2.2 Climate variability

Fluctuation is inherent to climate. Atmospheric fluctuations occur on all time scales, and extend from turbulence to "weather" time frames to geological eras. Climate statistics do not appear to exhibit statistical stationarity on any time scales (Bryson, 1997; Milly et al, 2008). Bryson stated this as an axiom: "The history of climate is a non-stationary time series." The term "climate variability" is generally reserved for temporal, rather than spatial, usage, a convention followed here. Climate variability has sources in external drivers (e.g., solar output, volcanic eruptions, orbital mechanics, atmospheric composition, ocean-land configurations, land surface alterations) and in internal dynamics associated with a multitude of feedbacks and subsystem interactions not forced by aforementioned external drivers. The term "natural variability" is sometimes employed to describe unforced internal dynamics. The subsystems interactions can act locally or at a distance ("teleconnections") via the agency of Earth's two main fluids, air and water. Some internal climate modes are temporally regular, even oscillatory, in nature, and others are chaotic, highly non-linear, and almost completely unpredictable. Temporally lagged behavior and interactions are also common. The climate system and its many subsystems are highly interconnected, in space and time, and it is essentially impossible to completely understand the variability at a chosen point even with a lengthy and accurate climate history from only that point.

Climate can be alternatively thought of as both an "enabler" of weather, and as a consequence of weather. Climate and weather are inseparable, and neither can be understood without reference to the other. Traditionally, in mathematical terms weather is often considered to be an initial value problem, and climate is a boundary value problem. However, boundary values on some time scales are initial values on other time scales. Similarly "change" in climate is merely slow variability on longer time scales, reflected in "change" in statistical descriptors of weather. This is why it is important to understand sources of "natural" multi-year and decadal variability, to form a perspective from which human and other external effects can be viewed, and hopefully disentangled.

2.2.1 Spatial scale considerations

Central tendencies of climate (e.g., means or totals) vary with spatial scale. A general expectation among climatologists is that spatial scales of temporal variability will be on the order of tens, hundreds, and even thousands of kilometers. Climate "anomalies", defined as a departure from long-term means, should show broad coherence over the scale of the driving mechanisms. These are often associated with teleconnection patterns that are continental in scale, reflecting fluctuations in the position and strength of the jet stream and subsequent continental-scale wave patterns. By contrast, fine scale structure in climate variability is quite plausible and even likely in the presence of topographic diversity, coastlines, glacial features, and urban settings. Furthermore, the strength of spatial correlations may differ between day and night. The atmosphere just above the surface tends to become decoupled at night, when vertical stability is greater, and nighttime minimums are more likely controlled by local circumstances. Fine scale structure in variability properties is not emphasized further in this chapter, but should be closely borne in mind because individual station measurements used to assess broad patterns may be subject to very local influences on the scale of tens to hundreds of meters. The determination of variability characteristics requires long (several decades) time series, and dense long-term homogeneous observational data sets in complex terrain are exceedingly scarce.

2.2.2 Temporal scales of variability

As noted earlier, the climate system exhibits variability over a very large range of time scales. Without records covering very long (geologic) periods of time at high temporal resolution, we cannot definitively characterize the complete spatio-temporal variability properties of climate. For this chapter we are primarily concerned variability on time scales between a few weeks or intraseasonal (fluctuate within a season), interannual (fluctuate year-to-year) and multidecadal (fluctuate over a 2-3 decade time period). Tectonic and orbital mechanisms change little over these time frames and hence are ignored.

Climate Mode	Characteristic Time Scale	Centers of Action	Indices	Predictability
ENSO	2-7 years	tropical eastern pacific and subtropical jet streams	SOI (atm), NINO3.4 (ocean temp), MEI (combo)	< 6 months
PNA	10-14 days	Quadrapole pattern over N. Pacific and N. American continent	PNA index (atm)	7 days
AO/NAO	10-14 days	Dipole of pressure/height between Arctic and midlatitudes	AO/NAO indices (atm)	7 days
PDO	40-70 years		North Pacific (ocean temp)	N/A
AMO	40-70 years	North Atlantic (subtropical focus)	North Atlantic (ocean temp)	N/A
MJO	30-70 days	Tropical Indian and Pacific Oceans	Tropical convection and divergence (atm)	2 weeks

Table 1: Climate oscillations, associated characteristic timescales, geographic foci, means through which they are quantified and estimated time horizon for skillful predicition.

2.2.3 Hemispheric patterns relevant to North America

Several recurrent patterns of climate variability affect the North American continent. Each pattern has different characteristics such as geographic extent, similarity of influence across seasons, and predominant expression at one or more characteristic time scales. Of importance to understanding and attribution, some of these time scales are long enough to appear as "trends" in observational records that only span a few decades. The temporal scale of these patterns can be traced back to the underlying mechanisms. For example, ocean-atmosphere patterns grow, decay and evolve much more slowly than purely atmospheric patterns. In some cases these features and patterns appear to have predictive value (prognostic), and in other cases appear to have descriptive value (diagnostic). These patterns are not mutually exclusive, but rather interact with one another, leading to reinforced or counteracting effects in specific locations and months. For long period oscillations (50-70 years), the observational record only covers about one and one-half oscillations, and further corroboration as to their continuous existence within the climate system must be obtained from indirect paleoclimate evidence.

