# Climate Change: Evidence, Models, and Speculation

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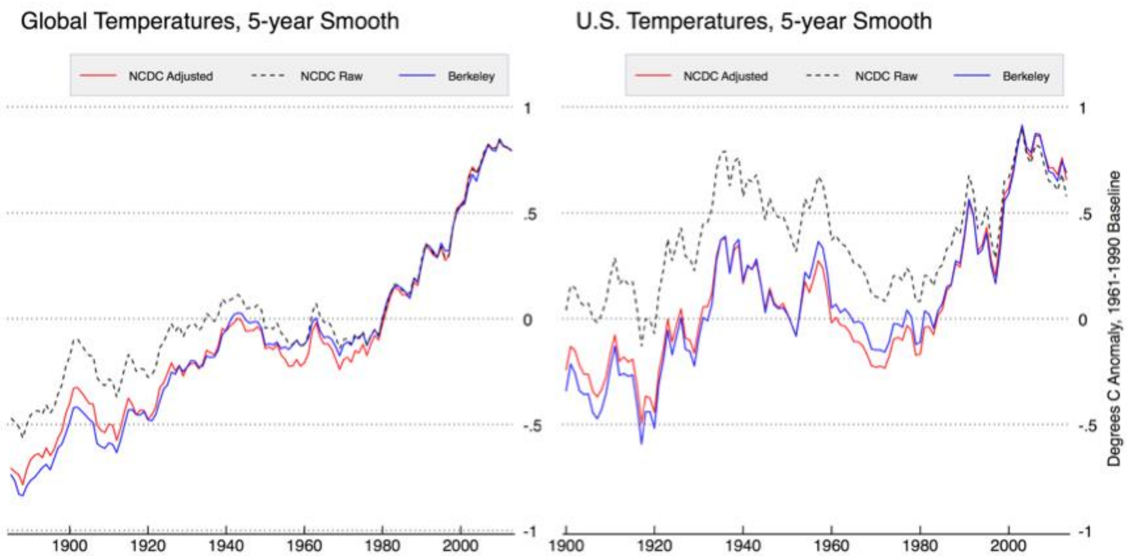
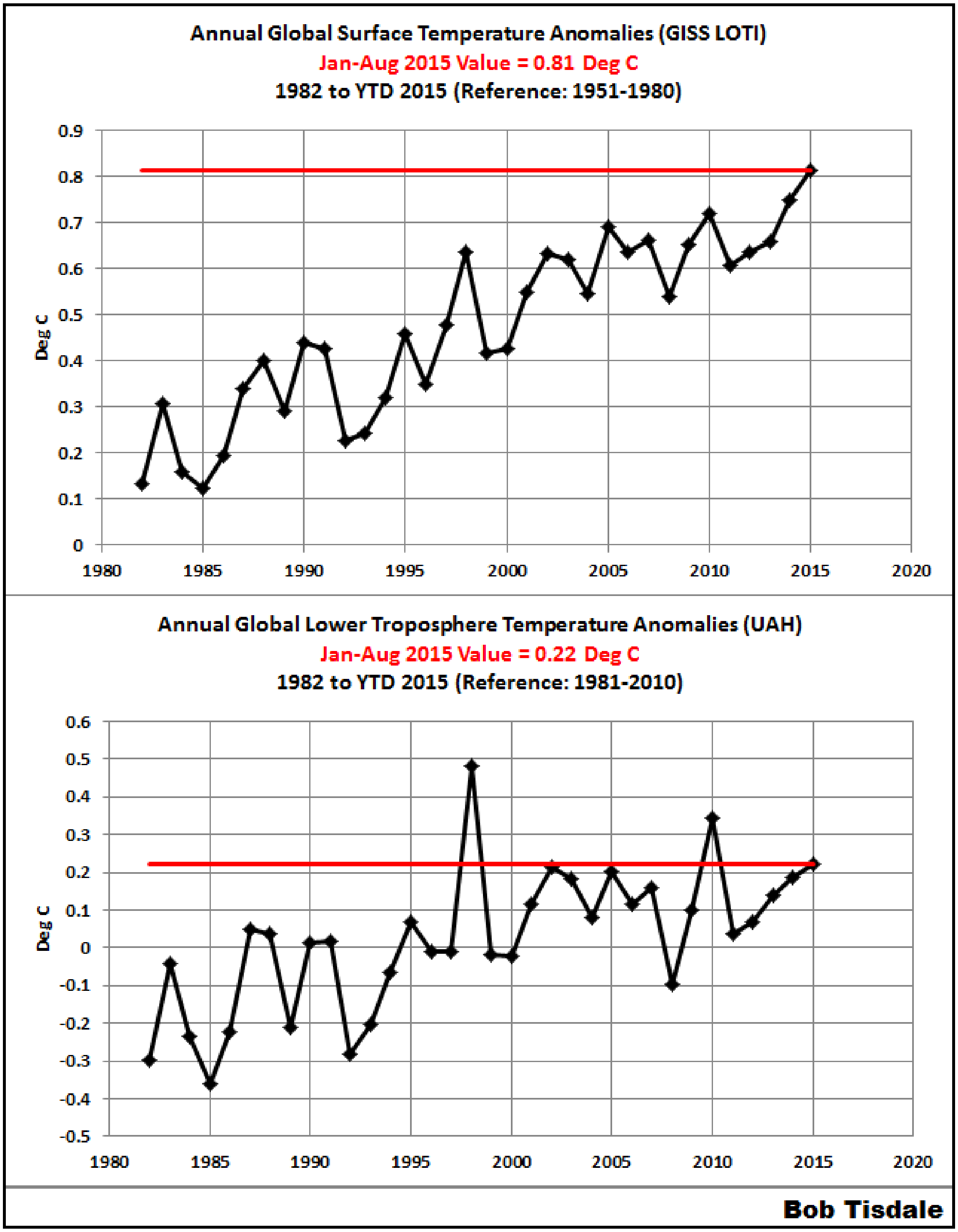
Climate Change is real. The climate is ever changing. Climate change is an observed fact happening today as in the past, and certainly in the future as well. Conventionally, 'climate' is defined as average weather over a 30-year interval, so statements that a certain year has been 'the warmest ever' or that yesterday was colder than today have little significance for the climate record. In addition, the climate varies vastly over the surface of the Earth [https://en.wikipedia.org/wiki/K%C3%B6ppen_climate_classification] and for the land area with altitude above sea level, so it is difficult to characterize the *global* climate by a single measure. Nevertheless, the difference between the yearly average temperature and its 30-year average, the *temperature anomaly* [the word 'anomaly' as used here does not carry the usual meaning of 'oddity, peculiarity, or incongruity'], is conventionally used as such a measure, when averaged over the globe. Herein lies a problem: the measurements are not evenly distributed over the globe (in space and time), and are particularly sparse over the oceans and high latitudes.

