Climate Change and the Future of ENSO

The El Niño/Southern Oscillation (ENSO) is a phenomenon that causes variations in oceanic and atmospheric conditions in the equatorial Pacific Ocean. These deviations from normal or "neutral" conditions are known as El Niño and La Niña events. During an El Niño event, easterly trade winds and equatorial currents slacken, and sea surface temperatures (SST) from the eastern equatorial Pacific to the maritime continent in the west (the region that includes Indonesia, the Philippines, and Papua New Guinea) are elevated. La Niña events have the opposite effects, strengthening winds and currents and cooling SSTs. In addition to the direct changes to atmospheric and oceanic behavior seen in the equatorial Pacific region, ENSO also has strong effects to Earth's entire climate system, causing droughts, flooding and severe storms in remote locations across the globe (Neelin & Latif, 1998). Still, the exact cause of ENSO irregularity is debated, with possible explanations including random atmospheric noise, deterministic chaos within the system, and background climate fluctuations (Cobb et al., 2003; Neelin & Latif, 1998). As anthropogenic greenhouse gas inputs into the atmosphere cause changes to the background temperature state globally, changes to the ENSO system may result from this global climate change. However, because ENSO dynamics are still not fully understood, predicting these changes can be difficult. Climate models attempt to determine how the ENSO system will be affected by future anthropogenic increases in the background climate; however, there is not a definite consensus across models as to how ENSO will respond to global warming, with some models predicting intensification, some predicting weakening, and some predicting no discernible change to the system (Collins et al., 2010). Still, some recent coral records of ENSO behavior show changes to the system associated with increasing background temperature (Urban et al., 2000), and many models, especially those that can recreate extreme ENSO events, expect both the frequency and severity of ENSO events to increase under global warming (Cai et al., 2015). Although there is no clear consensus on how the ENSO system will change as a result of anthropogenic greenhouse forcing, it is possible that ENSO behavior will intensify in the future, leading to economic and environmental impacts that would be seen across the globe.

In order to understand the effects of ENSO on the oceanic and atmospheric dynamics in the equatorial Pacific, it is important to understand how these systems behave under neutral conditions. At the equator, easterly trade winds dominate as the result of a convergence of surface winds that are deflected by the Coriolis force to blow from east to west. These easterly surface winds are one component of the Walker cell, which is the convective cell that controls the local atmospheric circulation in the equatorial Pacific region. The trade winds also drive equatorial surface currents in the ocean to flow from east to west, causing upwelling of cold, nutrient-rich water along the South American coast, and pooling of warm water near the maritime continent in the west. The SST gradient that arises from the surface currents also gives rise to an atmospheric pressure gradient: hot air rising over the maritime region creates a low-pressure zone, while in the east, where cool, dry air is sinking, air pressure is higher. This pressure gradient reinforces surface winds that blow from the east to the west over the equatorial Pacific. Under neutral conditions, the Walker circulation functions with warm air rising in the west, cool air descending in the east, and surface winds blowing from east to west down this pressure gradient. The east to west surface ocean currents that arise from these winds cause warm surface water to be pushed towards the west and pool up in the maritime region and a "cold tongue" of low SST to form in the east as cold water flows upwards to replace the water flowing to the west (Cai et al., 2015; Neelin & Latif, 1998). Because the ocean and atmosphere are constantly exchanging heat and water, they are strongly coupled, with a feedback that operates on timescales of weeks to months (Dunbar, 2000). Thus, changes to the atmospheric circulation will result in changes to the ocean currents (and vice versa), a phenomenon known as the Bjerknes feedback. This Bjerknes feedback is a positive feedback loop that allows the runaway effect that causes El Niño and La Niña events. If trade winds weaken, surface currents will also weaken since there is a weaker force that drives them. This will decrease the temperature gradient across the equatorial Pacific, as less cold water is upwelling in the east and less warm water is pooling in the west. This will also decrease the atmospheric pressure gradient between the east and the west, thus further slackening trade winds and promoting even more of a response from the system. This example would lead to an El Niño event, characterized by decreased wind and current strength, leading to a decrease in upwelling that causes unusually high SST in the eastern Pacific, but the reverse is also possible, where strengthened trade winds lead to higher temperature and pressure gradients, causing a La Niña event with colder than usual SST (Cai et al., 2015).

