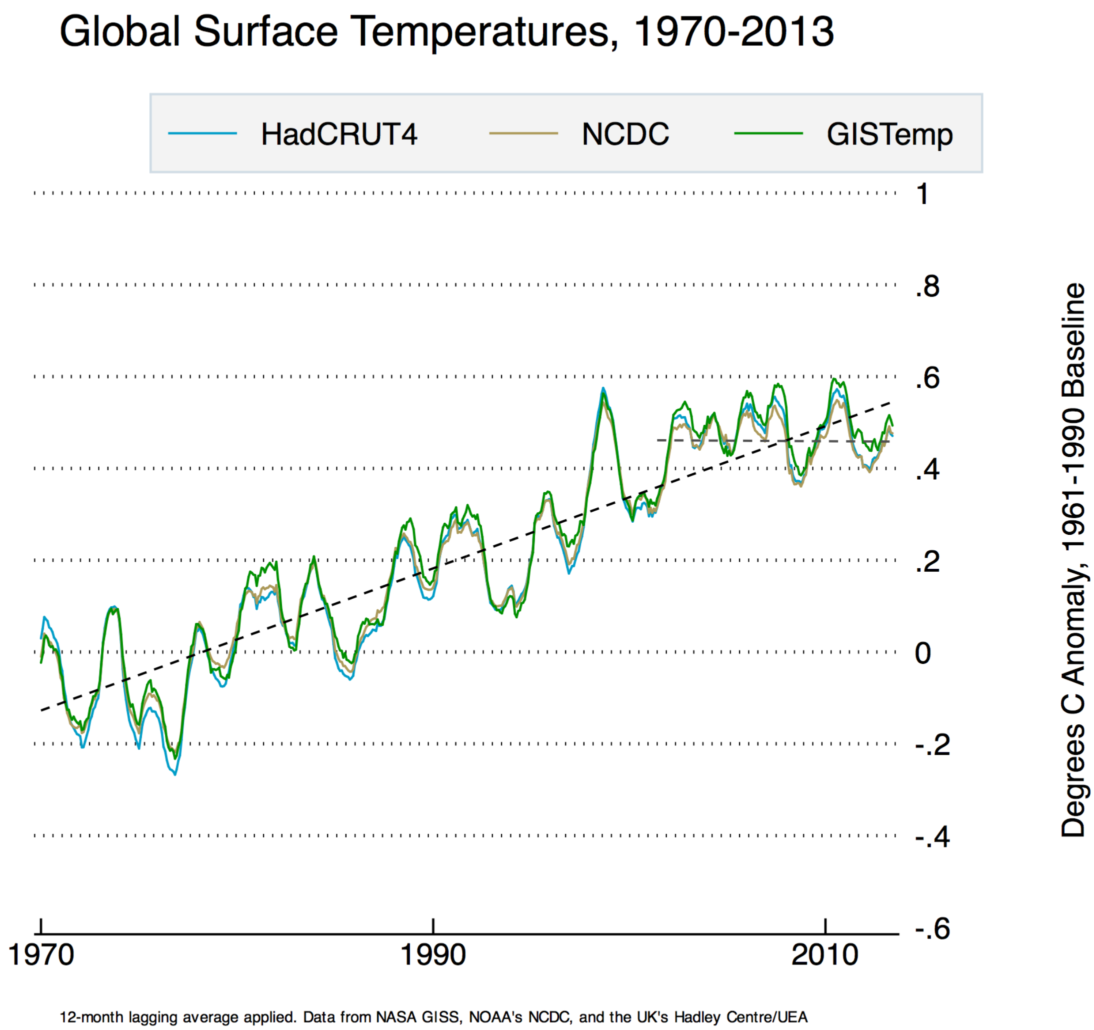
Examining the Recent "Pause" in Global Warming

Global surface temperatures have warmed more slowly over the past decade than previously expected. The media has seized this warming pause in recent weeks, and the UK's Met Office released a three-part series of white papers looking at the causes and implications. While there is still no definitive cause identified, some researchers point to a combination of more heat going into the deep oceans and downturns in multi-decadal cycles in global temperature as the primary drivers of the pause. Others argue that a plethora of recent small volcanoes, changes in stratospheric water vapor, and a downturn in solar energy reaching the earth may also be contributing to the plateau. While few expect the pause to persist much longer, it has raised some questions about the growing divergence between observed temperatures and those predicted by climate models.

To understand the pause in warming requires understanding the different ways we can measure global temperature. These include measurements taken from land-based temperature stations (mostly using mercury thermometers), ocean buoys, ships, satellites, and weather balloons.

Land/Ocean Temperatures

The most common estimate of global temperatures comes from a combination of land temperature stations with sea surface temperature data from ships and buoys. There are three main global land/ocean surface temperature series, produced by NOAA's National Climate Data Center (NCDC), NASA's Goddard Institute for Space Studies (GISTemp), and the UK's Hadley Center (HadCRUT).

