ATM 241, Spring 2020
Lecture 11b
El Niño Southern Oscillation

Paul A. Ullrich

paullrich@ucdavis.edu

Marshall & Plumb

Ch. 12.2

In this section…

Definitions

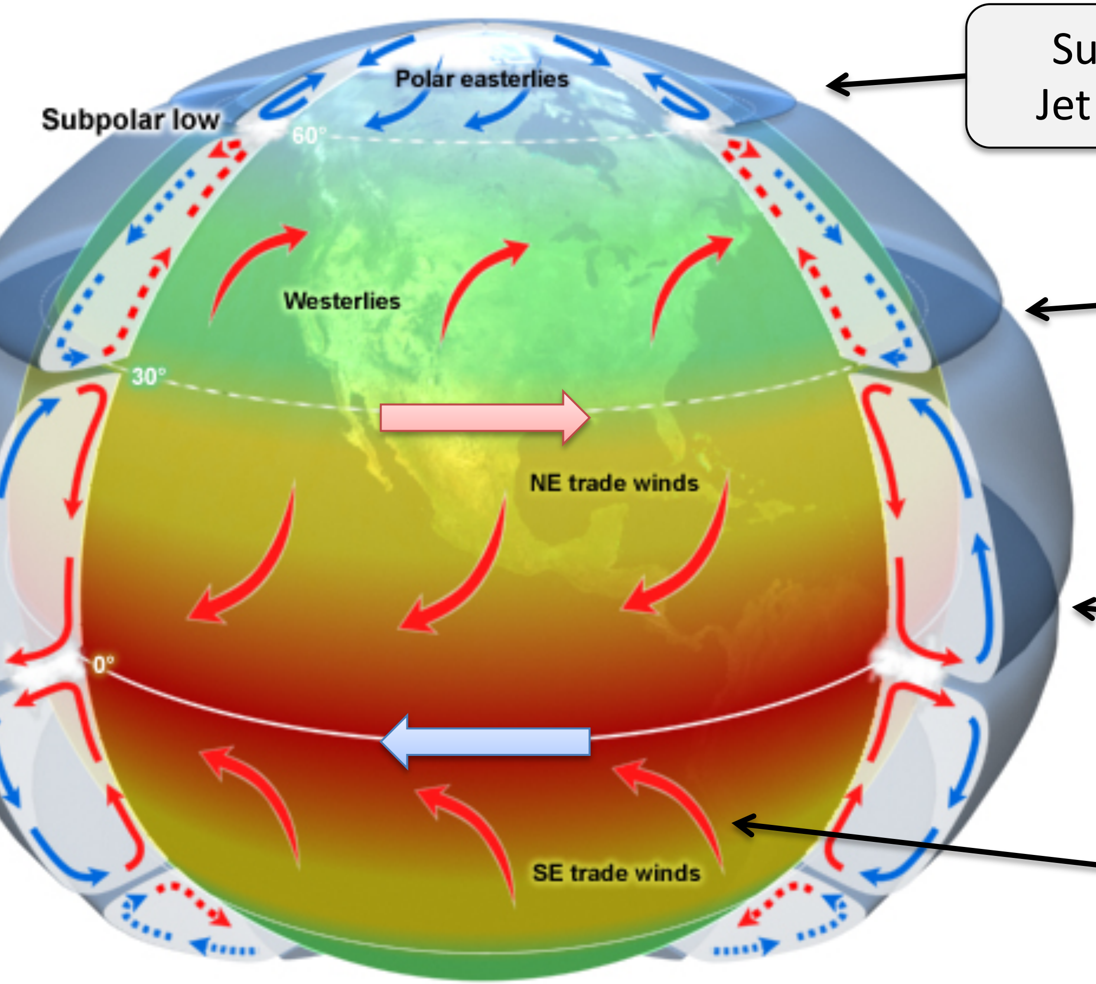
- Walker Circulation
- Bjerknes Feedback
- El Niño Southern Oscillation
- Southern Oscillation Index

Questions

- What are the major drivers of zonal tropical circulations?
- How are the ocean and atmosphere connected in the tropics?
- What is the normal state of the tropical Pacific?
- How does the tropical system swap between warm and cold states?
- What global impacts are related to El Niño and La Niña conditions?

Tropical Dynamics

Tropospheric General Circulation



Subpolar Jet Stream

Subtropical Jet Stream

Intertropical Convergence Zone (ITCZ, rising motion)

Curvature in the flow driven in large part by Coriolis force **(zero at equator)**

As discussed previously, this zonally symmetric view of the system does not account for zonal inhomogeneity, particularly differences between ocean and land.

The Tropical Atmosphere

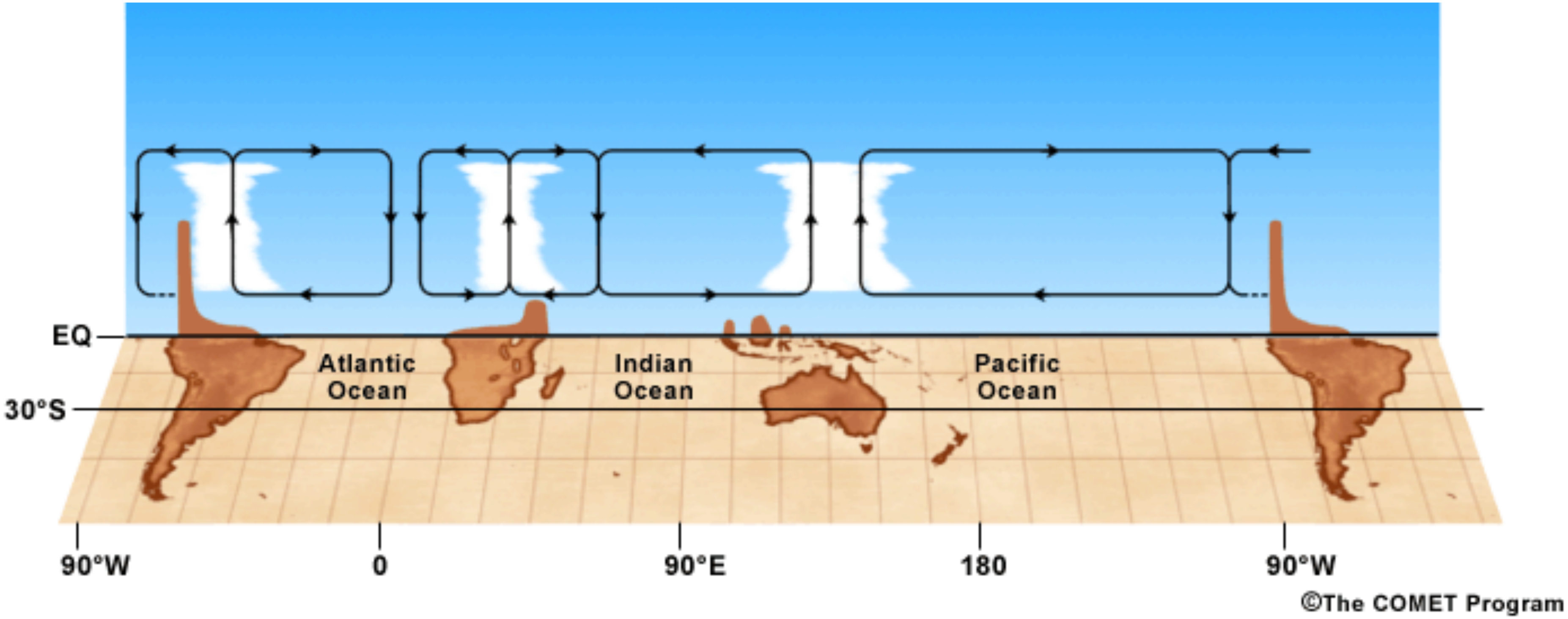
- Coriolis force is very small near the equator, meaning that geostrophic balance does not hold (and so baroclinic instability and thus frontal activity is largely absent).

- The tropics features a unique collection of waves and disturbances that are not found in the midlatitudes or polar regions (e.g. equatorial Rossby waves and equatorial Kelvin waves).

- Upward motion in this region primarily through convective activity, which is inherently chaotic in nature. However, some insights can be gained from understanding the drivers of **organized convection**.

- Surface temperature differences are important drivers of where convection (and subsidence) occurs.

The Tropical Atmosphere



Definition: The **Walker Circulation** is an equatorial circulation driven by **temperature differences over land and the ocean**.

Although flow generally tends to be easterly in the tropics, the vanishing Coriolis force results in surface temperature differences playing a greater role in motion.

The Tropical Atmosphere

- The **Walker Circulation** is thus a conceptual model of air flow in the tropics caused by differences in heat distribution between ocean and land.

- Warmer land surface temperatures (and colder ocean temperatures) are driven by differences in the heat capacities of these surfaces.

- The Walker circulation (zonal, along the equator) is perpendicular to the Hadley circulation (which describes meridional motions and energy/moisture/momentum exchanges between the tropics and midlatitudes).

The Tropical Ocean

Equatorial zonal momentum equation (beta plane)

$$-\beta y v = \frac{1}{\rho_{\text{ref}}}\left(-\frac{\partial p}{\partial x} + \frac{\partial \tau_x}{\partial z}\right)$$

If we assume zonal symmetry $\frac{\partial p}{\partial x} = 0$

and so over the depth of the Ekman layer

$$\langle v \rangle \approx -\frac{\tau_{wind_x}}{\beta y \rho_{\text{ref}}}$$

Near the equator $\tau_{wind_x} < 0$ and so

$$\begin{cases} \langle v \rangle < 0 & \text{if } y < 0, \\ \langle v \rangle > 0 & \text{if } y > 0. \end{cases}$$

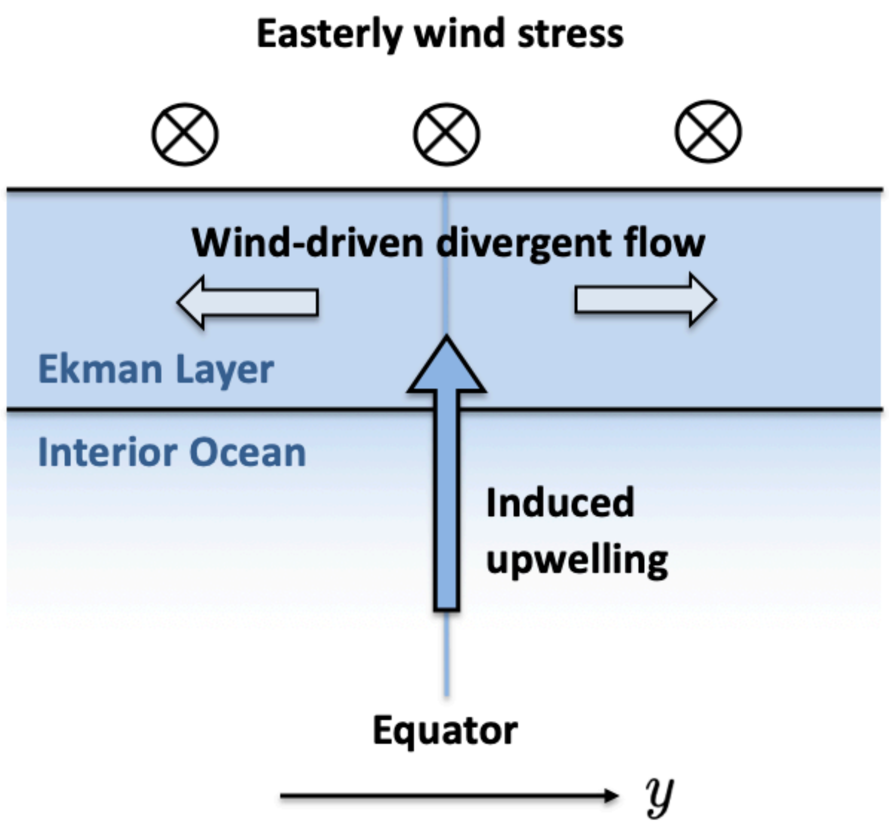
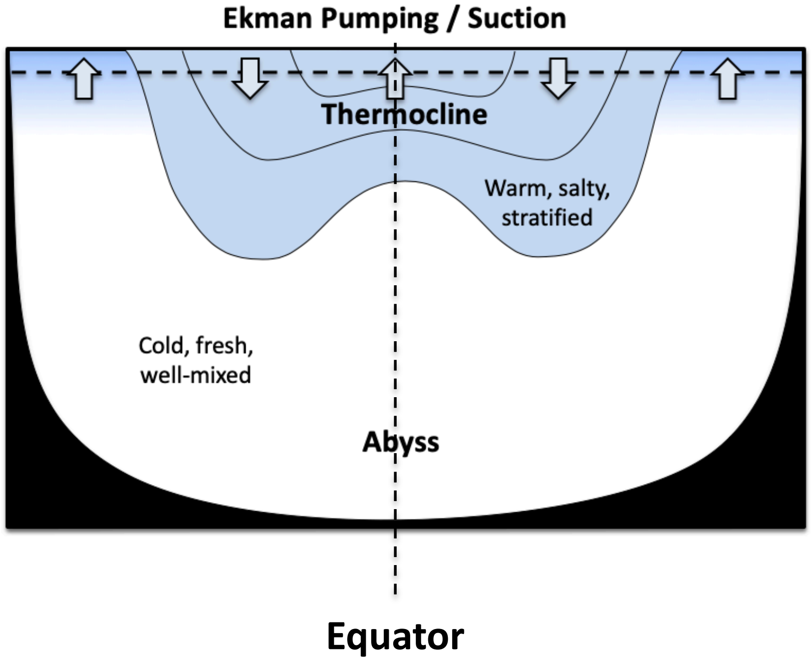
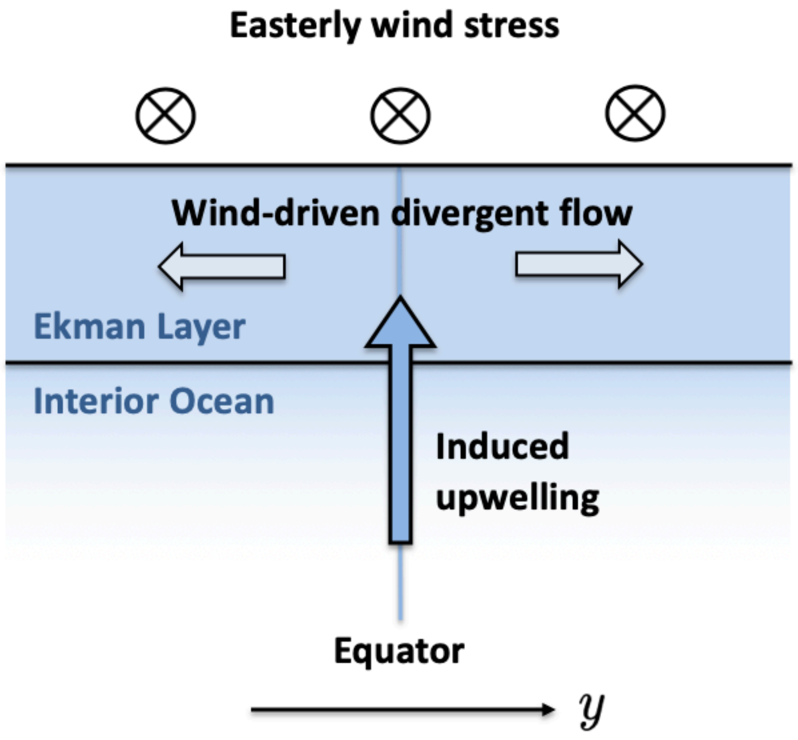


