El Niño Southern Oscillation

Introduction

One of the leading modes of interannual variability within the tropics is manifest by the El Niño Southern Oscillation, or 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 variability in the Walker circulation in terms of ENSO.

Key Concepts

- What is meant by "El Niño Southern Oscillation"?
- How is ENSO analyzed and observed?
- How does ENSO impact the zonal Walker circulation in the tropics?
- How does ENSO impact large-scale mid-latitude weather patterns?
- What physical processes lead to El Niño and/or La Niña events?
- How is ENSO forecast?

The El Niño Southern Oscillation

ENSO is a coupled atmospheric-oceanic process caused by the oscillatory redistribution of heat and atmospheric momentum in the equatorial Pacific Ocean. The term "coupled" means that the atmosphere and ocean work in harmony with one another; forcing in one modulates 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. It should be noted that it is uncertain whether El Niño and La Niña cycles force changes in sea level pressure patterns or whether the inverse is true; from a coupled perspective, however, they can be viewed as reliant upon and modulating one another.

El Niño and La Niña refer to the oceanic component of ENSO and reflect modulations in the strength of the easterly trades and pattern of sea surface temperatures across the equatorial Pacific Ocean. El Niño is characterized by weakened or reversed tropical easterly trades and the concurrent warming of equatorial sea surface and below-sea surface temperatures across the eastern and central tropical Pacific. Conversely, La Niña is characterized by strengthened easterly trade winds and the concurrent cooling of equatorial sea surface and below-sea surface temperatures across the eastern and central tropical Pacific. El Niño events typically last 9-15 months whereas La Niña events typically last 1-3 years. Transitions from El Niño to La Niña events tend to occur more rapidly than the inverse. These transitions should be viewed as akin to an asymmetric wave; no two concurrent events are identical, nor does a La Niña or El Niño event have to transition to the other before another like event can occur.

Modulations in the trade winds can be viewed as a driver of oceanic temperature changes via their impacts on upwelling and downwelling, whereby enhanced (reduced) easterly winds enhance (weaken) upwelling and result in cooler (warmer) oceanic temperatures in the tropical eastern and central Pacific. However, holistically, the trade winds are coupled to (versus exclusively driving) oceanic temperature changes, much as described before with the Southern Oscillation and sea level pressure patterns.

The Southern Oscillation was first substantiated by Sir Gilbert Walker, who noticed an oscillatory pattern within the sea level pressure differences between Darwin, Australia and Tahiti while attempting to forecast the Asian and Australian monsoons. The normalized measure of this difference in sea level pressure, dubbed the Southern Oscillation Index (SOI), provides one of the primary means of monitoring the state and evolution of ENSO. The SOI is expressed by:

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

where p_{diff} is the difference in monthly mean sea level pressure between Tahiti and Darwin, $\overline{p_{diff}}$ is the long-term climatology of the difference in monthly mean sea level pressure between Tahiti and Darwin, and $\sigma\left(\overline{p_{diff}}\right)$ is the standard deviation of the long-term climatology. Because of the leading 10, a scaling factor, values of the SOI are expressed in terms of *tenths* of standard deviations above or below normal. Given the basic relationship between horizontal pressure gradients and winds, the SOI may be viewed as a proxy for the strength of the trade winds.

p_{diff} is computed as the monthly mean sea level pressure at Tahiti minus that at Darwin. Lower values of sea level pressure are associated with warmer values of sea surface temperature. Thus, for El Niño, lower (higher) than normal sea level pressure is experienced at Tahiti (Darwin). For La Niña events, higher (lower) than normal sea level pressure is experienced at Tahiti (Darwin). As a result, negative (positive) values of the SOI reflect El Niño (La Niña) conditions.

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, commonly referred to as the "Niño 3.4" region. El Niño periods are characterized by a positive ONI greater than or equal to 0.5°C; La Niña periods are characterized by a negative ONI less than or equal to -0.5°C. These criteria must be exceeded for five or more months in order 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 over the region bounded by 4°S-4°N and 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 off of the leading mode of variability (dubbed the "first principal component") of six bimonthly-averaged variables over the tropical Pacific: sea level pressure, zonal 10-m wind, meridional 10-m wind, sea surface temperature, surface air temperature, and cloud fraction (tied to precipitation and deep, moist convection).

