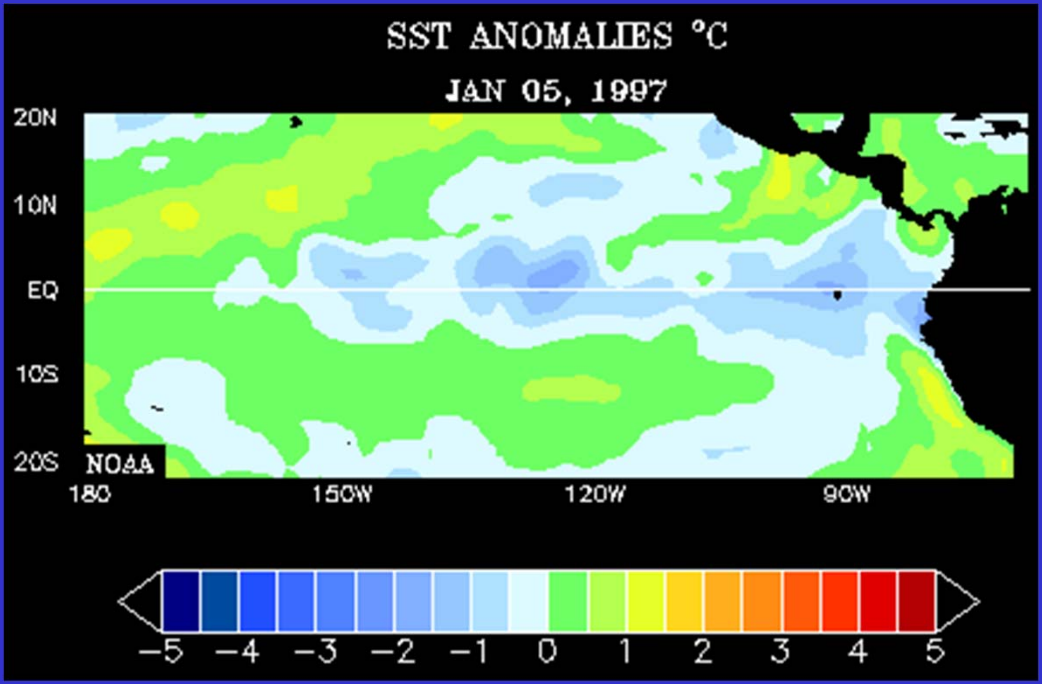
Lecture 8: Natural Climate Variability



- ❑ Extratropics: PNA, NAO, AM (aka. AO), SAM
- ❑ Tropics: MJO
- ❑ Coupled A-O Variability: ENSO
- ❑ Decadal Variability: PDO, AMO

Unforced vs. Forced Variability

- We often distinguish between unforced variability and variability forced by natural or anthropogenic causes.
- Unforced variability arises from the 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 variability can occur on a variety of time scales from that of a week or two that we normally associate with weather; to intraseasonal variability that might result from internal atmospheric dynamics or interactions between the ocean and the atmosphere; to interannual variability that might result from ocean–atmosphere interactions on time scales of a few years; to natural 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.

Internal Atmospheric Variability

- **Extratropics:**

  PNA = Pacific / North American Pattern

  AM = Annular Mode

  SAM = Southern Annular Mode

  AO = Arctic Oscillation (the same as the Annular Mode)

  NAO = North Atlantic Oscullation

- **Tropics:**

  MJO = Madden Julian Oscillation

Atmospheric Circulation

Zonal Wind

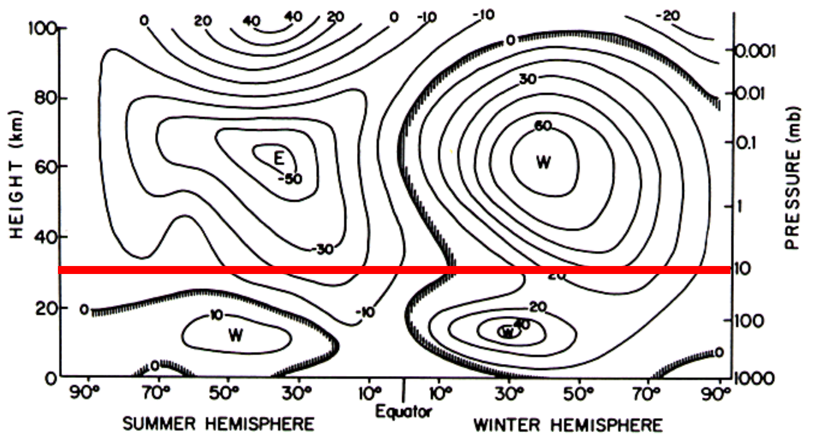
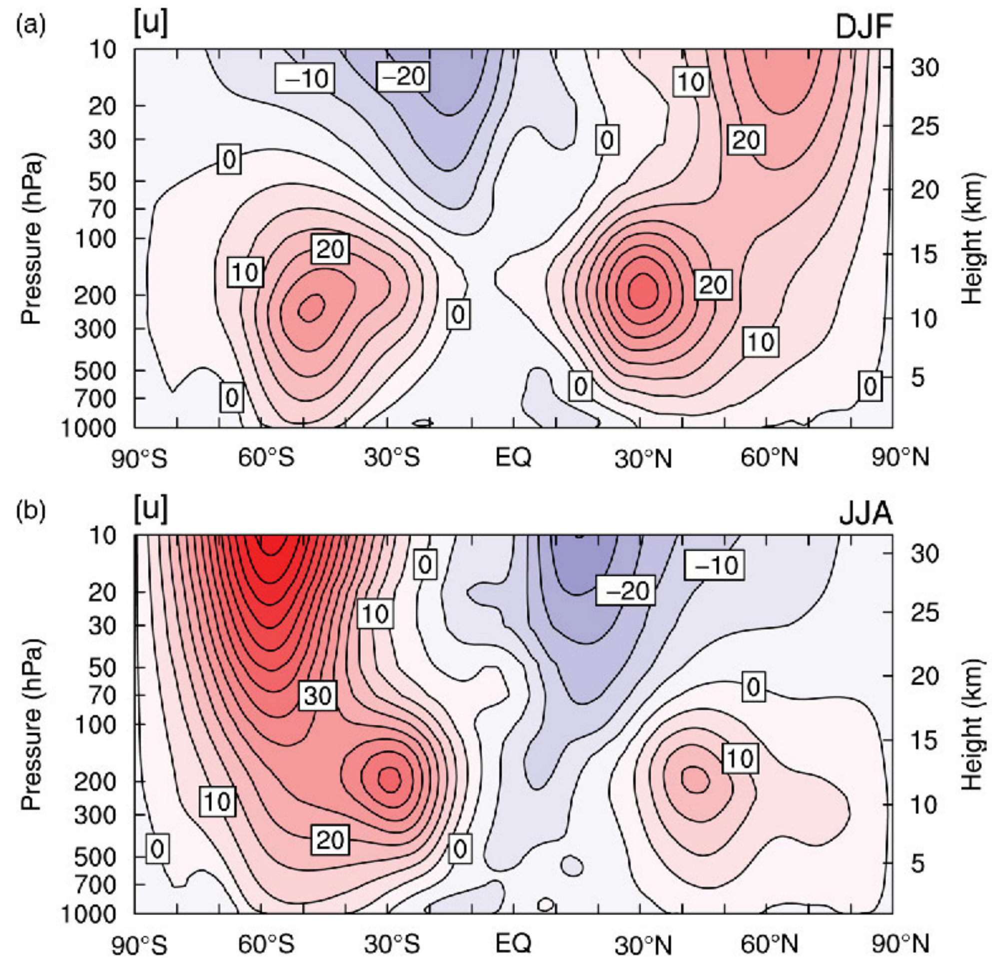


Fig. 1.4. Schematic latitude–height section of zonal mean zonal wind ($m\ s^{-1}$) for solstice conditions; W and E designate centers of westerly (from the west) and easterly (from the east) winds, respectively. (Courtesy of R. J. Reed.)



(from *Global Physical Climatology*)

ESS200
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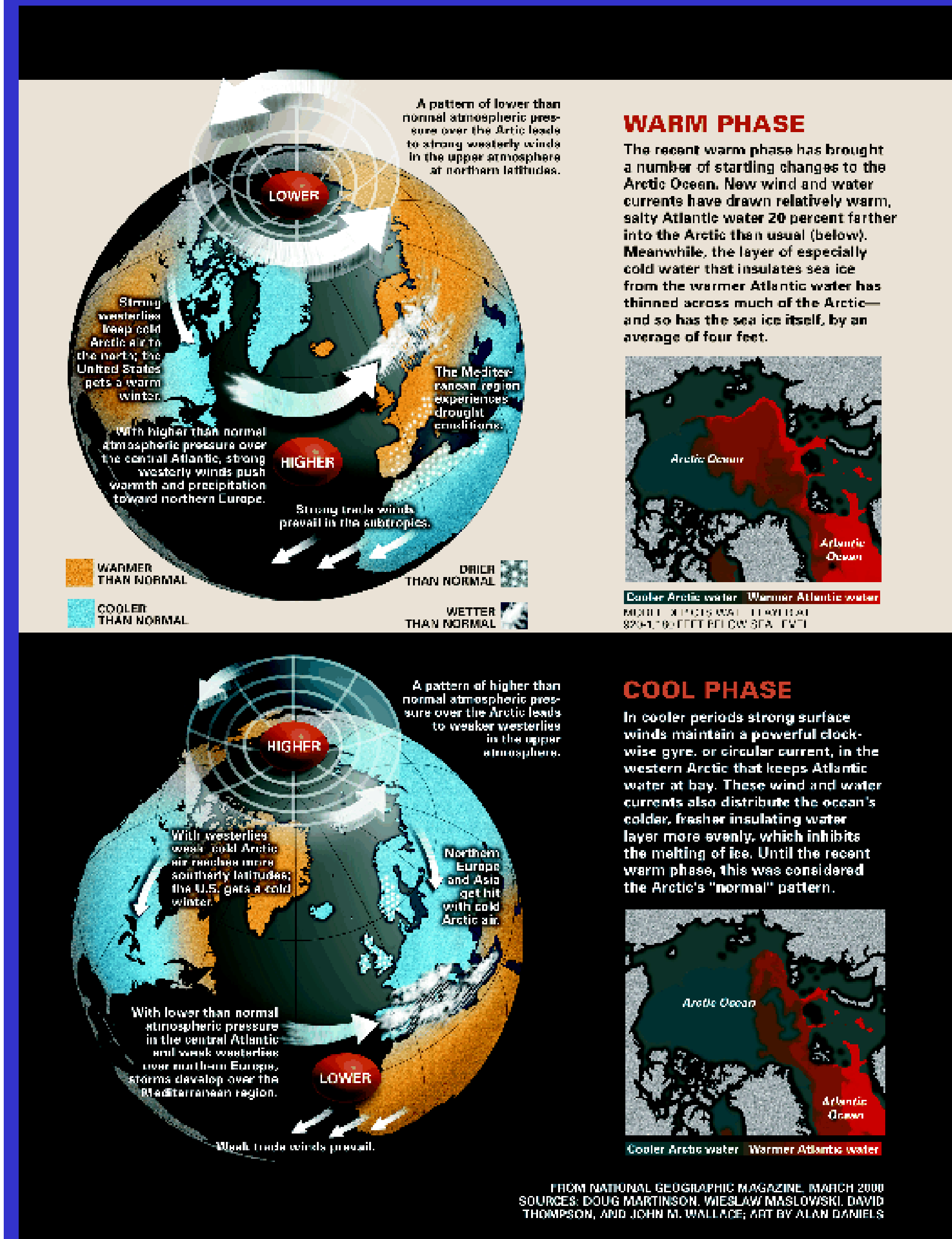
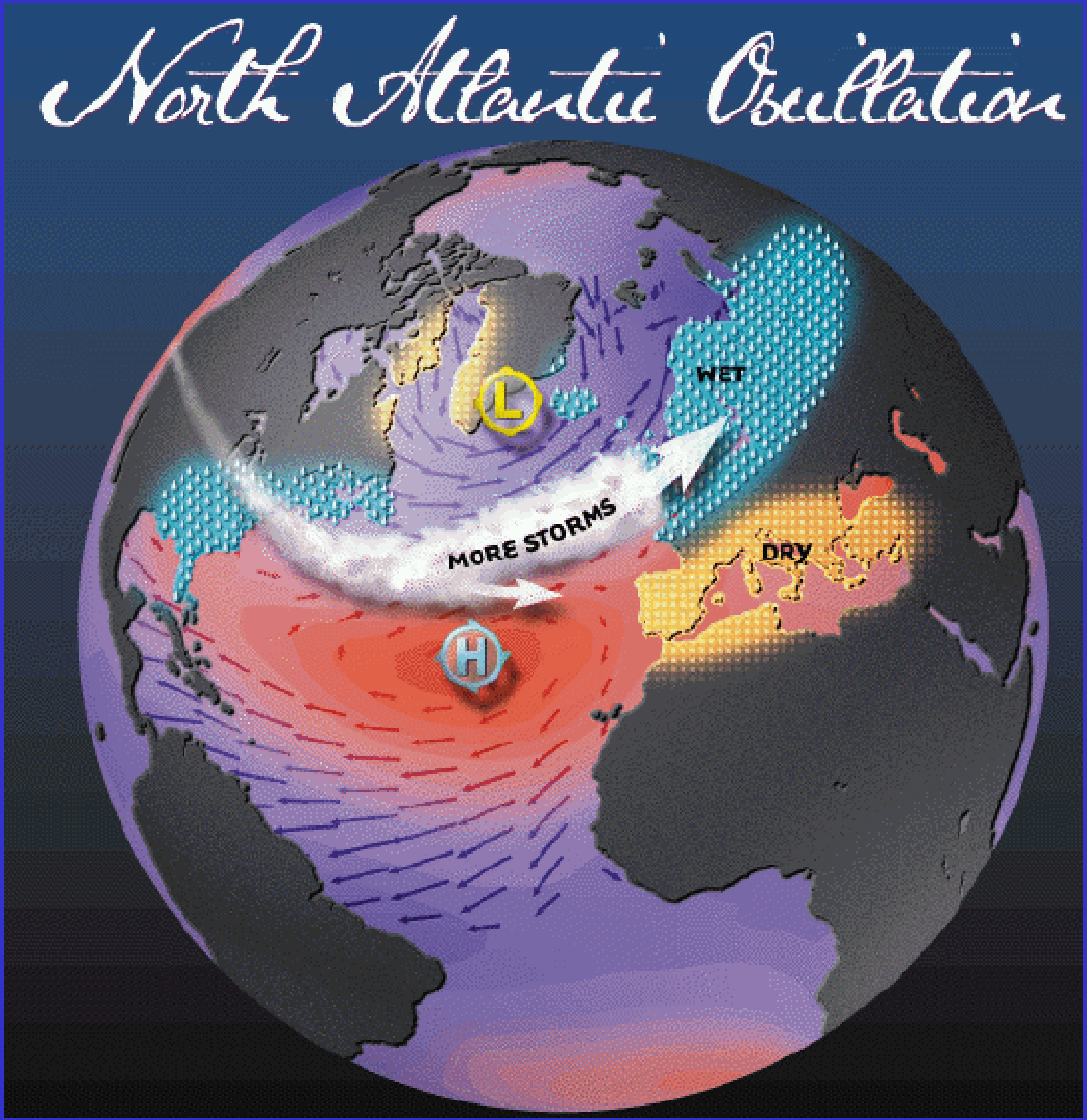


