1. **The Role of the Oceans**
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    b. Summary: Discusses how ocean cycles (Pacific Decadal Oscillation, El Niño-Southern Oscillation, Atlantic Oscillation, Atlantic Multidecadal Oscillation, etc.) affect global average temperature

Introduction

In chapter two, there was discussion about the various components of the climate system and their interactions via the exchange of heat and mass. What is clear is that the combined heat capacity and mass of the atmosphere is the smallest among the components of the climate system (e.g., Piexoto and Oort, 1992). As such, the time needed for atmosphere to adjust to external forcing is quite rapid (one to three weeks) compared to that of the other parts of the climate system. The oceans on the other hand, have the highest heat capacity of the parts of the climate system as well as being three orders of magnitude more massive than the atmosphere. Since water covers 71% of the earth's surface, the oceans are bound to exert a very strong influence on global atmospheric temperatures. Given the fact that the atmosphere is generally transparent to solar radiation, as a first approximation, the atmosphere receives its energy from the underlying surface. In other words, in general, the atmosphere is considered as a servant to the Earth's surface.

The behavior of geophysical fluids such as the oceans and atmosphere are governed by very basic physical conservations laws such conservation of mass, momentum, and energy, and they are described in many atmospheric science (e.g., Ahrens and Henson, 2022) and climate textbooks (e.g., Rohli and Vega, 2017). These basic principles are represented by a highly non-linear set of differential equations called the "primitive equations". These principles and equations when solved in a general way can represent the naturally occurring wavelike motions that are observed when a geophysical fluid is forced. These motions are named in accord with the force which restores the initial balance, and these waves can be generated internally or at the interface between fluid layers of differing densities (e.g., Pedlosky, 1987, Ch. 3). The simplest or most relatable example is something many of us have done and that is throw a stone into a tranquil water body. The stone disturbs the water surface and gravity attempts to restore equilibrium to the water surface. These wave motions will have various characteristic time-scales depending on the forcing and the composition and density of the fluid. The goal here is not to discuss the physics and mathematics of these motions, but to give the basic background regarding the principles that describe some well-known natural oscillations in the ocean and atmosphere. Also, a description of how these oscillations impact weather and climate, especially global temperatures will accompany this background.

Some of these oscillations or cycles are germane to the oceans which then exert strong influence on the atmosphere and are relatively recently described but not necessarily well understood (e.g., Pacific Decadal Oscillation – PDO). Others have been known for a long time and represent the complex relationships between the oceans and atmosphere (e.g., El Niño and Southern Ocean – ENSO, North Atlantic Oscillation - NAO). What is common among them is that these oscillations will exert their influence on each other as well as on weather and climate regardless of any longer-term trends that have been observed. The rest of this chapter will explore the connection between these atmospheric and oceanic phenomena and global temperature.

Ocean - Atmosphere Interactions

The El Niño and Southern Oscillation

The phenomenon referred to as El Niño and Southern Oscillation (abbreviated as ENSO) became common knowledge in the public domain during the strong El Niño event of 1982 -1983. El Niño refers to the irregular warming (approximately every two to eight years) of the upper part of the ocean in the Eastern Tropical Pacific (see e.g., Philander, 1990, Diaz and Markgraf, 2000 and Fig. 1). The El Niño is not new but was finally recognized in the scientific literature during the 1960s (e.g., Bjerknes 1966, 1969) and connected with Southern Oscillation. The Southern Oscillation describes the mean sea level pressure difference between Tahiti and the city of Darwin Australia. This difference is typically positive but becomes negative during an El Niño. The opposite or cold phase of what is now viewed as an irregular cycle is called the La Niña, and anomalously cold waters would be observed in Figure 1 where the anomalously warm waters are located.

The typical El Niño cycle begins with subtle changes in the atmosphere and ocean circulations during the spring of a particular year, and the dynamics involves waves discussed in the introduction. The surface water of the Eastern Tropical Pacific begins to warm throughout the summer and fall, resulting in maximum sea surface temperature (SST) anomaly during December and January (e.g., Diaz and Markgraf, 2000). The bottom panel in Fig. 1 shows one type of El Niño pattern which occurred during December 2015 close to the maximum of the 2015 – 2016 event. These SST anomalies change the surface heat distribution on Earth often over an area larger than the United States. This heating has a profound impact on the path of the jet stream and consequently the weather worldwide as shown by many peer-reviewed studies, but especially over North America. The jet stream is responsible for the poleward transfer of excess energy, momentum, and moisture which characterizes the tropics to the polar regions which have relative deficits of the aforementioned quantities.