No single index is capable of representing all ENSO variability; however, most capture substantial portions of this variability. When used individually, the base state of ENSO across the entire tropical Pacific may be obtained. When used in conjunction with one another, a view of the zonal structure of ENSO may be obtained.

The Niño 3.4 region referred to above is commonly used to assess the oceanic state in conjunction with ENSO. This is because of two factors: one, sea surface temperature variability in the central Pacific signals the strongest effect on shifting precipitation patterns from the western to the central equatorial Pacific (i.e., shift in the Walker circulation) and two, numerical forecasts of ENSO tend to exhibit the greatest skill when initialized with data from this region. Occasionally, data from the Niño 1+2 (far eastern equatorial Pacific), Niño 3, and/or Niño 4 regions are used to assess ongoing changes in or the zonal structure of an El Niño or La Niña event.

Impacts of ENSO upon the Walker Circulation

Variability in the Walker circulation is intricately tied to ENSO. As demonstrated in previous lectures, the Walker circulation is manifest is driven by both atmospheric and oceanic heating. ENSO-driven Walker circulation variability arises through the modulation of oceanic heating. Recall that an El Niño event is characterized by anomalously warm waters in the eastern and central equatorial Pacific and anomalously cold waters in the western equatorial Pacific. As the net heating becomes strongest in the central equatorial Pacific, this results in the eastward shift of the ascending branch of the Walker circulation such that ascent is promoted in the central equatorial Pacific. Conversely, a La Niña event is characterized by anomalously warm waters in the western equatorial Pacific and anomalously cold waters in the eastern and central equatorial Pacific. This results in a stronger mean Walker circulation. Note that it is not the underlying physics of the Walker circulation, as outlined by the Gill (1980) conceptual model, that change in response to ENSO but rather the heating-driven circulatory structure associated with the Walker circulation.

Impacts of ENSO upon Tropical and Mid-Latitude Weather Patterns

ENSO's impacts upon climate are far-reaching, encompassing both the tropical and higher latitudes. The greatest impacts are felt in and near the equatorial Pacific and are most significant during the winter months. In the tropics, El Niño events bring heavy precipitation and flooding to northwestern South America. In the equatorial eastern Pacific, anomalous oceanic warmth results in losses of oceanic wildlife populations vital to the economies of coastal South America. Anomalously dry conditions, often associated with drought, are found in the western Pacific. Rainfall associated with the Asian and particularly Australian monsoons is significantly reduced during El Niño. The inverse is true for La Niña; anomalously cool and dry conditions are found near the coast of South America while anomalously west conditions are found in the western Pacific. In particular, rainfall associated with the Asian monsoon is significantly enhanced during La Niña. As La Niña more closely resembles the base state of the coupled ocean-atmosphere system, it is anomalies associated with El Niño that are more climatically and statistically significant. Further, El Niño typically results in fewer tropical cyclones in the Atlantic and greater numbers of tropical cyclones in the eastern Pacific, whereas La Niña typically results in greater numbers of tropical cyclones in the Atlantic and fewer tropical cyclones in the eastern Pacific.

El Niño and La Niña impact weather patterns in the higher latitudes through the modulation of the mean Rossby wave pattern across the Pacific and the Americas. This modulation results from near-equatorial heating that excites poleward-propagating Rossby wave trains. Concordant with the modulation of the mean Rossby wave pattern are displacements or disruptions of the jet streams across the Americas. In the Northern Hemisphere, El Niño shifts the wintertime subtropical jet stream southward, thereby shifting the mean storm track southward and resulting in enhanced rains in the southern United States, Central America, and the Caribbean. La Niña shifts the wintertime jet stream northward, resulting in reduced rains and warmer conditions across these same regions. The Pacific Northwest and Alaska, meanwhile, benefit from enhanced rains as a result of this northward shift in the jet stream. The impact of ENSO is mitigated with continued eastward progression across North America as the Rossby wave train weakens and modes of Atlantic variability become dominant.

