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Large-scale circulation and climate variability

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Abstract

1. The tropics have expanded poleward by about 70 to 200 miles in each hemisphere over the period 1979-2009, with an accompanying shift of the subtropical dry zones, midlatitude jets, and storm tracks *(medium to high confidence)*. Human activities have played a role in this change *(medium confidence)*, although confidence is presently *low* regarding the magnitude of the human contribution relative to natural variability.

2. Recurring patterns of variability in large-scale atmospheric circulation (such as the North Atlantic Oscillation and Nordlem Annular Mode) and the atmosphere-ocean system (such as El Niño-Southern Oscillation) cause year-to-year variations in U.S. temperatures and precipitation *(high confidence)*. Changes in the occurrence of these patterns or their properties have contributed to recent U.S. temperature and precipitation trends *(medium confidence)*, although confidence is *low* regarding the size of the role of human activities in these changes.

5. Large-Scale Circulation and Climate Variability

KEY FINDINGS

1. The tropics have expanded poleward by about 70 to 200 miles in each hemisphere over the period 1979–2009, with an accompanying shift of the subtropical dry zones, midlatitude jets, and storm tracks (*medium to high confidence*). Human activities have played a role in this change (*medium confidence*), although confidence is presently *low* regarding the magnitude of the human contribution relative to natural variability.

2. Recurring patterns of variability in large-scale atmospheric circulation (such as the North Atlantic Oscillation and Northern Annular Mode) and the atmosphere–ocean system (such as El Niño–Southern Oscillation) cause year-to-year variations in U.S. temperatures and precipitation (*high confidence*). Changes in the occurrence of these patterns or their properties have contributed to recent U.S. temperature and precipitation trends (*medium confidence*), although confidence is *low* regarding the size of the role of human activities in these changes.

5.1.Introduction

The causes of regional climate trends cannot be understood without considering the impact of variations in large-scale atmospheric circulation and an assessment of the role of internally generated climate variability. There are contributions to regional climate trends from changes in large-scale latitudinal circulation, which is generally organized into three cells in each hemisphere—Hadley cell, Ferrell cell and Polar cell—and which determines the location of subtropical dry zones and midlatitude jet streams (Figure 5.1). These circulation cells are expected to shift poleward during warmer periods (Frierson et al. 2007; Sun et al. 2013; Vallis et al. 2015; Mbengue and Schneider 2017), which could result in poleward shifts in precipitation patterns, affecting natural ecosystems, agriculture, and water resources (Seidel et al. 2008; Feng and Fu 2013).

[INSERT FIGURE 5.1 HERE]

In addition, regional climate can be strongly affected by non-local response to recurring patterns (or modes) of variability of the atmospheric circulation or the coupled atmosphere–ocean system. These modes of variability represent preferred spatial patterns and their temporal variation. They account for gross features in variance and for teleconnections which describe climate links between geographically separated regions. Modes of variability are often described as a product of a spatial climate pattern and an associated climate index time series that are identified based on statistical methods like Principal Component Analysis (PC analysis), which is also called Empirical Orthogonal Function Analysis (EOF analysis), and cluster analysis.

On intraseasonal to interannual time scales, the climate of the United States is strongly affected by modes of atmospheric circulation variability like the North Atlantic Oscillation (NAO)/Northern Annular Mode (NAM), North Pacific Oscillation (NPO), and Pacific/North American Pattern (PNA) (Hurrell and Deser 2009; Linkin and Nigam 2008; Ning and Bradley 2016). These modes are closely linked to other atmospheric circulation phenomena like blocking and quasi-stationary wave patterns and jet streams that can lead to weather and climate extremes (Grotjahn et al. 2016). On an interannual time scale, coupled atmosphere–ocean phenomena like El Niño–Southern Oscillation (ENSO) have a prominent effect (Halpert and Ropelewski 1992). On longer time scales, U.S. climate anomalies are linked to slow variations of sea surface temperature related to the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO) (Newman et al. 2016; Enfield et al. 2001; Goldenberg et al. 2001).

These modes of variability can affect the local-to-regional climate response to external forcing in various ways. The climate response may be altered by the forced response of these existing, recurring modes of variability (Perlwitz et al. 2008). Further, the structure and strength of regional temperature and precipitation impacts of these recurring modes of variability may be modified due to a change in the background climate (Palmer et al. 2008). Modes of internal variability of the climate system also contribute to observed decadal and multidecadal temperature and precipitation trends on local to regional scales, masking possible systematic changes due to an anthropogenic influence (Deser et al. 2016). However, there are still large uncertainties in our understanding of the impact of human-induced climate change on atmospheric circulation (Shepherd 2014; Vallis et al. 2015). Furthermore, the confidence in any specific projected change in ENSO variability in the 21st century remains *low* (Christensen et al. 2013).

5.2 Modes of Variability: Past and Projected Changes

5.2.1 Width of the Tropics and Global Circulation

Evidence continues to mount for an expansion of the tropics over the past several decades, with a poleward expansion of the Hadley cell and an associated poleward shift of the subtropical dry zones and storm tracks in each hemisphere (Hartmann et al. 2013; Davis and Birner 2013; Feng and Fu 2013; Birner et al. 2014; Karnauskas and Ummenhofer 2014; Lucas et al. 2014; Quan et al. 2014; Brönnimann et al. 2015; Garfinkel et al. 2015; Norris et al. 2016; Reichler 2016). The rate of expansion is uncertain and depends on the metrics and data sources that are used. Recent estimates of the widening of the global tropics for the period 1979–2009 range between 1° and 3° latitude (between about 70 and 200 miles) in each hemisphere, an average trend of between approximately 0.5° and 1.0° per decade (Lucas et al. 2014). While the roles of increasing greenhouse gases in both hemispheres (Bindoff et al. 2013; Vallis et al. 2015), stratospheric ozone depletion in the Southern Hemisphere (Waugh et al. 2015), and anthropogenic aerosols in the Northern Hemisphere (Allen et al. 2012; Kovilakam and Mahajan 2015) have been

implicated as contributors to the observed expansion, there is uncertainty in the relative contributions of natural and anthropogenic factors, and natural variability may be dominating (Adam et al. 2014; Allen et al. 2014; Garfinkel et al. 2015).

Most of the previous work on tropical expansion to date has focused on zonally averaged changes. There are only a few recent studies that diagnose regional characteristics of tropical expansion. The findings depend on analysis methods and datasets. For example, a northward expansion of the tropics in most regions of the Northern Hemisphere, including the Eastern Pacific with impact on drying in the American Southwest, is found based on diagnosing outgoing longwave radiation (Chen et al. 2014). However, other studies do not find a significant poleward expansion of the tropics over the Eastern Pacific and North America (Lucas and Nguyen 2015; Schwendike et al. 2015). Thus, while some studies associate the observed drying of the U.S. Southwest with the poleward expansion of the tropics (Feng and Fu 2013; Prein et al. 2016), regional impacts of the observed zonally averaged changes in the width of the tropics are not understood.

