE 5 GMST (surface-air temperature) anomalies over the past century. NOTES: Temperature anomalies are shown as the annual mean relative to 1951–1980, with individual years shown as grey bars and a 5-year running mean overlaid in bold. During positive IPO phases (index of PDV), the GMST anomaly slope is steeper, indicating faster surface temperature increase, while during negative IPO phases, the slope is fairly small. SOURCE: England et al. (2014).

POGA (Pacific Ocean-Global Atmosphere) pacemaker[2] experiment in which model runs specifying the cycles of internal Pacific variability in SST (from observations) better match observations of GMST than the model runs without Pacific cycles temporally synced to the observations (Figure 6).

Xie pointed out that GMST, regardless of the robustness of current estimates of this metric, is not measured directly; rather, it represents the average of temperature measured across the globe. Therefore, a lot can be learned about what is driving GMST variability by “unpacking the data” to look for spatial and seasonal patterns. For example, an examination of the slowdown period (in this case, 2002-2012) reveals that colder winter temperatures characterized the slowing trend (Figure 7, January-February-March [JFM] dip). During a Northern Hemisphere winter, storms inject heat from the tropics into the high latitudes; however, during a cold phase of the IPO, the tropics are cooler and transfer less heat. During the summer, the storms do not contribute as much heat to higher latitudes, which allows external forcing (such as GHGs) to dominate the warming trend. Therefore, as Xie explained, wintertime is a distinct seasonal fingerprint of the negative IPO. The pacemaker experiment (POGA-H) also shows the same result.

Mechanisms Driving Pacific Decadal Variability

Antonietta Capotondi of the University of Colorado delved more deeply into the mechanisms that could be driving low-frequency decadal shifts in tropical Pacific climate, ENSO characteristics, and PDV. Several mechanisms for this variability have been

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[2] In this context, a “pacemaker experiment” refers to specifying a certain variable (in this case tropical Pacific SST decadal variability) and allowing the free-running coupled model to respond.

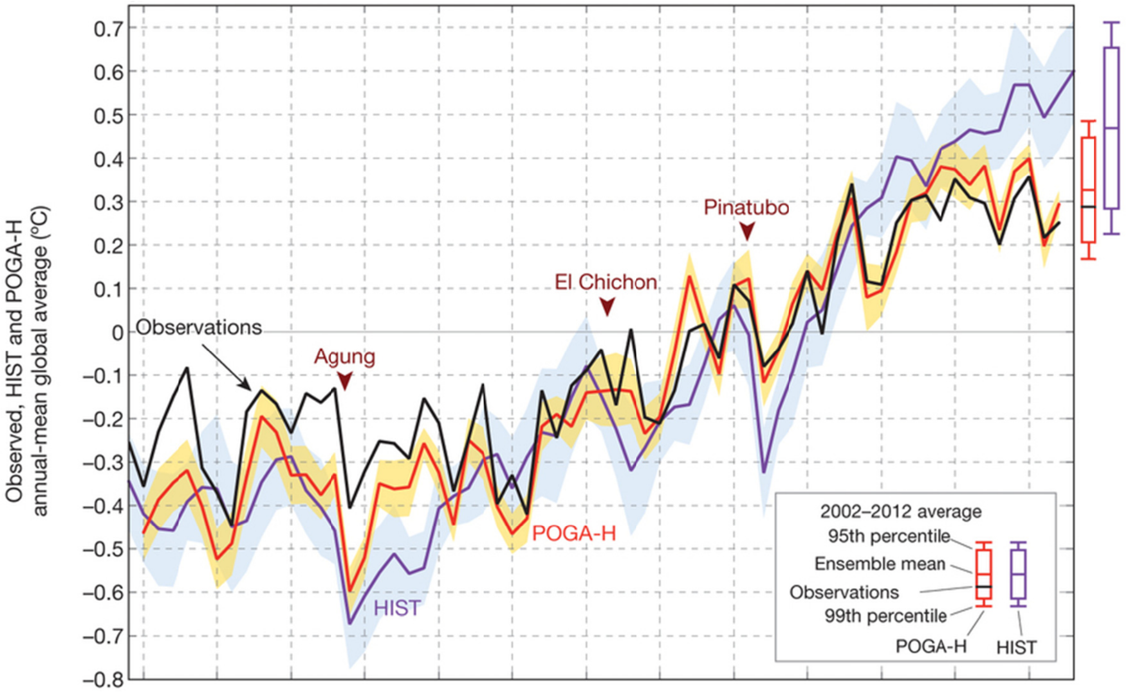

FIGURE 6 Observed and simulated global temperature trends (C). NOTES: Pacific Ocean-Global Atmosphere (POGA) pacemaker experiments show that model runs with imposed Pacific SST variability (red line) match observations (black line) much more closely than models without (purple line, free-running coupled model forced only with observed atmospheric composition changes and the solar cycle). Anomalies are deviations from 1980-1999 averages. Bars on the right show the ranges of ensemble spreads. SOURCE: Kosaka and Xie (2013).

proposed. One possible explanation relies on changes in the strength of the wind-driven upper-ocean overturning circulation known as Subtropical-Tropical Cells (STCs). The STCs are characterized by an equatorward subsurface flow, upwelling along the equator, and poleward flow in the thin surface Ekman layer[3]. Capotondi said that her own studies have shown that the changes in the strength of the STCs are associated with the adjustment of the equatorial thermocline[4] to changes in the surface winds (Capotondi et al., 2005).

Capotondi tried to answer the question of which winds were driving the process by studying the abrupt shift in the PDO (an index of PDV, see Box 4) and in the tropical Pacific climate that occurred in 1976-1977, the last time the PDO shifted from a cool to warm phase. Her comparison of wind stresses from the period 1960-1976 to the period 1977-1997 reveals that the biggest differences in wind stress between the two periods are found at 10 S and 13 N. At these latitudes, a large standard deviation of the pycnocline[5] depth is associated with enhanced Rossby wave[6] activity, which exhibits a pronounced decadal component (Capotondi and Alexander, 2001; Capotondi et al., 2003). Thus, tropical PDV

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[3] The Ekman layer is the layer in a fluid where flow results from a balance between pressure gradient, Coriolis and turbulent drag forces. For example, wind blowing North over the surface of water creates a surface stress and a resulting Ekman spiral is found below it.

[4] A thermocline is the transition layer between warmer mixed water at the ocean's surface and cooler deep water below.

[5] The pycnocline is a boundary layer in the ocean that separates water of differing densities due to temperature or salinity gradients.

[6] Rossby waves are a natural phenomenon in the ocean and atmosphere that owe their properties to Earth's rotation. Oceanic Rossby waves move along the thermocline.

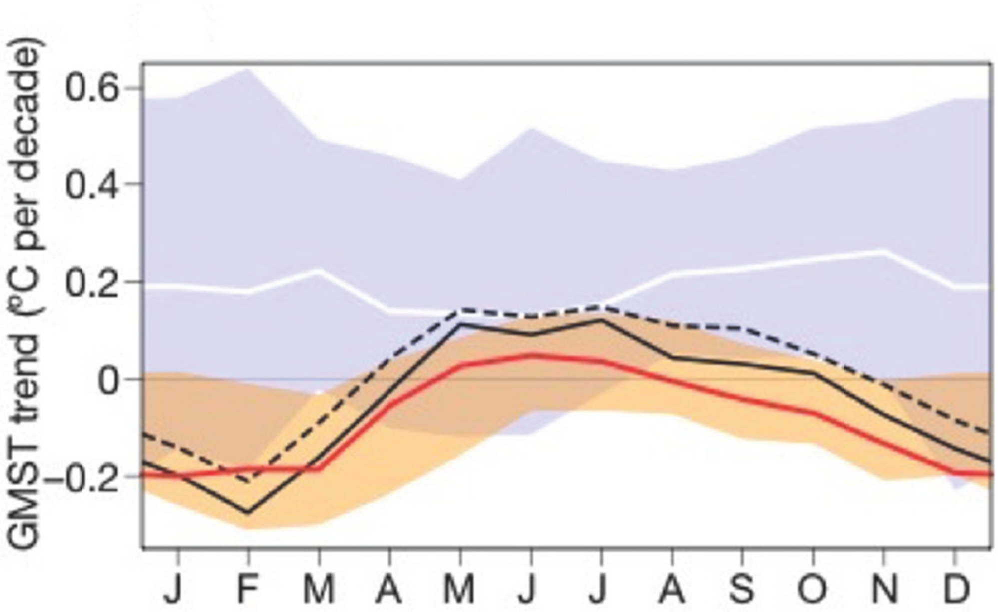

FIGURE 7 Trend of seasonal (3 months) mean GMST for 2002-2012. NOTES: Internal variability (negative IPO) dominates in winter (January-February-March), whereas external forcing (white line, based on the historical experiment extended by RCP4.5 scenario (HIST) dominates in summertime (May-June-July). Black solid curves are based on HadCRUT4 GMST (observations). Black dashed curves are based on Karl et al. (2015) GMST data. Red curves with orange shading are the tropical Pacific pacemaker experiment forced by HIST radiative forcing (POGA-H). SOURCE: Kosaka and Xie (2015).

may originate within the tropics and be communicated to the extra-tropics through atmospheric teleconnections via the STCs. However, it is not clear whether changes in equatorial SSTs could feed back into the anomalous tropical winds that drive the STCs, and provide a deterministic mechanism for these tropical decadal climate variations.

An important aspect of tropical PDV is the possible decadal modulation of the interannual ENSO phenomenon. Such decadal modulation may originate from, and/or cause, changes in the tropical Pacific mean state. A study of the changes in ENSO behavior after the 1976-1977 climate shift using Linear Inverse Modeling[7] shows that the null hypothesis that those changes are driven by climate noise cannot be rejected (Capotondi and Sardeshmukh, 2016). Thus, tropical PDV, as well as the PDO, may be driven by random system behavior and have limited predictability.

Yochanan Kushnir from Columbia University reminded the audience of the seminal work of Zhang et al. (1997) that discriminated between the patterns of PDV from that of the interannual variability of ENSO. He then discussed recent work by Newman et al. (2016) that suggests that PDV (in this case, the PDO) is likely not a single physical "mode" but rather the arbitrary sum of several different patterns that owe their existence to different dynamical processes. Newman et al. used LIM to separate the North Pacific SST variability

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[7] Linear Inverse Modeling (LIM) uses observations to extract the intrinsic linear dynamics that govern the climate. In a LIM model, representations of climate dynamics become more exact as the system becomes more chaotic, whether this chaos arises internally from turbulence or externally from unknown disturbances.

BOX 4

The 1976-1977 Climate Shift

During the 1976-1977 winter season, the atmosphere-ocean climate system over the North Pacific Ocean abruptly shifted. In the ocean, sea surface temperatures (SSTs) cooled in the central North Pacific Ocean and warmed off the coast of western North America, reflected in a shift toward the domination of the positive phase of the Pacific Decadal Oscillation (PDO) (see Figure). The decadal shift in the Pacific Ocean not only was accompanied by changes in the biota of the Pacific basin (Mantua et al., 1997), but also had widespread impacts on continental climate, making it ripe for further study. These impacts included a transition to warmer temperatures in the northwest United States, decreased storminess in the southeastern United States (Trenberth and Hurrell, 1994), and drought in the western United States (Cayan and Peterson, 1989; McCabe et al., 2004). Such impacts on people are another important motivation for studying PDV.

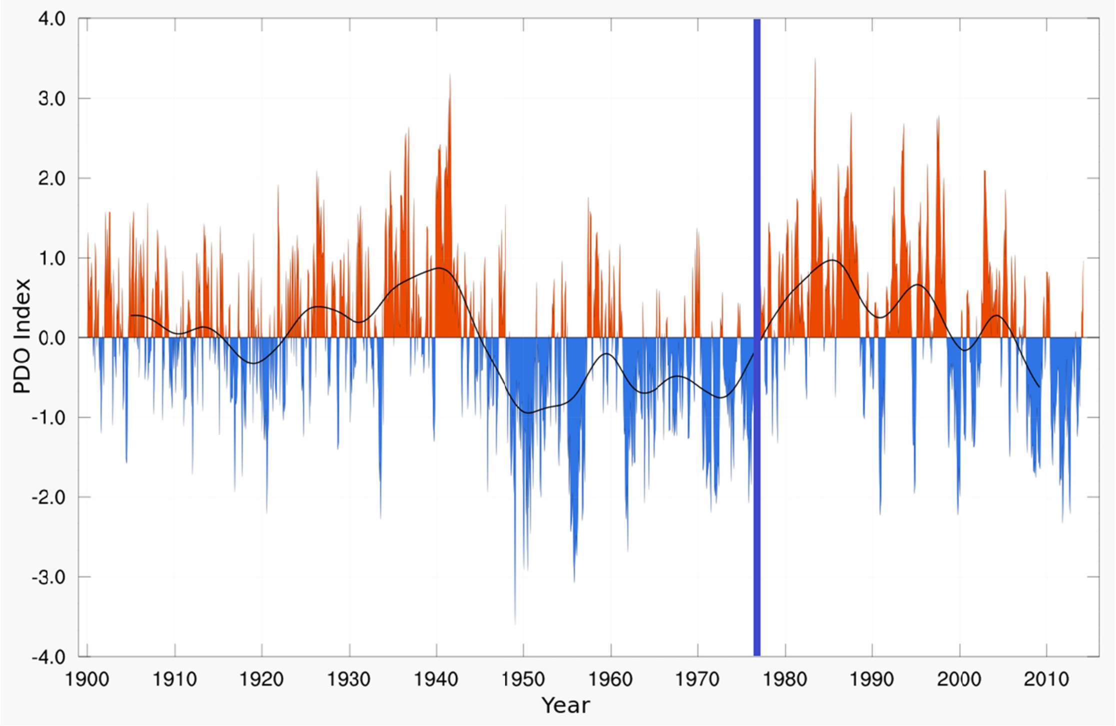

FIGURE PDO index from 1900 to 2015. NOTES: The 1976-1977 shift is indicated by the vertical blue bar, where there is an obvious phase shift from mostly blue/negative PDO index to mostly red/positive PDO index. SOURCE: Adapted from Antonietta Capotondi presentation, September 3, 2015.

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into three distinct basin-wide "dynamical modes," which closely resemble the leading rotated EOFs (Figure 8). When combining their observed historical intensity and phase relationship (Figure 9), they reproduce the historic record of the PDO.

Examination of the time series of these different patterns over the past century (Figure 9) reveals that they would combine to exhibit a decline in tropical SST at the time of recent GMST warming slowdown. According to Newman et al., the complexity of PDV poses challenges for predictability of the phenomenon, because models would have to achieve the difficult task of capturing the different components of PDV and their governing mechanisms. Similarly, this complexity will hamper representative reconstructions of the PDO using paleoclimate proxies unless the evolution of the different components is captured. Closing gaps in the understanding of these components would involve added observations of the ocean and atmosphere and would improve the ability of coupled models to capture the underlying processes and patterns.

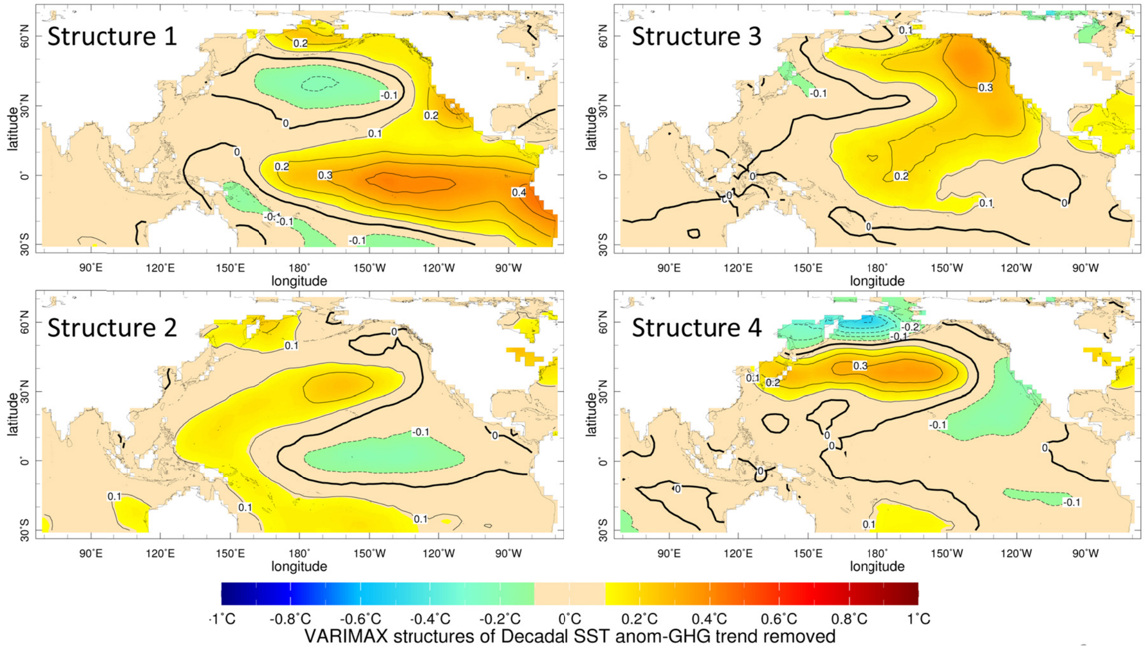

FIGURE 8 Rotated EOF analysis produces these four leading spatial patterns of PDV, which are closely related to the modes of the LIM analysis performed by Newman et al. (2016). SOURCE: Yochanan Kushnir presentation, September 3, 2015.

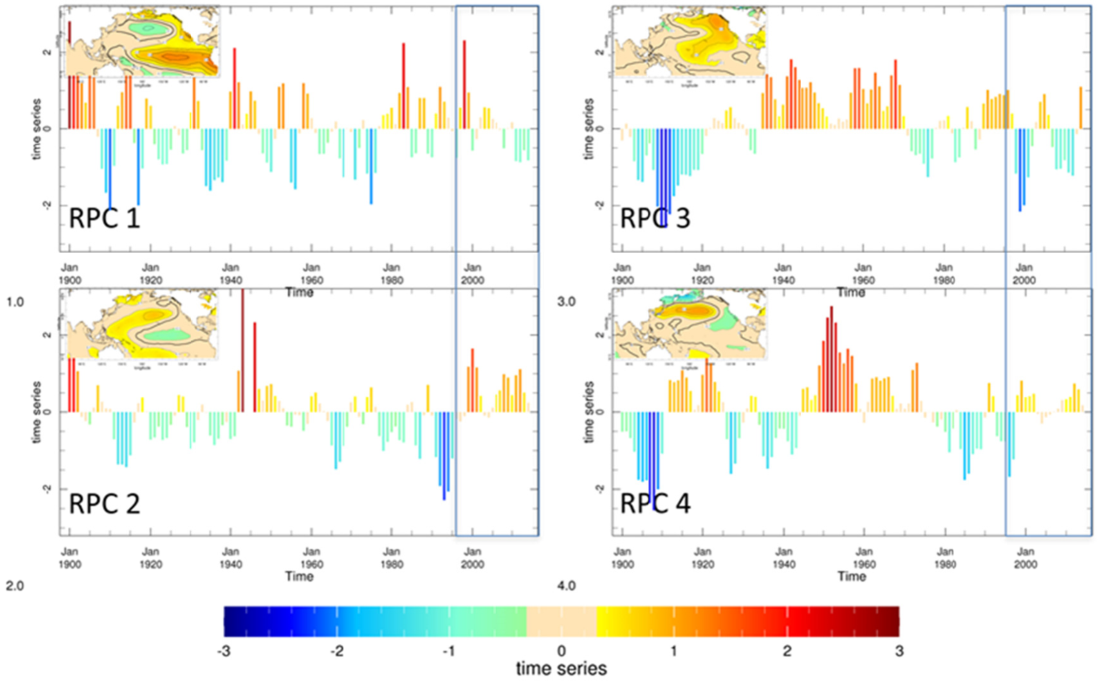

FIGURE 9 Time series of each rotated EOF shown in Figure 8. NOTES: Vertical blue line indicates the start of the slowdown period, where RPC1 and 2 are both positive and 3 and 4 are both negative. It is this specific combination of these components that describes the Pacific SST trend during the slowdown in GMST rise during this period. SOURCE: Yochanan Kushnir presentation, September 3, 2015.