North Atlantic Oscillation
= Arctic Oscillation
= Annular Mode

North Atlantic Oscillation

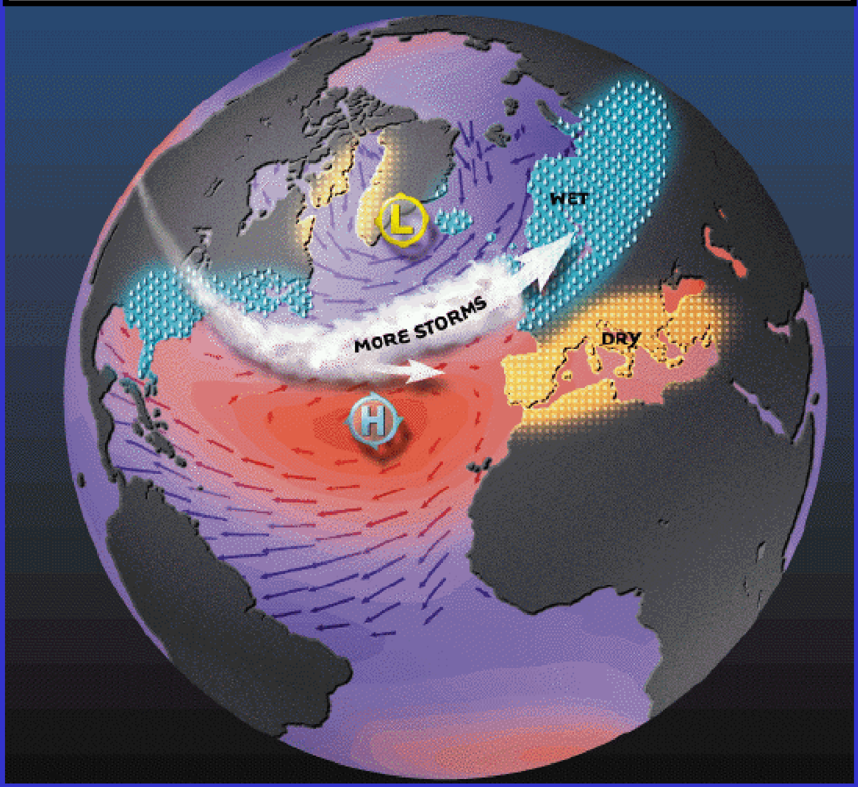


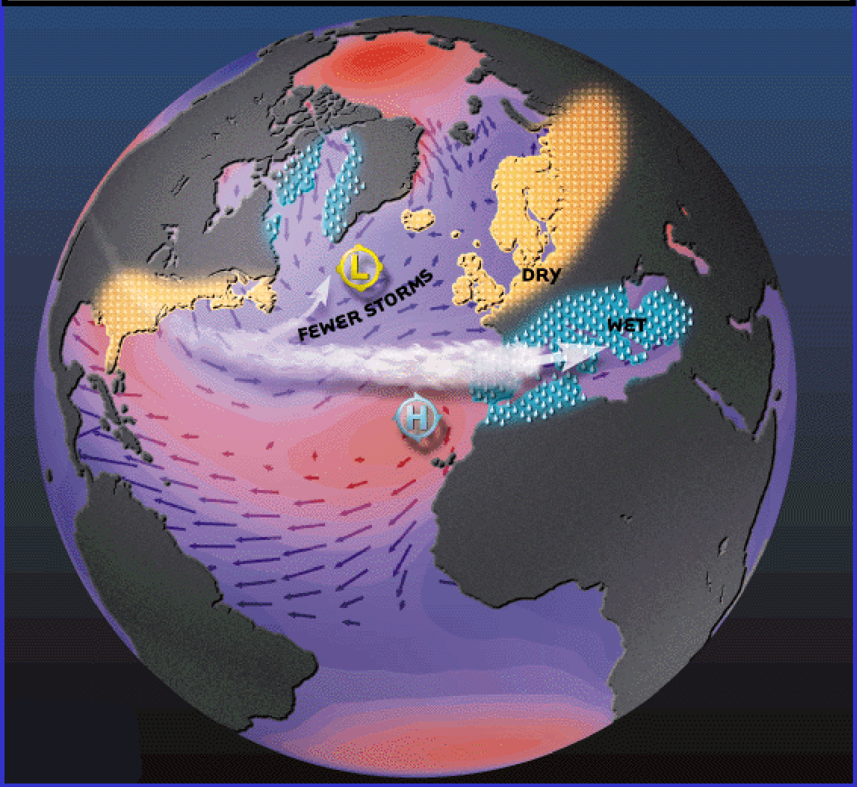
(from http://www.ldeo.columbia.edu/res/pi/NAO/)

- The NAO is the dominant mode of winter climate variability in the North Atlantic region ranging from central North America to Europe and much into Northern Asia.
- The NAO is a large scale seesaw in atmospheric mass between the subtropical high and the polar low.
- The corresponding index varies from year to year, but also exhibits a tendency to remain in one phase for intervals lasting several years.

Positive and Negative Phases of NAO

Positive Phase	Negative Phase



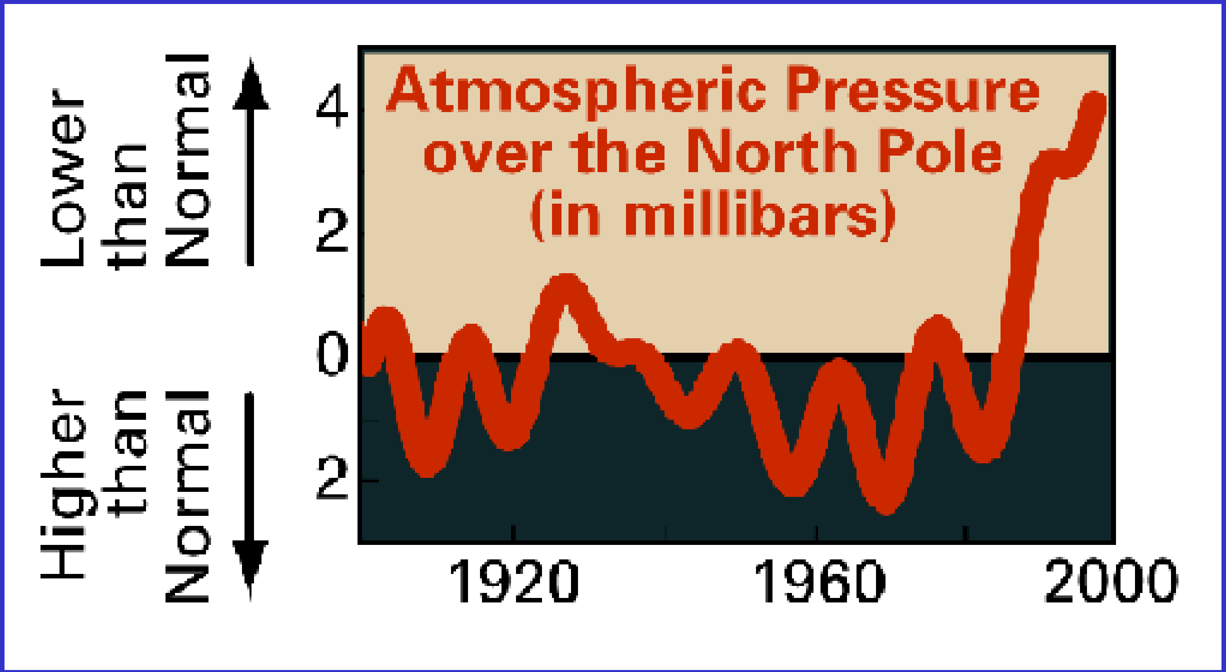


- ❑ A stronger and more northward storm track.
- ❑ A weaker and more zonal storm track.

Dynamics Behind NAO

- The North Atlantic Oscillation is considered as a natural variability of the atmosphere.
- However, processes in the ocean and stratosphere and even the anthropogenic activity can affect its amplitude and phase.
- Surface winds of the NAO can force sea surface temperature variability in the Atlantic Ocean.
- Feedbacks from the ocean further affect NAO variability.

Decadal Timescale of Arctic Oscillation



- The Arctic Oscillation switches phase irregularly, roughly on a time scale of decades.
- There has been an unusually warm phase in the last 20 years or so, exceeding anything observed in the last century.

Pacific North American (PNA) Pattern

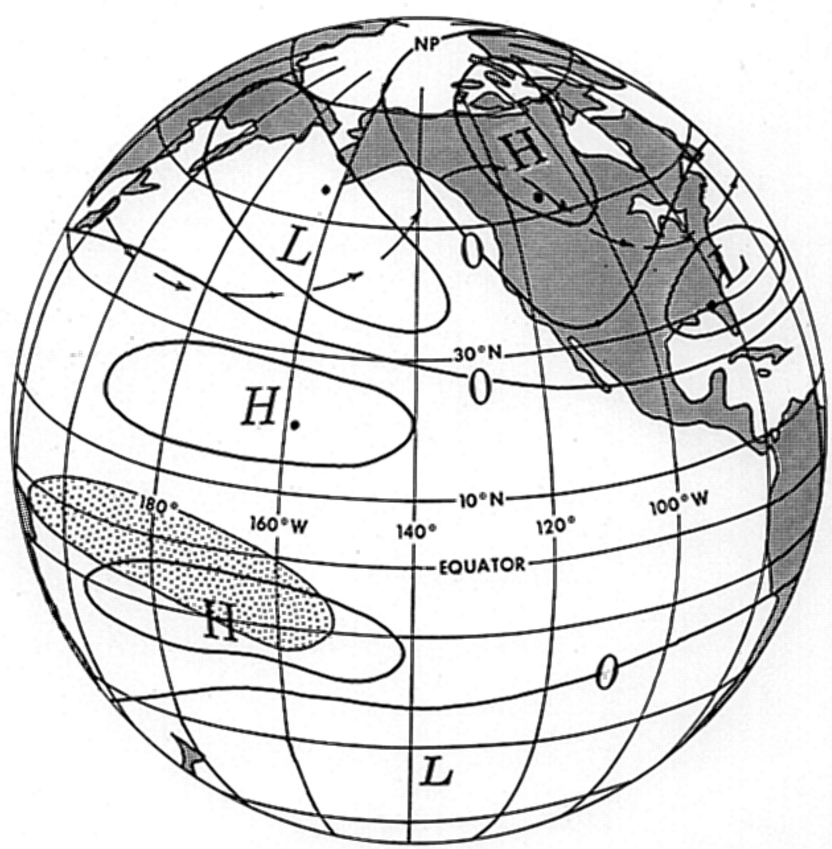
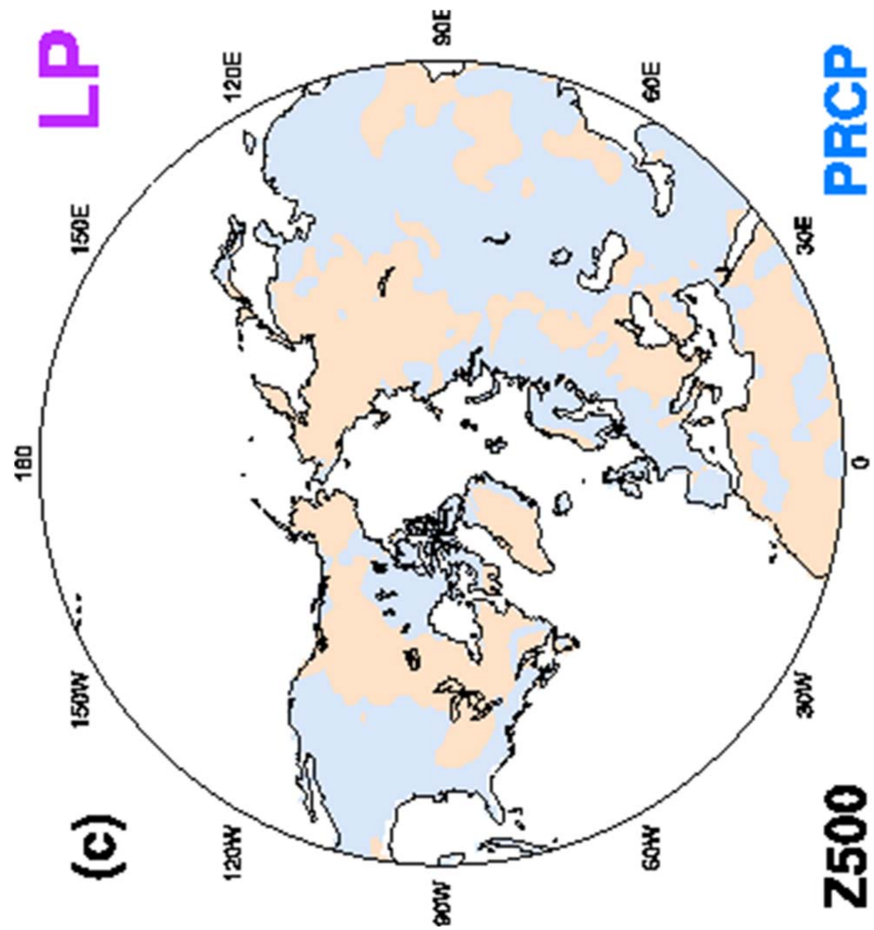


Figure 1.26. A schematic diagram of the Pacific North American (PNA) pattern of middle- and upper-tropospheric geopotential height anomalies during a Northern Hemisphere winter that coincides with El Niño conditions in the tropical Pacific. The arrows depict a midtropospheric streamline as distorted by the anomaly pattern, with pronounced "troughing" over the central Pacific and "ridging" over western Canada. Cloudiness and rainfall are enhanced over the shaded area. The dots indicate the stations used in the time series mentioned in Table 1.1. [From Horel and Wallace (1981).]

(from Horel and Wallace 1981)

Regression of Z500 and Precipitation to ENSO Index

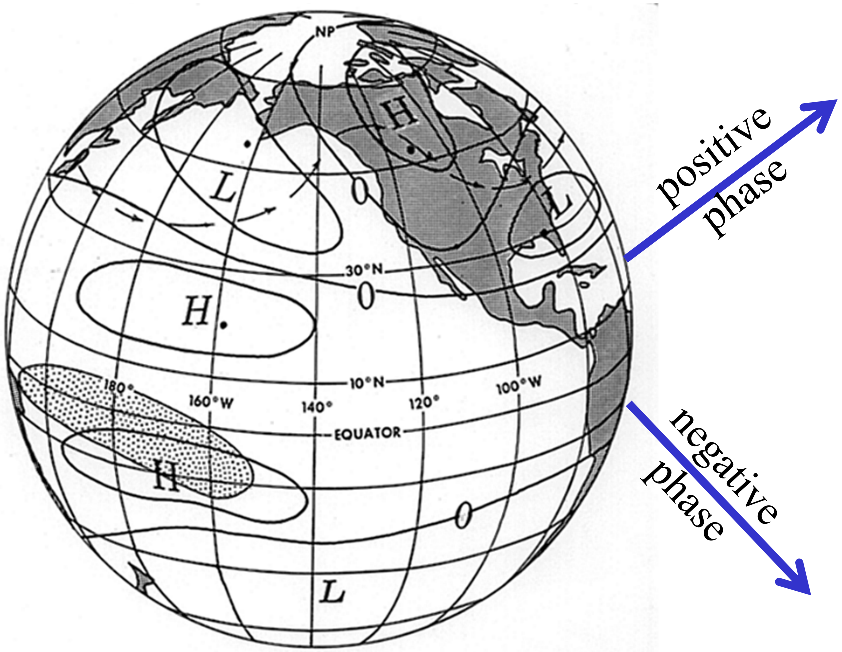


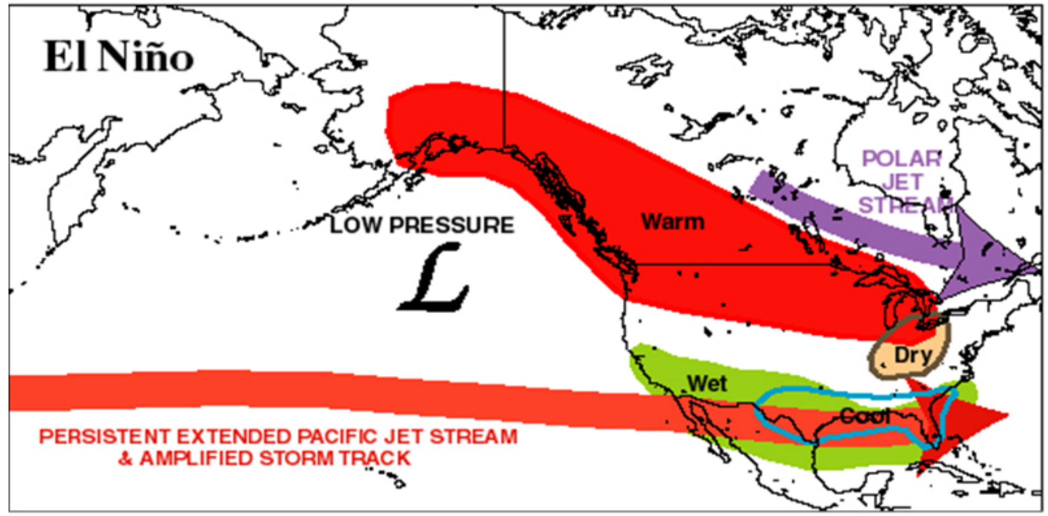
(Wu, Hsieh and Shabbar, 2005)