From Fig. 1 we can also infer that the El Niño is responsible for depositing heat energy into the tropical atmosphere from the ocean surface. This energy will be distributed eventually worldwide by the jet stream. Within a fluid this happens by contact (conduction) and transfer in bulk fluid elements (convection). If the underlying surface is warmer than the atmosphere, energy will be transferred into the atmosphere by conduction and evaporation of water from the surface into the atmosphere. This heat will be distributed into the atmosphere by convection and condensation during the formation of clouds and precipitation.

We can estimate the potential of El Niño to warm the global atmosphere simply through the process of conduction. If we consider a unit volume of water (one meter cubed), its mass is about 1000 kg. The SST anomalies in the area bounded by 170° W to 120° W longitude and from 5° S to 5° N latitude are used to determine whether the Pacific is in the El Niño, La Niña, or neutral state (see Climate Diagnostics Bulletin, 2022). If the mean SSTs are 1.0° C above normal within this area over a depth of 150 m, we can calculate how much energy could be deposited into the atmosphere from the oceans provided all this warm anomaly in the volume described above was dispersed in this direction. This calculation is based on the heat capacity and density of the ocean included in well-known formulations (e.g., Tilly et al. 2008). If we consider that the heat capacity of the atmosphere is roughly one quarter that of water and its density is roughly 0.001, distributing this energy over the entire volume of the atmosphere results in the atmosphere being warmed by approximately 0.75º C (1.4 F).

