The Global 3-Dimensional Structure of Climate associated with the Atlantic Multidecadal Oscillation

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ABSTRACT

The Atlantic Multidecadal Oscillation (AMO) is a dominant driver of climate on multidecadal timescales characterized by alternating cool and warm phases that disguise and enhance the effects of global warming respectively. Despite this, some climate models remain unable to generate a realistic AMO-like signal, prompting the UN Intergovernmental Panel on Climate Change (IPCC) to target the AMO as a research priority that will make significant contributions to the upcoming Fifth Assessment Report. This study uses a global climate reanalysis database covering 60 years (one full AMO cycle) to regress a number of climate variables (e.g., temperature, precipitation, pressure and winds at various altitudes) onto an AMO index in order to reconstruct the climate effects of the AMO. The goals of this study are to advance a better understanding of the AMO and its effects on climate, reveal global teleconnection patterns and provide a high-quality reconstruction of AMO-related climate that can be used as a benchmark for the improvement of climate models via 'hindcasting'. Improved climate forecasts in turn have significant implications (e.g., extension of drought and monsoon forecasts beyond the current seasonal timescales) and provide opportunities for more informed societal decision-making (e.g., better long-term water management strategies and more appropriate agricultural planning in affected areas).

INTRODUCTION

Sea surface temperatures (SSTs) play an important role in regulating climate, influencing the rate at which energy from the ocean is transferred to the atmosphere via turbulent and radiative energy exchange (e.g., Deser et al 2009). Due to high inertia, oceans are dominant drivers of multidecadal climate variability that impacts billions through its sustained effects on agriculture, water resources, fisheries and public health (Mehta et al 2000).

A dominant climate mode on multidecadal timescales is the Atlantic Multidecadal Oscillation (AMO), characterized by alternating phases of warm and cool SST anomalies throughout the North Atlantic basin from 0 to 70° N (Schlesinger & Ramankutty 1994; Kerr 2000). Instrumental records beginning in the 1850s suggest that each warm and cool phase persists for two to three decades, completing a full cycle roughly every 60 years (Figure 1). Between each extreme (i.e., warm and cool) phase exists a transition (or 'organizational') phase lasting up to a decade in which SST anomalies appear essentially unchanged as the North Atlantic adjusts to a new regime (Gray et al 2004; Dima & Lohmann 2007).

The influence of the AMO on the Atlantic hurricane main development region is well established (Goldenberg et al 2001; Knight et al 2006; Zhang & Delworth 2006; Enfield & Cid-Serrano 2009). Information about the AMO contributes to the seasonal hurricane forecasts produced by the US National Oceanic and Atmospheric Administration (NOAA), which notes the cool AMO years from 1970 to 1994 averaged 3 to 4 hurricanes per year whereas the 1995 return to the current AMO warm phase featured 11 hurricanes (NOAA website). This correlation holds for the previous AMO warm phase as well: Djikstra et al (2006) found 47 intense hurricanes (Class 3 or above) during a 1950-1964 warm AMO period but only 19 intense hurricanes during a corresponding 1970-1984 cool AMO phase. Specifically, the AMO may influence hurricanes via its effects on the Atlantic Warm Pool (AWP – see Wang et al 2006), a region of SSTs warmer than 28.5°C that develops every summer and includes areas of the tropical eastern Atlantic Ocean, Caribbean Sea and Gulf of Mexico. A warm AMO promotes a larger AWP area that both reduces vertical wind shear and increases the moist static instability of the troposphere, both of which favor the intensification of tropical storms into major hurricanes (Knight et al 2006) and suggest the AWP may be a dynamic and thermodynamic link through which the AMO exerts its effects on hurricane activity (Wang et al 2008a).

A warm AMO may also be linked to accelerated Arctic warming (Chylek et al 2009) and therefore a contributing factor in the more-rapid-than-projected loss of Arctic sea ice extent (SIE) that has occurred since the mid-1990s (e.g., Comiso 2006) and coincides with the onset of the current AMO warm phase.

