Fact sheet for "Causes of differences between model and satellite tropospheric warming rates"

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Question 1: What is the main issue that you look at in your paper?

Answer: Our paper looks at satellite and climate model estimates of global-mean changes in the temperature of the lowest layer of Earth's atmosphere – the troposphere. It tries to understand why there are differences between modeled and observed tropospheric warming rates over the period of satellite atmospheric temperature measurements (January 1979 to December 2016). These differences have an interesting time signature. In the last two decades of the 20th century, differences between modeled and observed tropospheric warming were generally small. But during most of the early 21st century, the average warming in models was larger than in observations.

We asked whether such differences between modeled and observed warming rates could be explained by natural internal variability of the climate system. Natural internal variability arises from phenomena like El Niños, La Niñas, decadal oscillations in the Pacific,[1] and the Atlantic Multidecadal Oscillation (AMO).

We found that natural internal variability can explain most of the relatively small differences between modeled and observed tropospheric warming in the last two decades of the 20th century, but can't fully explain why model tropospheric warming is larger than in the satellite data during much of the early 21st century.

Question 2: What is your bottom-line finding?

Answer: The bottom line is that the differences between modeled and observed tropospheric warming contain useful diagnostic information. We use this information to test hypotheses about the causes of these warming rate differences. One hypothesis is that internal variability alone can explain why model tropospheric warming in the early 21st century is larger than in satellite data. Our findings suggest this hypothesis is very unlikely to be correct.

Based on our results, it is far more likely that the early 21st century differences between modeled and observed tropospheric warming rates are due to the combined effects of two factors: 1) Random differences[2]

[1]Such as the closely-related Interdecadal Pacific Oscillation (IPO) and Pacific Decadal Oscillation (PDO).

[2]We analyzed simulations performed with atmosphere-ocean models of the climate system, which produce their own random sequences of internal climate variability. In such models, there is no "synching up" (except by pure chance) between the random sequences of internal variability in the observations and in the model simulations. Different sequences of internal variability in "model world" and in the real world are not a scientific surprise – they are expected, and they can contribute to short-term differences between modeled and observed warming rates.

in how modes of internal variability actually behaved in the real world and in the model simulations; and 2) The fact that some of the external cooling influences which affected "real world" temperature in the early 21st century were not accurately represented in the model simulations.

Question 3: What are the "external cooling influences" you are referring to in your paper?

Answer: Examples of such external cooling influences include a series of moderate volcanic eruptions, a long and unusually low minimum in the Sun's energy output during the last solar cycle, and an uptick in particulate pollution from Chinese coal-fired power plants. The model simulations were performed before reliable, up-to-date information became available about how these external cooling factors evolved in the early 21st century.[3]

Question 4: Do the problems in representing these external cooling influences point to systematic errors in how sensitive the models are to human-caused greenhouse gas (GHG) increases?

Answer: No, not at all. We are talking about known, well-studied problems with some of the external, climate-influencing "forcing factors" that were used in the model simulations. These problems have nothing to do with the issue of how sensitive models are to GHG increases.

Question 5: Haven't some scientists claimed that the larger-than-observed model warming in the early 21st century is solely due to over-sensitive models?

Answer: Yes, such claims have been made and continue to be made. We tested the "over-sensitive models" claim in our paper, and found that it does not explain the actual differences between modeled and observed tropospheric warming behavior. Nor does a combination of "over-sensitive models" and natural internal variability plausibly explain the differences. None of our findings call into question the reality of long-term warming of Earth's troposphere and surface, or cast doubt on prevailing estimates of the amount of warming we can expect from future increases in GHG concentrations.

Question 6: In a recent paper in *Scientific Reports*, you find that satellite measurements do not show any signs of "leveling off" of tropospheric warming over the past two decades. Aren't those findings at odds with the findings of the *Nature Geoscience* paper?

Answer: No. The findings of the two papers are entirely consistent. The *Scientific Reports* paper compares the satellite tropospheric temperature trend over the past 20 years with many samples of 20-year trends obtained from model simulations of natural internal climate variability.[4] Even though the most recent 20-year warming trend is smaller than in earlier parts of the satellite record,[5] it is still significantly larger than the range of 20-year trends caused by internal climate variability alone. From our *Scientific Reports* study, there is no evidence that satellite data show "leveling off" of tropospheric warming in the last two decades.

The *Nature Geoscience* paper focuses on different model simulations. It looks at simulations of historical climate change, and asks whether differences between model-simulated and observed tropospheric warming

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[3]Consider a hypothetical climate model with perfect representation of all important physical processes in the real-world climate system. If such a model were used to simulate historical climate change, but the simulation left out important external cooling influences that affected the real world, the simulated historical warming would tend to be larger than observed.

[4]Model estimates of natural internal variability were obtained from so-called "control runs", with no year-to-year changes in GHGs, volcanic aerosols, the Sun's energy output, or other external factors.

[5]For reasons that are explained in the last paragraph of the answer to Question 2.

could be due to different sequences of internal variability in the real world and in model world. It finds that internal variability alone cannot convincingly explain why models do a reasonable job capturing observed tropospheric temperature changes in the late 20th century, but not in the early 21st century. It also finds that "over-sensitive models" cannot explain the curious structure of model-versus-observed warming rate differences.

The key point here is that the two studies pose different scientific questions. The answers to these questions are complementary, not contradictory.

Question 7: What is the major remaining uncertainty in your study?

Answer: We think that the main uncertainty is in the model estimates of internal climate variability. We rely on these variability estimates to test the two hypotheses mentioned above – that differences between modeled and observed warming rates during much of the early 21st century could be due to: 1) internal variability alone; or 2) the combined effects of "over-sensitive models" and internal variability. If models systematically underestimated the size and the timescales of the major "real-world" internal variability modes, it would be less easy for us to rule out hypotheses 1 and 2.

The problem here is that satellite temperature records are relative short, and are a mixture of both internal variability and temperature responses to external factors (changes in GHGs, particulate pollution, the Sun, volcanic aerosols, *etc.*). Reliably teasing out the internal variability from such a short, mixed record is a tough job. To be clear: model control simulations[6] can give us pure "unmixed" estimates of internal variability. Observations cannot, so there is some irreducible uncertainty in judging how well models capture key features of "real world" internal variability.

Previous work that we've done has not found a systematic low bias in model estimates of tropospheric temperature variability, but there is some evidence that current models might underestimate the timescale of the IPO. A lot more work needs to be done in comparing modeled and observed variability. We hope that our paper will provide impetus for such work.

Question 8: What are some of the major lessons you've learned?

Answer: One of the lessons learned is that "forcing matters". Through the pioneering work of Susan Solomon and many others, we've learned a lot about the external influences that affected real-world temperature in the early 21st century. We now understand that if we systematically misrepresent these external influences in model simulations, we'll see differences between modeled and observed warming rates. We need to do a better job understanding how these external influences actually changed in the real world, and we need to put our best estimates of these forcing factors into model simulations. This type of work is now happening.

Another valuable lesson learned is that "natural internal variability matters", particularly when one is comparing modeled and observed temperature changes with different sequences of internal variability, and over short periods (1-2 decades). Many scientists (and many of the authors of the *Nature Geoscience* paper) have devoted years of their careers to the task of improving the understanding of internal variability.

These lessons will enable us to do two things. First, to more reliably separate internal variability and external influences in observed climate records. And second, to better quantify the relative contributions of internal variability and external influences to the differences between simulated and observed warming rates. The "lessons learned" will help us to better diagnose the causes of these differences.

[6]See footnote 4.