Several major sources of variability that could affect North American climate are next discussed. Then, the attendant effects on climate are subsequently described where this has been at least partly established.

2.2.3.1 ENSO. El Nino / Southern Oscillation

El Nino and La Nina are the warm and cool phases, respectively, of ocean surface temperatures on, and a few degrees of latitude either side of, the equator between Peru and approximately the International Date Line. This status can be described by several measures. Most common are the terms, El Nino and La Nina that refer *exclusively* to ocean temperatures. The Southern Oscillation (SOI), by contrast, is defined *exclusively* as an atmospheric phenomenon. The measure consists of opposing differences in sea level pressure departures from long-term average, over a wide area centered approximately on Tahiti and a second area centered on northern Australia. Though the two measures are distinct, they are correlated over time in a manner that varies through time (McCabe and Dettinger, 1999) and are physically interlinked, so that the names are merged in the common acronym ENSO (El Nino/Southern Oscillation). Reflecting terminology origins, ENSO is said to be in the warm phase when positive ocean surface temperature departures are present in the ENSO region, and when the SOI is negative. A third measure of ENSO status is in wide usage as well. The Multivariate ENSO Index (MEI) formulated by Wolter and Timlin (1993) based on co-variability among six descriptors that correlate with ENSO and with each other, and is derived from a principal components analysis of pressure, north-south and east-west wind, ocean and air temperatures, and cloudiness across the Pacific. El Nino conditions correspond to positive MEI.

ENSO is the largest source of interannual global climate variability and the most widely studied (e.g., Bjerknes, 1969; Rasmussen and Carpenter, 1982; Livezey et al, 1997). Tropical ocean surface temperatures and atmospheric pressure across the Pacific work together through positive feedbacks involving the east-west "Walker circulation" and tropical convection to create this coupled atmosphere-ocean pattern. Together, the two patterns vary with an irregular period of typically 2-7 years, and are often not predictable with current knowledge beyond around 6-months. Of note, ENSO conditions have favored the cool phase (La Nina) since around 2000.

Though the primary centers of action for ENSO are in the tropical Pacific, its influence extends well beyond this area in longitude and in latitude. Alterations in the strength and position of the subtropical jet stream in the Pacific sector lead to large scale influences in climate patterns across the Northern Hemisphere. The influence of ENSO on North America is most prominent in the cool season, affecting the entire West Coast from Alaska to Baja, the US/Mexico border region eastward to Florida, and the Ohio River Valley (e.g., Redmond and Koch, 1991; Livezey et al, 1997).

The main effects of El Nino and La Nina are seen mostly in western North America, with an important exception. The most pronounced is the north-south dipole pattern of temperature and precipitation anomalies centered over the western continental U.S. in winter. This pattern of response begins in early October and lasts through the end of March. El Nino is preferentially associated with wet winters in the American Southwest (extending southward to near southern Baja Peninsula), and with dry winters in the Pacific Northwest and southwest Canada, essentially the drainage basin of the Columbia River. To the north, this pattern again switches sign around the Queen Charlotte Islands, with wet conditions seen along coastal Alaska from about Yakatut to Kodiak Island. The effects extend inland to the crest of the Sierra Madre and the Rockies, and in Alaska to no farther than south of the crest of the Alaska Range. Along the U.S.-Mexican border, El Nino is associated with wet winters from southern California across to the San Juan Mountains of Colorado and eastward to Georgia and Florida. Effects in the U.S. Southeast are nearly as pronounced as they are in the desert Southwest. The Ohio River Valley is usually drier during El Nino. Nearly the opposite effects are seen with La Nina,. In the Southwest El Nino leads to an increase in the number of days with precipitation and in the average precipitation per wet day (Woolhiser et al., 1993), and vice-versa for much of the Pacific Northwest.

The effects of ENSO just noted relate mostly to large scale winter storms and is particularly. influential in water resources in the western United States because the majority of its annual precipitation occurs during the cool season. A few effects of ENSO can occur during the warm season. Summertime associations with La Nina have been noted in the upper Midwest United States (Kahya and Dracup, 1994; Trenberth et al., 1988). El Nino tends to increase the upper level winds from the west over the tropical Atlantic and Caribbean Sea, and the resulting increased wind shear helps suppress tropical storm development in summer and autumn. In the Eastern Pacific west of Mexico, normally nearly twice as active as the Atlantic, tropical storms become more numerous with El Nino, and a few more of them recurve into the desert Southwest. Late summer in southern Mexico and Costa Rica generally experiences drier conditions with El Nino (Ropelewski and Halpert, 1987, 1989; Giannini et al., 2000).