A warm AMO is responsible for decreased precipitation throughout much of the Americas. Most of the continental United States experiences decreased precipitation (Enfield et at 2001) and increased regional-scale wildfire frequency (Kitzberger et al 2007) during a warm AMO. The warm AMO-associated droughts in northeast Brazil (Hastenrath 1993; Folland et al 2001; Knight et al 2006) that are sometimes accompanied by famine (Glantz 1999) remain one of the only documented Southern Hemisphere connections with the AMO.

The AMO climate effects extend to regions far removed from the Atlantic, favoring stronger summer monsoons in Asia (Zhang & Delworth 2006; Lu et al 2006) and India (Goswami et al 2006) due to the strengthening of the meridional tropospheric temperature gradient. A cool

AMO can be particularly devastating in this region where approximately one billion people depend on timely and sufficient rainfall for rice production (Wang 2006).

Beyond climate effects, a warm AMO may alter the abundance and distribution of phytoplankton in the Atlantic (Antoine & Morel 2005; Martinez et al 2009) and in some Florida estuaries (Briceño & Boyer 2009). Phytoplankton are responsible for half the world's primary productivity, converting 100 million tons of carbon from CO2 into organic material daily (Behrenfeld et al 2006); therefore, population disruptions could impact atmospheric and ocean surface CO_2 concentrations and biogeochemical cycling (Falkowski & Wilson 1992). Alternatively, disruptions could also propagate up the food chain. Zooplankton, which feed on phytoplankton and with whom they enjoy a tight trophic coupling, serve as the main diet of juvenile salmon. A warm AMO-altered phytoplankton (and therefore zooplankton) distribution has been suggested as a primary driver of recent mass mortality of juvenile salmon at sea (Condron et al 2005; Friedland et al 2009) despite restocking efforts (Condron et al 2005), and decreased salmon populations have been shown in turn to alter the behavior of Atlantic bottlenose dolphins by decreases in pod size (Lusseau et al 2004).

The Sahel region of Africa is especially sensitive and cool AMO phases have long been associated with prolonged drought and periodic famine (Folland et al 1986; Zhang & Delworth 2006; Knight et al 2006). Inhabitants depend on the brief rainy season for subsistence agriculture, livestock and hydropower (Navarra 1999). The previous cool AMO was associated with a particularly severe famine from 1968 through 1974 that left 100,000 dead, millions displaced and devastated the agricultural infrastructure of five countries (Navarra 1999). In response, an emergency World Food Conference was organized that itself led to the development of a specialized UN agency, the International Fund for Agricultural Development, whose mission is to assist subsistence farmers with more appropriate agricultural planning (IFAD website).

The persistent Sahel droughts during a cool AMO can generate up to 4 times higher dust transport via dust storms throughout the Atlantic (Prospero and Lamb 2003; Brooks & Legrand 2003). Dust itself plays a role in climate due to its reflective and radiative properties as well as providing extensive cloud condensation, a climate feedback that can further modulate temperatures and precipitation (Prospero et al 2003). This mineral dust is also rich in iron, an important and sometimes limiting nutrient for phytoplankton, and could stimulate increases in phytoplankton abundance though ocean 'seeding' with implications for primary productivity and carbon cycling in the eastern North Atlantic (Prospero et al 2003).