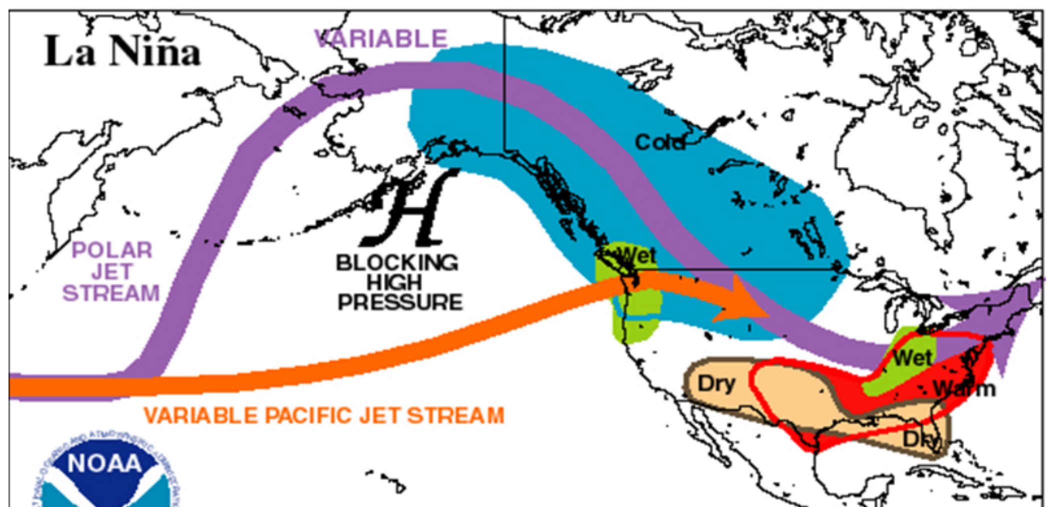
(downloaded from **Prof. William Hsieh** @ UBC)

PNA and Pacific Jetstreams

The positive phase is associated with an enhanced East Asian jet stream and with an eastward shift in the jet exit region toward the western United States.







The negative phase is associated with a westward retraction of that jet stream toward eastern Asia, blocking activity over the high latitudes of the North pacific, and a strong split-flow configuration over the central North Pacific.

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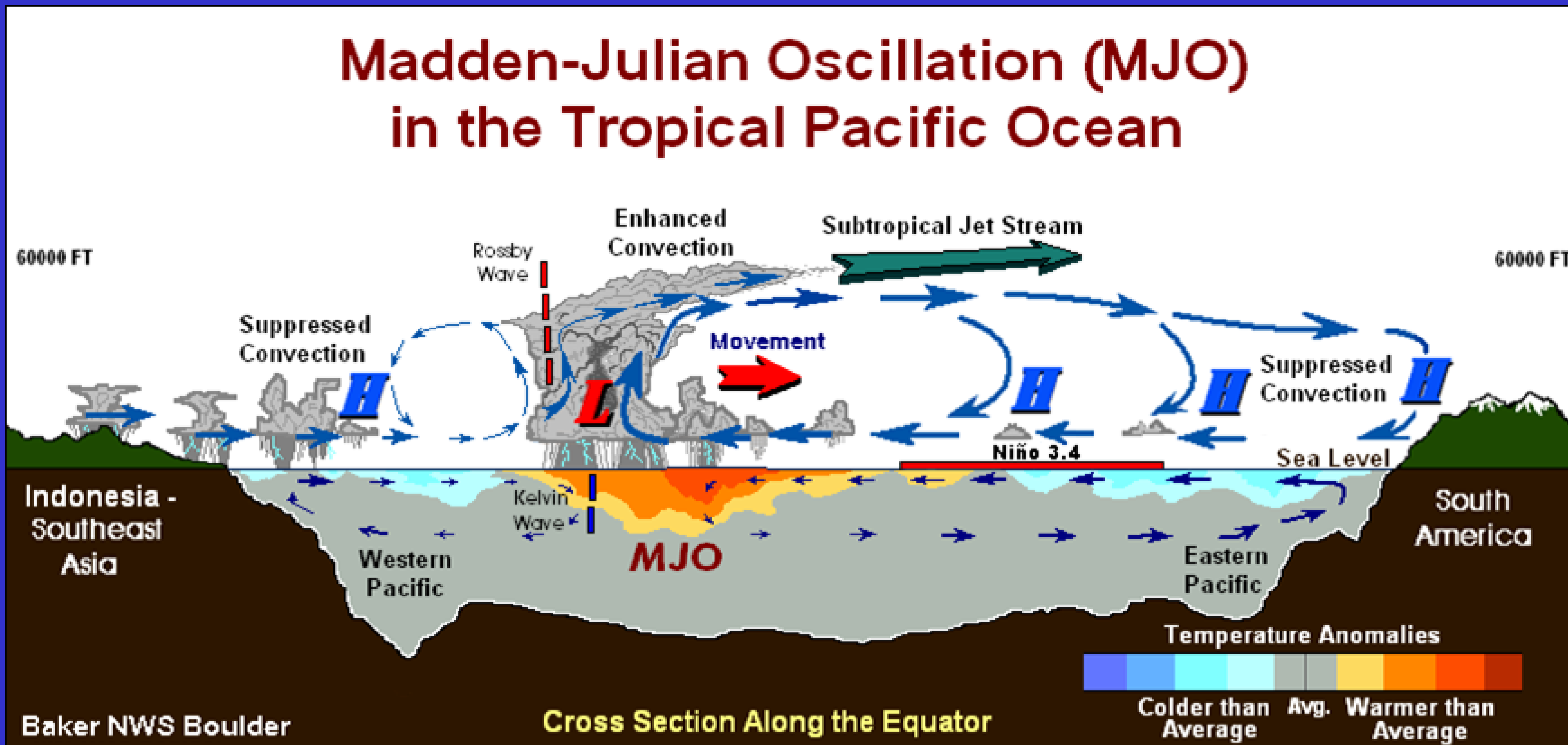
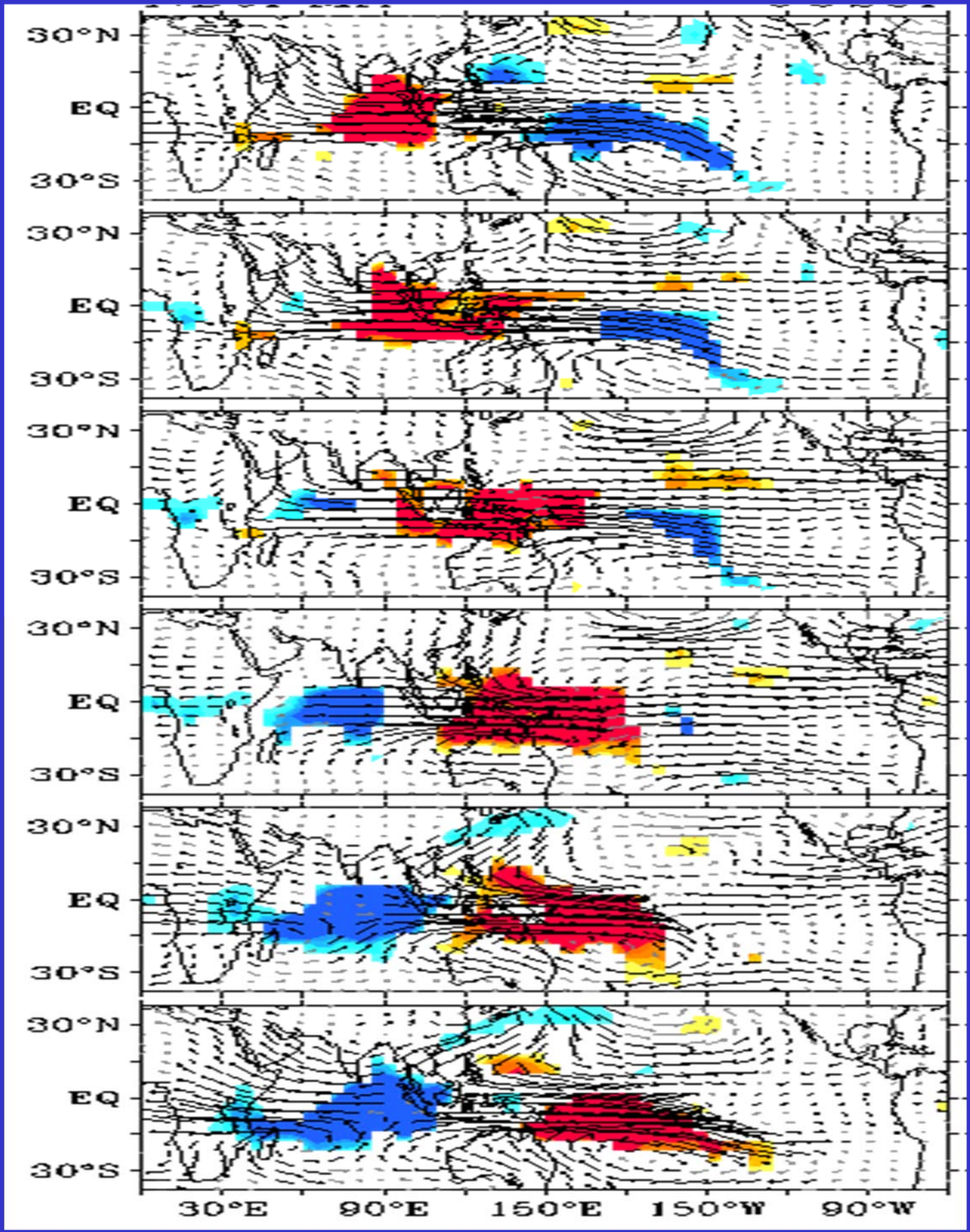
Madden Julian Oscillation (MJO)



- ❑ Basic Features
- ❑ Generation Mechanisms

MJO: Convection-Circulation Coupling



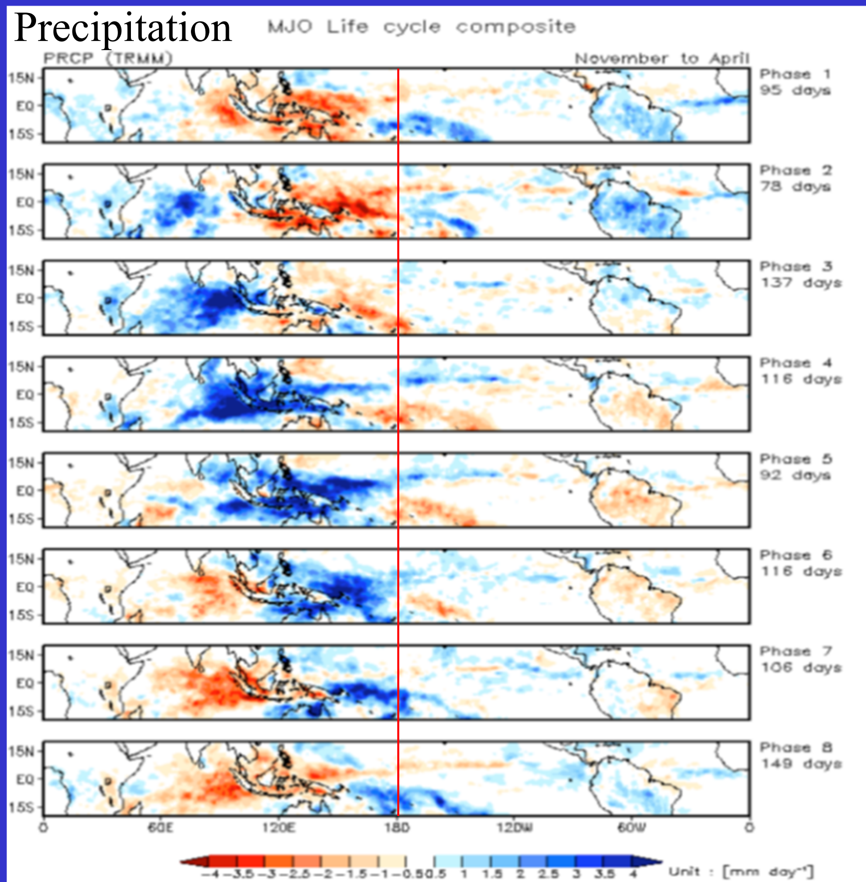
Rainfall rate and U850

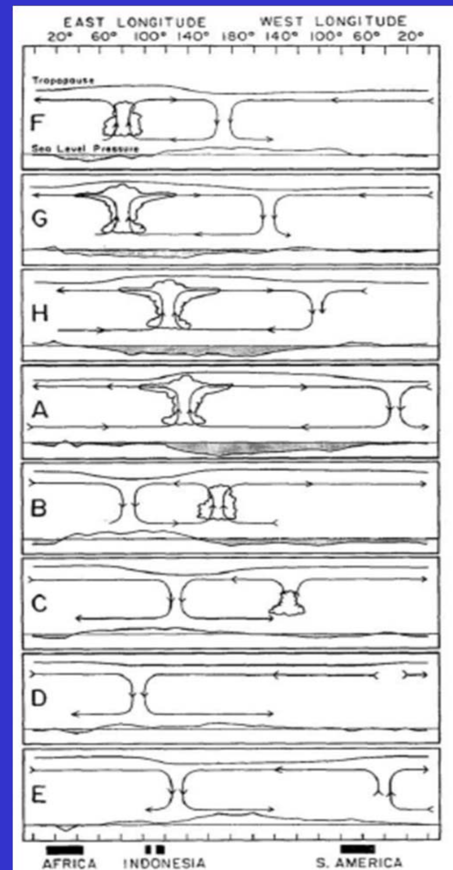
- ❑ Centers of enhanced and suppressed convections connected to each other through large-scale circulation

➔ **MJO is a coupled convection-circulation phenomenon.**

(Weng and Yu 2010)