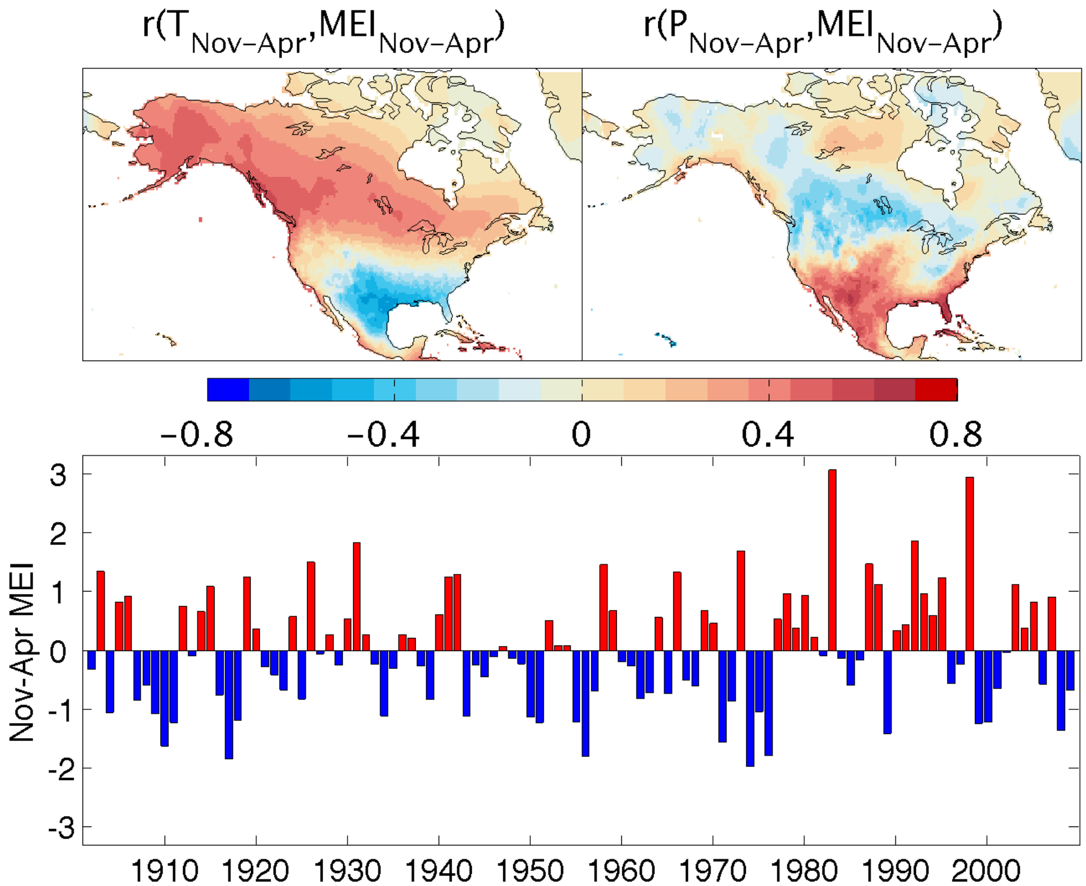

Figure 1: Top: Spatial correlation between Multivariate ENSO Index (MEI) for Nov-Apr and concurrent temperature (left) and precipitation (right), 1901-2009. Bottom: Time series of standardized MEI for Nov-Apr from 1901/02 - 2008/09.

After the "1976 shift" in Pacific climate, the frequencies of La Nina events (a decrease) and of El Nino (an increase) changed dramatically, comparing the preceding and succeeding two decades. As a consequence, locations with a positive precipitation response to El Nino saw an increase in precipitation. The Southwest United States saw its wettest two decades in the historical record. This "trend" decreased in magnitude during the 2000s when La Nina became more frequent. Whether such changes in ENSO return frequencies or ENSO locations (central versus eastern Pacific) are themselves perhaps a manifestation of climate change remains a matter of discussion (Ashok and Yamagata, 2009).

Because global climate is a connected system, there are likely to be some linkages between the phenomena in this section. However, it does appear that to a first approximation, the relation between ENSO and North America is not greatly affected by any but the Pacific Decadal Oscillation (below).