Observations and modeling indicate the phase of the AMO tracks changes in the intensity of the thermohaline circulation (THC – e.g., Knight et al 2005). A warm (cool) AMO is associated with a strengthened (weakened) THC. Although a consensus has not yet emerged involving the life cycle of the AMO, a compelling conceptual model (Dima & Lohmann 2007) based primarily on time-lag observational analysis that incorporates positive and negative feedbacks as well as 'memory' (lag times) notes that a warm AMO/strong THC transports more heat to, and therefore warms, the North Atlantic. Sea level pressure (SLP) decreases over the North Atlantic and Europe but, after a lag time of 10 years, increases in the North Pacific. This pronounced Atlantic-Pacific SLP gradient drives an intensification of polar northerlies (the primary driver of Arctic sea ice export to the North Atlantic) and extends into Fram Strait (an area east of Greenland responsible for most Arctic sea ice export to the North Atlantic). The sea ice-induced increased freshening of the North Atlantic in turn acts as a negative feedback to the AMO by interfering with North Atlantic Deep Water (NADW) formation, weakening the THC and generating a switch to a cool AMO (Dima & Lohmann 2007).

The Great Salinity Anomaly (GSA) that began in the late 1960s (Dickson et al 1988), involving a massive amount of Arctic freshwater export to the northern North Atlantic, likely helped trigger the onset of the 1970-1990 AMO cool phase (Dima & Lohmann 2007). The GSA freshening trend of the upper ocean persisted in the northern North Atlantic until a reversal in the mid-1990s (Holliday et al 2008) that coincides with a 1995 switch to a warm AMO and continues, reaching salinity maximums in the northeast North Atlantic subpolar gyre and Fram Strait last seen in the 1960s and exceeding the historical temperature record maximum (Holliday et al 2008).

Since the AMO is a temperature-based record, however, it is likely at least partially confounded by the effects of anthropogenic global warming (AGW), which also influences climate on similar timescales (e.g., Rahmstorf et al 2007). Although the AMO remains a dominant climate mode, its effects are superimposed on those of AGW such that a cool and warm AMO alternately disguise and enhance the effects of AGW (Enfield et al 2001; Keenlyside et al 2008). The ability to achieve complete signal separation of AGW from the AMO remains ongoing (e.g., Ting et al 2009; Guan & Nigam 2009; Enfield & Cid-Serrano 2009; Zhang & Delworth 2009); therefore, a better understanding of multidecadal variability has been targeted as a research priority for its contribution towards properly attributing the effects of AGW. A March 2009 United Nations Intergovernmental Panel on Climate Change (UN IPCC) workshop identified a need for better understanding the AMO (IPCC Workshop website) that a June 2009 UN IPCC Scoping Meeting predicted would make important contributions to the UN IPCC Fifth Assessment Report (AR5) to be released in 2013 (IPCC AR5 Scoping Meeting website). That same year, the US National

Research Council tasked the US Climate Change Science Program to better characterize the AMO in order to improve climate change forecasts (National Research Council 2009).

A challenge to better understanding the AMO is the relatively short 150-year instrumental record, which provides coverage of only two full cycles, less than the six preferred for statistical characterization. Proxy reconstructions have been used infer AMO activity for up to 500 years (Gray et al 2004; see also Gray et al 2003; Hetzinger et al 2008), and the increasing development of multiproxy networks will be particularly useful (Delworth & Mann 2000).

This study takes an alternative and complementary approach, providing a high-resolution reconstruction of global climate associated with one full cycle of the AMO. The goals of this study are to: 1) provide a refined understanding of the AMO and its climate effects; 2) identify possible global teleconnection patterns; and 3) improve the accuracy of climate model projections by improving GCM simulation of multidecadal natural variability. This 3-dimensional reconstruction of AMO-related climate will provide information useful in hindcasting, a standard technique in which modelers run GCMs backward in time to compare model results with actual observations: the higher the similarity, the more confidence can be attached to projections of future climate.

Ultimately, increasing the accuracy and reliability of GCM projections on multidecadal timescales could make significant social and economic contributions by providing better information to policymakers and resource managers and could provide the basis for extension of drought predictions beyond current seasonal timescales and better long-term water management and agricultural planning in affected areas. Reliable decadal forecasts would be particularly useful since these timescales are conducive to designing and implementing mitigation and adaptation strategies.

