Climate Modeling

Climate Variability: Patterns and Indices

Unforced vs. Forced Variability: causes

- We often distinguish between unforced variability and variability forced by natural or anthropogenic causes.
- Unforced variability arises from the **natural** internal dynamics without any specific cause.
- Forced variability can be associated with some change in the boundary conditions of the climate system, such as a volcanic eruption or solar variability on the **natural** side, or gas or aerosol emissions by human activities on the **anthropogenic** side.

Unforced (natural) Variability: time scales

Unforced variability can occur on a variety of time scales:

- a week or two that we normally associate with weather
- intraseasonal variability that might result from internal atmospheric dynamics or interactions between the ocean and the atmosphere
- interannual variability that might result from ocean–atmosphere interactions on time scales of a few years
- internal variability that may last up to a thousand years, about the time it takes to turn over the global ocean.
- Variability that lasts thousands to millions of years may be caused by interactions between variations in Earth’s orbital parameters and its cycles of carbon and ice.

Patterns of Climate Variability

- Climate variability is not uniform in space; it can be described as a combination of some "preferred" spatial patterns. The most prominent of these are known as **modes** of climate variability, which affect weather and climate on many spatial and temporal scales.
- The best known and truly periodic climate variability mode is the seasonal cycle. Others are quasiperiodic or of wide spectrum temporal variability.
- Climate modes themselves and their influence on regional climates are often identified through spatial **teleconnections**, i.e., relationships between climate variations in places far removed from each other.

Patterns/Modes of variability are described using specific “indices”

- Traditionally, indices of climate variability were defined as linear combinations of seasonally averaged anomalies from meteorological stations chosen in the proximity of maxima and minima of the target pattern.
- Since gridded fields of climate variables are now available, appropriate regional averages often replace station data. The strongest teleconnections in a climate field are also identified by pairs of grid points with the strongest anti-correlation.
- Today we have a group of the most prominent modes of large-scale climate variability and the corresponding various indices used to define them. Changes in these indices are associated with large-scale changes in climate fields.

Main indices of Climate Variability

- Are those that generally have been (A) used by a variety of authors and (B) defined relatively simply from raw or statistically analyzed observations of a single surface climate variable, so that observational datasets longer than a century exist.
- The multiplicity of indices defining the same climate phenomenon arises because no index can achieve a perfect separation of a target phenomenon from all other effects in the real climate system. As a result, each index is affected by many climate phenomena whose relative contributions change with time periods and data used. Limited length and quality of observational record compounds this problem. Thus the choice of indices is always application specific

Established Indices of Climate Variability (with global or regional influence)

Climate Phenomenon	Index name	Index Definition	Primary References	Characterization / Comments
El Niño – Southern Oscillation (ENSO) - canonical, Eastern Pacific ENSO	NINO3	SST anomaly averaged over (5°S–5°N, 150°W–90°W)	Cane et al. (1986); Rasmusson and Wallace (1983)	Traditional SST-based ENSO index
	NINO3.4	SST anomaly averaged over (5°S–5°N, 170°W–120°W)	Trenberth (1997)	Used by NOAA to define El Niño/La Niña events. Detrend-ed form is close to the 1st PC of linearly detrended global field of monthly SST anomalies (Deser et al. 2010)
	Cold Tongue Index (CTI)	SSTA (6°N–6°S, 180°–90°W) minus global mean SSTA	Deser and Wallace (1990)	Matches "cold tongue" area, subtracts effect of the global average change
	Troup SOI	Standardized for each calendar month MSLP difference: Tahiti minus Darwin, x10	Troup (1965)	Used by Australian Bureau of Meteorology
	SOI	Standardized difference of standardized MSLP anoma-lies: Tahiti minus Darwin	Trenberth (1984)	Maximizes signal to noise ratio of linear combinations of Dar-win/Tahiti records
	Darwin SOI	Standardized Darwin MSLP anomaly	Trenberth and Hoar (1996)	Introduced to avoid use of the Tahiti record, considered suspi-cious before 1935.
	Equatorial SOI (EQSOI)	Standard difference of standard MSLP anomalies over equatorial (5°S–5°N) Pacific Ocean; east (130°W–80°W) minus west (90°E–140°E)	Bell and Halpert (1998)	
Central Pacific El Niño (Modoki)	El Niño Modoki Index (EMI)	SSTA: [165°E–140°W, 10°S–10°N] minus ½[110°W–70°W, 15°S–5°N] minus ½[125°E–145°E, 10°S-20°N]	Ashok et al. (2007)	A recently identified ENSO vari-ant: Modoki or Central Pacific El Niño (non-canonical)

Climate Phenomenon	Index name	Index Definition	Primary References	Characterization / Comments
Pacific Decadal and Interdecadal Variability	Pacific Decadal Oscillation (PDO)	Ist PC of the N. Pacific SST anomaly field (20°N–70°N) with subtracted global mean	Mantua et al. (1997); Zhang et al. (1997)	
	Intedecadal Pacific Oscillation (IPO)	The 3rd EOF3 of the 13-year low-pass filtered global SST, projected onto annual data	Folland et al. (1999); Power et al. (1999)	
	North Pacific Index (NPI)	SLP (30°N–65°N, 160°E–140°W)	Trenberth and Hurrell (1994)	
North Atlantic Oscillation	Lisbon/Ponta Delgada-Stykkisholmur/Reykjavik North Atlantic Oscillation (NAO) Index	Lisbon/Ponta Delgada minus Stykkisholmur/Reykjavik standardized MSLP anomalies	Hurrell (1995)	A primary NH teleconnection both in MSLP and Z500 anomalies (Wallace and Gutzler 1981); one of rotated EOFs of NH Z500 (Barnston and Livezey 1987) . MSLP anomalies can be monthly, seasonal or annual averages. Each choice carries to the temporal resolution of the NAO index produced that way.
	Gibraltar - Reykjavik NAO Index	Gibraltar minus Reykjavik standardized MSLP anomalies	Jones et al. (1997)	
	PC-based NAO Index	Leading PC of MSLP anomalies over the Atlantic sector (20°N–80°N, 90ºW–40ºE)	Hurrell (1995)	
Annular modes: Arctic Oscillation (AO), a.k.a. Northern Annular Mode (NAM) Index and Antarctic Oscillation (AAO), a.k.a. Southern Annular Mode (SAM) Index	PC-based AO index	Ist PC of the monthly mean MSLP anomalies poleward of 20°N	Thompson and Wallace (1998, 2000)	Closely related to the NAO
	PC-based AAO index	Ist PC of 850hPa or 700hPa height anomalies south of 20ºS	Thompson and Wallace (2000)	
	Grid-based AAO index: 40°S–65°S difference	Difference between normalized zonal mean MSLP at 40°S and 65°S, using gridded SLP analysis	Gong and Wang (1999)	
	Grid-based AAO index: 40°S–70°S difference	Same as above but uses latitudes 40°S and 70°S	Nan and Li (2003)	
	Station-based AAO index: 40°S–65°S	Difference in normalized zonal mean MSLP at 40°S and 65°S, using station data	Marshall (2003)	

Climate Phenomenon	Index name	Index Definition	Primary References	Characterization / Comments
Pacific/North America (PNA) atmospheric tele-connection	PNA pattern index	¼[Z(20°N, 160°W) - Z(45°N, 165°W) + Z(55°N, 115°W) - Z(30°N, 85°W)], Z is the location's standardized 500 hPa geopotential height anomaly	Wallace and Gutzler (1981)	A primary NH teleconnection both in MSLP and Z500 anomalies
Atlantic Ocean Thermohaline circulation	Atlantic Multi-decadal Oscillation (AMO) index	10-yr running mean of de-trended Atlantic mean SST anomalies (0°–70°N)	Enfield et al. (2001)	Called "virtually identical" to the smoothed first rotated N. Atlantic EOF mode
	Revised AMO index	As above, but subtracts global mean anomaly instead of de-trending	Trenberth and Shea (2006)	
Tropical Atlantic Ocean non-ENSO variability	Atlantic Niño Index, ATL3	SSTA (3°S–3°N, 20°W–0°)	Zebiak (1993)	Identified as the two leading PCs of detrended tropical Atlantic monthly SSTA (20°S–20°N): 38% and 25% variance respectively for HadISST1, 1900–2008 (Deser et al. 2010)
	Atlantic Niño Index, PC-based	1st PC of the detrended tropical Atlantic monthly SSTA (20°S–20°N)	Deser et al. (2010)	
	Tropical Atlantic Meridional Mode (AMM)	2nd PC of the detrended tropical Atlantic monthly SSTA (20°S–20°N)		
Tropical Indian Ocean non-ENSO variability	Indian Ocean Basin Mode (IOBM) Index	The 1st PC of the IO de-trended SST anomalies (40°E–110°E, 20°S–20°N)	Deser et al. (2010)	Identified as the two leading PCs of detrended tropical Indian Ocean monthly SSTA (20°S–20°N): 39% and 12% of the variance, respectively, for HadISST1, 1900–2008 (Deser et al. 2010)
	Indian Ocean Dipole mode (IODM), PC-based index	The 2nd PC of the IO detrended SST anomalies (40°E–110° E, 20°S–20°N)		
	Indian Ocean Dipole Mode Index (DMI)	SST anomalies: 50°E–70°E, 10°S–10°N)-(90°E–110°E, 10°S–0°)	Saji et al. (1999)	
Cold Ocean – Warm Land (COWL) Variability	COWL Index	Linear best fit to the field of deviations of NH temperature anomalies from their spatial mean; the COWL pattern itself is proportional to the covariance pattern of the NH spatial mean with these deviations.	Wallace et al. (1995); Thompson et al. (2008)	Useful for removing some effects of natural climate variability from spatially averaged temperature records.