2.2.3.2 PDO, Pacific Decadal Oscillation

First identified by Mantua et al (1997), the Pacific Decadal Oscillation is realized in sea surface temperatures of the North Pacific from about 20 N to the Gulf of Alaska. The pattern of ocean surface temperature anomalies consists of warmer than normal waters along the West Coast (approximately 20-60 N) concurrent with cooler than normal waters north central Pacific south of Anchorage and Southwest Alaska in its positive phase, and with opposite temperature departures in its negative phase. The characteristic time to complete a typical "cycle" (very irregular) is on the order of 50 years or so, spending 2-3 decades in each of its opposite modes. The pattern first came into prominence after the previously mentioned dramatic basin-wide "1976 shift" in Pacific climate (Ebbesmeyer et al., 1991; Trenberth and Hurrell, 1994). The spatial pattern of the PDO shows similarities to that of ENSO, but with much weaker signal in the tropics. Though visually similar, the two time series are only poorly correlated in time. The phase of the PDO has been shown to modify the typical effects of ENSO in some areas, such as the Pacific Northwest in winter (Hamlet and Lettenmaier, 1999; Gershunov and Barnett, 1998). Whether the PDO exists as an independent phenomenon or represents an integrated sum of multiple nearby and remote forcings including ENSO in combination with annual reemergence of North Pacific ocean surface temperature anomalies (Newman et al., 2003), or has some other origin, has not been definitively decided.

PDO Effects. The phase of the PDO, sometimes in concert with other phenomena noted herein, does alter the probability distribution of seasonal precipitation, and to a lesser extent temperature in different parts of North America, mostly in its western portions, over a broad latitudinal extent from northern Mexico to Alaska (Biondi et al, 2001; D'Arrigo et al, 2001). With its long time scale, PDO variations can masquerade as trends over periods of 20-30 years, as well as masking or amplifying observed trends. Unfortunately, a number of widely used data sets extend from about World War II to present, or about this length of time. The PDO was negative for much of the 1940s-1970s and reverting to a positive phase in the 1980s-1990s with the 1976 shift. This oscillation coincides with strong increases in anthropogenic radiative forcing, resulting in challenges in attribution of changes. Moreover, the lack of observed cycles of the PDO during which widespread climate observations are available is a limiting factor. This suggests that caution should be used when linking any observed phenomena to the PDO.

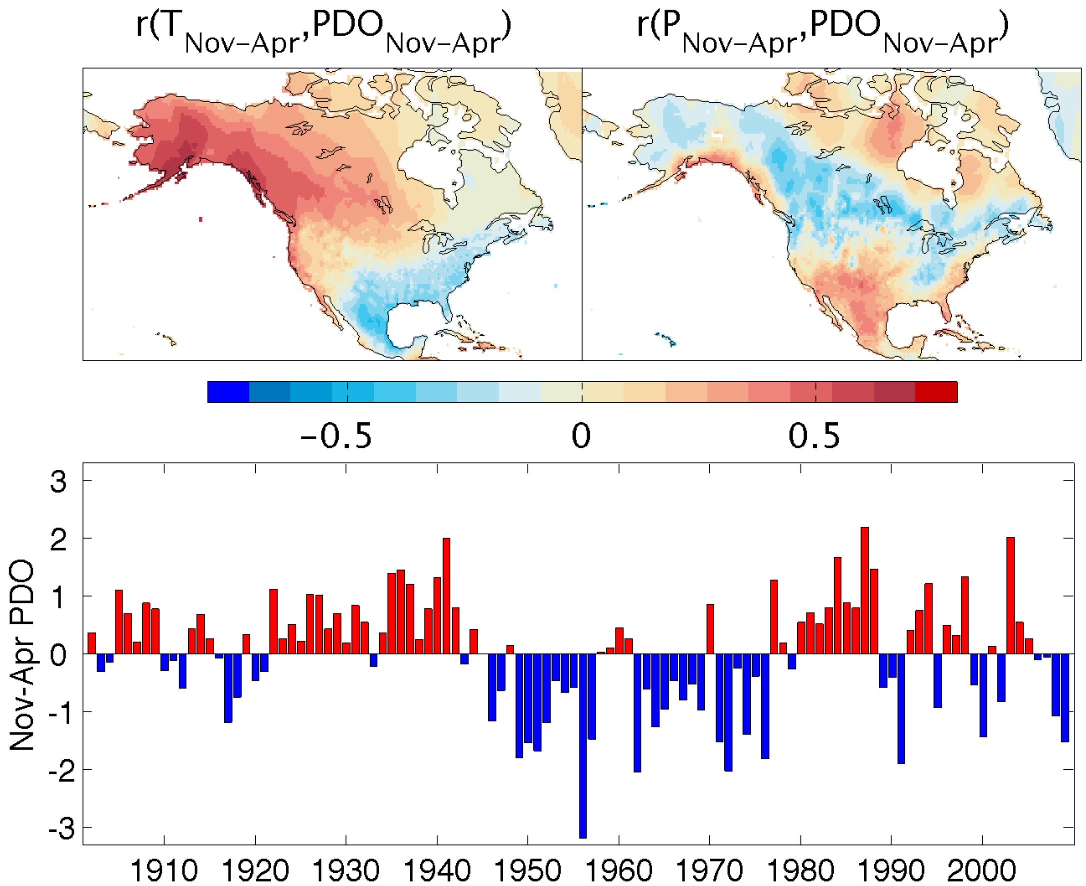

Figure 2: Top: Spatial correlation between the Pacific Decadal Oscillation (PDO) for Nov-Apr and concurrent temperature (left) and precipitation (right), 1901-2009. Bottom: Time series of standardized PDO for Nov-Apr from 1901/02 - 2008/09.