Because of this positive feedback behavior, it takes only a small change in atmospheric or oceanic conditions to trigger a powerful El Niño or La Niña event, meaning they can be brought about by minor, random fluctuations (Dunbar, 2000). Since global warming is not simply a consistent increase in temperature across the globe, it is possible that it could influence the temperature gradients that allow the Walker circulation to progress. So far, we have observed a faster trend of warming in the eastern Pacific than the central Pacific and maritime continent. This is due to the fact that SST in the east is colder to begin with and is not in equilibrium with the atmosphere like the west, as upwelled cold water masses in the east have not been in contact with the atmosphere for a long time like the pooled masses in the west (Cai et al., 2015; Collins et al., 2010). This contributes to the overall trend of weakening Walker circulation over the past 60 years, as an important driver of the Walker circulation is the atmospheric pressure gradient that arises from the SST gradient. With a Walker circulation that is weaker to begin with, it may become even easier to tip the system into an El Niño extreme (Cai et al., 2015). However, an increase in background temperature state will have varied effects of the different couplings at play in the Bjerknes feedback, so the response of ENSO to climate change may not be so simple.

Several processes participate in the Walker circulation and Bjerknes feedback that may have a role on ENSO variability. These include upwelling along the west coast of South America, wind stress driving currents, flattening and shoaling of the thermocline, heat transport away from the equator, and atmospheric damping of SST anomalies (Collins et al., 2010). With an increased background temperature state caused by climate change, Walker circulation will be weakened. This will cause a decrease in upwelling, as trade winds slacken and the wind stress that drives surface currents is weakened. This lowering of the temperature gradient that results from decreased inputs of cold upwelled water could cause enhanced ENSO activity (Cai et al., 2015; Collins et al., 2010). Another process that may promote ENSO events is the flattening and shoaling of the thermocline. During El Niño events, the warm water travels from the pool in the west back towards the east in a series of very large, long-wavelength, slow moving waves (Dunbar, 2000). These waves cause a flattening of the thermocline across the equatorial Pacific. The thermocline (which separates the warm surface mixed layer from the cold deep ocean) is usually deep in the west under the warm pool and shallow in the east where upwelling is occurring, but as warm water travels to the east during an El Niño, the thermocline becomes both flatter and shallower as warm water spreads out over a larger area (Collins et al., 2010). The weakening of the Walker circulation will contribute to a flattening and shoaling of the thermocline's mean state, pushing it closer to El Niño conditions and promoting El Niño events (Collins et al., 2010). In addition, increased background climate will cause an increase in heat transport away from the equator as the higher atmospheric temperatures will preferentially warm the surface ocean. This will cause increased temperature gradients across the thermocline between the mixed layer and the deep ocean, and a more thermally stratified water column. Because of this, warm water will be forced to flow outward from the equator, causing greater advection poleward (Cai et al., 2015). The transport of warm water away from the equator will further contribute to the shoaling and flattening of the thermocline, promoting intensified ENSO activity (Collins et al., 2010).

Although global climate change will promote many responses in the equatorial Pacific that favor increased ENSO activity, there are also processes at play that would tend to weaken the ENSO system. With an increased background temperature, damping of SST anomalies by the atmosphere is expected. Higher temperatures promote an increase in evaporation and cloud formation over this region, leading to a negative feedback as clouds block incoming shortwave radiation that reaches the ocean, thus cooling the region. Increasing this damping effect is expected to weaken El Niño growth, as it will prevent the formation of the SST anomalies that are characteristic of these ENSO events (Cai et al., 2015; Collins et al., 2010). Because the increase in background climate due to global warming will have varied effects on the different feedbacks that control ENSO activity, it can be difficult to predict what effect anthropogenic climate change will have on ENSO. Indeed, Collins et al. found that out of several complex coupled global circulation models (CGCMs) that attempt to predict ENSO changes by modeling ocean and atmospheric dynamics under climate change, some predicted ENSO activity to increase, some predicted ENSO activity to decrease, and some saw no significant change in the ENSO system (2010). As the mechanisms of the ENSO system involve many couplings and feedbacks that will have different responses to climate change, there is not a clear consensus as to how this system will evolve in the future.

