El Niño Southern Oscillation

Introduction

The leading mode of interannual (or multiyear) variability in the tropics is the El Niño Southern Oscillation (ENSO). Much research has been undertaken to better understand what ENSO is, how El Niño and La Niña events form and evolve, and how it impacts weather patterns across the tropics and beyond. In this section, we will explore these topics and contextualize the Walker circulation's interannual variability in terms of ENSO.

Key Questions

- What is the atmospheric component of the El Niño Southern Oscillation?
- What is the oceanic component of the El Niño Southern Oscillation?
- What are the similarities and differences between commonly used methods for identifying and tracking the evolution of the El Niño Southern Oscillation?
- How do diabatic heating shifts associated with the El Niño Southern Oscillation influence tropical and midlatitude weather patterns?
- How does anomalously weak upwelling contribute to the development of anomalously warm ocean temperatures in the central and eastern equatorial Pacific Ocean associated with El Niño?

The El Niño Southern Oscillation (ENSO)

ENSO is a coupled atmosphere-ocean system associated with an oscillatory redistribution of oceanic heat and atmospheric momentum in the equatorial Pacific Ocean. The term "coupled" means that the atmosphere and ocean work in harmony with one another, with forcing in one modulating the other and vice versa. The Southern Oscillation refers to the atmospheric component of ENSO and reflects shifts in patterns of sea-level pressure across the tropical Pacific that occur in conjunction with El Niño (warm) and La Niña (cold) ENSO phases. El Niño and La Niña refer to ENSO's oceanic component and are characterized by shifts in patterns of near-surface ocean temperatures in the equatorial Pacific Ocean. Both represent the leading form of variability in the Pacific Ocean branch of the Walker circulation.

El Niño and La Niña both cause and are caused by variations in the strength of the easterly trade winds. El Niño is characterized by weakened or reversed trade winds, which warms the equatorial near-surface ocean temperatures in the eastern and central equatorial Pacific Ocean. Conversely, La Niña is characterized by strengthened trade winds, which cools equatorial near-surface ocean temperatures in the eastern and central tropical Pacific Ocean. Transitions between El Niño and La Niña are quasi-oscillatory and recur roughly every 2-5 years. However, no two pairs of El Niño and La Niña events are alike, there is no guarantee that an El Niño event will immediately be followed by a La Niña event, and transitions from El Niño to La Niña typically occur more rapidly than transitions from La Niña to El Niño.

Trade winds modulations drive ocean temperature changes through their impacts to Ekman transport along the Equator. Recall that the climatological easterly trade winds result in equatorial upwelling due to Ekman transport. Stronger easterly trade winds induce a stronger Coriolis deflection (which is directly proportional to the atmospheric wind or oceanic current speed), in turn resulting in stronger Ekman transport. As a result, stronger easterly trade winds are associated with stronger equatorial upwelling with La Niña. Conversely, weakened trade winds induce a weaker Coriolis deflection, in turn resulting in weaker Ekman transport and thus weaker equatorial upwelling with El Niño. If the trade winds become westerly, the sign of the Coriolis deflection changes, resulting in equatorial downwelling and warmer near-surface ocean temperatures with stronger El Niño events!

The Southern Oscillation was first discovered by Sir Gilbert Walker, using the same sea-level pressure data from Darwin, Australia and Tahiti from which he identified the Walker circulation. The long-term-average of these data identify the Walker circulation, whereas interannual variations in these data identify ENSO.

The Southern Oscillation can be quantified using the difference in sea-level pressure between Darwin and Tahiti, known as the Southern Oscillation Index (SOI):

$$SOI = \frac{10(p_{diff} - \overline{p_{diff}})}{\sigma(\overline{p_{diff}})} \quad (1)$$

p_{diff} is the difference in monthly averaged sea-level pressure between Tahiti and Darwin, which is computed as the value at Tahiti (central Pacific) minus that at Darwin (far western Pacific). Climatologically, warmer ocean temperatures are found at Darwin than at Tahiti. Due to surface sensible heating, this results in lower sea-level pressures (from thickness arguments) at Darwin than at Tahiti. Thus, the climatological p_{diff}, given by $\overline{p_{diff}}$, is positive. $\sigma(\overline{p_{diff}})$ is the standard deviation of the climatological p_{diff}, with the leading 10 being a scaling factor. The SOI has units of tenths of standard deviations above or below normal.