MJO: Convection

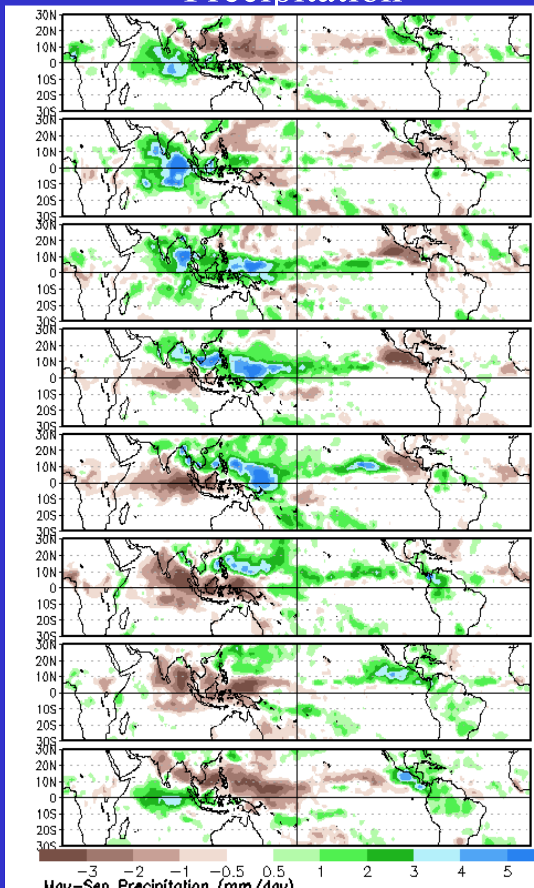




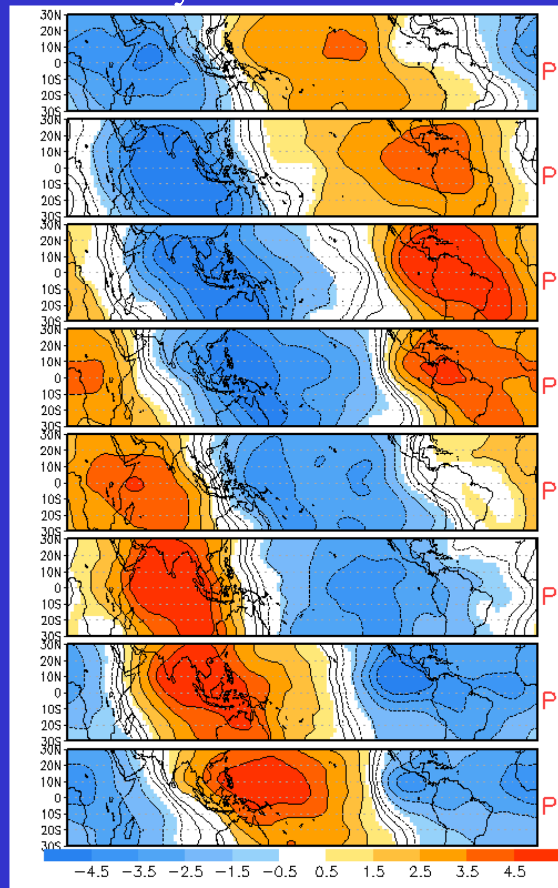
- The MJO is generally best developed in the region from the southern Indian Ocean eastward across Australia to the western Pacific Ocean
- The convection and the related cloudiness and precipitation tend to die out east of 180º latitude

MJO: Circulation

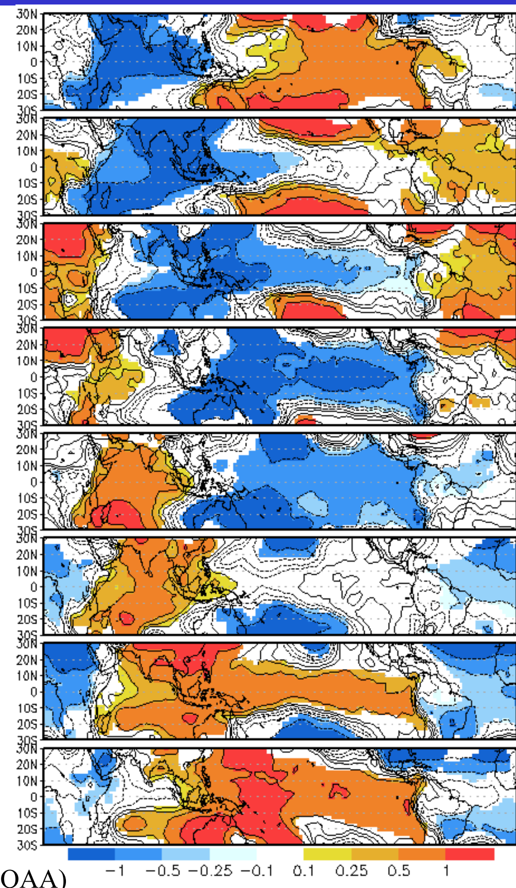
Precipitation



Velocity Potential at 200mb



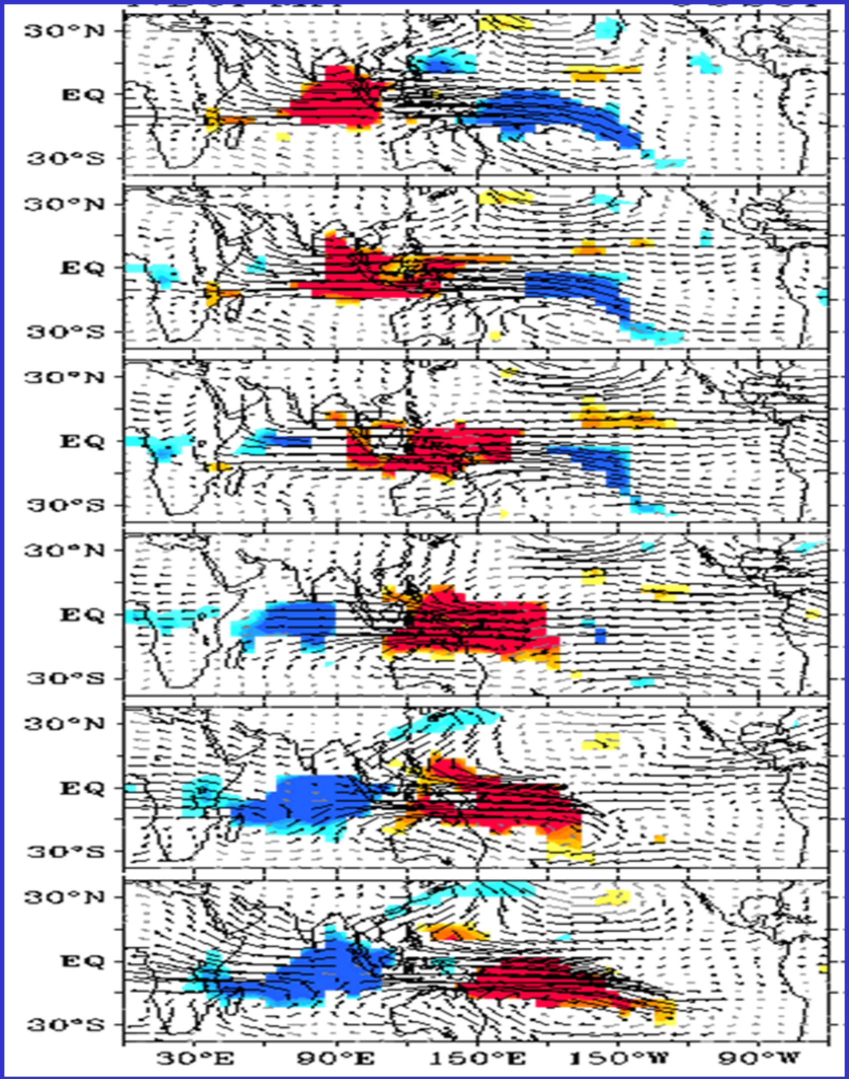
Sea Level Pressure



(from NOAA)

- While the convection and the related cloudiness and precipitation tend to die out east of 180º latitude, the MJO wind and surface pressure signal continues eastward through the eastern Pacific, South America, and into the tropical Atlantic.
- MJO propagates around latitude circles and is a planetary-scale phenomenon.

MJO: Zonal Wind Anomalies Only



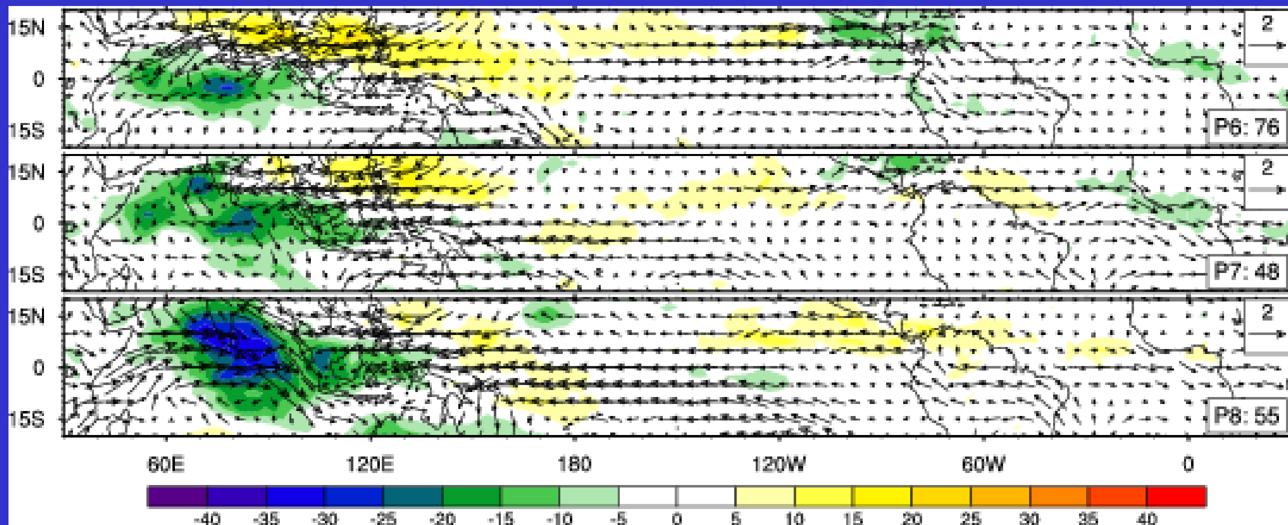
(Weng and Yu 2010)

- MJJO wind anomalies are mostly in the zonal (i.e., east-west) component.