Indian Ocean Variability

A number of studies reconciled the slowdown in GMST rise and the top of atmosphere (TOA)[8] radiation imbalance (which would indicate a warming planet) by an anomalous heat flux into the ocean (e. g., Meehl et al., 2011; Kosaka and Xie, 2013). Those studies indicate a substantial portion of the heat missing from the atmosphere is expected to be stored in the subsurface Pacific Ocean. Veronica Nieves introduced observational evidence of heat storage in the Indo-Pacific region and, to a lesser extent, in the Southern Ocean (Nieves, 2015), as discussed earlier in this chapter. Caroline Ummenhofer from the Woods Hole Oceanographic Institution presented complementary evidence that Indian Ocean variability plays an important role in global ocean heat content and has several important regional climate implications. The Indian Ocean has also been shown to have the strongest correlation between SSTs and GMST since 1900 as compared to other ocean basins (Figure 10, bottom).

Despite this correlation, the Indian Ocean, particularly the western Indian Ocean, has exhibited significant surface warming especially during the last 10 ten years of the recent slowdown (Roxy et al., 2014). This warming is inconsistent with changes in air-sea surface heat fluxes (Yu et al., 2007), suggesting that ocean dynamics play a role in redistributing heat in this region. For example, there is evidence that the subsurface warming in the Indian Ocean has compensated for cooling in the Pacific Ocean via increased heat transport from the Pacific Ocean to the Indian Ocean, carried by the Indonesian Through Flow (Lee et al., 2015; Nieves et al., 2015). As a result, the heat content of the Indian Ocean has increased abruptly (Figure 10, top), which accounts for greater than 70 percent of the global ocean heat gain in the upper 700 m during the past decade (Lee et al., 2015). Nieves et al. (2015) found that warming in the 100-300 m layer of the Indian and Pacific Oceans has compensated for cooling in the top 100 m layer of the Pacific Ocean since 2003. Ummenhofer explained that these recent trends, and the extensive subsurface cooling in the tropical Indian Ocean until the early 2000s, are likely related to multi-decadal variations in Pacific wind forcing (Ummenhofer et al., 2016).

Ummenhofer then discussed how decadal to multi-decadal changes in the upper-ocean properties in the Indian Ocean affect the frequency of Indian Ocean dipole events in different decades. The Indian Ocean dipole is the leading mode of variability in the Indian Ocean and influences regional climate (Figure 11), impacting rainfall and flooding in East Africa; the Indian monsoon and ENSO-Asian monsoon teleconnection; droughts and wildfires in Indonesia; and rainfall, droughts, and bushfires in Southeast Australia.

Decadal Variability in the Atlantic

Atlantic Multidecadal Variability (AMV, also known as the Atlantic Multidecadal Oscillation or AMO, see Box 3) is an index of the swings in the North Atlantic SSTs. The AMV is associated with significant climate impacts both regionally and globally, from northeast Brazilian and African Sahel rainfall (Folland et al., 1986, 2001; Rowell, 2003) to

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[8] Together with data derived from ocean heat content increases, radiometers on satellites are used to make TOA measurements of the amount of infrared energy leaving Earth's atmosphere. This amount is subtracted from the amount of solar radiation entering Earth's atmosphere to determine Earth's energy budget—that is, the energy that remains in Earth's climate system. For Earth's temperature to be stable over long periods of time, incoming and outgoing energy must be equal—a state referred to as radiative equilibrium or radiative balance. If more energy is leaving than entering, then Earth's climate will cool. If more energy is entering than leaving, then Earth's climate will warm. For more information, see Farmer and Cook (2013).

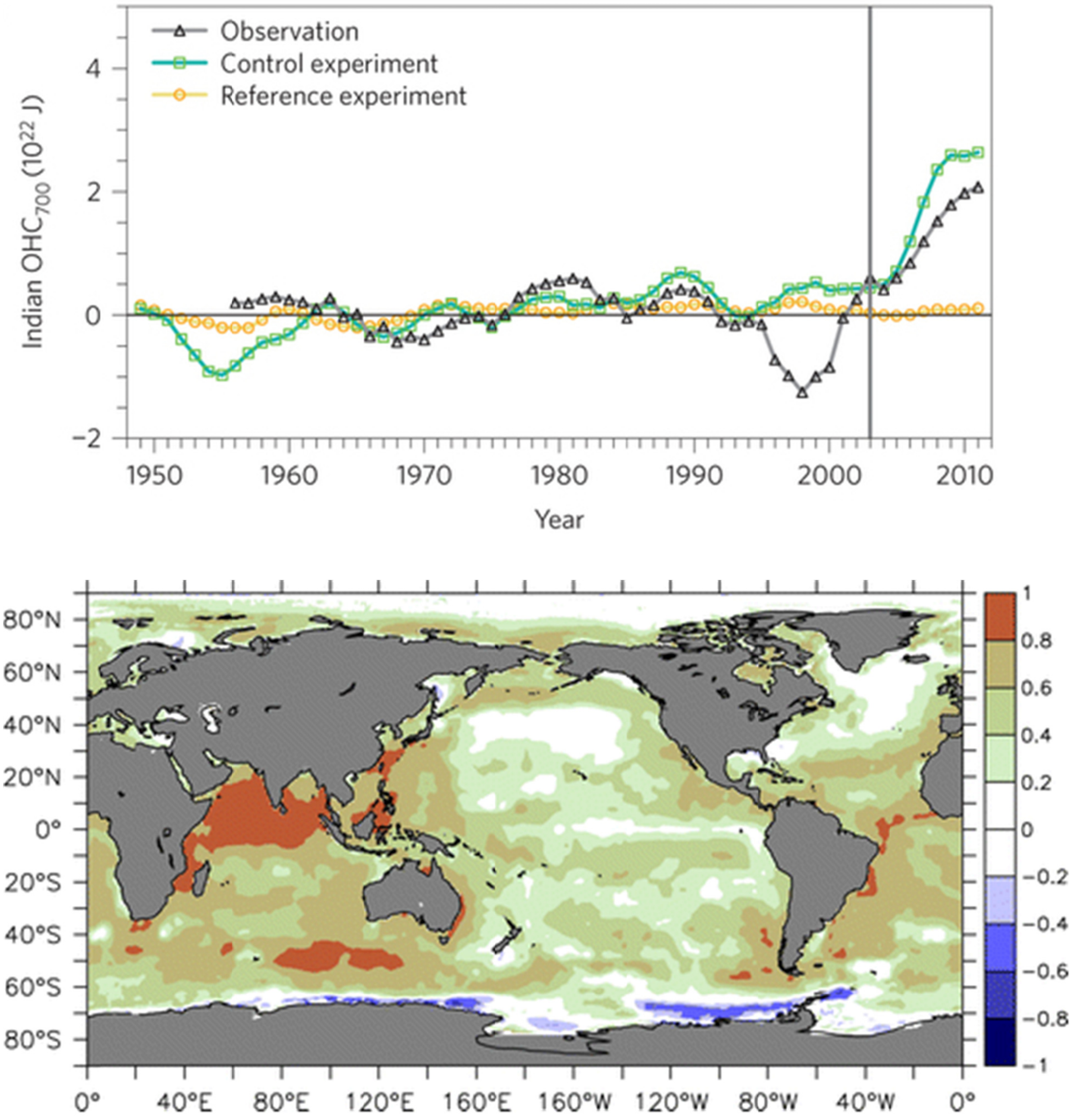
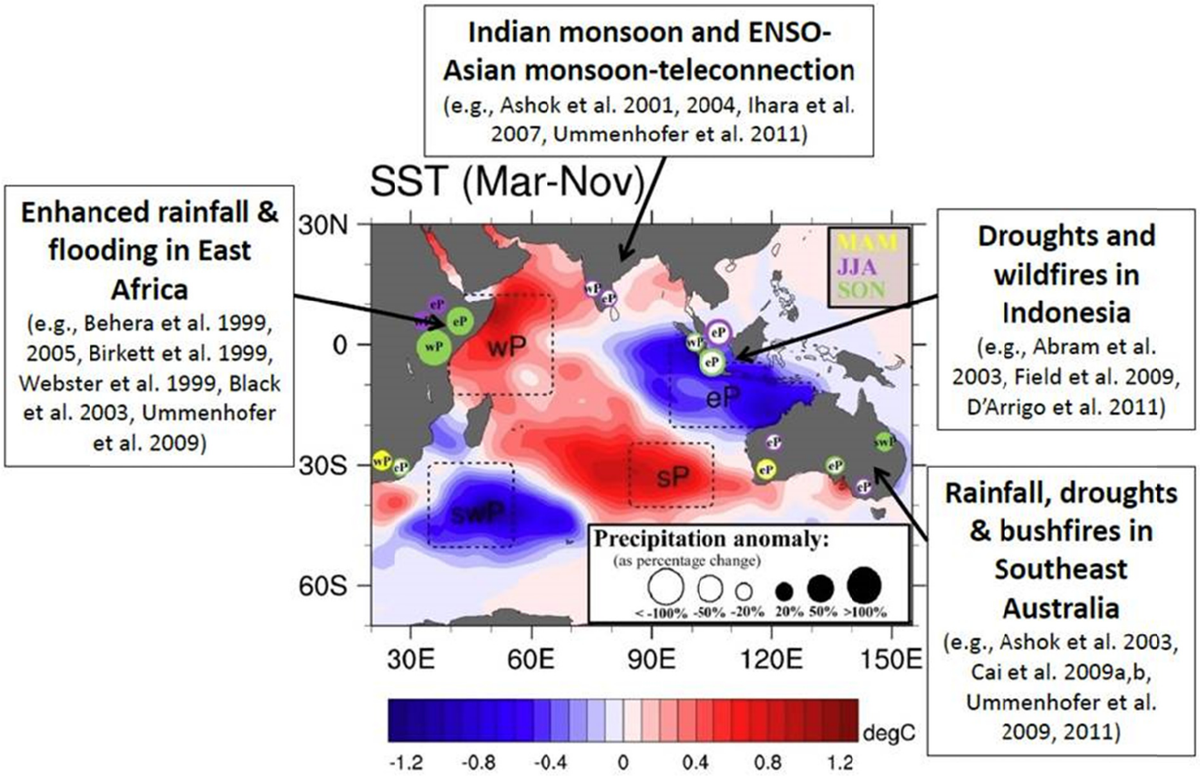


FIGURE 10 (Top) Indian Ocean heat content in the upper 700 m during 1950-2010. Indian Ocean heat content increased abruptly during the GMST slowdown period (in this case, 2003, after the vertical bar). (Bottom) Observed correlation between annual global mean SST and the annual SST at each grid, during 1901-2012. NOTE: The warming trend of SSTs over the Indian Ocean has been largely in phase with the overall trend in the GMST over the past century. SOURCE: (Top) Lee et al., 2015; (Bottom) Roxy et al., 2014.



Indian monsoon and ENSO-Asian monsoon-teleconnection
(e.g., Ashok et al. 2001, 2004, Ihara et al. 2007, Ummenhofer et al. 2011)

Enhanced rainfall & flooding in East Africa
(e.g., Behera et al. 1999, 2005, Birkett et al. 1999, Webster et al. 1999, Black et al. 2003, Ummenhofer et al. 2009)

Droughts and wildfires in Indonesia
(e.g., Abram et al. 2003, Field et al. 2009, D'Arrigo et al. 2011)

Rainfall, droughts & bushfires in Southeast Australia
(e.g., Ashok et al. 2003, Cai et al. 2009a,b, Ummenhofer et al. 2009, 2011)

FIGURE 11 Schematic depicting some of the regional impacts of Indian Ocean SST anomalies. NOTES: The SST anomalies (˚C) are shown as the average over the March-November months. Specific regions characteristic of various tropical and subtropical Indian Ocean dipoles are indicated by the dashed boxes. The anomalous rainfall associated with these regions of SST anomalies is shown by circles around the Indian Ocean rim countries. Filled (empty) circles denote an increase (decrease) in precipitation (as percentage change), with the size of the circle reflecting the magnitude of change and the color of the circle the season. SOURCE: Adapted from Ummenhofer (2010).

European and North American summer climate (Enfield et al., 2001; McCabe et al., 2004; Sutton and Hodson, 2005). Despite these important impacts, the mechanisms of the AMV are not well understood. Although many studies suggest that the AMV is associated with (or driven by) changes in the Atlantic Meridional Overturning Circulation[9] (AMOC)—a zonally integrated representation of Atlantic Ocean circulation (Folland et al., 1986; Gray et al., 1997; Delworth and Mann, 2000; Knight et al., 2005)—other studies suggest aerosols and intrinsic atmospheric variability as possible drivers of the AMV (e. g., Booth et al., 2012; Clement et al., 2015).

Many participants presented on the importance of Pacific variability as a driver for global trends, but there is also work to suggest that Atlantic variability can drive Pacific patterns (Ruprich-Robert, 2016). Other participants presented on mechanisms and drivers of Atlantic variability as well as teleconnections (atmospheric and ocean bridges) between the Atlantic and Pacific basins.

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[9] The Atlantic Meridional Overturning Circulation (AMOC) is a major circulation pattern in the Atlantic Ocean that involves the northward flow of warm, salty water in the upper/near-surface layers of the Atlantic Ocean to the North Atlantic and Nordic Seas, and the southward flow at depth of the cold, dense waters formed in those high-latitude regions.

Relationship of the AMOC and the NAO

Some modeling studies suggest that AMOC variability itself is driven by surface buoyancy fluxes associated with the NAO, which is primarily an atmospheric phenomenon that exhibits variability on many timescales, including on decadal timescales (see Box 3). Variability in the NAO has a strong influence on surface climate across the Atlantic basin and beyond (Thompson and Wallace, 2000). Tom Delworth from the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) and Gokhan Danabasoglu from NCAR discussed their work investigating AMOC variability and mechanisms, including related decadal and longer timescale climate variability in the Atlantic, and the role of decadal variability in the NAO.

Delworth highlighted the potential role of the NAO in driving AMOC variability. He presented modeling experiments in which he added heat fluxes to the North Atlantic Ocean associated with the positive phase of the NAO and then examined the resulting response of AMOC and the rest of the climate system (both regionally and globally). His results show that many impacts (e. g., temperature, sea ice extent, and vertical shear of the zonal wind) have larger amplitude at longer timescales because of the role of feedbacks and the time integral of transports. He then applied NAO forcing based on the observed NAO index and concluded that the AMOC response and associated climatic impact depend on the model's internal AMOC characteristics and mean state. Delworth also showed that models simulate NAO-induced AMOC changes over the historical record consistent with observations of various regions and phenomena: early 20th century warming, cooling in the 1960s-1970s, and warming in the 1980s-1990s of the Subpolar North Atlantic Ocean (70 W-0 W, 30 N-65 N); Arctic sea ice extent; tropical atmospheric circulation; and changes in the Southern Ocean. He concluded that NAO variability drives AMOC variability, particularly on multidecadal scales, although what generates NAO variability on these longer timescales remains unknown.

Because there are no long-term and continuous observations of AMOC and related variables, models remain essential tools for studies of AMOC variability and mechanisms. Danabasoglu presented a systematic assessment of the impacts of several ocean model parameter choices on AMOC characteristics in the Community Earth System Model (CESM, a fully coupled global climate model), with the primary goal of identifying robust and non-robust aspects of AMOC variability mechanisms. Danabasoglu changed some loosely constrained parameter values used in several ocean model subgrid-scale parameterizations, specifically: vertical mixing, submesoscale mixing, mesoscale mixing, and horizontal viscosity parameterizations. He also performed additional sensitivity experiments in which atmospheric initial conditions were perturbed to provide a baseline ensemble set for the parameter sensitivity experiments. He found that both the amplitude and timescale of AMOC variability differ considerably among the simulations, with the dominant timescale of variability ranging from decadal to centennial. Details of how the density anomalies that lead to AMOC changes are derived also differ.

Despite these differences, he noted several important, robust aspects of AMOC variability: (1) the Labrador Sea is the key region with upper-ocean density and boundary layer depth anomalies preceding AMOC anomalies; (2) enhanced Nordic Sea overflow transports do not lead to increased AMOC maximum transports; (3) after AMOC intensification, subsequent weakening is due to advection of positive temperature anomalies into the model's deep water formation region; and (4) persistent positive NAO anomalies play a significant role in setting up the density anomalies that lead to AMOC intensification via surface buoyancy fluxes.

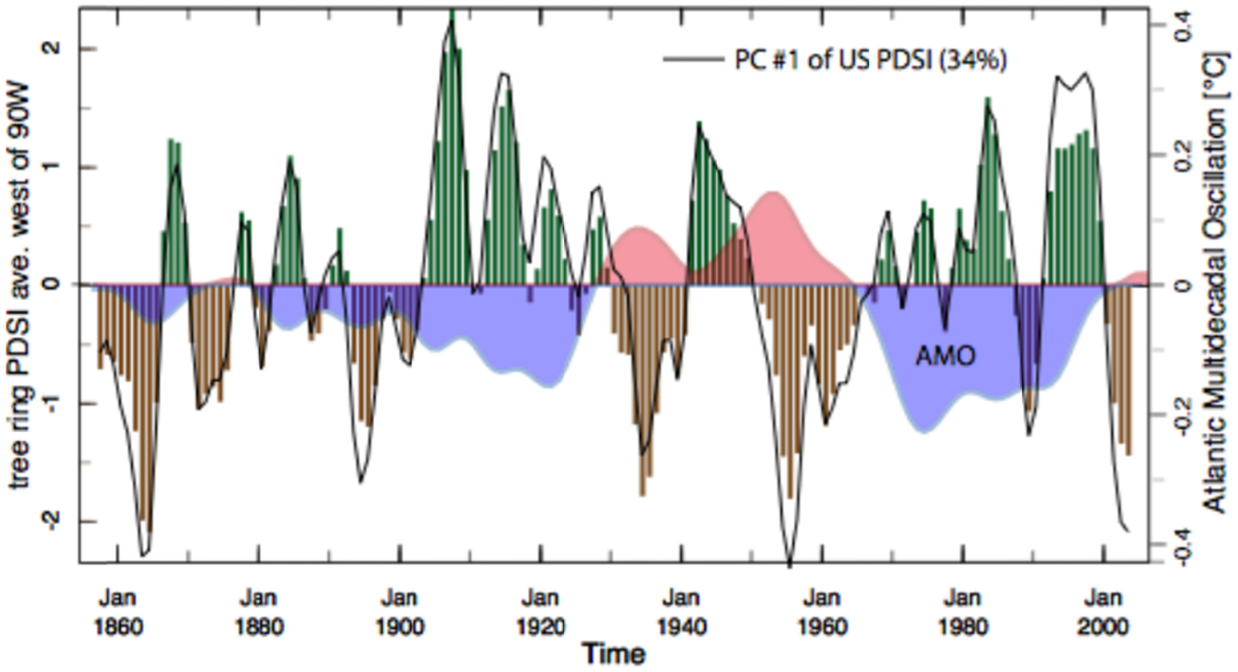

FIGURE 12 Long-term AMO records show a close relationship between AMO variability (purple [negative] and pink [positive] shaded regions) and the frequency and severity of droughts in the western United States as measured by the Palmer Drought Severity Index (PDSI; brown [negative] and green [positive] bars). SOURCE: Mingfang Ting presentation, September 3, 2015; PDSI data from Cook et al. (2004).