During El Niño events, near-surface ocean temperatures are warmer than normal at Tahiti. This results in a lower-than-normal sea-level pressure in Tahiti, in turn reducing the value of p_{diff}. As a result, El Niño events are characterized by a negative numerator in (1) and thus by a negative SOI. Conversely, near-surface ocean temperatures are colder than normal at Tahiti during La Niña events. This results in a higher-than-normal sea-level pressure in Tahiti, in turn increasing the value of p_{diff}. As a result, La Niña events are characterized by a positive numerator in (1) and thus by a positive SOI.

Other indices are commonly used to monitor ENSO and its evolution. These include, but are not limited to, the following:

- **The Oceanic Niño Index (ONI) -** Computed as the three-month average of sea-surface temperature departures from normal across the central equatorial Pacific Ocean between 120°-170°W. El Niño events are characterized by a positive ONI ≥ 0.5°C; La Niña events are characterized by a negative ONI ≤ -0.5°C. These criteria must be exceeded for five or more months for an event to be classified as either El Niño or La Niña.

- **The Japanese Meteorological Agency (JMA) Index -** Computed similarly to the ONI, except between 150°-90°W and with a five-month (rather than three-month) running average. The ± 0.5°C criterion must be met for at least six consecutive months, including October through December, for an event to be classified as either El Niño or La Niña.

- **Equatorial SOI Index -** Akin to the SOI, except using the area-averaged monthly mean sea-level pressure over the regions bounded by 80°W-130°W, 5°N-5°S and 90°E-140°E, 5°N-5°S rather than Tahiti and Darwin, respectively.

- **Multivariate ENSO Index (MEI)** – The MEI is based on the leading combined mode of variability of five variables (sea-level pressure, sea-surface temperature, 10-m zonal and meridional wind, and outgoing longwave radiation) over the tropical Pacific Ocean averaged over two-month periods.

No single index represents all ENSO variability, but most capture a substantial part of this variability. The greatest differences between indices comes through the regions over which they are calculated, particularly in terms of the longitudes considered. The region considered by the ONI is the most commonly used region, but it is not always able to fully represent ENSO events because different El Niño and La Niña events have different longitudinal extents.

Impacts of ENSO on Tropical and Midlatitude Weather Patterns

On average, ENSO's greatest impacts are seen in the equatorial Pacific and are most significant during the local winter months. El Niño events bring heavy precipitation and flooding to northwestern South America; however, the associated anomalous oceanic warmth leads to reduced oceanic wildlife populations that are vital to coastal South America's economies. El Niño events are also often associated with anomalously dry conditions in southeast Asia and northern Australia. La Niña events are often characterized by the inverse of El Niño events, with anomalous cold and dryness near South America and anomalous wetness near Asia and Australia. Since La Niña more closely resembles the climatological coupled ocean-atmosphere system, anomalies associated with El Niño are typically more climatically and societally significant.

ENSO can also influence tropical weather outside of the equatorial Pacific. Perhaps the most significant of these influences occurs with tropical-cyclone activity in the eastern North Pacific and North Atlantic basins. El Niño typically results in less tropical cyclones in the North Atlantic and more tropical cyclones in the eastern North Pacific, whereas La Niña typically results in more tropical cyclones in the North Atlantic and less tropical cyclones in the eastern North Pacific.

El Niño and La Niña impact higher-latitude weather patterns by modulating the mean Rossby-wave pattern across the Pacific Ocean toward the Americas. El Niño and La Niña modify the locations and intensities of oceanic sensible heating and atmospheric latent heating in the equatorial Pacific Ocean:

- **El Niño**: Weakened easterly trade winds result in the maximum oceanic sensible warming being displaced from the western to the central equatorial Pacific Ocean. Both are associated with the displacement of the Walker circulation's ascending branch to the central equatorial Pacific Ocean, resulting in atmospheric latent warming becoming displaced here as well.
- **La Niña**: Strengthened easterly trade winds enhance upwelling in the eastern equatorial Pacific Ocean, resulting in a larger zonal ocean temperature gradient across the Pacific. This strengthens the Walker circulation while maintaining its climatological positioning, resulting in increased atmospheric latent warming where it is typically located.