One method that attempts to predict the effects of climate change on ENSO conditions in the future is to look at historical records of ENSO events and background climate in the past. Some of the most well-preserved records come from the isotopic composition of coral skeletons from the equatorial Pacific region. This calcium carbonate paleothermometer uses the relationship between temperature and the extent of isotopic fractionation to predict the SST of the water that the calcite skeleton of the coral is precipitating from. At lower temperatures, a greater extent of isotopic fractionation occurs between the oxygen isotopes in the water that the calcite is precipitating from and the calcite itself. The heavy oxygen isotope ^{18}O is favored in coral skeletons since bonds formed by heavy species are more thermodynamically stable, so the $\delta^{18}O$ values of these coral skeletons will be higher at low temperatures when there is a greater extent of fractionation. Inversely, at high temperatures, there will be less fractionation, and $\delta^{18}O$ in the coral skeletons will be lower (Clark & Fritz, 1997). Thus, by measuring the $\delta^{18}O$ values of the calcium carbonate that composes coral skeletons, past SST can be reconstructed. Since corals can grow for hundreds of years, and the conditions at different times will be recorded in different parts of the coral's skeleton, these measurements provide a high-resolution climate history. And because the main influence on SST in the equatorial Pacific region is the ENSO conditions, and corals from Pacific atolls can accurately record the temperature conditions in this region, the coral records also provide a reconstruction of ENSO activity (Cobb et al., 2003). During El Niño events, when there are positive SST anomalies in the eastern and central Pacific, corals skeletons from these areas will have lower $\delta^{18}O$ due to a lesser extent of fractionation caused by the higher temperatures. Likewise, during La Niña events, when SSTs are depressed, the $\delta^{18}O$ values of coral skeletons will be greater as a result of the greater fractionation of oxygen isotopes (Cobb et al., 2003).

Using this technique, several historical records of ENSO conditions have been created. A reconstruction of central Pacific climate used fossil corals from Palmyra Atoll in order find SST during several intervals over the past millennium. This reconstruction showed that even without greenhouse forcing, ENSO is highly irregular, changing in intensity and switching back and forth from decadal to interannual variation several times (Cobb et al., 2003). In this study, Cobb et al. found that over the entire 1000-year time span, there was not a significant relationship between background climate state and ENSO variability. However, the study did suggest that the ENSO system could undergo "regime changes" (Cobb et al., 2003). Under natural climate fluctuations, ENSO might be highly variable, but would stay within a predictable range of behavior. With anthropogenic greenhouse forcing, which is causing unprecedented, rapid temperature increases, the ENSO system could be shifted into a new regime with more extreme behavior.

Other studies have found that changes in ENSO behavior due to climate change have already been observed. Urban et al. created a 155-year climate and ENSO reconstruction from corals of Maiana Atoll in the western central Pacific (2000). This reconstruction agreed with both another reconstruction using corals from Tarawa Atoll as well as instrumental data for the recent portion of the past 155 years for which this data was available. Urban et al. found that while there was a slight trend of warming throughout the entire time interval, there was a significant shift in climate that occurred in 1976, when 0.6°C of warming occurred compared to the past 25 year average (2000). From 1855 to around 1900, decadal variability dominated the ENSO system. Then, in the late nineteenth and early twentieth centuries, the system shifted towards interannual variation with a period of 5-7 years. The last shift towards an even shorter period with an average of 4 years coincided with the sharp background temperature increases. Based on these observations, Urban et al. concluded that ENSO variability was in fact linked to anthropogenic climate change, since changes from decadal to interannual variability aligned with the onset and acceleration of global warming (2000).