Figure: Schematic meridional cross section of the near-equatorial upwelling induced by westward wind stress at the equator.

The Tropical Ocean

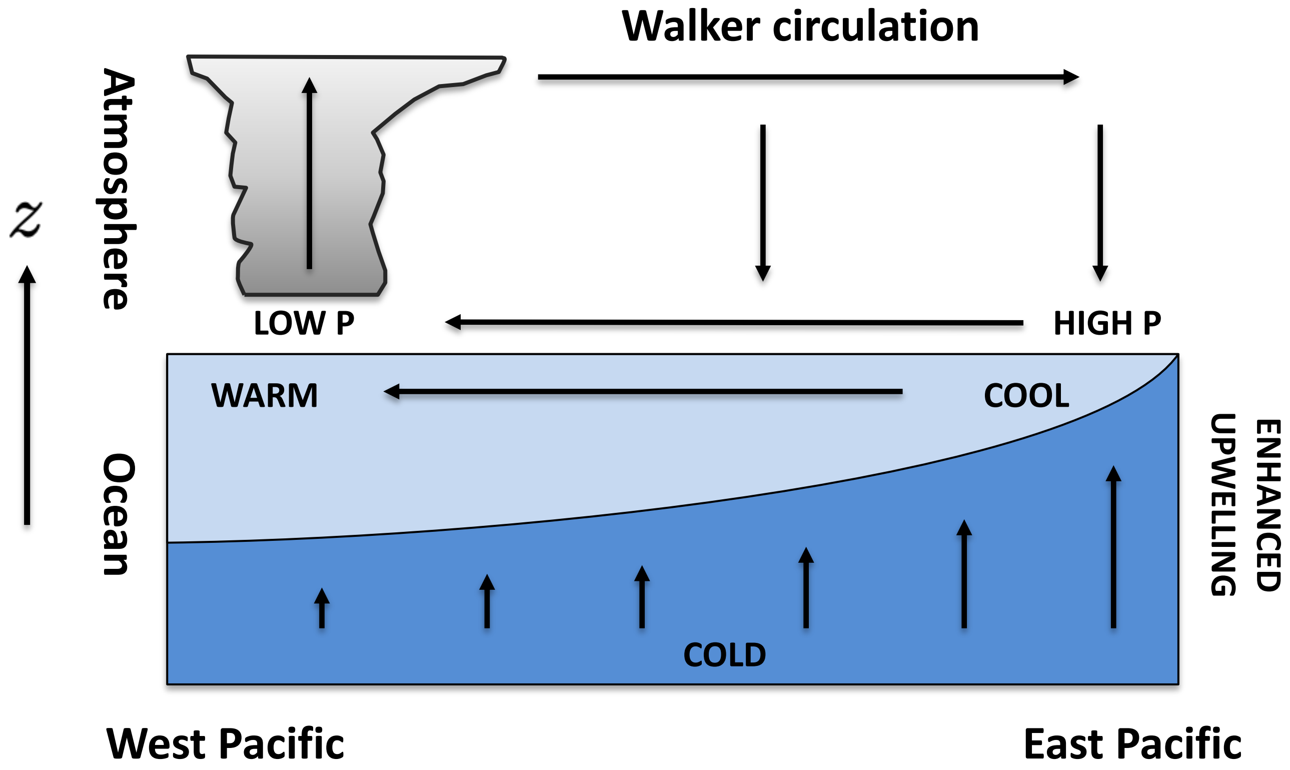
The **equatorial strip is a region of upwelling** since the trade winds drive fluid away from the equator in the surface layer and so demand a supply of water from below.





Air/Sea Interactions in the Tropics

Figure: Since the Pacific ocean is bounded, the westward equatorial current induced by the wind stress “pushes” warm water towards the western Pacific. Meanwhile, upwelling brings cold ocean waters to the surface in the east. This combination leads to a **deeper thermocline in the west** and a **shallower thermocline in the east**.



Air/Sea Interactions in the Tropics

Warmer oceanic temperatures and accumulated waters naturally leads to higher sea levels in the Western Pacific.

A circulation emerges from this pattern where sinking waters in the western Pacific recirculate and rise in the east.

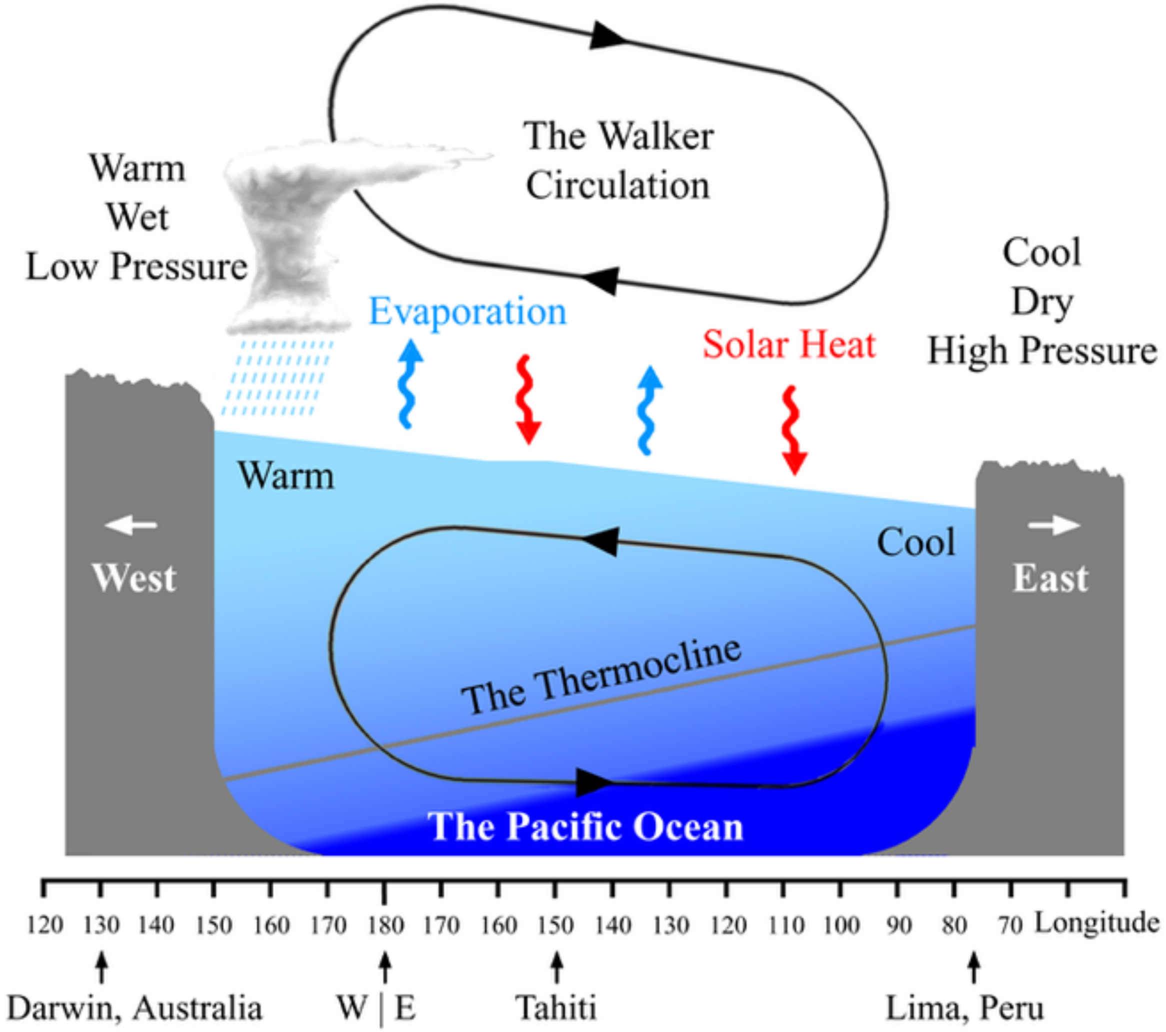


Figure: Schematic diagram of the quasi-equilibrium of the southern oscillation. (Source: Wikipedia)

Air/Sea Interactions in the Tropics

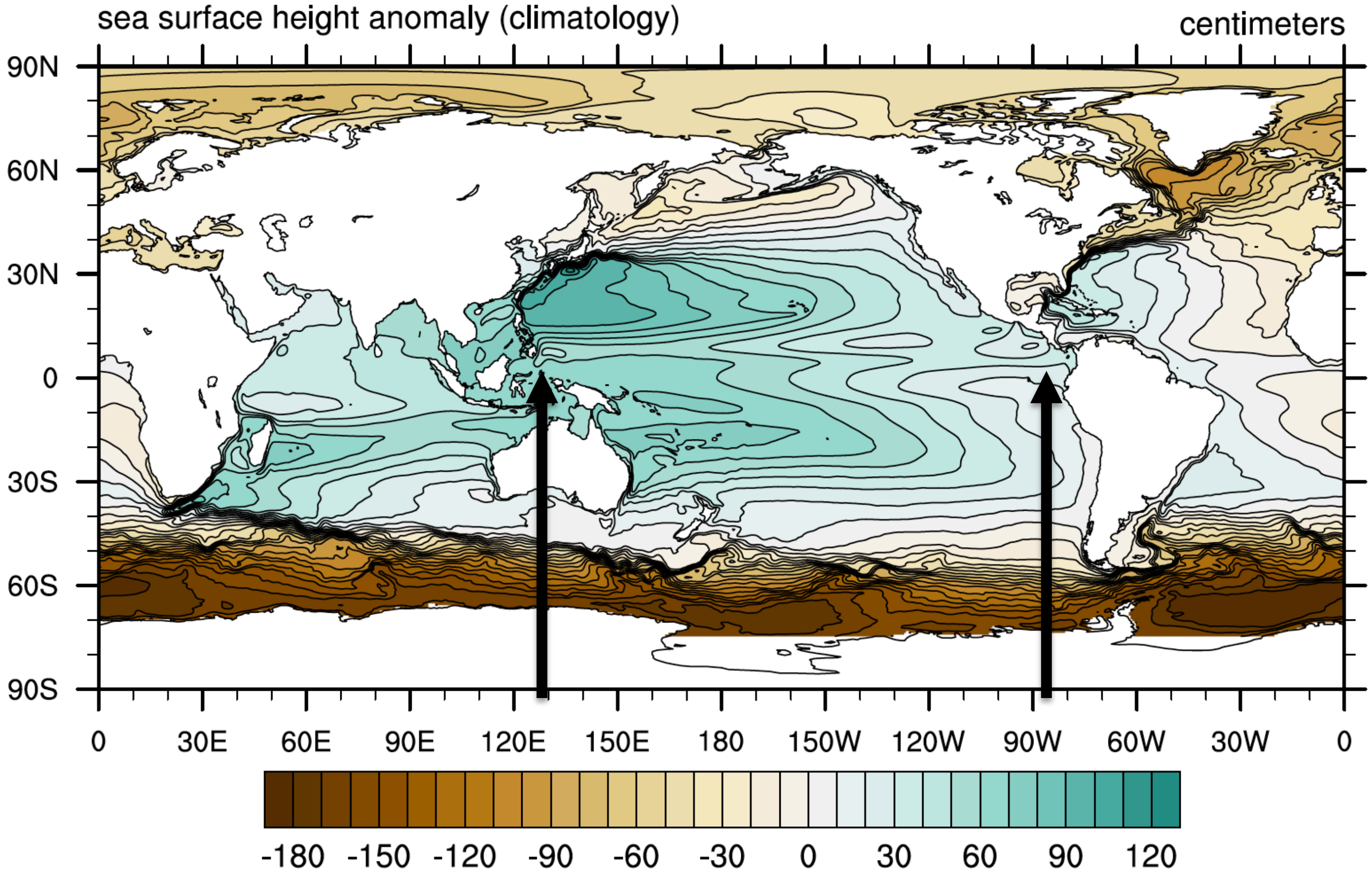


Figure: Easterly winds along the equator leads to warmer ocean temperatures and **enhanced sea surface height** along the western edge of the Pacific basin.

