White Paper #2 - Some Societal Impacts of ENSO

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1. Introduction

We monitor oceanic and atmospheric conditions and air-sea interactions over the Tropical Pacific for many reasons. One of these is for forecasts of Tropical Pacific conditions, because the state of the El Niño - Southern Oscillation phenomenon affects so many nations around the basin and around the world. This brief document for the Tropical Pacific Observing System 2020 (TPOS 2020) workshop will describe some examples of the impacts of the El Niño - Southern Oscillation on seasonal weather anomalies in temperature and precipitation, marine ecosystems, tropical cyclones, changes in atmospheric CO_2 concentration and recent conditions in Latin America. We make no attempt to be comprehensive; the literature is full of other examples of phenomena connected to ENSO with a societal impact. For those interested in further examples, we call the reader's attention to a paper authored mostly by members of the International Research Institute for Climate and Society (Zebiak et al., 2014) for an excellent overview and material additional to that presented here.

ENSO is a coupled air-sea phenomenon with global reach, but maximum anomalies in the Tropical Pacific, that typically spans from boreal summer through the following boreal spring, peaking in boreal winter. Thus it is convenient to categorize years as being "El Niño" years, "ENSO-neutral" years, or "La Niña" years. A notation introduced early in the modern study of ENSO was to characterize the years in which major anomalies first appeared as "Yr (0)" and the previous and succeeding years as "Yr (-1)" and "Yr (+1)" (Rasmussen and Carpenter, 1982), but for many impacts it is sufficient to identify the Yr (0), and it is understood that anomalies extend from mid-Yr (0) into Yr (1). Yr (0) traditionally has been identified as the year in which some measure of the ENSO-state of the climate system exceeds and remains beyond some threshold value for some period of time. Traditional measures of ENSO have included the Troup Southern Oscillation Index (SOI), a normalized measure of the sea level pressure (SLP) difference between Tahiti and Darwin, and several area-averages of sea surface temperature anomaly (SSTA) near the equator (NIÑO 1, 2, 3, 3.4, 4). With appropriate smoothing, Darwin SLP alone has been used to study the longer time history of ENSO. There also are asymmetries between El Niño and La Niña (Deser and Wallace, 1990), which are evident in the ENSO measures and in the associated impacts (Larkin and Harrison, 2002; Harrison and Larkin, 2002), which means that attempting to characterize ENSO impacts by simple correlation with an ENSO measure time series can lead to results that are not fully typical of either ENSO state.

Deser and Wallace (1987) noted that the different ENSO measures did not always agree on whether a particular year was an "El Niño" year. As ENSO impacts have been more thoroughly investigated, the effects of the criterion selected for year identification on impact associations has become clear: different regions of the planet have ENSO associations that sometimes can be optimized by selecting particular ENSO measures. The idea that there are at least two different types of El Niño events with different associated impacts has recently also been advocated (e.g., Larkin and Harrison, 2005; Ashok and Yamagata, 2009; Chiodi and Harrison, 2013). We shall offer an example below of how the use of a particular ENSO measure can optimize the connection to a seasonal weather impact. In many cases, a useful 'big picture' view of ENSO societal impacts can be obtained via simple compositing of the anomalies based on El Niño or La Niña Yr (0)s. However, the big picture glosses over many important aspects of event-to-event variability, and is vulnerable to the effects of a few years with major surface anomalies.

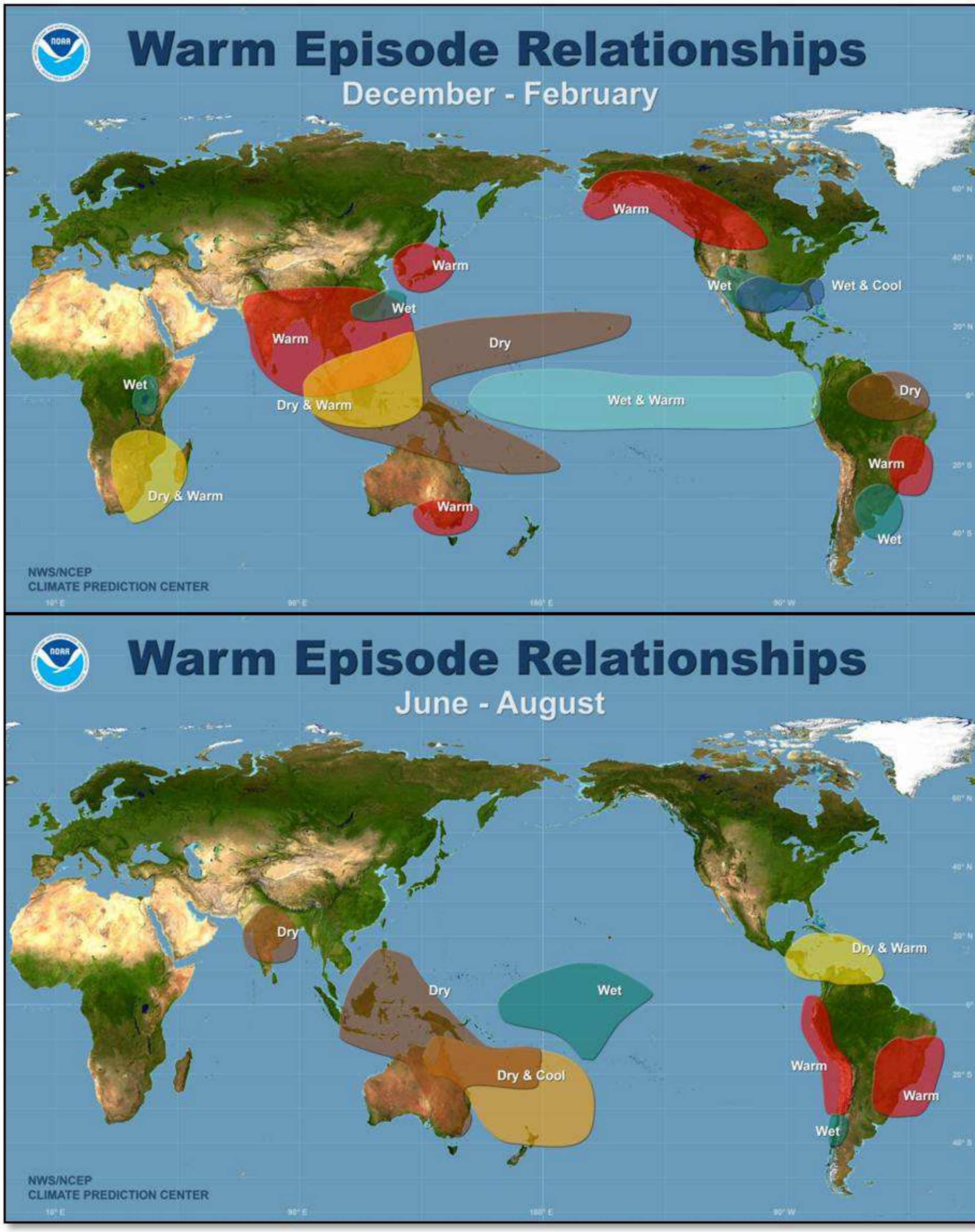
ENSO, while an event with a typical duration of substantial anomalies lasting about one year, and with events occurring sporadically with an average time of several years (e.g., Harrison and Larkin, 1998; Larkin and Harrison, 2001; Larkin and Harrison, 2002), also exhibits very substantial multi-decadal variability (e.g., Harrison and Chiodi, 2014). This makes inferences about trends in ENSO statistics challenging (Harrison and Larkin, 1997). Because a considerable percentage of the Tropical Pacific ocean surface is anomalously warm or cool during a major ENSO event, the ENSO statistics of a particular decade can have a significant effect on global surface temperature especially if the North Pacific has a widespread anomaly of the same sign (Ashok and Yamagata, 2009). Recently there has been much interest in the extent to which there has been little global surface warming over the past 15 years, and it has been suggested that the recent frequency of La Niña events may be a significant factor (Kosaka and Xie, 2013). Whether the statistics of ENSO events will change as the planet warms is an area of much current interest.