Effects of the AMV on U. S. Drought

The AMV has been shown to affect the frequency and severity of droughts across North America (Ting et al., 2011). The decadal oscillations in the hydroclimate of the western United States (associated with ENSO) reach extreme severity during the warm and neutral phases of the AMV. For example, the U. S. Great Plains and the Southwest experienced the extremely dry conditions of the Dust Bowl and the persistent Texas drought in the 1930s and the 1950s, respectively. Droughts were less frequent or severe when the AMV was in its cold phase in the early 1900s and from 1965 to 1995.

Mingfang Ting of the Lamont-Doherty Earth Observatory of Columbia University said that although the recent U. S. drought is clearly related to the negative phase of the IPO as well as to the global warming trend, the contribution of the AMV may actually be more significant and widespread than is commonly assumed. Longer-term records show a correlation between a negative AMO and positive Palmer Drought Severity Index (PDSI, a measure of drought) in the western United States (Figure 12).

Ting's work examines the interconnection between the tropical Pacific and tropical Atlantic on decadal timescales, which she said is crucial in realistically representing the hydroclimate impacts of the AMV on North America. She said that many models overestimate the ENSO association with the AMV. Her research shows that models more closely match the observed AMV-North American drought connection when the tropical Pacific SST anomalies associated with the AMV are smaller (< 0.5 degrees). Thus, the observed relationship between warm AMV and dry North America can be severely underestimated in models depending on how decadal tropical Atlantic SST anomalies are

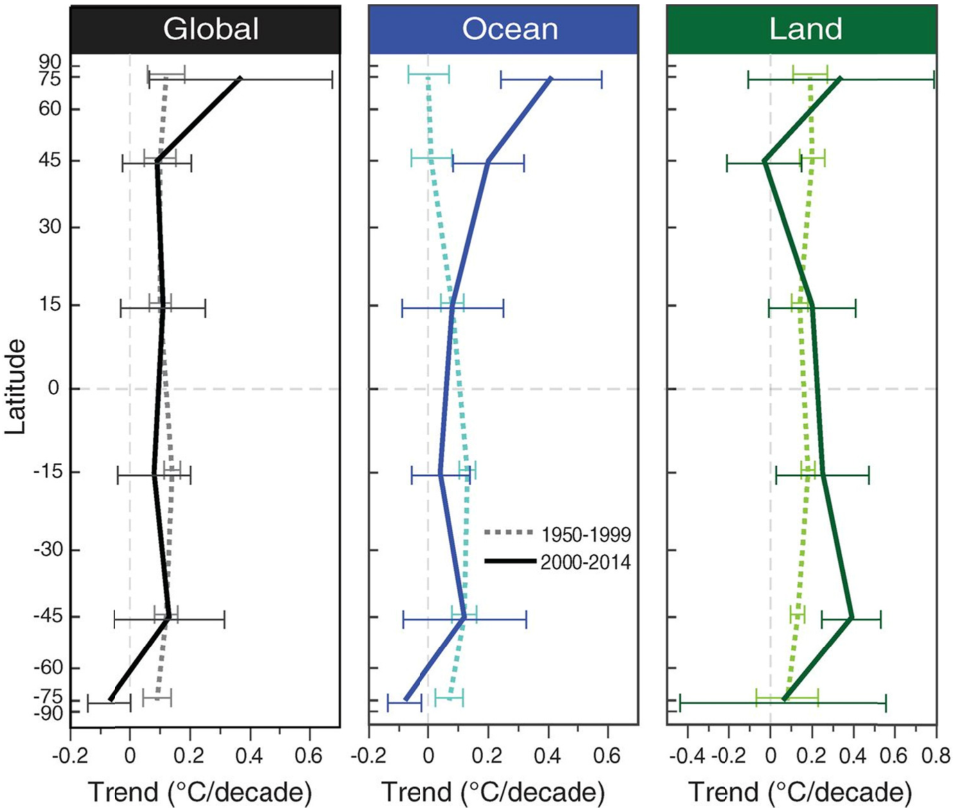

FIGURE 13 This figure shows latitudinal profiles of global, ocean, and land surface temperature trends, for the period 1950-1999 (dashed lines) and the past 15 years (2000-2014, solid lines), where the largest change occurred poleward of 45 N and least change occurred poleward of 45 S. SOURCE: Karl et al. (2015).

generated in CMIP5[10] models—whether the relationship is dominated by ENSO conditions in the tropical Pacific or subpolar North Atlantic SST anomalies. Ting said that removing the decadal ENSO impacts on the tropical Atlantic in models produced better agreement between models and observations in terms of atmospheric teleconnections.

Decadal Variability and the Poles

GMST also varies along latitudes on decadal timescales; in particular, there is a pronounced decadal pattern of amplified warming from 2000 to 2014 in the Arctic and slower warming in the Antarctic region (Figure 13). The trends in Antarctic temperature and other associated variables, including sea ice extent, have not been well captured by models, indicating that a better process-level understanding of mechanisms and drivers in that region is needed, according to some participants. In contrast, accelerated warming in the Arctic has been well modeled and observed, highlighting the importance of considering regional variation in surface temperature trends (and data availability with which to calculate trends) and associated regional implications in the context of decadal variability.

Regardless of any slowdown in a globally averaged warming trend, all parts of the Arctic have warmed, which was a topic discussed by James Overland from NOAA's Pacific Marine Environmental Laboratory. This warming is manifested in loss of snow and

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[10] Coupled Model Intercomparison Project (CMIP) phase 5.

approximately 70 percent of sea ice volume over the past century, and does not seem to be associated with any one mode of internal variability.

The warming trend in the Arctic may have an impact on mid-latitude weather and climate variability, but these connections are still controversial (NRC, 2014). The length of the available data series is too short and weather is too chaotic to make a definitive link, said Overland. However, it is understood that as the Arctic warms more quickly, the temperature gradient between the Arctic and the equator is reduced. Overland also said that most researchers think that warming overall will dominate weather patterns, but there will be specific episodic and regional impacts from Arctic warming. Overland showed, as an example of regional impacts, that loss of sea ice in the Kara Sea will weaken winds across East Asia, leading to a strong Siberian High, pushing storms into Japan and China. For more examples, see NRC (2014).

Although the Arctic has been warming and sea ice disappearing, the Southern Ocean has been (mainly) cooling and sea-ice extent has been growing slightly overall. John Marshall, from the Massachusetts Institute of Technology, examined the causes behind such geographic variability and argued that inter-hemispheric asymmetries in the mean ocean circulation (with sinking in the northern North Atlantic and upwelling around Antarctica) strongly influence the SST response to anthropogenic forcing. These asymmetries accelerate warming in the Arctic while delaying it in the Antarctic region. Additionally, while the amplitude of forcing from GHG emissions has been similar at the poles, significant ozone depletion only occurs over Antarctica, he explained.

The initial response of SSTs around Antarctica to ozone-related changes in surface wind trends is cooling, because the Ekman-driven flow in the ocean associated with strengthening westerly winds[11] drives cold water equatorward, away from Antarctica. This has potentially influenced the modest increases in sea-ice extents in the Southern Ocean. However, on longer timescales, ozone-induced changes in circulation patterns should result in warmer water being drawn up from below, resulting in warming of SSTs and likely sea-ice decline, explained Marshall.

The transition from SST cooling to warming is model dependent. Marshall used models to examine the effects of a step change in wind forcing. He explained that initially models all show cooling, but they respond in different ways over time (Figure 14). A fast response to a wind perturbation (equatorward transport of cooler water) led to cooling, while a slow response led to the upwelling of warmer water and overall warming, which would explain why some models show warming and some show cooling in the region on longer timescales.

What, then, is the mechanism that sets the crossover timescale from cooling to warming? As the wind blows water away from Antarctica, there is a cooling response. However, there is still warm water at depth, so by strengthening the wind, this water comes up from depth to eventually melt the ice, proposed Marshall. The stratification in the Southern Ocean in the seasonal ice zone is set by salinity, being fresh and cold at the surface, warm and salty below. Realistic vertical and horizontal temperature and salinity profiles in the region of seasonal sea-ice are very difficult to capture in models, which could explain why the models display differing behavior. Moreover, the temperature and salinity distributions are not well observed, which highlights the importance of sustaining subsurface observations in the seasonal ice zone, such as the Southern Ocean under-ice Argo program, Marshall concluded.

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[11] Winds from the west toward the east in the mid-latitudes (between 30 and 60 degrees).

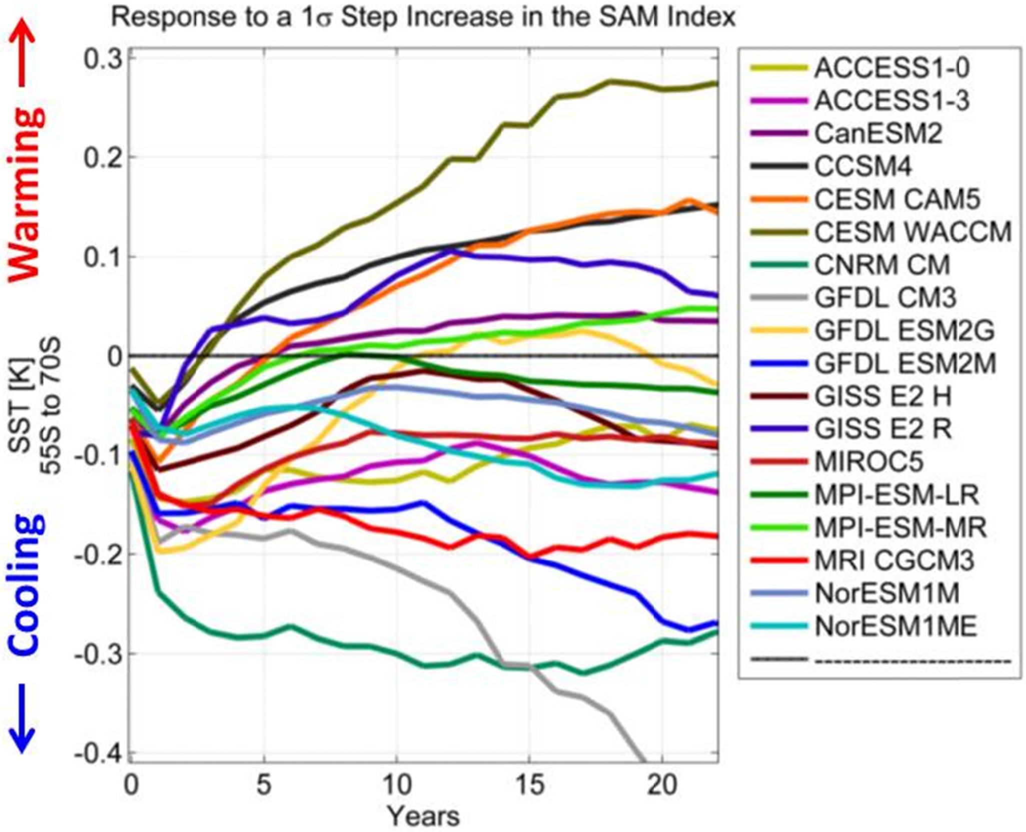

FIGURE 14 Different models respond differently to a step increase in the SAM (Southern Annular Mode) Index, which is related to the circumpolar winds in the Southern Hemisphere. NOTE: Their different responses affect the time in which (and whether or not they do) have a SST that crosses over from cooling (below the y=0) to warming (positive y values). Modified from Kostov et al. (2016). SOURCE: Adapted from John Marshall presentation, September 4, 2015.

In summary, basic principles of ocean circulation suggest that one would expect an asymmetric polar response in a warming climate, with accelerated warming in the Arctic and delayed warming in the Antarctic region. In addition, wind-driven changes around Antarctica, due to ozone depletion or natural variability, could account for recent cooling and recent sea-ice expansion, Marshall said. Inter-model differences in the Southern Ocean's response to wind may be related to different background stratification in the seasonal ice zone. The poles are also not well represented in earlier datasets used for calculating GMST, suggesting that, particularly for the Arctic, GMST trend calculations may be underestimated. Updates in the Karl et al. (2015) analysis include improvements in the representation of the existing Arctic dataset. For further discussion of data needs, see Overcoming Data Limitations.

The Role of External Forcing

Changes in external forcing, which can push Earth toward warming or cooling, could also be affecting recent GMST trends. It is well established that the long-term warming trend in the climate is caused mainly by increasing atmospheric concentration of human-caused greenhouse gases (GHGs). In addition, the rate of warming is affected by stratospheric aerosols produced from volcanic eruptions and manmade pollution, stratospheric ozone, tropospheric aerosols, solar irradiance, and water vapor content in the atmosphere (Schmidt et al., 2014). In considering the potential contribution of changes in external forcing to the slowdown, some participants made the point that global ocean heat content does not reveal an obvious slowdown in the warming trend in the past decade. If one considers ocean warming as a proxy for radiation imbalance, then the continued warming suggests that the amount of radiative imbalance at the top of the atmosphere may have remained unchanged between the 1990s and the 2000s, arguing against a significant effect of changes in external forcings on GMST.

Susan Solomon from the Massachusetts Institute of Technology provided a brief survey of radiative forcing changes during 2000-2014 that might have contributed to the decadal rates of global surface warming. Solomon compared Earth's radiative budget over the long term (1750-2009) to the short term (1999-2009) to show the differences in contributions from various sources (see Figure 15). She said that there is much more confidence now in measures of volcanic forcing. In contrast, there is high uncertainty in the data on tropospheric aerosols, and stratospheric H_2O may be a feedback that is not accurately represented in models.

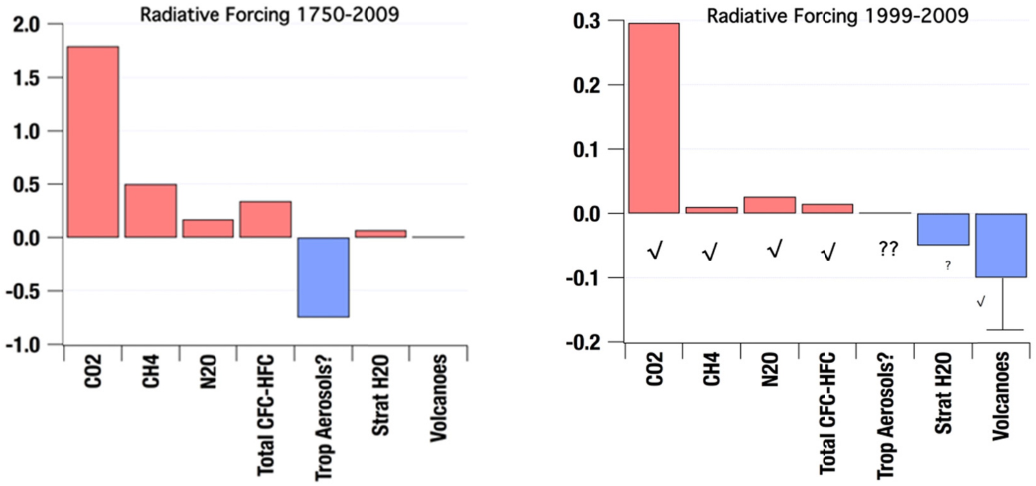

FIGURE 15 Sources of radiative forcing for 1750-2009 (left) and 1999-2009 (right). NOTES: In the recent period, observations from multiple sources show that volcanoes have had a larger contribution than is represented in the models (e. g., in CMIP5). Tropospheric aerosols are less well known (indicated by question marks); uncertainty in stratospheric water vapor is due in part to potential feedbacks not represented in models (small question mark) for the 1999-2009 period. Solar forcing may also contribute. SOURCES: (Left) IPCC (2007, 2013); (Right) http://www.esrl.noaa.gov/gmd/aggi/aggi.html; Solomon et al. (2010, 2011); Ridley et al. (2014); Gilford et al. (2016).

Volcanic eruptions may have significantly contributed to recent variability. Satellite data that were not available prior to the early 2000s show the influence of a series of eruptions after 2005 (Solomon et al., 2011; Ridley et al., 2014). A significant cooling (a few tenths of a degree) of tropical SSTs after the Nabro volcanic eruption in 2011 suggests a forced component to observed tropical sea surface temperature (SST) cooling (Santer et al., 2015).

Effects of Volcanic Eruptions on Climate

Large volcanic eruptions can inject columns of sulfur-rich gases into the troposphere and stratosphere, and clouds of these gases can circle the globe within weeks of the volcanic activity. The ash particles from the eruptions tend to be large enough to fall out quickly, but the sulfurous gases form highly reflective acidic aerosols that can have an even larger and long-lasting cooling effect on the surface than the volcanic ash. For more, see Robock (2000).

Solomon highlighted several reasons why the forcing from volcanic eruptions might be underestimated in models. Her own study of the optical depth of aerosols (a measure of the amount of light lost due to the presence of aerosols) concluded that the optical depth value post-2000 never reached zero, indicating that some aerosols were always present (Solomon et al., 2011). However, volcanic aerosols were set too low in Coupled Model Intercomparison Project Phase 5 (CMIP5) models, according to Solomon, which amounted to a net positive forcing in the models. Inclusion of more realistic forcing from background aerosols in the models has been shown to account for up to one-third of the recent GMST slowdown trend, or 0.05 C (Solomon et al., 2011).

In addition, recent work by Ridley et al. (2014) showed that satellite data do not measure the area between 15 km and the tropopause over the extratropics where a significant amount of volcanic material resides—as much as three times as what has been observed above that region by satellites. Thus, if LIDAR[1] data and weather balloons were used to fill in the data in that region, aerosol values would increase significantly (Ridley et al., 2014). Promising new methods have been developed to study the tropopause, which has also been difficult to observe. However a systematic plan to improve observations there is needed, said Solomon.

Stratospheric water vapor also could be playing a large role in GMST variability, according to Solomon. Limited data before the mid-1990s suggest that stratospheric water vapor increased up to 2000, which could be an important factor in the accelerated warming from 1980 to 2000 (Forster and Shine, 1999). Stratospheric water vapor significantly dropped after 2000 and stayed low through much of the 2000s (Figure 16). Average forcing for 2005-2014 from observed stratospheric water vapor changes has been estimated at -0.04 W/m^2 (Gilford et al., 2015), which might represent as much as 25 percent of the total forcing from all factors during that time, according to Solomon.