METHODS

The AMO Index as defined by Enfield et al (2001) was smoothed with a 121-month running mean to remove short-term variability, generating an AMO Smoothed Index (Figure 2a). This index was used to reconstruct the global climate associated with the extreme (i.e., warm and cool) phases of the AMO.

The AMO Transition Index was defined as the time derivative of the smoothed index (Figure 2b). The time derivative is calculated using the central difference scheme, excluding the first and last data points which are calculated by the forward and backward difference scheme respectively. Since transition phases of climate cycles exert climate effects as well (see Lin 2009), this index was used to reconstruct the AMO transition phase climate anomalies.

The National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) reanalysis database (Kalnay et al 1996) provides climate observations from 1948 through 2007 and is made available through the NOAA/Earth Systems Research Lab website: http://www.esrl.noaa.gov/psd/data/reanalysis/reanalysis.shtml.

This 60-year record of global climate provided by the NCEP/NCAR reanalysis dataset corresponds to one full AMO cycle, permitting a comprehensive characterization of the complete life cycle of the AMO. Numerous climate variables at the surface (i.e., SST, sea level pressure (SLP), zonal and meridional winds at 1000mb) and throughout the atmosphere (i.e., geopotential height and zonal and meridional winds at 500mb and 200mb) were regressed onto the AMO

Smoothed Index (to examine global climate associated with the extreme phases) and the AMO Transition Index (to characterize the transition phase).

The reconstruction of AMO-related climate was examined on seasonal timescales as well, including summer (JJA) and winter (DJF). However, for the purposes of this paper, the AMO transition phase and the AMO seasonal reconstructions will not be shown.

Figure 3 illustrates the output generated by regression of climate observations (top = SST and bottom = precipitation) in the NCEP/NCAR database onto the AMO Smoothed Index over the past 60 years.

RESULTS AND DISCUSSION

The schematic of Figure 4 shows the global 3-dimensional reconstruction of climate anomalies associated with AMO extreme phases over the past 60 years. The diagram indicates the climate anomalies associated with the AMO warm phase whereas an AMO cool phase would feature the opposite anomaly (e.g, a ‘wet and warm’ region on the diagram would experience ‘dry and cool’ conditions during a cool AMO). Generally, the steep horizontal temperature gradients and intensified thermal winds apparent in the vertical profile indicate a baroclinic atmosphere, a dynamically unstable state responsible for shaping the cyclones and anticyclones that dominate weather in the mid-latitudes.

Results from Figure 4 can be organized into four categories:

1) **Support for previous studies:**

   The reconstruction recreates the oppositely-signed Northern v Southern Atlantic Ocean SST anomalies that are a defining feature of the AMO (Kerr 2000).

The intensity of the Atlantic Warm Pool likely responsible for the AMO-hurricane association (Wang et al 2008a) strongly responds to the AMO and extends beyond Central America into the eastern tropical Pacific, a larger water mass that subsumes the AWP and is known as the Western Hemisphere Warm Pool (Wang et al 2008b).

Extensive cyclonic low pressure systems over the Atlantic and Europe provide a mechanism for precipitation increases in those areas (Knight et al 2006).

Intensified winds that penetrate India and southern Asia and broad areas of increased precipitation support enhanced monsoonal activity (Lu et al 2006).

Polar northerly winds projecting from the Arctic to the North Atlantic - the primary driver of Arctic SIE to the North Atlantic– are significantly intensified, potentially contributing to the accelerated loss of Arctic SIE (Dickson et al 1988; Dima and Lohmann 2007) that temporally corresponds with the 1995 switch to a warm AMO. Further, if the increased export of sea ice to the North Atlantic increases the amount of open ocean, the resulting loss of albedo could act as a positive feedback promoting increased warming.

2) Extension of previous studies:

Although dry conditions in the western United States (Enfield et al 2001) and northeast Brazil (Folland et al 2001) have previously been associated with a warm AMO, this reconstruction suggests those two regions comprise two geographically extreme poles joined by a contiguous stretch of drought-prone land including most of Central America.