2.2.3.3 PNA, Pacific North America

Western North America often experiences a large scale upper ridge at the same time the eastern half of the continent sees a deep trough. This common pattern in mid-level (3-10 km altitude) atmospheric pressure has two principal "centers of action" (with opposite signs) in the US Southeast and the Columbia River Basin, and two others (also of opposite signs) over the Gulf of Alaska and between Hawaii and the International Date Line (Wallace and Gutzler, 1981). This pattern may be partly caused by the east-west asymmetry in continental topography, the position of the jet stream and tropical Pacific ocean surface temperatures. Its temporal variability is strongest at timescales of approximately two-weeks, and can oscillate several times during a given season and is most pronounced during late autumn-spring. The PNA has somewhat similar influences on climate as the PDO and ENSO. Of particular note, the PNA has a strong influence on temperatures in northwestern North America during the cool season. In the Cascades of

Oregon and Washington state, a 1 unit increase in the PNA equates to approximately a 400-m increase in the freezing level and plays a significant role in the proportion of precipitation that falls as snow (Abatzoglou, 2011). Subsequently, the gradual increase in the PNA from mid-20th century to around 2000 has been suggested to contribute to the widespread decline in mountain snowpack in western North American (Mote et al., 2005; Abatzoglou, 2011). By contrast, many of the lowland snowfalls in Seattle and Portland have occurred during the negative phase of the PNA when snow levels drop to near sea-level. The PNA pattern does vary according to ENSO phase (Horel and Wallace, 1981; Redmond and Koch, 1991) as well as the phase of the PDO.

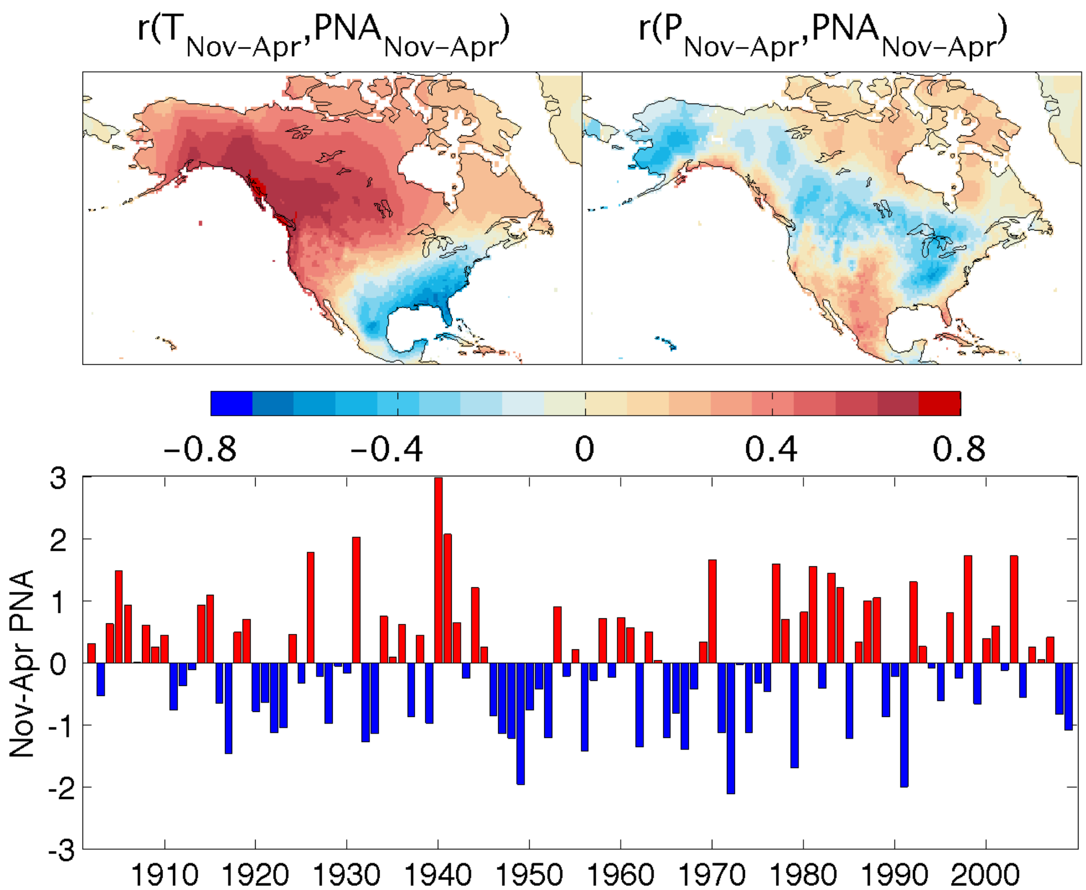

Figure 3: Top: Spatial correlation between Pacific North American pattern (PNA) for Nov-Apr and concurrent temperature (left) and precipitation (right), 1901-2009. Bottom: Time series of standardized PNA for Nov-Apr from 1901/02 - 2008/09.