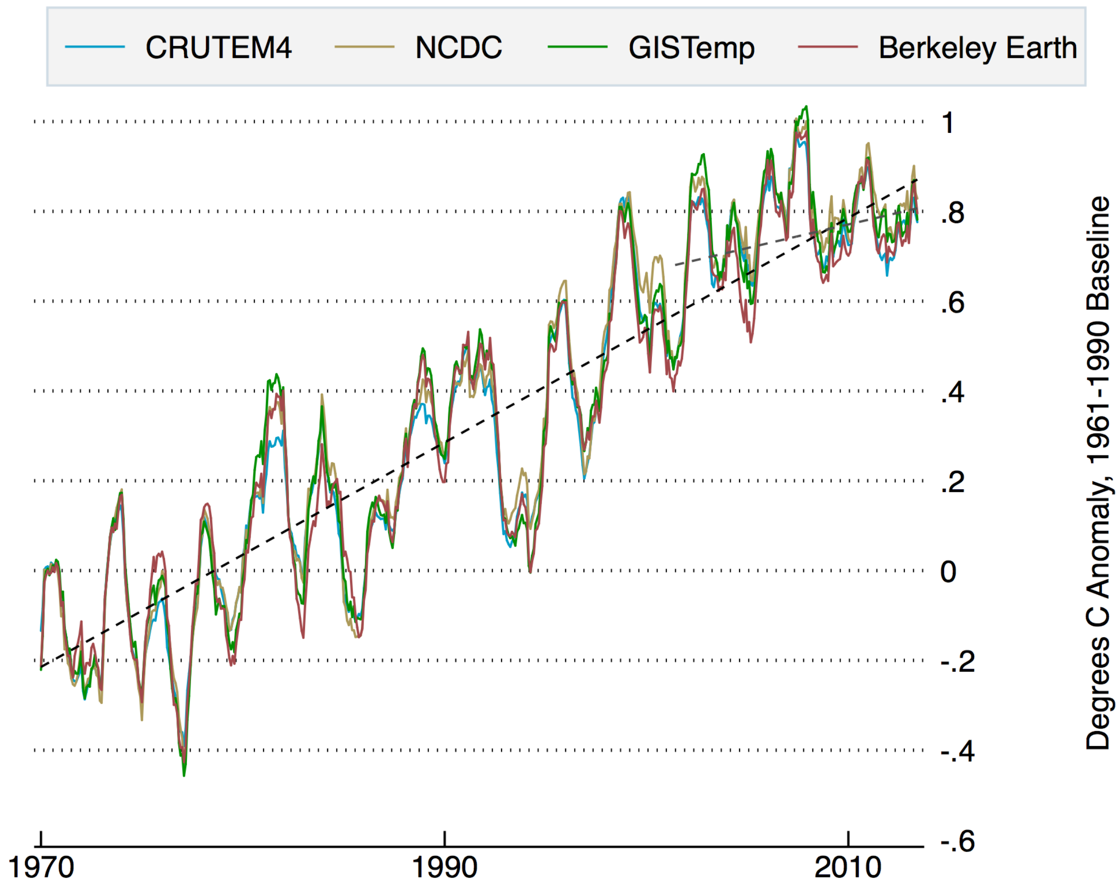


As shown in the figure above, all three series agree quite well on global temperatures. The dashed grey line shows the trend in temperatures since 2001, while the dashed black line shows the long-term trend since 1970. While the rise in global temperatures has slowed in recent years, it is not obviously divergent from the underlying long-term trend. On the other hand, periods with similar temperature stagnation were often associated with a major volcano (e.g. Pinatubo in 1992 or El Chichón in 1982), though the attribution is not clear-cut.

Land Temperatures Only

Land and ocean temperatures have diverged notably in recent years. Ocean temperatures generally rise more slowly than land temperatures, due to the large thermal inertia of the oceans. Since 2001, land temperatures have continued to rise, albeit slightly more slowly than in prior years.

Land Surface Temperatures, 1970-2013

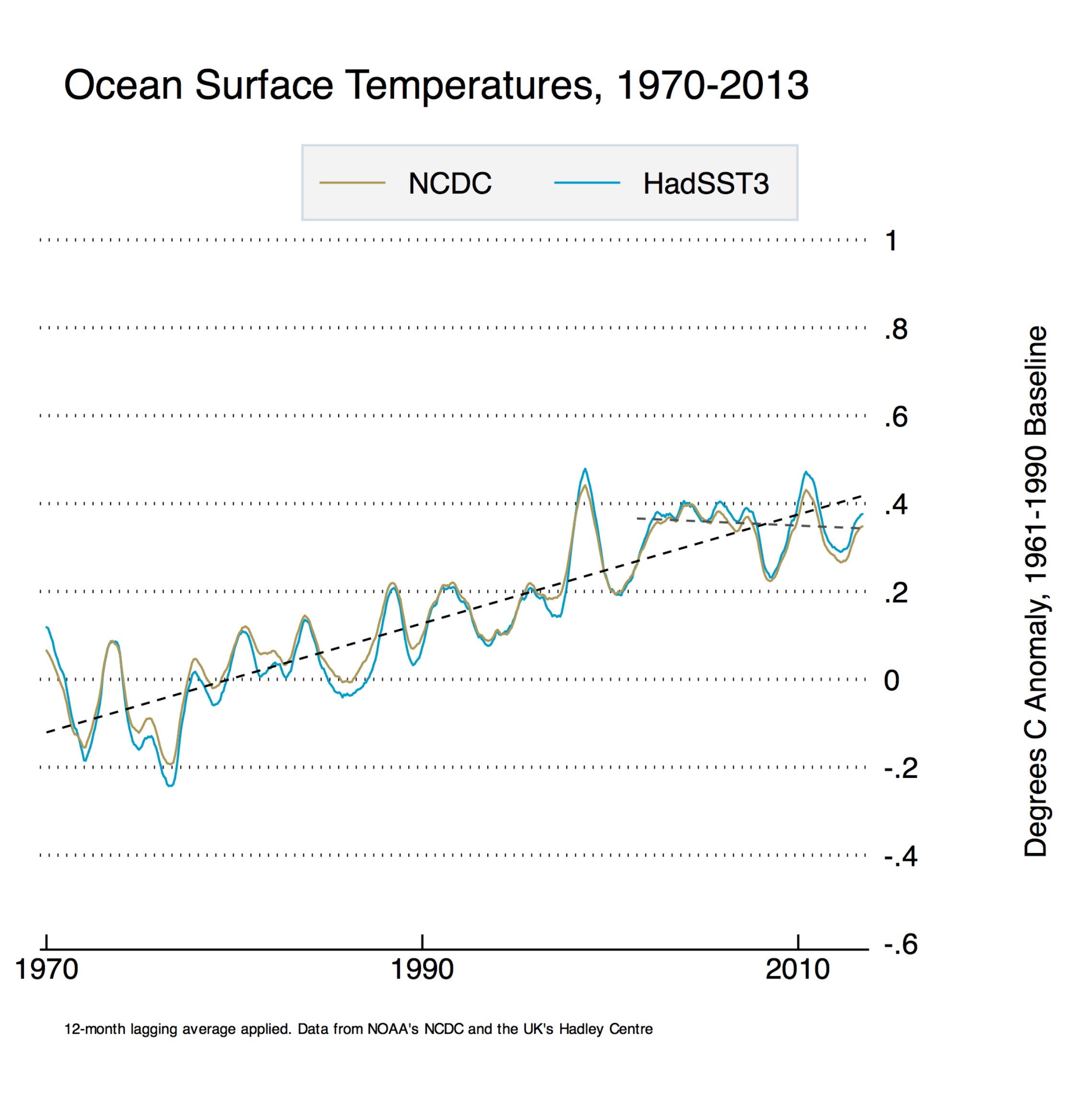


12-month lagging average applied. Data from Berkeley Earth, NASA GISS, NOAA's NCDC, and the UK's Hadley Centre/UEA

Here again the dashed grey line shows the trend since 2001, while the dashed black line shows the trend over the whole period. The major land series used are CRUTEM4 (the land component of HadCRUT4), NCDC, GISTemp, and Berkeley Earth.