Statistical derivation of patterns and indices

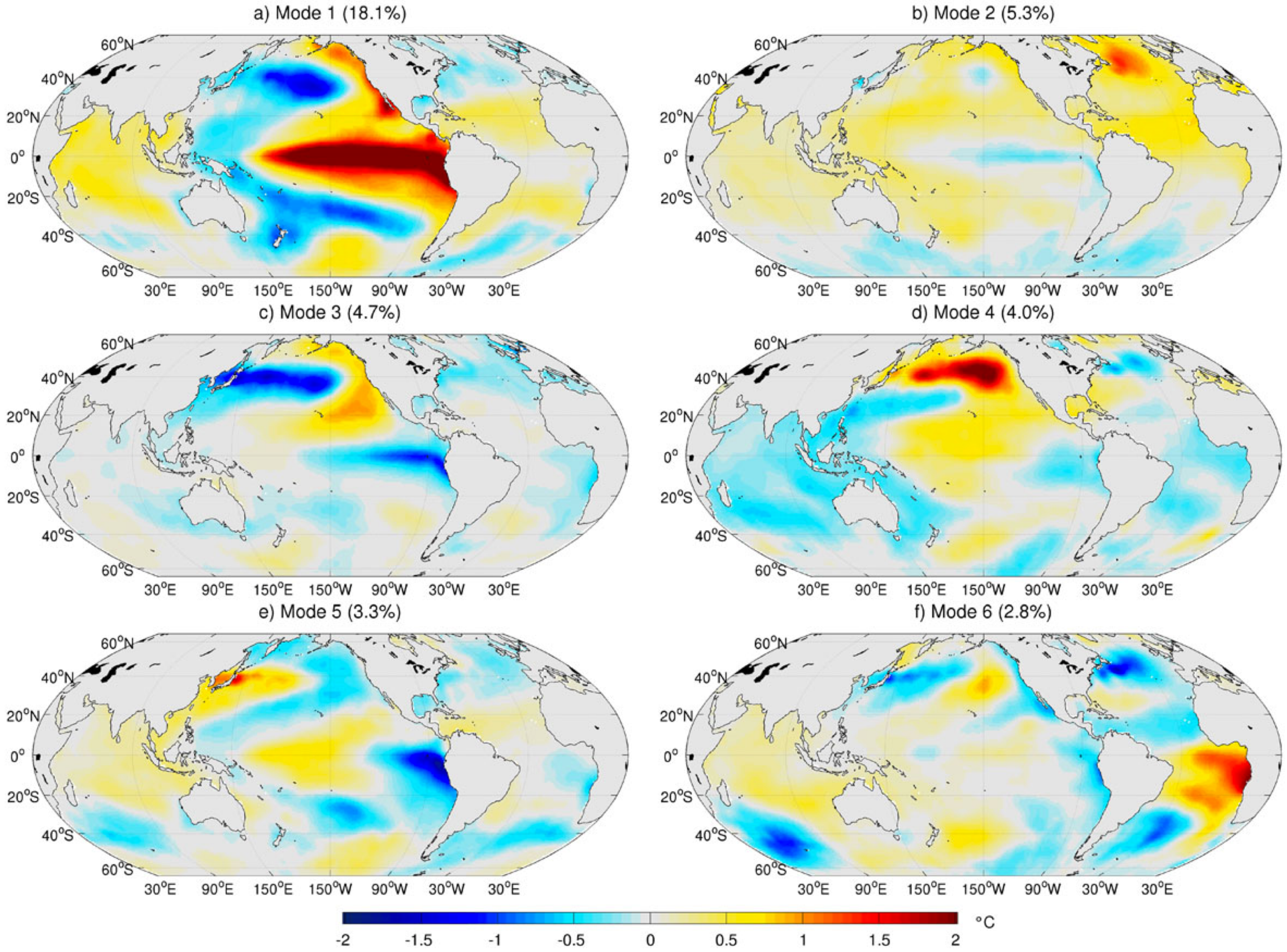
- More precisely modes of variability are often described as a product of a spatial climate pattern and an associated climate index time series that are identified based on statistical methods
- In climate studies spatial modes/patterns of variability and the ways they change with time are manly studied with the **Empirical Orthogonal Function** Analysis **(EOF).** In statistics, EOF analysis is known as **Principal Component Analysis (PCA)**.

Empirical Orthogonal Function (EOF)

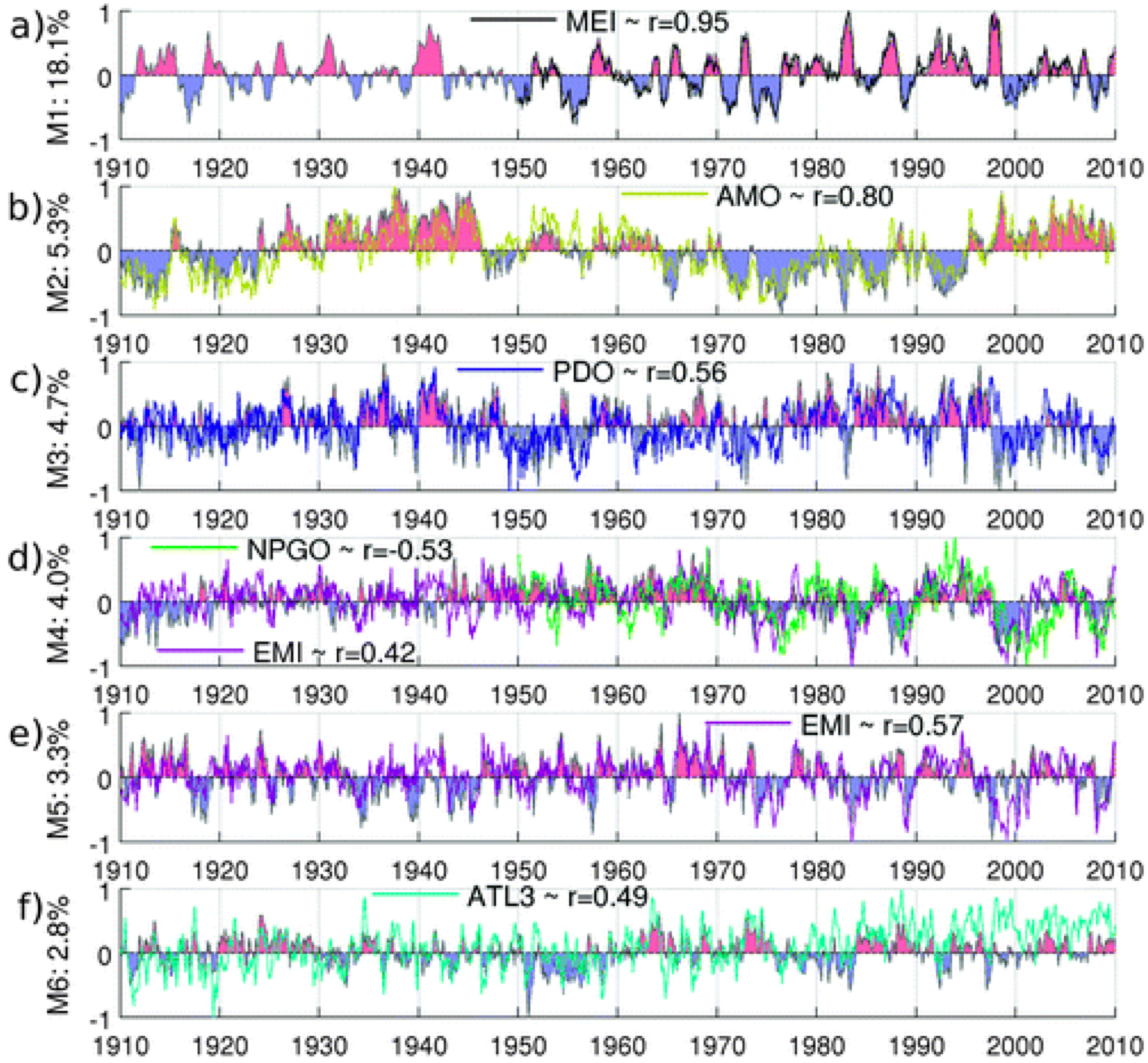
- EOF analysis is a multivariate statistical technique. However, there is no a priori hypothesis based on some probability distribution and, hence, no statistical test. Further, EOF analysis is not based on physical principles. Rather, a field is partitioned into mathematically orthogonal (independent) modes which sometimes may be interpreted as atmospheric and oceanographic modes ('structures').
- Typically, the EOFs are found by computing the eigenvalues and eigenvectors of a spatially weighted anomaly covariance matrix of a field. Most commonly, the spatial weights are the cos(latitude) or, better for EOF analysis, the sqrt(cos(latitude)). The derived eigenvalues provide a measure of the percent variance explained by each mode.

Empirical Orthogonal Function (EOF)

- Each mode is composed of a **spatial pattern** (the so-called EOF) and a principal component (PC) **time series** that represents the temporal evolution of the EOF pattern. A given mode can be reconstructed by multiplying the EOF (space) by its PC (time).
- Atmospheric and oceanographic processes are typically 'red' which means that most of the variance (power) is contained within the first few modes. The time series of each mode (aka, principle components) are determined by projecting the derived eigenvectors onto the spatially weighted anomalies. This will result in the amplitude of each mode over the period of record.
- The first six modes EOF analysis of global sea surface temperature (SST) are found to be associated with well-known regional climate phenomena: the El Niño–Southern Oscillation (ENSO), the Atlantic Multidecadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO), the North Pacific Gyre Oscillation (NPGO), El Niño Modoki, and the Atlantic El Niño.



Global EOF spatial patterns of the first six SST modes calculated from ERSST v3b for the 1910-2009 period. Reproduced from Messié and Chavez (2011)



Time series (1910–2009) of the principal components (PCs) associated with the first six global EOF modes

Atmospheric Climate Variability Modes: by zone

➢ Extratropics:

- Pacific/North American Pattern (PNA)
- North Atlantic Oscillation(NAO)
- Northern Annular Mode (NAM)/Arctic Oscillation (AO)
- Southern Annular Mode (SAM)

➢ Tropics:

- Madden Julian Oscillation (MJO)

From SST: Coupled Atmosphere-Ocean Variability

- El Niño–Southern Oscillation (ENSO)
- Pacific Decadal Oscillation (PDO)
- Inter-decadal Pacific Variability (IPO)
- Atlantic Multi-decadal Variability (AMO)

Different time scale of variabilities

➢On intraseasonal to interannual time scales,

- North Atlantic Oscillation(NAO)
- Northern Annular Mode (NAM)
- North Pacific Oscillation (NPO)
- Pacific/North American Pattern (PNA)

➢On an interannual time scale

- El Niño–Southern Oscillation (ENSO)

➢On longer time scales

- Pacific Decadal Oscillation (PDO)
- Atlantic Multidecadal Oscillation (AMO)

The El Niño-Southern Oscillation (ENSO)

- It is a naturally occurring phenomenon that involves fluctuating ocean temperatures in the equatorial Pacific. The warmer waters essentially oscillate back and forth across the Pacific, much like water in a bath tub. For much of the globe, the phenomenon is known as a dominant force causing variations in regional climate patterns.
- The pattern generally fluctuates between two states: warmer than normal central and eastern equatorial Pacific SSTs (**El Niño**) and cooler than normal central and eastern equatorial Pacific SSTs (**La Niña**). Often, sea surface temperatures (SSTs) are used to identify this oscillation, but it is important to understand that changes in sub-surface ocean temperatures are the first to respond to an oncoming change in the ENSO phase.