In addition to historical ENSO records, there is also evidence that global warming may cause an increase in the frequency and intensity of ENSO events in climate models. The Coupled Model Intercomparison Project Phase 5 (CMIP5) compiles the results of several global coupled ocean-atmosphere general circulation models, which attempt to predict ENSO dynamics in the future. Using CMIP5 models, Cai et al. found that several of these models agree that the projected slackening of Walker circulation in the equatorial Pacific will cause more frequent extreme El Niño events, which in turn will provide favorable conditions for extreme La Niña events immediately following (2015). In this study, Cai et al. stress the differences between weak and extreme El Niño events, as well as the asymmetry between extreme El Niño and extreme La Niña. During extreme El Niño events, the maximum SST anomaly is in the eastern equatorial Pacific, while the maximum SST anomaly during weak El Niño events is found in the central Pacific. Inversely, the anomaly center of extreme La Niña events is in the central Pacific and that of weak La Niña events is in the eastern Pacific. Because the slackening of the Walker circulation promotes the frequency of eastward-propagating positive SST anomalies, since a smaller perturbation is required to disrupt the circulation, this increases the occurrences of extreme El Niño events. 12 out of 21 models that were able to produce extreme El Niño events agreed that the frequency and amplitude of extreme El Niño events will increase in the future under increasing background temperatures. 15 of these 21 models predicted an increase in amplitude of extreme La Niña, and 17 predicted an increase in extreme La Niña frequency (Cai et al., 2015). Additionally, the occurrence of an extreme El Niño event promotes the formation of an extreme La Niña event in its wake, as the shoaling of the thermocline and increase in SST during an El Niño cause a sharper poleward temperature gradient in the surface ocean. This gradient will cause a gradual flow of warm water outward towards the poles, which can eventually lead to the rapid cooling and negative SST anomalies in the central Pacific of a La Niña event (Cai et al., 2015; Collins et al., 2010). Indeed, 75% of the modelled increase in extreme La Niña events is seen after extreme El Niño events (Cai et al., 2015).

Based on these models that are able to predict extreme ENSO events, there is evidence that ENSO activity will increase under global warming. Still, because of the varied effects of climate change on processes that promote or dampen ENSO activity (Collins et al., 2010) and the fact that some models do not agree on the predicted behavior of ENSO under global warming (L. Chen et al., 2015; Philip & van Oldenborgh, 2006), it is not definitively clear how the ENSO system will evolve in the future. By comparing differing models from CMIP5 that predicted both increases and decreases in ENSO amplitude under global warming, Chen et al. found that the main factor associated with this change in amplitude was the meridional width of the SST anomalies caused by ENSO events (2015). Wider, more spread out anomalies caused less of a thermocline response, which in turn lead to weaker Bjerknes and zonal advection feedbacks. This corresponded with a weakening of ENSO amplitude. Narrower SST anomalies had a greater effect on the thermocline, increasing ENSO amplitude through stronger Bjerknes and zonal advection feedbacks (L. Chen et al., 2015). Later studies found that the meridional width of ENSO SST anomalies was controlled by the Pacific subtropical cells (STC) (L. Chen et al., 2017). With stronger STC circulation, there is a greater poleward transport of surface water, causing an SST anomaly with a greater meridional width. A weaker STC circulation will cause the opposite effect. This means that STC strength is inversely correlated with ENSO amplitude; stronger STC circulation leads to lower amplitude ENSO events and vice versa (L. Chen et al., 2017). Most CMIP5 models agree that the poles will have a more rapid temperature increase caused by global warming than the tropics. Because the tropics are already quite warm, temperature in this region is controlled by a negative feedback where increased temperature causes greater evaporation and more cloud formation, which in turns blocks incoming shortwave radiation, causing temperatures to fall again. The poles, which start out cold, will experience less of this damping effect, allowing temperatures to rise faster. L. Chen et al. expect that this uneven warming is likely to decrease the strength of the STC, and if that is the case, ENSO amplitude may increase as a result of global warming (2017).