3) Contradictory findings:

Although previous observations and models suggest a warm AMO is associated with decreased precipitation throughout the United States (with the exception of the Pacific Northwest and Florida – e.g., Kelly & Gore 2008), this reconstruction suggests a warm AMO may correspond to a slight increase in precipitation in the eastern US that varies spatially by season (not shown). A high pressure anticyclonic system covers much of the North America and is especially pronounced over the US. This system is also known as a 'blocking high' due to its tendency to affect the formation and deflect the movement of wintertime storm tracks, and it likely explains the decreased wintertime US precipitation. However, the reanalysis shows increased precipitation during summertime that, on an annual average basis, slightly overcompensates for wintertime decreases. On the other hand, the discrepancy could be a result of the NCEP/NCAR precipitation field, identified as one of the least reliable variables (Kalnay 1996).

4) Novel findings:

Baines (2005) proposed a series of mechanisms to explain an observed correlation between long-term climate variations in the Sahel and southwest Australia. A robust Sahel response to the AMO would suggest the possibility of an AMO-Australia link that is supported by this reconstruction. Whereas the Sahel and western Australia share similar precipitation anomalies (i.e., warm AMO favors increased precipitation), opposing conditions (decreased precipitation) predominate over eastern Australia.

Whereas others have reported a North Pacific co-oscillation (Knight et al 2005), this appears to be merely the northern component of a larger ‘horseshoe’ pattern across the western and into the southern Pacific that appears very similar to SST conditions associated with La Niña or the Pacific equivalent of a cool AMO, the La Niña-like Pacific Decadal Oscillation (PDO) cool phase. Further, we hypothesize this SST horseshoe pattern is generated by an AMO Atlantic-Pacific teleconnection that involves the intensified WHWP SSTs and northeasterly trade winds over the Central American isthmus. Further, the reconstruction shows enhanced northeasterly trade winds in the central and western Pacific (and increased SST anomalies in the western Pacific), suggesting the Atlantic-Pacific teleconnection signal via Central America is amplified by Bjerknes feedback, a tropical Pacific phenomenon in which small changes in winds or SSTs are amplified by the other and propagate westward (Bjerknes 1969). The reconstruction indicates three likely centers of action involved in this signal propagation: a strengthened Pacific/Hawaiian High and South Pacific Subtropical High as well as decreases in the West Pacific Warm Pool.

The importance of this tropical ocean AMO teleconnection and its climate effects are especially notable following analysis of the AMO transition phase (not shown) and the PDO extreme (warm and cool) and transition phase. These reconstructions (not shown) reveal a deeper AMO-PDO connection that will be detailed in a separate paper also currently in preparation.

CONCLUSION

Low-frequency natural climate variability is resistant to easy characterization due primarily to a short and sparse record of quality observations. A better understanding of the AMO will improve decadal climate change projections and, because of the timescales involved, is a source of potential predictability associated with valuable social and economic benefits. This global reconstruction of AMO-related climate reveals new teleconnection patterns and should prove useful for hindcasts that can improve the accuracy of climate model simulations of natural variability, increasing confidence of future projections and allowing for more informed political and managerial decisions.