Regarding solar forcing, Solomon said that a symmetric cyclic forcing has little or no net effect on Earth's energy budget. However, from 2000 to 2012, solar forcing was not a symmetric cycle. Hansen et al. (2011) estimated that there was about -0.1 W/m^2 from solar forcing over that period. The solar drivers in the CMIP5 simulations were overestimated because the last solar-cycle minimum was lower and the present weak solar cycle started later than assumed at the time, which may have contributed to the models' projection of warming (Schmidt et al., 2014).

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[1] Light Detection and Ranging (LIDAR) is a surveying technology that measures distance using laser light.

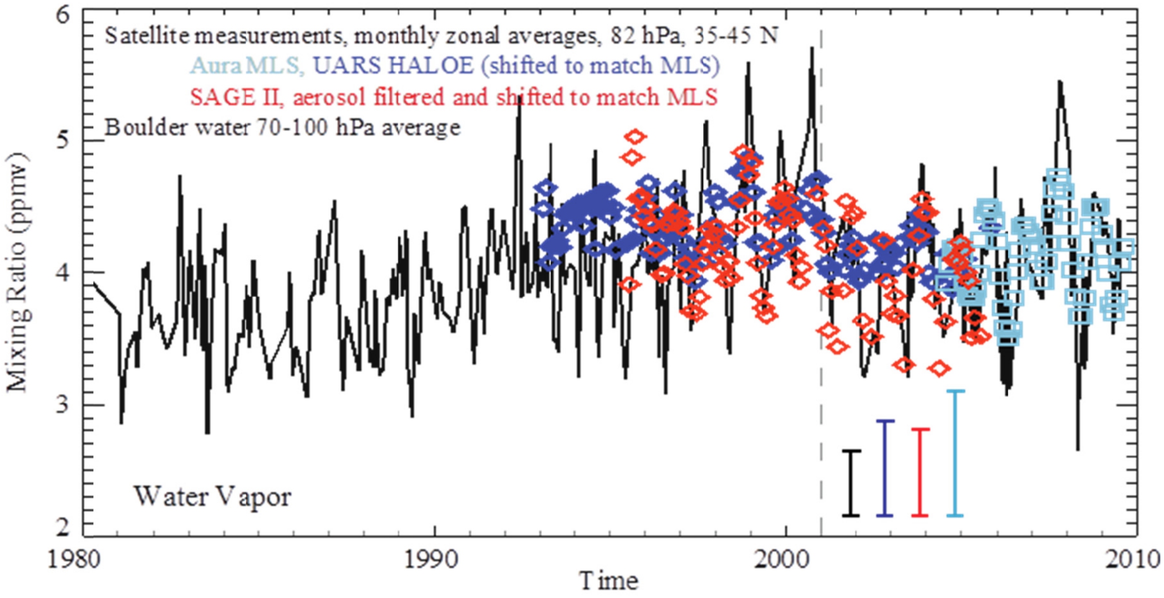

FIGURE 16 Limited data before the mid-1990s suggests that stratospheric water vapor increased up to 2000, which could be an important factor in the accelerated warming from 1980 to 2000 (Forster and Shine, 1999). NOTES: Increased measurements are included from Aura MLS (turquoise squares), UARS HALOE (blue diamonds), and SAGE II (red diamonds) instruments. After 2000 (vertical dotted bar), stratospheric water vapor significantly dropped and stayed low through much of the 2000s. SOURCE: Solomon et al. (2010).

Overcoming Data Limitations

Understanding of decadal climate variability is limited by the relatively short length of many climate records, meaning that only a few decadal cycles may be recorded (NRC, 1995). Limited spatial coverage also presents a challenge in that many parameters and processes are not fully characterized with available observations. Several participants discussed their work filling in observational records that can inform understanding of decadal variability.

Gaining Insight from Paleoclimate Data

The study of natural climate variability, in particular to meet the need to separate out human-induced climate effects, requires studying climate variability of the past, before humans played a role. Information about past climate conditions is contained in historical records and “proxy” indicators, such as polar ice caps, tree rings, and corals.

Decadal variations in zonal wind strength can play a role in internal climate variability and consequently the rate of global temperature rise. However, past observations of wind strength and direction for the Pacific Ocean are very sparse, said Diane Thompson from Boston University, who studies coral records to help fill in the gaps in information. Her studies have focused on the period 1910-1939, when about one-third of the 20th century GMST warming occurred despite weak external forcing, suggesting that an important role by internal variability. However, there are very few wind observations for this early 20th-century warming period with which to test the role of tropical Pacific winds in this warming.

Thompson studies corals that grew just outside of a westerly facing lagoon on Tarawa, an atoll in the central Pacific Ocean. Because the lagoon is shielded from the prevailing easterly trade winds, trace metals, particularly manganese, accumulate there gradually over time. Westerly winds associated with the onset of El Niño events produce wave action that releases manganese from the enriched lagoonal sediments, which is then incorporated into coral skeletons. The coral skeletons also record the warming and freshening (due to increased rainfall) that the resulting El Niño event brings to the island.

Thompson presented a new coral record from 1890 to 2010 showing that ENSO-related westerly winds are associated with spikes in manganese (Figure 17; Thompson et al., 2015). These spikes of manganese in the coral skeleton (and thus bursts of winds from the west) were more frequent during the early 20th-century period of rapid warming and less frequent when warming leveled off in the mid-20th century. Thompson said that this wind reconstruction corroborates and extends the idea that periods of strong Pacific (easterly) trade winds (and less frequent pulses of westerly winds) are associated with cooler equatorial Pacific surface temperature and a slower rate of global warming. Conversely, periods of weaker trade winds (and more frequent pulses of westerly winds) are associated with warmer equatorial Pacific surface temperature and a faster rate of global warming. Thompson is conducting the same study in other equatorial atolls with westerly facing lagoons to replicate and extend this record and reconstruct past trade wind variability across the western tropical Pacific.

Kim Cobb from Georgia Tech presented work using oxygen isotopes in corals to reconstruct tropical Pacific SST, precipitation, and salinity over the past 1,000 years. Cobb compared the coral records to the evolution of 20th-century Pacific Decadal Variability (PDV) to help separate natural variability from potential human-caused trends in Pacific climate. Cobb

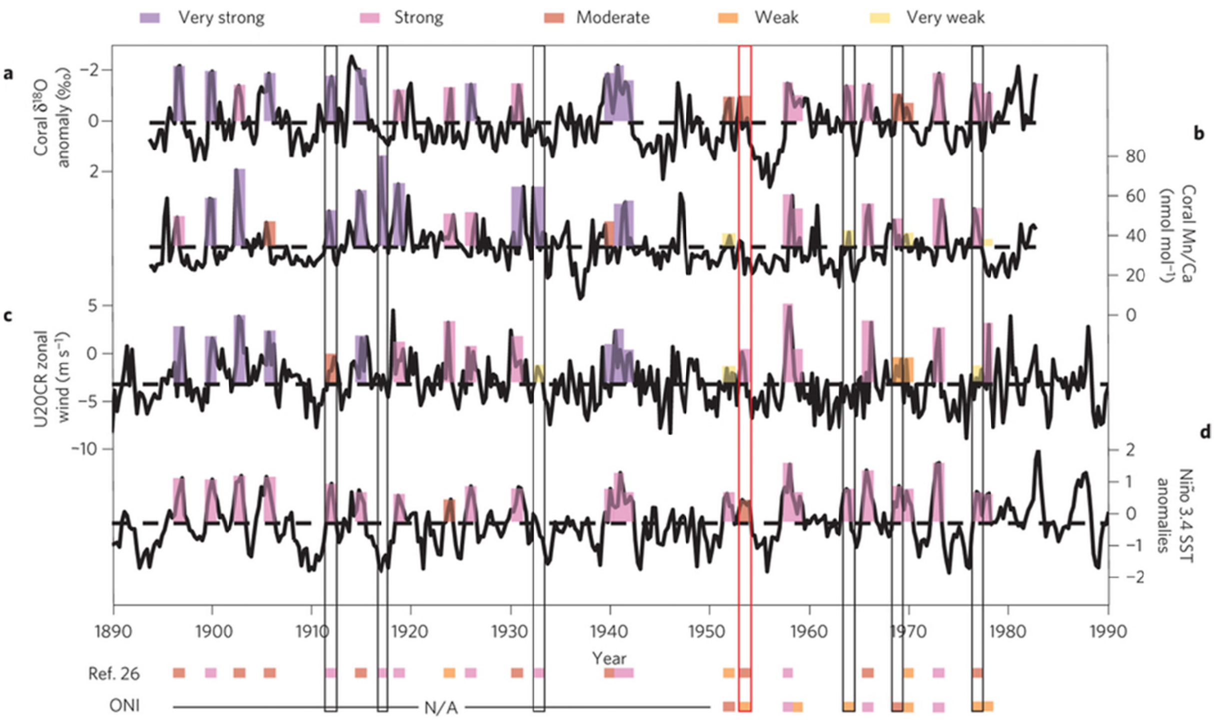

FIGURE 17 Westerly winds associated with El Niño events (4th row = NINO3 index; 3rd row = ensemble mean zonal winds from the 20th-century reanalysis [20CR]) are correlated with spikes in coral Mn/Ca (2nd row) and also spikes in coral delta 18 oxygen (δ^{18}O, 1st row), indicating fresher (less salty) and warmer water associated with El Niño conditions at Tarawa. SOURCE: Thompson et al. (2015).

conducts her research in the middle of the tropical Pacific on Palmyra, Fanning, and Christmas Islands, which she notes are very well positioned for study of the history of the PDV and other decadal climate phenomena (Figure 18).

The oxygen isotopic composition (δ^{18}O) of skeletal aragonite in reef-building corals is a well-established proxy for reconstructing tropical SST and hydrological variability. Coral δ^{18}O is inversely proportional to temperature and positively correlated to ocean salinity. Lower coral δ^{18}O values reflect warmer and/or wetter conditions, while higher coral δ^{18}O values reflect cooler and/or drier conditions (e. g., Corrège, 2006). Cobb said coral δ^{18}O records from the Northern Line Islands provide 10-20 points per year of information—equivalent to monthly resolution records that can be directly compared to monthly-resolved instrumental climate records and climate model output. A suite of coral δ^{18}O records from the Northern Line Islands is interchangeable with SSTs from these sites over the past several decades (Figure 19). Moreover, coral δ^{18}O records from samples thrown up onto beaches across the Northern Line Islands—referred to as “fossil” corals—are interchangeable with those derived from coral cores drilled from living coral colonies (Figure 19). By combining living coral and fossil coral archives from across the Northern Line Islands, Cobb has amassed more than six centuries worth of monthly-resolved climate reconstructions from the central tropical Pacific that span various intervals of the last millennium (Figure 20).

The existing Line Islands coral δ^{18}O reconstruction shows a late 20th-century trend toward warmer and/or fresher conditions in the central tropical Pacific that may be associated with the rise of atmospheric GHGs. However, the relative contributions of warming versus

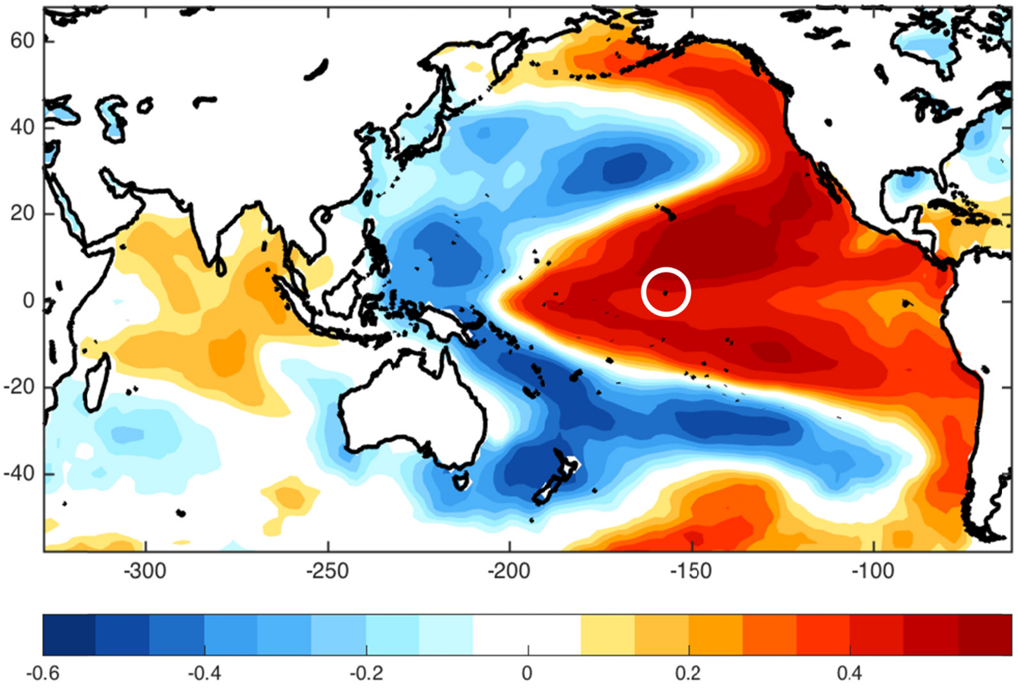

FIGURE 18 Map showing location of the Northern Line Islands (circled), including Palmyra (6N, 162W), Fanning (4N, 160W), and Christmas Island (2N, 157W) with respect to a regression map of Pacific SST variability. Figure modified after Di Lorenzo et al. (2015). NOTE: Coral oxygen isotopic records from the Northern Line Islands capture natural and anthropogenic decadal-scale variability (i. e., Cobb et al., 2001; Nurhati et al., 2009, 2011). SOURCE: Adapted from Kim Cobb presentation, September 3, 2015.

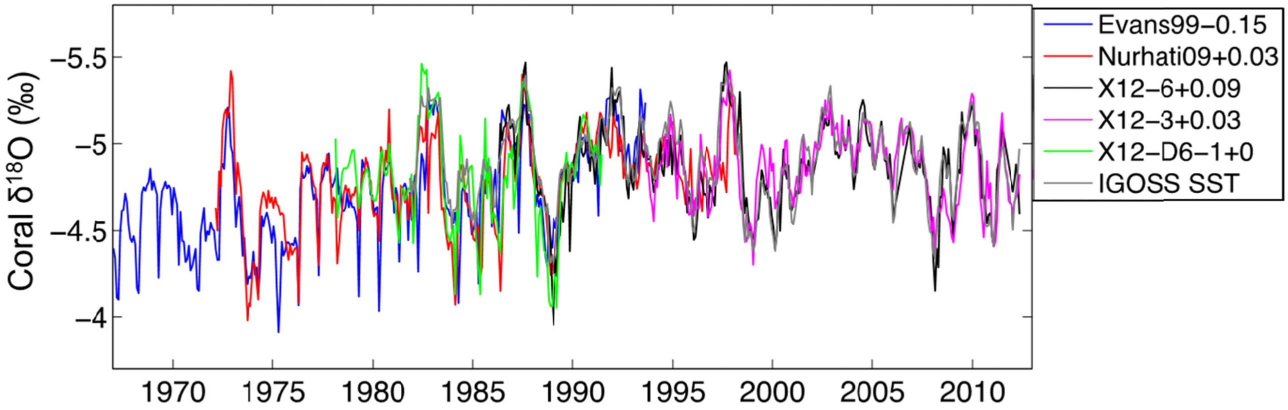

FIGURE 19 Modern coral $\delta^{18}O$ records from Christmas Island track very closely to SSTs (in black) and also to fossil coral $\delta^{18}O$ records (in green). NOTES: Comparison of monthly-resolved coral $\delta^{18}O$ records from Christmas Island (2N, 157W) with monthly instrumental SST from the gridbox containing Christmas Island (IGOSS; Reynolds et al., 2002). Records plotted include Evans et al. (1999) (blue) and Nurhati et al. (2009) (red), as well as unpublished data from the Cobb lab (Grothe et al., 2016). All coral records were drilled from living coral colonies, except for X12-D6 (green), which represents a U/Th-dated "fossil" coral. Offsets that were applied to each of the coral $\delta^{18}O$ records prior to plotting are referenced in the figure legend, in units of per mil. SOURCE: Kim Cobb presentation, September 3, 2015.

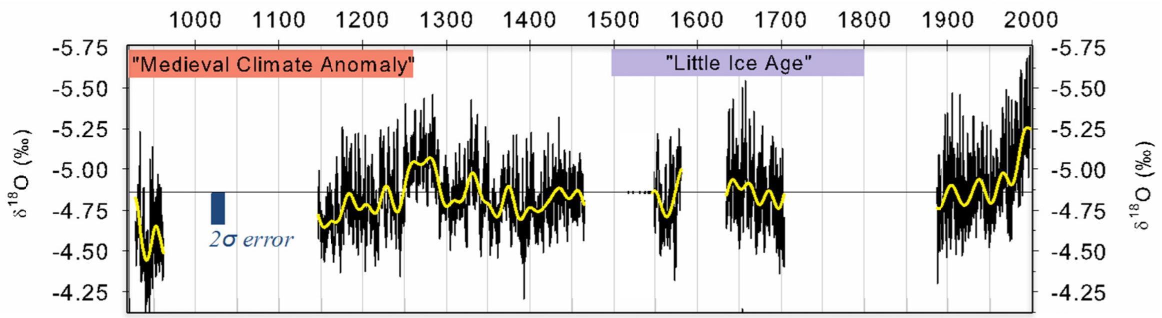

FIGURE 20 Delta 18 oxygen isotope reconstruction pre-1000 to 2000. Cobb's "temperature reconstruction" so far clearly shows the later 20th-century trend toward lighter oxygen isotopes, indicating warmer and fresher ocean surface water conditions. NOTES: Monthly-resolved coral oxygen isotopic ($\delta^{18}O$) records (black) from Palmyra Island (6N, 162W) spanning from 930 to 1998 AD, discontinuously, shown with a 10-year running average (yellow line). All data prior to 1886 originate from so-called "fossil" corals collected on ocean-facing beaches, subsequently dated by U/Th techniques (Cobb et al., 2003a). Data from 1886 to 1998 are derived from a living coral colony (Cobb et al., 2001); all other data are fossil coral data presented in Cobb et al. (2003b) and Dee et al. (in preparation). The rough time intervals of the so-called "Medieval Climate Anomaly" and the "Little Ice Age" are also shown, together with a vertical blue bar indicating the 2sigma uncertainty associated with single coral records (see spread of offsets denoted in legend for Figure 19)—in this plot only applicable to the 930-960 AD and 1550-1580 AD intervals. All other intervals are constrained by 3-8 overlapping coral records. SOURCE: Kim Cobb presentation, September 3, 2015.

freshening in driving the observed coral $\delta^{18}O$ trend is a key question with important implications for the detection and attribution of climate changes in this area.

Cobb advocated for the continued development of additional long, high-resolution coral reconstructions from other islands in the region (i. e., nearby Christmas Island) to constrain the natural vs. anthropogenic contributions to recent trends from across the Pacific. Recognizing that most of these high-quality, high-resolution climate reconstructions will be based on the isotopic variability of water isotopes (i. e., corals, cave stalagmites, lake records, marine sediments), Cobb underscored an urgent need to understand how seawater and rainwater $\delta^{18}O$ vary in the Pacific through both space and time, because that variability is translated directly into geologic proxies of climate variability. New research focused on bringing new empirical constraints from observational evidence of the modern system is a promising way forward, in addition to the continued investigation of water isotope-equipped simulations of past and future climate variability. The vast trove of high-quality paleoclimate records represents the best way of extending back the instrumental record of climate long enough to characterize the spatio-temporal patterns of natural decadal-scale variability, and how they differ from those signals related to anthropogenic climate change, according to Cobb.