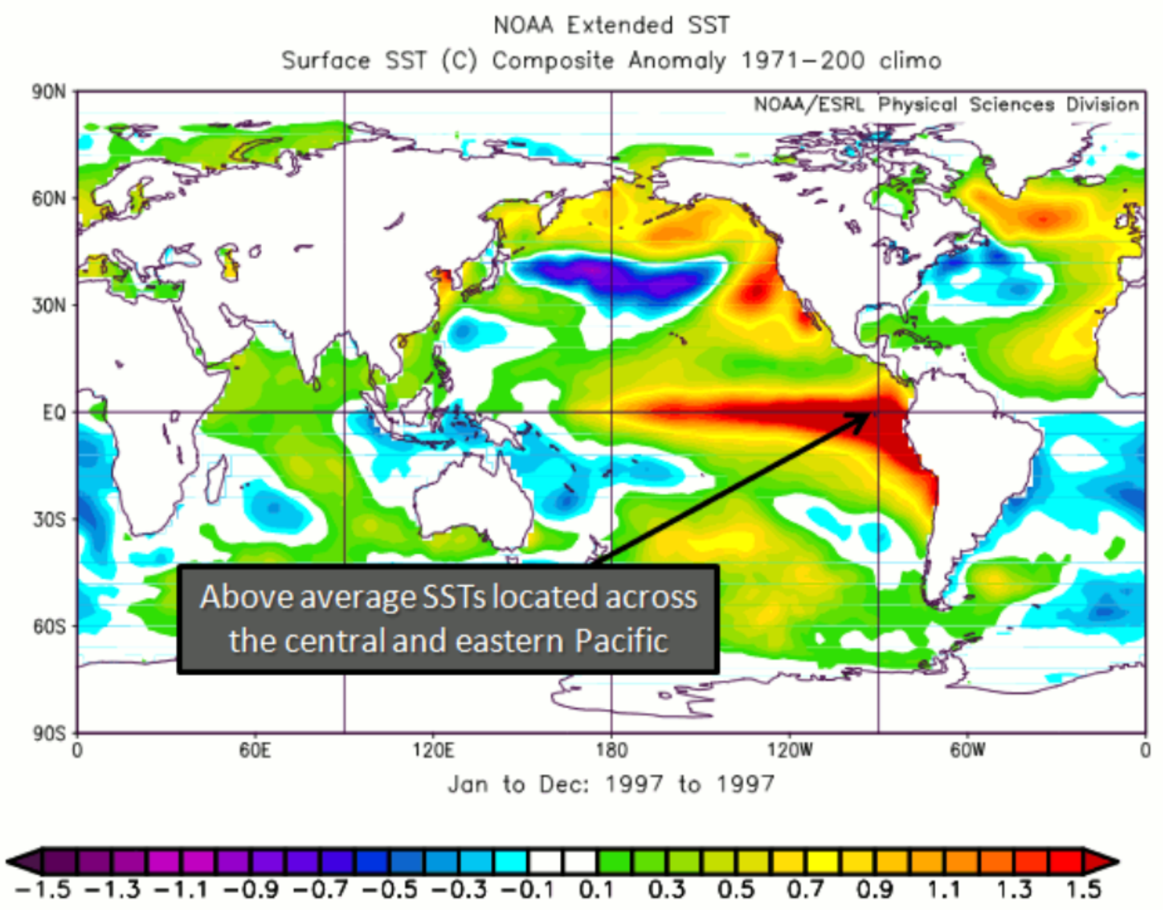
The El Niño-Southern Oscillation (ENSO)

- For instance, when ENSO is transitioning into a warm phase the sub-surface temperatures begin to warm above average, while a shallow layer of near average temperature remains at the surface. Eventually, the surface ocean temperatures will respond to the warming of the sub-surface temperatures, and a warm phase of the ENSO cycle ensues. The same cycle occurs, only opposite, for the cool phase of ENSO.
- When temperatures in the ENSO region of the Pacific are near average it is known as <u>ENSO neutral</u>, meaning that the oscillation is neither in a warm nor cool phase. Typically, atmospheric patterns during ENSO neutral are controlled more by other climate patterns (NAO, PNA) that vary on shorter timescales.

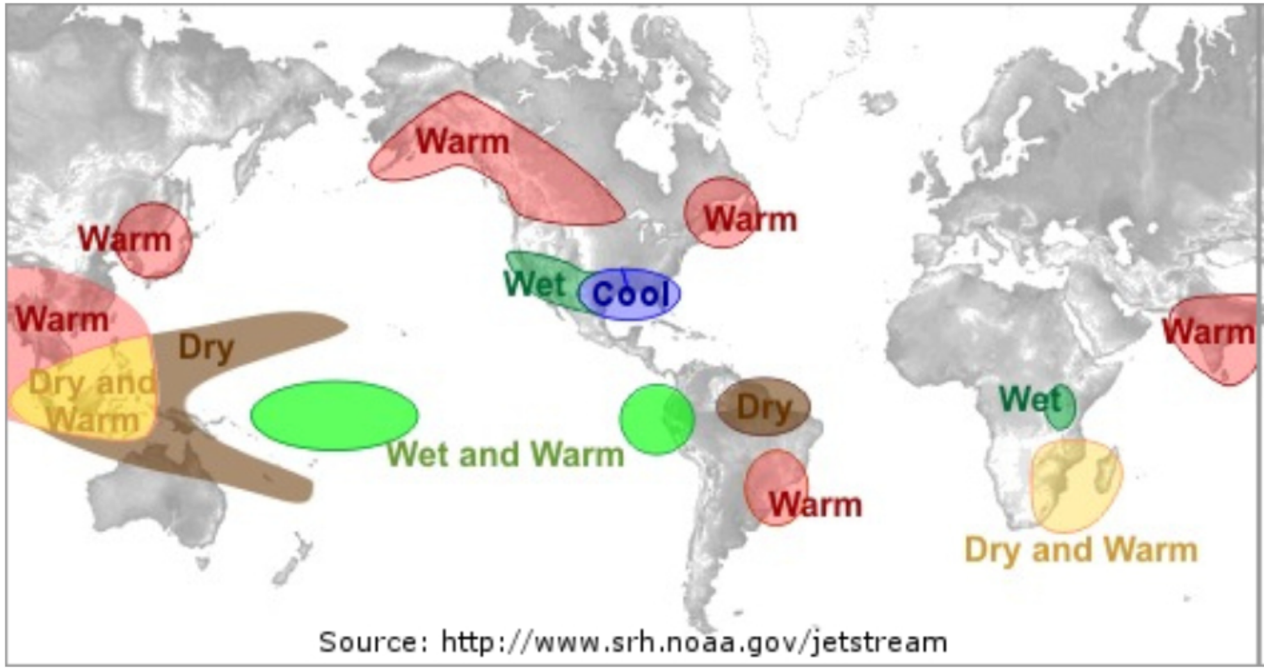
El Niño (Warm Phase)

The warm phase of the ENSO cycle features warmer than normal SSTs across the central and eastern equatorial Pacific along with:

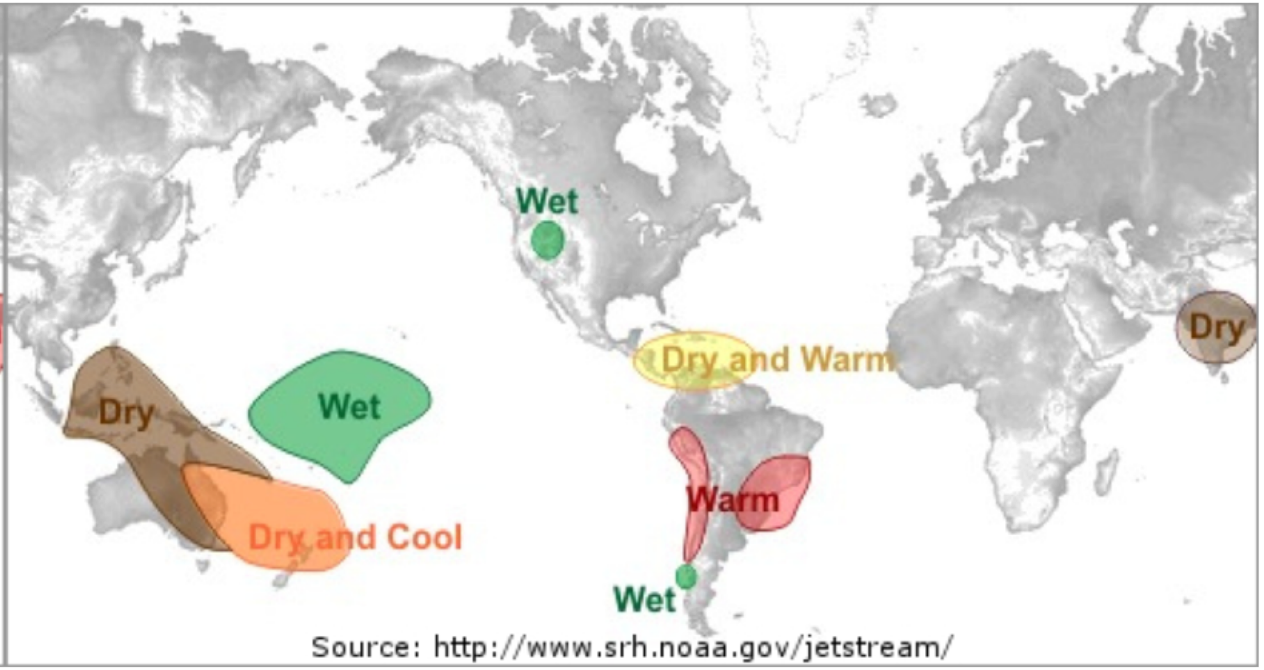
- Weaker low-level atmospheric winds along the equator
- Enhanced convection across the entire equatorial Pacific
- Effects are strongest during northern hemisphere winter due to the fact that ocean temperatures worldwide are at their warmest. This increased ocean warmth enhances convection, which then alters the jet stream such that it becomes more active over parts of the U.S. during El Niño winters. This results in ***enhanced precipitation across the southern U.S., including NC***
- In the southeast, ***winter temperatures are often cooler than normal***
- During hurricane season (June to November), the jet stream is aligned in such a way that the vertical wind shear is increased over the Caribbean and Atlantic. The increased wind shear helps to prevent tropical disturbances from developing into hurricanes



