Title slide: Hello, my name is Benjamin Goldman, and I am presenting an in-progress study titled "The Impact of Anthropogenic Forcing on ENSO Amplitude" Have you ever experienced an especially rainy winter, or weirdly hot summer? This phenomenon is most likely caused by El Nino.

This study is on the impact of climate change on El Nino. Research on this subject is important because El Nino has a drastic effect on human society, by controlling rainfall and drought patterns all over the world. El Nino Southern Oscillation, or ENSO, is a cyclical change in the temperature of the equatorial Pacific Ocean. ENSO is one of the most influential elements of the climate system, and yet it is one of the most complex. The mechanics of ENSO are illustrated in this diagram, in which reduced upwelling in the eastern pacific increases sea surface temperature and disrupts air currents, increasing rainfall in the central and eastern pacific.

Shown here is average global air temperature since 1880. There is a significant increase in global temperature, driven by greenhouse gas emissions, known as global warming, shown by the red smoothed line. Importantly, this is a long-term trend, which may not be visible on smaller time scales. The other main aspect of this graph is the small-scale modulation of air temperature shown by the black line, which disappears once the graph is smoothed. This form of variability is known as internal variability or noise, and it can cloud researcher's measurement of longer-term trends. Internal variability includes phenomena such as the yearly monsoon season and ENSO. Much of climatology is focused on the interaction between these 2 scales of change over time.

There has been considerable progression in research on the role of climate change in ENSO. Some studies predict that ENSO intensity would increase, while others predict a decrease. In 2017, Chen et. al addressed this disagreement, finding that differences in the modelling of the air currents above the Pacific may be responsible. In 2018, Maher et. al studied ENSO intensity predictions in a large group of climate models, and found that ENSO amplitude increases under global warming, with internal variability contributing greatly to noise. Additionally, Cai et. al. in 2018 found increased ENSO variability in the Eastern Pacific across different models, helping to resolve the lack of consensus using a method called EOF analysis, which is more flexible than methods in previous studies. Past research on ENSO and climate change is inconclusive. My study does not aim to end this ambiguity, but help to clarify things. Also, there is little research on the effect of individual forcing factors, such as greenhouse gasses, on ENSO.

It is still unknown how large of an impact humans have on El Nino. The first goal of my study is to estimate future changes to ENSO amplitude. I aimed to do this for a number of forcing environments. Additionally, a goal of this study is to determine the statistical significance of these changes. Next, this study analyzes the role of individual factors, the most important of which are greenhouse emissions and aerosol emissions, as well as a few natural factors. Also, this study aims to examine the physical mechanism responsible for any observed chnges.

My main source of data is NCAR Climate Lab's Community Earth System Model Large Ensemble, or CESM1 LE, which is a group of copuled model simulations. A coupled model uses an input of climate forcing records and predictions, and uses equations to simulate the interaction between Earth's atmosphere and ocean, and outputs the earth's climate state each month. An ensemble is a collection of model simulations with the same forcing input, the same physics simulation, but different initial conditions. This setup allows researchers to determine which changes to the Earth's climate are caused by climate forcing, and which are caused by internal variability. The Large ensemble also contains a control simulation with all forcing fixed at its levels in 1850.

The first step in my methodology was to measure ENSO intensity in each simulation. To do this, I used a common procedure of measuring ENSO amplitude, to take the variance of the sea surface temperature in the Nino 3.4 region of the Pacific ocean, which is depicted in the map. I calculated the variance using a process called windowing, where you calculate the variance for the 240 months, or 20 years, centered around a point, and then move that point forward by one month and repeat the process. I then calculated the mean and standard error for each ensemble, and the mean and standard error for the control run.

ENSO is a very noisy, or chaotic phenomenon, with slight differences in initial conditions leading to very different results. This noise is clearly shown in the graph, showing the wide range of ENSO amplitude between different members. This chaotic property is why ensembles are necessary, as when you combine all of these data points, long-term trends can be detected, although they may be faint.

The results of the previous calculation are shown on the graph. The blue line represents the 20-year variance of the fully forced ensemble. The colored envelope surrounding it represents the standard error, which is dependent on the number of members of the ensemble, and the grey bar represents 1, 2, and 3 standard errors from the control mean. There is an increase in variance in the fully forced ensemble, which exceeds two standard errors from the control, suggesting that the change is statistically significant. Interestingly, the variance decreases in the late 21st century, and is below the control in the mid 20th century, suggesting that the influence of climate change is nonlinear and internal variability plays a large role.

The next stage in the methodology is to determine how large of a role individual factors play in ENSO intensity. To do this, I took advantage of the CESM1 Single Forcing Ensemble. The single forcing ensemble contains simulations forced with all factors except one of them, so for example, the greenhouse gas ensemble is forced by aerosol emissions, biomass burning, land use, and ozone. To determine the role of individual factors, I randomly selected members from each single forcing ensemble and subtracted it from a random member of the full forcing ensemble, and repeated this process 1000 times for each group. This process of repeated random selection is known as the Bootstrap process.

The results of this process are shown on the graph. According to the data, greenhouse gasses and aerosol emissions likely increase ENSO intensity. However, the relationship between the single factors and the full forcing scenario is not additive, meaning that the sum of all of the results from the single factors is not similar to the fully-forced scenario, as shown in plot F. This means that the individual factors behave differently together compared to separately. This question merits further research.

The most recent stage of my methodology and results is an analysis of the physical processes through which climate change affects ENSO intensity. To do this, I calculated the correlation coefficient between the ENSO strength calculated in previous steps and ocean temperature. To improve the statistical reliability of the data, I detrended and smoothed both timeseries. The next slide has the results of this computation.

Shown here is the correlation coefficient between ENSO amplitude and ocean temperature across the equatorial pacific. The left is a slice stretching across the equator where the x-axis is longitude, while the right is a slice through the central pacific, where the x-axis is latitude. The y-axis in both graphs is ocean depth, and color represents the correlation coefficient. The 3 plots in each column contain the three major forcing scenarios, These graphs show that ENSO intensity is correlated with the difference between the upper and central layers of the tropical pacific, also known as stratification. Additional calculations are necessary to further validate this result, as well as further analysis and discussion of these figures.

Although this study is still in progress, a number of conclusions can be drawn which address the research goals of the study. First, there is likely to be an increase in ENSO intensity during the coming century. It is unknown how probable or great this increase will be. The major contributors to this predicted increase is a combination of human greenhouse gas and aerosol emissions. Also, it is clear that stratification plays an important role in the impact of global warming on ENSO.

My mentor and I need to do a deeper analysis of the role of internal variability in ENSO. We will also measure correlation between ENSO intensity and other ocean qualities, such as potential density and salinity, as well as a deeper analysis of the role of stratification. Deeper statistical analysis also will be done to further quantify the extent and likelihood of changes to ENSO under global warming. Finally, we need to compare these results with similar analyses of other models. The application of this project and others like it is to help humans to prepare for future changes to the earth's climate.

Acknowledgements: The data used in this study was created at NCAR's computer laboratories. My mentor, Dr. John Fasullo provided crucial help in this study, and his colleague, Peter Gent, helped analyze the results in context of oceanography.