Ocean Surface Temperatures Only

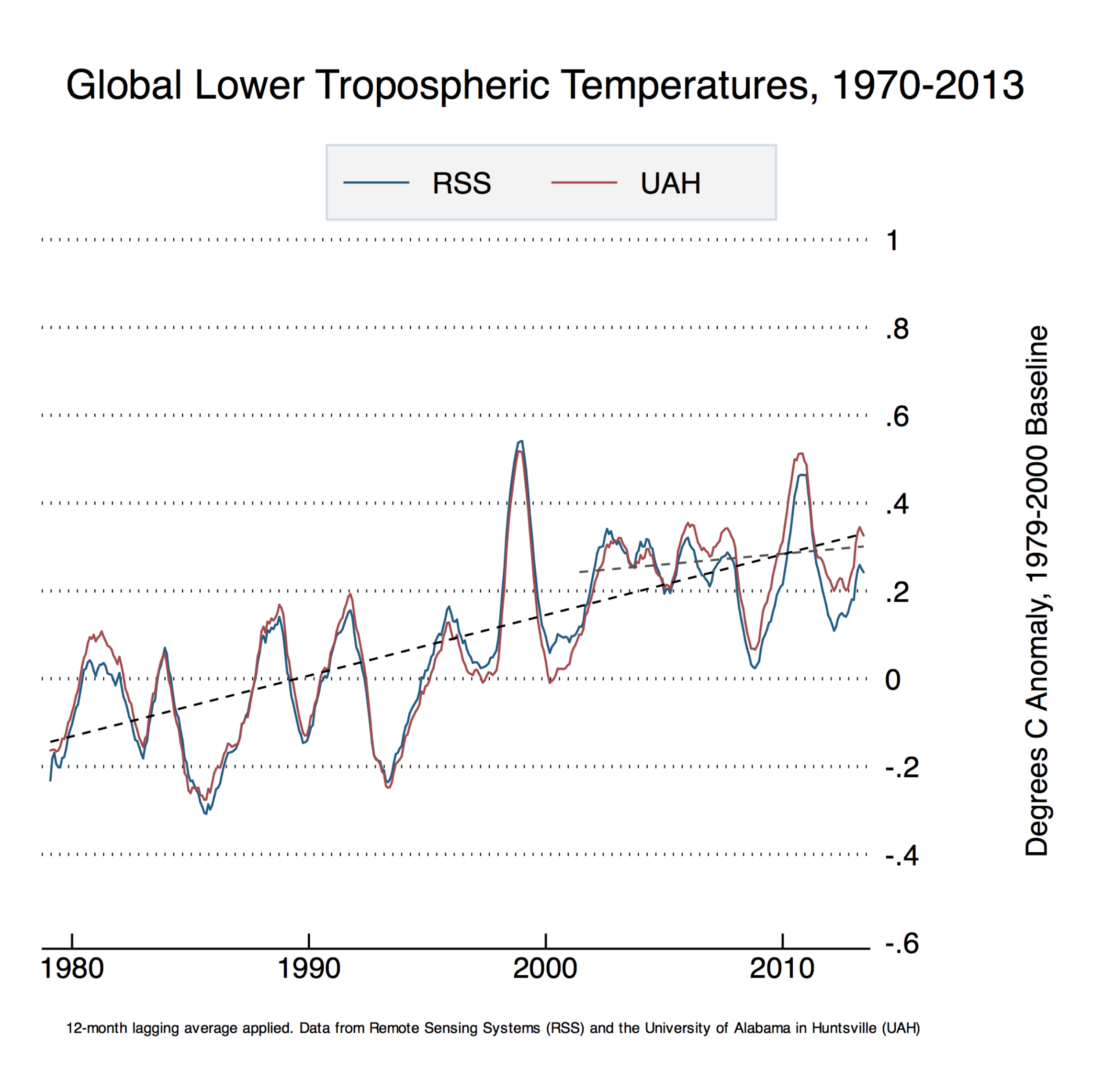
The majority of the decline in global surface temperatures in recent years has been concentrated in the oceans. The figure below shows two of the major sea surface temperature records: HadSST3 from the Hadley Center and NCDC's ERSST series.



Ocean temperatures have cooled slightly in recent years, after a large jump upwards in 2000/2001.

Lower Tropospheric Temperatures

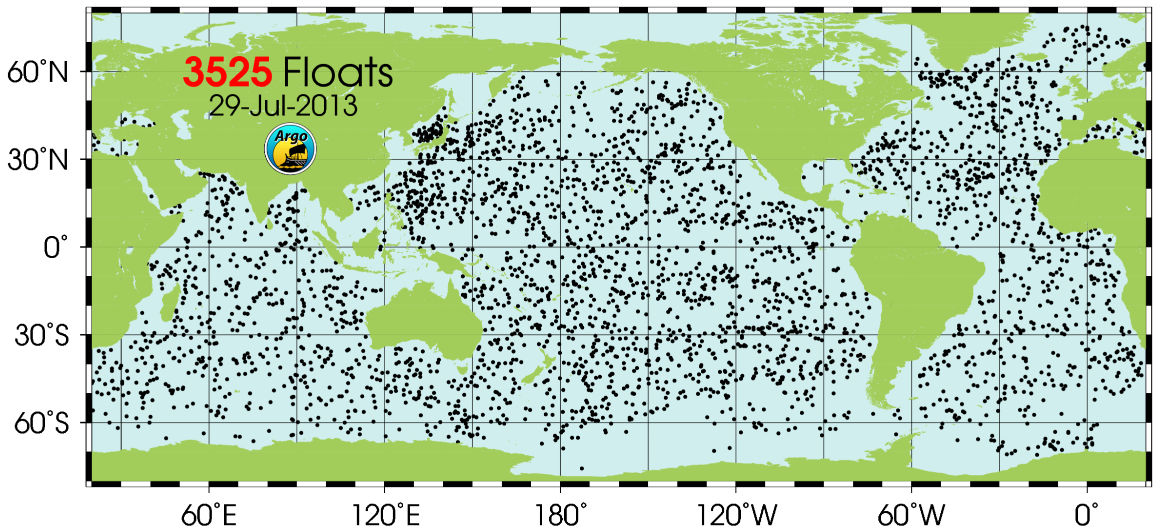
Global temperatures can also be estimated based on data from satellites in orbit. These use instruments to measure radiance from the earth to determine temperature, and tend to have quite good spatial coverage of the earth (excluding some high-latitude regions). While there is still some uncertainty regarding how to best correct for issues like orbital drift and transitions to different satellites, satellite-based records now fairly closely mirror surface-based records, albeit with slightly lower trends. The discrepancy between satellite and surface trends is an outstanding issue that still needs to be resolved.



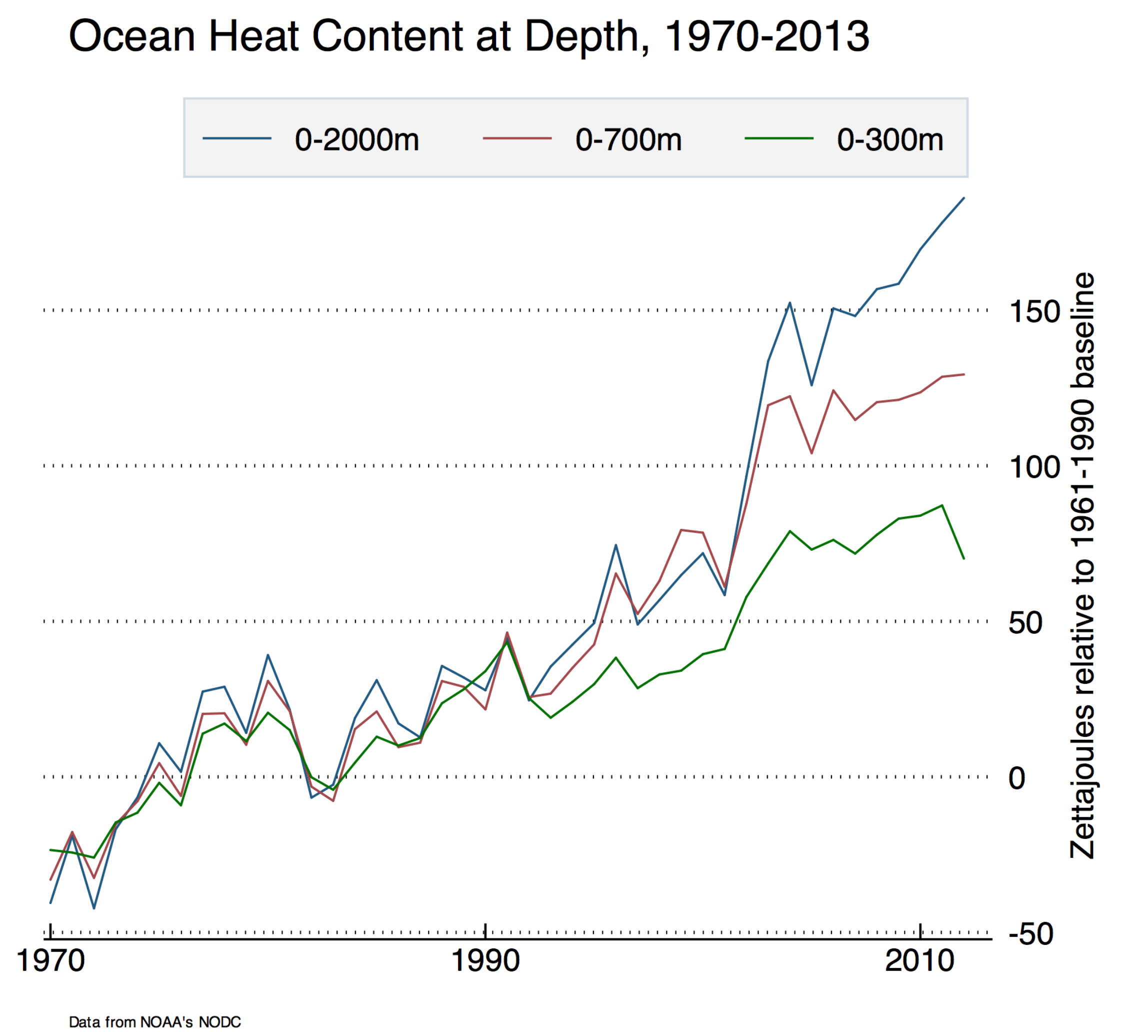
Satellite records show some stagnation of temperatures in recent years, somewhere between the land and ocean surface records.

