SCRIPT

Hello, my name is Ben Goldman, and this is my presentation *The Impact of Anthropogenic Forcing on ENSO Amplitude.*

Everyone, or almost everyone, knows that climate change is real. However, global warming is but one aspect of the way that the Earth's atmosphere changes over time. Even more than global warming, we humans are really at the mercy of smaller-scale climate variability, the differences we see between individual years and decades. A single year of drought can ruin lives, while a particularly strong rainy season can wash away entire cities. Both of these modes of climate variability are summarized in figure 1, where there is both a smaller-scale fluctuation in average global temperature between years as well as a larger-scale increase in air temperature between 1850 and the present.

What causes long-term climate change? The major drivers of climate change are shown in figure 2. greenhouse gas emissions increase global air temperature by trapping heat radiation, aerosol emissions cool the climate by reflecting heat before it reaches the surface, biomass burning includes things like forest fires, and land use and land cover includes deforestation and agriculture. In this study, these drivers are collectively known as *forcing factors*

So now we know what drives long term climate change, but what controls small scale climate variation? The Earth's year-to-year climate is governed by a variety of processes and cycles, but the most influential is ENSO, or El Niño Southern Oscillation. Controlled by the temperature of the Pacific Ocean, ENSO has vast economic and societal impacts. Figure 3 illustrates some of these effects, as it shows difference in sea temperature between an El Niño year and a La Niña year and the average temperature. During ENSO's warm phase, El Niño, higher Pacific oceans decrease the output of Central American fisheries, flooding in the eastern United States and South America, and droughts in Indonesia. In contrast, the cool phase, La Niña, often causes wildfires in northern California, higher rates of hurricanes in the Atlantic, and droughts in parts of South America. Due to these immense impacts on human societies, it is vital that we improve our prediction of ENSO, especially under climate change.

The influence of climate change on ENSO is not a new question. A 2014 showed that there is a statistically significant difference in certain aspects of records of ENSO events between the decades in 1990 and 2000. A 2017 study examined paleontological records and simulations of ENSO intensity during the last ice age, a period dominated by reduced carbon dioxide levels. They found that reduced greenhouse gas levels may have caused reduced ENSO intensity, establishing a positive correlation between greenhouse gas levels and ENSO amplitude. Finally, another 2017 study used simulations of future climate under global warming, and found that these simulations contained significantly increased ENSO activity.

While these studies do suggest that ENSO may become stronger due to global warming, there are still a number of questions that must be answered. First, none of these studies examined the impact of each separate forcing using a large number of simulations, meaning that it is not yet clear how large of a role global warming plays in comparison to other factors. Additionally, there is still some disagreement between studies on whether ENSO will significantly strengthen in the future. Given this gap, I formulated two main questions. First, do the well-established climate models CESM1 and CESM2 predict increased or decreased ENSO intensity in the future? Second, Is this predicted increase or decrease due to human activities?

On to the methods and results section.

All of the raw data in my experiment came from the CESM, Community Earth System Model and was provided by my mentor. I used versions 1 and 2, where version 2 is more recent and thus may be more accurate. These simulations model the earth's future climate by receiving an input of recorded and predicted forcing levels. After running their internal code on the input data, the models output a variety of variables on a latitude-longitude grid. These models produce predictions that cover most of the 21st century, and therefore are extremely useful for examining future behaviour of climate change. I used Sea Surface Temperature, or SST. The models output data that ranges from 1850 through 2100. These simulations are run repeatedly, around 40 times each, with slightly different initial conditions. This process enables researchers to derive a statistical sample, vastly increasing the reliability of their predictions. My mentor also provided me with single forcing ensembles, simulations from the same model that were input with only one forcing factor (such as only greenhouse gasses). This dataset enables me to compare the impact of each factor on ENSO activity. I used these listed software packages for a variety of tasks, including preparing the data, conducting statistical analysis, and plotting.

This slide shows the first group of steps in my methodology. My mentor conducted the first step of running the CESM climate models with an input of the forcing records and predictions. After receiving sea surface temperature as an output from the models, I first calculated the mean tropical Pacific temperature at each month for each simulation. This temperature has been shown to represent ENSO's state at any particular time, where higher temperature indicates an El Niño event and lower temperature is correlated with La Niña events. From this dataset I did a windowed variance calculation to derive a second time-series that represents ENSO's intensity. This calculation involved finding the variance of a 20-year span of months, and then repeating that process for all months in the dataset. Finally, I found the mean and standard error across all the simulations for both the CESM1 and CESM2.