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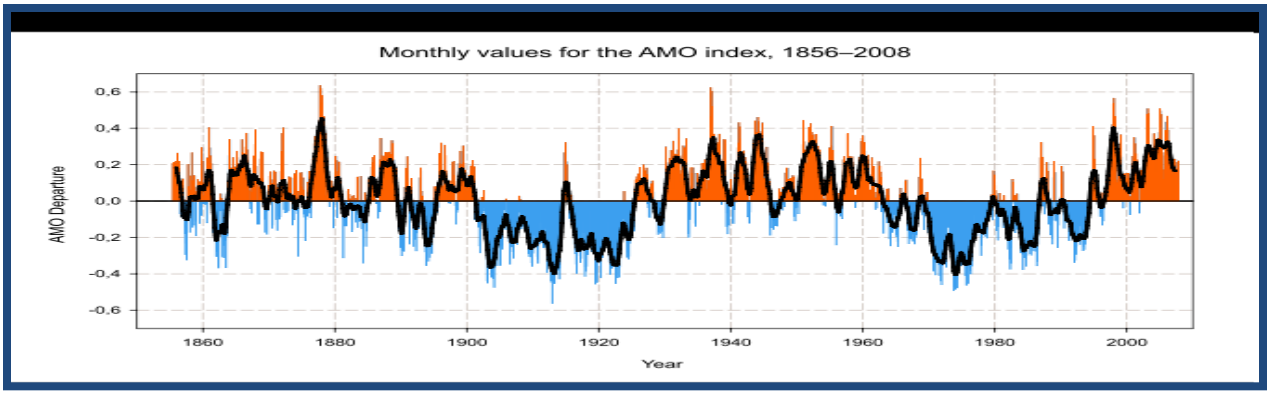


Figure 1: An observational record of the slowly oscillating warm and cool SST anomalies of the North Atlantic from 0 to 70°N that represent the AMO warm and cool phases. Figure taken from NOAA.

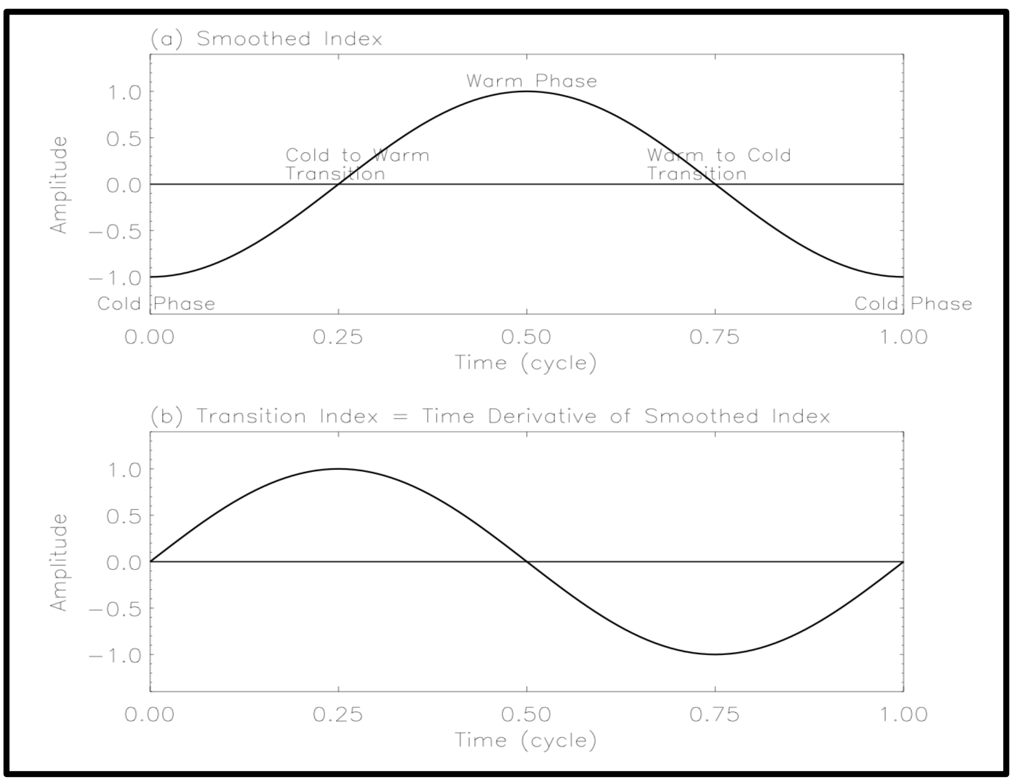
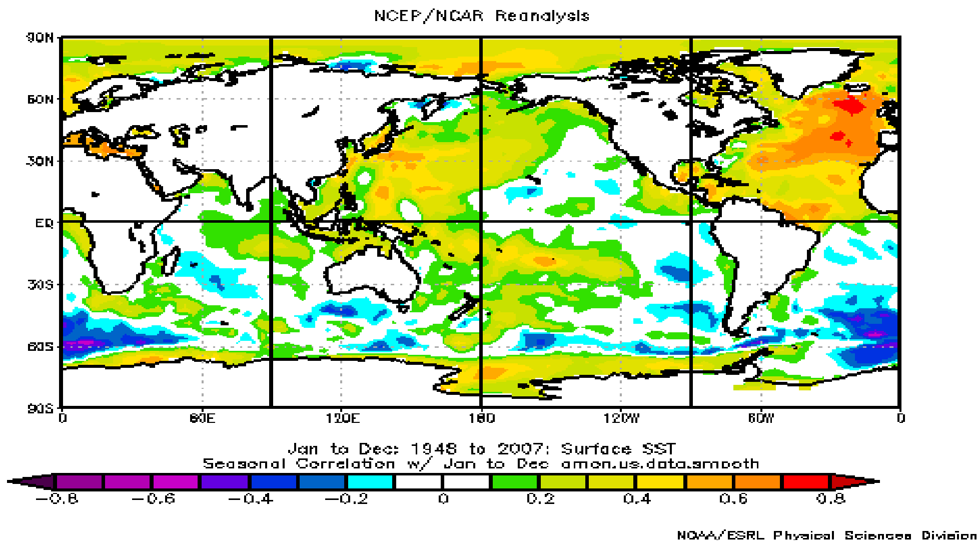