Deep Ocean Temperatures

In recent years, a global network of automated buoys have given us a much better picture of what is going on below the surface in the ocean. These buoys automatically dive deep down into the ocean every day, taking temperature measurements as they slowly rise and transmitting them back to a central database via satellite. The figure below, via Argo, shows the location of buoys currently active in the world's oceans.



While measurements of deep ocean temperatures existed further back in the past, they were taken in much more limited locations as Argo buoys were not widely deployed until after 1999. However, scientists have still been able to use more limited data to reconstruct temperatures down to 2000 meters much further back in time, as shown in the figure below.



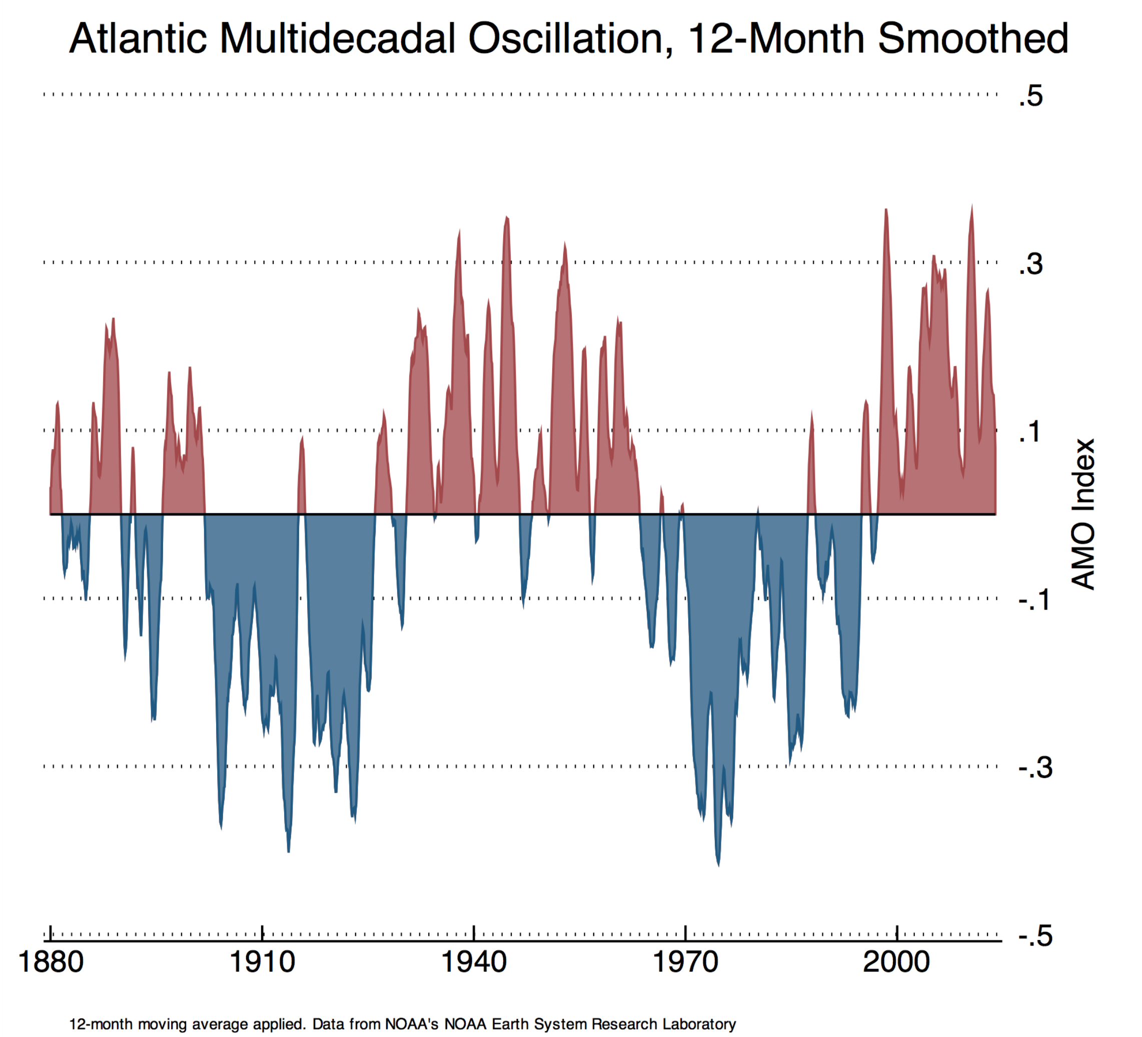
Total ocean heat content has increased by around 200 zettajoules since 1970, and about 255 zettajoules since 1955. This has caused the oceans (0-2000 meters) to warm about 0.09 C over this period. As the UK's Met Office points out, if the same amount of energy went into the lower atmosphere it would have caused about 36 C warming! The oceans are by far the largest heat sink for the earth and absorb the vast majority of extra heat trapped in the system by increasing concentrations of greenhouse gases.

It is interesting to note that overall deep ocean heating (0-2000 meters) shows no sign of a slow down in recent years, though shallower layers (0-300 meters and 0-700 meters) do. The fact that the slowdown in surface warming has been concentrated in the ocean surface temperatures (and not in land temperatures) has led a number of scientists to posit that the pause in ocean surface warming may be driven in part by increased heat uptake in the deep ocean. Some research has

suggested that El Nino-related changes in trade winds are a possible mechanism driving changes in deep ocean heat uptake through greater boundary layer mixing.