Typical El Niño Effects: December Through February



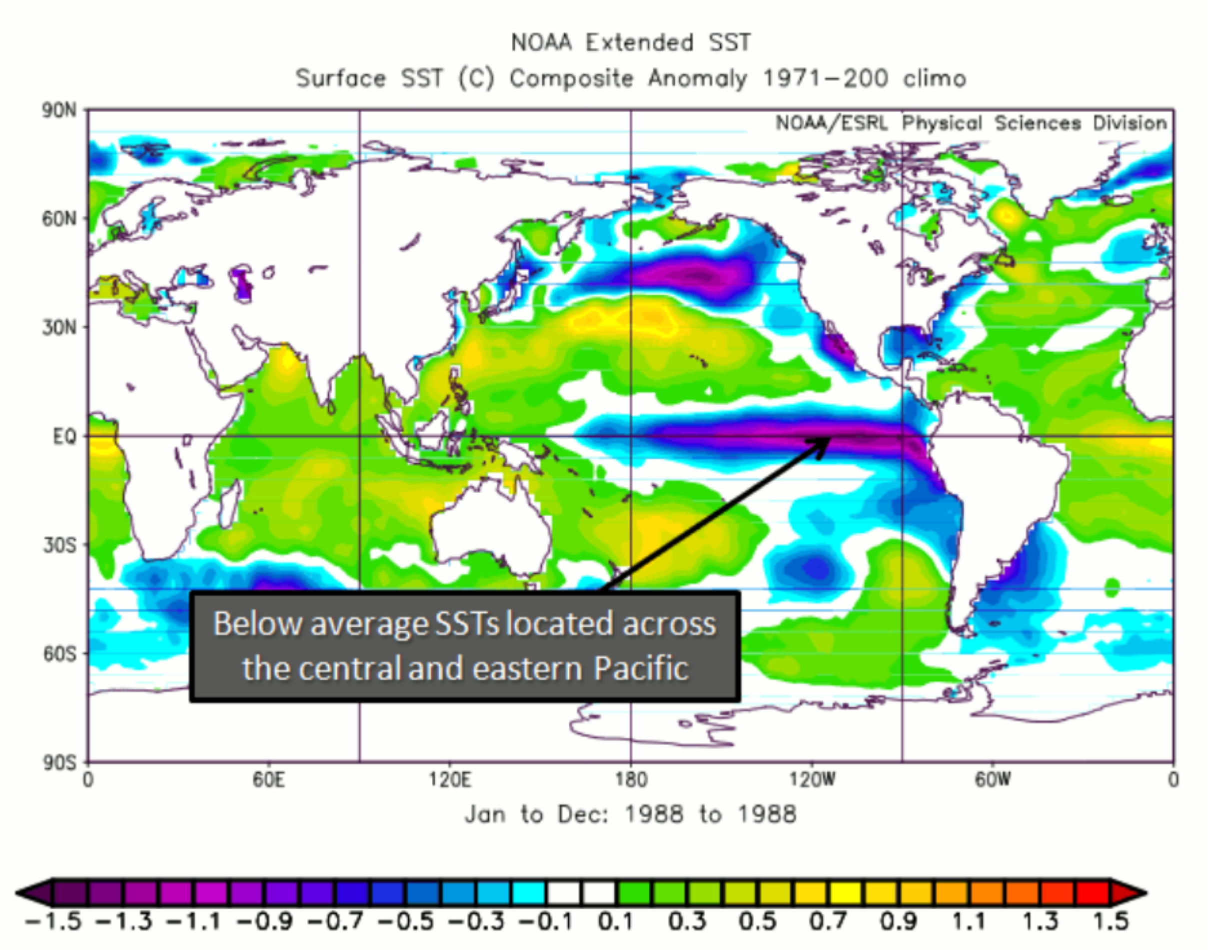
Typical El Niño Effects: June Through August

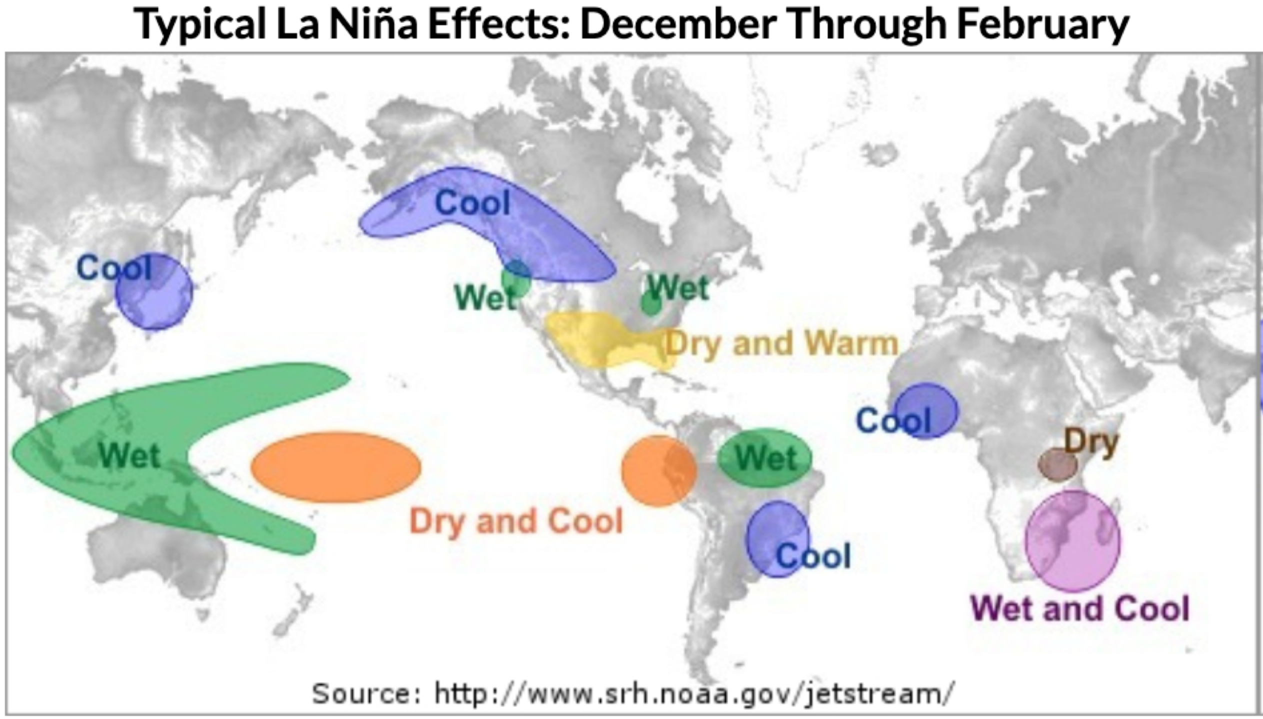


La Niña (Cool Phase)

This phase of the ENSO cycle features cooler than normal SSTs across the central and eastern equatorial Pacific along with:

- Stronger low-level atmospheric winds along the equator
- Decreased convection across the entire equatorial Pacific results in a more suppressed southern jet stream. Consequently, ***the southern U.S., including NC, sees less precipitation***
- In the U.S., ***winter temperatures are often warmer than normal in the southeast***, and cooler than normal in the Northwest
- During hurricane season (June to November), upper level winds are much lighter, and therefore more favorable for hurricane development in the Caribbean and Atlantic