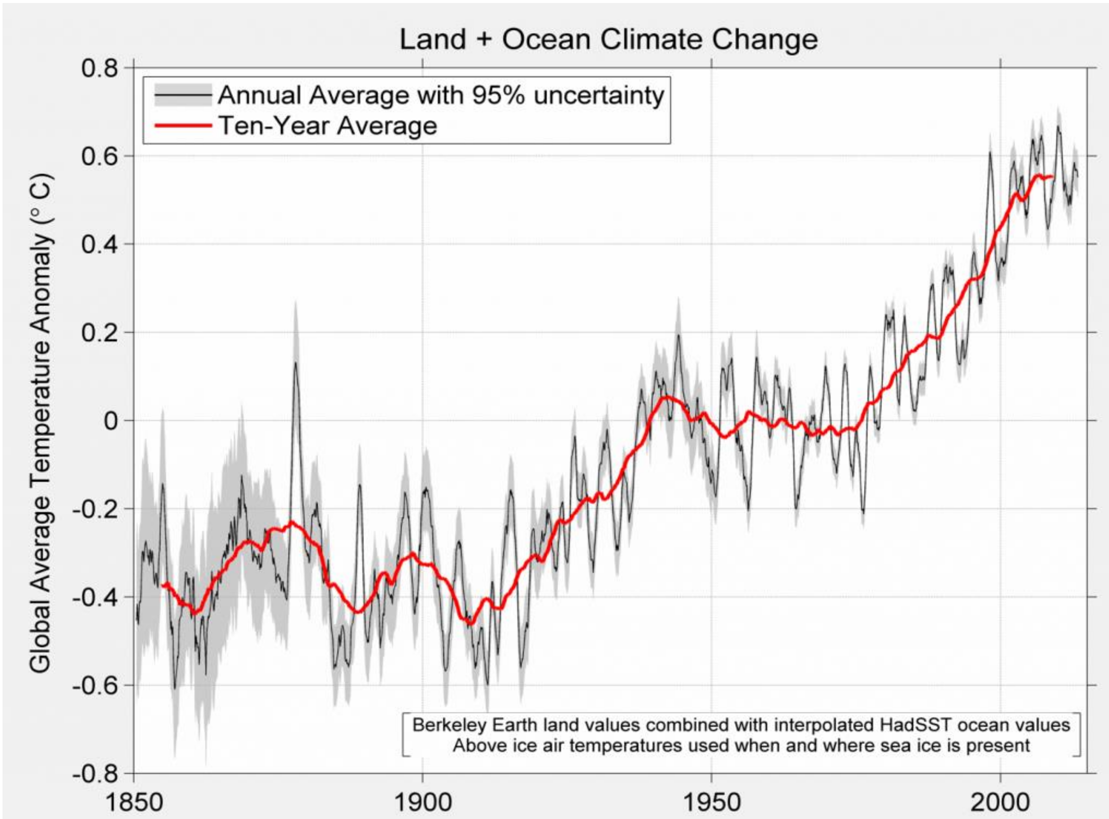
## Temperatures over Land

Various schemes are used to extrapolate (or fill in) the sparse data in order to approximate global coverage. Needless to say, such filling in (making up data) is open to criticism and uncertainty. In addition, various effects, such as the Urban Heat Island effect (https://en.wikipedia.org/wiki/Urban_heat_island) and changes related to station siting issues and 'correction' of perceived or real errors in the record lead to ever changing 'adjustments' of the record, curiously almost every new adjustment is in the sense of reducing early values and increasing recent values, thus constituting a part of literally man-made global warming. Figure #1 shows the effect of homogenization and adjustments (http://berkeleyearth.org/understanding-adjustments-temperature-data/):



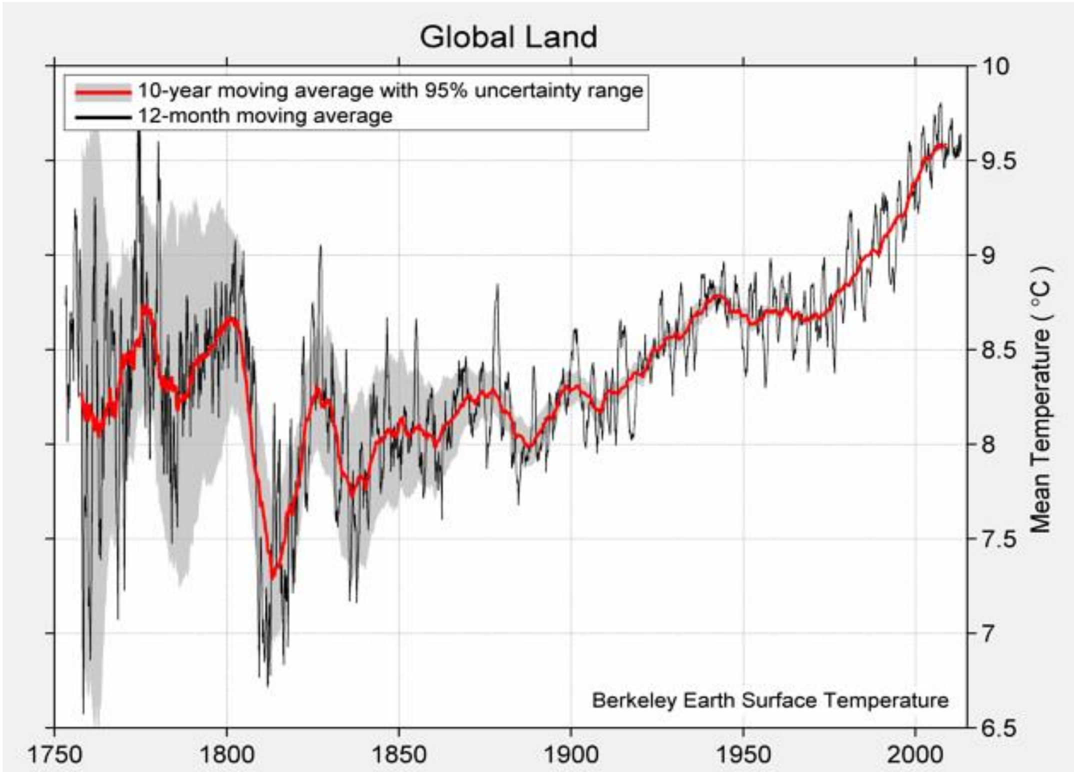



Adjustments made to correct faulty data are, of course, both necessary and desirable as we shall see in the section about the long-term variation of solar activity. Another example, Figure #2, is the difference between the NASA (GISS) adjusted data and the data derived from satellite measurements. Be that as it may, we can consider the 'BEST' estimate of global temperature anomalies (from http://berkeleyearth.org/land-and-ocean-data/), Figure #3:

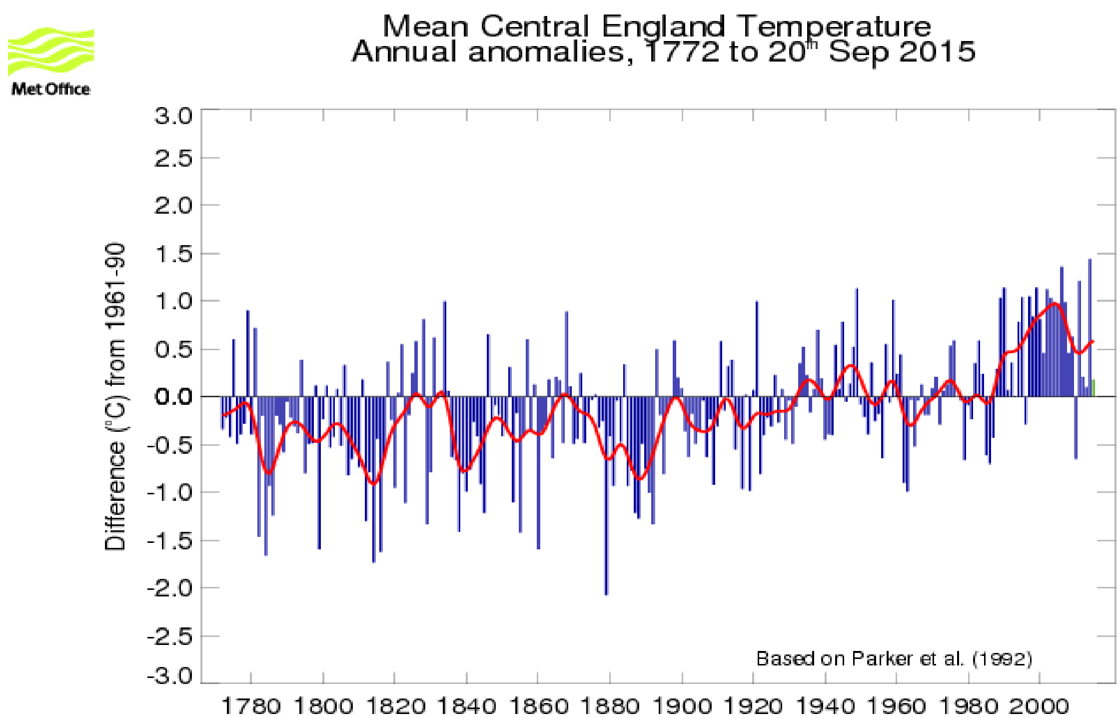



The Berkeley Earth Surface Temperature Study (2015) created this merged data set by combining 1.6 billion temperature reports from 16 preexisting data archives. Whenever possible, they used raw data rather than previously homogenized or edited data. Still, even this record incorporates some interpolated ocean values so there is wiggle room for further 'improvements'. It is probably significant that the increase from 1910-1945 is very similar to the increase from 1975-2002, and that there was a 'pause' from 1945-1975 and a clear hint of a similar plateau 2003-2015. It is not clear whether the latter pause will continue, and in any case it has to continue for a total of 30 years to be considered a 'firm' climate change. If you compare Figures #3 and #1 (based on an earlier analysis) you will notice that the warming from 1900 to 2000 differ, 0.95°C and 1.35°C, respectively. This is typical of the 'state-of-the-art'. Other historical datasets have been altered extensively. Analysis of the U.S. Historical Climatological Network (USHCN) shows that less than 10% of the data survives in the climate record as unaltered data.