Figure 2a: The AMO Smoothed Index: the AMO index defined by Enfield et al (2001) is smoothed with a 121-month running mean to remove short-term variability and used to reconstruct climate of the AMO extreme (warm and cool) phases.

Figure 2b: The AMO Transition Index is defined as the time derivative of the smoothed index and is calculated using the central difference scheme, excluding the first and last data points which are calculated by the forward and backward difference scheme respectively.



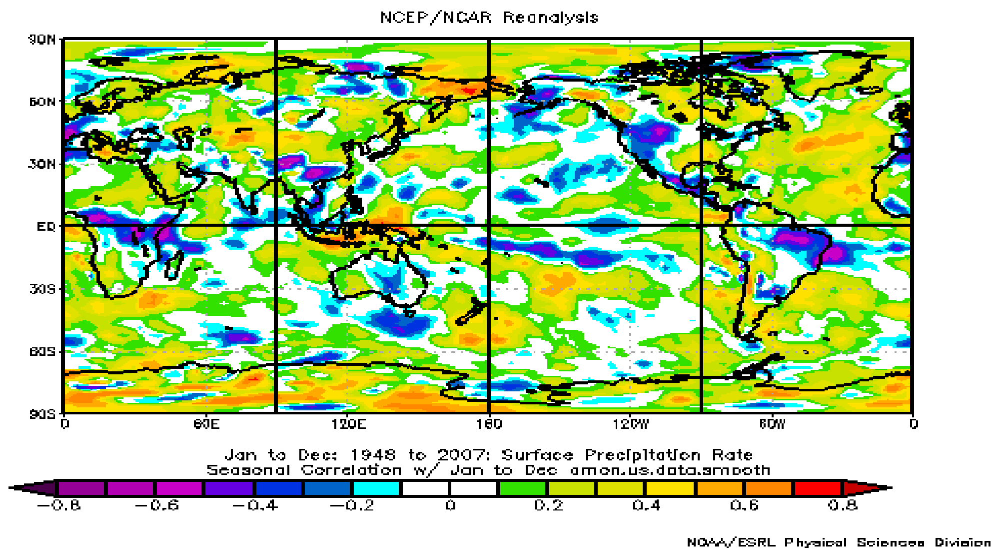


Figure 3: Global annual SST anomalies (top) and global precipitation anomalies (bottom) from the NCEP/NCAR reanalysis database spanning 1948-2007 and regressed onto the AMO Smoothed Index.