Bjerknes Feedback

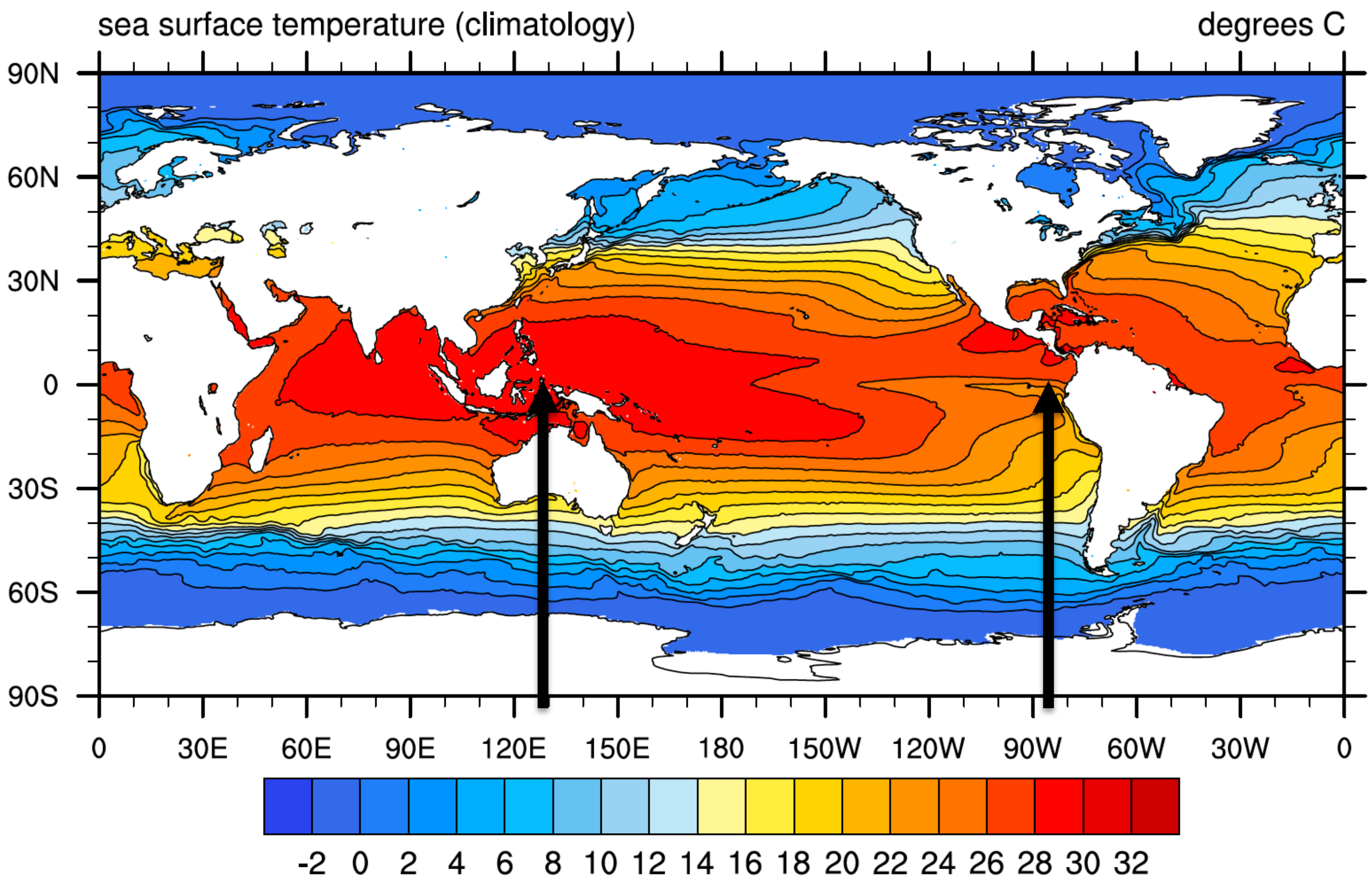


Figure: Easterly winds along the equator leads to **warmer ocean temperatures** and enhanced sea surface height along the western edge of the Pacific basin.

Air/Sea Interactions in the Tropics

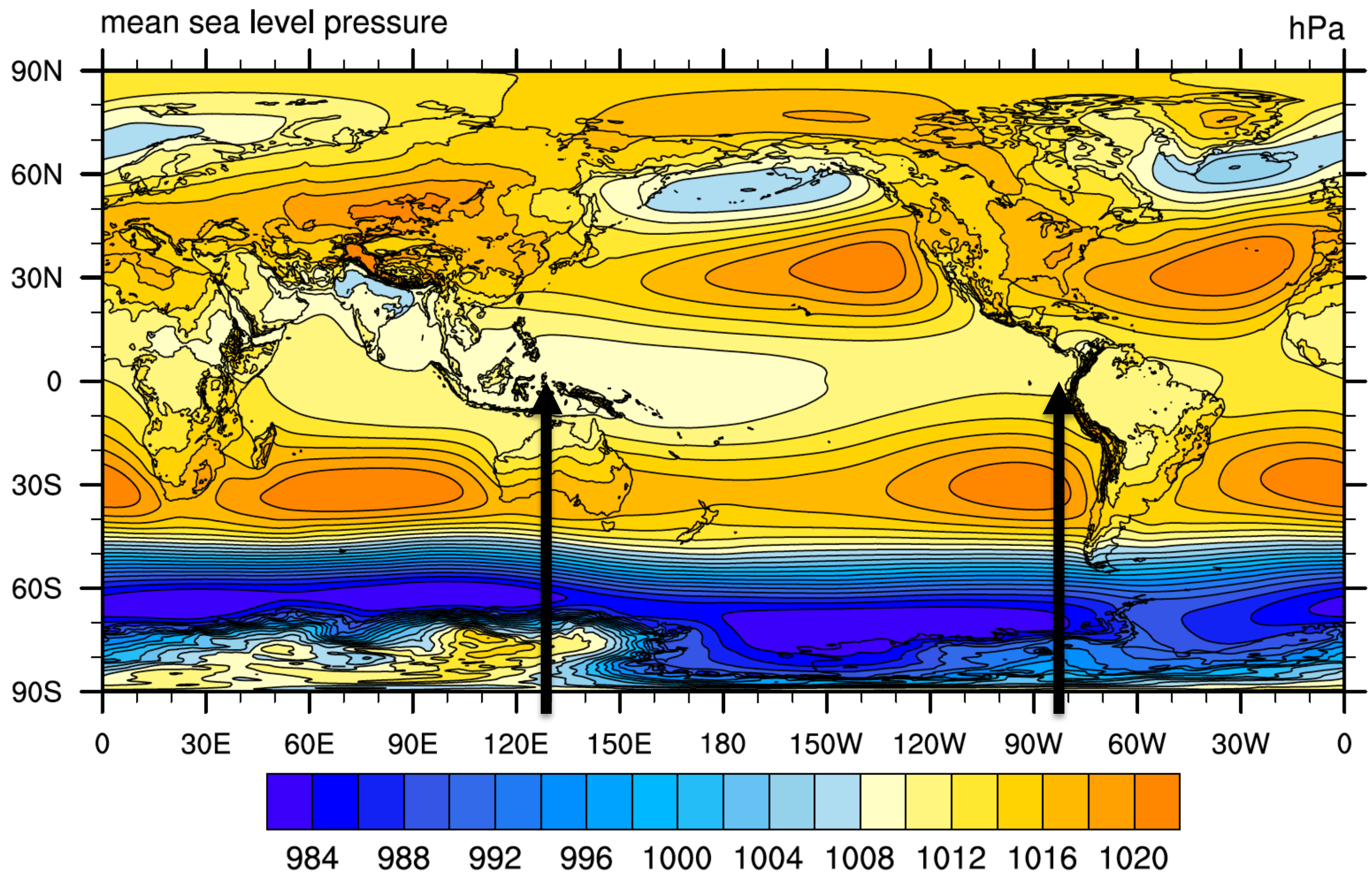
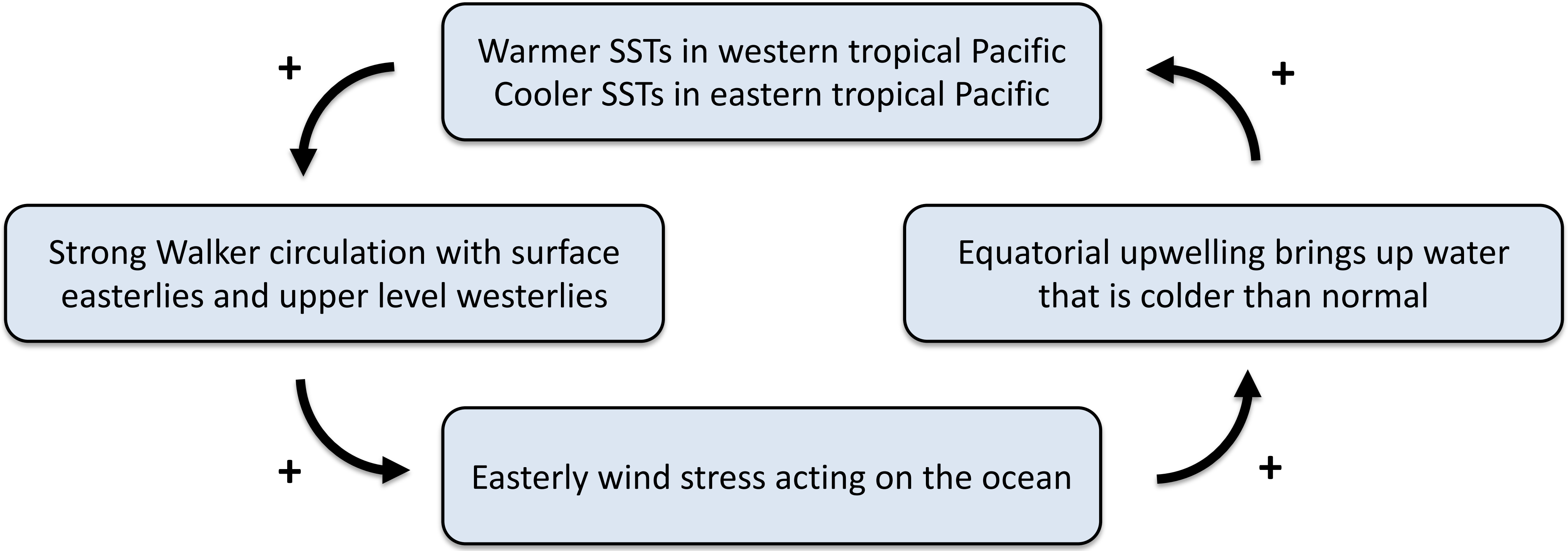


Figure: The presence of warmer surface waters in the west enhances local convection, producing lower surface pressures and driving atmospheric convergence.