2.2.3.4 AO/NAO, Arctic Oscillation / North Atlantic Oscillation

The North Atlantic Oscillation (NAO) consists of an alternation between the strength of the subtropical high pressure system commonly located near the Azores Islands, and the low-pressure system commonly located in the North Atlantic near Iceland (the Iceland Low). The Arctic Oscillation (AO) exhibits a similar north-south seesaw in atmospheric pressure, but spans all longitudes and covers the polar cap north of about 60 N. The AO and NAO patterns are strongly correlated and considered by some to be part of the same phenomena, with extra emphasis over the North Atlantic sector in the case of the NAO. This north-south seesaw in atmospheric pressure displaces the westerly jet stream to the north or south, alters the position of the storm track and associated precipitation, and modulates the temperature of air masses in midlatitudes and over the poles. The positive phase of the AO/NAO strengthens the sub-polar jet stream and allows for warmer air to move further north in the extratropics while the cold air is maintained over the pole. During the negative phase of the AO/NAO, the westerly jet stream weakens and migrates southward and allows for cooler Arctic air to dive southward into midlatitudes, thus increasing the potential for cold air outbreaks and snow storms across southerly latitudes in eastern North America (Thompson and Wallace, 1998).

Fundamentally, the AO and NAO are a dominant pattern of atmospheric variability and do not require coupled ocean-atmosphere interaction. This results in an intrinsic time scale of these patterns on the order of approximately two weeks (Feldstein, 2003). However, observations show substantial interannual and decadal variability in these atmospheric patterns. The NAO underwent a significant increase in positive strength during the latter half of the 20th century and is thought to have contributed up to half of the observed surface warming during winter across parts of northern Europe (Thompson et al., 2000). By contrast, recent studies suggest that the amplified warming of the Arctic and associated loss of sea ice has decreased the latitudinal temperature gradient near the Arctic Circle, and the corresponding pressure gradient, weakening the barrier between cold air over the Arctic and that in midlatitudes (Francis and Varvus, 2012). In association, longer-term trends in climate variability do influence regional trends in temperature and precipitation and often obscure or amplify anthropogenically forced change (e.g., Abatzoglou and Redmond, 2007).