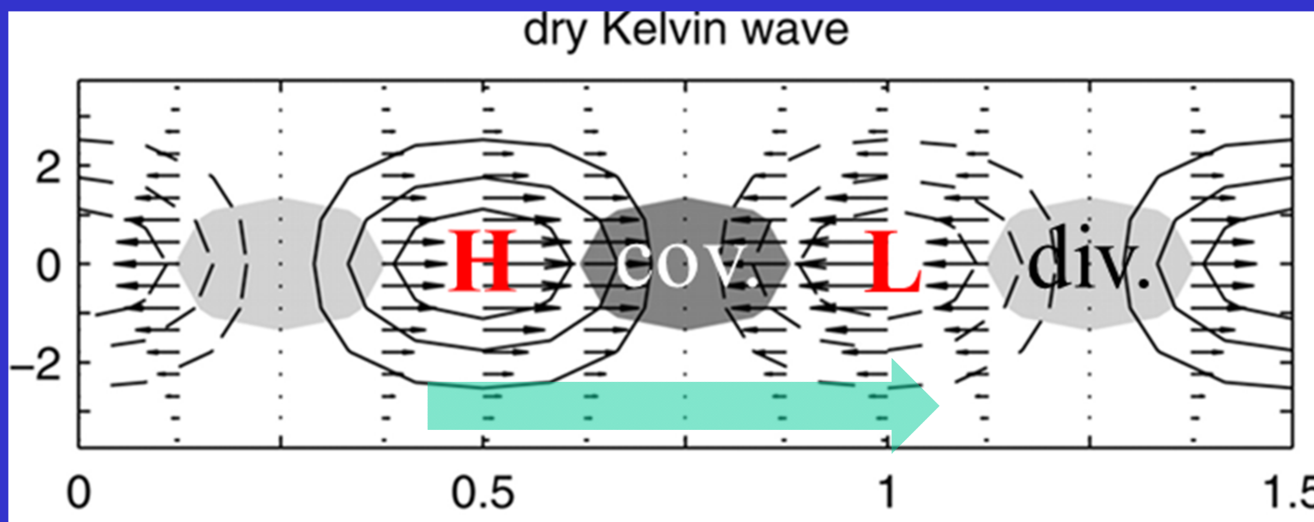
Equatorial Kelvin Wave

OLR & U850

MJO



Kelvin Wave



Dry Kelvin wave: C=30-60 m/sec

Moist Kelvin Wave: C=12-15 m/sec

MJO: C=5 m/sec

Coupled Atmosphere-OceanVariability

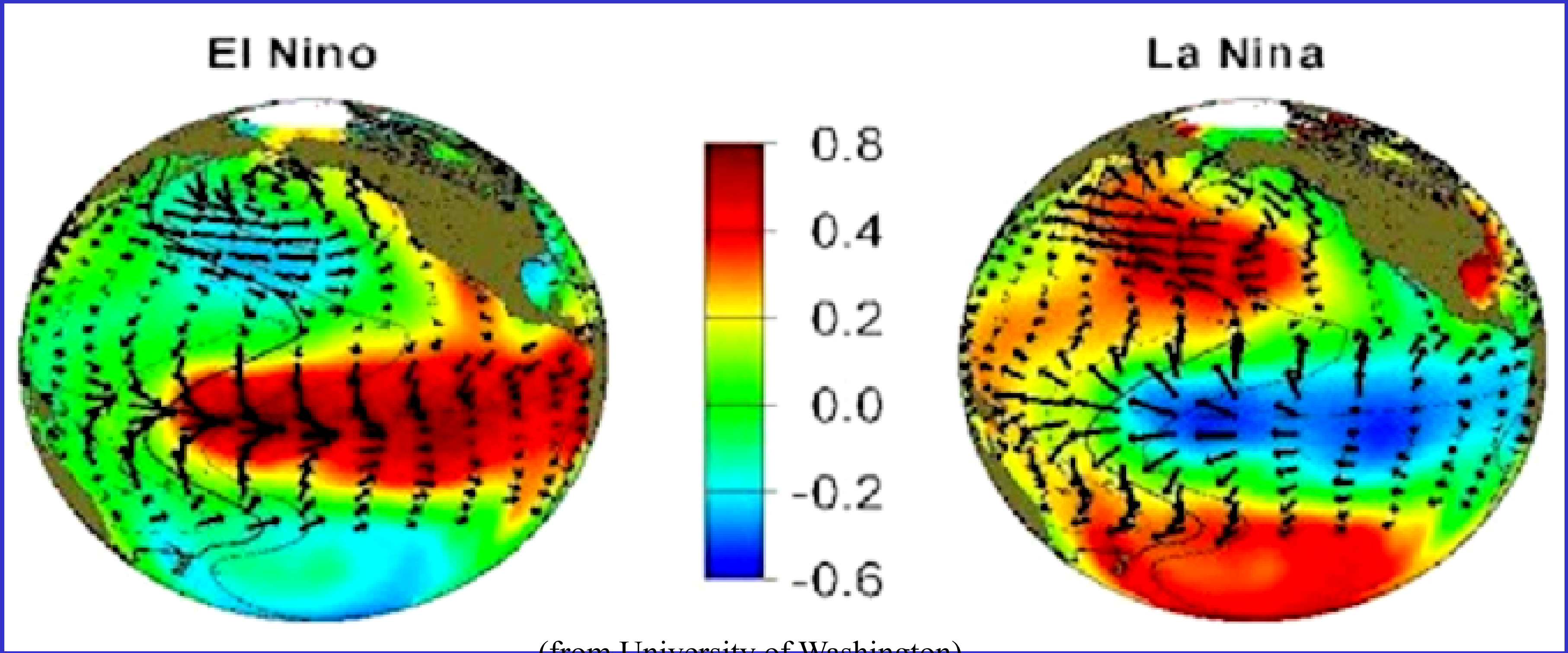
ENSO = El Nino – Southern Oscillation

PDO = Pacific Decadal variability

IPO = Inter-decadal Pacific Variability

AMO = Atlantic Multi-decadal Variability

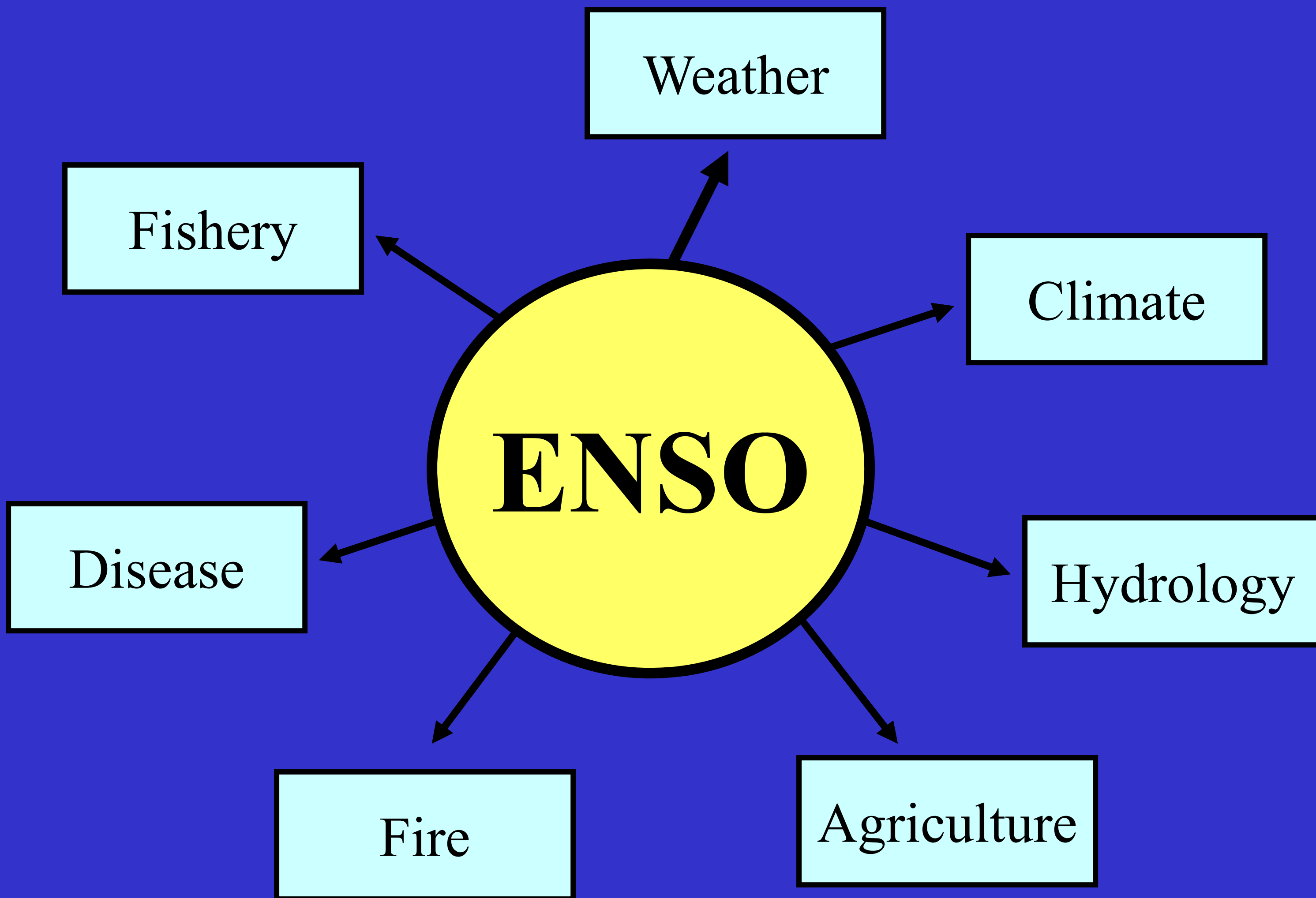
El Nino-Southern Oscillation



(from University of Washington)

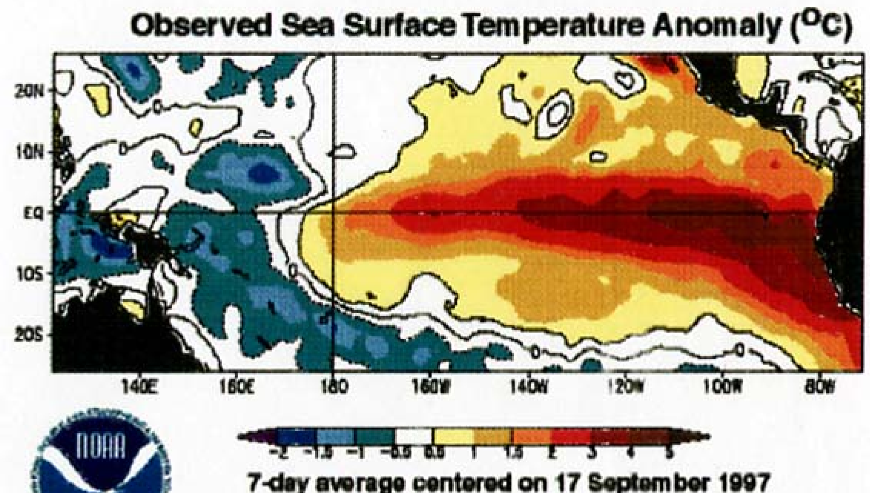
❑ ENSO is the largest interannual (year-to-year) climate variation signal in the coupled atmosphere-ocean system that has profound impacts on global climate.

ENSO-Related Research



El Niño: originally, an oceanic phenomenon

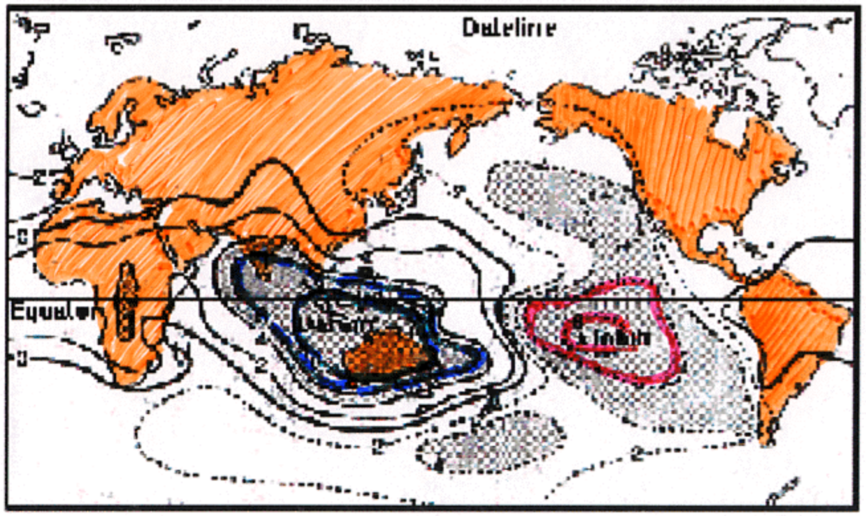
- Every two to seven years, the waters warm up along the western-most shores of South America.
- Peruvian sailors who fished in this region, were the first to notice and to give a name to this phenomenon.
- Because the phenomenon would usually begin to peak around the Christian Christmas holiday, the sailors named the odd phenomenon "El Niño" meaning "the Christ Child."



Climate Prediction Center/NCEP/NWS

Southern Oscillation: an atmospheric phenomenon

In 1910s, Walker found a connection between barometer readings at stations on the eastern and western sides of the Pacific (Tahiti and Darwin). He coined the term **Southern Oscillation** to dramatize the ups and downs in this east-west seesaw effect.



(from Rasmusson 1984)

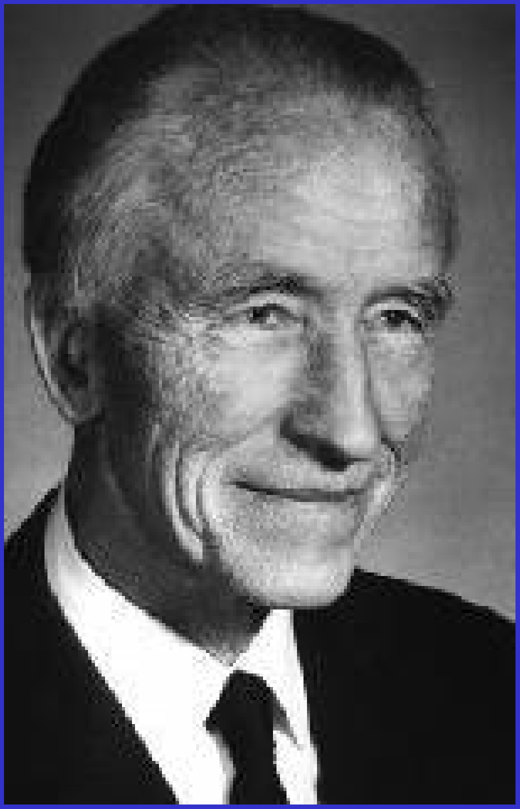
Sir Gilbert Walker

El Nino and Southern Oscillation

❑ Jacob Bjerknes was the first one to recognizes that El Nino is not just an oceanic phenomenon (in his 1969 paper).

❑ In stead, he hypothesized that the warm waters of El Nino and the pressure seasaw of Walker's Southern Oscillation are part and parcel of the same phenomenon: the ENSO.

❑ Bjerknes's hypothesis of coupled atmosphere-ocean instability laid the foundation for ENSO research.



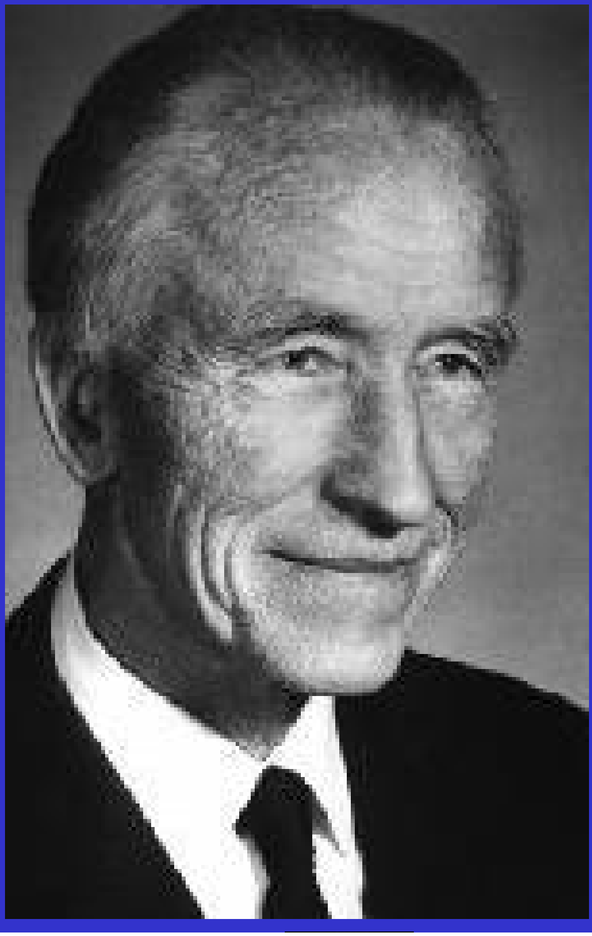
Jacob Bjerknes

Pioneers in Modern Meteorology & Climatology

Weather: Polar Front Theory

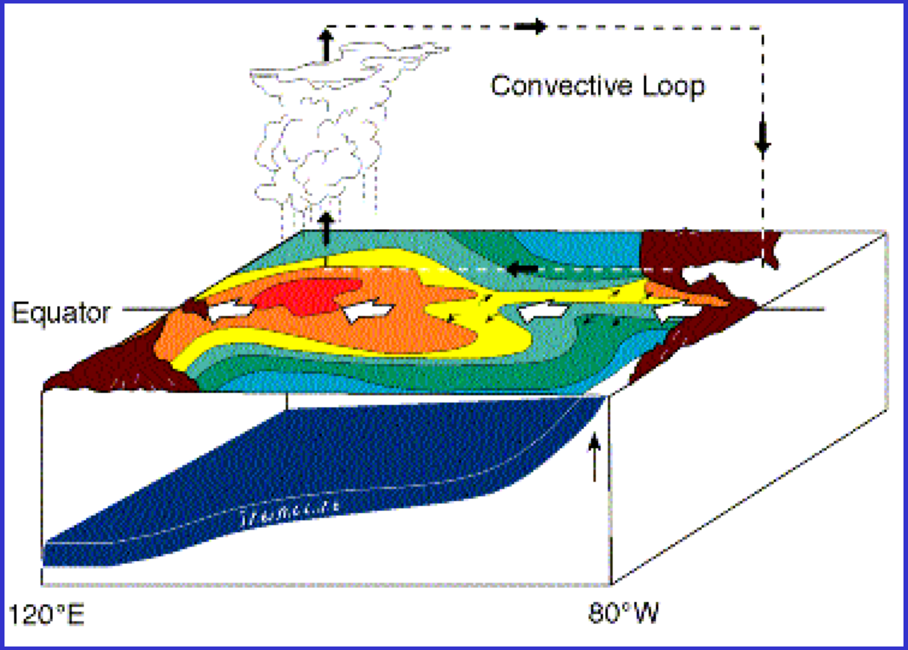
Vilhelm Bjerknes (1862-1951)

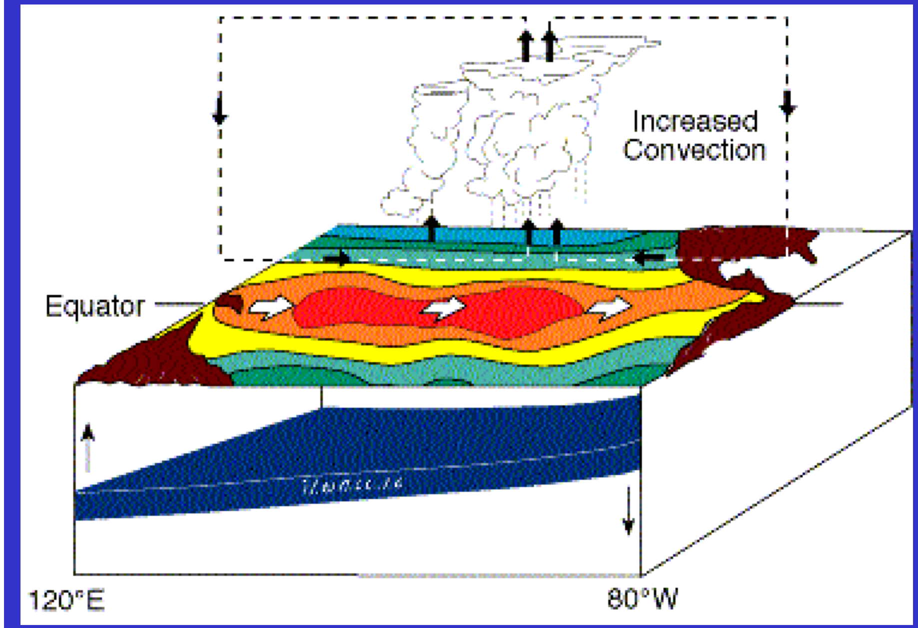
Climate: El Nino-Southern Osci.