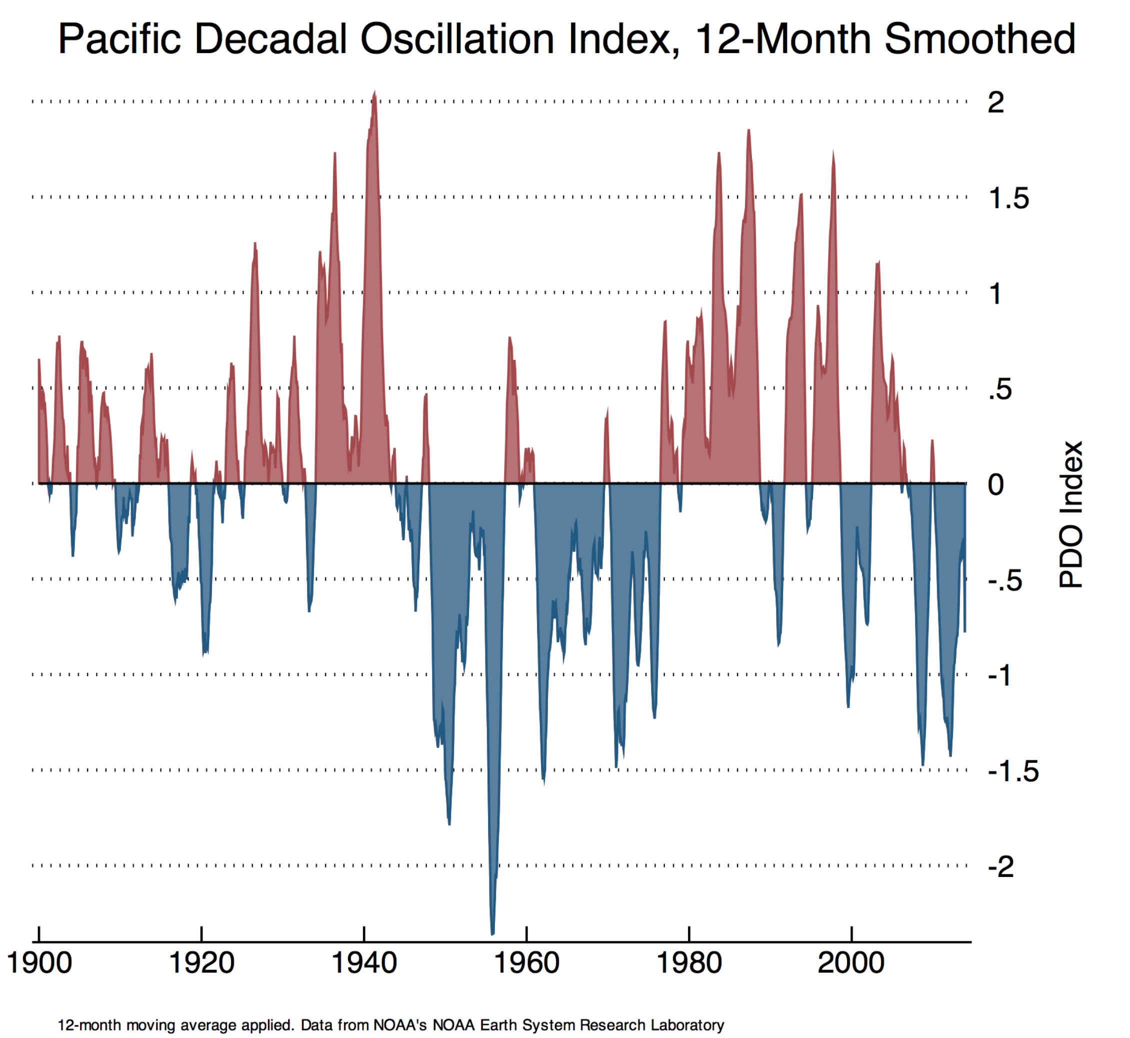
Multi-Decadal Cycles

There are a number of inter-decadal and multi-decadal cyclical patterns observable in the climate system, particularly in ocean surface temperatures. These include the Atlantic Multidecadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO), which operate over a period of a few decades, and El Nino Southern Oscillation (ENSO), which has a period of three to seven years. While ENSO tends to average out over periods of more than a decade, the AMO and PDO can both potentially impact the climate over longer periods of time.



The AMO is generally calculated by subtracting out the linear trend from 1880 to present in North Atlantic sea surface temperatures. This approach isn't perfect, and may overestimate the magnitude of natural variability in recent years, but there is a clear cycle present in the North Atlantic that can contribute to variations in global temperatures. The Met Office, for example, cites a paper arguing that variations in the AMO can change global temperatures by around 0.1 C. A paper by Muller et al recently published in the Journal of Geophysical Research (JGR) argues that the AMO could be responsible for some of the "2-15 year variability" observed in global land temperatures.

While the AMO has not changed much in the past 10 years, the strong increase in North Atlantic temperatures between 1970 and 2000 may have contributed to the rapid rise in global temperatures over that period, and the leveling out of the AMO may help make the observed pause in warming more likely.