Integrating Land Datasets, including the Arctic

The Karl et al. (2015) result that NOAA NCEI's Huai-Min Zhang presented (see section on Challenges in Examining Climate Trends) highlights the importance of data homogenization and bias correction in observed SSTs. Matt Menne, also of NOAA NCEI, described some of the issues encountered in NOAA's efforts to improve land surface station temperature data known as the International Surface Temperature Initiative (ISTI). These data are being used to produce a new NOAA analysis of land surface air temperature since the late 19th century.

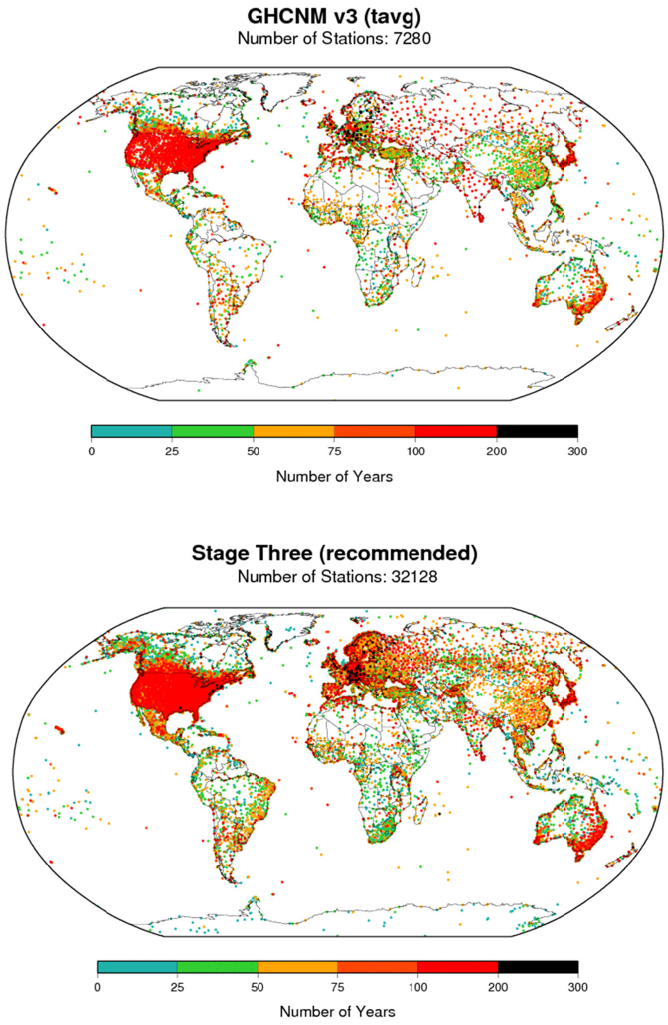

FIGURE 21 Comparison of number of stations and length of records (indicated by color) in NOAA's old land dataset (top) and the recently released land dataset (bottom). SOURCE: Matt Menne presentation, September 3, 2015.

NOAA recognized the need to create a temperature dataset for land for use in reanalysis that is as robust as the International Comprehensive Ocean-Atmosphere Dataset (ICOADs). Progress to increase the dataset has been slow because there are multiple source archives to combine, which usually exist in different formats. Other challenges include devising a system for near real-time updates, managing station histories and metadata, and developing a system for documenting, tracking, and addressing errors. NOAA has already reconciled monthly and daily data and is now working on reconciling the hourly data, according to Menne.

NOAA released a new version of the dataset with many more stations and longer records (Figure 21). In general, there is better sampling of land areas, with a higher spatial density of station records. This is important, Menne said, because artificial shifts at local stations, such as station moves, instrument changes, land use changes, and time of observation changes, can be larger than the climate signal, and the impact of such changes can be quantified by comparing nearby station records. Globally today, there is oversampling at

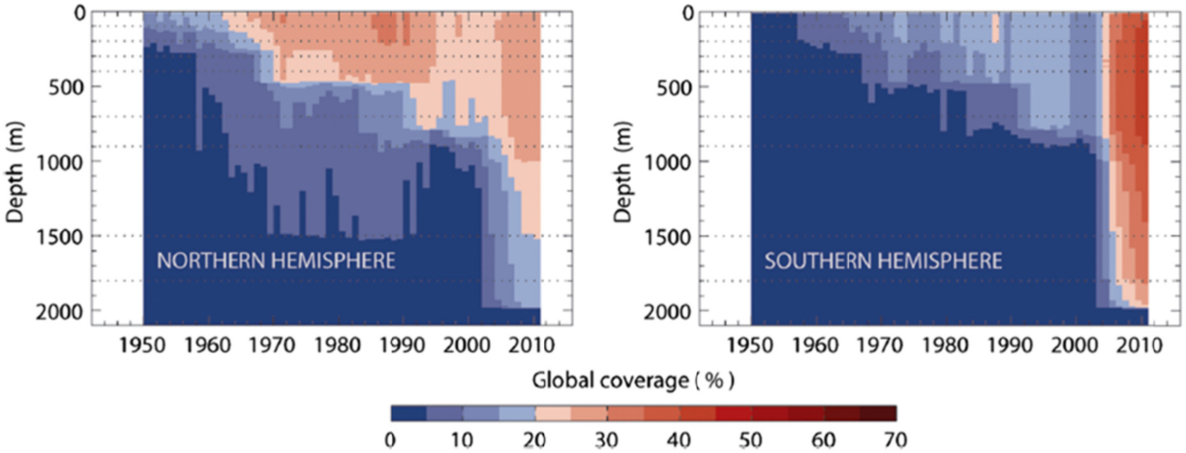

FIGURE 22 Observational sampling coverage for temperature in the upper 2000 m of the ocean (both Northern Hemisphere [top] and Southern Hemisphere [bottom]) has improved dramatically since the early 2000s with new Argo data (increasing coverage indicated by shift from blue to red). Such shifts introduce large uncertainties in the calculation of climate trends. SOURCE: Abraham et al. (2013).

airport locations that were previously in city centers. Therefore, although people have been worried in the past about the effects on readings from urbanization, Menne said the more obvious signal today is from ruralization of the climate record (given that airports are in rural areas), which could introduce a cooling bias.

Menne noted that data coverage in the Arctic is particularly sparse. Filling in more data from the Arctic region could alter understanding of the GMST trend over the past 15 years quite substantially. An important question is what part of the global climate signal is being missed because of inaccurate accounting for the large changes that have occurred in the data-sparse Arctic regions?

Filling in data gaps using model-data integrations and reanalysis

Formal model-data synthesis (loosely termed data assimilation[1]) seeks to optimally combine information contained in observations from several data streams (many that are sparse) and models that obey known conservation laws exactly. Products of this data assimilation can then be used to study climate variability over longer timescales than the strictly observational records would allow. Different techniques lead to different pitfalls in the use of these products: for example, Veronica Nieves, NASA Jet Propulsion Laboratory, presented some results that show the limitations of ocean reanalyses products in capturing the depth trend. Reanalyses tend to overestimate the slowdown and warming rates, and thus if heat starts to be transported in deeper layers of the ocean, these products will require improved analysis at depth, according to Nieves (Nieves et al., 2015).

Patrick Heimbach of the University of Texas at Austin discussed problems with developing climate hindcast[2] studies using reanalysis[3] products. First, reanalyses do not account for

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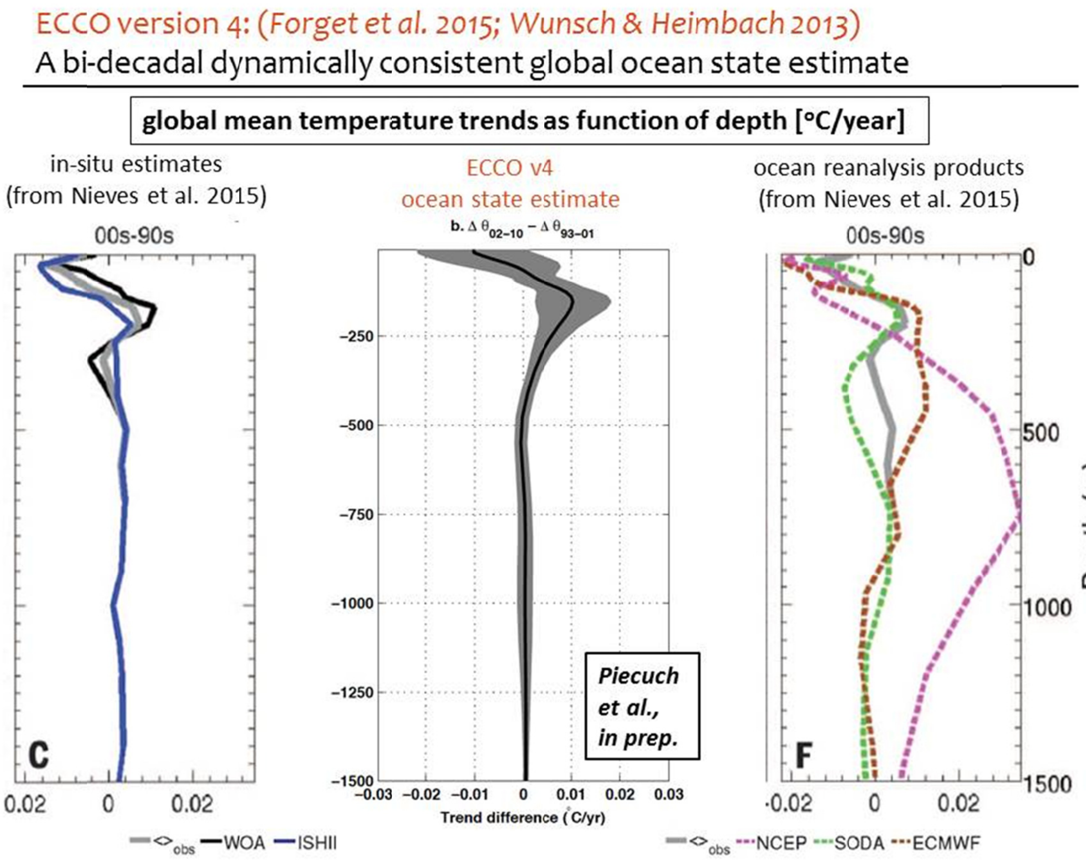
[1] Data assimilation is a cyclical procedure in which scientists compare recently collected observational data with the forecast model output. The model is then adjusted to reflect the known output before a new forecast is initiated.

[2] A hindcast refers to the output from numerical simulation or prediction models of past events or history. These hindcasts can be analyzed to determine how well the model output matches the known observations of that event.



ECCO version 4: (*Forget et al. 2015; Wunsch & Heimbach 2013*)

A bi-decadal dynamically consistent global ocean state estimate

global mean temperature trends as function of depth [°C/year]

FIGURE 23 Visual comparison of the observations from Nieves et al. (2015) (left) to the ECCO version 4 ocean state estimate (center) and other ocean reanalysis products (right) for the trend difference between 1993-2002 and 2003 onward (00s-90s). SOURCE: Patrick Heimbach presentation, September 3, 2015.

ongoing and continual spatio-temporal improvements to observing systems. For example, the large warming trend at the end of the 1970s in ERA40[4] is an artifact of large changes in observational coverage at the end of the 1970s. The same problem applies to the ocean and persists today (Stammer et al., 2016), as observational coverage continues to improve, for example, in measuring temperature in the deep ocean (Figure 22).

Additionally, reanalyses were actually created for weather forecasting, not climate studies, said Heimbach. In particular, so-called ocean reanalyses, like atmospheric reanalyses, do not conserve properties over time, in particular heat and freshwater (Wunsch and Heimbach, 2013). This is a problem for assessing decadal changes in climate properties that often are subtle residuals of large regional variations (Wunsch, 2016). Doing so introduces artificial heat sources or sinks that are a product of the reanalysis method and are not a measure of the actual physical properties being represented, according to Heimbach.

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[3] Reanalysis refers to the reprocessing of observational data spanning an historical period using a consistent modern analysis system.

[4] ERA40 is a widely respected reanalysis by the European Centre for Medium-Range Weather Forecasts (ECMRWF) of global atmosphere and surface conditions from September 1957 through August 2002. ERA-Interim, a precursor to a revised extended reanalysis product to replace ERA-40, is now available here: http://apps. ecmwf. int/datasets/data/interim-full-daily/levtype=sfc/.

Heimbach has been using the ECCO (Estimating the Circulations & Climate of the Ocean) product, which he said is deliberately not called a reanalysis product, but instead an "ocean state estimate" (Wunsch and Heimbach, 2007). The ECCO design is free of artificial heat (and freshwater) sinks and sources. It places a premium on known conservation laws and uses diverse satellite and in-situ data streams forward *and backward* in time. Ocean heat content estimates at depths from the latest ECCO version 4 (Forget et al., 2015) are much closer to the in-situ estimates than in the various reanalysis products considered by Nieves et al. (2015), according to Heimbach (Figure 23). ECOO version 4 has also been used to show that even though global mean SST has stagnated, ocean heat content has increased fairly steadily (Figure 24). Designing, maintaining, and coping with coherent observational records of climate quality will require long-term inter-generational commitments to sustain stable observing systems (Wunsch et al., 2013).

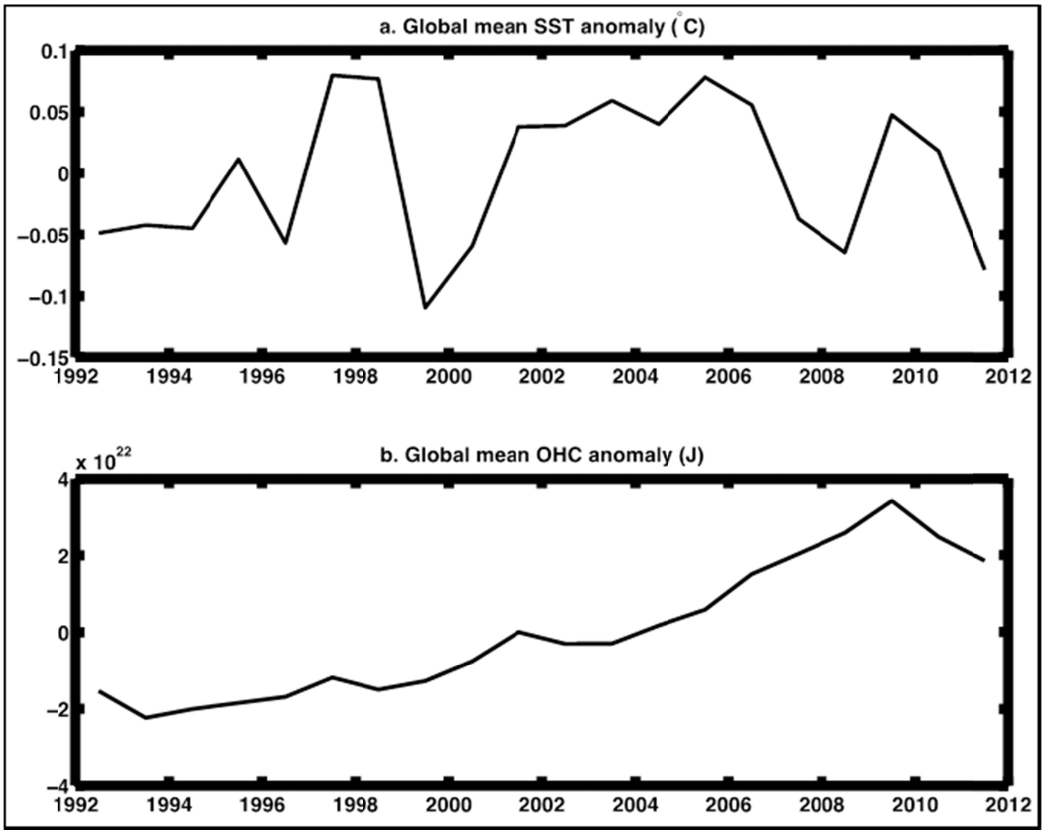

FIGURE 24 Results from ECCO version 4 confirm that whereas SST may have stagnated over the period 1992-2011, ocean heat content increase has not. NOTES: Global mean SST anomalies fluctuate between positive and negative values over the period 1992-2012 (top), while OHC anomalies (bottom) are positive over the period 2003-2012. SOURCE: Courtesy C. Piecuch, R. M. Ponte, and P. Heimbach.

Toward Predictability

The degree to which climate is predictable on decadal timescales has enormous societal relevance: For example, what if decision makers knew they had 30 years versus 10 years to prepare for the large shifts in drought frequency and intensity expected in western North America as a consequence of global warming? Many workshop participants agreed that better understanding of the mechanisms of decadal variability extends beyond diagnosing the causes of recent variability in global mean surface temperature (GMST) to providing the basis for predicting the evolution of climate over decadal timescales. Many participants pointed out that the ability to predict climate on decadal timescales, if possible, would help to direct investments in climate adaptation and more generally to guide longer-range planning.

Although much progress has been made, predictive power is still generally lacking. For example, the Interdecadal Pacific Oscillation (IPO) phase could explain much of the slowdown in GMST rise, but it is not yet understood what triggers changes in IPO phases. Without a deeper understanding of the mechanisms that cause patterns such as the Pacific Decadal Oscillation (PDO), IPO, and Atlantic Multidecadal Oscillation (AMO), it will be difficult to predict how and when slowdown-like features will occur, and how these features will manifest regionally.

Several workshop participants presented work that more directly addresses and tests our current predictive capabilities, specifically regarding how well current models could have predicted the most recent GMST slowdown trend, forecasting how long the current slowdown might last, and prospects for predictability given current observational networks.

Predicting the Current GMST Trend

Michael Mann from Pennsylvania State University presented recent work indicating that the answer to whether or not internal decadal variations are predictable can depend on the method used to separate internal variability from the forced trend (Frankcombe et al., 2015). Linear de-trending[1] of the observed record and other simplified differencing techniques are often used to perform this separation. In many experiments, residual time series that result from de-trending are assumed to represent internal variability. However, Mann found that such methodologies inflate the assessment of how predictable natural internal variability may be, because they incompletely remove the forced signal, which is more predictable.

To reach this conclusion, Mann compared a series of Coupled Model Intercomparison Project Phase 5 (CMIP5) model runs to observations of the GMST. He and his co-authors first estimated the forced (external) component of recent decadal variability using historical runs from CMIP5. Such models exhibit internal decadal variability, but because the model runs are not initialized with observations, the decadal variability in each model run is just one possible manifestation of internal decadal variability in the Earth system. This model-specific and uninitialized decadal variability is thus largely canceled out when the average of all such model runs is calculated, leaving the imprint of the forced climate response. Mann regressed the actual observations of GMST variability onto this model-estimated

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[1] De-trending is a statistical means of removing a trend from a model time series, usually used to remove a feature thought to distort or obscure the relationships of interest.

forced component of the recent evolution of GMST. The residual, or leftover, variability in the observations can be considered the fingerprint of natural, internal variability. The forced signal can then be scaled to match the historical time series of each individual ensemble member. This "scaling" method also provides estimates of model sensitivities to different types of external forcing (Frankcombe et al., 2015).

