El Niño and Probability

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Overview

The laws of probability are useful for day-to-day activities, such as beating a friend at a game of poker, trying to win the lottery, and even guessing the chances that a favorite sports team will win a big game.

As researchers from NOAA's Climate Diagnostics Center (CDC) recently reported, these rules of chance are also essential for climate forecasting. In a paper published in the *Journal of Climate*, Prashant Sardeshmukh, Gilbert Compo, and Cécile Penland used probability calculations to show that a large set of data is the key for learning how the El Niño Southern Oscillation (ENSO) affects weather outside of the tropics. Furthermore, a dataset this large can be used to detect the impact of ENSO related shifts in the mean state and changes in variability on the risk of seasonal climate extremes.

The results from this study indicate that it's not enough to use instrumental data collected from thermometers, barometers and other weather-measuring devices over the past 100 years, since this instrumental record contains no more than a few dozen ENSO events. Rather, the CDC research team found that using climate models to create larger data sets can give additional useful information about how ENSO affects weather around the world.

Benefits of Large Datasets

The importance of using a large data set can be illustrated in a simple study of coin tosses. Any honest coin has a 50-50 chance of landing on heads or tails, which means that if a coin is flipped 100 times, it's likely that about 50 of the flips will show heads, and about 50 will show tails. With 100 flips, the coin-tosser will have a good chance of predicting a 50 percent chance (probability) of getting a heads or a tails on any one of the flips. But if the coin is flipped only a few times, this 50-50 split may be harder to achieve. It's easy to imagine that 5 tosses could produce 1 heads and 4 tails, or 3 heads and 2 tails, or all heads and no tails. Drawing a conclusion about the probability of getting a heads or tails on any toss based on only 5 flips - a small sample size - can lead to inaccurate results.

Similar challenges exist when trying to use a small data set to understand the effects of ENSO [a phenomenon in which sea surface temperatures in the Eastern Pacific Ocean become higher or lower than the long-term average and cause changes that reverberate through the atmosphere perturbing weather patterns] on a system as complex as climate. But now, with increasingly sophisticated models and computer power, researchers don't have to rely only on the instrumental record. The climate science community can also create large data sets (ensembles) to more accurately identify the links between ENSO and resulting weather patterns.

ENSO Impacts

ENSO is one of the most significant, yet predictable, shifts in global weather. Its impacts are easiest to see in tropical areas, but it can also affect weather outside of the tropics. For instance, an El Niño winter, in which sea surface temperatures are higher than normal in the east central Pacific, brings cooler and wetter weather to the Southern United States, and warmer and drier weather to the Pacific Northwest. A La Niña winter in the east central Pacific, on the other hand, has lower than normal sea surface temperatures and causes nearly opposite weather patterns.

Describing ENSO impacts on weather not only provides better information on how the climate system works in general, but it also gives researchers clues about the likelihood that extreme weather events - from floods and droughts, to blizzards and heat waves - will take place in areas outside of the tropics. This advance warning helps people prepare, and so reduces the loss of lives and other damage extreme weather can cause.

Researchers know there is a connection between ENSO and weather outside of the tropics, but remain challenged when forecasting how a specific ENSO event will affect weather in these areas. One reason that forecasts are difficult is that ENSO's impact on weather outside of the tropics is small, and so is almost obscured by the climate's natural variability in these areas. That's why a large sample size is important: Only with enough data points can researchers distinguish natural variability from the outside influence.

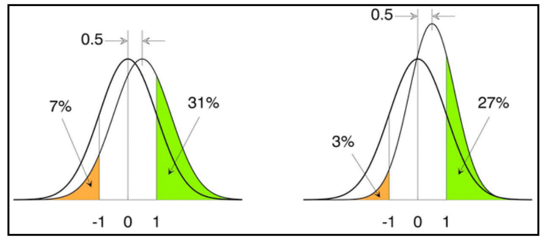

Figure 1. Probability density functions (PDFs) in the left panel illustrate the impact of changes in the mean on the probability of extreme values (left panel). PDFs in the right panel illustrate impact of changes in both the mean and the spread on the probability of extreme values. Green (orange) shading indicates an increase(decrease) of the probability of extreme values.