The financial costs to society of ENSO events have been estimated to be as much as $25 billion for the extreme 1997-1998 El Niño. Lazo et al. (2011) have estimated that for the US, as well as Australia, the economic consequences of ENSO events can be on the order of 1% of national GDP, which is very substantial indeed. Goddard and Dilley (2005) have, however, emphasized that a thoughtful consideration of the 'cost' of ENSO events involves consideration of many factors, not least placing the frequency of weather 'disasters' in comparison with the typical frequency and severity of occurrences during ENSO-neutral years. Also important is the consideration of the vulnerability of the regions most strongly affected. Therefore, skillful forecasts of ENSO events, with sufficient lead time, offer the possibility of greatly reducing impacts in some regions.

We now offer several examples of ENSO connections to climate variability that affects societies.

2. Seasonal Weather Anomalies

A big picture overview of seasonal weather impacts associated with ENSO events was offered by Ropelewski and Halpert (1987 and 1989), and Halpert and Ropelewski (1992), and is summarized in Figure 2.1 and 2.2. The areas affected are indicated schematically and the magnitude of the seasonal anomalies is not indicated, but it tells the now-familiar story of ENSO seasonal weather impacts. Regions are affected across the globe, but most strongly in and adjacent to the Tropical Pacific and over the Americas. Effects are felt in December - February (DJF) as well as in June - August (JJA).



High Resolution Images can be found at:
http://www.cpc.ncep.noaa.gov/products/precip/CWlink/ENSO/ENSO-Global-Impacts/

Figure 2.1 - Large scale seasonal weather anomalies associated with the warm phase of ENSO (El Niño).

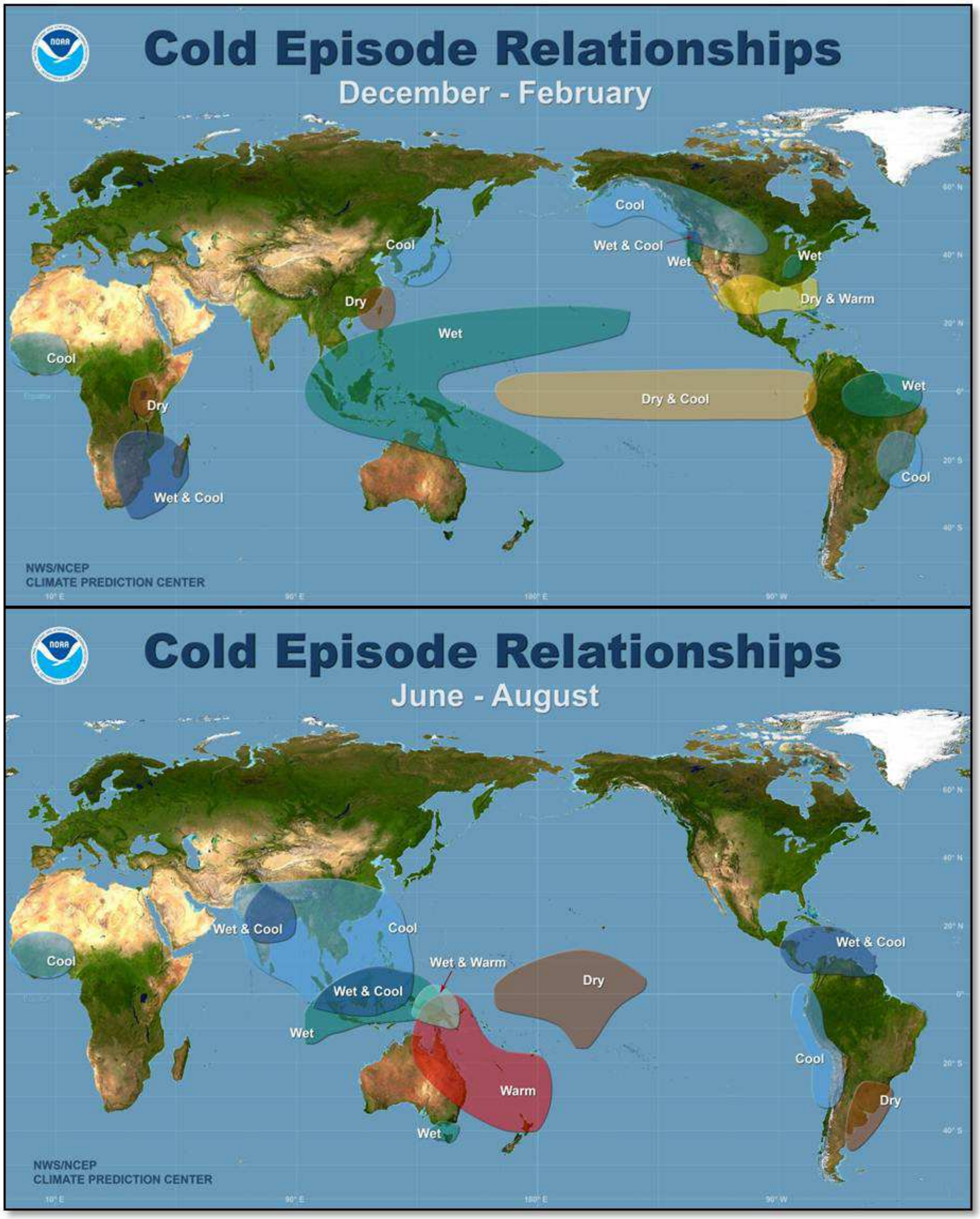


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Figure 2.2 - Large scale seasonal weather anomalies associated with the cold phase of ENSO (La Niña).

However, these figures do not convey the interesting complexity of ENSO-seasonal weather associations. Using the now wide-spread NIÑO3.4 SSTA measure of ENSO, particularly with a low threshold of 3-month-running-average value in excess of 0.5C (-0.5C) to identify El Niño (La Niña) years, leads to many years being designated El Niño or La Niña, and many of the seasonal anomalies during these years are not a sign for one of those events as suggested by Figures 2.1 and 2.2. Under these measures of ENSO, there is very strong event-to-event variation in seasonal weather anomaly. Larkin and Harrison (2005) noted that winter seasonal weather anomalies over the US were substantially affected by how El Niño events were defined, and suggested that it was useful to treat events with anomalies primarily in the central Pacific (which they called Dateline events) as distinct from events that spanned the eastern and central Pacific (which they called Conventional events). There has been considerable research done on how best to characterize ENSO events when the focus is on seasonal weather anomalies. Another perspective has introduced the concept of El Niño Modoki for the Central Pacific El Niño events (e.g., Ashok et al, 2007). A third perspective has used the characteristics of outgoing long wave radiation (OLR) to identify events (Chiodi and Harrison, 2010 and 2013).

The OLR perspective turns out to have considerable skill in identifying El Niño events with much less event-to-event seasonal weather anomalies. Figure 2.3 shows time series of NIÑO3.4 SSTA and of the OLR index proposed by Chiodi and Harrison (2013). The years identified as distinctive by the OLR index are a subset of the years typically identified as El Niño events by a common NIÑO3.4 criterion, so we shall speak of “OLR El Niño” and “Non-OLR El Niño” years.

