Fact sheet for:

"Quantifying stochastic uncertainty in detection time of human-caused climate signals"

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Question 1: *What are "Large Initial Condition Ensembles"?*

Answer: Large Initial Condition Ensembles (LEs) are computer model simulations of climate change. A Large Initial Condition Ensemble is performed with a single climate model. Each LE typically has between 30 and 100 individual "members" (also called "realizations"). Each ensemble member starts from a different state of the atmosphere, or from a different state of the atmosphere and the ocean. The differences in the initial state between different ensemble members are often very small in the atmosphere but can be appreciable in the ocean. Because of chaotic variability in the climate system, the atmosphere loses memory of the initial atmospheric state within weeks to months of the start of the simulation. In the ocean, the time required to lose memory of the initial ocean state is longer (years to decades).

In essence, a Large Ensemble is a way of generating "many Earths" – many plausible trajectories of historical and future climate change. Each trajectory consists of signal and noise. The signal is the response of the climate system to external factors. Human-caused increases in atmospheric levels of greenhouse gases (GHGs) are one example of an external factor. The noise arises from natural processes within the climate system, such as El Niños and La Niñas. Each LE member has a different sequence of climate noise. This is why a Large Initial Condition Ensemble yields an envelope of climate trajectories rather than a single trajectory (see Figure 1).

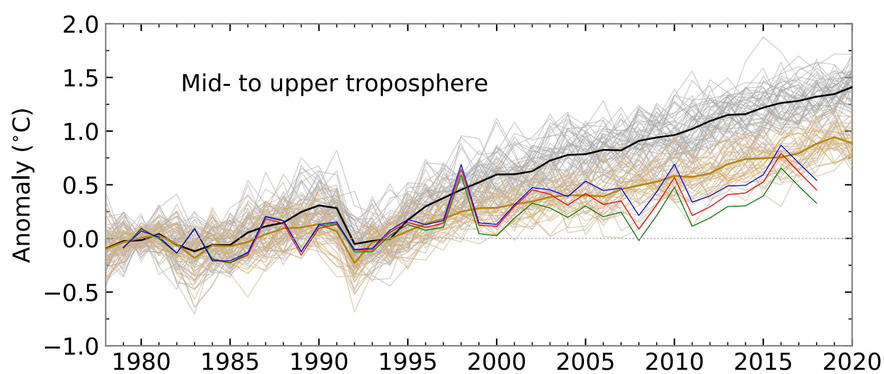

Figure 1: Trajectories of global-mean annual-mean tropospheric warming in Large Initial Condition Ensembles (LEs) produced with version 2 of the Canadian Earth System Model (CanESM2) and with version 1 of the U.S. Community Earth System Model (CESM1). There are 50 individual members of the CanESM2 LE (in light grey) and 40 individual members of the CESM1 LE (in light brown). The ensemble averages of the LEs are plotted in black for CanESM2 and in dark brown for CESM1. Satellite tropospheric temperatures are from Remote Sensing Systems in Santa Rosa (RSS; in red), the NOAA Center for Satellite Applications and Research in Maryland (STAR; in blue), and the University of Alabama at Huntsville (UAH; in green). Temperature changes are expressed as departures from the model and satellite annual averages over the three-year period from 1979 to 1981.

With a sufficiently large number of ensemble members, a Large Initial Condition Ensemble provides a reliable estimate of signal and noise in the particular climate model used to generate the LE. A Large Initial Condition Ensemble is a useful testbed for trying out different methods of separating signal and noise in the real world, where we have only one "sample" of signal and noise (and where there will always be some uncertainties in estimating signal and noise).

Question 2: *What does "stochastic uncertainty" mean?*

Answer: In every one of the 50 CanESM2 LE members and 40 CESM1 realizations in Figure 1, there is global-mean warming of the troposphere over the period of satellite atmospheric temperature measurements (1979 to 2018). As many previous studies have shown, this global-mean warming signal is primarily due to fossil fuel burning. Human-caused tropospheric warming is occurring in the presence of natural internal variations in climate. This climate noise explains why there is "spread" in the light grey and light brown climate change trajectories shown in Figure 1.

Let's say we are interested in estimating the time when a human-caused tropospheric warming signal exceeds some measure of the temperature variability associated with El Niños, La Niñas, and other natural cycles in the climate system. Further, let's assume we choose this noise threshold to be the +0.5°C line in Figure 1. If we define the detection time t_d as the time at which warming in an individual LE member first exceeds and then remains above +0.5°C, we would obtain 50 different t_d values from the CanESM2 LE and 40 different t_d values from the CESM1 LE.