Due to human-induced greenhouse gas increases, the Hadley cell is likely to widen in the future, with an accompanying poleward shift in the subtropical dry zones, midlatitude jets, and storm tracks (Scheff and Frierson 2012a,b; Barnes and Polvani 2013; Collins et al. 2013; Feng and Fu 2013; Vallis et al. 2015; Mbengue and Schneider 2017). Large uncertainties remain in projected changes in non-zonal to regional circulation components and related changes in precipitation patterns (Barnes and Polvani 2013; Shepherd 2014; Simpson et al. 2014, 2016). Uncertainties in projected changes in midlatitude jets are also related to the projected rate of arctic amplification and variations in the stratospheric polar vortex. Both factors could shift the midlatitude jet equatorward, especially in the North Atlantic region (Karpechko and Manzini 2012; Scaife et al. 2012; Cattiaux and Cassou 2013; Barnes and Polvani 2015).

5.2.2 El Niño–Southern Oscillation

El Niño–Southern Oscillation (ENSO) is a main source of climate variability, with a two- to seven-year timescale, originating from coupled ocean–atmosphere interactions in the tropical Pacific. Major ENSO events affect weather patterns over many parts of the globe through atmospheric teleconnections. ENSO strongly affects precipitation and temperature in the United States with impacts being most pronounced during the cold season (Figure 5.2) (Ropelewski and Halpert 1987; Kiladis and Diaz 1989; Halpert and Ropelewski 1992; Hoerling et al. 2001; T. Zhang et al. 2016). A cooling trend of the tropical Pacific Ocean that resembles La Niña conditions contributed to drying in southwestern North America from 1979 to 2006 (Hoerling et al. 2010) and is found to explain most of the decrease in heavy daily precipitation events in the southern United States from 1979 to 2013 (Hoerling et al. 2016).

[INSERT FIGURE 5.2 HERE]

El Niño teleconnections are modulated by the location of maximum anomalous tropical Pacific sea surface temperatures (SST). Eastern Pacific (EP) El Niño events affect winter temperatures primarily over the Great Lakes, Northeast, and Southwest, while Central Pacific (CP) events influence temperatures primarily over the northwestern and southeastern United States (Yu et al. 2012). The CP El Niño also enhances the drying effect, but weakens the wetting effect, typically produced by traditional EP El Niño events on the United States winter precipitation (Yu and Zou 2013). It is not clear whether observed decadal-scale modulations of ENSO properties, including an increase in ENSO amplitude (Li et al. 2011) and an increase in frequency of CP El Niño events (Yeh et al. 2009; Lee and McPhaden 2010), are due to internal variability or anthropogenic forcing. Uncertainties in both the diagnosed distinct U.S. climate effects of EP and CP events and causes for the decadal scale changes result from the limited sample size of observed ENSO events in each category (Garfinkel et al. 2013; Deser et al. 2017) and the relatively short record of the comprehensive observations (since late 1970s) that would allow the investigation of ENSO-related coupled atmosphere–ocean feedbacks (Christensen et al. 2013). Furthermore, unforced global climate model simulations show that decadal to centennial modulations of ENSO can be generated without any change in external forcing (Capotondi et al. 2015). A model study based on large, single-model ensembles of atmospheric and coupled atmosphere–ocean models finds that external radiative forcing resulted in an atmospheric teleconnection pattern that is independent of ENSO-like variations during the 1979–2014 period and is characterized by a hemisphere-scale increasing trend in heights (T. Zhang et al. 2016).

The representation of ENSO in climate models has improved from CMIP3 to CMIP5 models, especially in relation to ENSO amplitude (Flato et al. 2013; Bellenger et al. 2014). However, CMIP5 models still cannot capture the seasonal timing of ENSO events (Sheffield et al. 2013). Furthermore, they still exhibit errors in simulating key atmospheric feedbacks, and the improvement in ENSO amplitudes might therefore result from error compensations (Bellenger et al. 2014). Limited observational records and the nonstationarity of tropical Pacific teleconnections to North America on multidecadal time scales pose challenges for evaluating teleconnections between ENSO and U.S. climate in coupled atmosphere–ocean models (Coats et al. 2013; Deser et al. 2017). For a given SST forcing, however, the atmospheric component of CMIP5 models simulate the sign of the precipitation change over the southern section of North America (Langenbrunner and Neelin, 2013).

Climate projections suggest that ENSO will remain a primary mode of natural climate variability in the 21st century (Christensen et al. 2013). Climate models do not agree, however, on projected changes in the intensity or spatial pattern of ENSO (Christensen et al 2013). This uncertainty is related to a model dependence of simulated changes in the zonal gradient of tropical Pacific sea surface temperature in a warming climate (Christensen et al. 2013). Model studies suggest an eastward shift of ENSO-induced teleconnection patterns due to greenhouse gas-induced climate change (Meehl and Teng 2007; Kug et al. 2010; Stevenson 2012; Zhou et al. 2014). However,

the impact of such a shift on ENSO-induced climate anomalies in the United States is not well understood (Seager et al. 2012; Zhou et al. 2014).

In summary, there is *high confidence* that, in the 21st century, ENSO will remain a main source of climate variability over the United States on seasonal to interannual timescales. There is *low confidence* for a specific projected change in ENSO variability.

5.2.3 Extra-tropical Modes of Variability and Phenomena

NORTH ATLANTIC OSCILLATION AND NORTHERN ANNULAR MODE

The North Atlantic Oscillation (NAO), the leading recurring mode of variability in the extratropical North Atlantic region, describes an opposing pattern of sea level pressure between the Atlantic subtropical high and the Iceland/Arctic low. Variations in the NAO are accompanied by changes in the location and intensity of the Atlantic midlatitude storm track and blocking activity that affect climate over the North Atlantic and surrounding continents. A negative NAO phase is related to anomalously cold conditions and an enhanced number of cold outbreaks in the eastern United States, while a strong positive phase of the NAO tends to be associated with above-normal temperatures in this region (Hurrell and Deser 2009; Thompson and Wallace 2001). The positive phase of the NAO is associated with increased precipitation frequency and positive daily rainfall anomalies, including extreme daily precipitation anomalies in the northeastern United States (Archambault et al. 2008; Durkee et al. 2008).

The Northern Annular Mode/Arctic Oscillation (NAM/AO) is closely related to the NAO. It describes a pressure seesaw between mid- and high latitudes on a hemispheric scale, and thus includes a third anomaly center over the North Pacific Ocean (Thompson and Wallace 1998; Thompson and Wallace 2000). The time series of the NAO and NAM/AO are highly correlated, with persistent NAO and NAM/AO events being indistinguishable (Deser 2000; Feldstein and Franzke 2006).

The wintertime NAO/NAM index exhibits pronounced variability on multidecadal time scales, with an increase from the 1960s to the 1990s, a shift to a more negative phase since the 1990s due to a series of winters like 2009–2010 and 2010–2011 (which had exceptionally low index values), and a return to more positive values after 2011 (Bindoff et al. 2013). Decadal scale temperature trends in the eastern United States, including occurrences of cold outbreaks during recent years, are linked to these changes in the NAO/NAM (Hurrell 1995; Cohen and Barlow 2005; Overland et al. 2015; Overland and Wang 2015).