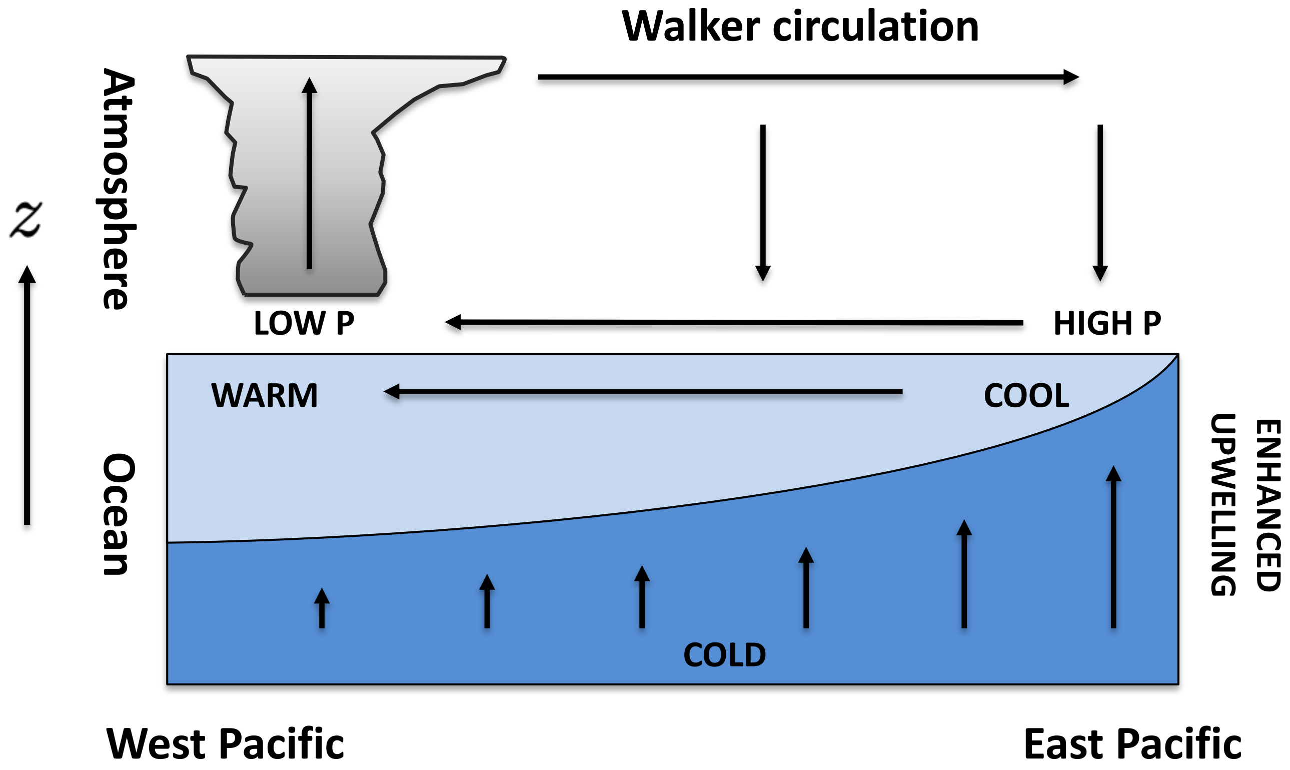
Bjerknes Feedback (Positive Phase)



Definition: The **Bjerknes feedback** refers to the positive feedback cycle in the tropics that is responsible for enhancing the sea surface temperature gradient and amplifying the easterly wind stress.

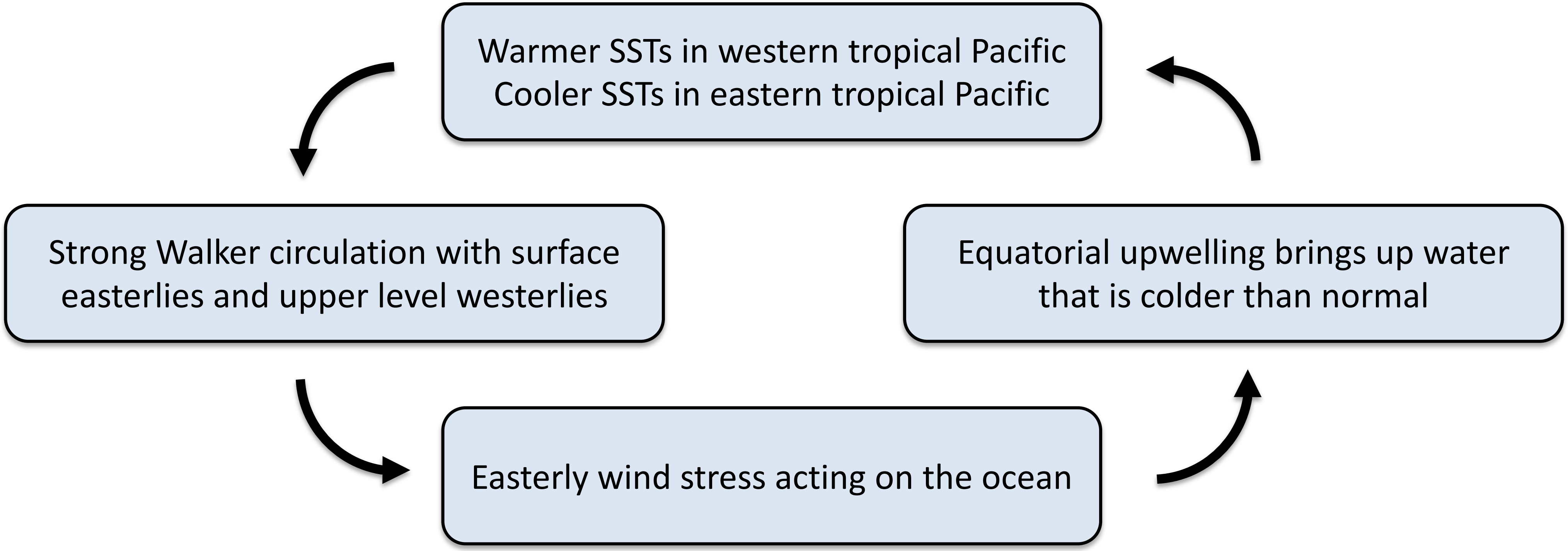
Air/Sea Interactions in the Tropics

Figure: Since the Pacific ocean is bounded, the westward equatorial current induced by the wind stress "pushes" warm water towards the western Pacific. Meanwhile, upwelling brings cold ocean waters to the surface in the east. This combination leads to a **deeper thermocline in the west** and a **shallower thermocline in the east**.



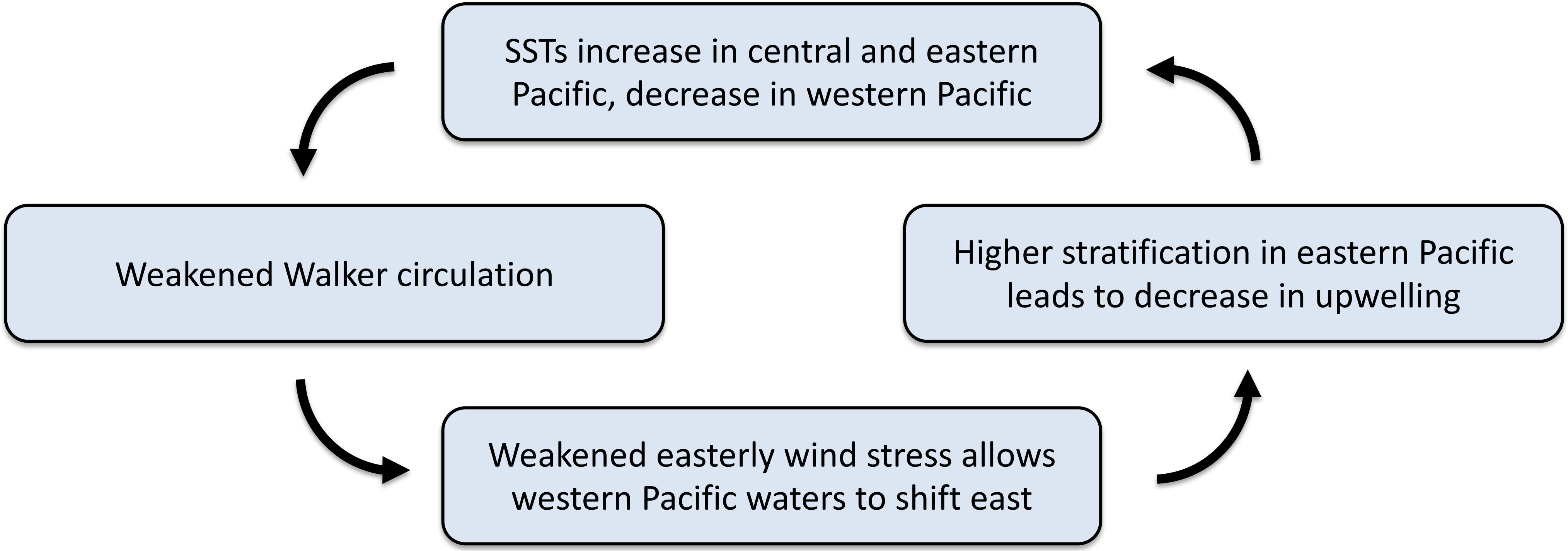
El Niño Southern Oscillation

Bjerknes Feedback (Positive Phase)



Anomalous forcing (either extratropical effects in the atmosphere or a relaxation in the tilt of the thermocline) can interrupt the Bjerknes feedback, driving it in reverse.

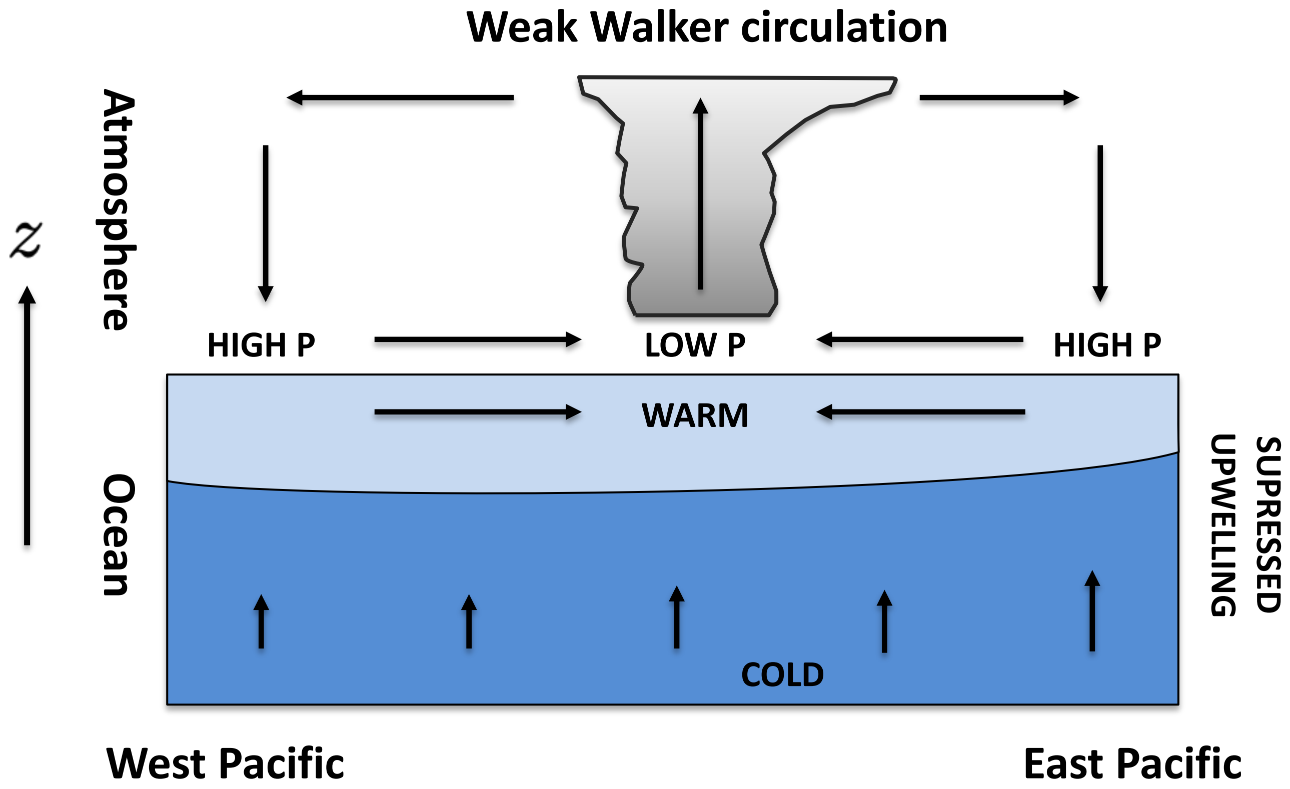
Bjerknes Feedback (Negative Phase)



As the Walker circulation weakens, feedbacks between atmosphere and ocean drive it weaker still.

Equatorial El Niño Conditions

Figure: Under a weakening Walker circulation, eastern wind forcing at the oceanic surface is reduced. Warmer surface waters shift eastward, leading to suppressed upwelling. With warmer waters now in the center of the Pacific, the region of deep convection shifts to this region as well. This combination leads to a **more uniform thermocline across the Pacific**.