Jacob Bjerknes (1897-1975)

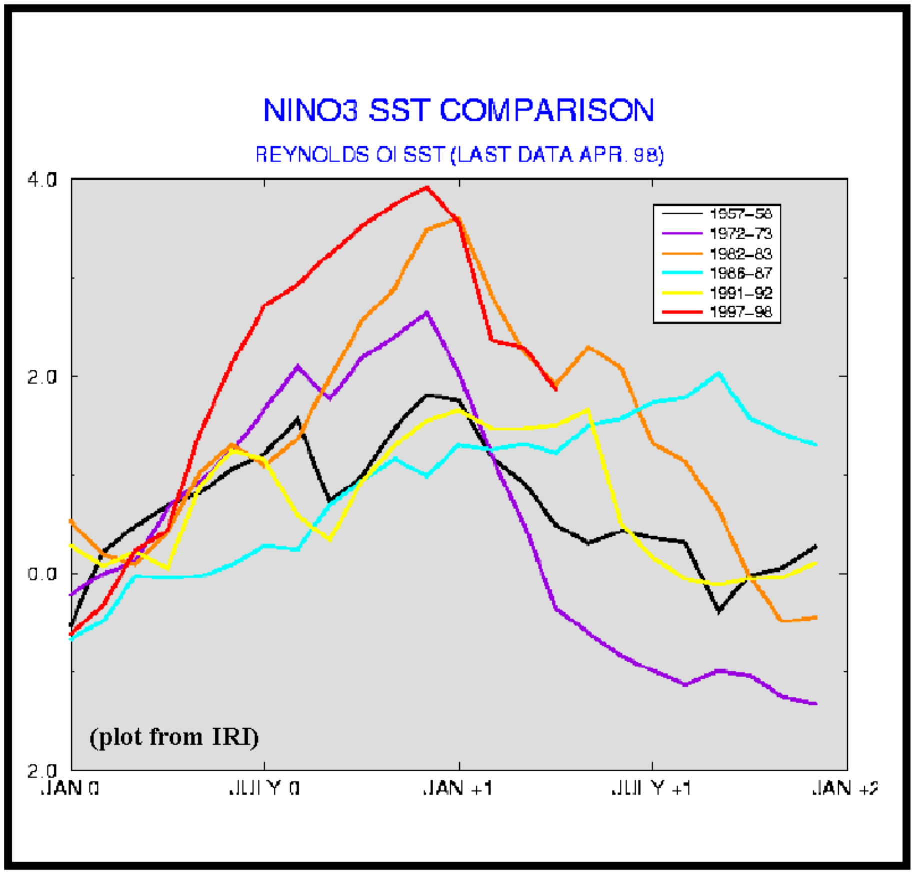
Coupled Atmosphere-Ocean System





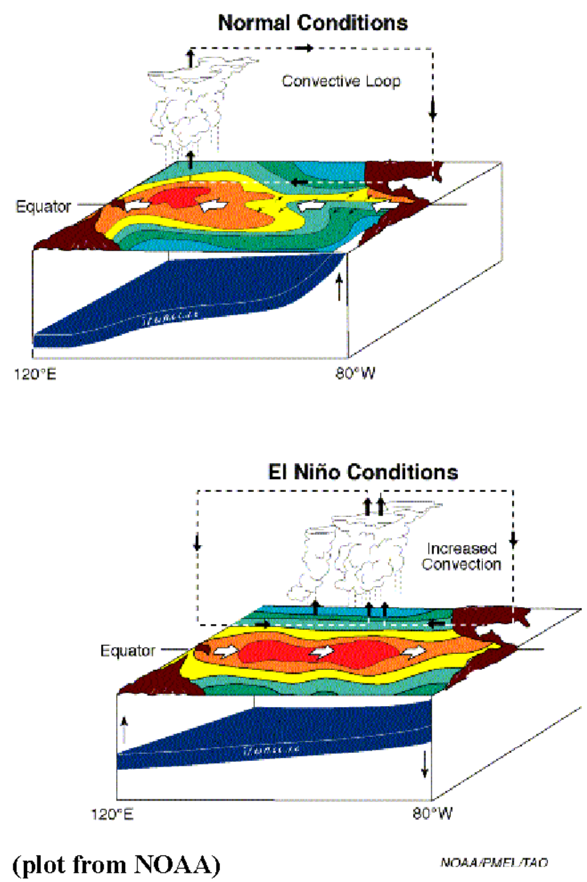
(from NOAA)

ENSO's Phase-Lock to the Annual Cycle



- ❑ Composition analyses have shown that ENSO events tend to onset, grow, and decay at certain seasons of the year (Rasmusson and Carpenter 1982).

Growth Mechanism



(plot from NOAA)

The growth mechanism is responsible for amplifying SST anomalies during both the warm and cold phases of the ENSO cycle.

- Positive feedbacks from the interaction between the atmosphere and ocean provide a mechanism for SST anomalies to grow in the tropical Pacific during ENSO events.

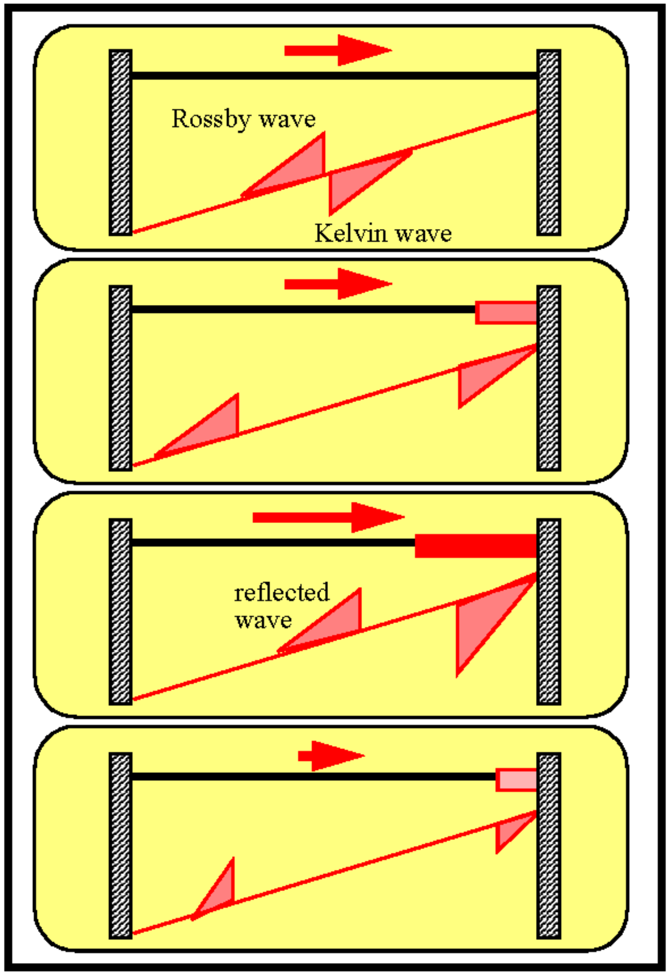
- This coupled instability mechanism was first proposed by Bjerknes (1966, 1969) based on statistical correlations and was later demonstrated by many modeling studies.

Phase-Transition Mechanism

Any successful theory for the phase-transition mechanism has to be able to (1) provide a negative feedback to reverse the phase of the ENSO cycle, and (2) account for the long period associated with the cycle.

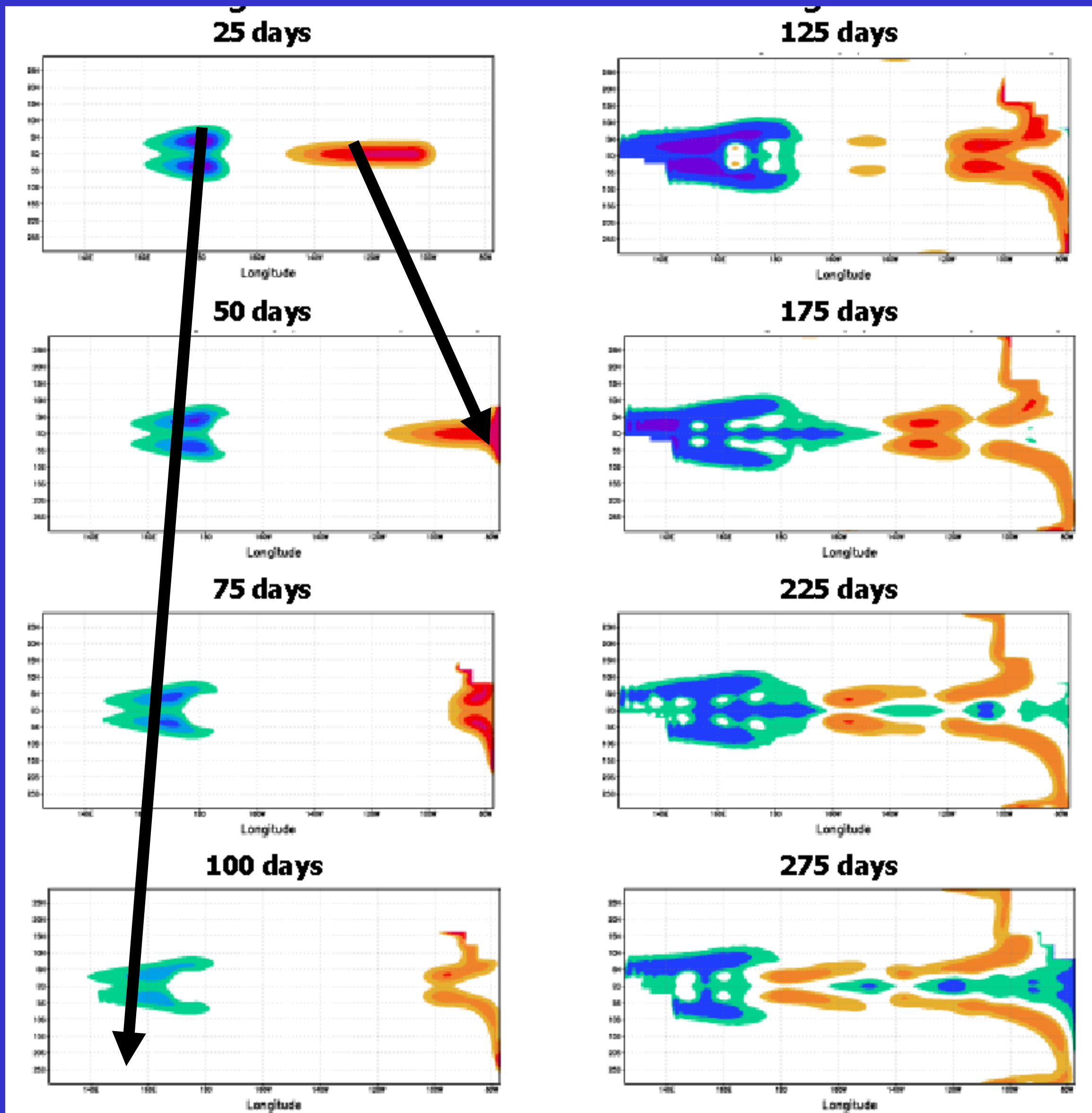
- **Delay Oscillator Theory** (Schopf and Suarez 1988; Battisti and Hirst 1989)
  - Ocean memory is carried by thermocline depth through reflection and propagation (i.e., the delay) of ocean waves (i.e., subsurface ocean dynamics dominants).
  - ENSO period is determined by the wave propagation and reflection time.
- **Slow SST-Fast Wave theory** (Neelin 1991; Neelin and Jin 1993; Jin and Neelin 1993a,b)
  - ocean memory is provided by SST through heat storage in the mixed layer (i.e., surface thermodynamics dominants).
  - ENSO period is determined by air-sea interaction and surface ocean advections.
- **Recharge Oscillator Theory** (Wyrkti 1975, 1985; Cane et al. 1986; Zebiak 1989; Jin 1997)
  - ocean memory is carried by the zonal-mean ocean thermocline depth, which is constantly in non-equilibrium with equatorial wind stress on ENSO timescales (i.e., subsurface ocean dynamics dominants).
  - ENSO period depends on the time needed to adjust the non-equilibrium mean thermocline depth at the equator throughout the tropical Pacific basin-wide.

Delayed Oscillator Theory



- Wind forcing at the central Pacific: produces a downwelling Kevin wave propagating eastward and a upwelling Rossby wave propagating westward.
- wave propagation: the fast kelvin wave causes SST warming at the eastern basin, while slow Rossby wave is reflected at the western boundary.
- wave reflection: Rossby wave is reflected as a upwelling Kelvin wave and propagates back to the eastern basin to reverse the phase of the ENSO cycle.
- ENSO period: is determined by the propagation time of the waves.

Wave Propagation and Reflection



(Figures from IRI)

- It takes Kevin wave (phase speed = 2.9 m/s) about 70 days to cross the Pacific basin (17,760km).
- It takes Rossby wave about 200 days (phase speed = 0.93 m/s) to cross the Pacific basin.

Why Only Pacific Has ENSO?

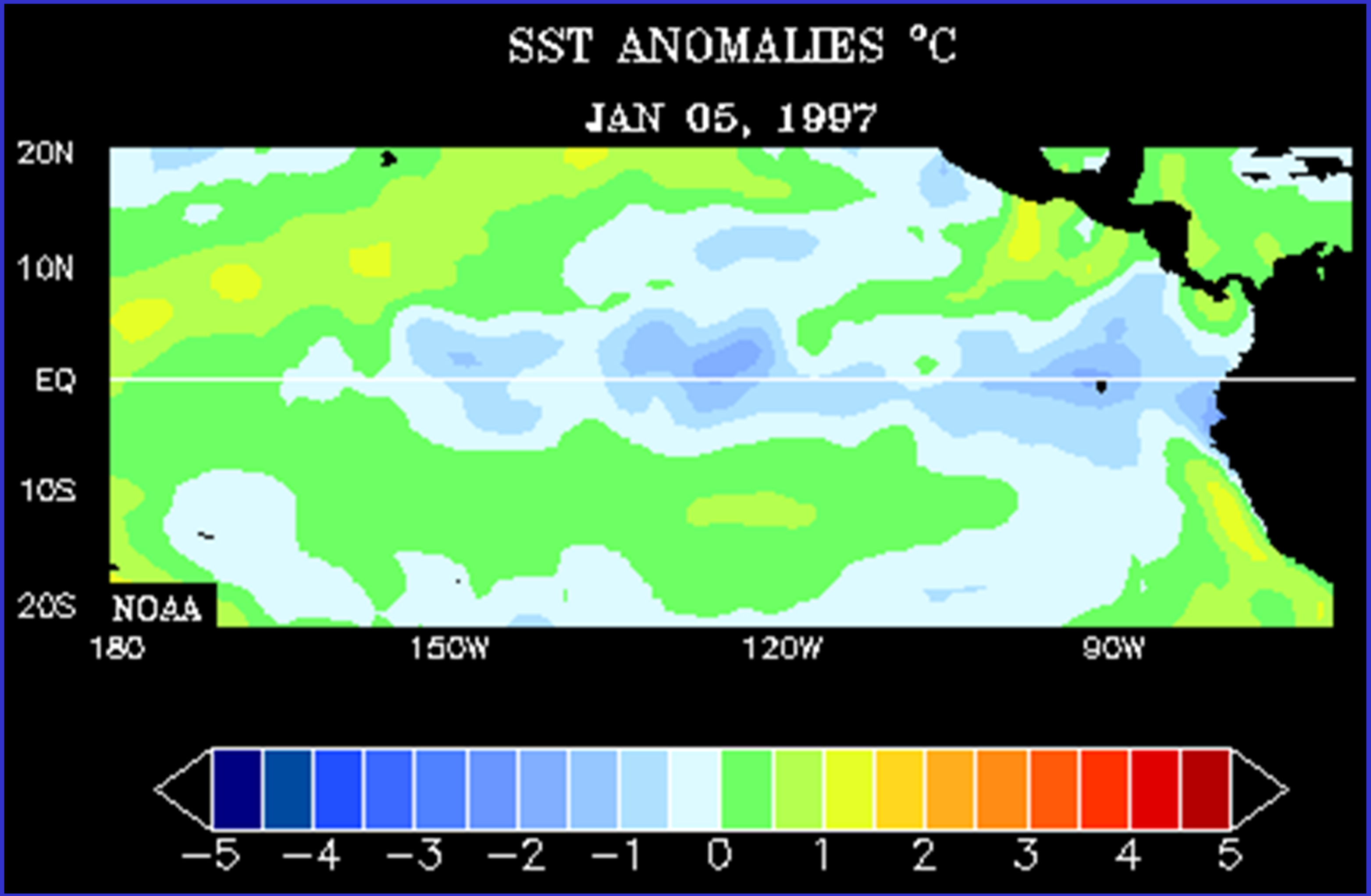
- Based on the delayed oscillator theory of ENSO, the ocean basin has to be big enough to produce the “delayed” from ocean wave propagation and reflection.

- It can be shown that only the Pacific Ocean is “big” (wide) enough to produce such delayed for the ENSO cycle.

- It is generally believed that the Atlantic Ocean may produce ENSO-like oscillation if external forcing are applied to the Atlantic Ocean.