These forms of diabatic heating incite Rossby-wave trains that propagate poleward with increasing eastward deflection along great-circle routes at higher latitudes. Changes in the intensity and position of the Walker circulation's ascending branch also change the Hadley cell's poleward branch and subtropical jet.

In the Northern Hemisphere, El Niño shifts the wintertime subtropical jet stream equatorward, thus shifting the mean storm track southward and increasing rainfall in the southern United States, Central America, and the Caribbean. Conversely, La Niña shifts the wintertime jet stream and mean storm track northward, thus decreasing rainfall in these same regions while increasing precipitation in the Pacific Northwest and Alaska. The impact of ENSO is mitigated with continued eastward progression across North America as the Rossby-wave train weakens and modes of Atlantic Ocean variability become dominant.

Dynamical Theories for El Niño and La Niña Events

El Niño onset can be characterized by anomalously weak easterly or anomalous westerly trade winds. These anomalous winds form in response to some poorly understood external forcing and manifests as a *westerly wind burst*. Westerly wind bursts are characterized by 10-m zonal-wind anomalies of 5 m s^{-1} or greater over at least 10° longitude for at least two days.

One ENSO theory, the "delayed oscillator" theory, purports that a persistent westerly wind burst generates an eastward-propagating downwelling *oceanic* Kelvin wave. Oceanic Kelvin waves share some similarities with their atmospheric counterparts, but a full treatment of their dynamics is beyond the scope of this course. As one might expect given its name, the downwelling oceanic Kelvin wave warms the near-surface ocean temperatures along its path as they travel eastward at 2-3 m s^{-1} along the Equator over a multi-month period. In this theory, the forcing initiating the eastward-moving waves also initiates a slower-moving, westward-directed upwelling *oceanic* n = 1 equatorial Rossby wave, specifically the cyclonic half-wavelength of the full n = 1 equatorial Rossby wave (where cyclonic rotation is uniquely associated with upwelling because of Ekman transport). As might be expected given its name, this upwelling wave cools near-surface ocean temperatures along its path.

In the "delayed oscillator" theory, ENSO's oscillatory nature is a function of oceanic Kelvin and equatorial Rossby wave propagation and evolution. Downwelling oceanic Kelvin waves are reflected westward by the South America coast as downwelling (or anticyclonic) oceanic n = 1 equatorial Rossby waves. Upwelling n = 1 oceanic equatorial Rossby waves are reflected eastward by the Asia coast as upwelling oceanic Kelvin waves. The reflected waves first reinforce the warm east/cool west pattern fostered by the initial waves, but then ultimately reverse this warm east/cool west pattern as they pass each other in the central Pacific Ocean. This process takes about a year to complete given the three-month transit time for an oceanic Kelvin wave and eight-month transit time for an n = 1 oceanic equatorial Rossby wave across the equatorial Pacific.

The delayed oscillator theory for ENSO does a reasonable job at explaining why La Niña follows El Niño; however, it does not explain why El Niño follows La Niña. It also does not accurately describe the ENSO's periodicity given that transitions between El Niño and La Niña events typically occur slower than this model indicates.

A related ENSO theory is known as the Western Pacific Oscillator theory. Equatorial heating in the western Pacific Ocean initiates the cyclonic half-wavelength of an n = 1 equatorial Rossby wave. The resulting flow induces a westerly wind anomaly at the Equator that leads to downwelling that, in turn, warms the eastern equatorial Pacific Ocean. At the same time, the anticyclonic half-wavelength of an $n = 1$ equatorial Rossby wave to the west induces an easterly wind anomaly at the Equator that leads to upwelling and, in turn, cools western equatorial Pacific Ocean. This cooling later spreads east, counteracting the downwelling-induced warming and terminating the El Niño event. Wave reflection at the eastern and western ends of the basin is not a necessary condition for an ENSO event in the context of this theory.

A Simplified ENSO Thermodynamic Formulation

A simplified mathematical model for ENSO evolution is described by Zebiak and Cane (1987). This model assumes nothing about, nor provides insight into, *what* causes the ocean-current variations that result in El Niño or La Niña; rather, it provides a method of linking these variations to near-surface ocean temperature variability.