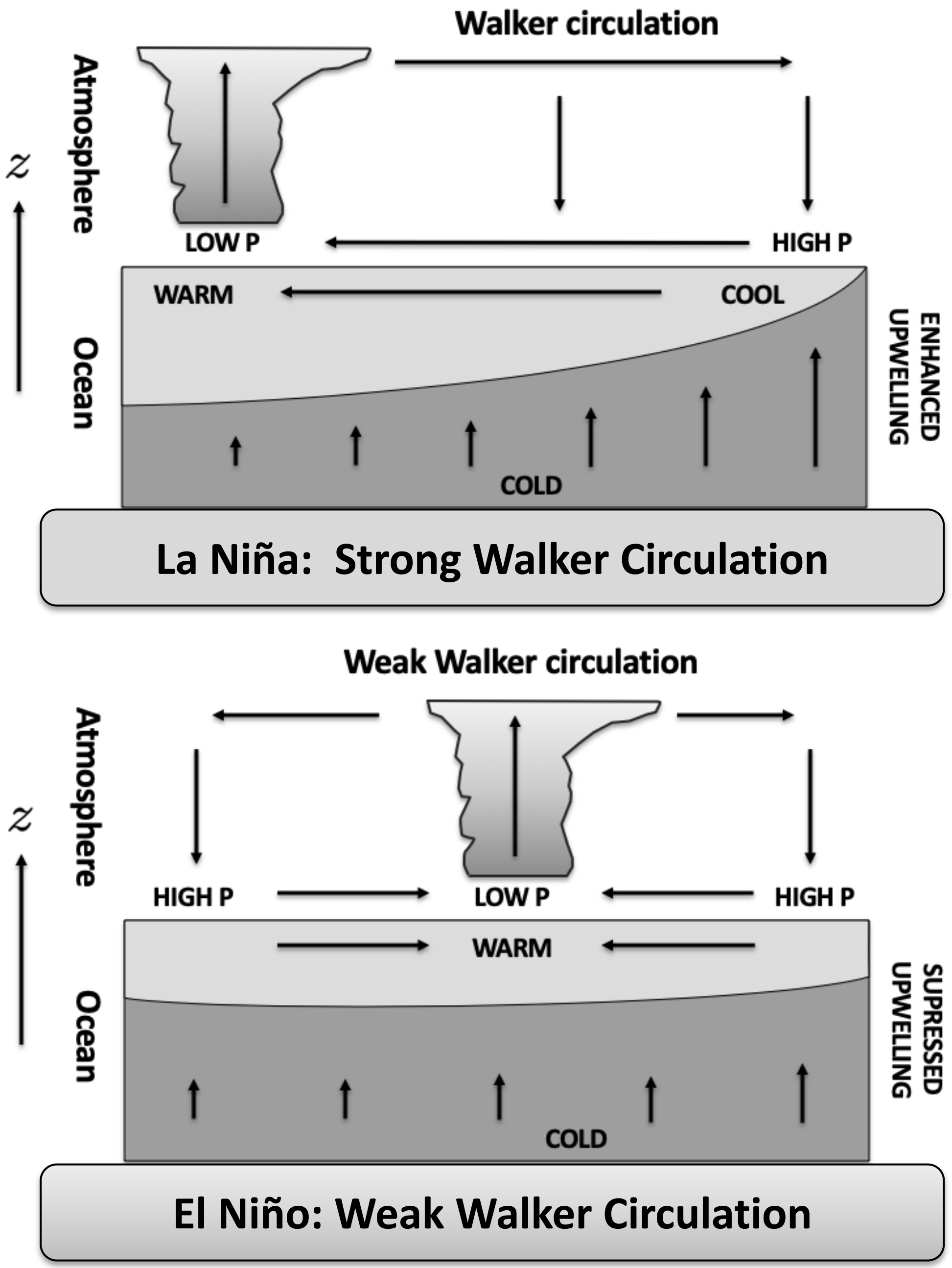


ENSO

Definition: El Niño – Southern Oscillation (ENSO) is a pattern of variation in winds and sea surface temperatures in the tropical Pacific ocean with a period of 2-7 years.

Figure: Schematic of the Pacific ocean-atmosphere system during (top) cold La Niña conditions and (bottom) warm El Niño conditions.

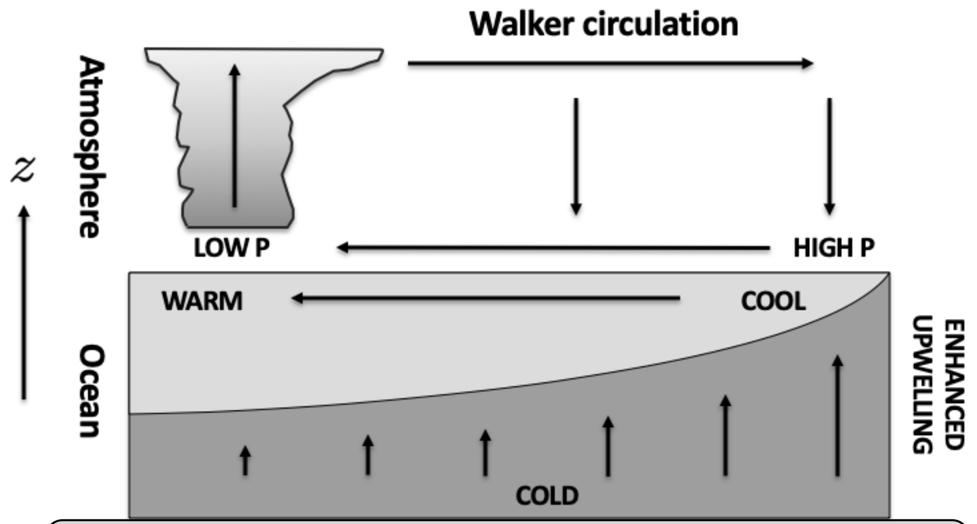
The transition process between these two states occurs because of **mutual interaction of the atmosphere-ocean system**.



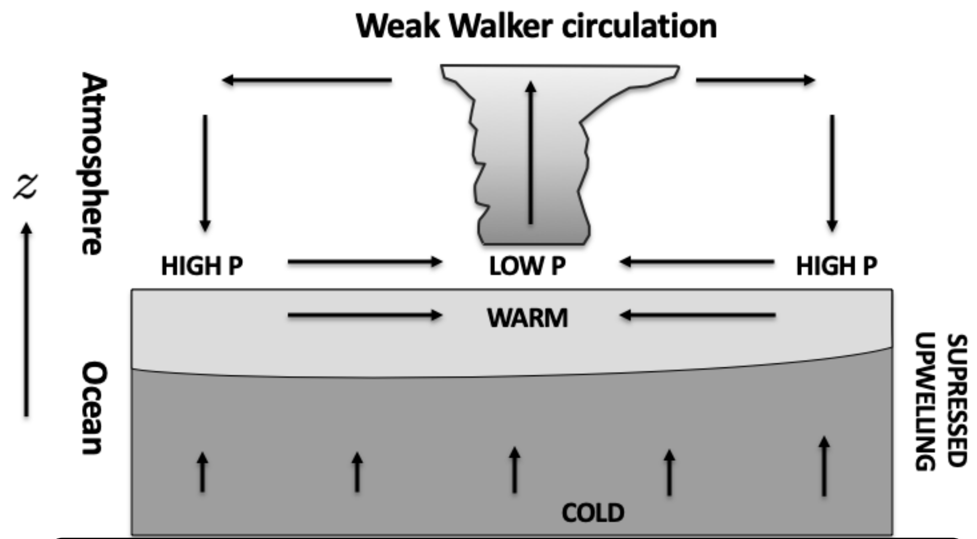
ENSO

Cold La Niña conditions correspond to an enhancement of the “neutral” state of the equatorial Pacific under a strengthening Bjerknes Feedback. Pressure decreases in the west and increases in the central Pacific.

During a warm El Niño event, the warm pool spreads eastward, bringing atmospheric convection with it and weakening the Walker circulation. Pressure increases in the west and decreases in the mid-ocean.



La Niña: Strong Walker Circulation

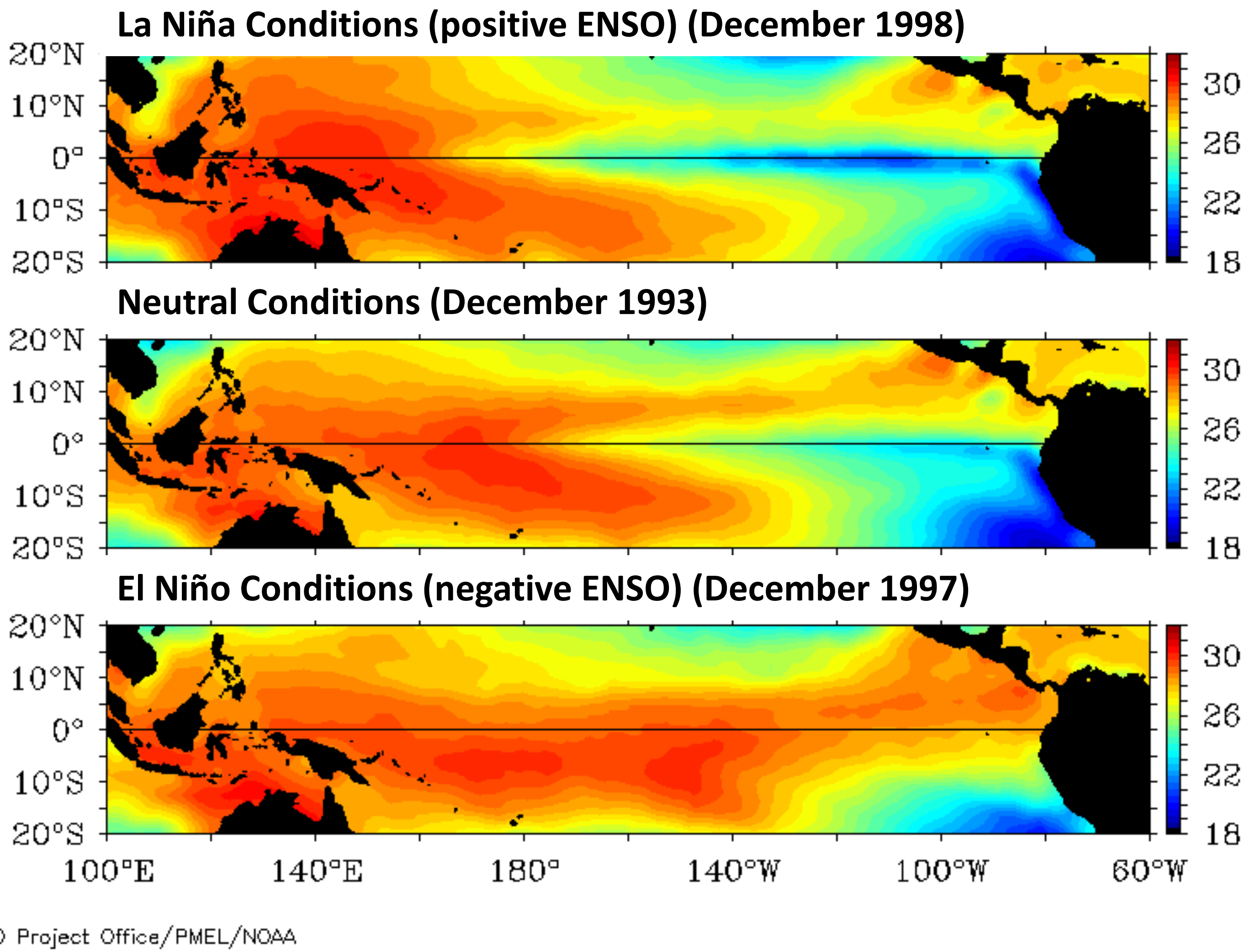


El Niño: Weak Walker Circulation

ENSO Sea Surface Anomalies

Figure: Sea surface temperature anomaly through the tropical Pacific under (top) La Niña conditions, (middle) neutral conditions, and (bottom) El Niño conditions.

Monthly Sea Surface Temperatures °C



El Niño Southern Oscillation

In summary:

- Climatologically average conditions are not necessarily representative of the persistent climatological state of the Pacific.

- In fact, the equatorial Pacific is subject to a non-seasonal variability induced by **enhancement (La Niña)** / **suppression (El Niño)** via the **Bjerknes Feedback**.

- El Niño and La Niña are the warm and cool phases of a recurring climate pattern across the tropical Pacific known as the **El Niño-Southern Oscillation (ENSO)**.

Transition to El Niño

A **weakening of the walker circulation** and/or **eastward movement of the warm pool** is the triggering mechanism for an El Niño event, leading to a process of steps which drive mutual interaction between the atmosphere-ocean system (feedback).