Typical La Niña Effects: December Through February
Cool
Cool
Wet
Wet
Dry and Warm
Wet
Cool
Wet
Dry and Cool
Cool
Dry
Wet and Cool
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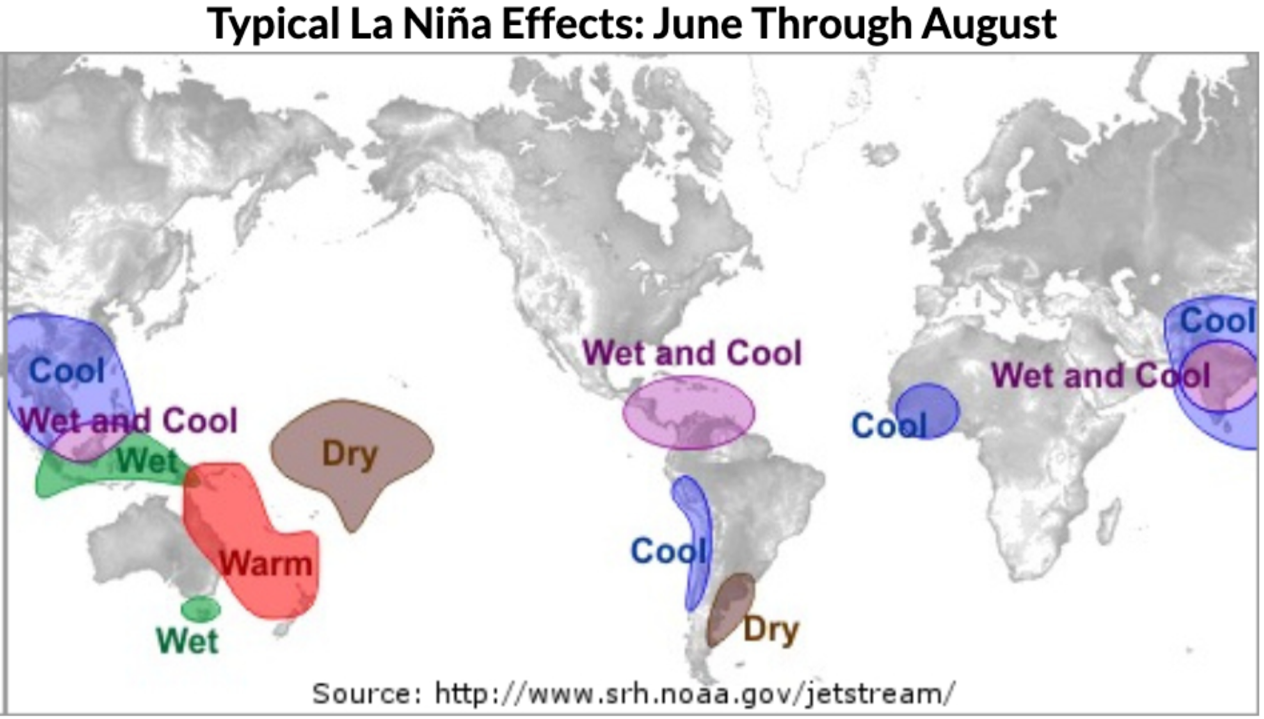
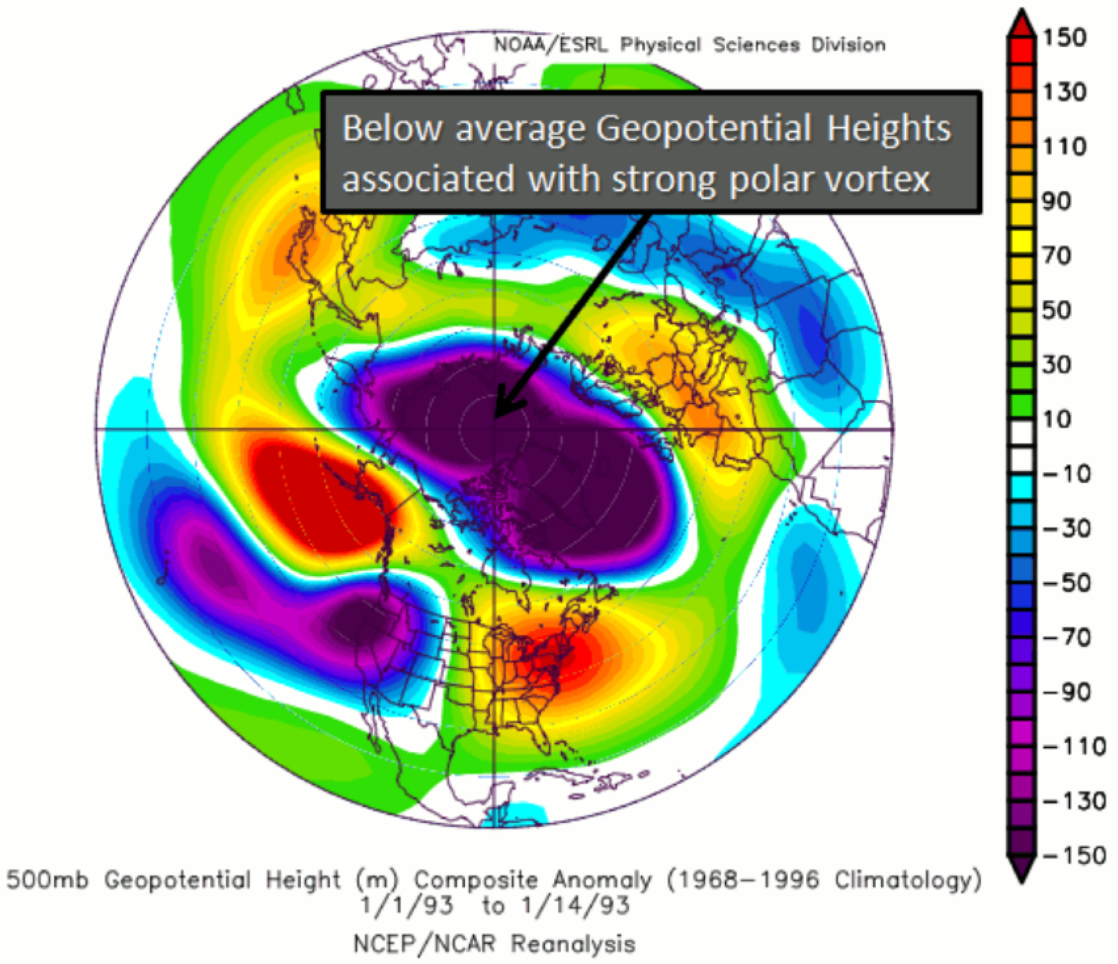
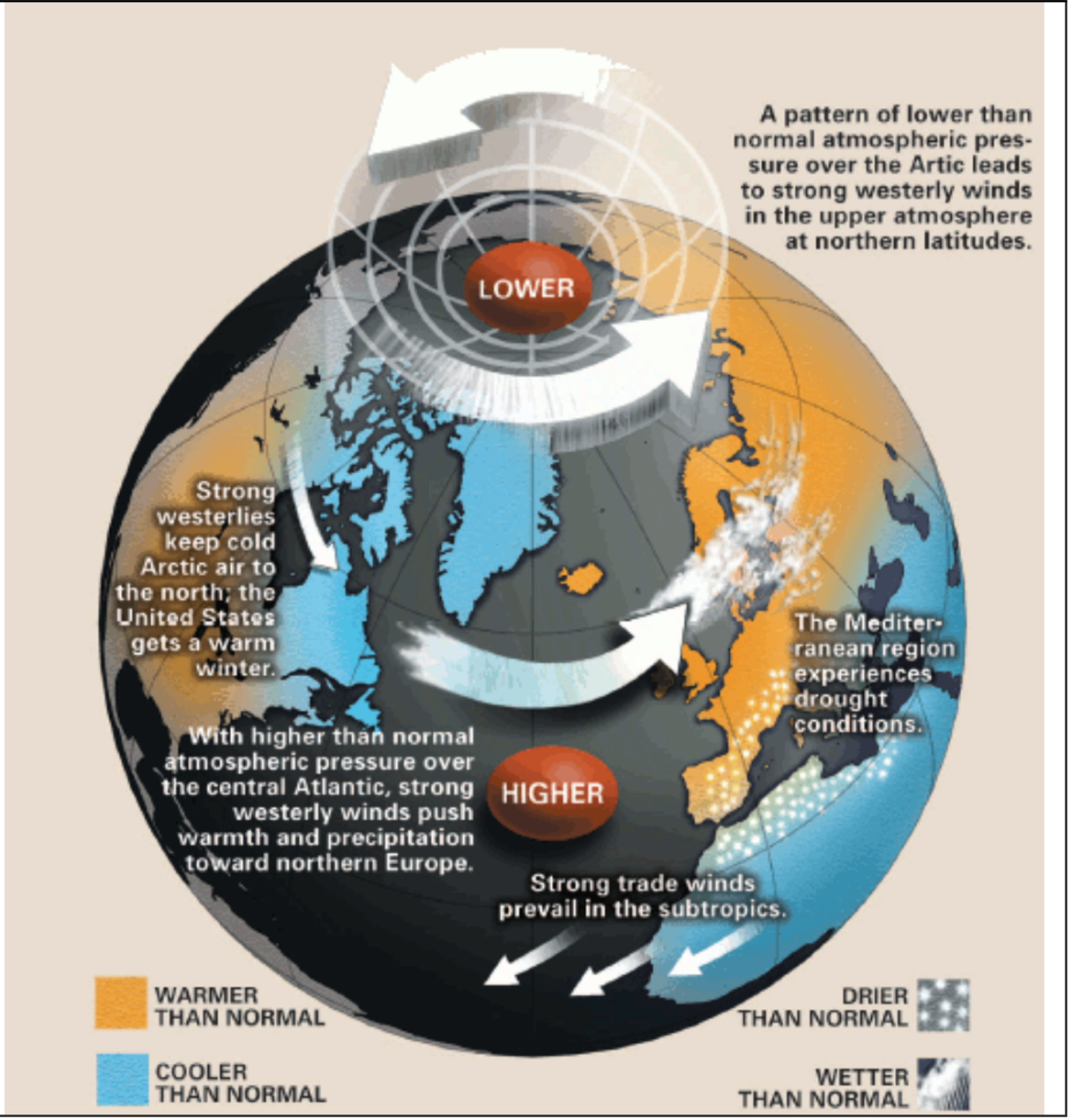

Typical La Niña Effects: June Through August
Cool
Wet and Cool
Wet
Dry
Warm
Wet
Wet and Cool
Cool
Dry
Cool
Wet and Cool
Cool
Source: http://www.srh.noaa.gov/jetstream/

The Arctic Oscillation(AO)

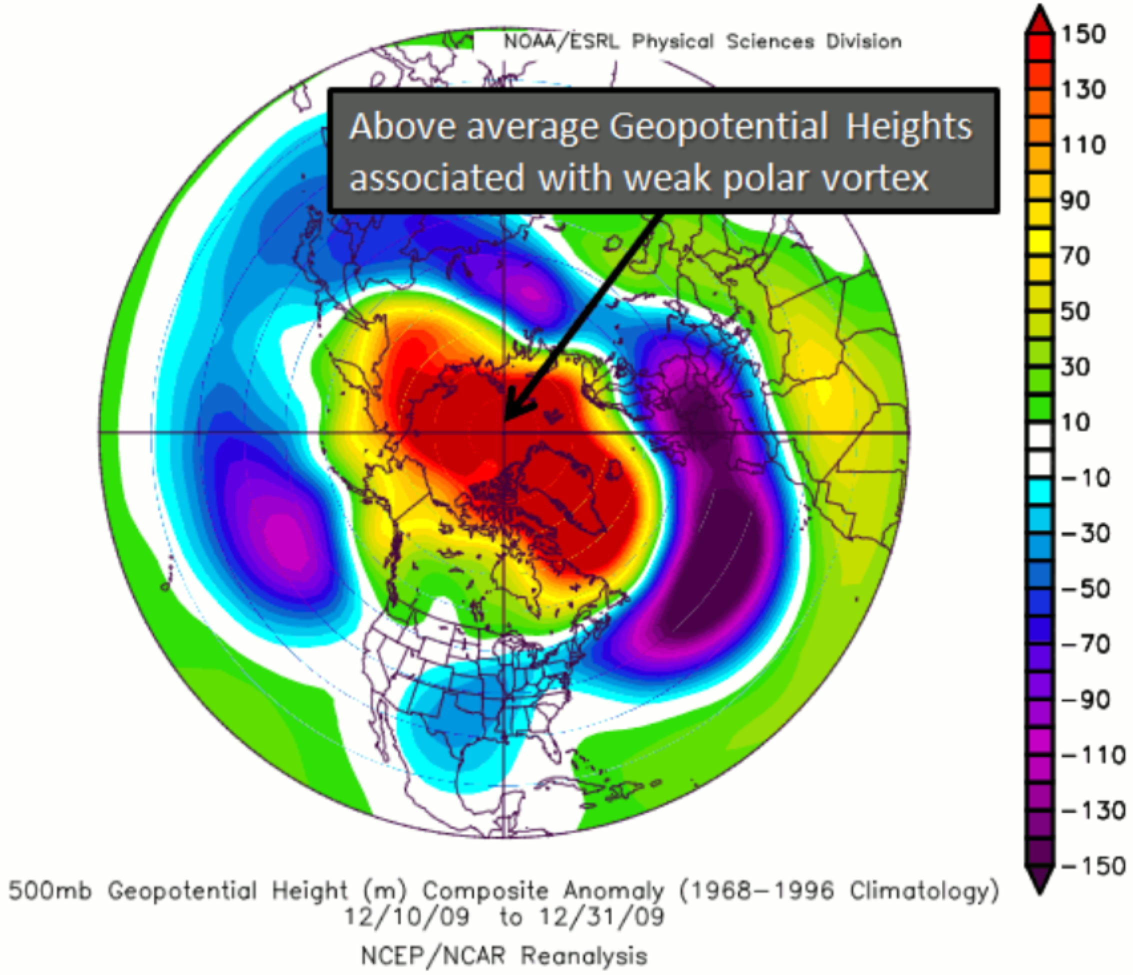
- It is a climate index of the state of the atmospheric circulation over the Arctic. It consists of a positive phase, featuring below average geopotential height (i.e. negative geopotential height anomalies) and a negative phase in which the opposite is true. In the negative phase, the polar low pressure system (i.e. the polar vortex) over the Arctic is weaker, which results in weaker upper level winds (the westerlies).
- The result of the weaker westerlies is that cold, Arctic air is able to push farther south into the U.S., while the storm track also remains farther south. The opposite is true when the AO is positive: the polar circulation is stronger which forces cold air and storms to remain farther north.
- The Arctic Oscillation often shares phase with the North Atlantic Oscillation (NAO)