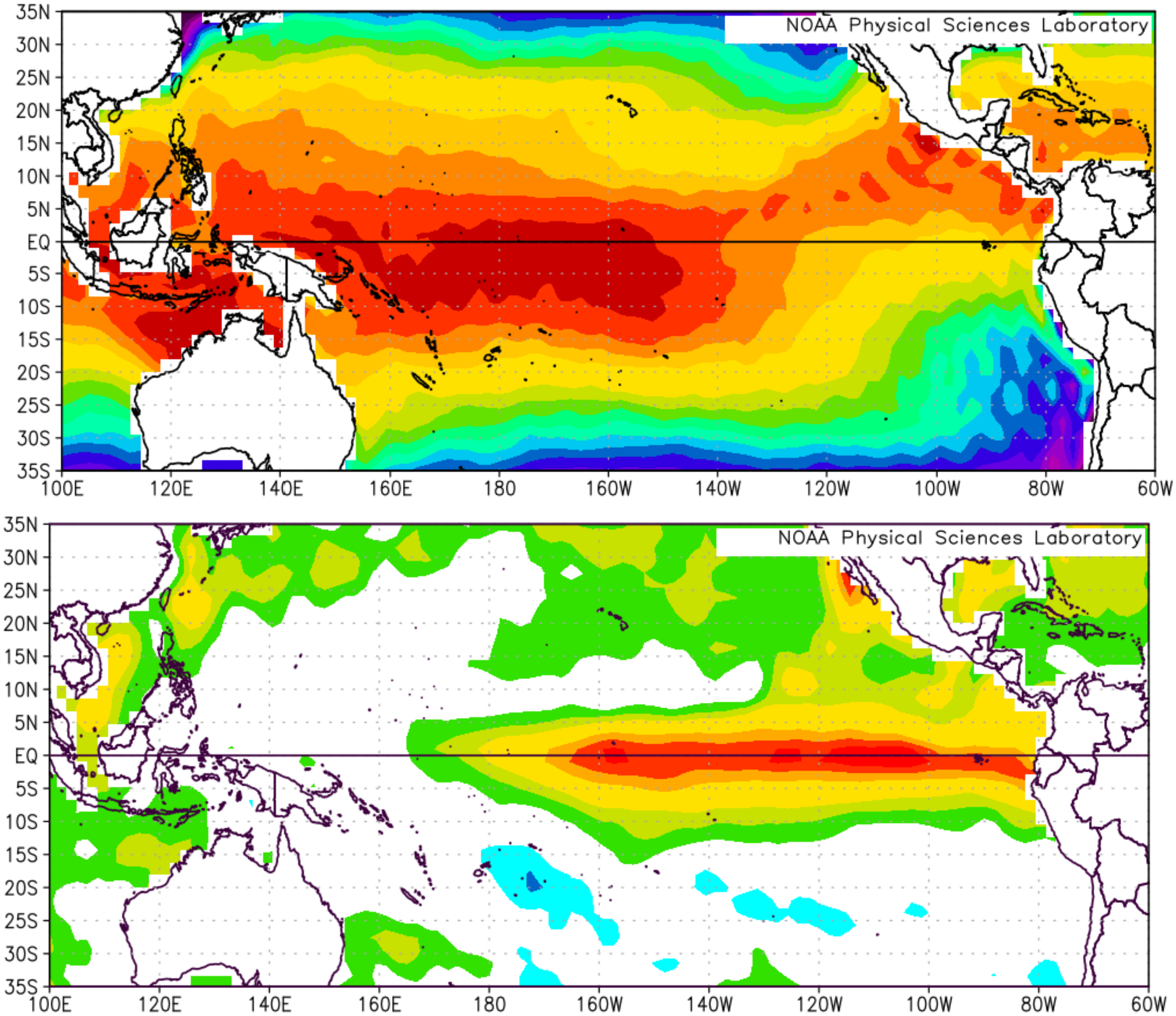

Figure 1. The tropical Pacific Ocean sea surface temperature (SST - ºC) (top) and anomaly (bottom) for December 2015. The anomalies are the difference between the December 2015 observations and the 1981-2010 mean temperature. The green color is positive SST anomalies of 0.5 – 1.0 ºC and each successive category is 0.5 ºC warmer. Source: National Oceanic and Atmospheric Administration Physical Science Laboratory NCEP/NCAR reanalyses data (https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html)

During the El Niño event of 2015 – 2016, the global atmospheric temperature as estimated by satellites (Fig. 2) warmed by approximately 0.6º C. This El Niño was associated with SSTs that were 2 – 3° C warmer than normal in the eastern Tropical Pacific within the box outlined above, which is far more than enough to account for the temperature spike in Fig. 2. The calculation above assumes an ideal scenario and not all of the energy associated with the El Niño warm anomaly would be transferred exclusively from the ocean into the atmosphere. The El Niño, however, provides a clear example of how a shorter-term event occurring within the ocean circulations can influence the global temperatures. Other recent El Niño temperature "spikes" (Fig. 2) are seen in 1997, 2009, and 2018, while La Niña cold "valleys" can be seen in 1998-1999, 2007, 2011, 2017, and in 2020.