The NAO's influence on the ocean occurs through changes in heat content, gyre circulations, mixed layer depth, salinity, high-latitude deep water formation, and sea ice cover (Hurrell and Deser 2009; Delworth et al. 2016). Climate model simulations show that multidecadal variations in the NAO induce multidecadal variations in the strength of the Atlantic Meridional Overturning Circulation (AMOC) and poleward ocean heat transport in the Atlantic, extending to

the Arctic, with potential impacts on recent Arctic sea ice loss and Northern Hemisphere warming (Delworth et al. 2016). However, other model simulations suggest that the NAO and recent changes in Northern Hemisphere climate were affected by recent variations in the AMOC (Peings and Magnusdottir 2014) for which enhanced freshwater discharge from the Greenland Ice Sheet (GrIS) may have been a contributing cause (Yang et al. 2016).

Climate models are widely analyzed for their ability to simulate the spatial patterns of the NAO/NAM and their relationship to temperature and precipitation anomalies over the United States (Flato et al. 2013; Ning and Bradley 2016; Gong et al. 2017). Climate models reproduce the broad spatial and temporal features of the NAO, although there are large differences among the individual models in the location of the NAO centers of action and their average magnitude. These differences affect the agreement between observed and simulated climate anomalies related to the NAO (Flato et al. 2013; Ning and Bradley 2016). Climate models tend to have a NAM pattern that is more annular than observed (Flato et al. 2013; Gong et al. 2017), resulting in a strong bias in the Pacific center of the NAM. As a result, temperature anomalies over the northwestern United States associated with the NAM in most models are of opposite sign compared to observation (Gong et al. 2017). Biases in the model representation of NAO/NAM features are linked to limited abilities of general circulation models to reproduce dynamical processes, including atmospheric blocking (Davini and Cagnazzo, 2014), troposphere–stratosphere coupling (Shaw et al. 2014), and climatological stationary waves (Lee and Black 2013; Shaw et al. 2014).

The CMIP5 models on average simulate a progressive shift of the NAO/NAM towards the positive phase due to human-induced climate change (Gillett and Fyfe 2013). However, the spread between model simulations is larger than the projected multimodel increase (Christensen et al. 2013), and there are uncertainties related to emissions scenarios (Ning and Bradley 2016). Furthermore, it is found that shifts between preferred periods of positive and negative NAO phase will continue to occur similar to those observed in the past (Deser et al. 2012; Christensen et al. 2013). There is no consensus on the location of changes of NAO centers among the global climate models under future warming scenarios (Ning and Bradley 2016). Uncertainties in future projections of the NAO/NAM in some seasons are linked to model spread in projected future Arctic warming (Cattiaux and Cassou 2013; Barnes and Polvani 2015; Ch. 11: Arctic Changes) and to how models resolve stratospheric processes (Christensen et al. 2013; Manzini et al. 2014).

In summary, while it is *likely* that the NAO/NAM index will become slightly more positive (on average) due to increases in GHGs, there is *low confidence* in temperature and precipitation changes over the United States related to such variations in the NAO/NAM.

NORTH PACIFIC OSCILLATION/WEST PACIFIC OSCILLATION

The North Pacific Oscillation (NPO) is a recurring mode of variability in the extratropical North Pacific region and is characterized by a north-south seesaw in sea level pressure. Effects of NPO on U.S. hydroclimate and marginal ice zone extent in the Arctic seas have been reported (Linkin and Nigam 2008).

The NPO is linked to tropical sea surface temperature variability. Specifically, NPO contributes to the excitation of ENSO events via the "Seasonal Footprinting Mechanism" (Vimont et al. 2003; Alexander et al. 2010). In turn, warm events in the central tropical Pacific Ocean are suggested to force an NPO-like circulation pattern (Di Lorenzo et al. 2010). There is *low confidence* in future projections of the NPO due to the small number of modeling studies as well as the finding that many climate models do not properly simulate the observed linkages between NPO and tropical sea surface temperature variability (Furtado et al. 2011; Christensen et al. 2013).

PACIFIC/NORTH AMERICAN PATTERN

The Pacific/North American (PNA) pattern is the leading recurring mode of internal atmospheric variability over the North Pacific and the North American continent, especially during the cold season. It describes a quadripole pattern of mid-tropospheric height anomalies, with anomalies of similar sign located over the subtropical northeastern Pacific and northwestern North America and of the opposite sign centered over the Gulf of Alaska and the southeastern United States. The PNA pattern is associated with strong fluctuations in the strength and location of the East Asian jet stream. The positive phase of the PNA pattern is associated with above average temperatures over the western and northwestern United States, and below average temperatures across the south-central and southeastern United States, including enhanced occurrence of extreme cold temperatures (Leathers et al. 1991; Loikith and Broccoli 2012; Ning and Bradley 2016). Significant negative correlation between the PNA and winter precipitation over the Ohio River Valley has been documented (Leathers et al. 1991; Coleman and Rogers 2003; Ning and Bradley 2016). The PNA is related to ENSO events (Nigam 2003) and also serves as a bridge linking ENSO and NAO variability (Li and Lau 2012).

Climate models are able to reasonably represent the atmospheric circulation and climate anomalies associated with the PNA pattern. However, individual models exhibit differences compared to the observed relationship, due to displacements of the simulated PNA centers of action and offsets in their magnitudes (Ning and Bradley 2016). Climate models do not show consistent location changes of the PNA centers due to increases in GHGs (Zhou et al. 2014; Ning and Bradley 2016). Therefore, there is *low confidence* for projected changes in the PNA and the association with temperature and precipitation variations over the United States.

BLOCKING AND QUASI-STATIONARY WAVES

Anomalous atmospheric flow patterns in the extratropics that remain in place for an extended period of time (for example, blocking and quasi-stationary Rossby waves)—and thus affect a region with similar weather conditions like rain or clear sky for several days to weeks—can lead to flooding, drought, heat waves, and cold waves (Petoukhov et al. 2013; Grotjahn et al. 2016; Whan et al. 2016). Specifically, blocking describes large-scale, persistent high pressure systems that interrupt the typical westerly flow, while planetary waves (Rossby waves) describe large-scale meandering of the atmospheric jet stream.

A persistent pattern of high pressure in the circulation off the West Coast of the United States has been associated with the recent multiyear California drought (Ch. 8: Droughts, Floods, and Wildfire; Swain et al. 2014; Seager et al. 2015; Teng and Branstator 2017). Blocking in the Alaskan region, which is enhanced during La Niña winters (Figure 5.2) (Renwick and Wallace 1996), is associated with higher temperatures in western Alaska but shift to lower mean and extreme surface temperatures from the Yukon southward to the southern Plains (Carrera et al. 2004). The anomalously cold winters of 2009–2010 and 2010–2011 in the United States are linked to the blocked (or negative) phase of the NAO (Guirguis et al. 2011). Stationary Rossby wave patterns may have contributed to the North American temperature extremes during summers like 2011 (Wang et al. 2014). It has been suggested that arctic amplification has already led to weakened westerly winds and hence more slowly moving and amplified wave patterns and enhanced occurrence of blocking (Francis and Vavrus 2012; Francis et al. 2017; Ch. 11: Arctic Changes). While some studies suggest an observed increase in the metrics of these persistent circulation patterns (Francis and Vavrus 2012; Hanna et al. 2016), other studies suggest that observed changes are small compared to atmospheric internal variability (Barnes 2013; Screen and Simmonds 2013; Barnes et al. 2014).