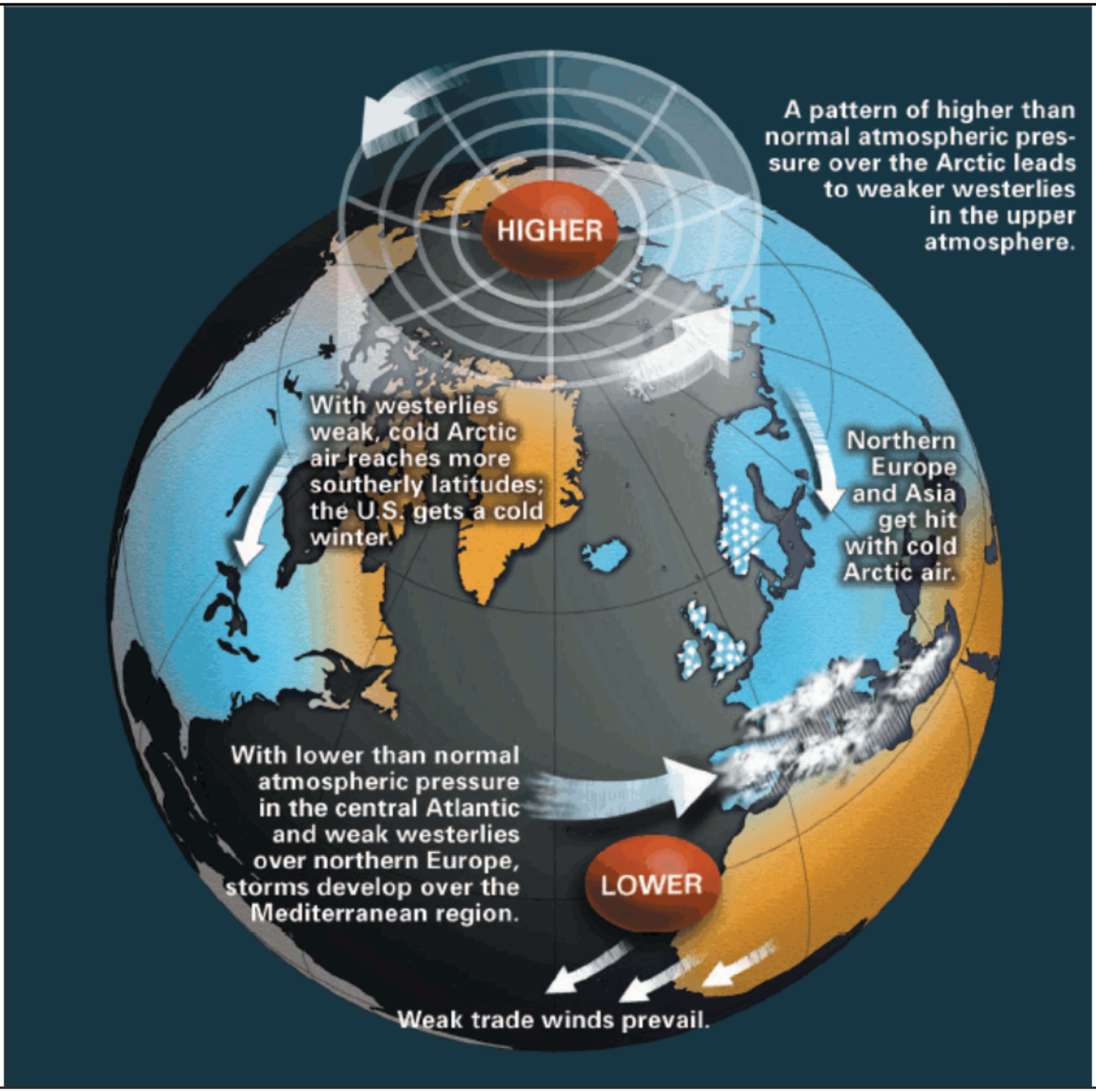
500mb Height Anomalies During a Positive AO





500mb Height Anomalies During a Negative AO





North Atlantic Oscillation (NAO)

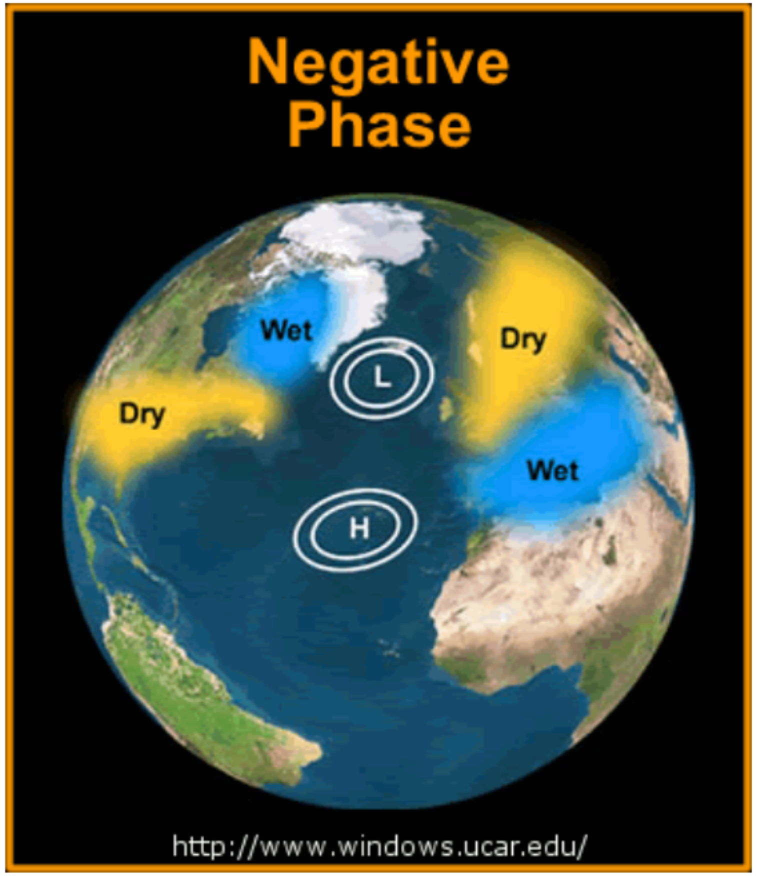
- The North Atlantic Oscillation (NAO) consists of two pressure centers in the North Atlantic: one is an area of low pressure typically located near Iceland, and the other an area of high pressure over the Azores. It is important to note that these two locations are most commonly used to measure the NAO, but studies have found that the pressure centers move around on a seasonal basis, and other locations have also been used for measuring this index.
- Fluctuations in the strength of these features significantly alters the alignment of the jet stream and ultimately affects temperature and precipitation distributions over US and Europe. It is also important to note that the AO and NAO are two separate indices that are ultimately describing the same phenomenon of varying pressure gradients in the northern latitudes and the resultant effects on temperature and storm tracks across the continents.

Positive NAO

During a positive NAO there is a strengthening of the Icelandic low and Azores high. This strengthening results in an increased pressure gradient over the North Atlantic, which cause the westerlies to increase in strength. The increased westerlies allow cold air to drain off the North American continent rather than letting it build up and move south.

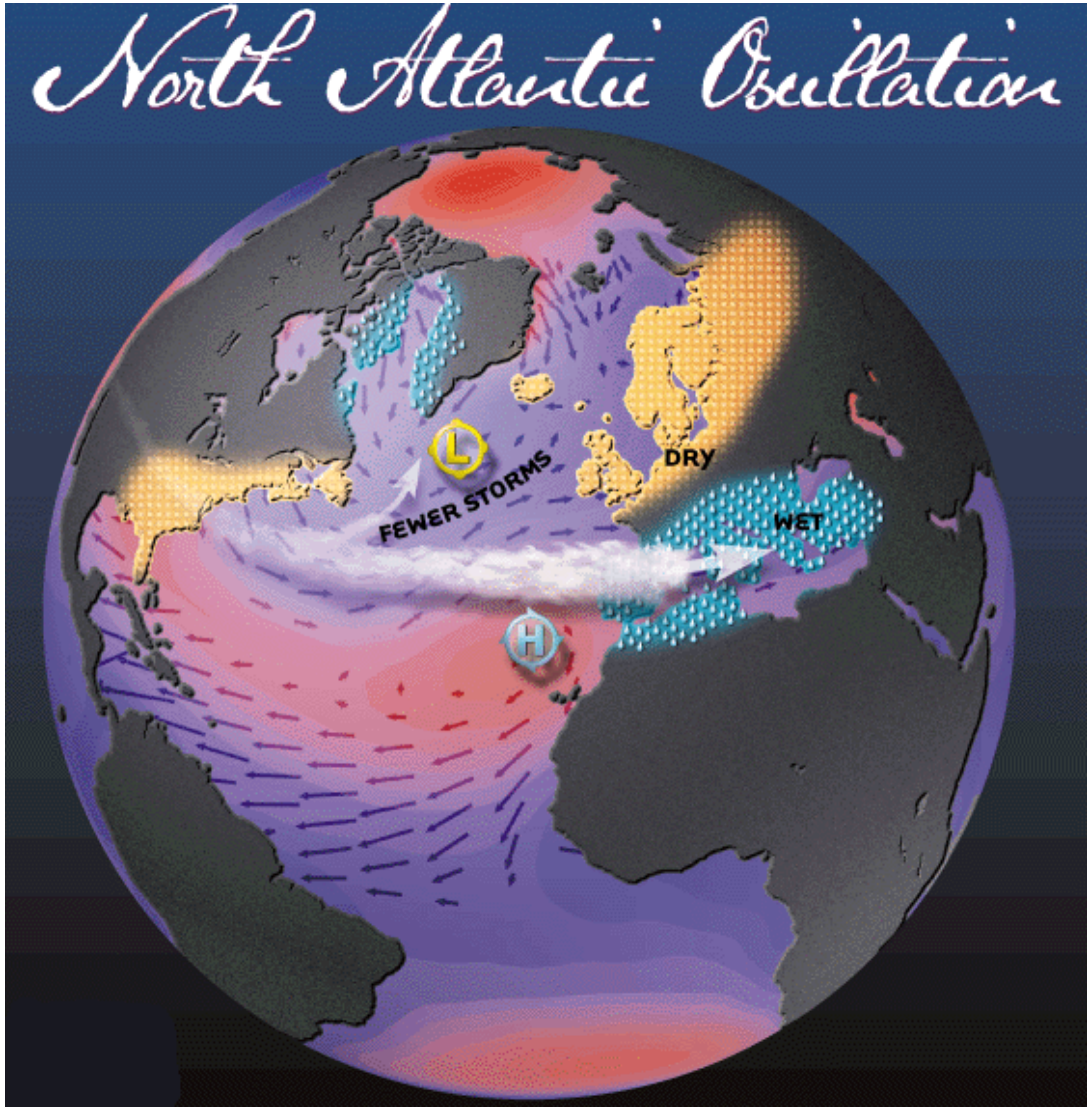
- Above average geopotential heights ? are observed over the eastern U.S., which correlates to above average temperatures
- The eastern U.S. often sees a wetter pattern with stronger storms during the winter season in this phase due to increased upper level winds
- Recent studies at the SCO indicate a **decreased potential for wintry weather in NC** due to the lack of cold air availability and above average temperatures associated with a positive NAO in this region