When testing the predictive capabilities of this estimate of internal variability, Mann found results consistent with the recent slowdown period. However, this prediction performed better at long leads than the lower bound error attached to the external forcing component. This result suggests an issue with this method because the prediction cannot perform with a lower error than the lowest error of one of its components (Mann et al., 2016). Prediction depends critically on how estimates of the forced signal are made. His team's prediction used a linear trend, which did not account for two large volcanic eruptions (El Chichon and Pinatubo) between 1982 and 2000. Thus, the underestimation of the forced signal masked itself as skill in the forecast.

The application of this approach to actual observations indicates that the AMO signal is currently at shallow maximum, while the PDO signal is now recovering after trending sharply downward through 2012 (Steinman et al., 2015). Further work with hindcast experiments suggests that the AMO signal exhibits skillful decadal predictability; results are less promising for the PDO and Northern Hemisphere mean temperature variability series. Mann's current forecast indicates an approach toward neutral conditions for the AMO over the next decade as the PDO continues toward positive values, suggesting a reversal of the GMST slowdown where internal variability will add to anthropogenic warming in the coming decades.

How Long Will the Slowdown Period Last?

Tom Knutson of the National Oceanic and Atmospheric Administration's (NOAA's) Geophysical Fluid Dynamics Laboratory (GFDL) estimated an upper bound for how long the current slowdown may last. To do so, he examined an ensemble of models within the CMIP5 experiment, used a method similar to that of Mann to extract the internal variability of the model, and chose the model (GFDL Coupled Physical Model [CM3]) that exhibited the strongest global mean internal decadal variability. Knutson chose to examine this model because it would have the greatest opportunity for long cool events.

Knutson then created a number of synthetic global mean surface temperature time series. For each, he used the observations from 1900 to 2000. He then appended a simulated temperature time series for 2000-2050 created by combining the average CMIP5 (RCP8.5) projections for the forced component with strong internal variability from cooling events simulated in the CM3 model. Using the average transient climate response (TCR) from the CMIP5 models, the synthetic time series can produce a slowdown period like that experienced to date, but which typically lasts no longer than the current slowdown. Knutson then adjusted the TCR from 1.8 C (CMIP5 unadjusted rate), to 1.3 C (estimate from Otto et al., 2013), and finally to 0.9 C (the low-end sensitivity from Otto et al., 2013). With a lower TCR, models can produce slowdown periods that match observations to date and can extend to about 2030. Given the specific choices made—that is, a model more likely to produce cooling events and low-end sensitivity TCR—this would represent an estimated upper bound for the potential length of the current GMST slowdown period, while assuming no strong volcanic eruptions or strong declines of solar forcing.

John Fyfe, Canadian Centre for Climate Modelling and Analysis (CCCma), presented some preliminary work by his group that suggests the slowdown has already ended. Unlike Knutson's work with CMIP5 model runs, Fyfe's unpublished estimates are based on the

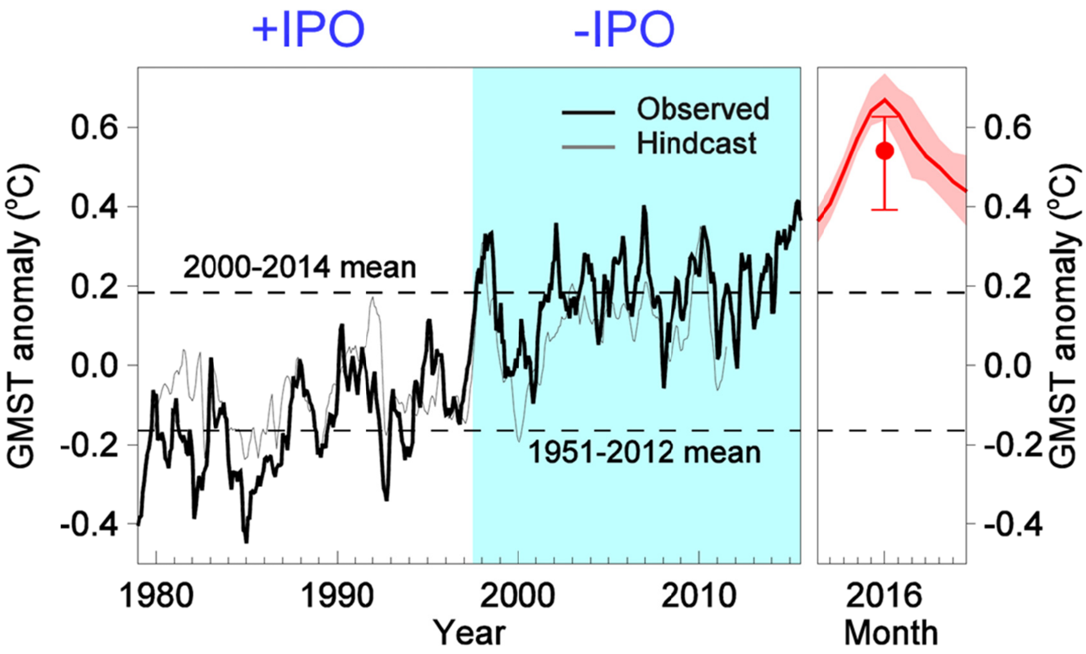

FIGURE 25 Observed (black, data from HadCRUT4.3) and hindcast (gray) for GMST anomaly from 1979 to 2015 (left hand box), and a 12-month forecast from Canadian seasonal-to-interannual prediction system (red) initialized July 31, 2015 (right hand box—note that the x-axis scale for the forecast period is months, whereas it is years for the hindcast period). NOTES: Anomalies are relative to 1921-2011 climatology and shown as monthly averages. The red dot is the average forecast value over the given 12-month period, and the error bar shows the 5-95 percent range of forecast values. SOURCE: John Fyfe presentation, September 3, 2015. © Her Majesty the Queen in Right of Canada, as represented by the Minister of Environment, 2016.

probability of a shift in the phase of the IPO generated using the Canadian seasonal-to-interannual climate forecast system (CanSIPS). Hindcasts from the forecast system match reasonably well with the observed record of the IPO, lending some confidence to the system's ability to forecast the IPO (Figure 25). Such forecasts suggest that GMST will be about 0.4 C degrees warmer over the next year than conditions over the past 15 years (e. g., it is likely to be substantially warmer in the next year than it has been on average during the recent slowdown period).

Fyfe then used a very large ensemble of model runs to assess the probability of an IPO sign change in 2015 (after an 18-year slowdown) and in 2020 (after a 23-year slowdown). Both probabilities were low: 10 percent and 3 percent, respectively. Given average temperatures in 2015 (at the time of the workshop) and the forecast for a very warm 2016, Fyfe suggested that the current negative IPO phase ended in 2015. He then looked at the temperature response in analogs from the large ensemble and found that the recent and forecast trends are consistent with an IPO shift. Thus, Fyfe concluded that the slowdown has ended or will end very soon.

The Role of Uncertainty

Baylor Fox-Kemper of Brown University discussed the uncertainty in our understanding, observations, and modeling of air-sea exchange, and what that uncertainty implies for predicting decadal climate variability. Air-sea exchange processes at a variety of scales affect how much heat is stored in the ocean; the errors associated with this term are of a magnitude similar to or greater than the observed slowdown. Fox-Kemper concluded that these uncertainties in the air-sea exchange rates, and consequently the global heat budget, should be reduced if we are to make robust predictions of decadal variability into the future.

The Argo array of ocean measurements provides the best available estimates of ocean heat content today. Even with these measurements, the error in the ocean heat content is very large and currently hinders any possibility of balancing global energy budgets on interannual to decadal timescales, according to Fox-Kemper. Given the huge extent and spatial variability of conditions in the ocean, many more observations are needed to decrease this uncertainty and allow for true predictability. Denser measurements, or more clever ways of interpolating the data (see also Overcoming Data Limitations), are needed, said Fox-Kemper, in order to estimate the ocean heat budget within an acceptable range of uncertainty. Similar uncertainties exist in current estimates of air-sea energy fluxes and top of the atmosphere (TOA) fluxes, and will also require more extensive observations (e. g., satellite measurements) in order to detect anomalies on these short timescales.

About the Argo Array

The Argo[a] array was initiated in the early 2000s and currently consists of 3,918 free-drifting instrumented profiling floats deployed to measure temperature and salinity profiles and velocity measurements of the upper 2,000 meters of the world's oceans. Every 10-12 hours, each float descends to a depth of about 2,000m before ascending to the surface again. During the time it takes to return, the floats takes around 200 measurements. Certain locations currently are supporting high densities of floats such as the Mediterranean Sea and Arabian Sea. Areas that are currently underrepresented are marginal seas, high-latitude regions, and boundary current regions. To maintain the array, about 800 floats must be deployed every year (Roemmich et al., 2009).

[a] See http://www. jcommops. org/board? =t=Argo.

In stochastic modeling[2] of decadal variability, predictability can arise if there are connections between regions, that is, if one region responds with a lag to well-observed conditions in another region (e. g., if the poles lead the tropics or the tropics lead the poles). Fox-Kemper said that this type of predictability likely explains why linear inverse models can exhibit some skill. Although available and useful in some contexts, stochastic modeling offers little support for the ability to make dynamical predictions in novel regimes. In order to make progress on dynamical decadal prediction, parameters must be better known than at present (or better data-assimilation techniques must be applied) and currently un-parameterized processes, particularly those affecting air-sea fluxes, must be represented. Fox-Kemper also noted that moving toward really useful decadal climate prediction would require a change of culture and orientation in the research community from exploration to operational forecasting (including the designation of forecast skill scores, validation, etc.).

Veronica Nieves explained that predicting GMST over the next two decades will require determination of the fate of heat that has been stored in the Pacific and Indian Oceans as a result of planetary warming. Some of this heat is already emerging toward the surface, which will drive GMST rise. One important question is whether some of the trapped heat will be absorbed into the deeper layers of the ocean and how that might affect global temperatures in the future. So far, there is not yet any observational evidence of large amounts of heat below 300 m, according to Nieves.

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[2] Stochastic modeling is used to estimate probability distributions of potential outcomes by allowing for random variation in one or more model input over time.

Frontiers and Research Opportunities

The last session of the workshop included a presentation of key messages developed over the course of the 2 days. Many of the messages have been discussed in depth previously in the report (see Box 1), and therefore are not repeated here. This section focuses on the discussions related to challenges and opportunities in observing and modeling decadal variability, as well as key knowledge gaps.

Metrics of Decadal Climate Variability

Many participants discussed ways to measure and detect decadal variability. In particular, they questioned whether global mean surface temperature (GMST) should continue to be used as the prominent metric for change. There are large uncertainties in calculating GMST, largely because of the lack of station data coverage in the Arctic, Antarctic, and African regions, according to some participants. Although remote sensing can help to address these data gaps, ground-truthing would be necessary to verify these measurements. Another concern is that GMST only measures part of the global energy budget, and a relatively small component at that. As such, variations in GMST do not fully reflect the effects of human-caused emissions on the climate system.

Despite these shortcomings, most workshop participants agreed that it is important to monitor and understand surface temperature, given that people live on Earth’s surface and there are long records of this metric relative to others. Shang-Ping Xie also pointed out that regional affects and impacts are much more important than a global average for informing decision makers. Xie argued that use of GMST as a metric causes information loss. He said that “unpacking the data” reveals seasonal and regional information that may hold the key to identifying important mechanisms.

In response to these limitations of GMST, some participants suggested alternative metrics that might be more accurate measures for global change. One possible metric is ocean heat content, particularly if expanded observations can help reduce current uncertainties. New observations would be most useful if the focus is on regions where heat uptake is thought to be the largest, including deep water formation regions in the high latitudes and the upper ocean. These observations would need to be more uniform, according to some participants, because Argo does not evenly sample the global ocean and thus is subject to sampling errors in large-scale averages or balances. Some participants noted that it would also be important to focus on where the change in heat uptake is thought to be largest (e. g., the top 300 m) and to include deep Argo measurements for multi-decadal timescales. Other participants noted that available ocean observational data (ocean temperature and heat content estimates) are within acceptable uncertainty, particularly after 2005 (Nieves et al., 2015).

Other possible metrics include the top of atmosphere (TOA) radiative balance, where there are still considerable inaccuracies; sea ice extent, which is well constrained by satellites but thickness and ice volume have only been possible to observe recently (via ICESAT and CRYOSAT); and global mean sea level (and sea level pressure), which would integrate the ocean and cryosphere response. Participants noted that adequate monitoring of climate change for studying decadal variability would truly require a combination of metrics, for example, the use of global sea level rise coupled with GMST.

Confronting Models with Observations

Regardless of the metric (or metrics) chosen to monitor global climate, the community's understanding of drivers and mechanisms of decadal change is limited by the existing data record. Participants agreed that sustaining and enhancing observing networks to better monitor the global climate system is important, but synthesis of existing observations to better understand past variability and associated processes is generally lacking. Observations are required for the verification and testing of decadal predictions, but data coverage is inadequate and the length of records is short relative to what is needed to validate variability and dominant processes in existing models. Much of the workshop involved proposing potential mechanisms and drivers of change, which were analyzed in the context of a given time period. However, given the relative brevity of the instrumental era, very few samples exist to consider.

Many workshop participants also recognized the need to continuously confront models with observations. Verification of model performance from observations is an important step toward developing prediction capability. Confronting models with observations is also important to distinguish forced and internal change through fingerprinting (e. g., Coupled Model Intercomparison Project Phase 6 [CMIP6] pacemaker experiments). Providing real-time forcing datasets for better synthesis of the current state would also be beneficial in improving this capacity, according to some participants.

Observational Challenges, Needs, and Opportunities

Some individual participants identified additional observational challenges, needs, and opportunities:

- The challenges in combining local measurements over ocean or land are worsened by differences in platforms and temporal integrity of local observations. Therefore, in addition to making new observations, maintenance of current observational systems is required at a minimum.
- Paleo proxies offer many opportunities, although synthesis of existing records is currently under resourced and underutilized.
- Sources of observations other than temperature could be used to improve understanding of decadal climate variability. Paleo records would provide isotopes (to compare to rainfall on land). Argo would provide not only temperature but also salinity and gradients of salinity.
- Other specific areas that would benefit from improved observations include
    - geographical distribution of aerosols below 15 km to determine contribution of external forcing, and
    - ocean isotope geochemistry in the equatorial Pacific to determine El Niño/La Niña occurrences during the past 1,000 years.

Modeling Challenges, Needs, and Opportunities

Some individual participants identified additional modeling challenges, needs, and opportunities:

- Regional patterns and cross-timescale interactions are important, but not all models can capture the full collection of processes and phenomena that have been deemed relevant to regional (or basin-scale) variability, which limits understanding.
- It is important to focus efforts on improving model representation of the modes of variability that have the potential for predictability, although the questions may still

remain: why are some modes more or less predictable? What are the mechanisms leading to this predictability?

- It is also important to employ a hierarchy of models—process-based, linear inverse models, and global climate models—to better explore the limits of predictability.
- Models could be used to inform observational needs.
- Other general areas for improvement identified include
    - model initialization (e. g., coupled assimilation),
    - reduced model uncertainties and bias (i. e., we do not yet know which biases affect variability on decadal timescales), and
    - better incorporation of known forcing and known uncertainties in forcing.

Knowledge Gaps

Although much progress is being made toward understanding decadal variability, as presented at the workshop, important questions remain, in particular in separating the contributions of each proposed driver. Many of the mechanisms examined might be driving decadal variability, but what is driving the mechanisms themselves? For example,

- If Pacific Decadal Variability (PDV) is a combination of different modes, how can they be parsed out? What role does each play? What is the mechanism for each mode?
- Although the North Atlantic Oscillation (NAO) seems to drive Atlantic Multidecadal Variability (AMV), what drives NAO multi-decadal variability?

Other knowledge gaps include the following:

- The connection between Arctic sea ice loss and mid-latitude weather, and the consequential regional effects;
- The role of and quantitative data on stratification of the deep Southern Ocean;
- The relative importance of atmospheric vs. oceanic bridges in linking stochastic processes at mid-to-high latitudes (how does local atmospheric forcing produce remote response(s) on decadal timescales?); and
- How heat trapped in the ocean will be transported into the deeper layers in the one or two decades and how that might affect global temperatures in the future.

Communication

Some participants highlighted the importance of the community reaching agreement on how to quantify and communicate the concept of uncertainty to reduce confusion among the public, as well as among those studying climate variability. The participants emphasized the need for scientists to be clear and careful about their definitions and derivations of uncertainty, because differences can be easily misconstrued by the public as disagreement.

Many participants believe it is important to not associate “variability” with “oscillation,” and in discussions of variability to provide quantitative clarity. In addition, the scientific community should define a minimum time interval over which to label a GMST trend, and potentially define trends associated with the adjectives “small,” “moderate,” “strong,” and “extreme.”

Way Forward

Many participants suggested that the way forward includes improvement of the mechanistic understanding of the processes and drivers (both internal and external) that contribute to decadal climate variability, assessment of this understanding, followed by development of prediction and attribution capabilities.

The emphasis on the recent slowdown period has stimulated a very useful area of research in decadal variability and predictability more broadly. Examination of the questions related to recent GMST trends can offer many scientific insights about the physical climate system. A key focus moving forward should be to use these insights to predict these longer time-scale variations in Earth's climate. Enhanced understanding of the dynamics and underlying physics of variability in the climate system would lead to higher quality information that could inform model development and validation, which the community can then use to make and verify predictions.

Some participants reiterated the importance of developing predictive capability for decadal variability of seasonal-to-interannual coupled ocean-atmosphere phenomena, including weather, for selected geographical areas for specific phenomena:

- El Niño/La Niña
- Tropical Atlantic
- Arctic sea ice
- Southern Ocean/Antarctic sea ice (surface winds, ocean stratification)
- Bottom- and intermediate-water formation

They noted, however, that some studies of predictability of this most recent, as well as other slowdown periods, have met with some success (see Toward Predictability).

In addition to improving prediction capabilities, addressing the gaps in knowledge of decadal climate variability could lead to better-informed climate change attribution studies, that is, the ability to detect the signals of anthropogenic climate change and internal variability distinctively for certain events with much greater accuracy. Both the prediction of decadal climate variability and attribution of specific climatic events and trends can be used to better inform decision makers.

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Appendix A
Statement of Task

An ad hoc committee of the National Academies of Sciences, Engineering, and Medicine will plan a workshop to bring together atmospheric and ocean climate experts to review the current science for decadal climate variability. Workshop participants will be asked to:

1. examine our understanding of the processes governing decadal-scale variability in key climate parameters, observational evidence of decadal variability and potential forcings, and model-based experiments to explore possible factors affecting decadal variations;
2. identify key science, observing, and modeling gaps;
3. consider the utility and accuracy of various observations for tracking long-term climate variability, anticipating the onset and end of hiatus regimes, and closing the long-term heat budget;
4. consider the utility of hiatus regimes as a metric for evaluating performance of long-term climate models; and
5. consider how best to communicate current understanding of climate variability, including potential causes and consequences, to non-expert audiences.