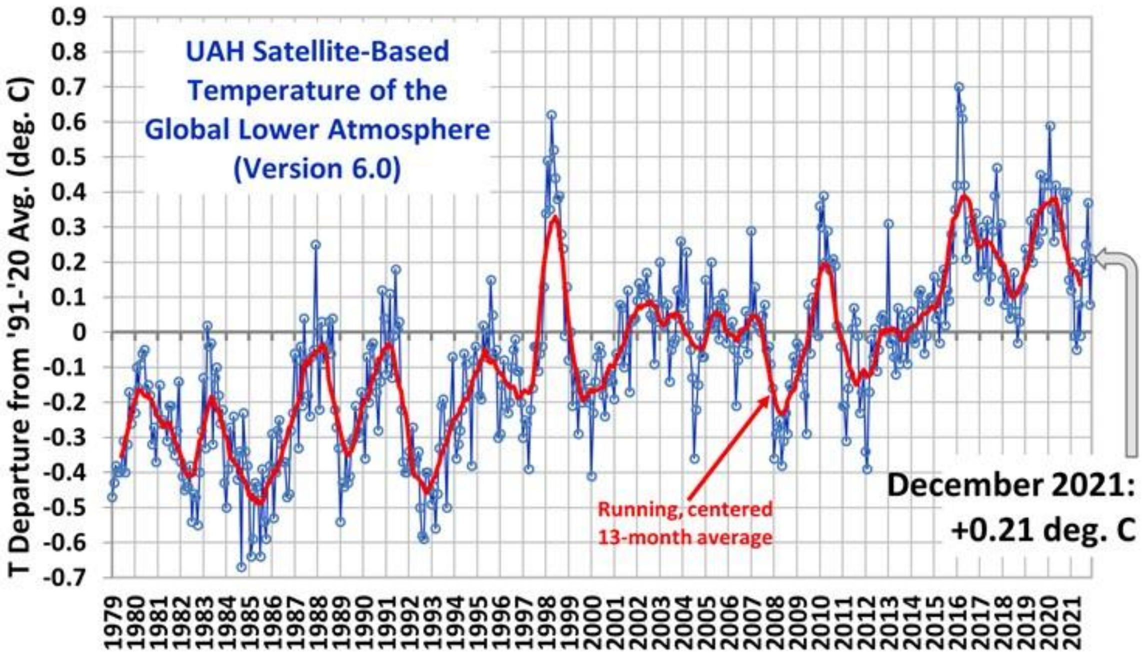

Figure 2. The monthly temperature anomaly (measured relative to the 1991-2020 global mean) of the global lower atmosphere (1979-2021) based on satellite measurements and provided by the University of Alabama-Huntsville (https://www.drroyspencer.com/latest-global-temperatures).

The Pacific Decadal Oscillation

The Pacific Decadal Oscillation (PDO) was not defined until relatively recently and among the first published papers to describe it were Mantua et al. (1997), Minobe (1997), and Zhang et al. (1997), while Gershanov and Barnett (1998) were among those who first described the influence of this phenomenon on North America surface weather. The first indications of the existence of the PDO occurred earlier in the 20th century as SSTs changed drastically within the Pacific Ocean during the late 1970s, and the event was first termed "The Great Climate Shift" or the "1976-1977 Climate Shift" (Miller et al. 1994).

The Pacific Decadal Oscillation can be described as a Pacific Ocean basin wide ENSO-like see-saw in the SSTs over a 50-to-70-year period (Fig. 3). The warm or positive phase of the PDO features a warm ENSO-like pattern for SSTs in the eastern tropics, but the cold phase shows cooler SSTs in the ENSO region. Dates marking the epochs of the PDO during the 20th century can be found on the website of the Joint Institute for the Study of the Atmosphere and Ocean at the University of Washington (Fig. 3). The warm phases persisted from 1924 – 1946, 1977 – 1998, and there is some indication that the later part of the 2010s showed the re-emergence this phase. The cool phase persisted from 1890 – 1924, 1947 – 1976, and 1998 – late 2010s. Recent research using tree ring data has traced the epochs of the PDO back to the 1st millennium AD (e.g., MacDonald and Case, 2005).