- The Indian Ocean is considered too small to produce ENSO.

1997-98 El Nino



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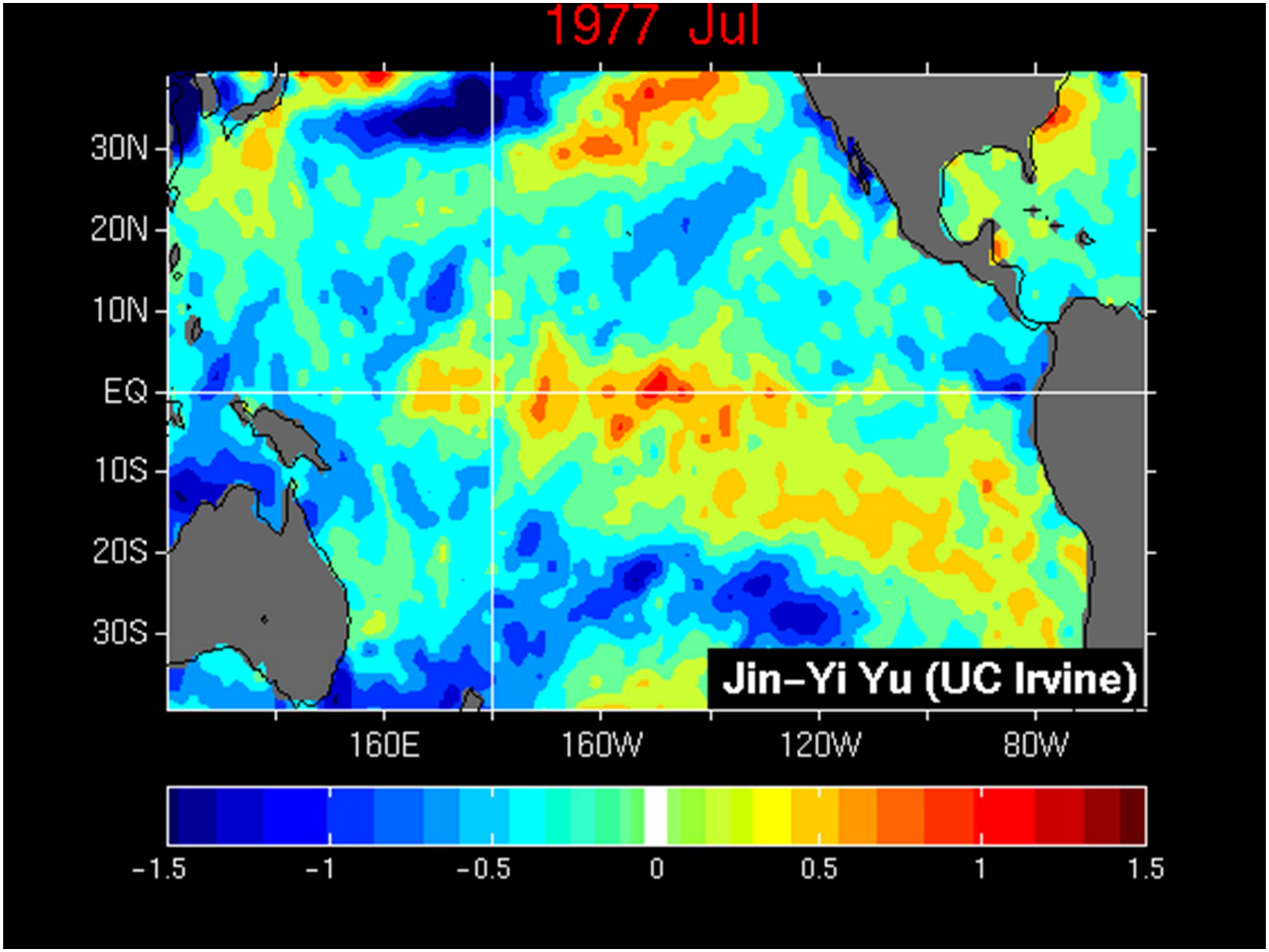
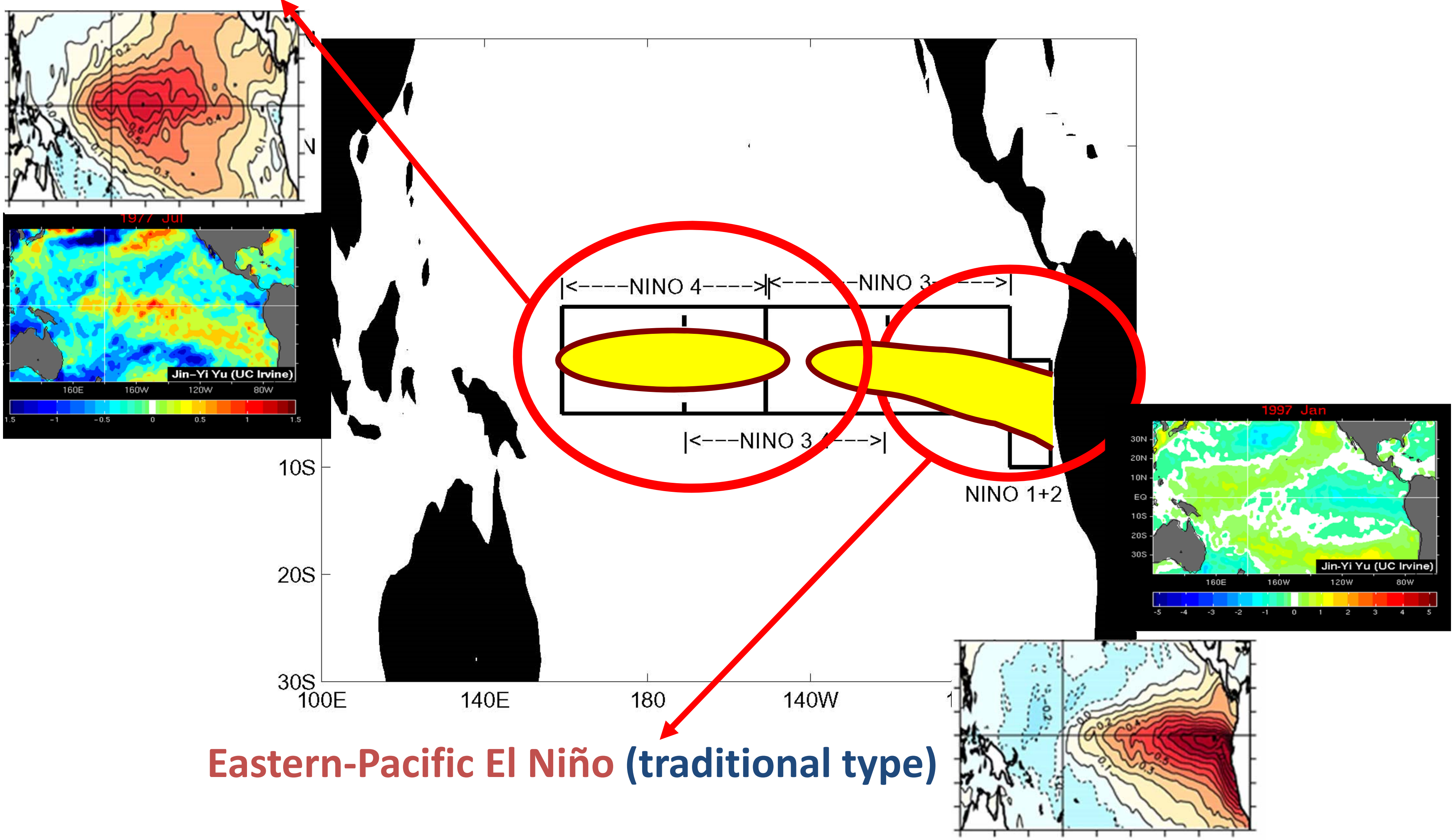
1977-78 El Niño



Two Types of El Niño = ENSO Diversity

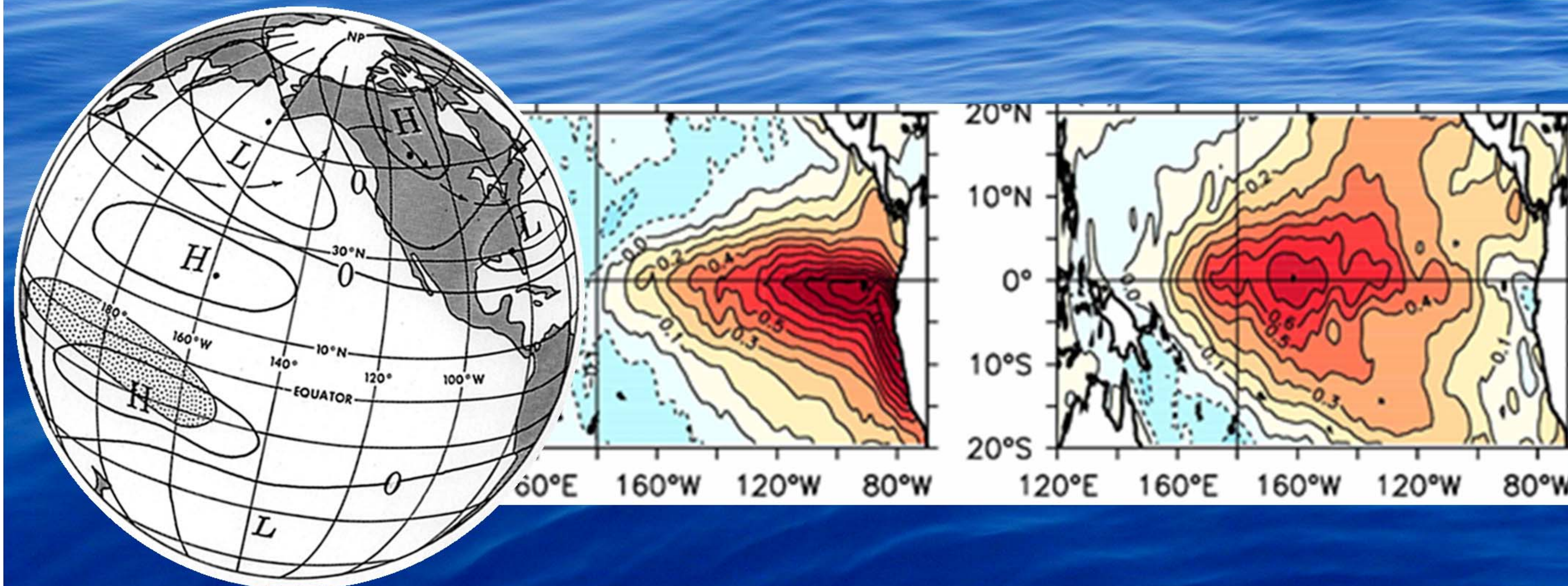
(Yu and Kao 2007; Kao and Yu 2009)

Central-Pacific El Niño (New Type)



Eastern-Pacific El Niño (traditional type)

ENSO Diversity



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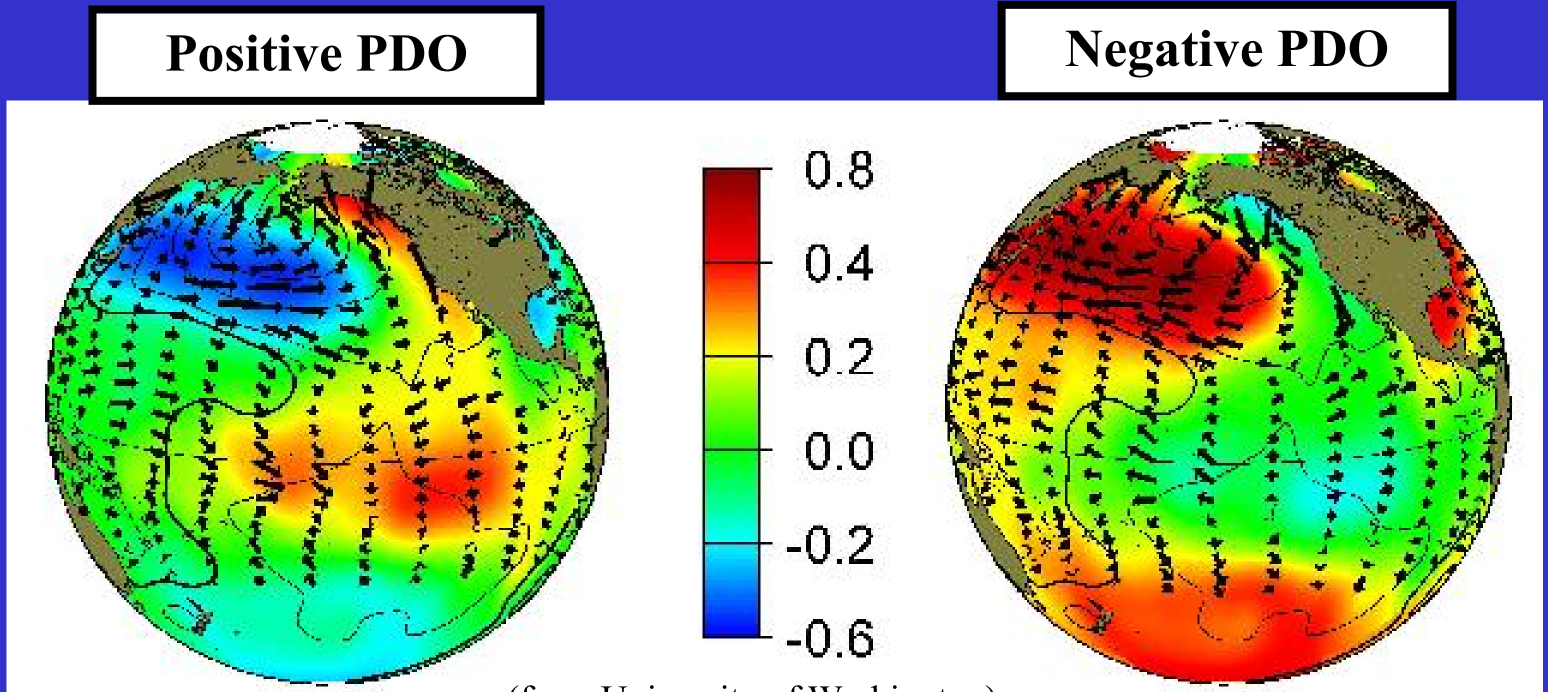
University of California, Irvine