Appendix B
Planning Committee Biographical Sketches

Gerald A. Meehl (Chair) is a Senior Scientist at the National Center for Atmospheric Research. He received his PhD in climate dynamics from the University of Colorado. His research interests include studying the interactions between naturally occurring internal climate variability and changing anthropogenic and natural forcings, particularly in the Indo-Pacific region, and quantifying possible future changes of weather and climate extremes in a warmer climate. He has been an author on all five of the Intergovernmental Panel on Climate Change (IPCC) climate change assessment reports, serving as contributing author (1990), lead author (1995), coordinating lead author (2001, 2007), and most recently lead author on the near-term climate change chapter for the IPCC AR5 that was completed in 2013. He was a recipient of the Jule G. Charney Award of the American Meteorological Society in 2009 and was chair of the National Research Council Climate Research Committee. Meehl is a Fellow of both the American Meteorological Society and the American Geophysical Union and a Visiting Senior Fellow at the University of Hawaii Joint Institute for Marine and Atmospheric Research. He serves as co-chair of the Community Earth System Model Climate Variability and Change Working Group, has been a member and co-chair of the World Climate Research Programme (WCRP) Working Group on Coupled Models (WGCM), which coordinates the Coupled Model Intercomparison Project (CMIP) international global climate model experiments addressing anthropogenic climate change, and is currently co-chair of the WCRP Modelling Advisory Council.

Kevin Arrigo is Donald & Donald M. Steel Professor in Earth Sciences, Victoria and Roger Sant Co-Directorship of the Earth Systems Program, at Stanford University where he has been on the faculty since 2005. He conducts laboratory and field studies, remote sensing, and computer modeling techniques to understand phytoplankton dynamics in regions ranging from the Southern Ocean to the Red Sea. In particular, he is interested in the role these organisms play in regulating the uptake of atmospheric carbon dioxide by the ocean, as well as in how they help structure marine ecosystems. He received his Ph. D. from the University of Southern California in 1992 and served as a member of the NRC Committee on a Science Plan for the North Pacific Research Board.

Shuyi S. Chen is a Professor of Meteorology and Physical Oceanography at the Rosenthal School of Marine and Atmospheric Science (RSMAS) of the University of Miami. Her research interest focuses on air-sea interactions and tropical meteorology, including hurricanes and coastal hazards. She leads a research group that developed the University of Miami Coupled Model (UMCM), a new-generation, high-resolution, coupled atmosphere-wave-ocean model for weather research and prediction. She has been a lead scientist of major observational field campaigns including the Hurricane Rainbands and Intensity Change Experiment (RAINEX) and the Coupled Boundary Layer Air-Sea Transfer (CBLAST)-Hurricane in the Atlantic, the Impact of Typhoon on the Ocean in the Pacific (ITOP), and the Dynamics of the Madden-Julian Oscillation (DYNAMO) over the Indian Oceans. She served as an editor for *Weather and Forecasting* and on panels of experts that testified in the U. S. Congressional Hearings on weather and climate in 2008 and 2013. She is a Fellow of the American Meteorological Society. Chen received her PhD from the Pennsylvania State University in 1990.

Lisa Goddard is the Director of the International Research Institute for Climate and Society and an adjunct associate professor within the Department of Earth and Environmental Sciences of Columbia University. She has been involved in El Niño and climate forecasting research and operations since the mid-1990s. She has extensive experience in forecasting methodology and has published papers on El Niño, seasonal climate forecasting and verification, and probabilistic climate change projections. Currently leading the IRI's effort on near-term climate change, Goddard oversees research and product development aimed at providing climate information at the 10-to 20-year horizon and how that low-frequency variability and change interacts with the probabilistic risks and benefits of seasonal-to-interannual variability. Most of Goddard's research focuses on diagnosing and extracting meaningful information from climate models and available observations. She also developed and oversees a new national postdoctoral program, the Post-docs Applying Climate Expertise Program (PACE), which explicitly links recent climate PhDs with decision-making institutions. Goddard holds a PhD in atmospheric and oceanic sciences from Princeton University and a BA in physics from the University of California at Berkeley.

Robert Hallberg is an oceanographer and the Head of the Oceans and Ice-sheet Processes and Climate Group at NOAA's Geophysical Fluid Dynamics Laboratory, and a lecturer on the faculty of Princeton University. He has a PhD in oceanography from the University of Washington and a BA in physics from the University of Chicago. He has spent many years developing isopycnal (density) coordinate ocean models to the point where they are now valuable tools for coupled climate studies, including extensive work on the robustness of the models' numerical techniques, and on the development or incorporation of parameterizations of a wide range of physical processes. The isopycnal coordinate ocean model that Dr. Hallberg developed provides the physical ocean component of the Geophysical Fluid Dynamics Laboratory's comprehensive Earth System Model (ESM2G), which was used in the Intergovernmental Panel on Climate Change's 5th Assessment Report, and its dynamic core is the basis for version 6 of the Modular Ocean Model (MOM6. Hallberg has used global-scale numerical ocean simulations to study topics as varied as the dynamics of Southern Ocean eddies and their role in the ocean's response to climate, sources of steric sea level rise, and the fate of the deep plumes of methane and oil from the Deepwater Horizon oil spill. Hallberg has been actively involved in three ocean Climate Process Teams, studying Gravity Current Entrainment, Eddy-Mixed Layer Interactions, and Internal Wave Driven Mixing. These teams aim to improve the representation of these processes in climate-scale models, based on the best understanding obtained from observations, process studies, and theory. He is currently working on coupling a dynamic ice-sheet and ice-shelf model with high-resolution versions of GFDL's coupled climate models for improved prediction of sea-level rise.

David Halpern is a Senior Research Scientist at the National Aeronautics and Space Administration/California Institute of Technology Jet Propulsion Laboratory. He analyses satellite and in-situ observations to improve understanding of coupled ocean-atmosphere interaction and climate phenomena, such as El Niño and La Niña, intertropical convergence zone, monsoon, and wind-driven ocean upwelling. He developed techniques to record in-situ observations of near-surface meteorological and upper-ocean circulation variables in both shallow and deep-sea environments. He is experienced in ocean circulation and ocean-atmosphere interaction research (more than 300 publications with 50 single- or first-author peer-review papers); has managed national and international programs; has taught graduate and undergraduate courses at the California Institute of Technology, the University of California Los Angeles, and the University of Washington, and has participated in numerous committees (20 as chair or co-chair, 9 as member of executive board, and 45 as member. Halpern had the privilege to serve in the White House Office of Science and Technology Policy and NASA's Earth Science Division. At OSTP, he co-founded the National Science and Technology Council Joint Subcommittee on Ocean Science and Technology and Task Group on Global Earth Observations. One of his major interests is enhanced integrated global ocean and atmosphere observations and large-scale process-oriented experiments to improve the accuracy of predictions of the global integrated Earth system. Halpern was co-chair of the Group on Earth Observations Science and Technology Committee and currently serves as co-chair of the GEO Data Sharing Working Group. He served two terms on the National Research Council's Advisory Panel for the Tropical Ocean and Global Atmosphere. He was editor of *Geophysical Research Letters* and is editor of *Eos*. Currently, he represents the Intergovernmental Oceanographic Commission to the Coordination Group for Meteorological Satellites, serves on the Joint Technical Commission for Oceanography and Marine Meteorology Task Team for Satellites, is chair of the Committee on Space Research (COSPAR) Task Group on the Group on Earth Observations (GEO), and represents the United States in the United Nations Bureau for the World Ocean Assessment. He is a Fellow of the American Association for the Advancement of Science, American Geophysical Union, American Meteorological Society, California Academy of Sciences, and International Academy of Astronautics. Halpern received a BSc. honors degree in geology and physics from McGill University and a PhD in physical oceanography from MIT.

Appendix C
Workshop Agenda

FRONTIERS IN DECADAL CLIMATE VARIABILITY: A WORKSHOP
September 3-4, 2015
Jonsson Conference Center Carriage House
314 Quisset Ave., Woods Hole, MA

THURSDAY, SEPTEMBER 3, 2015

7:30 A. M.	Shuttle pick up at Inn on the Square/Holiday Inn	
8:00 A. M.	Breakfast at Jonsson Center	
8:30 A. M.	Welcome, Introduction, Purpose of Workshop	*Jerry Meehl*
9:00 A. M.	Communication and framing of panel talks	*Susan Hassol and Brian Kahn*

PANEL 1: PACIFIC DECADAL CLIMATE VARIABILITY

Moderator: *Jerry Meehl*

9:10 A. M.	Presentations	
	• Tropical Pacific decadal variability and the global warming hiatus	*Shang-Ping Xie, Scripps*
	• Comparing simulated and observed and decadal trends	*John Fyfe, CCCma*
	• Tropical Pacific decadal variability: Oceanic processes and the possible important role of climate noise	*Antonietta Capotondi, CIRES/NOAA*
	• Pacific decadal climate variability: Phenomenon, evidence, and impacts	*Yochanan Kushnir, LDEO*
10:10 A. M.	Discussion	
10:40 A. M.	Break	

PANEL 2: ATLANTIC DECADAL CLIMATE VARIABILITY

Moderator: *Robert Hallberg*

11:00 A. M.	Presentations	
	• Robust and non-robust aspects of AMOC intrinsic variability and mechanisms in the Community Earth System Model (CESM)	*Gokhan Danabasoglu, NCAR*
	• Understanding tropical Atlantic decadal variability: The role of tropical Pacific versus subpolar Atlantic	*Mingfang Ting, LDEO*
	• The impact of the North Atlantic Oscillation on climate through its influence on the Atlantic Meridional Overturning Circulation	*Tom Delworth, GFDL*
	• Predictability of the recent slowdown and subsequent recovery of large-scale surface warming using statistical methods	*Michael Mann, Penn State*
12:00 P. M.	Discussion	
12:30 P. M.	Lunch	

PANEL 3: ASPECTS OF DECADAL VARIABILITY—PALEO EVIDENCE AND EXTERNAL FORCING

Moderator: *David Halpern*

1:30 P. M. Presentations

- Decadal variability in Pacific trade winds inferred from coral Mn/Ca: Implications for the rate of global warming *Diane Thompson, Boston University*
- Paleo-constraints on decadal climate variability in the tropical Pacific *Kim Cobb, Georgia Tech*
- Radiative forcing contributions to changes in recent rates of global warming *Susan Solomon, MIT*
- How long could the current hiatus in global warming last? *Tom Knutson, GFDL*

2:30 P. M. Discussion
3:00 P. M. Break

PANEL 4: OBSERVATIONS, OCEAN MIXING, AND DECADAL CLIMATE VARIABILITY

Moderator: *Kevin Arrigo*

3:30 P. M. Presentations

- Impact of data coverage and quality control on global surface temperature trends: Part 1—Overview and sea surface temperature aspects *Huai-min Zhang, NOAA*
- Impact of data coverage and quality control on global surface temperature trends: Part 2—Land surface air temperature aspects *Matthew Menne, NOAA*
- Pacific temporarily hid heat below surface *Veronica Nieves, JPL*
- Understanding decadal climate variability using formal model-data synthesis *Patrick Heimbach, UT Austin*

4:30 P. M. Discussion
5:00 P. M. Adjourn
5:30 P. M. Working dinner/Lobster boil

Friday, September 4, 2015

8:00 A. M. Breakfast
8:30 A. M. Convene and plan for day *Jerry Meehl*

PANEL 5: AIR-SEA INTERACTION AND OCEAN PROCESSES CONTRIBUTING TO DECADAL CLIMATE VARIABILITY

Moderator: *Shuyi Chen*

8:30 A. M. Presentations

- Consequences of uncertainty in air-sea exchange *Baylor Fox-Kemper, Brown*
- The ocean's role in polar climate change: asymmetric Arctic and Antarctic responses to greenhouse gas and ozone forcing *John Marshall, MIT*
- Arctic changes and mid-latitude weather linkages in the coming decades *James Overland, PMEL*
- Indian Ocean variability and its impact on regional climate *Caroline Ummenhofer, WHOI*

9:30 A. M. Discussion
10:00 A. M. Break

BREAKOUT GROUPS

10:30 A. M. Instruction for breakouts *Jerry Meehl*

1. **Observations of decadal climate variability**
    a. Co-leads: Patrick Heimbach, Caroline Ummenhofer
    b. Tasks:
        i. Identify observational gaps
        ii. Consider the utility and accuracy of various observations for tracking long-term climate variability, anticipating the onset and end of hiatus regimes, and closing the long-term heat budget

2. **Modeling decadal climate variability**
    a. Co-leads: Gokhan Danabagoslu, Shang-Ping Xie
    b. Tasks:
        i. Identify modeling gaps
        ii. Consider the utility of hiatus regimes as a metric for evaluating performance of long-term climate models

12:00 P. M. Lunch

1:00 P. M. Breakout groups report back *Jerry Meehl*

- 15 minutes per breakout group; 45 minutes discussion

PANEL 6: SYNTHESIS AND COMMUNICATING DECADAL CLIMATE VARIABILITY

Moderator: *Lisa Goddard*

2:15 P. M. Key workshop messages *Lisa Goddard and David Halpern*

2:30 P. M. Communicating climate science

- ***Susan Hassol, Climate Communication***
- ***Brian Kahn, Climate Central***

Discussion

3:30 P. M. Discussion of products *Jerry Meehl, Amanda Purcell, and committee members*

4:00 P. M. Workshop adjourns

Appendix D
Workshop Participants

Kevin Arrigo, Stanford University
Antonietta Capotondi, Cooperative Institute for Research in Environmental Sciences (CIRES)/National Oceanic and Atmospheric Administration (NOAA)
Shuyi S. Chen, University of Miami
Kim Cobb, Georgia Institute of Technology
Gokhan Danabasoglu, National Center for Atmospheric Research (NCAR)
Tom Delworth, Geophysical Fluid Dynamics Laboratory (GFDL)
Baylor Fox-Kemper, Brown University
John Fyfe, Canadian Centre for Climate Modelling and Analysis
Lisa Goddard, International Research Institute for Climate and Society (IRI)
Robert Hallberg, NOAA
David Halpern, National Aeronautics and Space Administration Jet Propulsion Laboratory (NASA JPL)
Susan Hassol, Climate Communication
Patrick Heimbach, University of Texas at Austin
Brian Kahn, Climate Central
Tom Knutson, GFDL
Yochanan Kushnir, Lamont Doherty Earth Observatory (LDEO)
James Overland, NOAA Pacific Marine Environmental Laboratory (PMEL)
Michael Mann, Pennsylvania State University
John Marshall, Massachusetts Institute of Technology (MIT)
Gerald A. Meehl, NCAR
Matthew Menne, NOAA
Veronica Nieves, NASA JPL
Susan Solomon, MIT
Diane Thompson, Boston University
Mingfang Ting, LDEO
Jim Todd, NOAA
Caroline Ummenhofer, Woods Hole Oceanographic Institution
Shang-Ping Xie, Scripps Institution of Oceanography
Huai-min Zhang, NOAA

National Academies of Sciences, Engineering, and Medicine Staff
Edward Dunlea
Rita Gaskins
Nancy Huddleston
Alison Macalady
Amanda Purcell
Sue Roberts
Amanda Staudt

Appendix E
Panel Presentation Abstracts

Tropical Pacific decadal variability and the global warming hiatus:
Shang-Ping Xie, Scripps Institution of Oceanography, UC San Diego

Global mean surface temperature (GMST) is known to rise following a major El Niño event. The tropical Pacific cooling that began in the late 1990s emerged as the leading mechanism for the slowdown of the GMST increase for the recent 15 years. An important question is how we can test this hypothesis among other mechanisms for the global warming hiatus. Much attention has been given to the annual mean GMST, but it is too narrow a focus to quantify the relative importance of the zoo of mechanisms.

We need to go beyond the annual mean GMST by unpacking it into seasonal and spatial dimensions and develop distinctive fingerprints of these various mechanisms. The pacemaker experiments with a GFDL climate model reveal the following fingerprints of the tropical Pacific cooling on the recent hiatus:

- The seasonal contrast between the GMST decrease in boreal winter and increase in summer;
- The decadal droughts over the Southwest U. S. (including California and Texas) for the past 15 years.

We show that the seasonal fingerprint is present in all the GMST datasets including the one recently released from NOAA.

We also need to develop metrics that distinguish forced change and internal variability. For example, planetary/ocean heat uptake is an important aspect of the transient climate response to anthropogenic radiative forcing, but is it also an essential element of internal decadal variability as is widely assumed in hiatus studies? Modeling studies suggest that the answer is probably no. This has important implications for observations.

Comparing simulated and observed and decadal trends:
John Fyfe, CCCma

Should it be done, and if so how do we separate, quantify and communicate the influences of uncertainty (model, forcing and observational) and internal variability? This question will be considered in the context of decadal trends in Pacific SST, GMST and Arctic sea ice extent. I'll touch on the Karl et al. result, and finish with a forecast for the end of the current GMST hiatus.

Tropical Pacific decadal variability: Oceanic processes and the possible important role of climate noise:
Antonietta Capotondi, University of Colorado/CIRES and NOAA/ESRL/Physical Sciences Division

In this talk I will start by reviewing some of the mechanisms proposed for tropical Pacific decadal variability, with emphasis on oceanic processes. Focus will be on the 1976/77 climate shift, as an example. I will then discuss the possible influence of the slowly varying mean tropical climate state upon ENSO characteristics, and discuss some of the proposed theories for the resulting decadal ENSO modulation. Finally, using a Linear Inverse Modeling (LIM) approach I will show that apparent changes in ENSO characteristics over decadal periods are within the expected range of noise-driven variations. Thus, we cannot reject the null hypothesis that decadal ENSO modulation may merely result from sampling variability, with important implications for predictability.

Pacific decadal climate variability: Phenomenon, evidence, and impacts

Yochanan Kushnir, Lamont-Doherty Earth Observatory, Columbia University

The concept of Pacific Decadal Climate Variability (PDV) was introduced in a series of high-visibility articles during 1990s (though J. Namias already discussed evidence for the existence of such low-frequency behavior in 1978. The phenomenon (initially referred to as the Pacific Decadal Oscillation—PDO) was identified when studying climate variability in the North Pacific and contrasting it with the strong interannual variability (ENSO) in the tropics. The PDV was found connected with important environmental impacts in the countries surrounding the Pacific Basin and with changes in ocean circulation patterns and ocean biology. The PDV however also affects the tropics as a slow and relatively small (compared to ENSO) fluctuation in the tropical Pacific east west SST gradient (referred to as the Inter-Decadal Pacific Oscillation, IPO), consistent variations in the strength of the trade winds, and consequently changes in convection and precipitation patterns. These changes in surface variables and tropical diabatic heating gradients make PDV an important forcing agent of a global climate dynamical response. Broadly speaking, the PDV is considered as an internally driven natural mode of variability though it may also be invoked by slow changes in external forcing. It is not fully understood whether there is a single unique form of PDV. Also, because of the relatively short instrumental record it's not clear what the time scale of PDV is, if there is a distinct one, and what controls this time scale. Moreover, already early after it was defined, the PDV was identified as associated with what appeared to be a perplexing, distinct rapid shift (around 1976) in North Pacific sea level pressure, winds, ocean temperatures and ocean currents. Paleoclimate proxies provide useful information in better characterizing the time scale and spatial pattern of PDV.