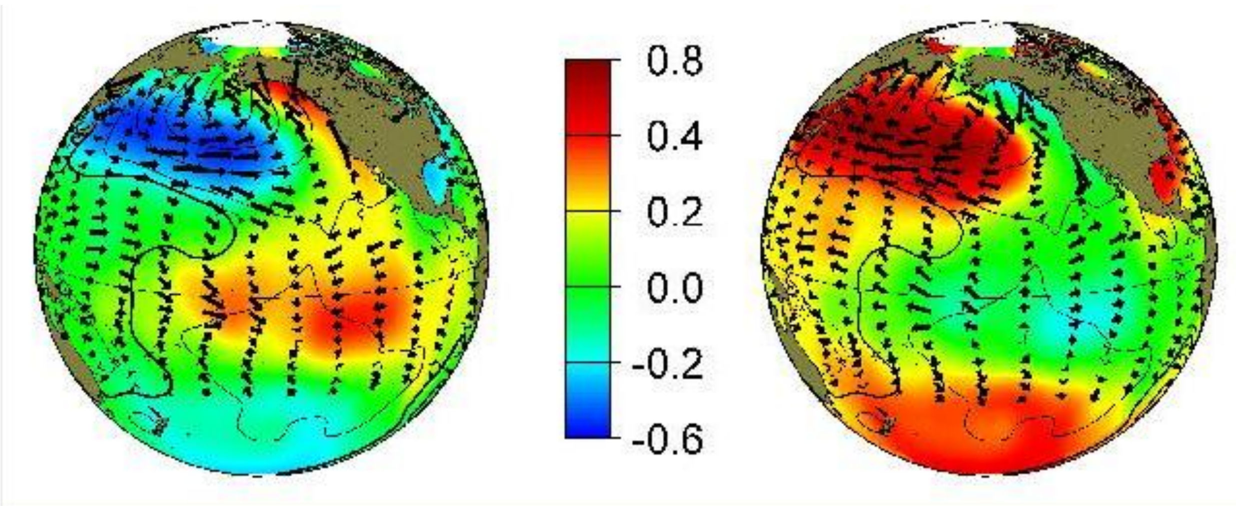

Figure 3. The Pacific Ocean SST patterns during the warm or positive (left) and cold or negative (right) phase of the PDO. Source: JISAO, University of Washington: http://research.jisao.washington.edu/pdo/.

The mechanisms governing the change in phase for the PDO epochs are not well understood, and recent studies have concluded that PDO is a result of combined physical processes such as tropical forcing and atmosphere–ocean interactions in the North Pacific (e.g., Newman et al., 2016). One of these may be a feedback process between these longer-term SST changes and ENSO. It is clear from looking at Fig. 3 that the positive or warm phase of the PDO would favor the occurrence of stronger El Niño events and weak La Niña events and vice versa during the negative or cool PDO phase. There is also a strong interaction between the two at intermediate time-scales (8 to 14 years) when studying a time series of the tropical Pacific SSTs (e.g., Mesta-Nunez and Enfield, 2001). Additionally, a time series of the PDO Index (see JISAO or a similar website) would show that the value is not uniformly negative or positive during the epochs defined above.

The PDO, like ENSO, has been shown to have an impact on the multidecadal scale for climate variables worldwide including the occurrence of droughts over North America (e.g., Cook et al. 2014) or the frequency and occurrence of stationary ridging events in the jet stream called atmospheric blocking (e.g., Lupo et al. 2019). There is a correspondence between the predominance of large-scale flow regimes in the Northern Nemisphere jet stream, a dynamic quantity called information entropy, and the phases of the PDO, as well as a rough correspondence to global temperature epochs as shown in, for example, van Geel and Ziegler (2013) and Kononova and Lupo (2020). Others, such as Wyatt and Curry (2014) suggest that relationships between oceanic and atmospheric circulation have a nearly 60-year variability or periodicity. Their work will be discussed later. However, given the discussion thus far, it should be clear that the positive phase of the PDO would be associated with increasing global temperature and the negative phase with decreases in a manner similar to that discussed with ENSO except over a longer period of time.

The Atlantic Multidecadal Oscillation

The Atlantic Multidecadal Oscillation (AMO) is somewhat similar to the PDO in that the time-scale is relatively long (about 60 - 80 years in total – Trenberth and Zhang, 2021), but this phenomenon is characterized by a distinct north-south SST pattern variation. During one phase (positive or warm), the tropical and far north Atlantic SSTs are anomalously warm while the central Atlantic is anomalously cool (Fig. 4) and vice-versa during the opposite (negative or cool) AMO phase. The AMO index (Fig. 4) is simply the SST anomalies averaged over the whole of the Atlantic Ocean (0 – 65° N and 80 W – 0°). Like the PDO, there is evidence of the AMO in proxy data (e.g., tree rings, ice cores, etc) going back for about 1000 years or more.