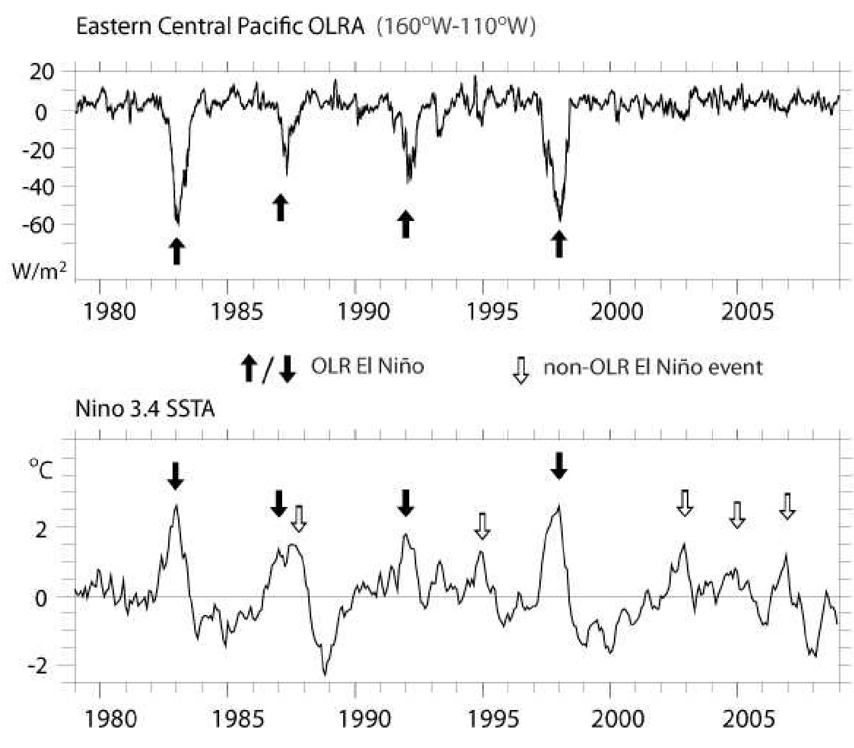

Figure 2.3 - An OLR index for El Niño events vs. NIÑO3.4 SSTA.

OLR El Niño years are characterized by the presence of deep atmospheric convection east of the normal region of deep convection; they accord to the Tropical Pacific waveguide wet anomaly in the Ropelewski and Halpert "Warm Episode" figures. Clearly there are only about half as many OLR El Niño years as Non-OLR El Niño years. The unique waveguide-convection feature of the OLR El Niño years has typically (3 out of 4 events) been apparent by the end of boreal fall of Yr 0, thereby distinguishing the OLR El Niño years from the other years before the arrival of the strongly affected boreal winter (DJF Yr 0/+1) season.

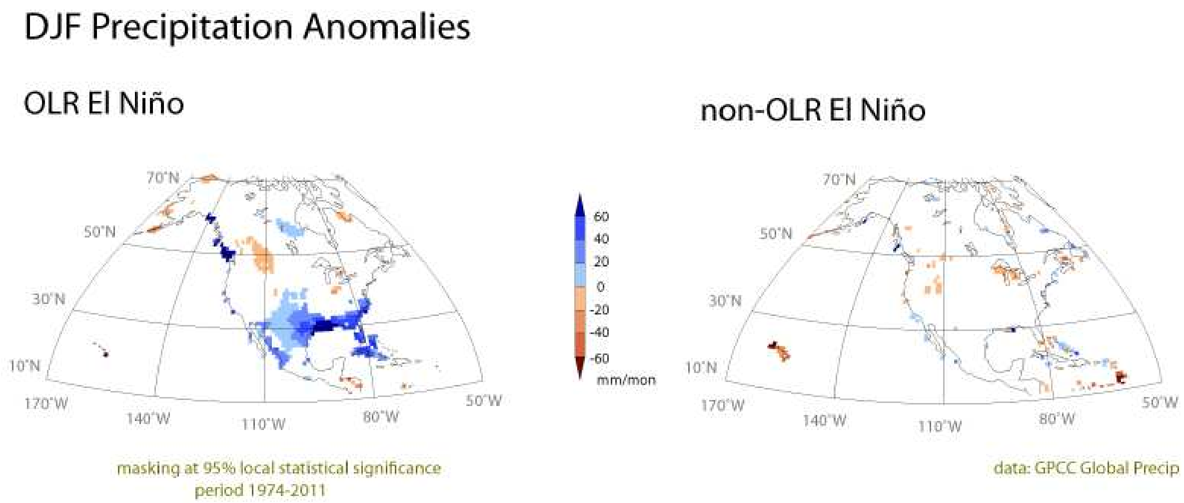

Figure 2.4 - El Niño 95% statistically significant DJF precipitation anomalies, OLR events vs. non-OLR events.

Figure 2.4 shows the DJF average OLR El Niño average and Non-OLR El Niño average surface precipitation anomalies over North and Central America. A striking result is that there are very few areas with any statistically significant (at 95%) precipitation anomalies for the Non-OLR El Niño average; the event-to-event variability in these events is large and of inconsistent signs. By contrast there are substantial areas of significant precipitation anomaly for the OLR El Niño average. Space constrains us from showing the individual year anomalies for all these years, but the OLR El Niño events show many common features in each event. Figure 2.5 presents DJF surface temperature anomaly averages, with the same overall result; the Non-OLR El Niño events do not exhibit much highly statistically significant average anomaly, whereas the OLR El Niño events have considerable regions of significance. As for precipitation, event-to-event variability is large in Non-OLR events and much smaller in OLR events.

The OLR El Niño results of Figures 2.4 and 2.5 show many differences in detail from the Ropelewski and Halpert type figures (2.1), but overall are quite similar. Some of the difference surely arises from the very broad-brush approach taken in Figs 2.1, but OLR observations are only available from 1974 so the set of events is also different. It remains to be determined if the success of the OLR El Niño approach, for seasonal weather anomalies, will persist in coming decades, given the large amount of multi-decadal variability of ENSO.

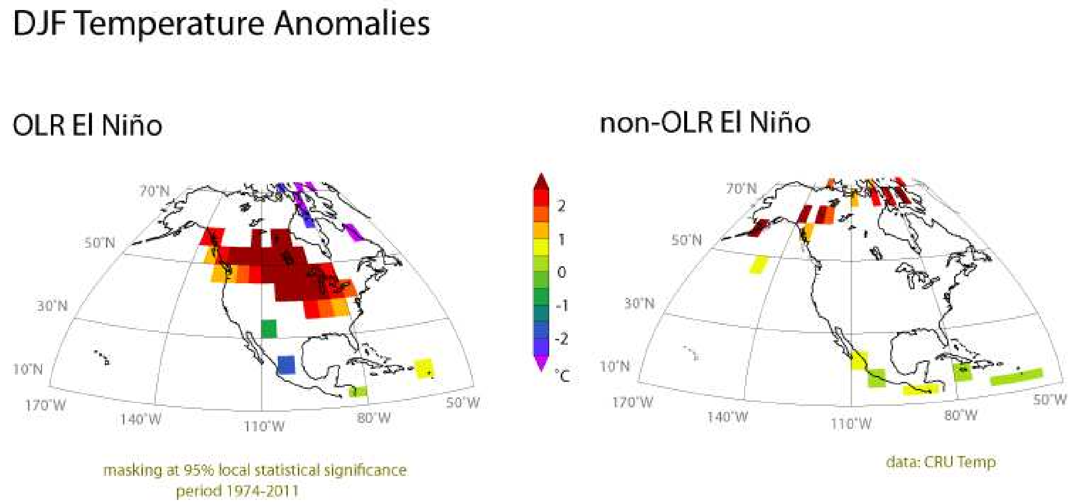

Figure 2.5 - El Niño 95% statistically significant DJF surface temp anomalies, OLR events vs. non-OLR events.

For ease of viewing, only results over North and Central America have been presented, but there is considerable power to the OLR approach for seasonal weather over most of the globe. Similar advantage in identifying La Niña years using an OLR index is also possible, but is not described here in the interests of space.

The take-home message concerning the relationships between El Niño and La Niña, and regional seasonal weather should be that there remains much to be explored about how to optimize characterization of these relationships. The tighter the relationships, the more skillful the seasonal weather predictions that can be offered to society. Each region of the globe that experiences substantial anomalies during ENSO events would be well advised to explore the most effective way of identifying those aspects of ENSO that are most determinative of their regional weather anomalies. The OLR perspective simply offers one new approach that might be useful for many regions.

3. Tropical Cyclones

For affected regions, tropical cyclones are among the most damaging of weather events. A big picture view of the areas of the globe can be gained from Figure 3.1, which is a satellite era summary of all tropical cyclone tracks. Many millions of humans are affected every year, and more developed regions can suffer losses in excess of a billion US Dollars from a single event.