A decrease of blocking frequency with climate change is found in CMIP3, CMIP5, and higher-resolution models (Christensen et al. 2013; Hoskins and Woollings 2015; Kennedy et al. 2016). Climate models robustly project a change in Northern Hemisphere winter quasi-stationary wave fields that are linked to a wetting of the North American West Coast (Brandefelt and Körnich 2008; Haarsma and Selten 2012; Simpson et al. 2014), due to a strengthening of the zonal mean westerlies in the subtropical upper troposphere. However, CMIP5 models still underestimate observed blocking activity in the North Atlantic sector while they tend to overestimate activity in the North Pacific, although with a large intermodel spread (Christensen et al. 2013). Most climate models also exhibit biases in the representation of relevant stationary waves (Simpson et al. 2016).

In summary, there is *low confidence* in projected changes in atmospheric blocking and wintertime quasi-stationary waves. Therefore, our confidence is *low* on the association between observed and projected changes in weather and climate extremes over the United States and variations in these persistent atmospheric circulation patterns.

5.2.4 Modes of Variability on Decadal to Multidecadal Time Scales

PACIFC DECADAL OSCILLATION (PDO) / INTERDECADAL PACIFIC OSCILLATION (IPO)

The Pacific Decadal Oscillation (PDO) was first introduced by Mantua et al. (1997) as the leading empirical orthogonal function of North Pacific (20°–70°N) monthly averaged sea surface temperature anomalies (Newman et al. 2016). Interdecadal Pacific Oscillation (IPO) refers to the same phenomenon and is based on Pacific-wide sea surface temperatures. PDO/IPO lacks a characteristic timescale and represents a combination of physical processes that span the tropics and extratropics, including both remote tropical forcing and local North Pacific atmosphere–ocean interactions (Newman et al. 2016). Consequently, PDO-related variations in temperature and precipitation in the United States are very similar to (and indeed may be caused by) variations associated with ENSO and the strength of the Aleutian low (North Pacific Index, NPI), as shown in Figure 5.3. A PDO-related temperature variation in Alaska is also apparent (Hartmann and Wendler 2005; McAfee 2014).

[INSERT FIGURE 5.3 HERE]

The PDO does not show a long-term trend either in SST reconstructions or in the ensemble mean of historical CMIP3 and CMIP5 simulations (Newman et al. 2016). Emerging science suggests that externally forced natural and anthropogenic factors have contributed to the observed PDO-like variability. For example, a model study finds that the observed PDO phase is affected by large volcanic events and the variability in incoming solar radiation (Wang et al. 2012). Aerosols from anthropogenic sources could change the temporal variability of the North Pacific SST through modifications of the atmospheric circulation (Yeh et al. 2013; Boo et al. 2015). Furthermore, some studies show that periods with near zero warming trends of global mean temperature and periods of accelerated temperatures could result from the interplay between internally generated PDO/IPO-like temperature variations in tropical Pacific Ocean and greenhouse gas-induced ocean warming (Meehl et al. 2013, 2016).

Future changes in the spatial and temporal characteristics of PDO/IPO are uncertain. Based on CMIP3 models, one study finds that most of these models do not exhibit significant changes (Furtado et al. 2011), while another study points out that the PDO/IPO becomes weaker and more frequent by the end of the 21st century in some models (Lapp et al. 2012). Furthermore, future changes in ENSO variability, which strongly contributes to the PDO/IPO (Newman 2007), are also uncertain (Section 5.2.2). Therefore, there is *low confidence* in projected future changes in the PDO/IPO.

ATLANTIC MULTIDECADAL VARIABILITY (AMV) / ATLANTIC MULTIDECADAL OSCILLATION (AMO)

The North Atlantic Ocean region exhibits coherent multidecadal variability that exerts measurable impacts on regional climate for variables such as U.S. precipitation (Enfield et al. 2001; Seager et al. 2008; Feng et al. 2011; Kavvda et al. 2013) and Atlantic hurricane activity (Gray et al. 1997; Landsea et al. 1999; Goldenberg et al. 2001; Chylek and Lesins 2008; Zhang and Delworth 2009; Kossin 2017). This observed Atlantic multidecadal variability, or AMV, is generally understood to be driven by a combination of internal and external factors (Delworth and Mann 2000; Enfield et al. 2001; Knight et al. 2006; Frankcombe et al. 2010; Mann et al. 2014; Terray 2012; Caron et al. 2015; Delworth et al. 2017; Moore et al. 2017). The AMV manifests in sea surface temperature (SST) variability and patterns as well as synoptic-scale variability of atmospheric conditions. The internal part of the observed AMV is often referred to as the Atlantic Multidecadal Oscillation (AMO) and is putatively driven by changes in the strength of the Atlantic Meridional Overturning Circulation (AMOC) (Delworth and Mann 2000; Miles et al. 2014; Trenary and DelSole 2016; Delworth et al. 2017). It is important to understand the distinction between the AMO, which is often assumed to be natural (because of its putative relationship with natural AMOC variability), and AMV, which simply represents the observed multidecadal variability as a whole.

The relationship between observed AMV and the AMOC has recently been called into question and arguments have been made that AMV can occur in the absence of the AMOC via stochastic forcing of the ocean by coherent atmospheric circulation variability, but this is presently a topic of debate (Clement et al. 2015, 2016; R. Zhang et al. 2016; Srivastava and DelSole 2017). Despite the ongoing debates, it is generally acknowledged that observed AMV, as a whole, represents a complex conflation of natural internal variability of the AMOC, natural red-noise stochastic forcing of the ocean by the atmosphere (Mann et al. 2014), natural external variability from volcanic events (Evan 2012; Canty et al. 2013) and mineral aerosols (Evan et al. 2009), and anthropogenic forcing from greenhouse gases and pollution aerosols (Mann and Emanuel 2006; Booth et al. 2012; Dunstone et al. 2013; Sobel et al. 2016).

As also discussed in Chapter 9: Extreme Storms (in the context of Atlantic hurricanes), determining the relative contributions of each mechanism to the observed multidecadal variability in the Atlantic is presently an active area of research and debate, and no consensus has yet been reached (Ting et al. 2009; Carslaw et al. 2013; Zhang et al. 2013; Tung and Zhao 2013; Mann et al. 2014; Stevens 2015; Sobel et al. 2016). Still, despite the level of disagreement about the relative magnitude of human influences (particularly whether natural or anthropogenic factors are dominating), there is broad agreement in the literature of the past decade or so that human factors have had a measurable impact on the observed AMV. Furthermore, the AMO, as measured by indices constructed from environmental data (e.g., Enfield et al. 2001), is generally based on detrended SST data and is then, by construction, segregated from the century-scale

linear SST trends that are likely forced by increasing greenhouse gas concentrations. In particular, removal of a linear trend is not expected to account for all of the variability forced by changes in sulfate aerosol concentrations that have occurred over the past century. In this case, increasing sulfate aerosols are argued to cause cooling of Atlantic SST, thus offsetting the warming caused by increasing greenhouse gas concentration. After the Clean Air Act and Amendments of the 1970s, however, a steady reduction of sulfate aerosols is argued to have caused SST warming that compounds the warming from the ongoing increases in greenhouse gas concentrations (Mann and Emanuel 2006; Sobel et al. 2016). This combination of greenhouse gas and sulfate aerosol forcing, by itself, can lead to Atlantic multidecadal SST variability that would not be removed by removing a linear trend (Canty et al. 2013).