Dynamical Theories for El Niño and La Niña Events

In our discussion of the Walker circulation, we discussed the relationship between easterly trade winds and zonal SST patterns. For easterly trade winds, the eastern (western) portions of oceanic basins tend to be cooler (warmer). The inverse is true for westerly trade winds. These patterns arise due to considerations related to upwelling and downwelling. The atmospheric response to the SST anomalies can be viewed as a factor aiding to maintain an ongoing El Niño or La Niña event. Ascent is favored over regions of warm SSTs; the release of latent heat by deep, moist convection associated with this ascent promotes lower-level convergence, strengthening the local trades. In the absence of other processes impacting the system, this would maintain the ongoing ENSO phase. However, this line of reasoning fails to explain how and why the system oscillates between La Niña and El Niño.

At a basic level, the onset of El Niño can be characterized by the presence of anomalously westerly winds. Such anomalous winds form when trade winds weaken and/or turn westerly in response to some external forcing such as the Madden-Julian Oscillation or an intense tropical cyclone. The forcing said to cause this change in the trade winds is known as a westerly wind burst and is characterized by surface zonal wind anomalies of 5 m s^{-1} or greater over at least 10° longitude and lasting at least two days.

A persistent westerly wind burst causes the generation of an eastward-propagating downwelling oceanic Kelvin wave. The physics and dynamics behind oceanic Kelvin waves are beyond the scope of this course. The downwelling wave results in the warming of sea surface and near-sea surface temperatures along its path. Oceanic Kelvin waves are trapped along the equator, are typically 5-10 cm high, hundreds of kilometers wide, and a few degrees °C warmer than surrounding waters. Eastward propagation of these waves at approximately 2-3 m s^{-1} results in a traverse period of the equatorial Pacific basin of approximately three months. Eastward-moving oceanic Kelvin waves are often associated with slower-moving, westward-directed upwelling equatorial Rossby waves that act to cool waters to the west. Note that this structure is akin to that observed with the typical structure of the Walker circulation itself. The net result is the development of El Niño-like oceanic conditions over the span of several months.

This forms the basis behind what is known as the "delayed oscillator" theory for ENSO. Using a shallow water model akin to that used to describe the Walker circulation, the oscillatory nature of ENSO can be shown to be a function of oceanic Kelvin and equatorial Rossby wave propagation and evolution. After an oceanic Kelvin wave reaches the coast of South America, it is reflected westward as a downwelling equatorial Rossby wave. Conversely, once a westward-moving equatorial Rossby wave reaches the coast of Asia, it is reflected eastward as a faster-moving upwelling oceanic Kelvin wave. The reflect waves act to first reinforce and ultimately reverse the warm east-cool west pattern fostered by the initial downwelling Kelvin and upwelling equatorial Rossby waves. However, the oceanic Rossby wave takes about eight months – versus the three of an oceanic Kelvin wave – to traverse the entire basin, leading to the reversal of the initial oceanic warming within a year of its onset.

The delayed oscillator theory for ENSO does a reasonable job at explaining why a La Niña event follows an El Niño event; however, it does not explain the termination of La Niña events. It also does not accurately describe the periodicity of ENSO given a slower observed transition between El Niño and La Niña events. A related theory is given by the "Western Pacific Oscillator" theory. Equatorial heating in the western Pacific gives rise to twin cyclones analogous to the twin cyclones that emerge from the equatorial Rossby wave mode solution to the shallow water system. The flow associated with these cyclones induces a westerly wind anomaly at the equator that leads to downwelling and warming of the eastern equatorial Pacific. At the same time, twin anomalous anticyclones about the equator to the west result in an easterly equatorial wind anomaly and cooling of the western equatorial Pacific. Eventually, this cooling spreads eastward, 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.

Other theories for the formation and evolution of ENSO events exist. These include the "linear stochastic," "recharge/discharge," "advective-reflective oscillator," and "unified oscillator" theories. For more information on these theories, the reader is referred to Section 4.2.1.3, "ENSO Theory," of *An Introduction to Tropical Meteorology, 2nd Edition*.