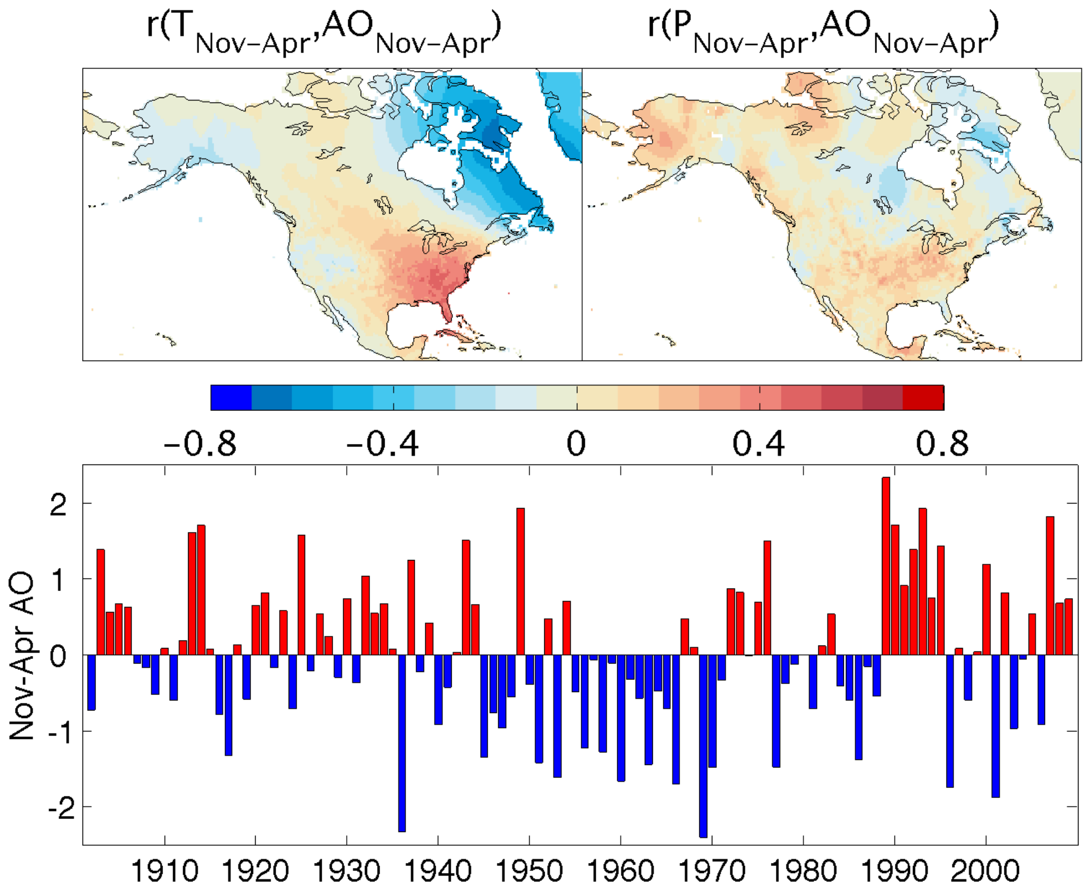

Figure 4: Top: Spatial correlation between Arctic Oscillation (AO) for Nov-Apr and concurrent temperature (left) and precipitation (right), 1901-2009. Bottom: Time series of standardized AO for Nov-Apr from 1901/02 - 2008/09.

2.2.3.5 AMO, Atlantic Multi-Decadal Oscillation

First noted by Enfield et al. (2001), the AMO refers to ocean surface temperatures in the North Atlantic poleward of 10 N and is the dominant spatial mode of variability of detrended ocean temperatures. The tripole pattern consists of higher ocean temperatures in the subtropics and the northern Atlantic, with somewhat less high ocean temperatures near Bermuda. Over the last century this pattern has shown four phase changes, at about 1900, 1930, 1970, and 1995, and thus an overall period of about 65 years during the one and one-half oscillations seen. Effects are seen in the southeast (Enfield et al, 2001), but have been reported as far west as the Colorado Rockies (McCabe et al, 2007; Switanek and Troch, 2011). The long timescales of the AMO, like the PDO, may be problematic in resolving phenomenon with less than centennial timescales.

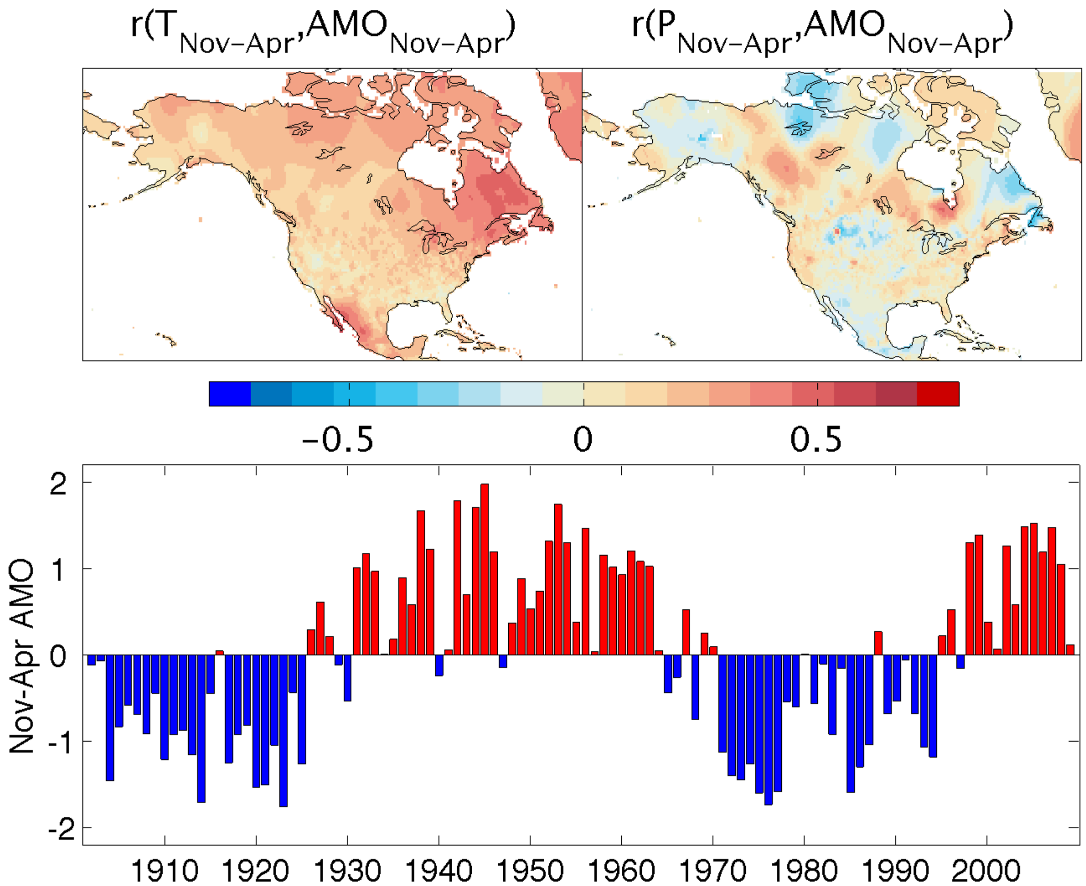

Figure 5: Top: Spatial correlation between Atlantic Multidecadal Oscillation (AMO) for Nov-Apr and concurrent temperature (left) and precipitation (right), 1901-2009. Bottom: Time series of standardized AMO for Nov-Apr from 1901/02 - 2008/09.