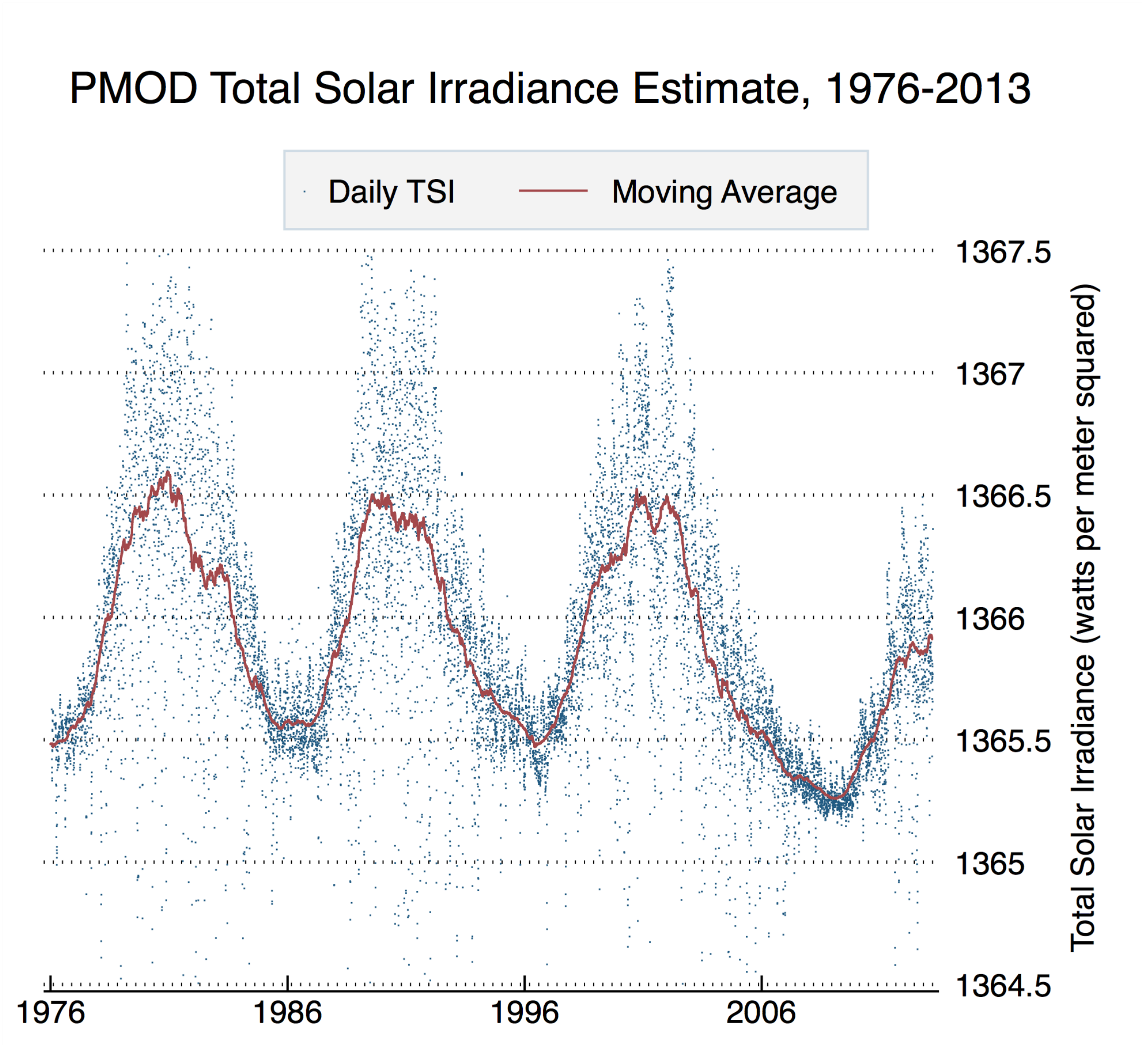


The Pacific Decadal Oscillation (PDO) is calculated rather differently from the AMO. The PDO is calculated by examining the difference in temperatures of the northern Pacific from global ocean temperatures as a whole, to isolate changes specific to that region. This approach more effectively removes any anthropogenic signals affecting the whole world than the simple linear detrending used in calculating the AMO.

The PDO has transitioned to a cold phase around the year 2000. While there still is quite a bit of uncertainty surrounding the effects the PDO on the earth's climate, the Met Office argues that "decadal variability in the Pacific Ocean may have played a substantial role in the recent pause in global surface temperature rise", arguing that Global Climate Models (GCMs) that show decadal-scale pauses in surface temperature warming tend to exhibit sea surface temperature patterns similar to those of the PDO in a cold phase. This is still highly uncertain, however, and much more work is required to better understand the role that multi-decadal variability in ocean temperatures plays in determining the Earth's surface temperatures.

Incoming Solar Radiation

The sun has a well-known (roughly) 11-year cycle in solar output that can have an influence on global temperatures, though most solar scientists consider it to be relatively minor. Estimates of the difference in temperatures between the peak (high point) and trough (low point) of the solar cycle range between about 0.05 C to 0.1 C, holding everything else equal. If solar cycles hold steady, this won't really impact trends over periods of 11 years, as the peaks and troughs will cancel out. However, the most recent solar cycle has been notable for the extended trough and low peak (at least so far). The figure below shows the PMOD compilation of solar irradiance measurements from a number of different satellites.

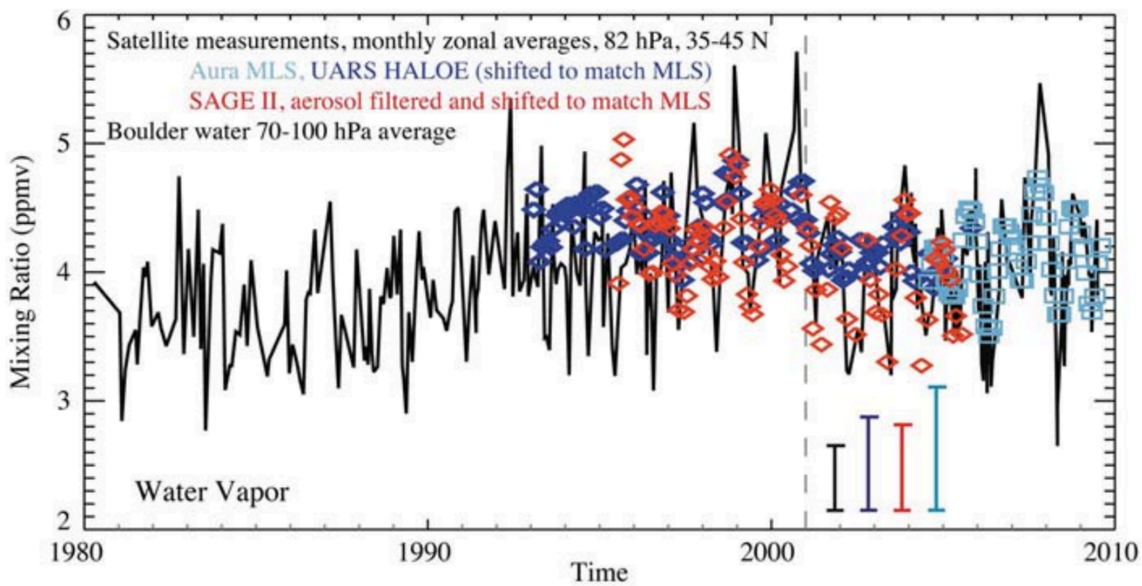


Daily observations and 12-month moving average shown. Data from PMOD: http://www.pmodwrc.ch/pmod.php?topic=tsi/composite/SolarConstant

The most recent trough in solar activity could play a role in depressing short-term trends, and the overall decline in total solar irradiance (TSI) in recent years relative to past solar cycles may be a small contributing factor in the decadal-scale pause. As the MET Office explains, "There is no doubt that the declining phase of the 11-year cycle of total solar irradiance has contributed to a reduction in incoming energy over the first decade of the 21st century, but still not enough to explain the pause in global surface temperature rise." On the other hand, climate models using up-to-date solar forcings don't show noticeably lower temperatures in the past decade, and that data runs counter to the idea that longer-term changes in the solar cycle are playing a major role in the pause. Similarly, the recent IPCC report significantly downgrades the magnitude of solar forcings and results presented in Rhode et al (2013) suggest that changes in solar forcings have a nearly negligible effect on climate.

Stratospheric Water Vapor

Water vapor in the upper atmosphere plays an important role in the earth's climate. The figure below, from [a paper in *Science*] by Susan Soloman and her colleagues shows a notable decline in stratospheric (high atmosphere) water vapor after the year 2000. They argue that this "very likely made substantial contributions to the flattening of the global warming trend since about 2000" and that temperatures between 2000-2009 would have warmed about 25 percent faster if stratospheric water vapor had remained constant. The figure below shows various different estimates of stratospheric water vapor content, with the pre- and post-2001 periods highlighted.



Soloman et al argue that El Nino has been one of the drivers of changes in stratospheric water vapor, noting that "The drop in stratospheric water vapor observed after 2001 has been correlated to sea surface temperature (SST) increases in the vicinity of the tropical 'warm pool' which are related to the El Nino Southern Oscillation (ENSO)".

That said, the models that Soloman et al use still show significant warming over the past decade even when stratospheric water vapor is declining (they give a rise of 0.10 C instead of 0.14 C, a 0.04°C difference). Based on these results, declining stratospheric water vapor would only account for about a quarter of the pause in warming. They also point out that an increase in stratospheric water vapor during the 1990s may have led to about 30 percent more warming during that decade than would have otherwise occurred. The error bars are also fairly wide on the measurements of stratospheric water vapor, which makes precise attribution difficult.