Distinguishing ENSO from natural variability is helpful because even if ENSO has small effects on average weather patterns, it may still cause significant changes in the overall distribution. For example, even a slight change in average weather pattern in response to ENSO can alter the likelihoods of extreme weather events, such as droughts, floods and storms. This idea is illustrated by Figure 1, where a small shift in the bell curve results in a significant change in the probability of having an extreme value. In the bell curve with the shift, there is no longer an equal chance of having an extreme positive value or an extreme negative value - rather, in this new graph it is four times more likely to have an extreme positive than an extreme negative. If the shifts illustrated in the graphs represented ENSO's effect on rainfall in an area, both the right and left panels would suggest that the area would be much more likely to be flooded with heavy rains than to suffer through a drought.

Research and Results

To look at how ENSO affects weather outside of the tropics, Sardeshmukh, Compo, and Penland first studied the historical record of ten El Niño years and ten La Niña years. They then used a climate model to create a larger sample size of 180 El Niño years, 180 La Niña years and 180 normal years, and compared how weather responses - such as temperature and precipitation - differed around the globe during the ENSO years. By comparing the historical record with the model results, the researchers could confirm that the model was on target.

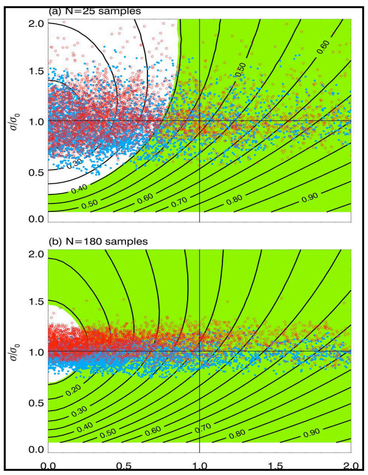

Figure 2. Contours indicate the expected value of Dks (the amplitude of the maximum difference in probability, change N(0,20) to N(0,1) and N(,2) to N(μ,□) between sampled normal distributions N(0,20) and N(,2), based on 50 000 Monte Carlo trials of (a) 25 and (b) 180 samples. Green shading indicates values significant at the 5% level, that is, the sample N(,2) distribution can be distinguished from the sample N(0,20) distribution. Scattered points represent the magnitudes of the mean and standard deviation of JFM-mean 500-mb heights in the El Niño (red) and La Niña (blue) GCM ensembles relative to those in the neutral ensemble, (a) using only the first 25 members of the 180 available members in the GCM ensembles, and (b) using all 180 members.

An analysis of the model results led the research team to conclude that a lot of data is needed to tell how ENSO affects weather. This finding is shown in Figure 2, in which each dot represents the modeled effects of ENSO on average weather patterns at one location around the world. Red dots represent El Niño years and blue dots represent La Niña years. Dots in the white area show locations at which researchers can't tell whether ENSO had an effect on weather. In the top graph, using only the first 25 instead of 180 model runs, it is impossible to tell if ENSO affected weather in most locations. However, in the bottom graph, where 180 model runs were used, a lot more dots fall outside of the white area, which shows that effects of ENSO on weather around the world are easier to pinpoint with larger samples.

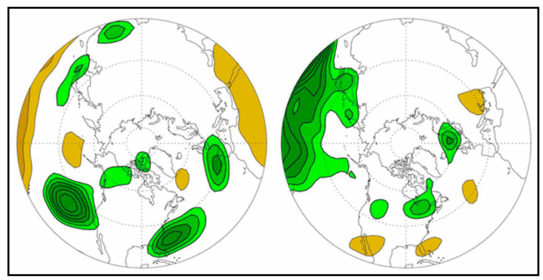

Figure 3. The change in the probability of extreme values of JFM-mean precipitation estimated from the AGCM for El Niño (left) and La Niña (right) ensembles. Green (orange) shading indicates an increase (decrease) of the probability of extreme values. The shading contours are 5% and 25%.