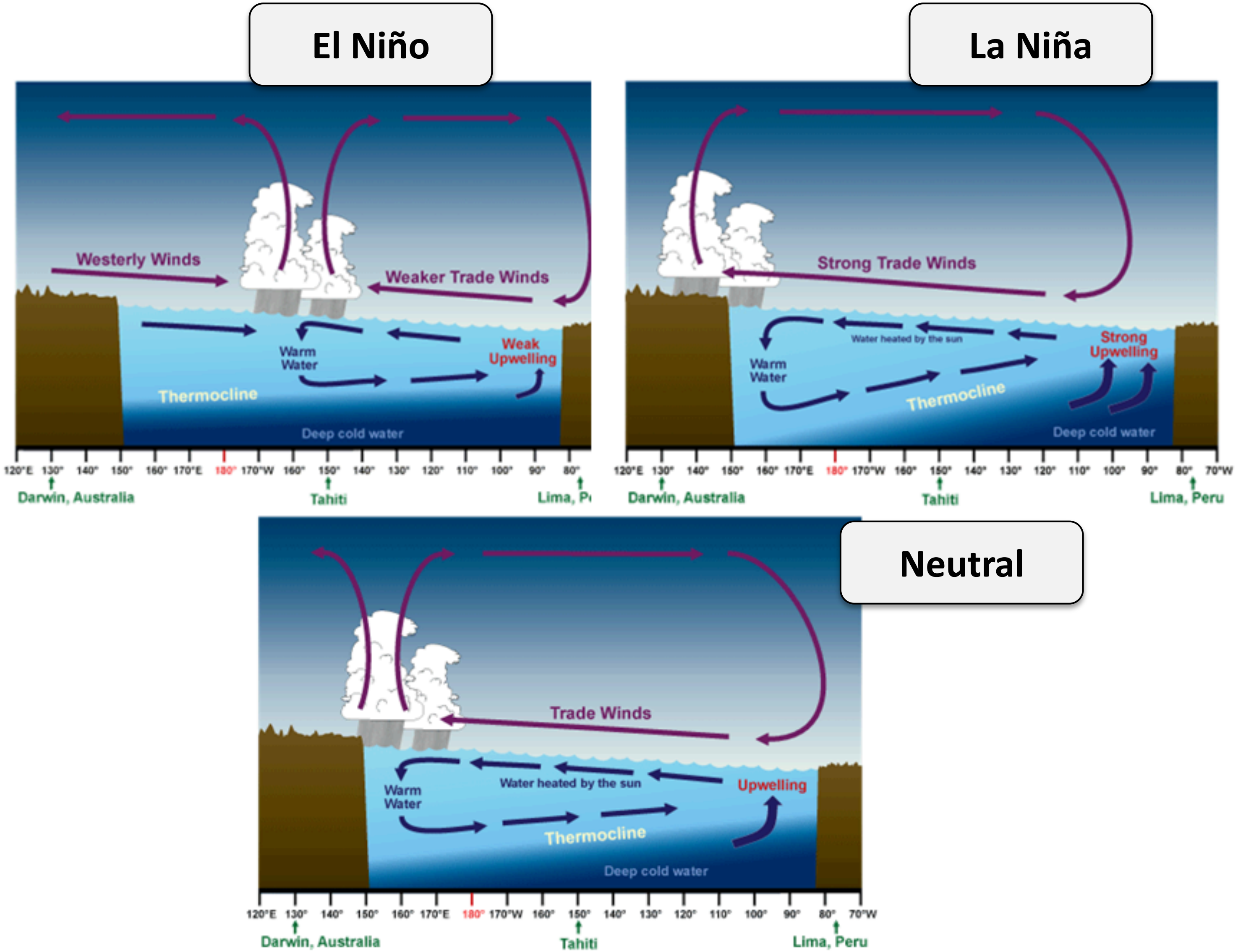
1. **The atmosphere responds to the ocean:** East-west pressure gradient is reduced due to changes to the lower boundary, leading to a weakening of the Walker circulation.

2. **The ocean responds to the atmosphere:** With a weakening wind stress equatorial upwelling is weakened and the thermocline deepens. This raises sea surface temperatures in the East.

The transition from El Niño to La Niña is from running the above feedback in reverse.

El Niño Southern Oscillation

Figure: Another depiction of conditions of the atmosphere and ocean under ENSO.



Southern Oscillation Index

The El Niño Southern Oscillation is usually quantified by the Southern Oscillation Index (SOI).

Definition: The **Southern Oscillation Index (SOI)** is defined as

$$SOI = 10 \times \frac{SLP_{Tahiti} - SLP_{Darwin}}{\sigma}$$

where σ denotes the standard deviation of the pressure difference.

Under this definition **La Niña** (enhanced Darwin SLP) corresponds to the **positive phase** of ENSO and **El Niño** (enhanced Tahiti SLP) corresponds to the **negative phase** of ENSO.

The Trans-Pacific Dipole

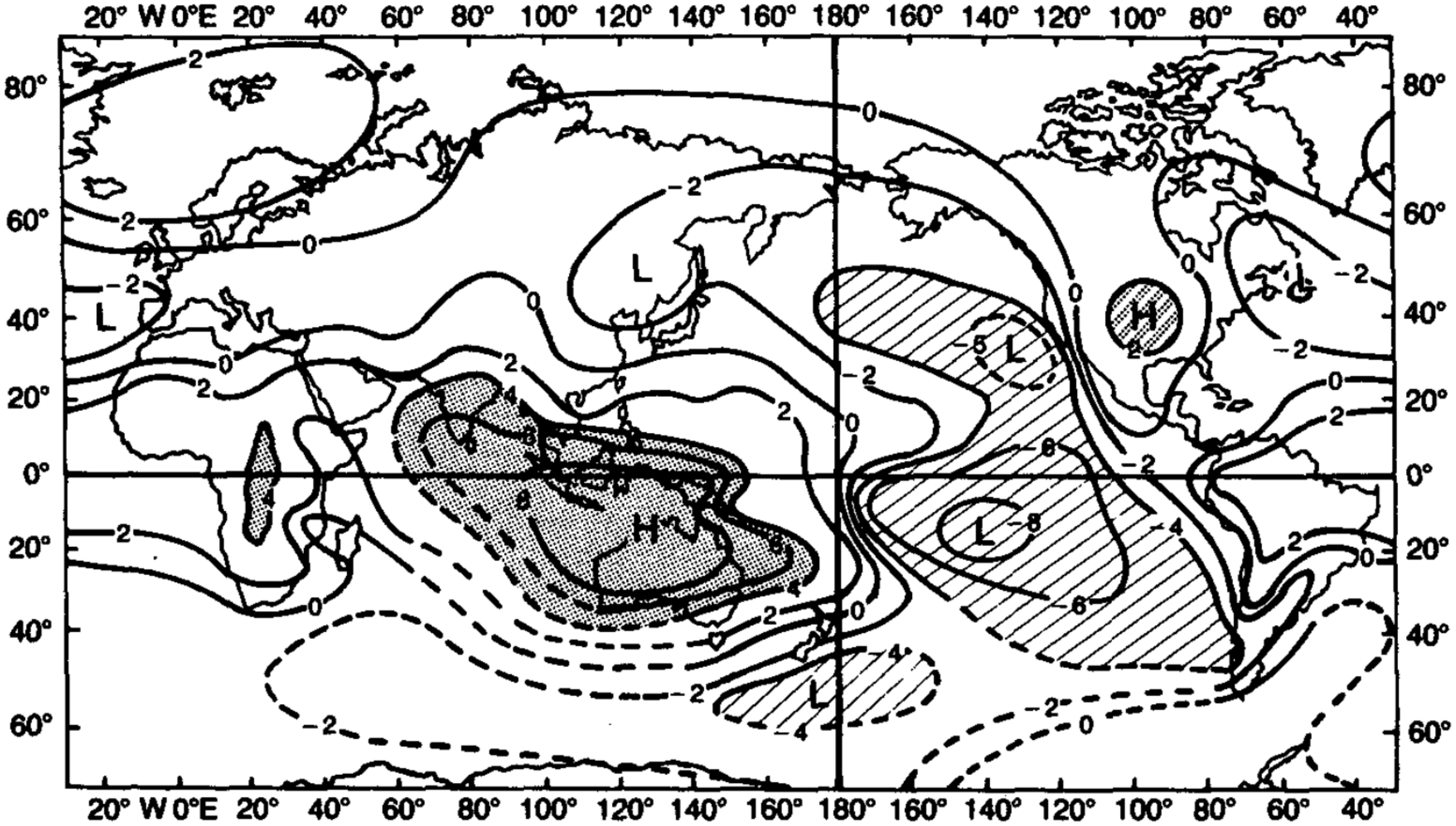


Figure: Correlations of the annual-mean sea level pressure with the SOI (from Trenberth and Shea 1987, Figure 1). Observe that high pressures over Darwin are almost perfectly correlated with low pressures over Tahiti and vice versa.