Figure 4 shows the results of this whole process, where the colored regions indicate standard error. Both the CESM1 and CESM2 have a statistically significant increase in the variance of tropical pacific temperature between 1850 and 2050.

Interestingly, this increase does not continue past 2050, as both models show slightly decreasing variance during the second half of the 21st century. The key takeaway from these data is that the model I use predicts increased ENSO intensity when simulating global warming. This indicates that we may be seeing increased ENSO activity over the 21st century.

The next step of my methodology was intended to determine the role of greenhouse gasses, aerosols, and other factors. To do this, I conducted the same group of steps from before, but using the single forcing ensembles provided by my mentor. Thus, the output data represents each factor's contribution to ENSO amplitude. The results are shown in figure 5, which contains the data for greenhouse gasses (ghg) and aerosols (aer). Land use and cover and biomass burning were not included because their data either did not have any significant change over time, indicating no contribution, or they contained too few simulations to be reliable. The greenhouse gas data on the bottom contains a steady increase in variance, which indicates that greenhouse gasses are the main factor that drives increasing ENSO intensity. In contrast, the aerosol record is less coherent. While it does show change over time, this change is not linear. This data indicates that aerosols may be driving the decreasing variance in the second half of the 21st century seen in the previous slide. The takeaway from this data is that human greenhouse gas emissions are likely what will cause increased ENSO activity in future decades.

The final step of my methodology was intended to provide more insight into what about ENSO activity is predicted to change in the future, what characteristics of ENSO will become more active. To do this, I conducted a wavelet analysis. ENSO's cycle can be viewed as a wave, oscillating between El Niño and La Niña events. Like a sound wave, ENSO has frequency and amplitude, although ENSO is not periodic, since no two El Niño events are identical. Wavelet analysis allows comparison between ENSO activity at a variety of frequency levels. It is akin to comparing the loudness of sound at a range of different frequencies or pitches. So I used wavelet analysis to derive ENSO intensity with a period of greater than 3 years and less than 3 years. For the CESM1, we see that ENSO with a period of greater than 3 years increased much more than that with a shorter period, or higher frequency. For the CESM2, we observe similar power levels for both shorter and longer period ENSO, except the greater than 3-year data decreases more after 2050. These two observations suggest that longer-period ENSO may be more susceptible to external forcing than ENSO with a faster cycle.

During this methodology, I conducted all the data analysis, produced all the figures of my data, wrote documentation, and did identified the key features of the results. My mentor reviewed my writing and results and compared them to his own parallel results. He also provided the raw data.

To review, my study answered two questions: *Do the CESM1 and CESM2 climate models predict increased or decreased ENSO intensity in the future?* and *Is the predicted increase (or decrease) due to human activities?* The answer to the first question is yes, both the CESM1 and CESM2 predict increased ENSO amplitude in future decades. My study answered the second question with another yes, since the greenhouse-only simulations exhibited a steady increase in ENSO amplitude while the others did not. Not only is the Earth becoming warmer, it is also becoming more temperamental and less predictable, and we need to be ready.

My study has a few limitations, the first of which being that the method used to record ENSO has been shown to be slightly inaccurate for certain models, although my own analysis showed that this was not an issue for the CESM. More importantly, climate models are only a simulation, thus they will always contain some inaccuracies. Although repeating the analysis on different simulations provided more validity, no model will ever be a perfect representation of the Earth's climate. This study will aid policy makers to prepare their infrastructure for increased ENSO-related weather in the future. We as a nation need to pay more attention to the harsh reality that our climate will become more variable and less stable as the earth warms. By bringing attention to this lesser known aspect of the climate crisis, my study plays a role in helping us to understand the complexity of the Earth's atmosphere.

The data used in this study came from models developed by the atmospheric scientist community that were run on computers at facilities from the National Center for Atmospheric Research. I would like to thank my teacher, my family, and my mentor for their amazing support these last few years and their dedication to this project.

These are my references! Thank you all for listening!