ENSO influences tropical cyclone activity in the Atlantic and Pacific, and to a somewhat lesser extent, the Indian Ocean. Therefore, information on the present and future states of the Tropical Pacific atmosphere-ocean system has societal benefits in terms of seasonal forecasts of tropical cyclones and their impacts. There exists a large body of work on ENSO and tropical cyclones; here we include only a brief review with a few citations for those interested in pursuing the subject further.

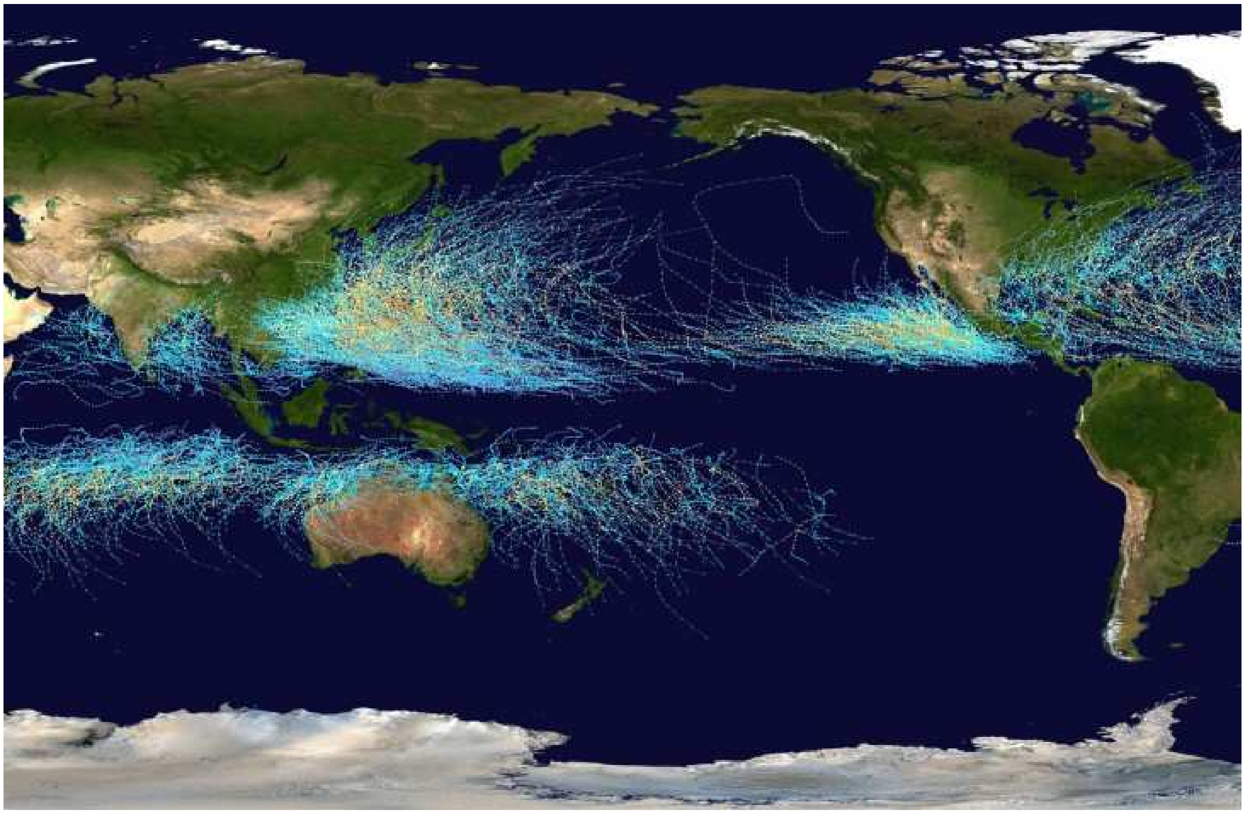

Figure 3.1 - Global tropical cyclone track summary (Source: http://www.wallpapersas.com/wallpaper/global-tropical-cyclone-tracks.html).

ENSO modulates the kinematic and thermodynamic properties of the environment related to the genesis, intensification and tracks of tropical cyclones, as reviewed by Landsea (2000), and Chu (2004). Its effects may be considered more direct in the Pacific and less direct in the Atlantic, with the latter response attributable to teleconnection patterns akin to those associated with ENSO-related seasonal weather anomalies outside of the Tropical Pacific. One of the systematic consequences of El Niño, for example, is an increase in the westerly wind in the upper troposphere across the Atlantic. This implies increased vertical wind shear, which suppresses the formation and intensification of tropical storms (Gray, 1984). It has also been shown that El Niño also tends to be accompanied by a more stable thermodynamic environment (Tang and Landsea, 2004). Hurricane seasons during El Niño also generally have fewer storms that form in the deep tropics from African easterly waves. This type of storm is more likely to enter the Caribbean Sea and make landfall in the US versus curving poleward over the open Atlantic Ocean. More or less opposite effects, in a general sense, have been found for La Niña, as illustrated in the tendency for the larger monetary damages during La Niña than El Niño (Figure 3.2, from Pielke and Landsea, 1999).

The Pacific Ocean includes three separate regions that feature tropical cyclones (Chu, 2004, among others). In the eastern North Pacific, tropical cyclone activity is enhanced during El Niño (opposite to that in the North Atlantic) and suppressed during La Niña. These variations in activity are less due to the frequency of individual storms (hurricanes) but rather more to ENSO's impact on their intensities. ENSO also tends to have effects on their tracks, with more hurricanes propagating into the central Pacific, including near the Hawaiian Islands, during El Niño.

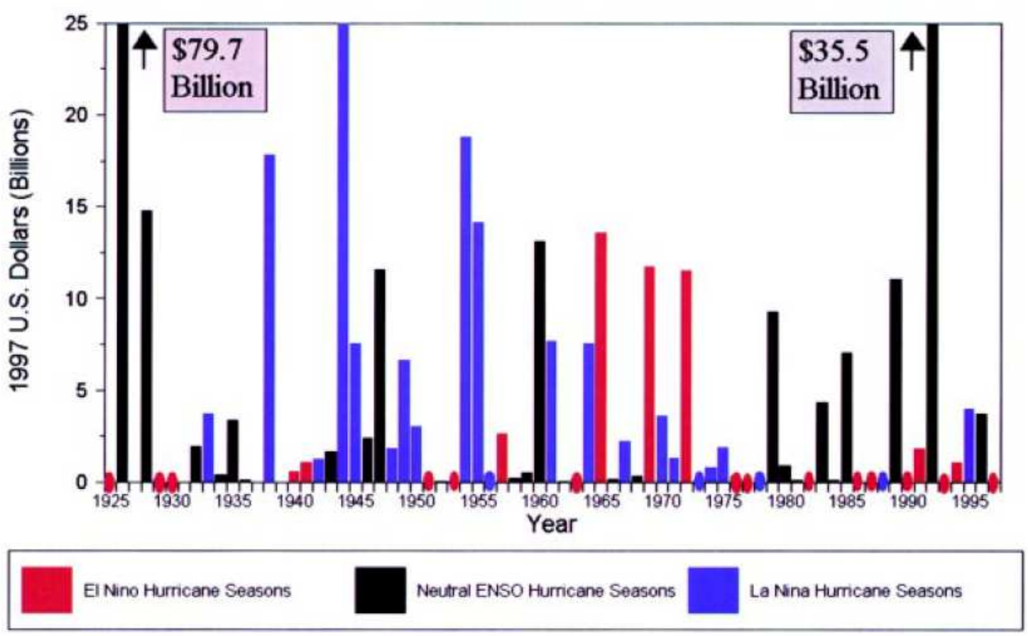

Figure 3.2 - Hurricane damage in normalized dollars for 1925-1997. Years with damages less than $500 million are indicated with ellipses on the x-axis (adapted from Pielke and Landsea 1999).