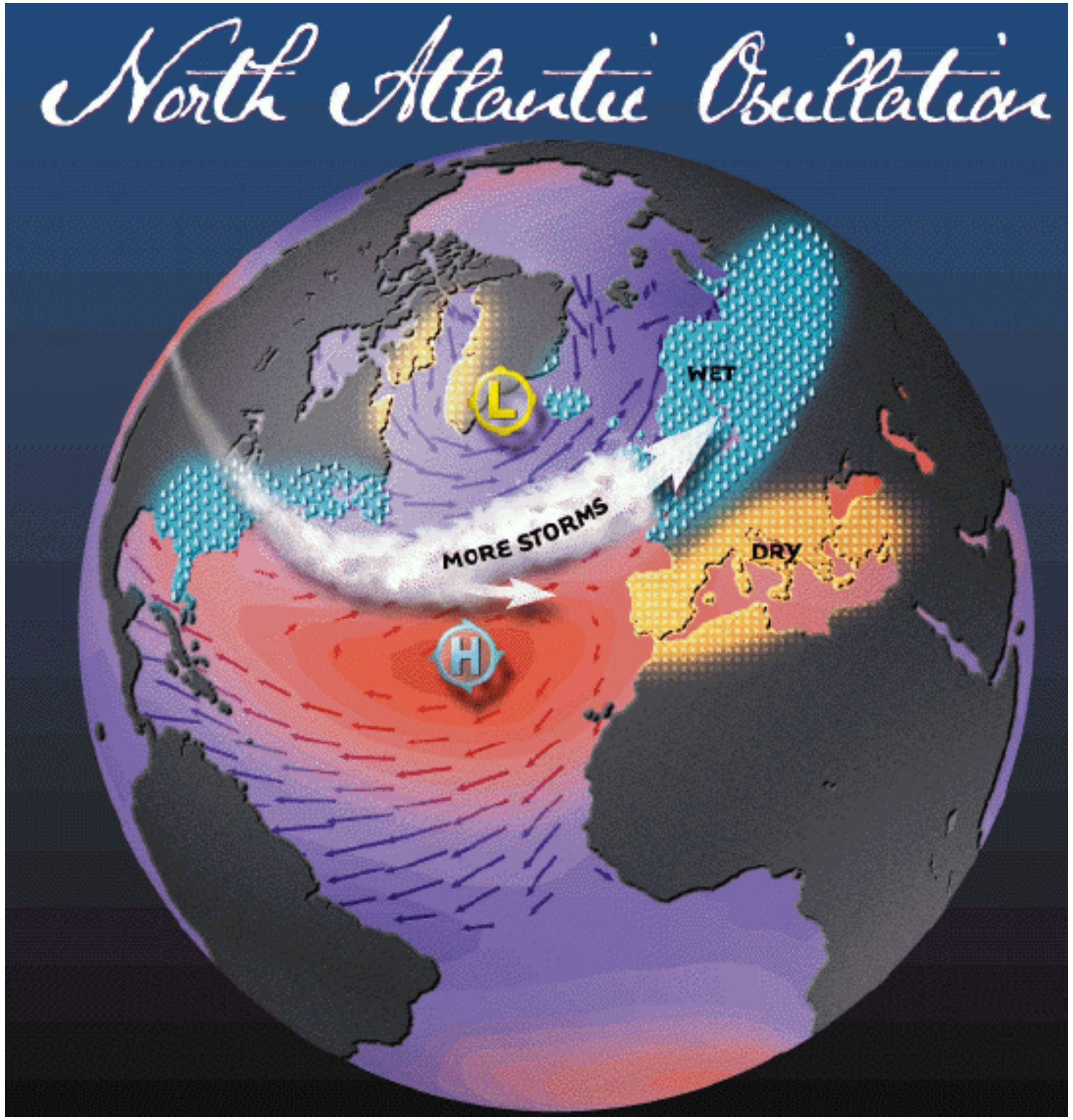
Negative NAO



A negative NAO indicates weakening of both the Icelandic low and Azores high, which decreases the pressure gradient across the North Atlantic. This decreased pressure gradient results in a slackening of the westerlies. The decrease in the westerlies allows cold air to build up over Canada, and this combined with below average heights (troughing) over the eastern U.S. gives the cold air a greater chance to move south and affect the eastern United States.

- Below average geopotential heights are often observed over the eastern U.S. during the negative phase of the NAO, which correlates to below average temperatures
- The eastern U.S. typically receives colder, drier air masses during the winter season in this phase
- Recent studies at the SCO indicate an **increased potential for wintry weather in NC** due to the position and availability of cold air, and a more favorable upper level pattern conducive to coastal storm tracks


North Atlantic Oscillation
L
H
FEWER STORMS
DRY
WET


North Atlantic Oscillation
L
H
MORE STORMS
WET
DRY

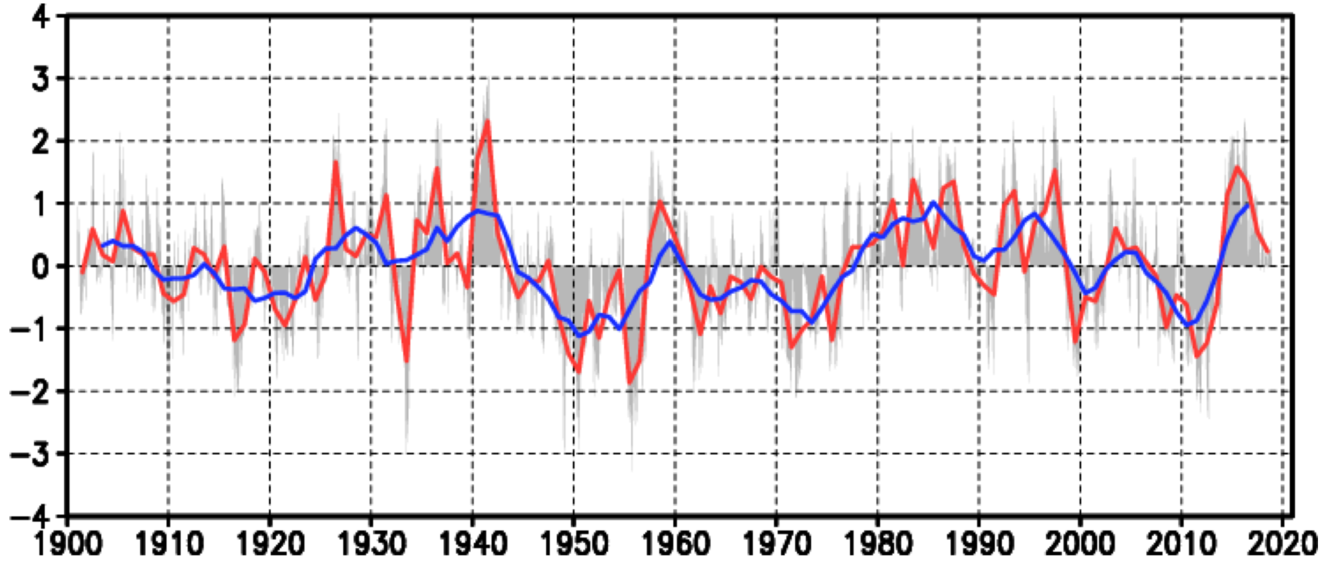
The Pacific Decadal Oscillation (PDO)

- It is a pattern of Pacific climate variability similar to ENSO in character, but which varies over a much longer time scale. The PDO can remain in the same phase for 20 to 30 years, while ENSO cycles typically only last 6 to 18 months. The PDO, like ENSO, consists of a warm and cool phase which alters upper level atmospheric winds.
- Shifts in the PDO phase can have significant implications for global climate, affecting Pacific and Atlantic hurricane activity, droughts and flooding around the Pacific basin, the productivity of marine ecosystems, and global land temperature patterns.
- Experts also believe the PDO can intensify or diminish the impacts of ENSO according to its phase. If both ENSO and the PDO are in the same phase, it is believed that El Niño/La Nina impacts may be magnified. Conversely, if ENSO and the PDO are out of phase, it has been proposed that they may offset one another, preventing "true" ENSO impacts from occurring.

The Pacific Decadal Oscillation (PDO)

- When the PDO index is positive (negative), SSTs in the central part of the North Pacific are likely to be lower (higher) than their normals
- In addition, when the index is positive (negative), sea level pressures (SLPs) values in the high latitudes of the North Pacific are likely to be lower (higher) than their normals. This indicates that the Aleutian Low is stronger (weaker) than its normal in winter and spring

➢**The PDO index** is an indicator of The PDO activity and defined as the projections of monthly mean SST anomalies onto their first EOF vectors in the North Pacific (north of 20ºN). The EOF vectors are derived for the period from 1901 to 2000, and climatology is defined as monthly mean for the same period. Globally averaged monthly mean SST anomalies are in order to eliminate the effects of the global warming.



The Pacific/North American teleconnection pattern (PNA)

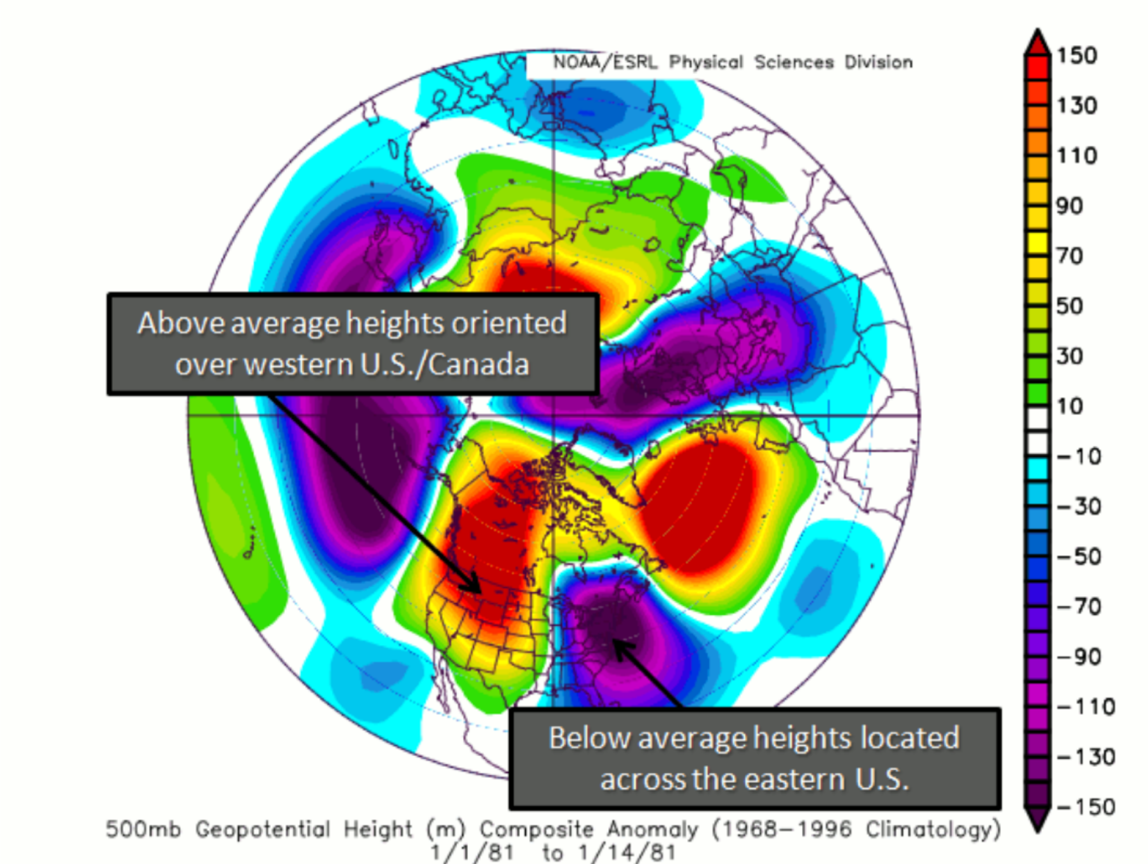
- It is one of the most recognized, influential climate patterns in the Northern Hemisphere mid-latitudes beyond the tropics. It consists of anomalies in the geopotential height fields (typically at 700 or 500hpa) observed over the western and eastern United States.
- It is important to note that the PNA has been found to be strongly influenced by the El Niño-Southern Oscillation (ENSO) phenomenon. The positive phase of the PNA pattern tends to be associated with Pacific warm episodes (El Niño), and the negative phase tends to be associated with Pacific cold episodes (La Niña).