Small Volcanic Eruptions

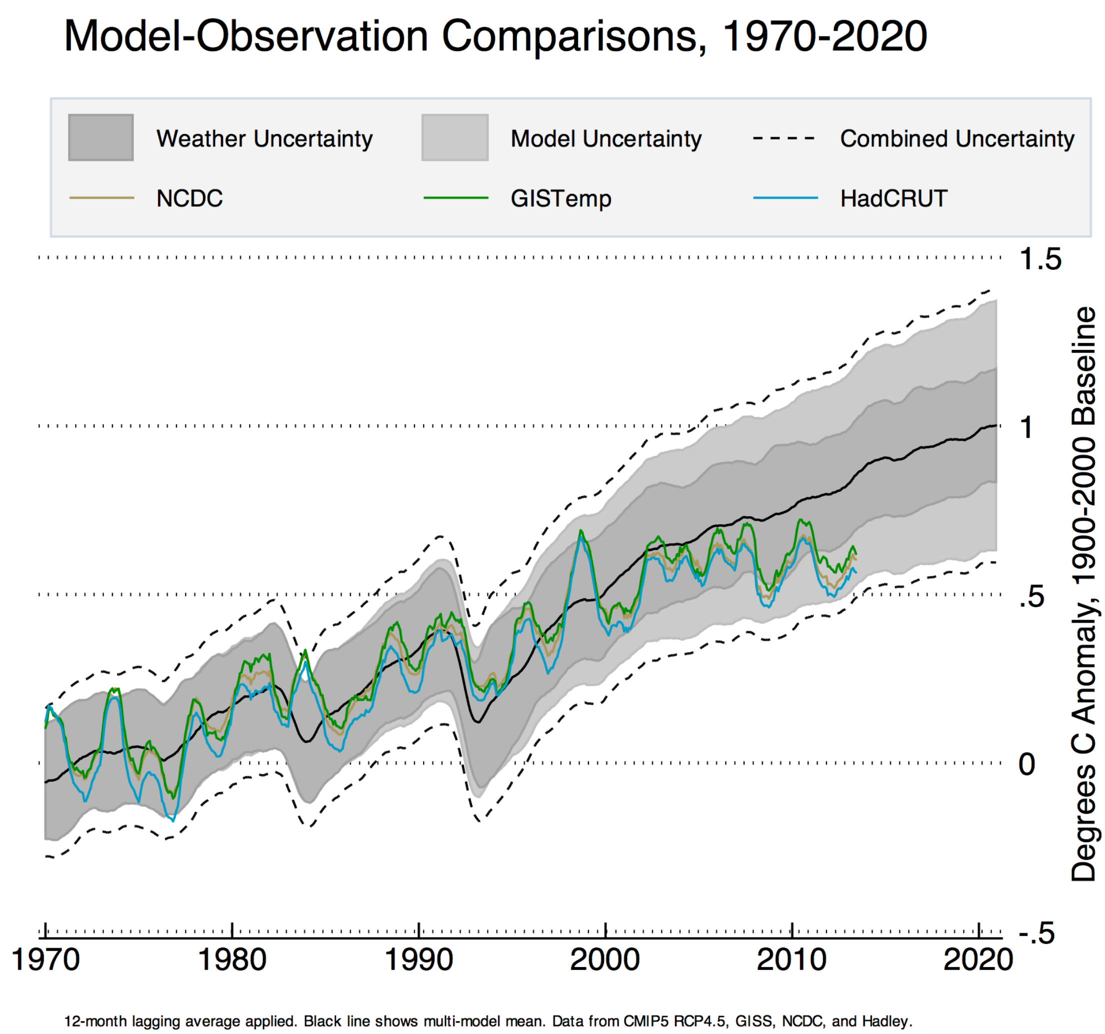
Stratospheric aerosols—small air-borne particles in the upper atmosphere—play an important role in the earth's climate. By scattering incoming solar radiation, they can significantly cool the earth. Historically, much of the study of stratospheric aerosols has focused on with large volcanic eruptions, which inject large amounts of sulfur dioxide into the stratosphere.

A recent paper by Ryan Neely and coauthors argues that multiple small volcanoes can also have a notable impact on stratospheric aerosols. They point out that "recent studies using ground-based lidar and satellite instruments document an increase in stratospheric aerosol of 4–10% per year from 2000 to 2010" and argue that "as much as 25% of the radiative forcing driving global climate change from 2000 to 2010 may have been counterbalanced by the increases in stratospheric aerosol loading over this period." They examine various potential causes of aerosol increases and identify a number of small volcanoes over the last decade as the most plausible source.

The MET Office downplays these results in their report, arguing that the effect would only be around -0.02 C to -0.03 C during the 2008-2012 period and "will not be detectable above climate variability." This relies on an analysis that has been submitted for publication but not yet published, however, and may be subject to revision in the course of the peer review process.