Robust and non-robust aspects of AMOC intrinsic variability and mechanisms in the Community Earth System Model (CESM)

Gokhan Danabasoglu, National Center for Atmospheric Research

Atlantic Meridional Overturning Circulation (AMOC) is presumed to play a major role in decadal and longer time scale climate variability and in prediction of the earth's future climate on these time scales. The primary support for such a prominent role for AMOC comes from coupled model simulations. They show rich AMOC variability, but time scales of variability and mechanisms differ substantially among models. A topic that remains largely unexplored is the role that an ocean model's subgrid scale parameterizations play in AMOC intrinsic variability. Here, we present an assessment of the impacts of several, loosely-constrained ocean model parameter choices on AMOC characteristics in CESM with the primary goal of identifying both robust and non-robust elements of AMOC variability and mechanisms. Specifically, we change parameter values in mesoscale, sub-mesoscale, vertical mixing, and lateral viscosity parameterizations in the ocean model. The characteristics of AMOC from these simulations are then compared with a three-member ensemble of experiments in which the initial atmospheric temperature field is slightly perturbed. We find that both the amplitude and time scale of AMOC variability differ considerably among all these experiments with dominant time scales of variability ranging from decadal to centennial. There are also substantial differences in the relative contributions of temperature and salinity anomalies to the positive density anomalies created in the model's deep-water formation (DWF) region prior to AMOC intensifications.

Nevertheless, we identify some robust elements of AMOC variability mechanisms. These include: i) The Labrador Sea is the key region with upper-ocean density and boundary layer anomalies preceding AMOC anomalies; ii) Enhanced Nordic Sea overflow transports do not lead to an increase in AMOC maximum transports; iii) Persistent positive phase of the North Atlantic Oscillation plays a significant role in setting up the density anomalies that lead to AMOC intensification via surface buoyancy fluxes; and iv) After AMOC intensification, subsequent weakening is due to advection of positive temperature anomalies into the model's DWF region.

Understanding tropical Atlantic decadal variability: The role of tropical Pacific versus subpolar Atlantic:

Mingfang Ting, Lamont-Doherty Earth Observatory, Columbia University

The Atlantic Multidecadal Variability (AMV) has been shown to affect precipitation globally. In particular, the frequency and severity of droughts across North America has been modulated by the phase of the Atlantic Multidecadal Variability (AMV) over the historical period. The decadal oscillations in U. S. West hydroclimate (associated with ENSO) reach extreme severity during the warm and neutral phases of AMV, such as in the 1930s and the 1950s when the U. S. Great Plains and the Southwest experienced the extremely dry conditions of the Dust Bowl and the persistent Texas drought, respectively. When AMV was in its cold phase in the early 1900s and from 1965 to 1995 droughts were less frequent or severe. The hydroclimate impacts of AMV are believed to be dominated by its tropical component through changes in tropical convection and related circulation changes.

This study explores the inter-connection between the tropical Pacific and North Atlantic using both available historical observations and the Climate Model Intercomparison Project Phase 5 (CMIP5) climate models. The interconnection between the tropical Pacific and the tropical Atlantic on decadal time scale is found to be crucial in realistically representing the hydroclimate impacts of the AMV on North America. We found that decadal ENSO variability plays a more dominant role in CMIP5 models compared to observations in causing the decadal tropical Atlantic SST anomalies. Depending on how decadal tropical Atlantic SST anomalies are generated in CMIP5 models, whether it is dominated by ENSO conditions in the tropical Pacific or subpolar SST anomalies, the warm AMV-dry North America relationship as observed can be severely underestimated in models. By examining how the tropical component of the AMV is generated, it provides a useful metric for evaluating the realism of the model AMV as well as understanding its physical mechanisms.

The impact of the North Atlantic Oscillation on climate through its influence on the Atlantic Meridional Overturning Circulation:

Tom Delworth, GFDL

Prominent multidecadal climate variations have been observed over the Atlantic and Arctic oceans and surrounding continents over the last 130+ years. Here we use climate model simulations to explore the possible role of multidecadal variations of the North Atlantic Oscillation (NAO) for this observed variability through its effect on the Atlantic Meridional Overturning Circulation (AMOC. Perturbation experiments are conducted in which patterns of anomalous fluxes corresponding to the NAO are added to the model ocean; in companion experiments no such fluxes are added. Differences between the experiments illustrate how the model ocean and climate system respond to the NAO. A positive phase of the NAO tends to strengthen the AMOC by extracting heat from the subpolar gyre, thereby increasing deepwater formation, horizontal density gradients, and the AMOC.

The flux forcings have the spatial structure of the observed NAO, but the amplitude of the forcing varies in time. The temporal variation of the imposed fluxes is one of the following types: (a) sudden switch on of the flux forcing, (b) vary the amplitude of the flux forcing sinusoidally in time with distinct periods varying from 2 to 200 years, (c) vary the flux forcing to match the observed time sequence of the NAO over the 20th and early 21st centuries. In the idealized experiments we show that the response of the AMOC to NAO variations is small at short time scales, but increases up to the dominant time scale of internal AMOC variability (20-30 years for the models used. The amplitude of the response of the AMOC, and associated oceanic heat transport, is approximately constant as the time scale of the forcing is increased further. In contrast, the response of other properties, such as hemispheric surface air temperature or Arctic sea ice, continues to increase as the time scale of the forcing becomes progressively longer. The larger response of temperature and sea ice is associated with an increased impact of radiative feedback processes at progressively longer time scales. The impact of the NAO on the AMOC and climate is a function of the dominant time scale of internal AMOC variability, as well as the background mean state. In the experiments using the observed sequence of the NAO we estimate the contribution of NAO-induced AMOC anomalies to climate variations in the 20th and early 21st centuries. We show that NAO-induced AMOC variations may have contributed substantially to multidecadal warming and cooling of the Northern Hemisphere, including cooling from the 1960s through the 1980s, and warming from the 1980s through the 2000s. We further show that such NAO-induced AMOC variations could have contributed to the observed reduction of sea ice in the 1990s and 2000s, as well as a possible remote influence on the Southern Ocean, including sea ice.

Predictability of the recent slowdown and subsequent recovery of large-scale surface warming using statistical methods

Michael E. Mann, Pennsylvania State University

The recent, temporary slowdown in large-scale surface warming has been attributed to both external and internal sources of climate variability. Using semi-empirical estimates of the internal low-frequency variability component in Atlantic, Pacific, and Northern Hemisphere surface temperature in concert with statistical hindcast experiments, we investigate whether the slowdown and its recent recovery were predictable in advance, and conclude that they likely were not. The internal variability of the North Pacific, which played a critical role in the slowdown, does not appear to be predictable in advance using statistical forecast methods. An additional minor contribution from the North Atlantic, by contrast, appears to exhibit some predictability. While our analyses focus on combining semi-empirical estimates of internal climatic variability with statistical hindcast experiments, some possible implications for initialized predictions are also discussed.

Decadal variability in Pacific trade winds inferred from coral Mn/Ca: Implications for the rate of global warming

Diane M. Thompson

Decadal variations in zonal wind strength and direction may play an important role in modulating the El Niño-Southern Oscillation (ENSO) and the rate of global temperature rise. However, historical observations of tropical Pacific winds are limited, and existing datasets disagree on long-term trends, emphasizing the need for independent data to assess zonal wind variability. Earlier work suggested that the ratio of manganese to calcium in corals from islands with westerly facing lagoons may record westerly winds associated with the onset and maintenance of El Niño events. These westerly wind anomalies trigger strong physical mixing and release of Mn from the Mn-enriched lagoonal sediments, which is incorporated into the coral skeleton. Here I present a new ~90 year Mn/Ca record from

Tarawa that provides further support for the link between the frequency of westerly winds and coral Mn/Ca. This new Mn/Ca record provides a means to assess westerly wind anomalies before the mid-20th century, when instrumental data from the tropical Pacific are scarce. Along with a Sr/Ca-SST reconstruction from the eastern tropical Pacific, this wind reconstruction corroborates and extends the idea, developed from models and analyses of the well-observed late 20th century, that periods of strong Pacific trade winds are associated with cooler equatorial Pacific SSTs and a slower rate of global warming, and vice versa. By adding Mn/Ca to the suite of coral tracers measured for paleoclimate reconstructions from appropriate sites, we can expand our view of past climate variability to include westerly winds, along with the more commonly reconstructed variables of SST and salinity. Development of additional Mn/Ca records from other equatorial atolls with westerly facing lagoons will be used to obtain a broader multivariate perspective on the dynamics of recent decadal climate variability.

Paleo-constraints on decadal climate variability in the tropical Pacific

Kim Cobb, Georgia Tech

The tropical Pacific is a prominent source of decadal-scale global climate variability, with a variety of coupled ocean-atmosphere dynamical processes giving rise to the Pacific Decadal Oscillation (PDO; Mantua et al., 1997) and the North Pacific Gyre Oscillation (NPGO; Di Lorenzo et al., 2008. Indeed, Pacific decadal variability has been implicated in the observed slow-down of global surface temperature over the last decade (Kosaka and Xie, 2013; England et al., 2014; Nieves et al., 2015), which is turn may be linked to the magnitude and spatial footprint of recent ENSO extremes (e. g. McPhaden and McClurg, 2011. Here we assess the characteristics of Pacific decadal variability over the last millennium using coral paleoclimate records of SST and hydrology, and compare these records to the evolution of 20th century Pacific decadal variability, with an eye towards isolating potential anthropogenic trends in Pacific climate.

Radiative forcing contributions to changes in recent rates of global warming:

Susan Solomon, Massachusetts Institute of Technology

This talk will briefly survey what is known and what is not known about radiative forcing changes during the period from 2000-2014, and will summarize how these can contribute to the decadal rates of global warming. In addition to greenhouse gases, changes in volcanic aerosol impacts, solar forcing, stratospheric water vapor and tropospheric aerosols will be discussed. Implications for future observational needs will be briefly described.

How long could the current hiatus in global warming last?

Thomas R. Knutson, NOAA GFDL

Global mean temperature did not rise steadily since the late 1800s but rose primarily during two rapid warming periods (early 20th century and late 20th century) which were separated by a pause in warming from about 1940-1970. Could another such multidecadal pause occur at the beginning of the 21st century, and if so by what processes could this occur? At one extreme, the current global warming "hiatus" could end shortly (or may have already ended. However, at the other extreme we ask: How long could the current hiatus in global warming potentially last? To explore this issue, we analyze the internal multidecadal variability of global mean temperature in the GFDL CM3 model control run and test the potential influence of such internal variability on 21st century global mean temperature evolution, including current projections of future warming from anthropogenic forcings (e. g., CMIP5 models. We also explore the plausibility of CM3's multidecadal variability based on comparisons with historical trends.

Impact of data coverage and quality control on global surface temperature trends: Part 1—Overview and sea surface temperature aspects

Huai-Min Zhang, NOAA National Centers for Environmental Information (NCEI)

The recent paper by Karl et al. (2015) highlighted the importance of data homogenization and bias correction in resolving the so-called global "Warming Hiatus" from observational analyses. In this talk we present the details of these impacts on the global and regional surface temperature trends in various time scales. The impacts are studied using the data quality control and bias correction processes used in the NOAA's centennial time scale sea surface temperature (SST) products, as well as the data gaps in the majorly available international datasets. Additional analysis of subsurface observations, mainly obtained by the Argo floats in recent decades, also shows continued warming over previous decades. Lastly, we analyze the consistency and discrepancy of satellite and in-situ based SSTs since the early 1980s when satellite data became available, and clarify their utilization limitations in determining the trends and other variabilities such as El Niño signals.

Impact of data coverage and quality control on global surface temperature trends: Part 2—Land surface air temperature aspects

Matt Menne, NOAA National Centers for Environmental Information (NCEI)

Land surface temperature air temperature (LSAT) records have been compiled from a variety of sources over the past few decades. Here we discuss the recent effort to improve land surface station temperature data holdings known as the International Surface Temperature Initiative (ISTI) and how these holdings are being used to produce a new NOAA analysis of land surface air temperature since the late 19th Century. A comparison of this latest analysis to other datasets will be discussed as well as efforts to extend global surface air temperature analysis over the Arctic Ocean.

Pacific temporarily hid heat below surface

Veronica Nieves, JPL

The recent hiatus in global warming was caused by a sequestration of heat in the subsurface tropical Pacific waters and was symptomatic of decadal variability. This natural variability is superimposed on the long-term human-caused warming trend, and dominates on a decadal time scale with large regional societal impacts. Heat traveled west in the subsurface 100-300 m depth layer (from the eastern Pacific to the central/western Pacific and Indian Ocean) due to unusually strong trade winds during the early 21st century. The important question is whether the trapped heat will move up to the surface when the Pacific changes to a warm phase or will it be absorbed into the deeper layers of the ocean in the next decade or two. If it mixes down, the significant unknown is how rapidly it will be vertically mixed into the ocean and how it will moderate global temperatures.

Understanding decadal climate variability using formal model-data synthesis

Patrick Heimbach, UT Austin

Formal model-data synthesis (loosely termed data assimilation) seeks to optimally combine information contained in observations from heterogeneous (and sparse) data streams and models that obey known conservation laws exactly. Different techniques lead to different pitfalls in the use of these products. In particular, so-called ocean reanalyses, like atmospheric reanalyses do not conserve properties over time, in particular heat and freshwater, thus rendering their use for assessing decadal changes in properties problematic. After illustrating the issue, we present results from a global bidecadal (1992-2011) dynamically consistent ocean state estimate, with an emphasis on global heat content changes and vertical redistribution of heat. Both show large lateral and vertical variations. Net vertical cooling at depth may be an expression of long term oceanic memory processes. We discuss challenges for designing an observing system suitable for understanding decadal climate variability and future requirements for estimation systems.

Consequences of uncertainty in air-sea exchange

Baylor Fox-Kemper, Brown University

The heat capacity of the ocean greatly exceeds that of the atmosphere, which leads to significant exchanges and variability of the coupled system on seasonal and longer timescales. I will describe some of the key processes in the air-sea exchange, emphasizing in particular those processes which are poorly observed and modeled—due to their intermittency and small scale—and insufficiently understood to be parameterized. I will then estimate their cumulative effect on the global heat budget and surface temperature, emphasizing the decadal and longer timescales.

The ocean's role in polar climate change: asymmetric Arctic and Antarctic responses to greenhouse gas and ozone forcing.

John Marshall, Massachusetts Institute of Technology

In recent decades, the Arctic has been warming and sea ice disappearing. By contrast, the Southern Ocean around Antarctica has been (mainly) cooling and sea-ice extent growing. We argue here that inter-hemispheric asymmetries in the mean ocean circulation, with sinking in the northern North Atlantic and upwelling around Antarctica, strongly influence the sea-surface temperature (SST) response to anthropogenic greenhouse gas (GHG) forcing, accelerating warming in the Arctic while delaying it in the Antarctic. Furthermore, while the amplitude of GHG forcing has been similar at the poles, significant ozone depletion only occurs over Antarctica. We suggest that the initial response of SST around Antarctica to ozone depletion is one of cooling and only later adds to the GHG-induced warming trend as upwelling of sub-surface warm water associated with stronger surface westerlies impacts surface properties.

Arctic changes and mid-latitude weather linkages in the coming decades:

James Overland, NOAA/Pacific Marine Environmental Laboratory, Seattle, WA

Ongoing temperature changes in the Arctic are large relative to lower latitudes; a process known as Arctic Amplification. Arctic temperatures have increased 2-3 times the rate of mid-latitude temperatures relative to the late 20th century, due to multiple interacting feedbacks driven by modest global change. Even if global temperature increases are contained to +2 C by 2040, Arctic (North of 60 N) monthly mean temperatures in fall will increase by +5 C. The Arctic is very likely to be sea ice free during summer before 2040 and snow cover will be absent in May and June on most land masses. Thus for the next few decades out to 2040, continuing rapid environmental changes in the Arctic are very likely, despite mitigation activities, and the appropriate response is to plan for adaptation to meet mean and extreme event changes. Mitigation is essential to forestall further disasters in the second half of the century. Whether these changes impact mid-latitude extreme weather events is complex and controversial, as the time period for observing such linkages is short [<10 years] and involves understanding direct forcing by Arctic changes on a chaotic climatic system. There is general agreement that there will be no net mid-latitude cooling, only a potential for impacting severe events. Linkages will be regional, episodic, and based on amplification of existing weather patterns such as Greenland atmospheric blocking and the Siberian High. It is important to note such future rapid Arctic amplification and the potential for environmental surprises.

Indian Ocean variability and its impact on regional climate

Caroline C. Ummenhofer, Woods Hole Oceanographic Institution

The Indian Ocean has sustained robust surface warming in recent decades, with warming rates exceeding those of other tropical ocean basins. However, it remains unclear how multi-decadal variability in upper-ocean thermal characteristics has contributed to these Indian Ocean trends. Temperatures and heat content exhibit extensive subsurface cooling for much of the tropical Indian Ocean since the 1950s, likely due to remote Pacific wind changes associated with the Interdecadal Pacific Oscillation/Pacific Decadal Oscillation. As such, multi-decadal wind forcing has masked increases in Indian Ocean heat content due to thermal forcing since the 1960s. However, wind and thermal forcing both contribute positively to Indian Ocean heat content since the turn of the century. Drastic increases in the heat content in coming decades are therefore likely; in fact, they have been implicated to play a role in the recent warming hiatus.

Multi-decadal variability in Indian Ocean characteristics has implications for regional climate: strength of the Austral-Asian monsoon system, regional hydroclimate, sea-level variations, and marine ecosystems are modulated by Indian Ocean variability. Better decadal predictions of Indian Ocean properties are therefore likely of considerable benefit to vulnerable societies in Indian Ocean rim-countries.

Science is not finished until it is communicated

Susan Hassol, Climate Communication

The enormous societal implications of climate science make effective communication essential. Deeply ingrained misconceptions and decades of disinformation make this more challenging, particularly when communicating about the complex topic of decadal climate variability. Providing context for this topic by reiterating what is known about recent climate change can help avoid people becoming confused or misled by details and uncertainties. This discussion will focus on ways to provide the needed context and communicate what is known about both human-induced climate change and natural decadal climate variability in simple, clear terms. Coming at the end of the workshop, it will be informed by the presentations and discussions of the latest science.

Appendix F
Song Lyrics[1]

To the tune of "Let's Call the Whole Thing Off" by George and Ira Gershwin:

Things have come to a slight impasse,
Global warming has been flat,
Some blame it on sampling
Others say "no, it's not that. "
Goodness knows what the truth will be
But it's only temporary
Meanwhile the skeptics global warming shun
Something must be done,

Don't say hiatus and don't say hi-ah-tus!
That's what we called it, and look what it got us,
Hiatus, hi-ah-tus, the skeptics, they got us,
Let's call the whole thing off.

He says Pacific and she says Atlantic
Where did the heat go, it's making us frantic
Atlantic, Pacific, the heat stores terrific
Let's call the whole thing off.
But oh, even where the data's sparse, we'll find a little hint
We'll use stats and modeling to parse a fingerprint

IPO, AMV, or PDV do you favor?
Could be the ENSO, in one or more flavor,
The AMOC, the tropics, there's so many topics,
Let's call the whole thing off.
But Oh, if we call the whole thing off, then we must part
And oh! If we have to part,
Then that might break my heart.
So you take the paleo, you take the poles
You look at forcings to fill in the holes
For we know we need each other,
So we better call the calling off off!
Let's call the whole thing off!

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[1] These lyrics were written by rapporteur Nancy Huddleston and performed at the working dinner on September 3, 2015. Lyrics do not represent the views of all workshop participants, the planning committee, or the National Academies of Sciences, Engineering, and Medicine.