Positive PNA

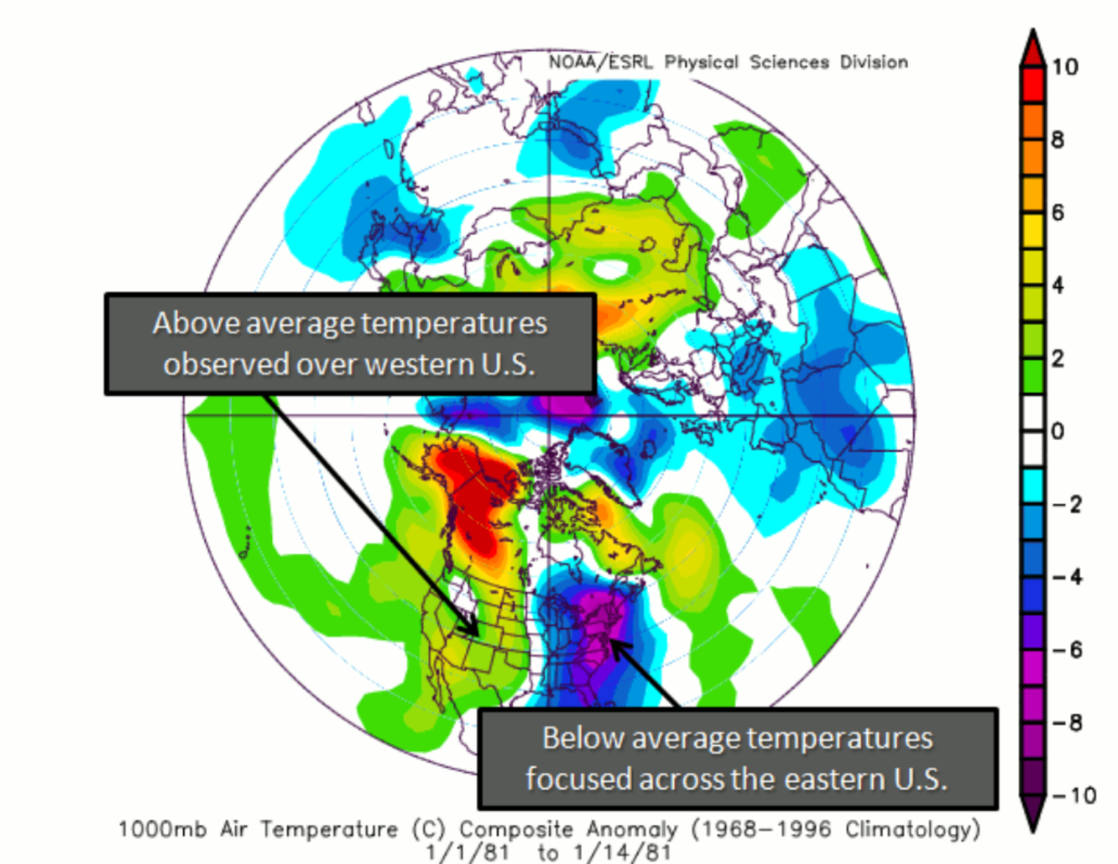
The positive phase consists of above normal geopotential heights over the western U.S. and below normal geopotential heights over the eastern U.S. This correlates to ridging over the western U.S., and deep troughing over the east. The net result of the height field pattern in this phase is that it forces cold air residing in Canada to plunge southeastward, which results in below normal temperatures over the eastern U.S. and above normal temperatures over the western U.S.

- Research at the SCO indicates that a positive PNA, especially during an El Niño year, produces an ***above average number of winter weather events in NC***

500mb Height Anomalies During a Positive PNA



Surface Temperature Anomalies During a Positive PNA

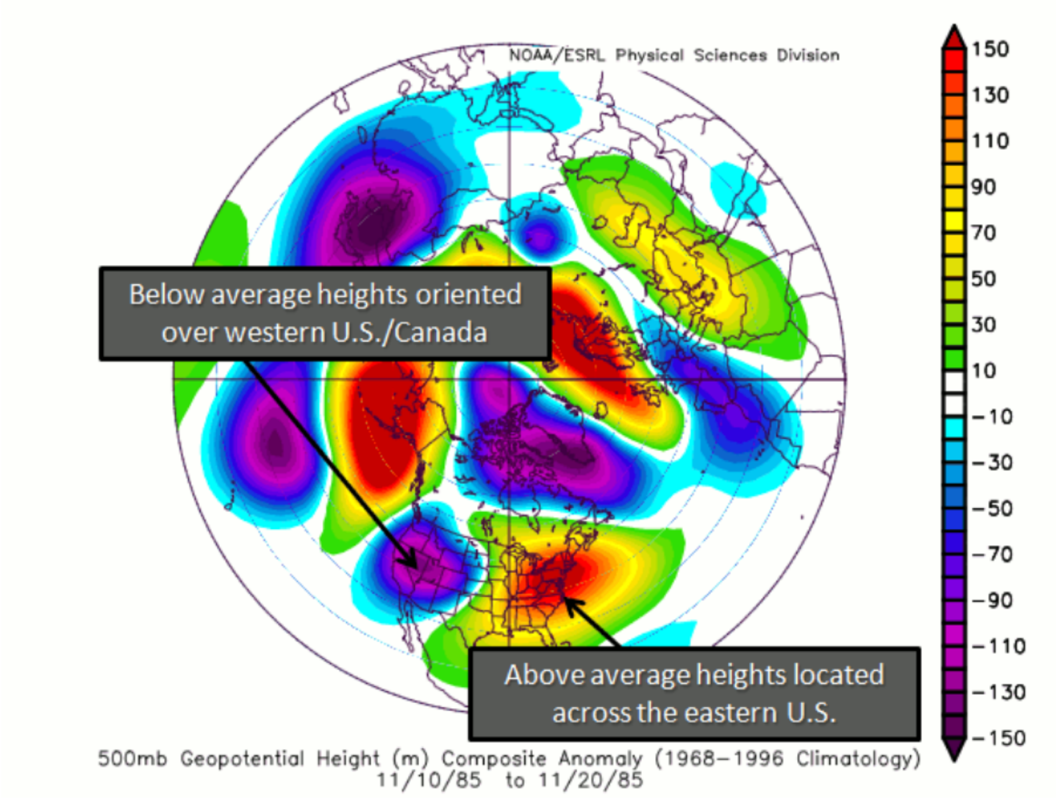


Negative PNA

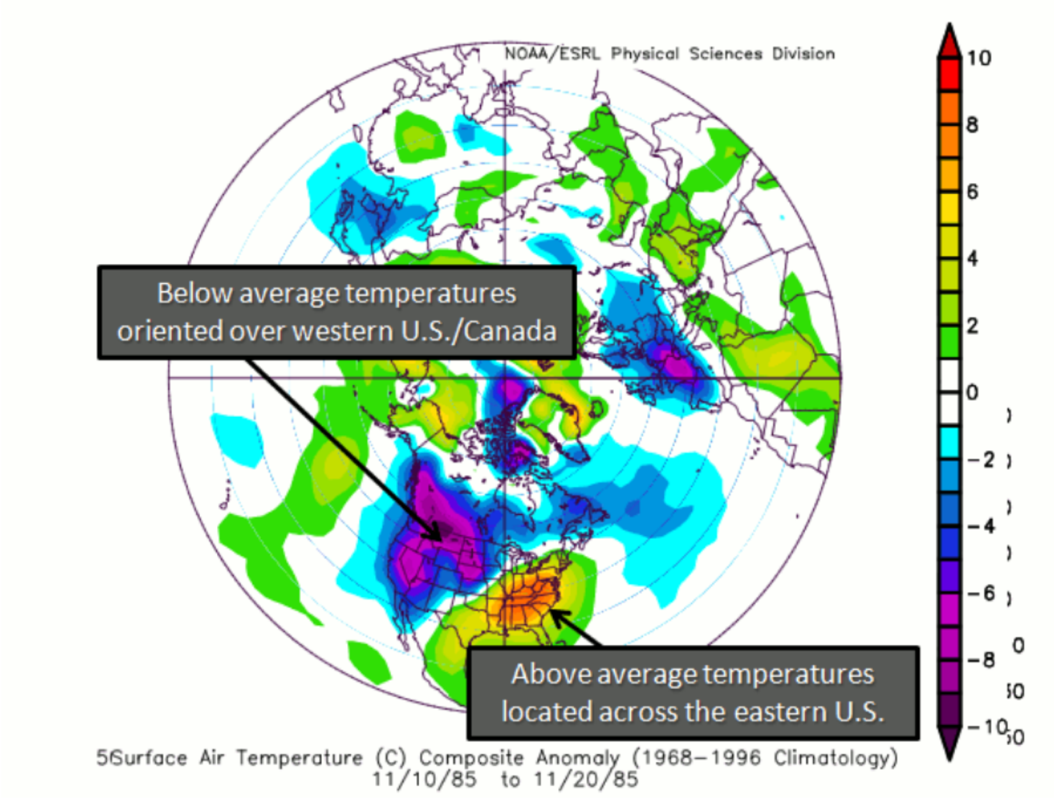
The negative phase features troughing and below normal geopotential heights over the western U.S. and ridging with above normal geopotential heights over the eastern U.S. The result is below average temperatures for the western U.S., and above average temperatures over the eastern U.S.

- Research at the SCO indicates that a negative PNA typically results in a ***reduced potential for winter weather in NC***

500mb Height Anomalies During a Negative PNA



Surface Temperature Anomalies During a Negative PNA



Resources (indices, graphics and data)

- Internationa weather/climate research centers keeps index calculations up to date

- https://www.ncdc.noaa.gov/teleconnections/
- https://www.esrl.noaa.gov/psd/data/climateindices/list/