This model couples Gill (1980)'s linear shallow-water model to a linear ocean model. Within this coupled modeling system, the equation for the evolution of surface ocean temperature anomalies is given by:

$$(2) \qquad \frac{\partial T'}{\partial t} = -\overrightarrow{u_1}' \bullet \nabla\left(\overline{T} + T'\right) - \overline{\overrightarrow{u_1}} \bullet \nabla T' - \{M(\overline{w_s} + w_s') - M(\overline{w_s})\}\overline{T_z} - M(\overline{w_s} + w_s')T_z' - \alpha T'$$

Barred terms in (2) represent mean fields and primes represent anomalies from these mean fields. u_1 is the surface ocean current's zonal velocity. w_s is the upper-ocean vertical velocity and is positive for upwelling. T_z is the vertical temperature gradient in the upper ocean. $M(\ )$ is defined as 0 where $(\ ) \le 0$ and as $(\ )$ where $(\ ) > 0$. This M function is only found on terms containing w_s and accounts for surface temperature changing only in response to upwelling and not to downwelling (which only changes subsurface temperatures). Please refer to Section 2b and the Appendix of Zebiak and Cane (1987) for a full listing of the assumptions inherent to the derivation of (2).

The terms of (2), from left to right, are as follows:

(a): The local time rate of change of the sea-surface temperature anomaly.

(b): Zonal advection of total (mean + anomalous) temperature by the anomalous ocean current.

(c): Zonal advection of anomalous temperature by the mean ocean current.

(d): Anomalous upward vertical velocity contributing to vertical temperature advection (of the mean temperature only) near the ocean's surface.

(e): Total (mean and anomalous) upward vertical velocity contributing to vertical temperature advection (of the anomalous temperature only) near the ocean's surface.

(f): Parameterized ocean-temperature restoration.

In this model, ocean-temperature changes are dominated by (d), the anomalous upward vertical advection (or upwelling) term. Upwelling, particularly in the upper 200 m, is the most important process modulating temperature anomalies. Terms (b) and (c) are relatively small owing to the relatively small velocities of the mean and anomalous ocean currents (~10 cm s^{-1}). Term (e) contributes about 10% of the total temperature anomaly. Term (f) exists solely to ensure that the sum of (b)-(f) balances (a).

For (a) to be positive, such that there is anomalous warming taking place, (d) must also be positive. Because ocean temperature increases upward toward the surface, $\overline{T_z}$ is positive. Thus, (d) is positive for $M(\overline{w_s} + w_s')$ < $M(\overline{w_s})$. This implies that w_s' must be negative – i.e., reflecting a downward-directed anomalous vertical velocity characterizing weakened upwelling – for El Niño development.

The model is capable of replicating ENSO's observed atmospheric structures and periodicity, particularly for El Niño, but is limited in its ability to simulate the real ENSO system.

Forecasting ENSO

Numerical models used to predict the evolution of ENSO are clustered into two basic types: dynamical and statistical models. Dynamical models consist of coupled ocean-atmosphere numerical prediction systems that predict ENSO phase by integrating the physical equations governing the ocean and atmosphere forward in time from an initial analyzed state. Statistical models use past information on the evolution of ENSO and related atmosphere and ocean fields to assess how the "current" ENSO state will evolve in the future. Both simple (i.e., multiple linear regression) and complex (i.e., machine-learning) statistical models exist.

Generally, statistical models fare well over short time periods (< 6 mo) with less skill thereafter. Dynamical models are generally less skillful and exhibit more variability from one model forecast to another but have improved in recent years. Statistical models tend to exhibit like-signed (i.e., warm or cold) biases whereas dynamical models exhibit greater spread in the biases of individual forecast models. ENSO forecasts tend to be least skillful in the winter and early spring owing to the "spring predictability barrier," the physical reasoning behind which remains uncertain. Stochastic processes, meteorological phenomena, and climate variability on larger scales than ENSO (i.e., decadal variability like the Pacific Decadal Oscillation) impact both ENSO phase and the skill of numerical models used to predict its phase.

For Further Reading

- Chapter 3, *An Introduction to Tropical Meteorology, 2nd Edition*, A. Laing and J.-L. Evans, 2016.
- Chapter 4, *An Introduction to Tropical Meteorology, 2nd Edition*, A. Laing and J.-L. Evans, 2016.
- Zebiak, S. E., and M. A. Cane, 1987: A model El Niño-Southern Oscillation. *Mon. Wea. Rev.*, **115**, 2262-2278.