In summary, it is unclear what the statistically derived AMO indices represent, and it is not readily supportable to treat AMO index variability as tacitly representing natural variability, nor is it clear that the observed AMV is truly oscillatory in nature (Vincze and Jánosi 2011). There is a physical basis for treating the AMOC as oscillatory (via thermohaline circulation arguments) (Dima and Lohmann et al. 2007), but there is no expectation of true oscillatory behavior in the hypothesized external forcing agents for the remaining variability. Detrending the SST data used to construct the AMO indices may partially remove the century-scale trends forced by increasing greenhouse gas concentrations, but it is not adequate for removing multidecadal variability forced by aerosol concentration variability. There is evidence that natural AMOC variability has been occurring for hundreds of years (Gray et al. 2004; Mann et al. 2009; Chylek et al. 2011; Knudsen et al. 2014; Miles et al. 2014), and this has apparently played some role in the observed AMV as a whole, but a growing body of evidence shows that external factors, both natural and anthropogenic, have played a substantial additional role in the past century.

5.3. Quantifying the Role of Internal Variability on Past and Future U.S. Climate Trends

The role of internal variability in masking trends is substantially increased on regional and local scales relative to the global scale, and in the extratropics relative to the tropics (Ch. 4: Projections). Approaches have been developed to better quantify the externally forced and internally driven contributions to observed and future climate trends and variability and further separate these contributions into thermodynamically and dynamically driven factors (Deser et al. 2016). Specifically, large "initial condition" climate model ensembles with 30 ensemble members and more (Deser et al. 2012; Deser et al. 2014; Wettstein and Deser 2014) and long control runs (Thompson et al. 2015) have been shown to be useful tools to characterize uncertainties in climate change projections at local/regional scales.

North American temperature and precipitation trends on timescales of up to a few decades are strongly affected by intrinsic atmospheric circulation variability (Deser et al. 2014; Deser et al. 2016). For example, it is estimated that internal circulation trends account for approximately

one-third of the observed wintertime warming over North America during the past 50 years. In a few areas, such as the central Rocky Mountains and far western Alaska, internal dynamics have offset the warming trend by 10%–30% (Deser et al. 2016). Natural climate variability superimposed upon forced climate change will result in a large range of possible trends for surface air temperature and precipitation in the United States over the next 50 years (Figure 5.4) (Deser et al. 2014).

[INSERT FIGURE 5.4 HERE]

Climate models are evaluated with respect to their proper simulation of internal decadal variability. Comparing observed and simulated variability estimates at timescales longer than 10 years suggest that models tend to overestimate the internal variability in the northern extratropics, including over the continental United States, but underestimate it over much of the tropics and subtropical ocean regions (Deser et al. 2012; Knutson et al. 2013). Such biases affect signal-to-noise estimates of regional scale climate change response and thus assessment of internally driven contributions to regional/local trends.

TRACEABLE ACCOUNTS

Key Finding 1

The tropics have expanded poleward by about 70 to 200 miles in each hemisphere over the period 1979–2009, with an accompanying shift of the subtropical dry zones, midlatitude jets, and storm tracks (*medium to high confidence*). Human activities have played a role in this change (*medium confidence*), although confidence is presently *low* regarding the magnitude of the human contribution relative to natural variability

Description of evidence base

The Key Finding is supported by statements of the previous international IPCC AR5 assessment (Hartmann et al. 2013) and a large number of more recent studies that examined the magnitude of the observed tropical widening and various causes (Davis and Birner 2013; Feng and Fu 2013; Birner et al. 2014; Karnauskas and Ummenhofer 2014; Lucas et al. 2014; Quan et al. 2014; Garfinkel et al. 2015; Waugh et al. 2015; Norris et al. 2016; Reichler 2016). Additional evidence for an impact of greenhouse gas increases on the widening of the tropical belt and poleward shifts of the midlatitude jets is provided by the diagnosis of CMIP5 simulations (Barnes and Polvani 2013; Vallis et al. 2015). There is emerging evidence for an impact of anthropogenic aerosols on the tropical expansion in the Northern Hemisphere (Allen et al. 2012; Kovilakam and Mahajan 2015). Recent studies provide new evidence on the significance of internal variability on recent changes in the tropical width (Adam et al. 2014; Allen et al. 2014; Garfinkel et al. 2015).

Major uncertainties

The rate of observed expansion of tropics depends on which metric is used. The linkages between different metrics are not fully explored. Uncertainties also result from the utilization of reanalysis to determine trends and from limited observational records of free atmosphere circulation, precipitation, and evaporation. The dynamical mechanisms behind changes in the width of the tropical belt (e.g., tropical–extratropical interactions and baroclinic eddies) are not fully understood. There is also a limited understanding of how various climate forcings, such as anthropogenic aerosols, affect the width of tropics. The coarse horizontal and vertical resolution of global climate models may limit the ability of these models to properly resolve latitudinal changes in the atmospheric circulation. Limited observational records affect the ability to accurately estimate the contribution of natural decadal to multi-decadal variability on observed expansion of the tropics.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Medium to high confidence that the tropics and related features of the global circulation have expanded poleward is based upon the results of a large number of observational studies, using a wide variety of metrics and data sets, which reach similar conclusions. A large number of studies utilizing modeling of different complexity and theoretical considerations provide compounding evidence that human activities, including increases in greenhouse gases, ozone depletion, and anthropogenic aerosols, contributed to the observed poleward expansion of the tropics. Climate models forced with these anthropogenic drivers cannot explain the observed magnitude of tropical expansion and some studies suggest a possibly large contribution of internal variability. These multiple lines of evidence lead to the conclusion of *medium confidence* that human activities contributed to observed expansion of the tropics.

Summary sentence or paragraph that integrates the above information

The tropics have expanded poleward in each hemisphere over the period 1979–2009 (*medium* to *high confidence*) as shown by a large number of studies using a variety of metrics, observations and reanalysis. Modeling studies and theoretical considerations illustrate that human activities, including increases in greenhouse gases, ozone depletion, and anthropogenic aerosols, cause a widening of the tropics. There is *medium confidence* that human activities have contributed to the observed poleward expansion, taking into account uncertainties in the magnitude of observed trends and a possible large contribution of natural climate variability.

Key Finding 2

Recurring patterns of variability in large-scale atmospheric circulation (such as the North Atlantic Oscillation and Northern Annular Mode) and the atmosphere–ocean system (such as El Niño–Southern Oscillation) cause year-to-year variations in U.S. temperatures and precipitation (*high confidence*). Changes in the occurrence of these patterns or their properties have contributed to recent U.S. temperature and precipitation trends (*medium confidence*), although confidence is *low* regarding the size of the role of human activities in these changes.