The western North Pacific both experiences a high frequency of tropical cyclones (typhoons) and is strongly influenced by ENSO, and so not surprisingly, the relationships here have received a fair amount of attention (Chan, 1985). The favored region of genesis for typhoons is shifted to the southeast during El Niño and this often results in longer tracks over warm water and hence greater intensities. They also tend to recurve sooner, and hence make landfall in the northern locations of Japan, South Korea and northern half of China. During La Niña, the landfall of typhoons is favored in the Philippines, Vietnam and southern China. The southwestern Pacific experiences a similar response with respect to ENSO. As shown in Figure 3.3 (adapted from Camargo et al., 2007), ENSO tends to shift the genesis region for tropical cyclones similarly for north and south of the equator in the western Pacific. But while there are fewer storms that develop in the vicinity of Australia during El Niño, the overall tropical cyclone activity here is actually greater when the SLP at Darwin was lower in the preceding season (Nicholls, 1979), i.e., when the SOI is negative.

The relationships between ENSO and Indian Ocean tropical cyclones are of a similar nature to those for the western Pacific. In particular, ENSO appears to have little systematic effect on the frequency of storms, but does influence genesis locations and tracks in the southwestern part of the basin, with implications for the risk of storms making landfall in Madagascar and southeast Africa.

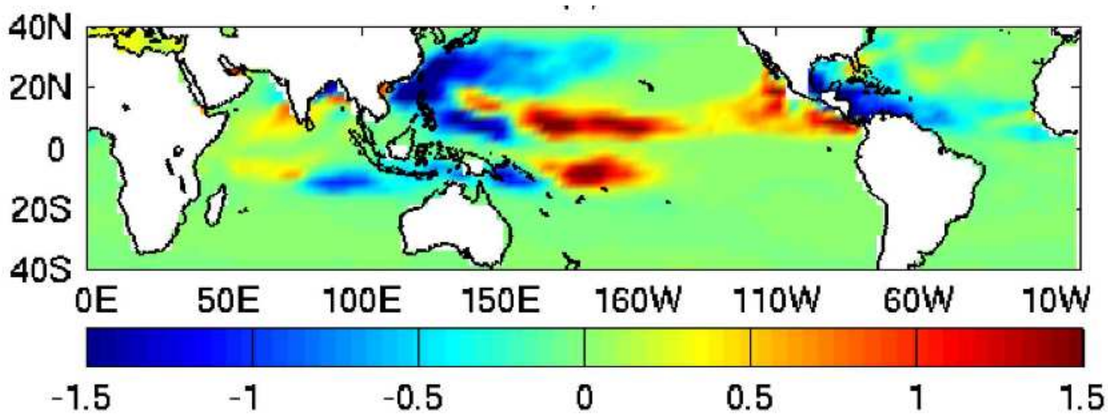

Figure 3.3 - Difference between El Niña and La Niña in terms of genesis potential (based on a combination of vorticity, vertical wind shear, potential intensity, and humidity) during August-October (adapted from Camargo et al., 2007).

Finally, we note that the linkages between ENSO and tropical cyclones are not fully understood. Future research should ultimately improve not just seasonal predictions, but could also address a number of open questions. For example, considerable recent attention has focused on the diversity in the nature of individual ENSO events. Some research has been carried out on how different kinds of events impact tropical cyclones (Kim et al., 2011), but there is more to be done. Many tropical cyclones undergo a transition to extra-tropical storms, especially late in the season, and these storms can be intense. The transitions are presumably modulated by perturbations in SST and mean atmospheric circulation patterns associated with ENSO, but these modulations have not been elucidated. From a climate perspective, tropical cyclones have been recognized for their role in transporting heat poleward (Emanuel, 2001), and it stands to reason that this process is influenced by upper ocean temperature patterns accompanying ENSO. How will global climate change impact the characteristics of ENSO related to tropical cyclones? These are issues of scientific interest and practical importance.

4. Ecosystem Impacts

Fluctuations in the atmosphere-ocean climate system associated with ENSO are known to impact a variety of marine ecosystems. The objective of this section is to point out the nature of some of these connections, drawing upon examples from the Pacific Ocean. Because the effects of ENSO can be large, its ramifications on ecosystems and fisheries are important from a host of perspectives (economic, conservation, cultural, etc.).

The eastern equatorial Pacific features the upwelling of nutrients from depth into the euphotic zone, and hence relatively high rates of primary production. As might be expected, ENSO modulates this process (Pennington et al., 2006), with implications for the entire marine food web (Barber and Chavez, 1983). Figure 4.1 from Harrison and Chiodi (2014) offers snapshots of satellite-based estimates of near-surface chlorophyll-a across the Tropical Pacific; one near the end of the major 1997 El Niño and the other in the middle of the intense 1998 La Niña. The suppression of upwelling in the first case results in a dramatic reduction of chlorophyll-a compared with the levels in the La Niña conditions.

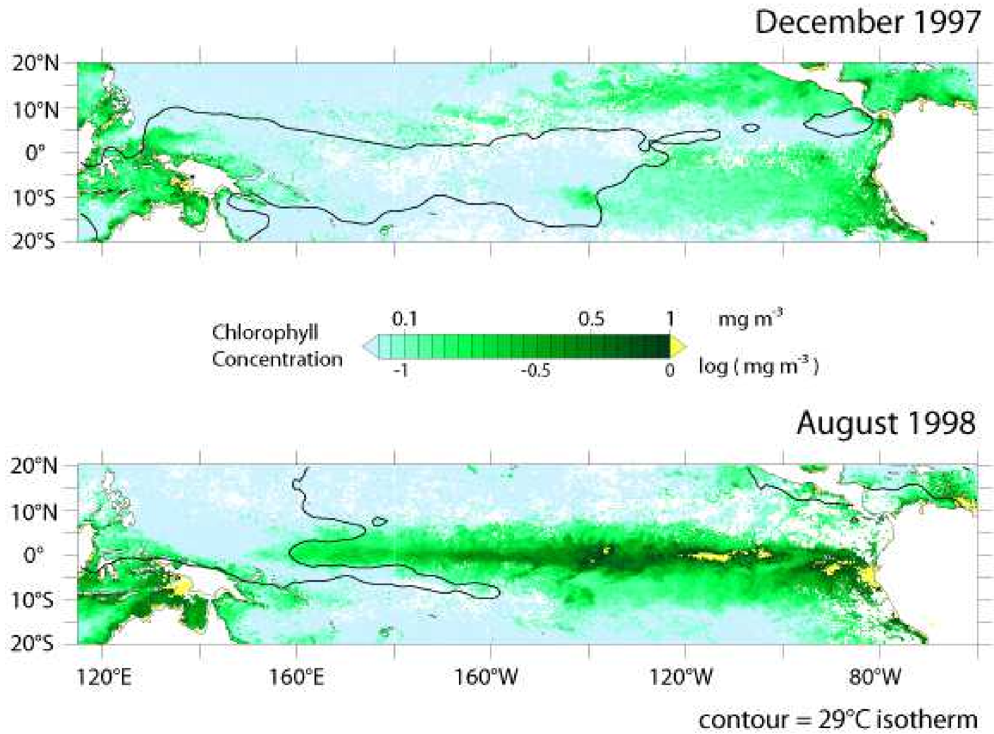

Figure 4.1 - Monthly average near-surface chlorophyll during peak El Niño conditions (December 1997) and strong La Niña conditions (August 1998).

ENSO's impacts on the ecosystem are not solely through bottom-up processes. For example, anomalies in upper ocean temperatures in the western Tropical Pacific with El Niño and La Niña result in systematic shifts in the range of longitudes favored by skipjack tuna (*Katsuwonus pelamis*) as shown in Figure 4.2 (from Lehodey et al., 1997). This species typically ranks as second or third worldwide in terms of catch by weight, and so being able to anticipate variations in its distribution is of great practical importance, particularly since it is targeted by fisheries from a number of countries and subject to international management. In addition, the inter-dependency among the various species comprising the ecosystem can produce indirect effects. Breeding success for two species of western Pacific pelagic terns is systematically related to ENSO (Figure 4.3; Devney et al., 2009); this relationship has been attributed in part to the accessibility of their prey (forage fish) which tend to be more concentrated near the surface in the presence of sub-surface predators such as tuna (Jaquemet et al., 2004).