While the possible increase in frequency and amplitude of ENSO events caused by anthropogenic climate change would have a direct effect on the equatorial Pacific region, the effects of increased ENSO activity would also be seen across the globe. Because ENSO activity can affect the dynamics of global atmospheric circulation, the deviations from neutral conditions that ENSO events cause can result in extreme weather events in other regions around the world. ENSO teleconnections, or the effects of ENSO activity that are physically remote from the central and eastern equatorial Pacific, include droughts in Australia and Indonesia and extreme flooding in Ecuador, northern Peru, and the southwest US during El Niño years, and increases in landfalling hurricanes in the Atlantic and tropical cyclones in the west Pacific, droughts in the southwest US, and flooding in west Pacific countries during La Niña years (Cai et al., 2015; Neelin & Latif, 1998). With increasing ENSO activity, there will also be increases in the frequency and severity of these extreme weather events caused by ENSO teleconnections, which could cause increases in the damages to property and ecosystems that these weather events cause. The economic losses due to storm damages from the 1997/98 extreme El Niño event were over 700 million USD in the US alone (Weiher, 1999). Even more economic losses from ENSO teleconnection will result from damages to the agriculture industry, as regional changes in weather patterns caused by ENSO events can decrease crop yields. Overall, the expected economic losses in the global agriculture system are 3-4 million USD per year if only the frequency of ENSO events increases, and over 1 billion USD per year if both frequency and intensity increase (C. C. Chen et al., 2001). In addition to the decrease in fisheries productivity of the west coast of South America as the direct result of the decrease in upwelling of cold, nutrient-rich water during El Niño years, fisheries in the Pacific Northwest are expected to face annual losses of 1 million USD as a result of increased ENSO activity (Weiher, 1999). As climate models and ENSO predictions improve in the future, some economic losses may be mitigated with accurate advanced notice of ENSO conditions and extreme weather events (Weiher, 1999). However, as global warming continues, if ENSO events become more frequent and severe as a result, the global damages incurred by ENSO teleconnections will only grow.

The El Niño/Southern Oscillation is a highly irregular system that has seen significant fluctuations through history, including changes between decadal and interannual variation and periods of enhanced or weakened intensity. Because the positive Bjerknes feedback controls the onset of ENSO events, it takes relatively small perturbations for these events to be set into motion by a runaway effect. However, several processes and feedbacks play a role in the ENSO system, and global climate change will not have the same effect on all of these, so some responses are expected to enhance ENSO activity, and others are expected to dampen it. Because of this, it can be difficult to predict exactly what effect the increasing background temperatures will have on ENSO frequency and intensity, and there is not a consensus seen across all models as to how ENSO will respond to climate change. Still, historical ENSO records from the oxygen isotope ratios of corals have already seen a shift from decadal to interannual variability in ENSO as a result of the onset of anthropogenic global warming (Urban et al., 2000). In addition, many models from CMIP5 that are able to recreate extreme ENSO behavior agree upon an increase in both the frequency and amplitude of extreme El Niño and La Niña events in the future, as Walker circulation is weakened as a result of uneven heating across the equatorial Pacific (Cai et al., 2015). There is also evidence that ENSO is influenced by the strength of the STC, so if STC circulation weakens, it is likely to enhance ENSO activity (L. Chen et al., 2017). If ENSO activity increases, so too will the extreme weather events that occur across the globe as a result of ENSO teleconnections, as well and the economic losses incurred due to those weather events (C. C. Chen et al., 2001; Weiher, 1999). On its own, anthropogenic climate change already poses great threats to world ecosystems and economies. With the addition of these consequences from enhanced ENSO activity, even more damages due to climate change can be expected in the future, further emphasizing the necessity of mitigation strategies for anthropogenic global warming.

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