Southern Oscillation Index

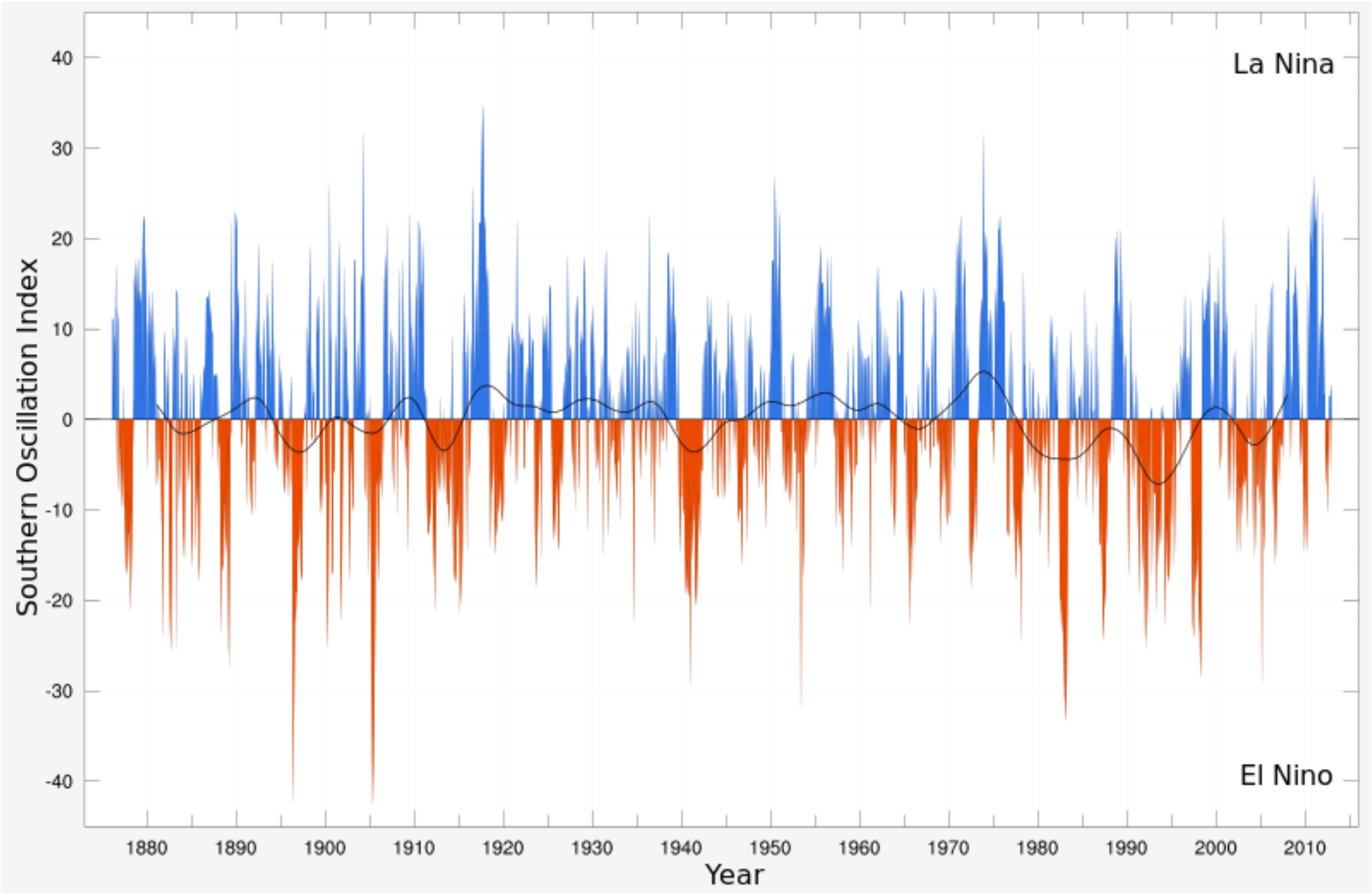


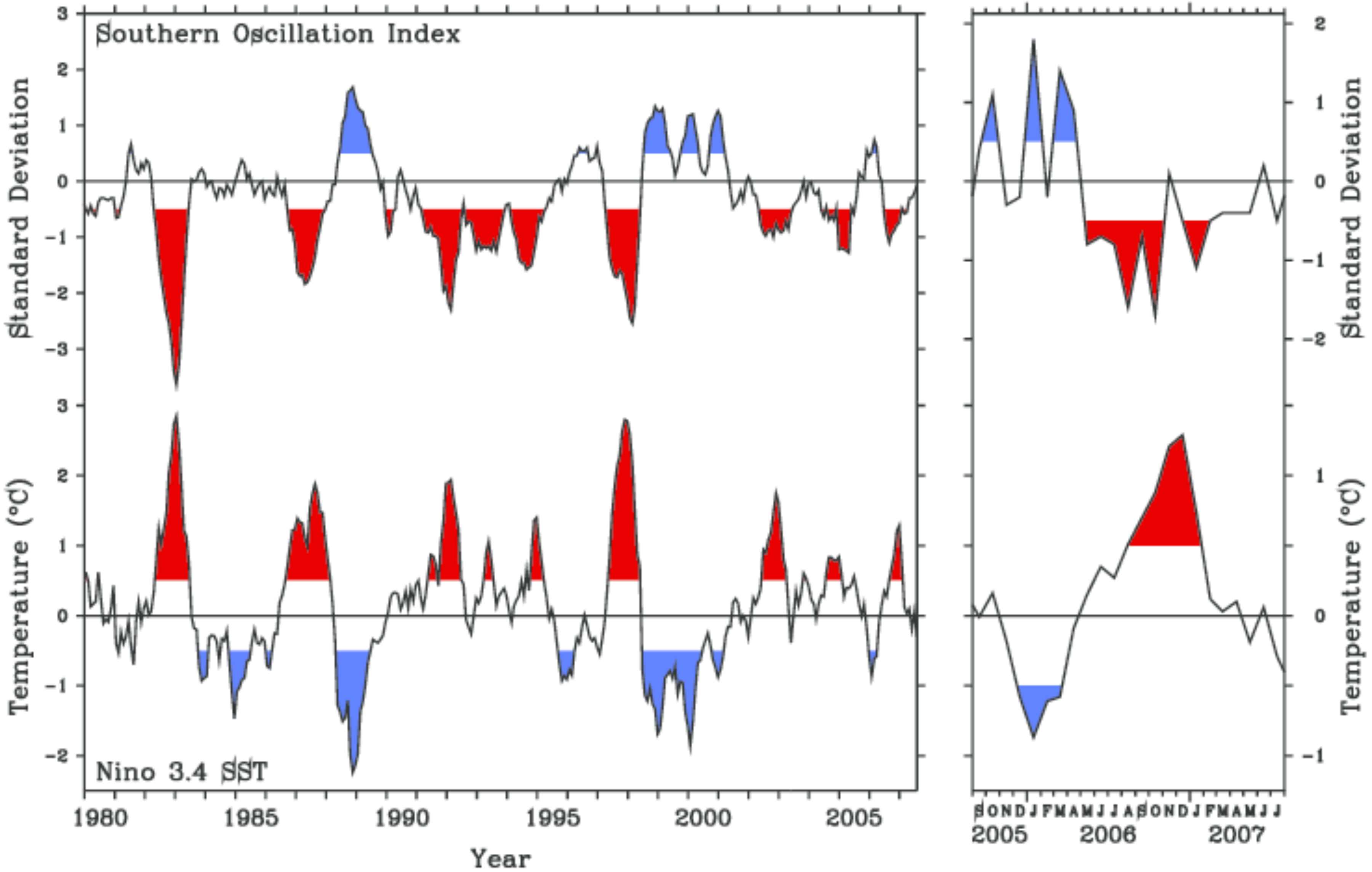
Figure: Southern oscillation index between Tahiti and Darwin, Australia. This index shows persistent but irregular fluctuations on periods of 2-7 years, with a few outstanding events.

Southern Oscillation Index

Figure: The Southern Oscillation Index (SOI, solid) and sea surface temperature in the Nino 3.4 region for the period 1980-2007.

The time series has been filtered to remove short-term oscillations.

Observe: Near perfect anti-correlation between SOI and SST.



El Niño Conditions (DJF)

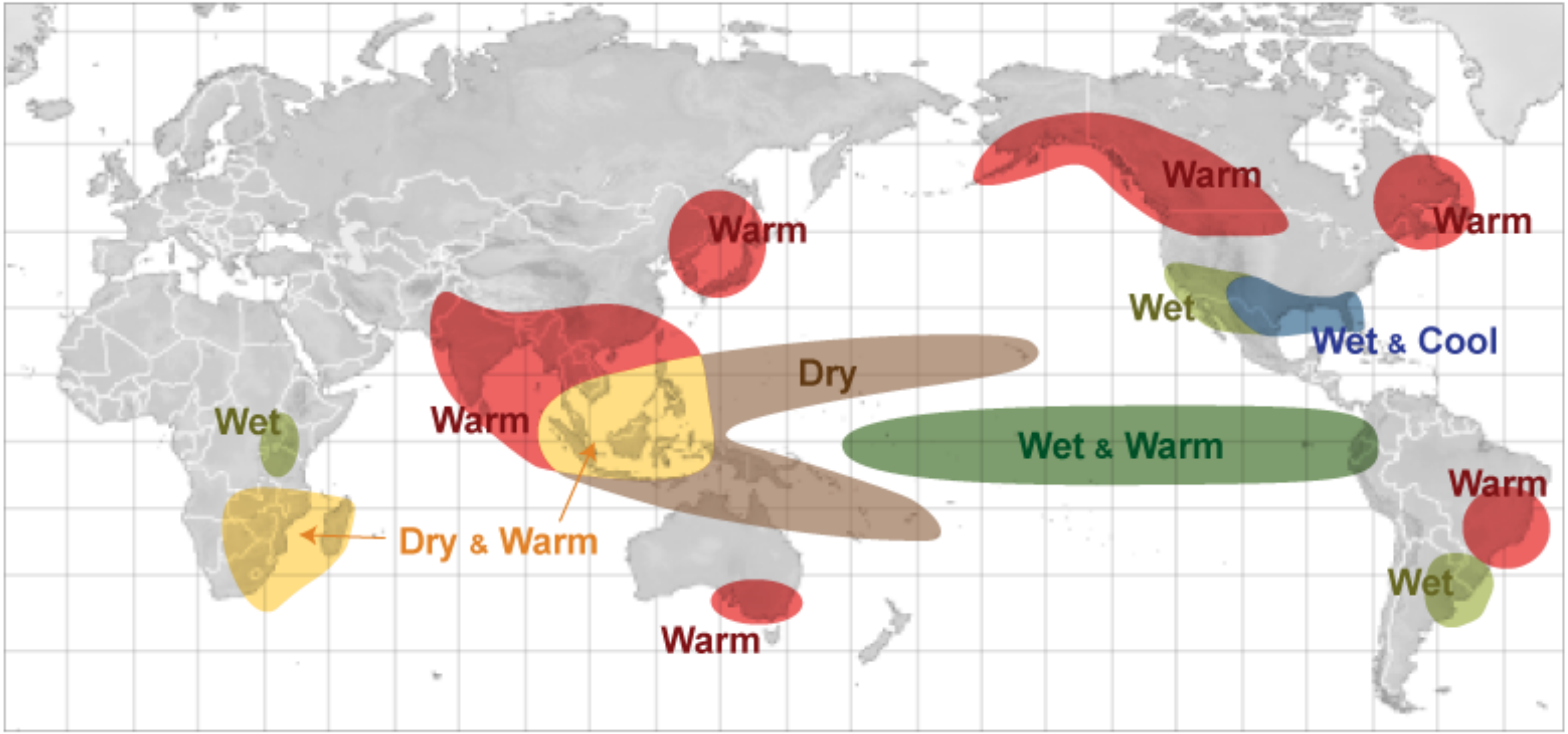


Figure: El Niño impacts for December through February (https://www.weather.gov/jetstream/enso_impacts)

El Niño Conditions (JJA)

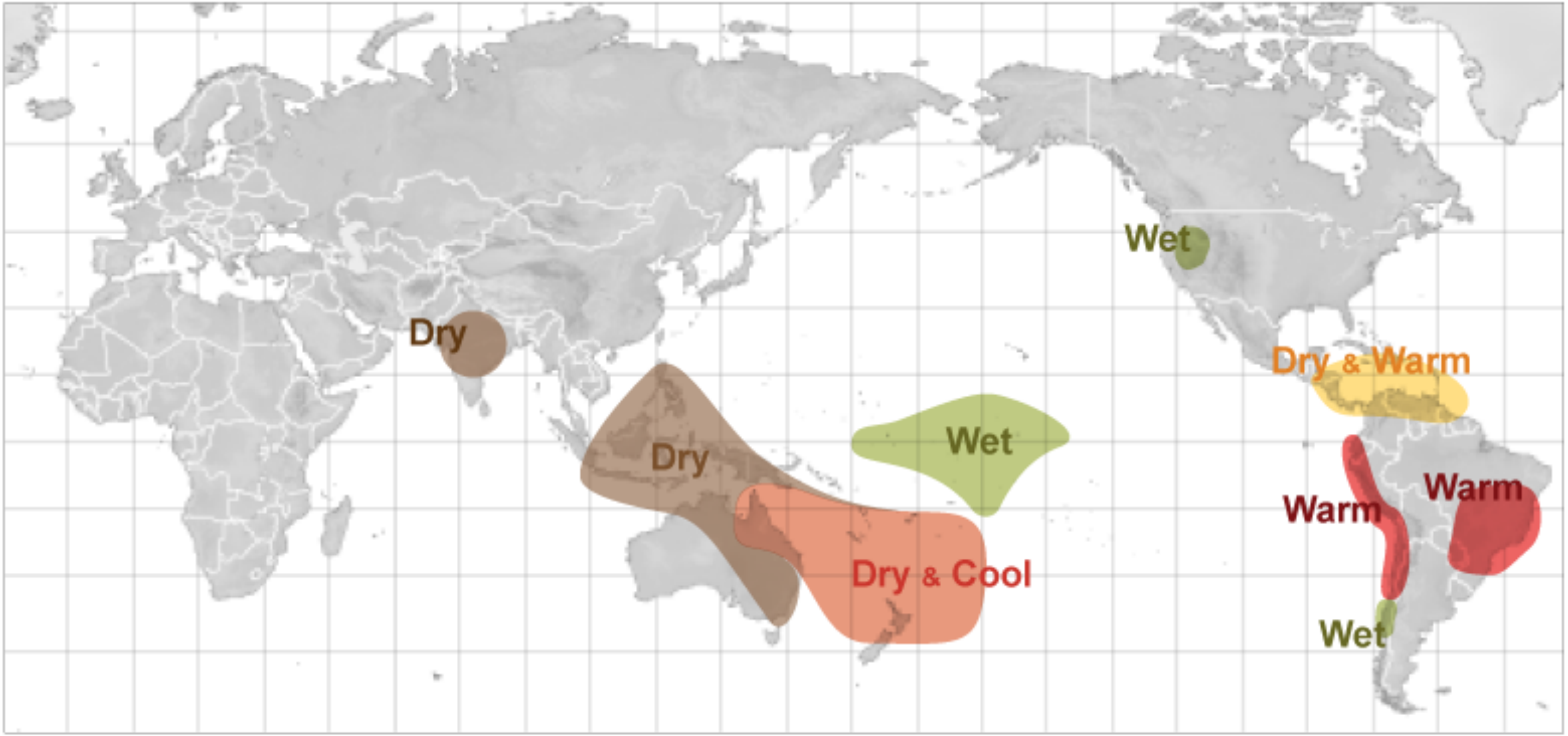
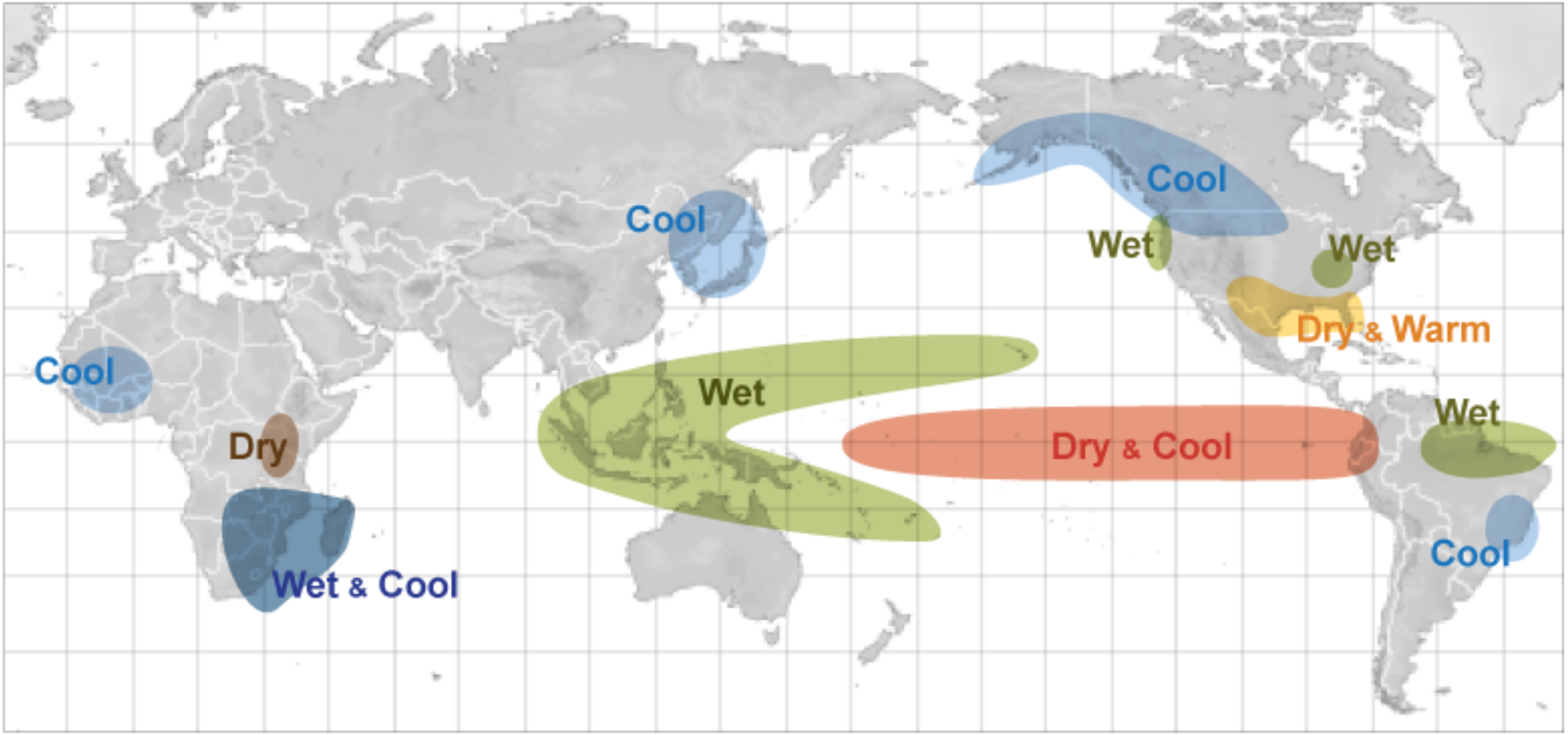