A variety of regions outside of the Tropical Pacific also have been shown to have a strong biological response to ENSO. A prime example is the California Current System (CCS), for which a large body of research has already been carried out (Chelton et al., 1982, McGowan et al., 1998, Chavez et al., 2002, among others). The physical connection between this region and the Tropical Pacific is through both coastally-trapped waves in the upper ocean, and the local response to anomalous winds accompanying large-scale atmospheric teleconnection patterns, primarily involving changes in the strength and location of the Aleutian Low. The typical result of El Niño is a depression of the thermocline and warmer SST, and a decline in lower-trophic level productivity, especially in the southern portion of the CCS.

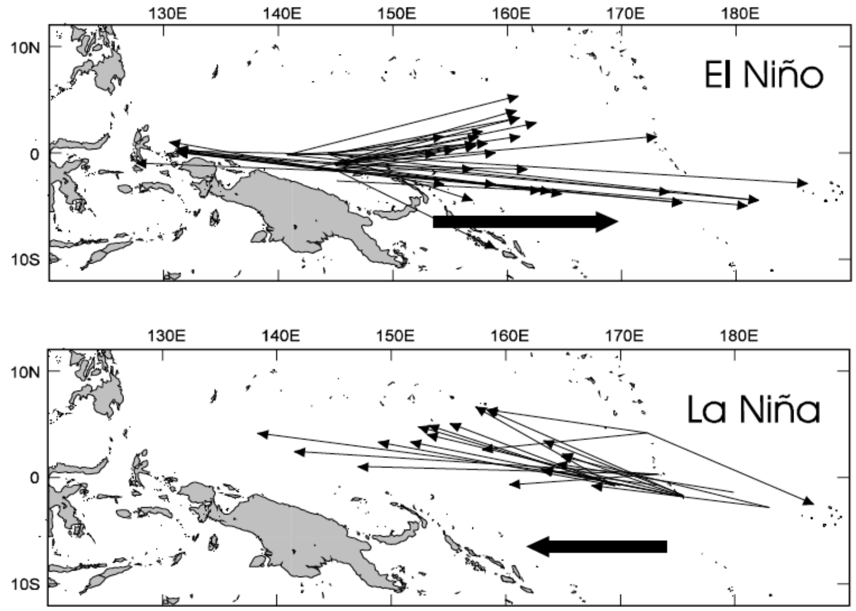

Figure 4.2 - Displacement of tagged skipjack tuna with ENSO events from a program carried out by the Secretariat of the Pacific Community (SPC) organization (adapted from Lehodey et al. 1997).

An important consequence of ENSO for the CCS is a change in zooplankton community structure. Hooff and Peterson (2006) have shown that sub-tropical (sub-arctic) species of copepods are favored off the coast of Oregon during El Niño (La Niña and neutral intervals), as shown in Figure 4.4.

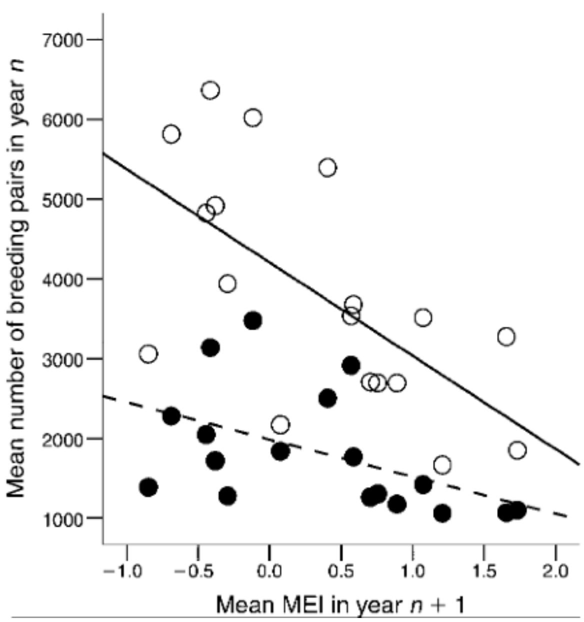

Figure 4.3 Number of breeding pairs of sooty terns (open circles) and common noddy (solid circles) on Michaelmas Cay of the Great Barrier Reef of Australia versus the Multivariate El Niño index (MEI) for the period of 1984-2001 (adapted from Devney et al. 2009).

This is an important effect because the copepod species frequent in this region that are characteristic of cooler waters tend to have relatively high lipid contents, and represent superior prey for juvenile salmon and other species ranging from forage fish to seabirds. It bears noting that ENSO's reach also extends well south of the tropics along the west coast of South America (Jordan) and as far as 60 N in the Gulf of Alaska (Bailey et al., 1995).

We close this sub-section with a few general points regarding linkages between ENSO and marine ecosystems, with relevance to other ENSO applications. Perhaps to an extent it is obvious, but it is worth emphasizing that the diversity in the strength and nature (e.g., longitude of peak anomalies) of ENSO events, and hence their remote effects/teleconnections, imply corresponding differences in the biological response (DiLorenzo et al., 2013 and references therein). The variability in the biological response means there is a potential for false attribution. That being said, accounting for the variability in the physical environment, including but not limited to phenomenon such as ENSO, should be incorporated in fisheries management.

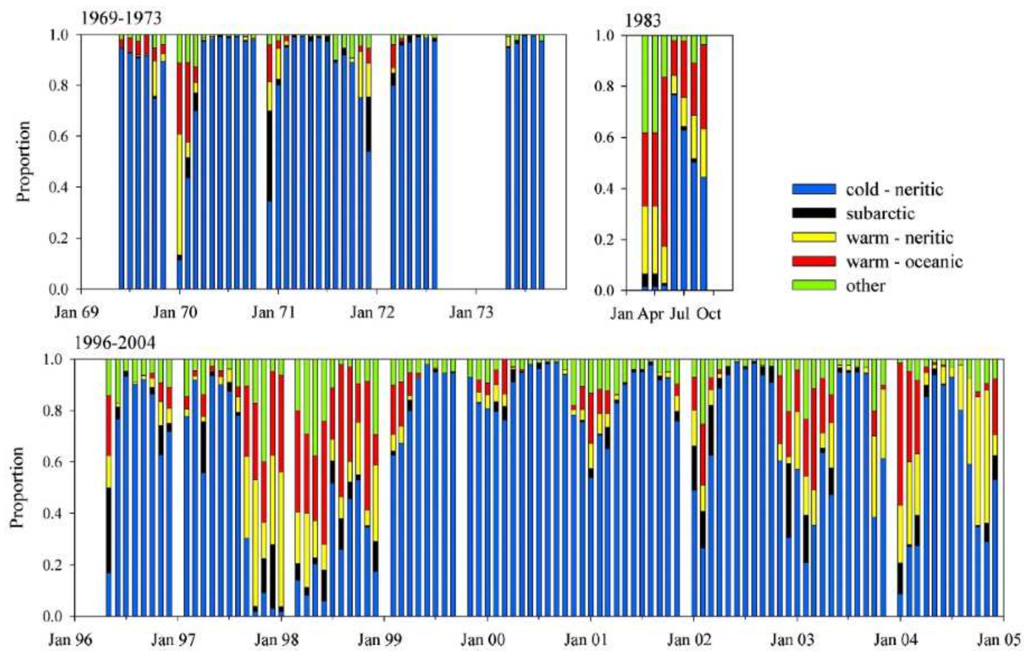

Figure 4.4 - Monthly average fraction of copepod assemblages relative to total copepod biomass. This time series includes the El Niño events of 1969-70, 1982-83, 1997-98 and 2002-03. It is normal to have a greater proportion of warm-water copepods in winter, when the prevailing winds are from the south, than during summer, when winds are from the north (adapted from Hooff and Peterson, 2006).

5. ENSO Impacts in Latin America, 2005 - 2012

To illustrate how ENSO events importantly affect the region of the world that gave the name "El Niño" to us, we consider the 'big picture' impact picture for Latin America and describe the weather anomalies associated with recent ENSO anomalous conditions. It is important to clarify that most of the documented impacts in the region are the result of the interaction of ENSO and the negative phase of the Pacific Decadal Oscillation (PDO). The last decade was characterized by predominant cooler than normal conditions in the South Eastern Pacific, and these modulate the ENSO influence at local level. The relationships are not clearly understood, and the attribution always will be a challenge, however, this compilation of impacts, which is based on expert reports from the different countries in Latin America, attempts to provide a first view of their magnitude, frequency, and diversity despite the relative moderate ENSO activity during these years.