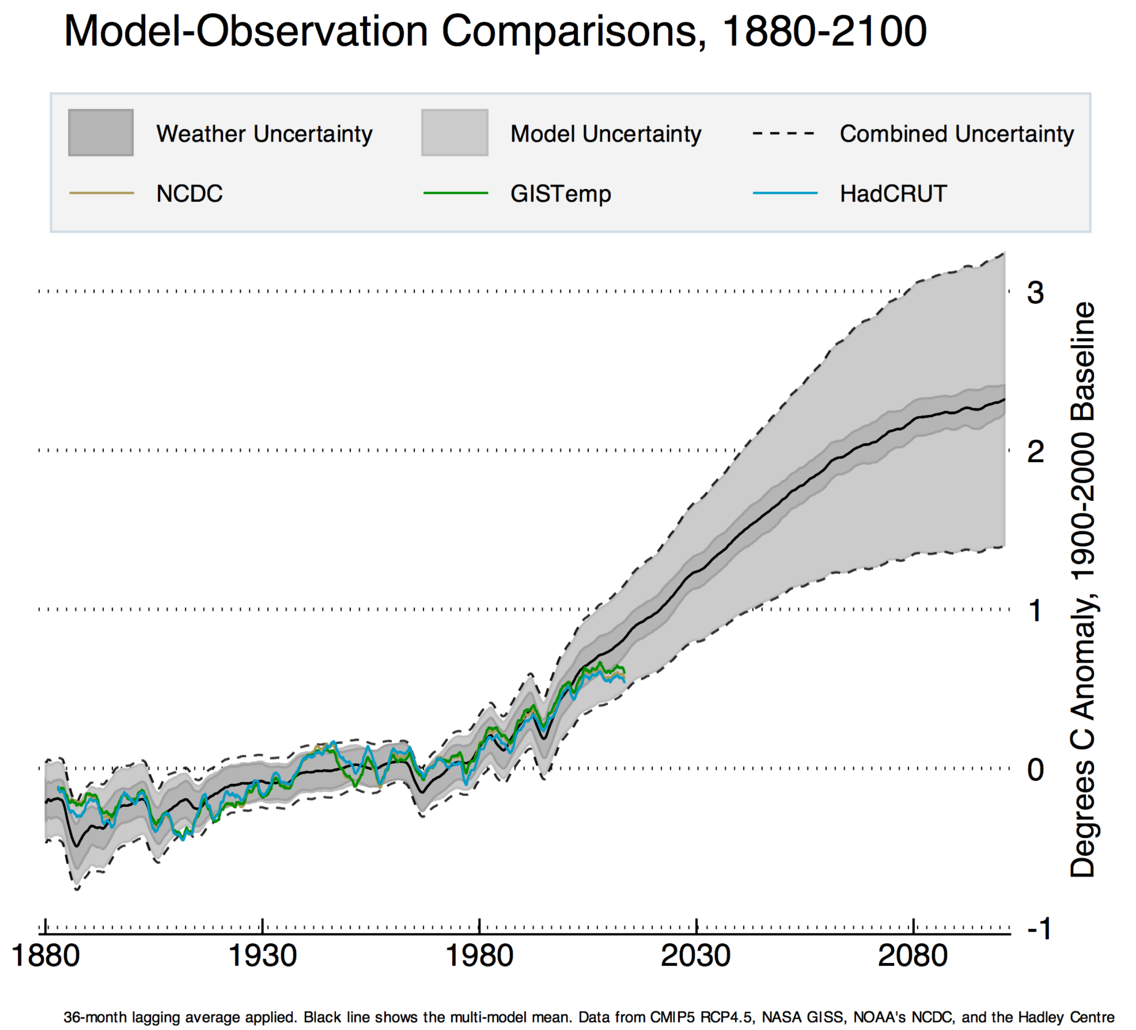
Climate Models and Observations

While it is difficult to distinguish the recent pause in global surface temperatures from the underlying long-term trend, the pause stands out much more vividly when compared to projections from the latest set of GCMs. These models predict warming of around 0.2 C per decade from 2000 to present on average.

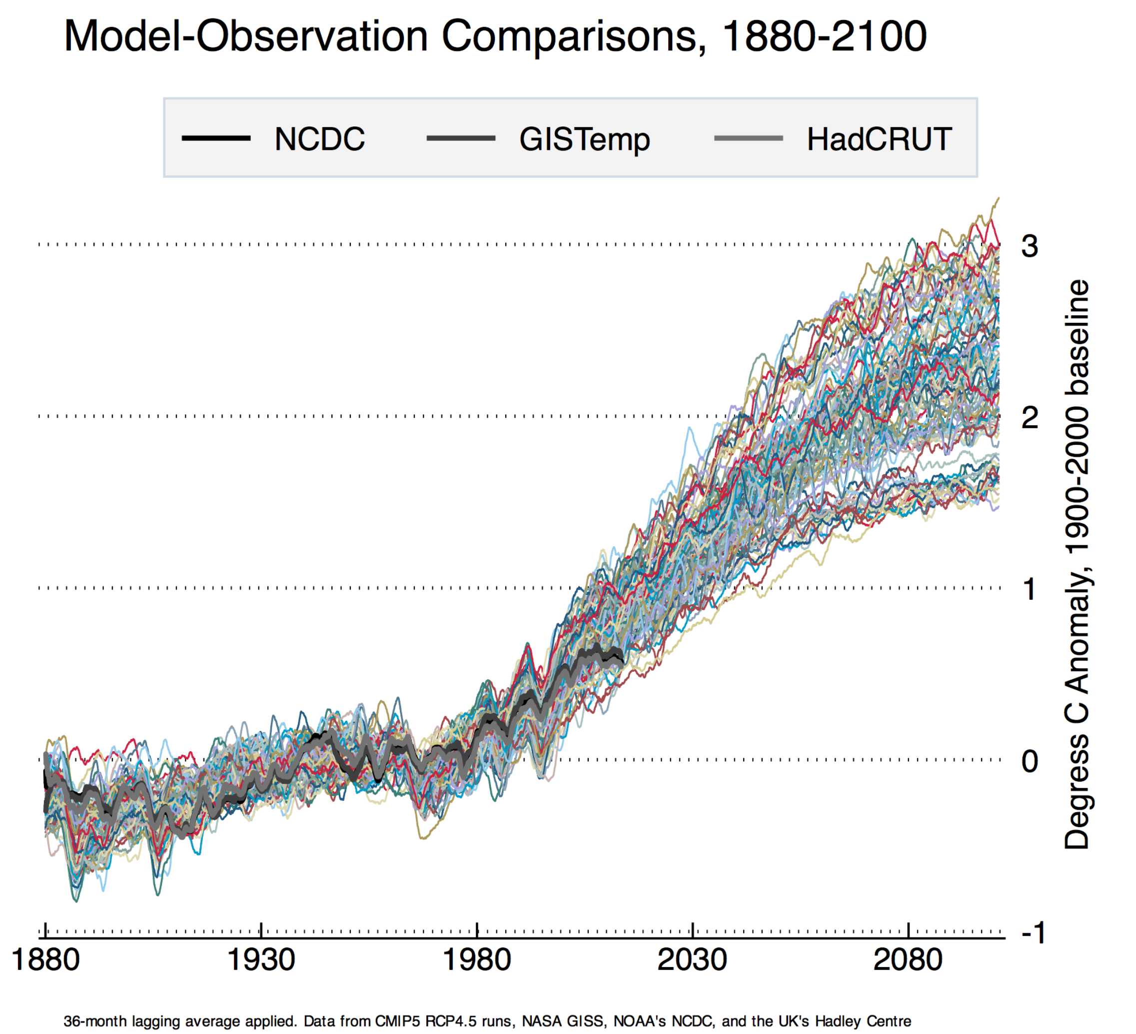


The figure above compares the three major global land/ocean temperature records to 105 unique runs involving 42 different GCMs used in the upcoming IPCC report. It shows the two-sigma (95th percent) confidence intervals as dashed back lines, with the solid black line representing the average of all models. The dark gray area represents the shorter term (less than 30 year) weather noise in the models, while the light gray area represents longer-term model uncertainty due to different physics, sensitivity, and other structural differences in the models.

While surface temperatures have generally remained fairly close to the multi-model mean in the past, the recent pause threatens to cause surface temperatures to fall outside the confidence interval of models in the next few years if temperatures do not rise.



The pause also stands out sharply if one looks at the full range of model projections, from 1880 to 2100. However, it's important to remember that all models are not created equal. Some will necessarily have more realistic parameters, better physical models, higher resolutions, etc. Simply averaging all the models together may not provide an accurate picture of variations in individual model performance.



The figure above shows all 105 model runs, and reveals significant differentiation among models. Generally speaking, models that are more consistent with recent temperatures tend to have slightly lower climate sensitivity than those that predict higher temperatures over the past few decades. A recent paper in Environmental Resource Letters used recent observations to argue that some of the highest sensitivity models may be inconsistent with the observational record.

There have been a number of new papers that use recent atmospheric, ocean, and surface temperature observations to argue that climate sensitivity may be lower than previously estimated (e.g. closer to 2 C than 4 C). These studies tend to be rather sensitive to the time period chosen, and a future warm decade could considerably change the picture. As with many things in science, there is still significant uncertainty surrounding climate sensitivity, and different approaches can obtain fairly different results. However, the longer the pause continues the more

people will begin to question whether GCMs are getting either multi-decadal variability or climate sensitivity wrong. What is clear is that there is still much we don't understand about the many different factors impacting the Earth's climate system, especially over periods as short as a decade.