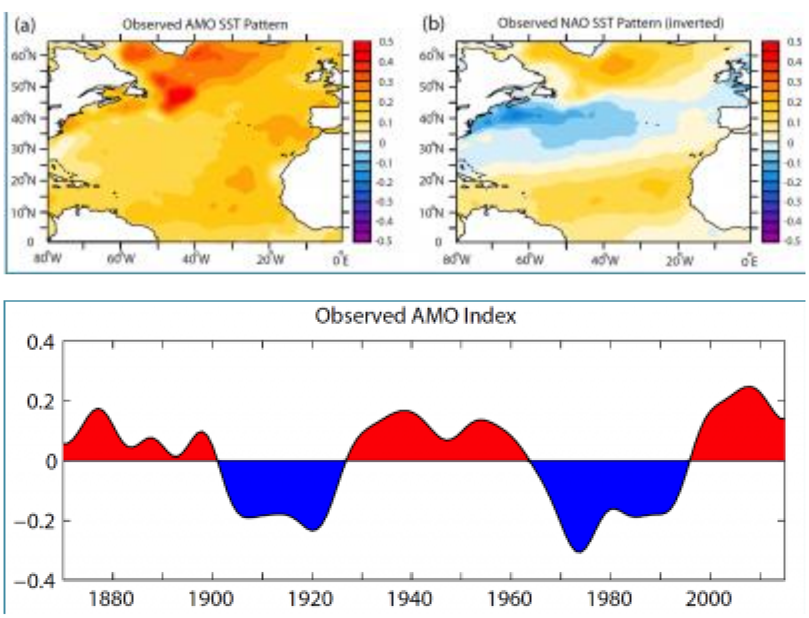

Figure 4: The Atlantic-wide SSTs (upper left) and SST anomalies (upper right) and AMO index (bottom) adapted from Trenberth and Zhang (2021).

A definitive mechanism for the cause of AMO has yet to be identified, but there is some evidence that changes in the Atlantic thermohaline circulation may at least partly drive the cycle (e.g., O'Reilly et al. 2016). Others have postulated an ocean-atmosphere feedback mechanism for the cause of the AMO (Yuan et al. 2016). The thermohaline circulation is a global deepwater circulation driven by changes in the density of oceanwater as driven by changes in salinity. Saltier water is more dense than fresher water and sinks (e.g., Knauss, 1988). These denser waters are formed by surface evaporation and surface currents such as the Gulf Stream carry this water mainly to the north Atlantic Ocean, and there the denser water sinks into the deeper ocean. The currents eventually mix waters across the entire globe via deep water currents with upwelling waters in the Southern Hemisphere and Northern Pacific.

Since the Atlantic part of this circulation is associated with the Gulf Stream, which is responsible for the relatively moderate climate of places like Northern Europe through the transport of heat in the surface ocean, the intensity or vigor of the thermohaline circulation impacts climate of the North Atlantic Ocean basin region. Changes in the strength of the thermohaline circulation occur on very long timescales (decades to centuries). If this circulation slows down, the climate of the North Atlantic can cool considerably, and such slowdowns were thought to cause temporary cold periods following the last ice age (e.g., the Younger Dryas – Carlson, 2010). In pop culture, an immediate shutdown of this circulation is the premise of the movie *The Day After Tomorrow* (2004). However, these topics are discussed in publications dealing with longer term climate change and variability.

On the decadal scale, the AMO has been linked to the occurrence of weather phenomena such as tropical cyclones and their intensity in the Atlantic basin (e.g., Klotzbach and Gray, 2008; Camargo et al. 2010). Many researchers have shown an impact on regional temperature and precipitation patterns in the Northern Hemisphere due to AMO, especially North America, Europe, and North Africa. The AMO can also be linked to changes in the Atlantic region general circulation and jet stream which will be discussed later. These changes can be quantified using the NAO Index.

While it may seem intuitive that the positive (warm) phase of the AMO would be associated with an increase in global temperature and the opposite for the cool phase, Maruyama (2019) found a more complex relationship between global temperature, AMO, and PDO. They found that during periods when the global temperature decreased, or increased little, (e.g., 1950 – 1976 and 1998 – 2012) the AMO was positive / warm generally while the PDO was negative / cool. During the increase in global temperature from the late 1970s to 1998, the PDO was positive / warm and the AMO was generally negative / cool. These results suggest there is a relationship between longer-term oceanic cycles themselves and global temperature.

Connections between these modes of variability in the ocean and atmosphere could be linked to one another and may change in sequence. This sequential change was likened to the "stadium wave", a pop culture phenomenon observed at well attended baseball or football games where fans stand and sit in sequence appearing as a propagating 'wave' of humanity to observers present or on television. The 'stadium wave' hypothesis was proposed by Wyatt et al (2012) and is characterized as multi-decadal variability in the climate signal that is associated with the propagation of a 'wave' of index phase changes across the Northern Hemisphere. The existence of this phenomenon in the Southern Hemisphere also is suspected.