Description of evidence base

The Key Finding is supported by a large number of studies that diagnose recurring patterns of variability and their changes, as well as their impact on climate over the United States. Regarding year-to-year variations, a large number of studies based on models and observations show statistically significant associations between North Atlantic Oscillation/Northern Annular Mode and United States temperature and precipitation (Thompson and Wallace 2001; Archambault et al. 2008; Durkee et al. 2008; Hurrell and Deser 2009; Ning and Bradley 2016;

Gong et al. 2017), as well as El Niño–Southern Oscillation and related U.S. climate teleconnections (Ropelewski and Halpert 1987; Kiladis and Diaz 1989; Halpert and Ropelewski 1992; Hoerling et al. 2001; Yu et al. 2012; Yu and Zou 2013; T. Zhang et al. 2016). Regarding recent decadal trends, several studies provide evidence for concurrent changes in the North Atlantic Oscillation/Northern Annular Mode and climate anomalies over the United States (Hurrell 1995; Cohen and Barlow 2005; Overland and Wang 2015; Overland et al. 2015). Modeling studies provide evidence for a linkage between cooling trends of the tropical Pacific Ocean that resemble La Niña and precipitation changes in the southern United States (Hoerling et al. 2010; Hoerling et al. 2016). Several studies describe a decadal modification of ENSO (Yeh et al. 2009; Lee and McPhaden 2010; Li et al. 2011; Capotondi et al. 2013). Modeling evidence is provided that such decadal modifications can be due to internal variability (Capotondi et al. 2015). Climate models are widely analyzed for their ability to simulate recurring patterns of variability and teleconnections over the United States (Furtado et al. 2011; Flato et al. 2013; Langenbrunner and Neelin 2013; Bellenger et al. 2014; Ning and Bradley 2016; Gong et al. 2017). Climate model projections are also widely analyzed to diagnose the impact of human activities on NAM/NAO, ENSO teleconnections, and other recurring modes of variability associated with climate anomalies (Christensen et al. 2013; Gillett and Fyfe 2013; Zhou et al. 2014; Ning and Bradley 2016).

Major uncertainties

A key uncertainty is related to limited observational records and our capability to properly simulate climate variability on decadal to multidecadal time scales, as well as properly simulate recurring patterns of climate variability, underlying physical mechanisms, and associated variations in temperature and precipitation over the United States.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is *high confidence* that preferred patterns of variability affect U.S. temperature on a year-to-year timescale, based on a large number of studies that diagnose observational data records and long simulations. There is *medium confidence* that changes in the occurrence of these patterns or their properties have contributed to recent U.S. temperature and precipitation trends. Several studies agree on a linkage between decadal changes in the NAO/NAM and climate trends over the United States, and there is some modeling evidence for a linkage between a La Niña-like cooling trend over the tropical Pacific and precipitation changes in the southwestern United States. There is no robust evidence for observed decadal changes in the properties of ENSO and related United States climate impacts. Confidence is *low* regarding the size of the role of human influences in these changes because models do not agree on the impact of human activity on preferred patterns of variability or because projected changes are small compared to internal variability.

Summary sentence or paragraph that integrates the above information

Recurring modes of variability strongly affect temperature and precipitation over the United States on interannual timescales (*high confidence*) as supported by a very large number of observational and modeling studies. Changes in some recurring patterns of variability have contributed to recent trends in U.S. temperature and precipitation (*medium confidence*). The causes of these changes are uncertain due to the limited observational record and because models exhibit some difficulties simulating these recurring patterns of variability and their underlying physical mechanisms.

FIGURES

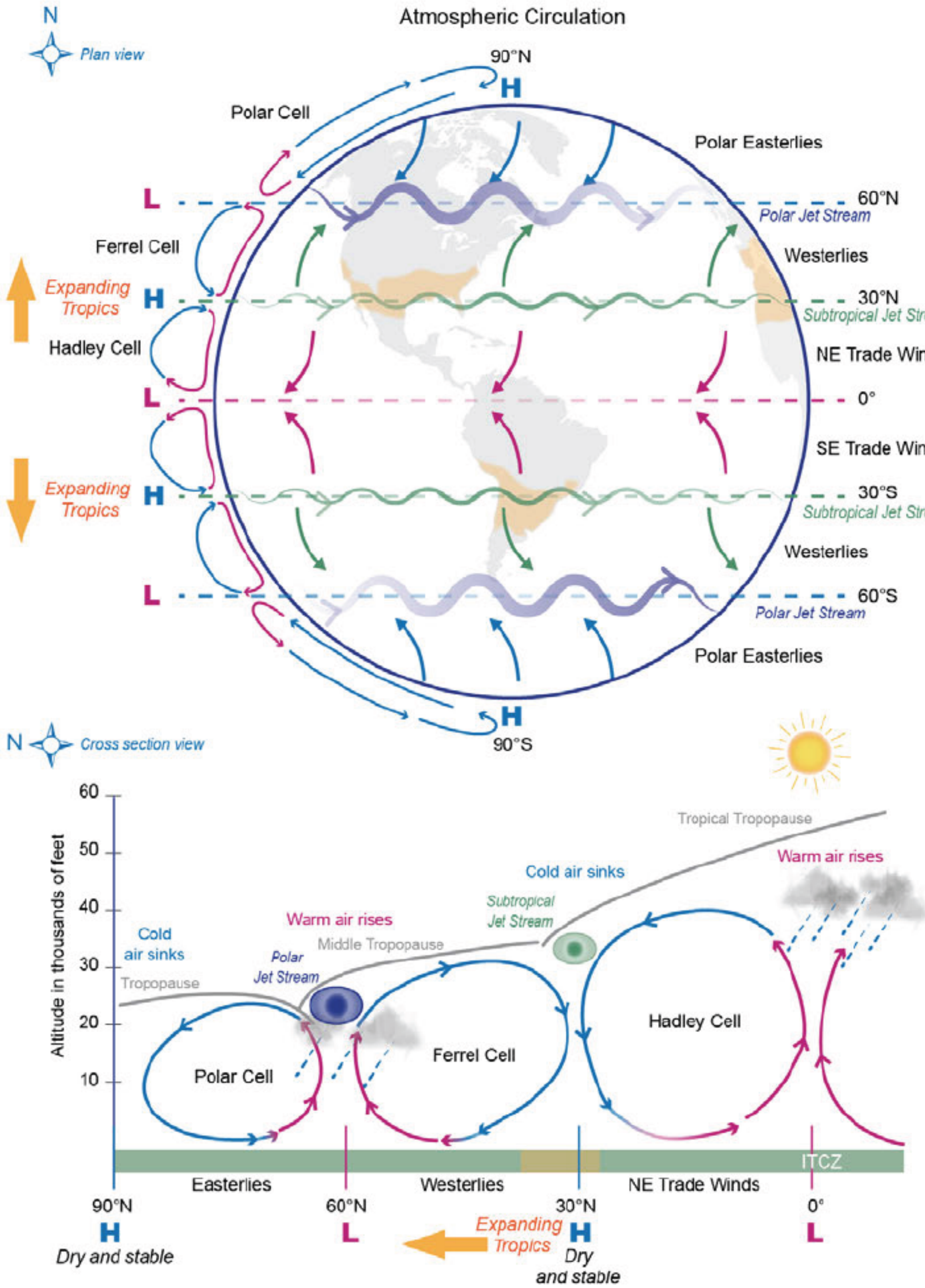

Figure 5.1: (Top) Plan and (bottom) cross-section schematic view representations of the general circulation of the atmosphere. Three main circulations exist between the equator and poles due to solar heating and Earth's rotation: 1) **Hadley cell** – Low-latitude air moves toward the equator. Due to solar heating, air near the equator rises vertically and moves poleward in the upper atmosphere. 2) **Ferrel cell** – A midlatitude mean atmospheric circulation cell. In this cell, the air flows poleward and eastward near the surface and equatorward and westward at higher levels. 3) **Polar cell** – Air rises, diverges, and travels toward the poles. Once over the poles, the air sinks,

forming the polar highs. At the surface, air diverges outward from the polar highs. Surface winds in the polar cell are easterly (polar easterlies). A high pressure band is located at about 30° N/S latitude, leading to dry/hot weather due to descending air motion (subtropical dry zones are indicated in orange in the schematic views). Expanding tropics (indicted by orange arrows) are associated with a poleward shift of the subtropical dry zones. A low pressure band is found at 50°–60° N/S, with rainy and stormy weather in relation to the polar jet stream bands of strong westerly wind in the upper levels of the atmosphere. (Figure source: adapted from NWS 2016).