Severe and persistent climate anomalies in Latin America and the Caribbean are closely linked with inter-annual variability (ENSO). The region comprises equatorial to mid-latitudes environments and a very wide diversity of climate regimes. The responses to different phases of ENSO include severe droughts, extreme rainfalls and temporal shifts in seasonal evolution. Considering the increasing vulnerability in the coastal zone and highlands, ENSO impacts are amplified with subsequent effects in economies and human wellbeing. This section describes climate impacts in Mexico, Central and South America associated with ENSO events during 2005-2012 years. In this period, 16.6% of years were under influence of El Niño (warm ENSO phase), 39.6% were under the influence of La Niña (cold ENSO phase), and 43.7% of those years were neutral. Hence, this last decade evidences the predominance of cooler SST anomalies. There were two warm events: 2006-2007 El Niño (moderate intensity), and 2009-2010 El Niño (stronger intensity but not comparable with 1982-1983). In contrast, there were five cold events: 2005-2006 La Niña (weak), 2007-2008 La Niña (moderate and extended to one year), 2008-2009 La Niña (weak), 2010-2011 La Niña (strong), and 2011-2012 La Niña (moderate).

In general terms, during La Niña occurrence, most of tropical South America to the East of the Andes is warmer than normal with more than normal rainfall in South Eastern Brazil. Conversely, southern South America is affected by rainfall negative anomalies and colder conditions. However, these typical teleconnections could be modulated for other climate variability modes (such us decadal), or more regional factors.

<u>Central American El Niño impacts</u>

El Niño 2006-2007

The 2006-2007 El Niño began in the second half of 2006. It was a short and weak episode, ending in the first quarter of 2007. A slight decrease in hurricane frequency in the Caribbean, and drier conditions than normal over Central America were observed during most of the year. Cold fronts with strong winds and rainfall affecting Guatemala, Honduras and Central Panama were recorded (Ramirez and Fernandez, 2007). Rainy season in Mexico was wetter than normal at the beginning of 2007 (Davydova-Belitskaya, 2007). During the first half of 2006, Brazil experienced a severe drought, which caused losses in 11% soybean and 48% wheat crops (Marengo and Baez, 2008). In contrast, during the 2006-2007 period, extreme rainfall and flooding comparable to the 1997-1998 ones occurred in Southern Brazil and Bolivia (Lopez and Russticucci, 2008).

El Niño 2009-2010

The 2009-2010 El Niño started in the second half of 2009. In July 2009, Mexico had the driest month since 1949 (Davidova-Belitskaya and Romero-Cruz, 2010). Drier than normal conditions were reported in Cuba and Venezuela, with strong impacts on the agriculture and energy sectors. During 2009, the tropical hurricane frequency was below normal (Amador et al., 2010). Drier than normal conditions were observed in Colombia, Ecuador, northeast Amazonia and Bolivia during the second half of 2009. In Paraguay, strong temperature anomalies were observed (4ºC to 5ºC) while above normal rainfall was reported in Brazil, Paraguay, Uruguay and Peru. These events forced the evacuation of thousands of people.

La Niña impacts

La Niña 2005-2006

The 2005-2006 La Niña started in the last quarter of 2005, and ended in mid-2006. Some related impacts were observed in Mexico with warmer and wetter than normal conditions associated with a high frequency of tropical cyclones, which affects several countries in Central America, especially Guatemala where a third of total population was impacted, as more than 1,000 people killed (Cortez Vazquez, 2006). Most of the Central American countries, especially Honduras, Nicaragua and Costa Rica, also experienced droughts with severe impacts on water resources and agriculture (Grover-Kopec, 2006). During 2005, most of South America evidenced below normal rainfall except for some specific areas in the northeast and southwest of the continent. The temperature was below normal on the Western coast of South America, but above normal on the Caribbean and Atlantic coasts (Rusticucci and Camacho, 2006). During the second half of 2005, Colombia was severely affected by La Niña. Intense and persistent precipitations caused flooding and landslides, which killed about 500 people, and destroyed more than 1,000 houses. Additionally, severe damage in basic infrastructure was reported (Pabon, 2006).

La Niña 2007-2008

La Niña 2007-2008 started in the second half of 2007, and ended in mid-2008. Mexico experienced above normal precipitation associated with an increased frequency of tropical storms and cold fronts. At the end of 2007, Tabasco City registered the worst flooding in the history, with over 80% of its area affected by the flood (Davydova-Belitskaya and Romero-Cruz, 2008). South America experienced very low temperatures in the south of the continent (-22ºC in Argentina and -18ºC in Chile (Marengo and Baez, 2008)), and positive precipitation anomalies between 40% and 60% in the Amazonia. Severe precipitations in Bolivia killed 30 people, and affected up to 25,000 people. More than 10,000 hectares of subsistence crops were destroyed, with more than 30,000.000 USD of losses (Ramirez, 2008). In Brazil, severe rainfalls killed 5 people and affected more than 50,000 people in Rio de Janeiro (Marengo et al., 2009).

La Niña 2008-2009

La Niña 2008-2009 started in the last quarter of 2008, and ended in the first quarter of 2008. It could be considered as an extension of the previous cold episode from 2007-2008. One of the associated impacts was the high frequency of tropical storms in 2008. Mexico evidenced a mean temperature anomaly of 0.7 ºC (Davydova-Belitskaya and Romero-Cruz, 2009). In most of Central America below normal precipitations were observed (Amador et al., 2009) during the first half of 2008. In South America, during 2008, above normal precipitation was reported at the coasts of Suriname, Guyana, Colombia and Ecuador, while in Venezuela, Colombia and southern Peru (Martinez et al., 2009) below normal precipitation was observed. During the first quarter of 2009, negative precipitation anomalies were reported in Southern Peru (-60%), Bolivia (-62%) and the Ecuadorian coast (-60%). In contrast, La Niña effects in Colombia were associated with positive precipitation anomalies between 40% and 70% (Martinez et al., 2010). During the first quarter of 2009, positive temperature anomalies between 3ºC and 4ºC were observed to the east of the Andes. In contrast, after La Niña finished in mid-2009, negative anomalies up to -3ºC were observed in Southern Brazil (Marengo et al., 2010). During the first months of 2009, positive precipitation anomalies between 25% and 50% were observed in the Amazonia while anomalies up 100% were registered in Northeast Brazil (Marengo, 2010).

La Niña 2010-2011

La Niña 2010-2011 started in mid-2010 and lasted approximately one year. The year 2010 has had a high frequency of tropical storms in the Caribbean (Amador et al., 2011). In August 2010, several tropical depressions coming from the Pacific caused intense rainfall along the southern Mexican coast (Davydova-Belitskaya and Romero-Cruz, 2011). La Niña influence was more evident during the first quarter of 2011, as most of South America reported below normal temperature with highest anomalies between -0.5ºC a -2ºC in Colombia, Ecuador and Peru. Several extreme cold temperatures (up to -20 ºC) were registered in the Bolivian-Peruvian Altiplano (Marengo et al., 2011). Positive precipitation anomalies associated with La Niña were reported in Venezuela (166%), Colombia (156 % to 200%), eastern llanos in Bolivia, central and northern highlands in Peru (400%) and in coastal areas of Ecuador and Peru (0 to 80%) (Martinez-Guingla et al., 2012).

La Niña 2011-2012

La Niña 2011-2012 started in the second half of 2011, and extended to the second half of 2012. In Mexico, the drought was persistent during 2011 jointly with high temperatures that reached an annual average anomaly of 1.1 ºC (second warmest year since 1971). This led to a record on burned areas caused by bushfires, with 956,405 hectares lost (Lobato-Sanchez, 2012). In South America, some of the remarkable impacts of La Niña were the positive precipitation anomalies in Ecuadorian highlands and northern and Central Peru (between 150%-800%) (Martinez-Guingla et al., 2012). During 2012, most of tropical South America to the East of the Andes was warmer than normal with anomalies up to 1ºC. In North of Paraguay and southern Bolivia, the temperature anomalies were up to 3ºC. In January 2012, strong precipitation was recorded in South East Brazil affecting 53 cities and killing 7 people. During the first quarter of 2012, above normal precipitation associated with La Niña were reported in Trinidad and Tobago (184%), Grenada (200%). In March 2012, Colombia was affected by severe flooding in 18 of the 32 departments with more than 66,000 affected people (Marengo et al., 2013). Conversely, the South of South America was affected during the first quarter of 2012 by deficit of precipitation (Bidegain et al., 2013).