Wyatt et al. (2012) examined observed SSTs and sea level pressure patterns and used eight indexes or indicators of ocean and atmosphere variability including some examined here (AMO, NAO, ENSO, and PDO). They also used various bioindicators such as fish populations to confirm interannual and interdecadal variability. Their paper showed for example that if we begin with a negative AMO, it would take about nine years for the NAO to become positive, then another five for the appearance of a positive ENSO. Then three years later the positive PDO appears, and 15 years later a positive AMO, a total of 32 years. It then takes another roughly 32 years (60 – 80 years) to sequence back to the negative AMO.

As this "stadium wave" relates to surface temperatures across at least the Northern Hemisphere and likely the globe, a warm North Atlantic (warm AMO) is associated with a decades long trend in cooling surface temperatures. Conversely, a cool North Atlantic (cool AMO) is associated with a decades long trend of warming surface temperatures. Thus the 'stadium wave' relates changes in the mode of these indexes to temperature trends, not necessarily surface or atmospheric temperature itself.

Atlantic Meridional Mode

The Atlantic Meridional Mode (AMM) is not the same as the AMO, but occasionally, these are confused for one another. This phenomenon occurs in the tropical Atlantic and is another example of ocean and atmosphere interactions or feedbacks. The AMM (e.g., Xie, 2009: Foltz et al. 2012) exhibits strong variability on the interannual and interdecadal time-scales. The positive phase of the AMM is characterized by warmer (cooler) than normal SSTs in the tropical north (south) Atlantic. Surface air pressure varies in step with the SST anomalies, becoming higher than normal over the anomalously cold SSTs and lower than normal over anomalously warm SSTs. The decadal mode of the AMM can be excited by the AMO (e.g., Delworth and Mann, 2000).

While the AMM has an impact on Atlantic tropical cyclone variability (positive AMM – increased Atlantic tropical cyclone activity – e.g,, Vimont and Kossin, 2007), any connection to northern hemisphere or global temperature is likely to be indirect or via the AMO.

North Atlantic Oscillation

The NAO is a teleconnection index in the atmosphere that is commonly misunderstood. This index on interannual and interdecadal time-scales is often errantly referred to as forcing itself. The NAO index is based on the difference in sea-level pressure between the Azores Islands in the Subtropical Atlantic and Iceland in the North Atlantic (e.g., Wilby et al. 1997). The former is dominated by a subtropical high, while the latter is dominated by a subpolar low. The positive NAO is associated with lower atmospheric heights and pressure across the higher latitudes and higher heights and pressure across the lower latitudes resulting in a more zonal (west to east or "flat") jet stream across the Atlantic and warmer temperatures in Europe. The negative phase results in a more meridional (north – south or "wavy") jet stream pattern across the Atlantic (Fig. 5).

The index itself is based on daily weather patterns and the daily value and change is related to the dynamic behavior of the Northern Hemisphere jet stream. Jensen et al. (2018) and references therein provide more detail on this behavior which has its roots in the primitive equations discussed in the introduction. Briefly, the Northern Hemisphere atmospheric flow has two relatively stable states that could be represented as a more zonal jet and a more meridional jet stream. The atmosphere remains in one of these two states for about 8 – 12 days at a time before transitioning to the other. However, the period between transitions is highly irregular lasting anywhere from 3 – 35 days. The NAO can be thought of as the Atlantic Ocean Basin version of the Northern Hemisphere dynamic variability as a whole and the dynamics can be represented using a simple model (e.g., Kravtsov et al. 2005, Luo et al. 2007).