2.2.3.6 MJO, Madden-Julian Oscillation

The MJO (sometimes ISO, Intra-Seasonal Oscillation) is an eastward propagating tropical wave with a time scale of 40-70 days (Madden and Julian, 1994). The time scale of 6 to 10 weeks is in the realm of short-term climate. A couplet consisting of an extensive complex of thunderstorms and general upward motion, accompanied by an adjoining area of subsidence and downward motion, slowly migrates to the east from the eastern Indian Ocean, across Indonesia, and into the equatorial western Pacific, decaying typically before reaching the International dateline where it encounters cooler ocean temperatures. The heat energy released by condensation in these tall convective towers can interact with the jet stream during its occasional southward excursions as it exits the Asian continent. This can in turn set up a wave train that propagates eastward across the Pacific to impinge on the North American west coast, bringing episodes of heavy precipitation (Mo and Higgins, 1998; Higgins et al, 2000; Jones, 2000). These "atmospheric rivers" can affect the character of a winter, especially at latitudes that are not normally continually affected by the jet stream (approximately 35 N southward). The phase of the MJO can be important in understanding variations in atmospheric regimes within a season and have been shown to influence the character of the North American Monsoon and modulate tropical cyclone activity in the Atlantic depending on the longitude of convective enhancement. There also appear to be interactions between MJO and ENSO and a current hypothesis is that the MJO can trigger and or modulate ENSO dynamics.

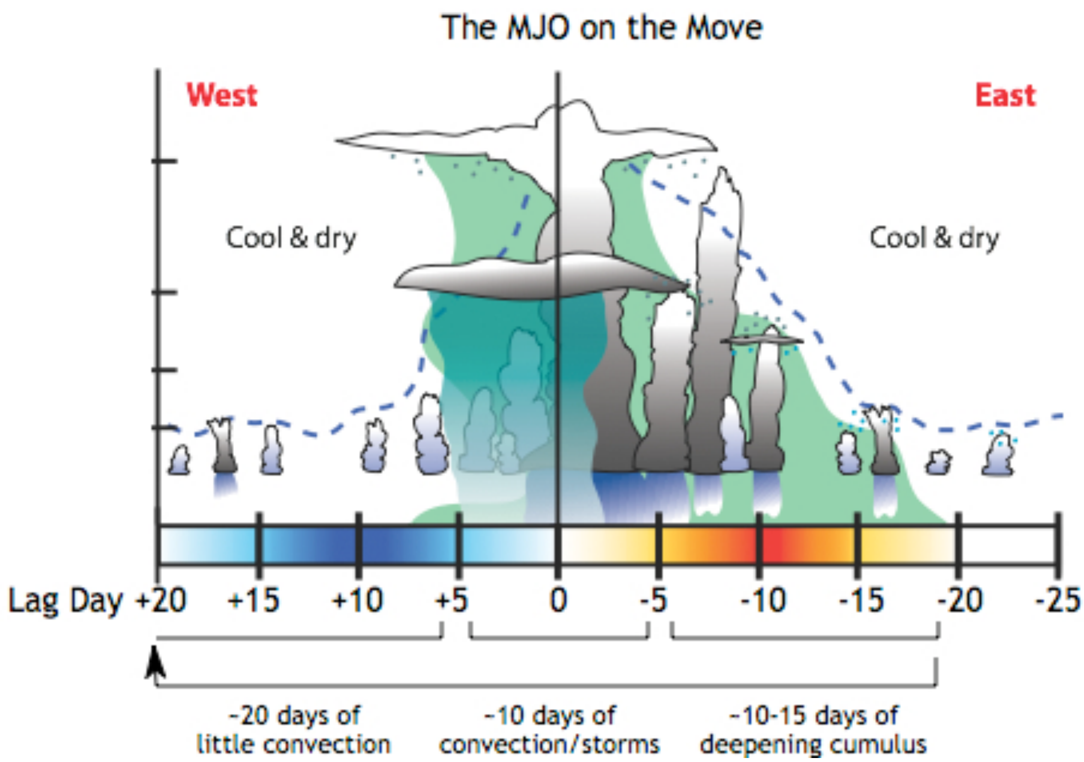

Figure 6: Schematic of the MJO from cmmap.org. In the above the convective towers are moving eastward. The colors in the bar at the bottom denote ocean surface temperature anomalies. The warm waters and less cloudy skies allow for strong thermal support to encourage the convective towers eastward. By contrast, it their wake, ocean temperatures are much cooler.

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