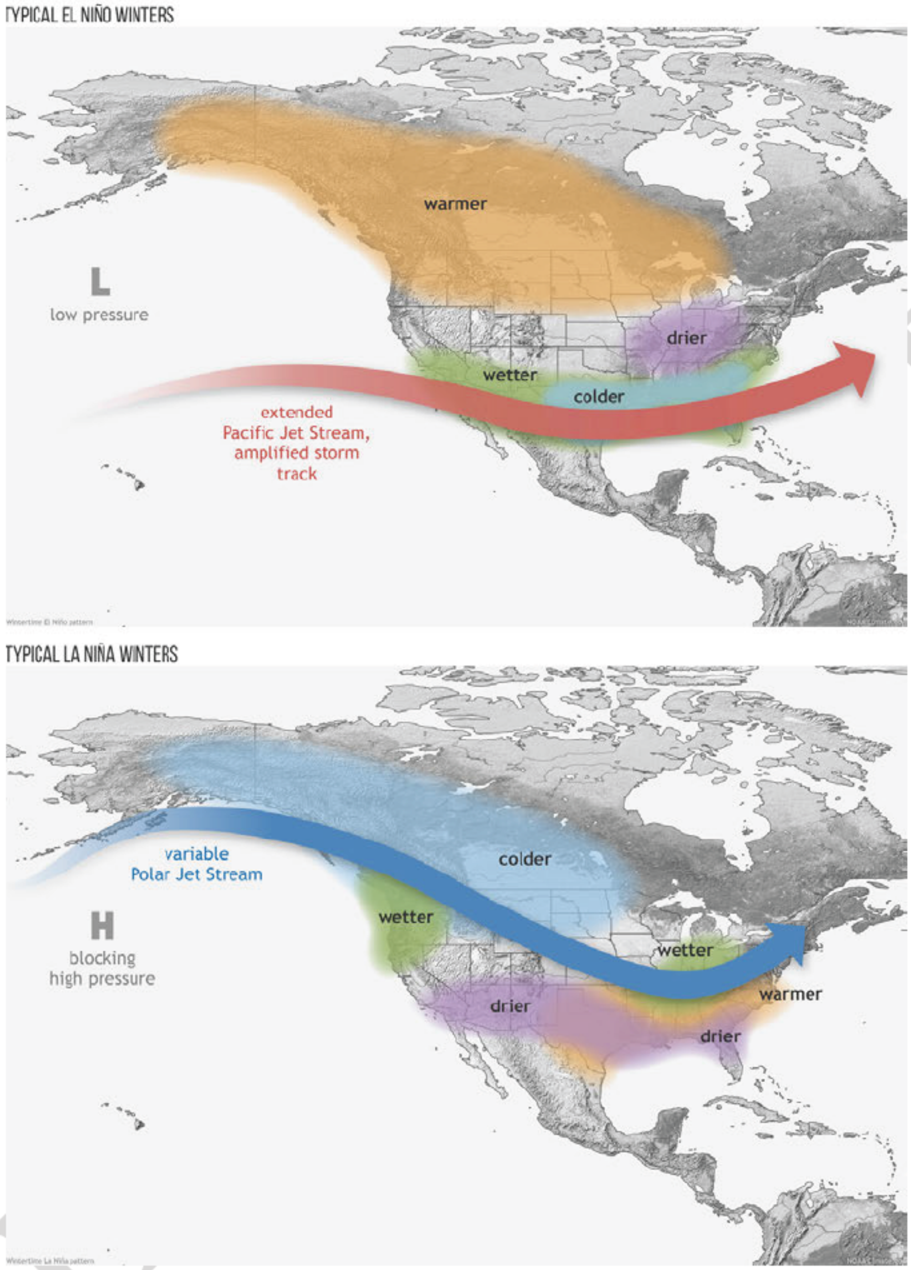

Figure 5.2: El Niño- and La Niña-related winter features over North America. Shown are typical January to March weather anomalies and atmospheric circulation during moderate to strong El Niño and La Niña conditions: (top) During El Niño, there is a tendency for a strong jet stream and storm track across the southern part of the United States. The southern tier of Alaska and the U.S. Pacific Northwest tend to be warmer than average, whereas the southern tier of United States tends to be cooler and wetter than average. (bottom) During La Niña, there is a tendency of a very wave-like jet stream flow over the United States and Canada, with colder and stormier than average conditions across the North, and warmer and less stormy conditions across the South. (Figure source: adapted from Lindsey 2016).