A representative mathematical model for the evolution of ENSO is given by Zebiak and Cane (1987). The atmospheric component to this model is given by the same linear shallow water framework of Gill (1980) outlined in our study of the Walker circulation. It is coupled to an ocean model that is also based off of linear dynamics, herein represented by a reduced gravity formulation. Within this coupled modeling system, the parameterized thermodynamic equation for the evolution of SST anomalies takes the form:

$$\frac{\partial T'}{\partial t} = -\vec{u}_1 \bullet \nabla\left(\overline{T} + T'\right) - \vec{\overline{u}}_1 \bullet \nabla T' - \left\{M\left(\overline{w_s} + w_s'\right) - M\left(\overline{w_s}\right)\right\}\overline{T_z} - M\left(\overline{w_s} + w_s'\right)T_z' - \alpha T' \qquad (2)$$

where a complete treatise upon the derivation and underlying assumptions inherent to (2) may be found in the Appendix and Section 2b, respectively, of Zebiak and Cane (1987). Bars represent mean fields and primes represent anomalies from these mean fields. u_1 and w_s represent horizontal surface currents and upwelling, respectively, and $M(\ )$ is defined as 0 where $(\ ) \leq 0$ and as ( ) where $(\ ) > 0$. T_z represents the vertical gradient in temperature between the top and bottom of some specified layer with depth H. The M function accounts for the fact that surface temperature is affected by vertical advection only in the presence of upwelling. It should be noted that (2) is an empirically-derived relationship for sea surface temperature anomaly changes in response to vertical displacements of the thermocline (the abrupt vertical gradient of *T* beneath the ocean's surface) and cannot distinguish between the various physical processes that actually contribute to thermocline variability in the ocean.

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): Advection of total (mean and anomaly) temperature by the anomalous oceanic current.

(c): Advection of anomaly temperature by the mean oceanic current.

(d): Anomalous upwelling acting on the mean vertical gradient of sea surface temperature.

(e): Total (mean and anomaly) upwelling acting on the anomalous vertical gradient of sea surface temperature.

(f): Newtonian cooling parameterization.

In this model, sea surface temperature changes are dominated by (d), the anomalous upwelling term. Upwelling, particularly in the upper 200 m, is the most important process modulating temperature anomalies in this model framework. 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 for balance purposes.

For (a) to be positive, such that there is anomalous warming taking place, (d) must be of like sign. As $\overline{T_z}$ is positive, the leading negative on (d) thus requires $M\left(\overline{w_s}+w_s'\right)<M\left(\overline{w_s}\right)$. This implies that w_s' must be negative, i.e., reflecting a downward-directed anomalous vertical velocity. Thus, weakened upwelling results in the warming of the central and eastern equatorial Pacific associated with El Niño. From the linear coupling of the ocean and atmosphere, it can be demonstrated that this warming occurs in response to the imposition of westerly wind stresses at equatorial latitudes, in line with basic ENSO theory. The model does a fairly good job in replicating the observed atmospheric structures and periodicity of ENSO, particularly El Niño, but is limited in its ability to simulate the real ENSO system.

Forecasting ENSO Cycles

Numerical models used to predict the evolution of ENSO are clustered into two basic types: dynamical and statistical models. Dynamical models are comprised of coupled oceanic-atmosphere numerical prediction systems that predict ENSO phase by integrating the primitive equations of the ocean and atmosphere forward in time from the initial analyzed state. Statistical models use past information on the evolution of ENSO and related atmospheric/oceanic fields to assess how the "current" state of ENSO will evolve into the future. Both simple (i.e., regression-based) and complex (i.e., neural network-based) forms of statistical models exist.

Generally, statistical models fare well over short time periods (< 6 mo.) with degrading 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 what is known as the "predictability barrier," the physical reasoning behind which remains uncertain. Stochastic processes, meteorological phenomena (particularly tropical cyclones), and climate variability on larger scales than ENSO (i.e., decadal variability in the form of 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, 2011.
- Chapter 4, *An Introduction to Tropical Meteorology, 2nd Edition*, A. Laing and J.-L. Evans, 2011.
- Zebiak, S. E., and M. A. Cane, 1987: A model El Niño-Southern Oscillation. *Mon. Wea. Rev.*, **115**, 2262-2278.