6. ENSO effects on the increase of atmospheric carbon dioxide

We have not addressed so far any of the various ways that ENSO can be important in the global scale evolution of planetary conditions. Climate change is on the minds of many, and understanding the persistent and time-varying impacts likely to occur in the future is important. ENSO plays a very significant role in determining the changes in atmospheric carbon dioxide concentration that are seen each year. In fact, the effects of a strong El Niño can account for nearly as much exchange of carbon between the earth's surface and the atmosphere as anthropogenic activity. The effects of La Niña on the global carbon cycle, on the other hand, typically counteract, to a substantial extent, the effects of anthropogenic carbon emissions. The strong effects of natural variability in the observed atmospheric growth rate are clearly seen in Figure 6.1 (Harrison and Chiodi, 2014), which plots the atmospheric carbon dioxide concentration time series from Mauna Loa (black curve; Keeling et al.,2001) along with the estimated amounts of carbon dioxide emitted by the burning of fossil fuels (Boden et al., 2011), scaled such that the concentration curve would track emissions if all emitted carbon dioxide remained airborne and there were no other sources of variability. Evidently, much of the emitted carbon is re-absorbed by the surface (ocean and land) and the strong year-to-year variability in the observed carbon dioxide concentration is contributed by sources other than fossil fuel consumption.

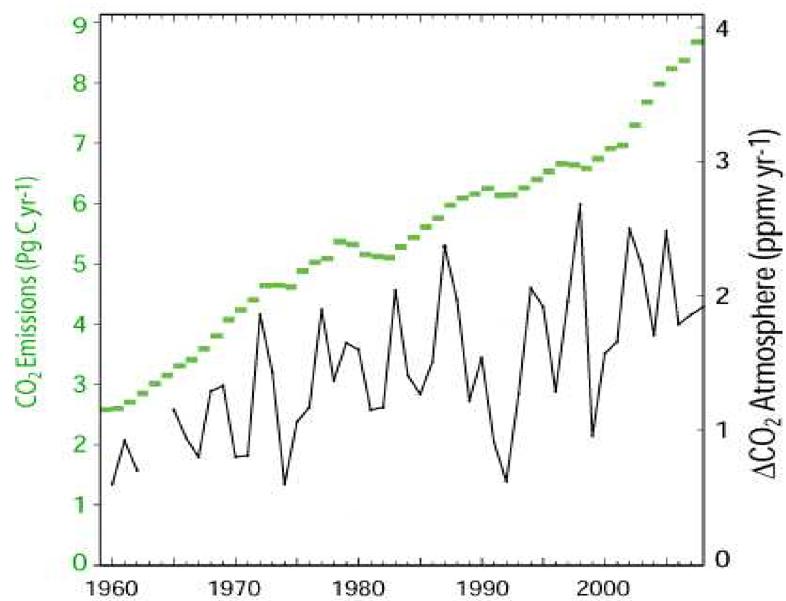

Figure 6.1 - Atmospheric concentration of CO2 (Mauna Loa) and year to year change in concentration. Note strong interannual variability in change of concentration.

Figure 6.2 shows the annual increase in atmospheric carbon dioxide concentration year by year once the trend from fossil fuel emissions is removed and shows the strong similarity of behavior between El Niño years (the conspicuous exception is 1991-92, with the strong Mt Pinatubo explosion). Concentration changes of the opposite-sign, but very similar event by event behavior, are seen during La Niña years. Figure 6.3 shows the composite effects of El Niño and of La Niña events; La Niña effects are smaller than those from El Niño and occur somewhat differently during the year, but still account for a substantial change in the atmospheric growth rate. The La Niña average and El Niño average effects listed in Figure 6.3 are roughly 1/3rd and 2/3rd of the average annual growth rate seen over the last 50 years.

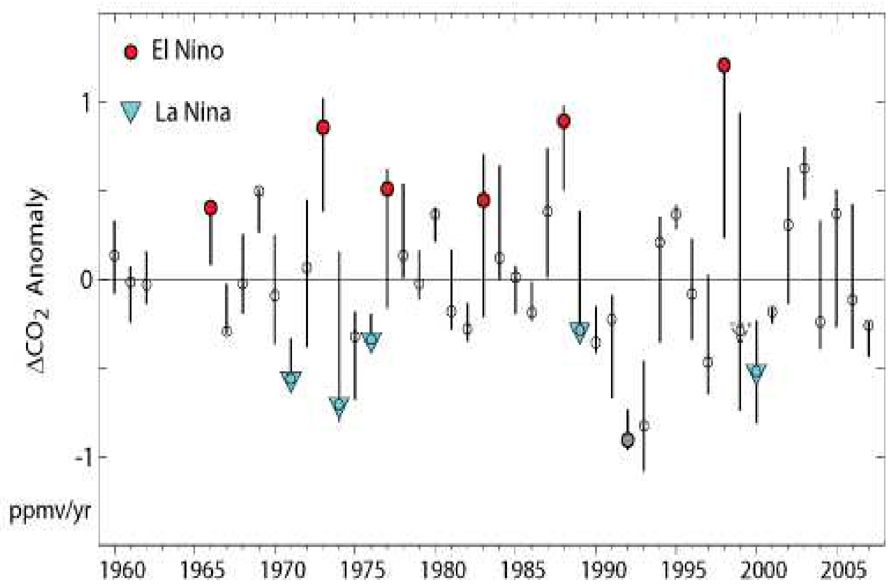

Figure 6.2 - Year to Year change in concentration, with trend removed. El Niño and La Niña years identified.

Clearly, if the statistics of ENSO are to change under global climate change, as has been suggested recently by analysis of the CMIP3 and CMIP5 coupled climate change models, the future trajectory of atmospheric carbon will also be affected.

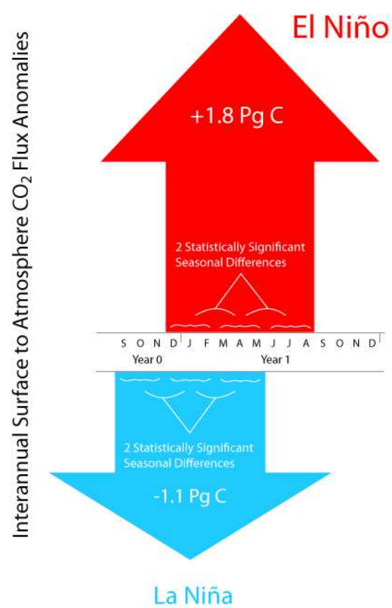

Figure 6.3 - The average effect of El Niño and La Niña years on atmospheric carbon dioxide concentration, and the seasons over which the change takes place.

7. Discussion

We have provided several examples of how ENSO affects conditions that have societal impact. Understanding how to predict ENSO events better as well as how different sorts of ENSO events affect different nations in different seasons, remains very much a work in progress despite the efforts of the ENSO research, prediction and impacts communities. Many societies suffer profound impacts, on average, during El Niño and/or La Niña events. The companion impacts paper to this one (Zebiak et al., 2014) provides examples of impacts on agriculture and health, which we have not addressed here. Other White Papers prepared for this workshop will provide insight into the challenges of better observing, understanding and predicting ENSO events.

ENSO is also connected with other large scale climate anomaly patterns, and these connections are the subject of on-going research. There are well known links to low frequency SSTA variability of the North Pacific, which can be considered from the perspectives of the Pacific Decadal Oscillation or North Pacific Oscillation or the Inter-Pacific Oscillation. There are also links to Indian Ocean patterns of SSTA variability, which can be considered on their own or through the Indian Ocean Dipole perspective.

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