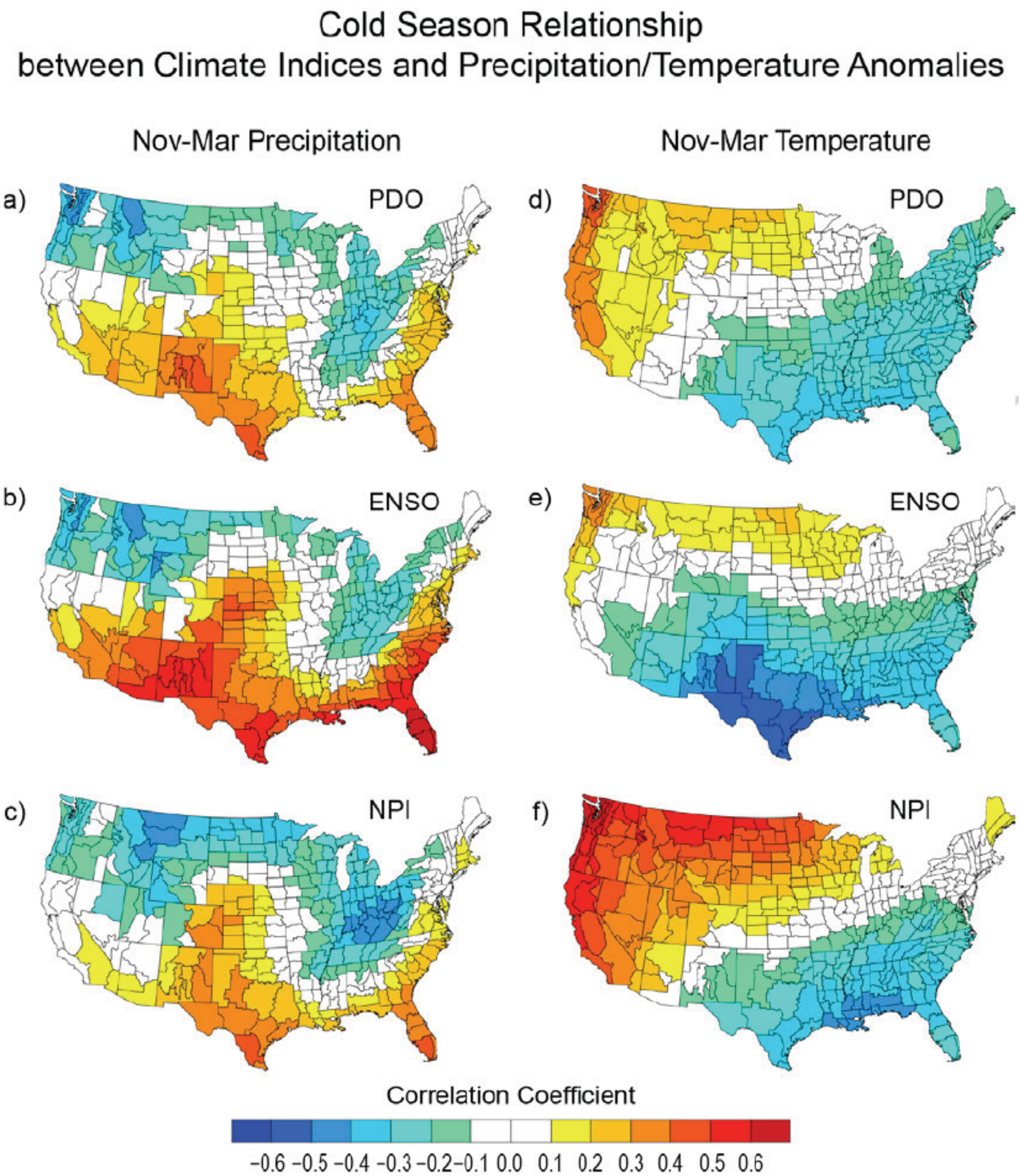

Figure 5.3: Cold season relationship between climate indices and U.S. precipitation and temperature anomalies determined from U.S. climate division data (Vose et al. 2014), for the years 1901–2014. November–March mean U.S. precipitation anomalies correlated with (a) the Pacific Decadal oscillation (PDO) index, (b) the El Niño–Southern Oscillation (ENSO) index, and (c) the North Pacific Index (NPI). November–March U.S. temperature anomalies correlated with (d) the PDO index, (e) the ENSO index, and (f) the NPI. United States temperature and precipitation related to the Pacific Decadal oscillation are very similar to (and indeed may be caused by) variations associated with ENSO and the Aleutian low strength (North Pacific Index). (Figure source: Newman et al. 2016; © American Meteorological Society, used with permission).

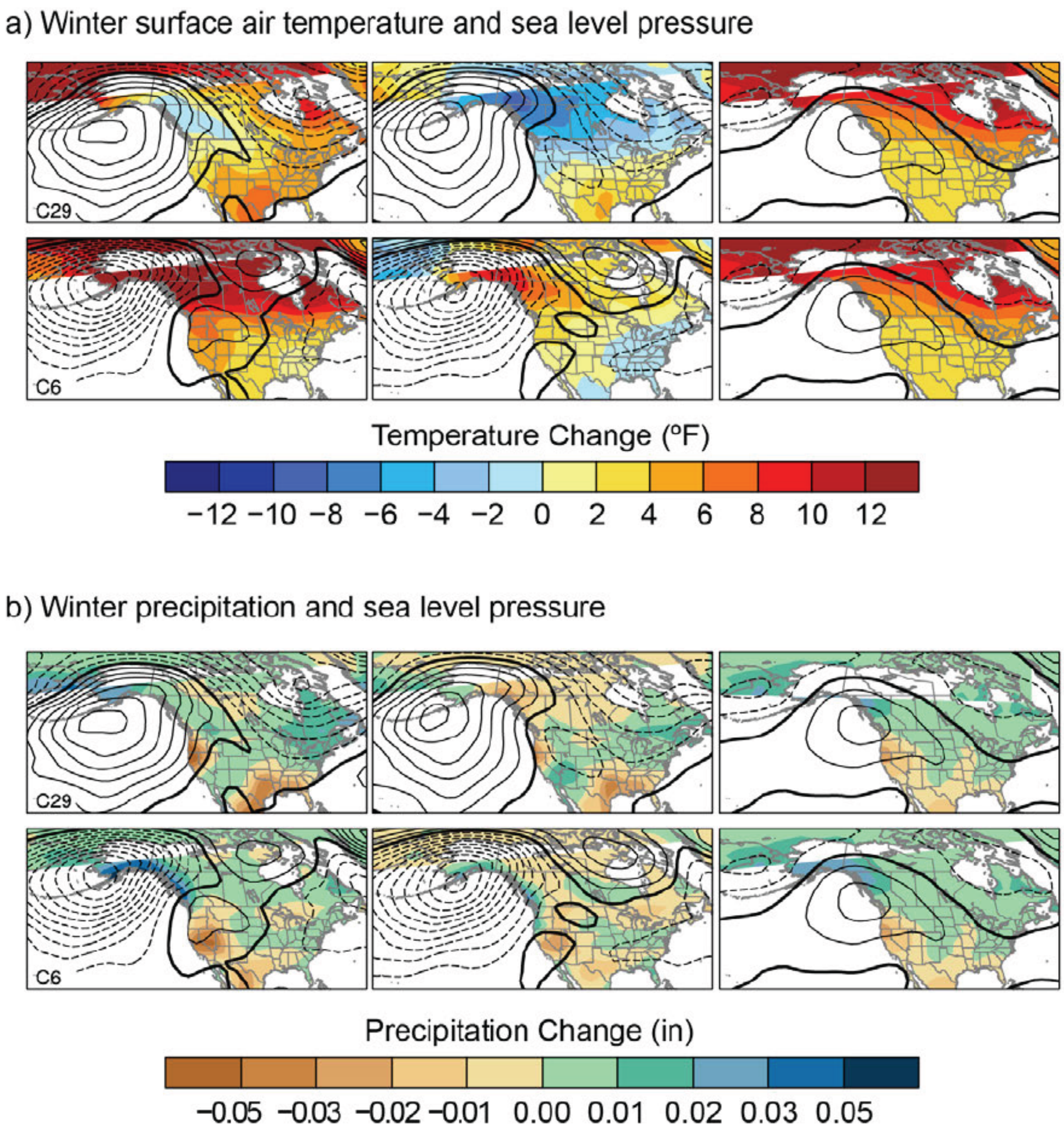

Figure 5.4: (left) Total 2010–2060 winter trends decomposed into (center) internal and (right) forced components for two contrasting CCSM3 ensemble members (runs 29 and 6) for (a) surface air temperature [color shading; °F/(51 years)] and sea level pressure (SLP; contours) and (b) precipitation [color shading; inches per day/(51 years)] and SLP (contours). SLP contour interval is 1 hPa/(51 years), with solid (dashed) contours for positive (negative) values; the zero contour is thickened. The same climate model (CCSM3) simulates a large range of possible trends in North American climate over the 2010–2060 period because of the influence of internal climate variability superposed upon forced climate trends. (Figure source: adapted from Deser et al. 2014; © American Meteorological Society, used with permission).

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