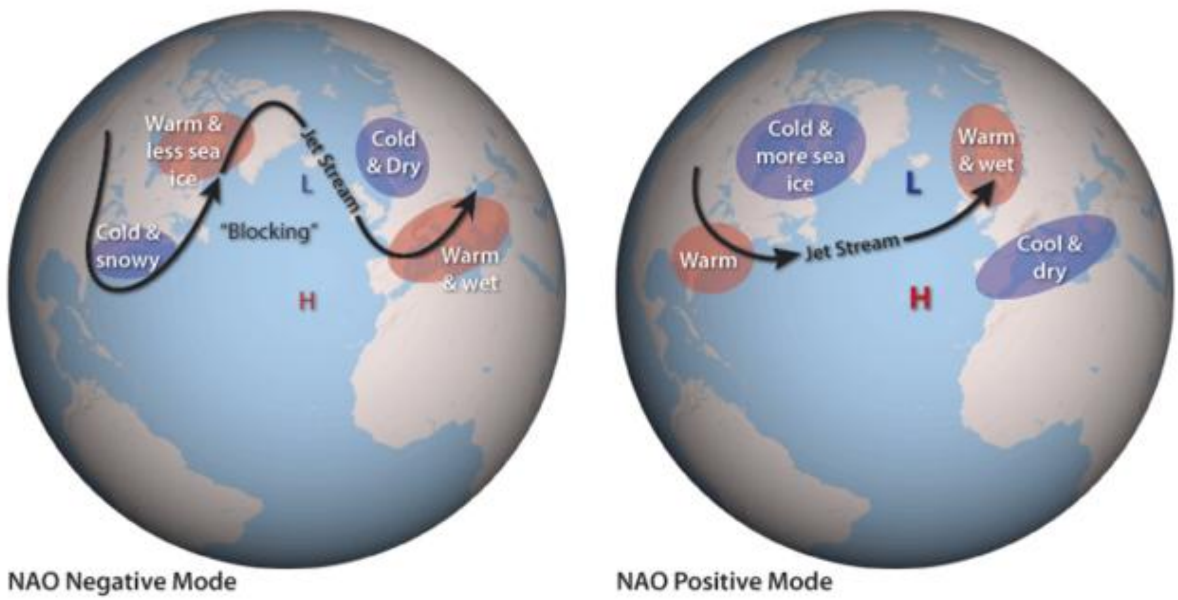

Figure 5: The typical jet stream and surface sensible weather conditions associated with the NAO. Credit: https://www.climate.gov/news-features/understanding-climate/climate-variability-north-atlantic-oscillation.

A daily (or monthly) time series of this index is available through the NOAA Climate Prediction Center (2022). An analysis of the index would show strong variability on the sub-seasonal (less than four months) to seasonal time-scales. It is known that the time series of the daily or monthly NAO index values possess interannual (e.g., DaCosta and de Verde, 2002, Mokhov and Smirnov, 2004) or interdecadal (e.g., Wang et al. 2012, Woolings et al. 2015) variability as well. Thus, the NAO will correlate on different time-scales to mid-latitude phenomena such as atmospheric blocking (Lupo et al. 2019). However, the forcing or cause of interannual or interdecadal variability in the NAO index will have its roots in the oceanic indexes examined here such as the AMO and even external variability such as solar cycles (e.g., Ludecke et al. 2020). The dynamics of other atmospheric indexes such as the Pacific North American (PNA) Index or the Arctic

Oscillation (AO) is similar to that of the NAO and interannual and interdecadal variability will arise for similar reasons to the NAO as well (e.g., Jensen et al. 2018; Lupo et al. 2019)

Conclusions

This chapter is a review of interannual and interdecadal cycles that are driven by oceanic and atmospheric mechanisms and how they can influence global atmospheric temperature. Here the El Niño and Southern Oscillation phenomenon is used to demonstrate the physics associated with changes in the oceanic distribution of heat and then how it is redistributed through the atmosphere. This includes a calculation to show that the heat released from only a part of the warm anomaly associated with the 2015-2016 El Niño could be solely responsible for a spike in atmospheric temperature that appears in the monthly record of satellite derived 40-year temperature record for the global lower atmosphere.

Then prominent and familiar oceanic cycles are discussed including their background and the potential to have an influence on global temperatures over the time scale of decades. This chapter also highlights how the PDO and AMO could interact with each other and be related to global temperature. Then a review of a relatively new theory about the long-term connections between sequential changes in all these cycles called the “stadium wave” hypothesis and how these changes relate to global temperature trends. Finally, the NAO, which is a prominent atmospheric teleconnection, is discussed in relation to the fundamental dynamics of short-term atmospheric variability and long-term variations in this index as forced by ocean cycles. This index is commonly misunderstood as to what information is conveyed.

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