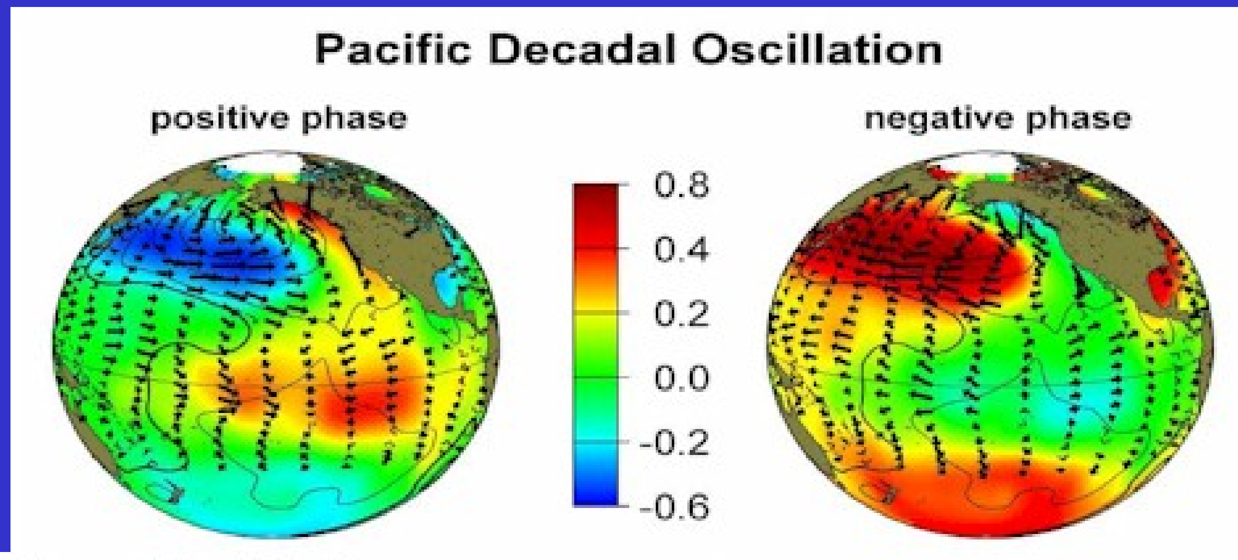
Pacific Decadal Oscillation

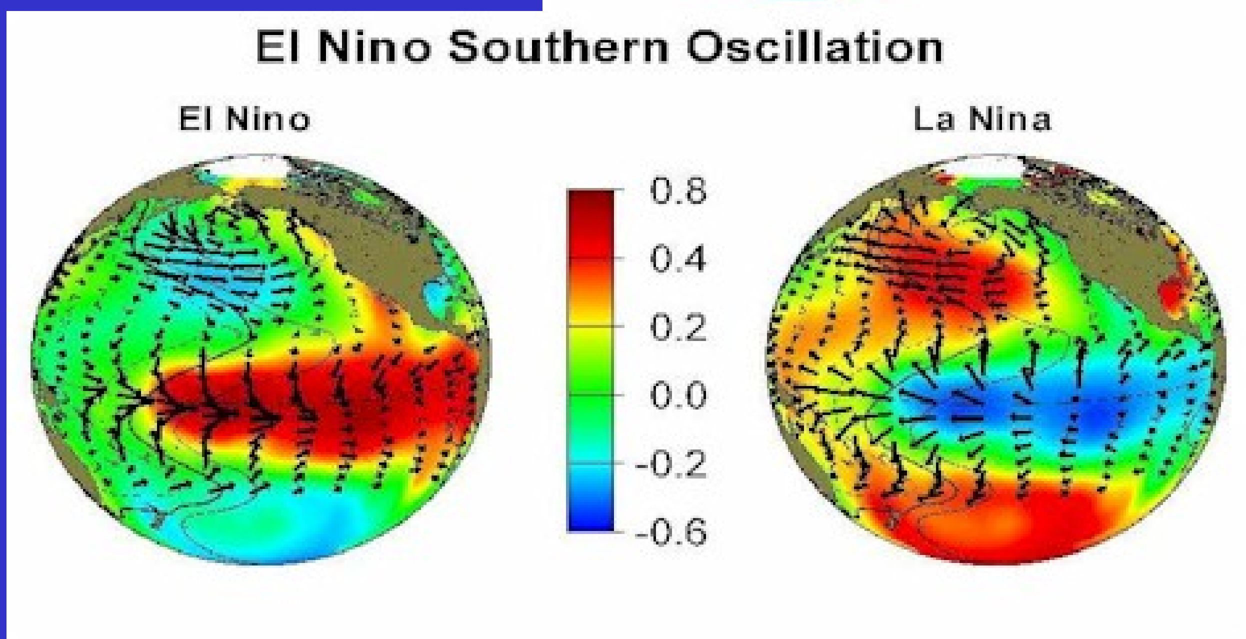


(from University of Washington)

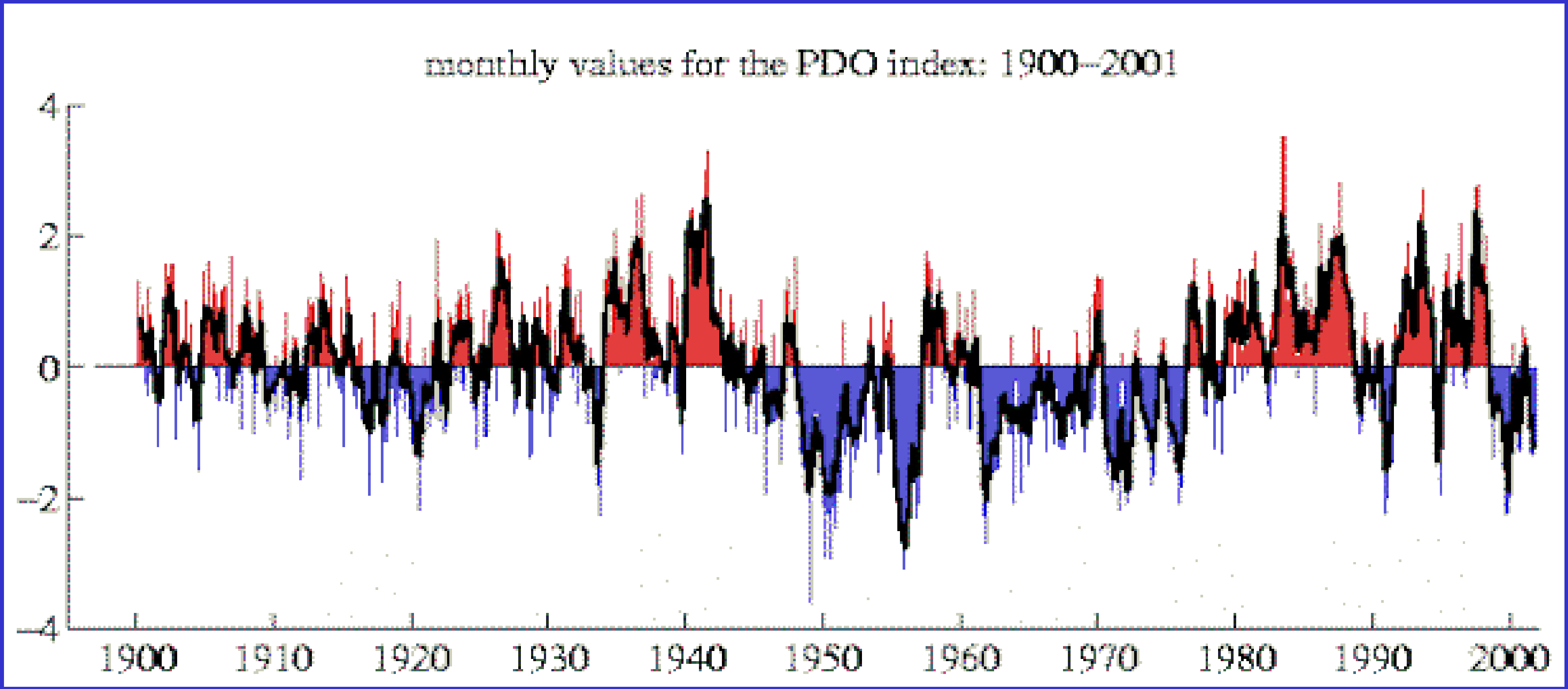
- "Pacific Decadal Oscillation" (PDO) is a decadal-scale climate variability that describe an oscillation in northern Pacific sea surface temperatures (SSTs).
- PDO is found to link to the decadal variations of ENSO intensity.

ENSO and PDO


Pacific Decadal Oscillation
positive phase
negative phase
0.8
0.4
0.2
0.0
-0.2
-0.6

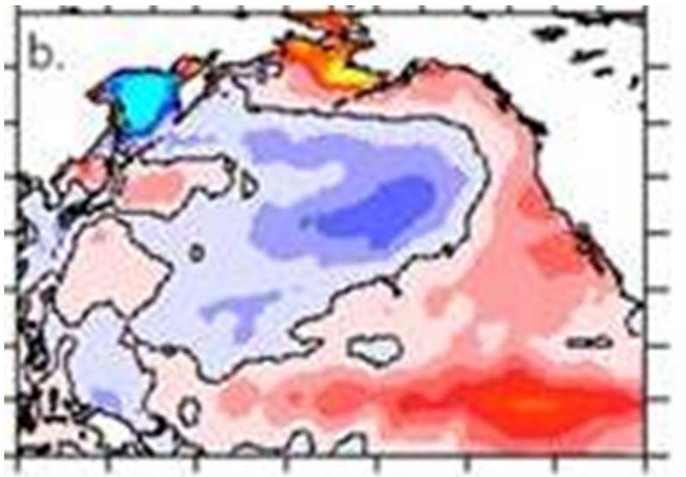

El Nino Southern Oscillation
El Nino
La Nina
0.8
0.4
0.2
0.0
-0.2
-0.6

PDO Index

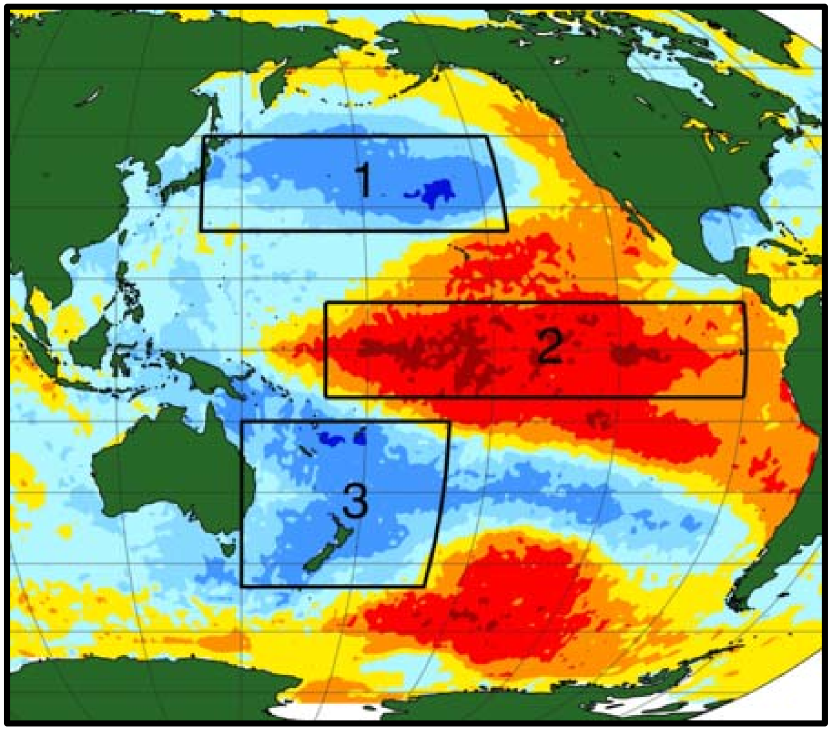

monthly values for the PDO index: 1900–2001
4
2
0
-2
–4
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000

PDO and IPO

Pacific Decadal Oscillation

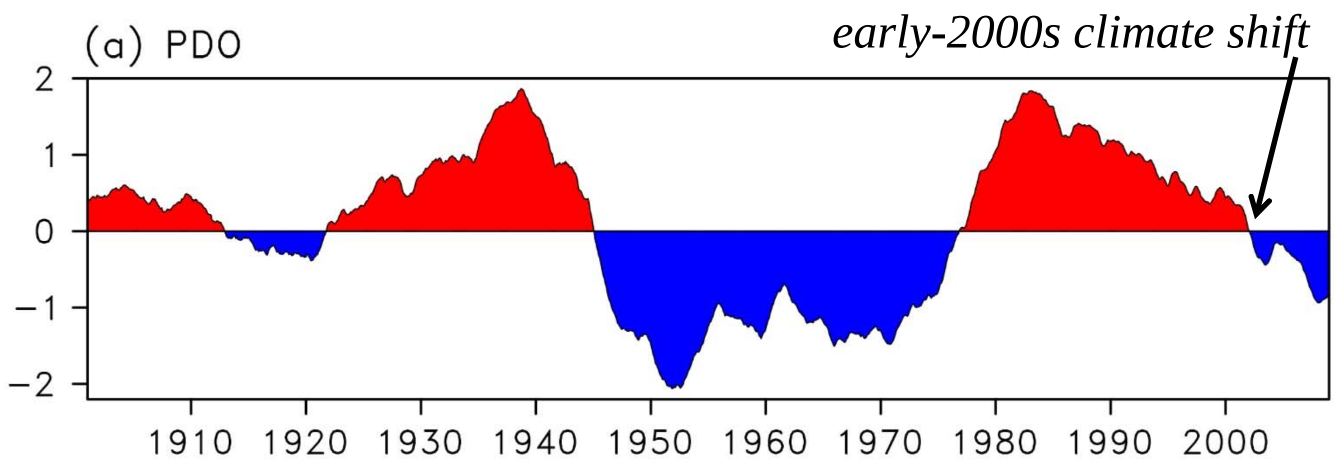


Inter-decadal Pacific Oscillation

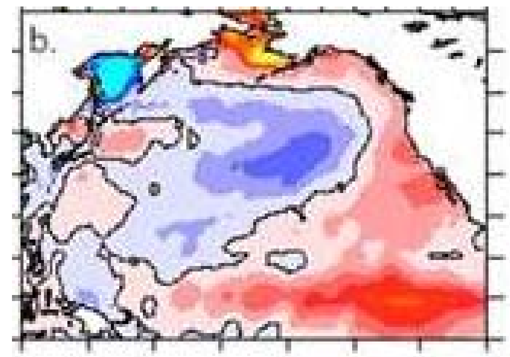


(from Henley et al. 2015)

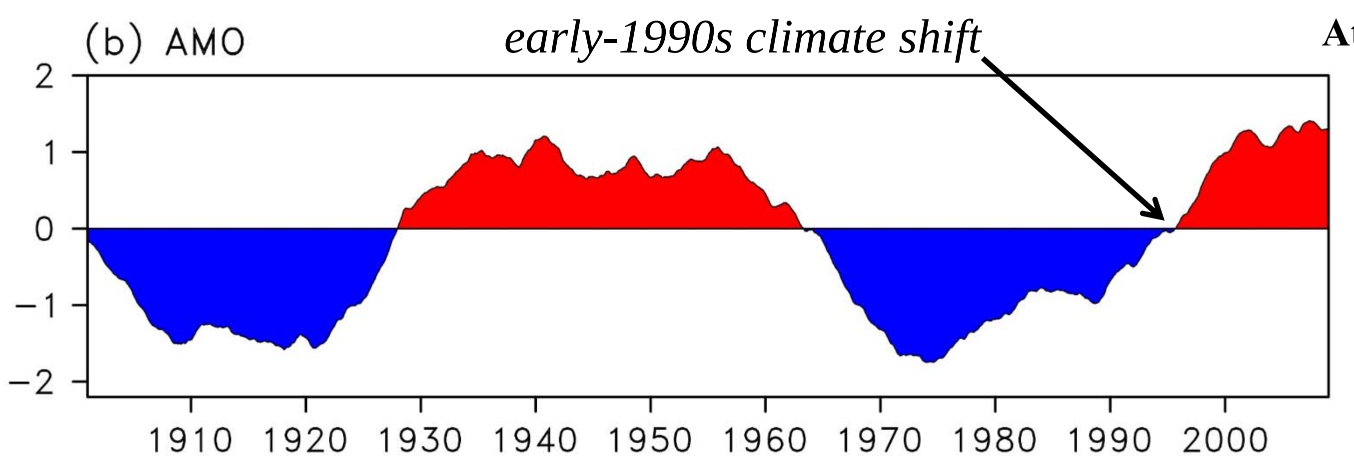
Middle-1990s or Early-2000s Climate Shift?



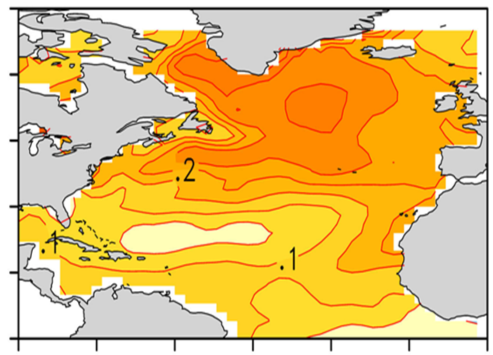
Pacific Decadal Oscillation



(from NOAA)



Atlantic Multi-decadal Oscillation



(from Yu et al. 2015)

PDO, IPO, and AMO Indices