The large number of model runs provided the research team with an opportunity to explore how ENSO related shifts in the mean state and changes in variability can alter the risk of extreme events. This type of analysis was motivated by an interest in determining the usefulness of seasonal forecasts to identify predictable climate extremes. In only a few regions in the United States are the ENSO related altered risk of extreme seasonal mean winter precipitation significantly different relative to the risk of extremes under "normal" conditions (Figure 3). Under El Niño conditions there is a significant increase in the risk for wet and flooding conditions in

California (left panel). Under La Niña conditions there is a significant increase in the risk for dry and wildfire conditions in Florida (right panel). Not only is there an ENSO related climate signal in these regions but the altered risk for climate extremes is a potentially predictable aspect of seasonal climate.

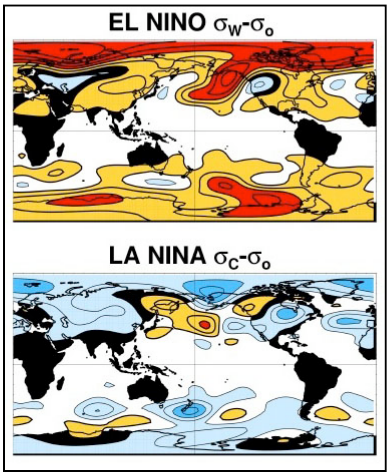

Figure 4. The difference between the standard deviations of the 500-mb height El Niño and neutral GCM ensembles (top panel) and La Niña and neutral GCM ensembles (bottom panel). The 500-mb height plots are drawn at 2-m intervals starting at 1-m. Positive values, or an increase in variability, are indicated by red whereas negative values, or a decrease in variability, are indicated by blue shading.

In addition to highlighting the need for large samples, the researchers found that El Niño and La Niña events do not have equal and opposite effects on weather patterns. El Niño seems to cause a stronger, but more variable response, than La Niña in many areas around the world. The greater variability in 500-mbar height during El Niño years is illustrated in Figure 4, where red areas with greater variability than average. In El Niño years, many areas have more vaiable weather than normal, while in La Niña years, many areas have less variable weather than normal. Even though La Niña may affect weather outside the tropics less than El Niño does, the effects of La Niña may be more predictable because the impacts are less variable or uncertain.

Concluding Remarks

The analysis and forecast of probability distributions and extreme event risks associated El Niños and La Niñas can be improved by advances in large ensemble predictions. Sardeshmukh, Compo, and Penland's results illustrate the need for a large number of climate model simulations to distinguish between the "noise" associated with natural variability and the ENSO signal of an increase or decrease in the likelihood of climate extremes, especially to estimate reliably changes outside of the extratropics. This work also documented that the response to ENSO conditions is not a mirror image (symmetric). The weather event responses to El Niños tend to be stronger but more variable whereas the responses to La Niñas, though more consistent, are not as large.

Enhanced climate forecasting capabilities are need to enable regional and national managers to plan for the impact of extreme weather events in response to future climate variability, and change. Improvements in the "physics" used in the construction of climate models can and will enhance simulation of climate variability (such as ENSO) and the associated impact or signal. However, equally important, and perhaps delivering a greater bang for the buck, is the approach of running a large number of simulations with an existing state-of-the-art climate model in order to resolve changes in the risk of extreme events associated with different climate conditions.

By documenting the importance of large-scale sample size, this study will help other climate scientists refine their own research on detecting and forecasting ENSO impacts on weather making future climate weather forecasts more reliable.

References

Sardeshmukh, P.D., G.P. Compo, and Cecile Penland (2000). Changes Associated with El Niño, *Journal of Climate*, **13**: 4268-4286.

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