In each model LE, we could then calculate the range t_r (in years) between the latest and the earliest signal detection time. In our paper, t_r is a measure of stochastic uncertainty in detection time – the uncertainty that arises from the year-to-year and decade-to-decade vagaries of natural internal climate variability (see Figure 2).

One way of thinking about this stochastic uncertainty is by considering what happens when the slowly evolving human-caused tropospheric warming signal approaches the +0.5°C threshold. In one of the 50 CanESM2 realizations, for example, human-caused warming might coincide (by pure chance) with a decade of natural warming arising from a positive phase of the Interdecadal Pacific Oscillation (IPO). This synchronicity of long-term human-caused warming and short-term natural warming would lead to earlier detection of an anthropogenic warming signal. Alternately, if a natural decadal cooling event occurred as the human-caused warming signal approached the +0.5°C threshold, signal detection time would be delayed.

Question 3: *Are you looking at the time required to detect warming signals in global-mean temperature?*

Answer: No, we are not. Our study does not define detection of a human-caused signal by looking at the time when global-mean tropospheric warming exceeds some chosen natural variability threshold. Instead, we are looking at geographical patterns of climate change – for the entire globe, for the Northern Hemisphere, and for the Southern Hemisphere. This type of pattern-based analysis is called "climate fingerprinting". We perform fingerprinting for temperature changes in these three geographical regions and in three different atmospheric layers: the lower stratosphere, the mid- to upper troposphere, and the lower troposphere.

Question 4: *What is new about this research?*

Answer: Previous work with LEs focused on local changes at individual model grid-points. Such research has tried to identify regions and climate variables that might serve as "canaries in the coal mine" for the detection of anthropogenic climate change. To date, however, LEs have rarely been used for pattern-based climate fingerprint studies. No previous study has used LEs to estimate stochastic uncertainty in fingerprint detection time. This is what we do here (see answer to Question 2). Nor has previous research used LEs to probe the signal-to-noise (S/N) properties of stratospheric and tropospheric temperature changes.

Question 5: *What are some of your principal findings?*

Answer: We list some of our principal findings below.

Earlier signal detection in the stratosphere.

We can detect human-caused cooling of the lower stratosphere 2 to 4 years earlier than we can detect human-caused warming of the troposphere (see Figure 2). Cooling of the lower stratosphere is mainly due to the impact of ozone-depleting substances on stratospheric ozone levels. Warming of the troposphere is primarily driven by GHG increases arising from fossil fuel burning.

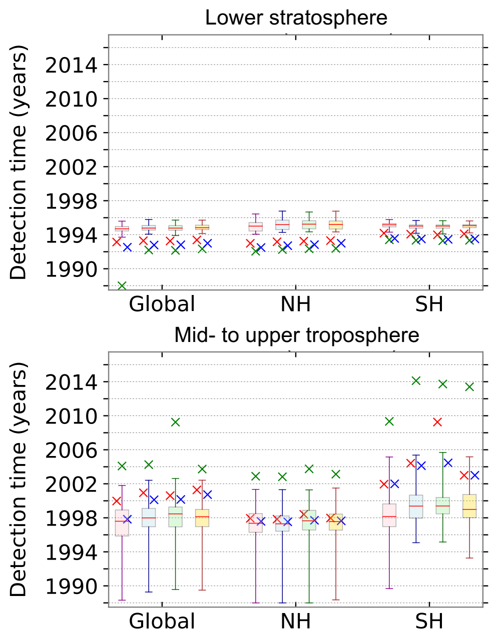

Figure 2: Fingerprint detection time t_d in the temperature of the lower stratosphere (TLS; top panel) and in the temperature of the mid- to upper troposphere (TMT; bottom panel). Detection times in the "box-and-whiskers" plots are from the CanESM2 Large Ensemble (LE). The CanESM2 model was used to perform a simulation with historical changes in all major anthropogenic and natural external forcings ("ALL"). The TLS and TMT fingerprints calculated from the CanESM2 ALL ensemble capture geographical patterns of human-caused stratospheric cooling and human-caused tropospheric warming. These fingerprints are searched for in each of the 50 individual CanESM2 ensemble members. The vertical bars in the box-and-whiskers plots span the range t_r between the earliest and latest fingerprint detection times. The height of each bar is a measure of the stochastic uncertainty in fingerprint detection time in CanESM2. The red horizontal line in each bar is the median detection time in the 50-member ensemble, and the box is the range between the 25th and 75th percentiles of detection time. There are separate results for fingerprint patterns calculated over the entire globe, the Northern Hemisphere (NH), and the Southern Hemisphere (SH). For each region there are four different box-and-whiskers plots because four different estimates of natural variability were used to estimate detection time. The colored crosses show the time required to detect the CanESM2 TLS and TMT fingerprints in actual satellite temperature data sets developed by Remote Sensing Systems (red crosses), the NOAA/STAR group (blue crosses), and University of Alabama at Huntsville (green crosses). By comparing the red horizontal lines in the upper and lower panels, we can see that the median fingerprint detection time occurs around 1995 for stratospheric temperature and between 1997 to 1999 for tropospheric temperature. The stochastic uncertainty in fingerprint detection time is larger for tropospheric temperature.