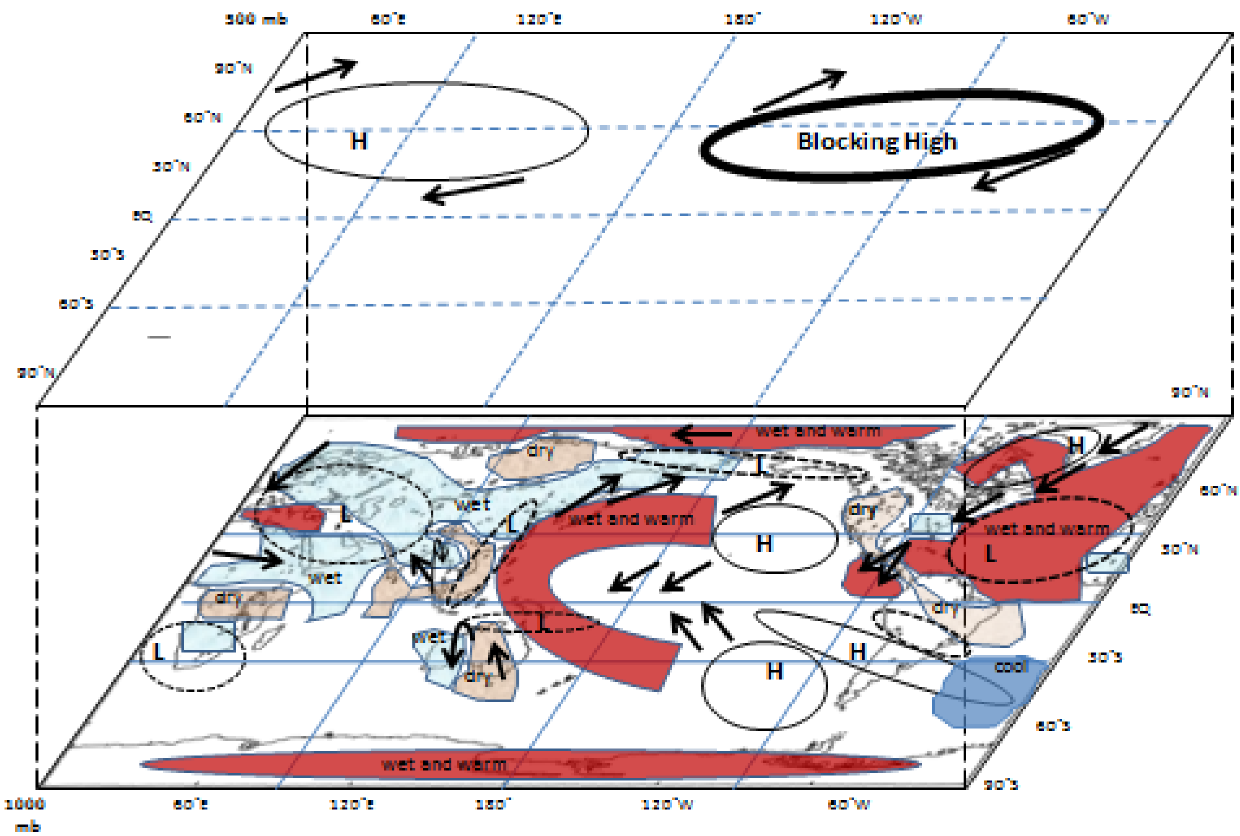


Figure 4: Schematic of the global 3-dimensional structure of climate associated with the AMO warm phase (climate anomalies of the cool phase are opposite those shown in the schematic).