Figure: El Niño impacts for June through August (https://www.weather.gov/jetstream/enso_impacts)

La Niña Conditions (DJF)



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La Niña Conditions (JJA)

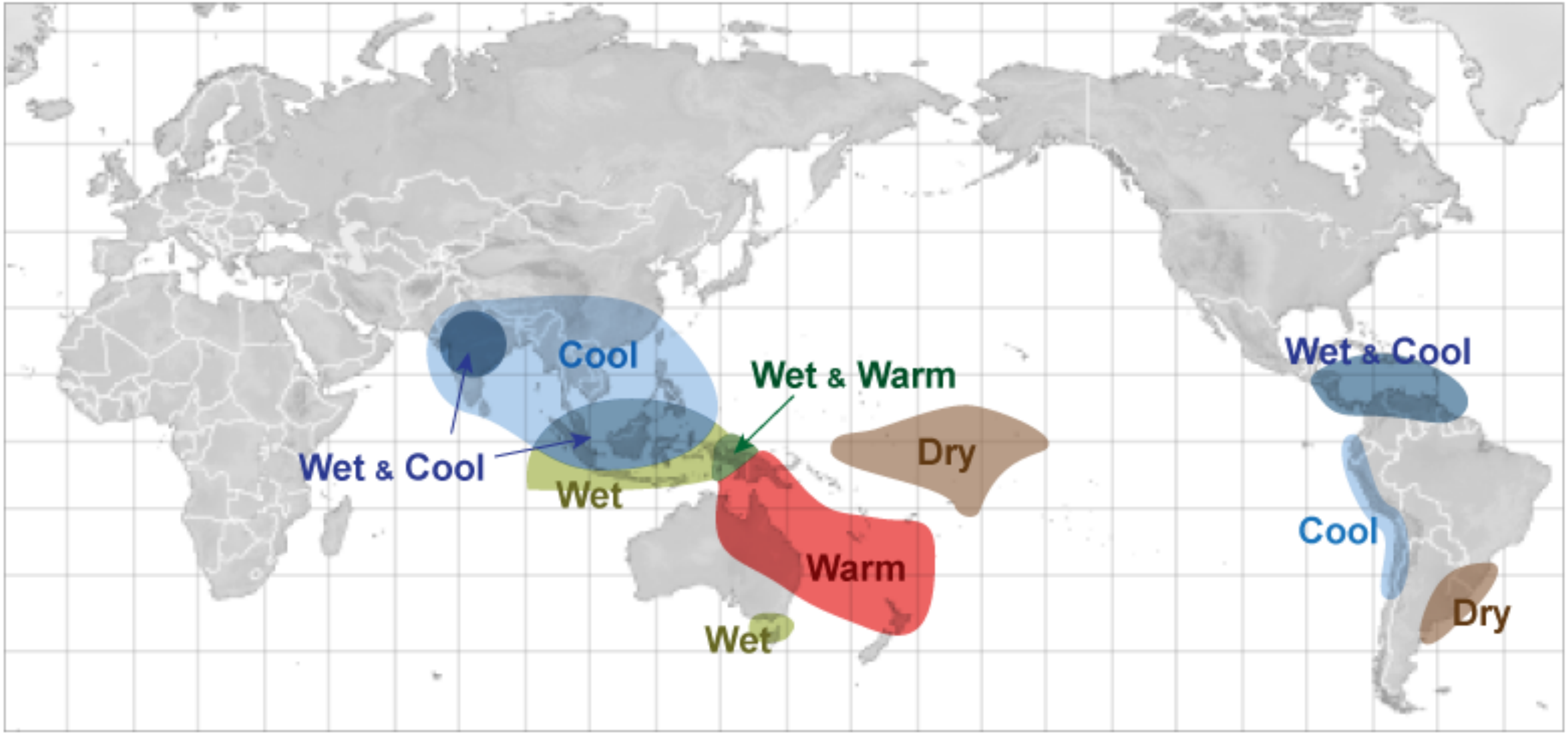
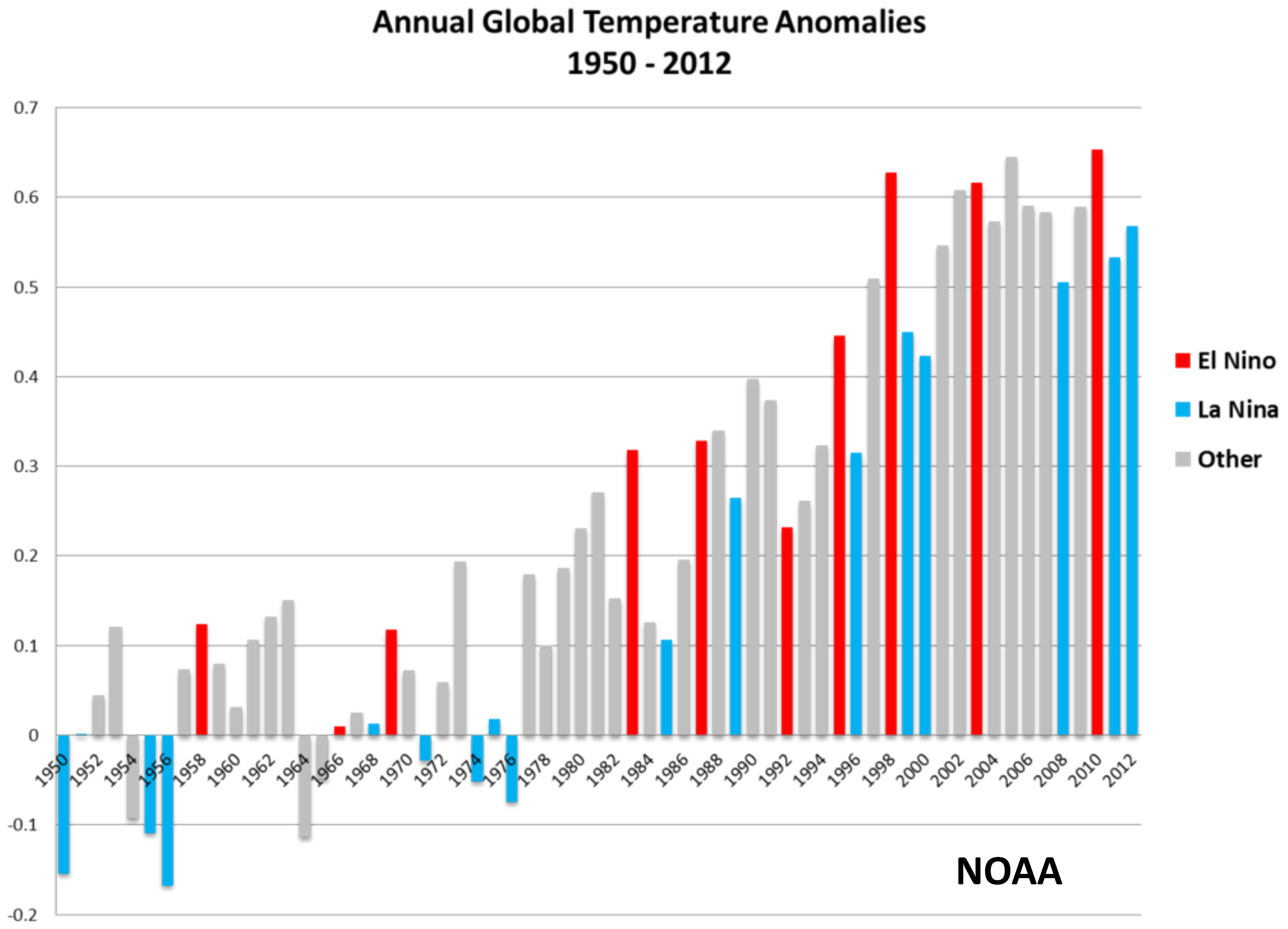


Figure: La Niña impacts for June through August (https://www.weather.gov/jetstream/enso_impacts)

El Niño and Global Temperatures

Figure: Annual global temperature anomalies for years from 1950-2012. El Niño years are shown in red. La Niña years are shown in blue.

The substantial effect of El Niño on global average surface temperature is clearly evident.

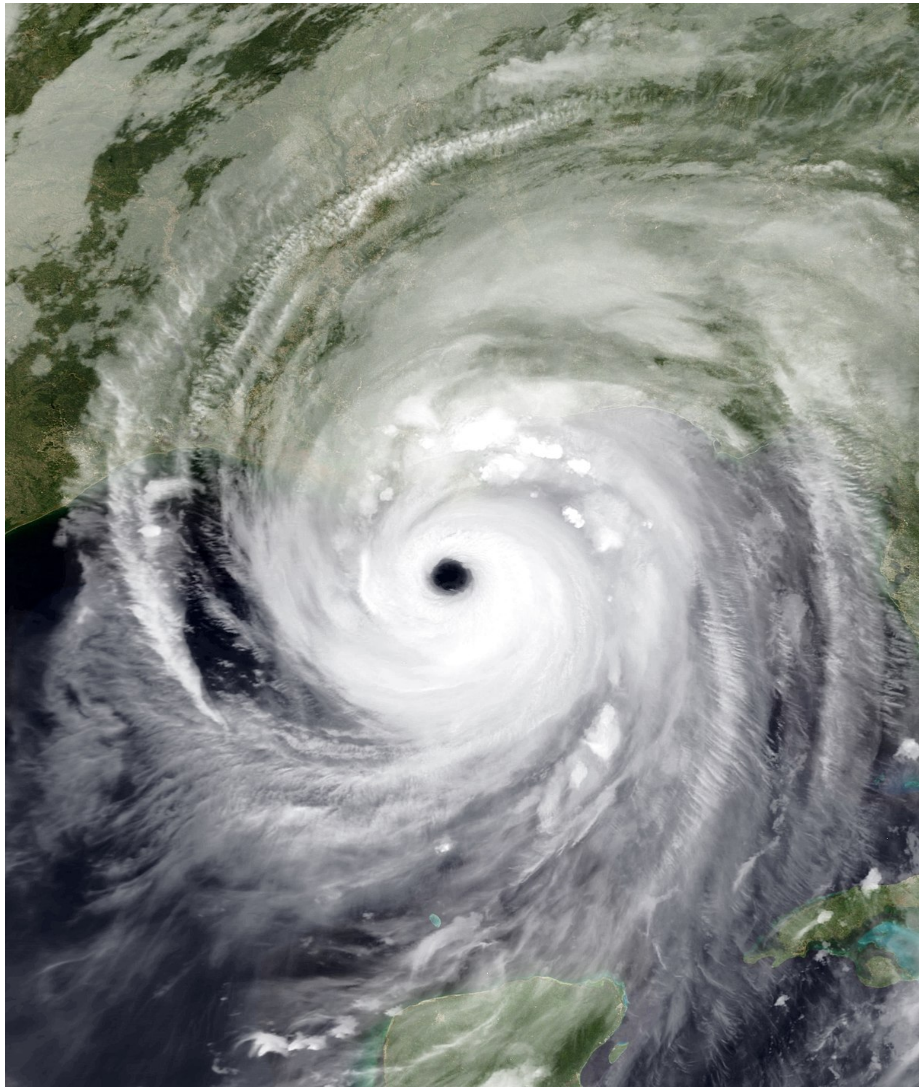


El Niño and Tropical Cyclones

Tropical cyclone activity in the North Atlantic basin is particularly sensitive to El Niño influences. When a moderate to strong El Niño is present, the North Atlantic basin experiences:

- A substantial reduction in cyclone numbers
- A 60% reduction in number of hurricane days
- An overall reduction in system intensity

This change is due to stronger than normal westerly winds during El Niño years.



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Thank You!