There are several reasons why earlier detection of a stratospheric cooling signal makes good physical sense. First, the noise of natural climate variability is substantially smaller in the stratosphere than in the troposphere. Lower noise levels make signal detection easier in the stratosphere.

Second, the eruption of Mt. Pinatubo in 1991 caused short-term stratospheric warming and tropospheric cooling. These changes are of opposite sign to the gradual human-caused cooling of the stratosphere and warming of the troposphere. In simple terms, large volcanic eruptions partly mask anthropogenic signals. The "volcanic masking" after Pinatubo lasted longer in the troposphere than in the stratosphere (because tropospheric temperature is more strongly affected by the large heat capacity of the ocean). Longer volcanic masking contributes to delayed anthropogenic signal detection in the troposphere.

Larger stochastic uncertainty in fingerprint detection time in the troposphere.
The stochastic uncertainty in fingerprint detection time, t_r (see answer to question 2) is between 8 and 15 years in the troposphere. It is smaller in the lower stratosphere (between 1 to 3 years). This difference is partly due to the smaller noise of natural climate variability in the lower stratosphere.

Consistency between fingerprint detection time in satellite tropospheric temperature data and model LEs.
We find that fingerprint detection time in satellite tropospheric temperature data is, in most cases, within the stochastic uncertainty in fingerprint detection time obtained from the CanESM2 and CESM1 LEs. This is true in 60% of the cases for CanESM2 and in 88% of the cases for CESM1.

Inconsistency between fingerprint detection time in satellite stratospheric temperature data and model LEs.
In most cases, fingerprint detection time in satellite lower stratospheric temperature data is outside of the stochastic uncertainty in fingerprint detection time estimated from the CanESM2 and CESM1 LEs. Detection occurs earlier in the satellite data than in the LEs because lower stratospheric cooling over the 40-year satellite era is larger in the data than in either LE.

For tropospheric warming, the higher sensitivity model yields closer agreement with observed detection time.
Equilibrium Climate Sensitivity (ECS) is a measure of the eventual global warming that would occur for a doubling of preindustrial atmospheric CO_2 levels. CESM1 has higher ECS than CanESM2 (4.1°C versus 3.68°C, respectively). Yet the lower-ECS CanESM2 model has larger warming than the higher-ECS CESM1 model (see Figure 1).

This result seems paradoxical but has a straightforward explanation. It arises because the cooling caused by anthropogenic aerosols (particularly through the effect of aerosols on cloud properties) is substantially larger in CESM1 than in CanESM2. High ECS and large tropospheric warming in CESM1 is partly offset by CESM1's large aerosol-induced cooling.

Detection time results were relatively insensitive to uncertainties in internal variability estimates.
We looked at four different estimates of natural internal variability. Three of these estimates were from CanESM2 LEs. One of the estimates was from a large multi-model ensemble of preindustrial control runs (from simulations performed under phase 5 of the Coupled Model Intercomparison Project; "CMIP5"). Surprisingly, we found that the leading patterns of natural internal climate variability were similar in these four different noise data sets. This suggests that these leading noise patterns capture large-scale modes of atmospheric temperature variability that are relatively well-represented in current models.

Detection time differences between satellite data sets can be as large as stochastic uncertainty in t_d.
The Alabama tropospheric temperature data show reduced tropospheric warming relative to the other two satellite temperature data sets (see Figure 1). This reduced warming largely explains why detection of the model-predicted tropospheric warming fingerprint pattern occurs later in UAH than in RSS or STAR data (see bottom panel of Figure 2). These observational differences in detection time can be as large as the stochastic uncertainty in signal detection time calculated from the CanESM2 and CESM1 LEs. Even in the Alabama satellite data, however, the model-predicted tropospheric warming fingerprints are always detectable with high statistical confidence by no later than 2018, the last complete year of the satellite data.

Question 6: *Where do you go from here? What's next?*

Answer: We'd like to understand whether "CESM1 world" – with its high climate sensitivity and its high cooling from anthropogenic aerosols – is more realistic than "CanESM2 world" (with lower climate sensitivity and lower cooling from anthropogenic aerosols). Answering this question will require that the climate modeling, observational, and diagnostic communities find innovative ways of reducing the existing uncertainties in both climate sensitivity and aerosol forcing.