The BEST data allows reconstruction of the average Land temperatures back to 1753, but with very large error bars on the early values, Figure #4:

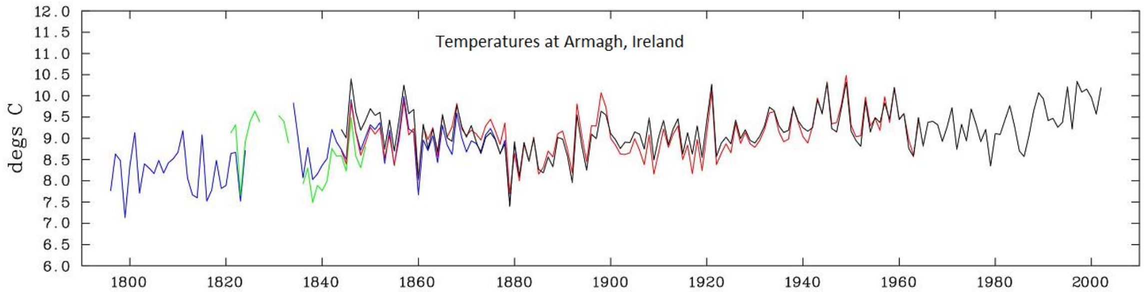



The longest **regional** instrumental record is the Central England Temperature record (http://www.metoffice.gov.uk/hadobs/hadcet/), Figure #5:



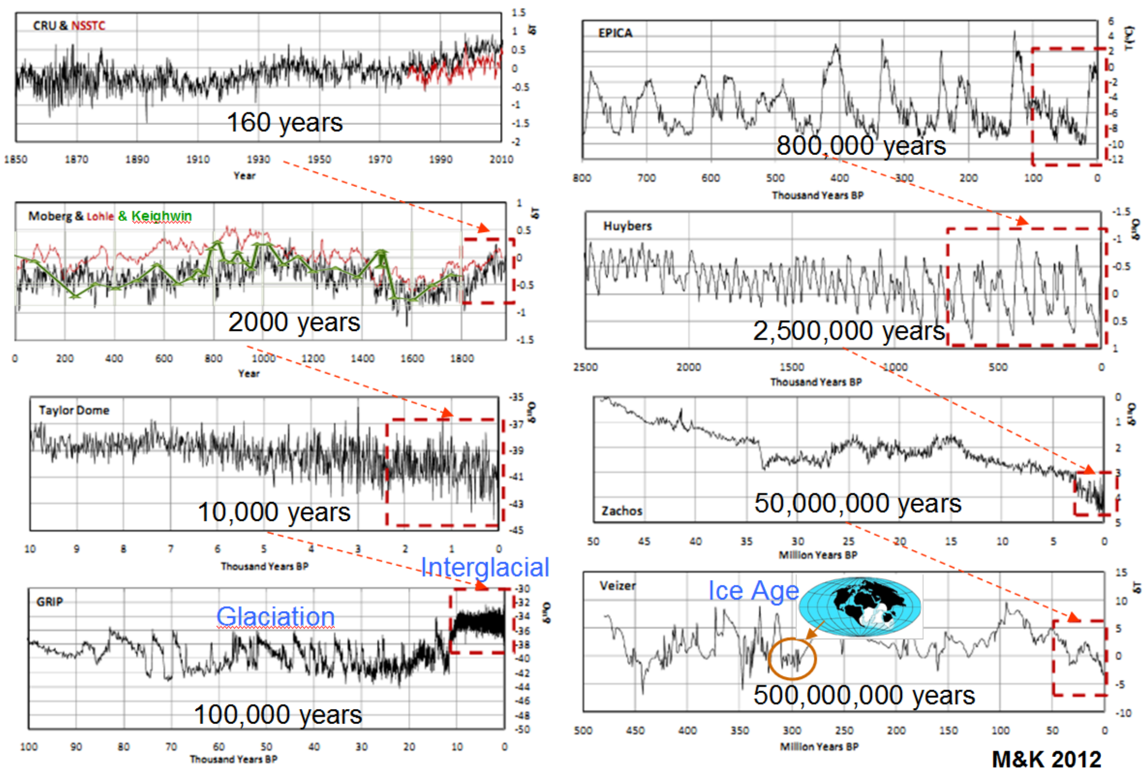

The CET record actually follows the Global record rather closely.

Another long series is the measurements of air temperature at Armagh Observatory (Ireland), showing substantially the same variation as CET and confirming the long-term increase over the past 200 years (Butler et al. 2005, [http://climate.arm.ac.uk/calibrated/airtemp/](http://climate.arm.ac.uk/calibrated/airtemp/)), Figure #6:




The plot shows the mean annual temperature at Armagh Observatory 1796-2002 from three independent series: (blue, black, and red) and from the Dunsink Patch data (green, 1825-1833). "Almost every climate scientist agrees that the world is warmer now than it was in the late 19th century; however, is this really all that remarkable in view of the historical and geological evidence for climate change over past millennia?" (John Butler).

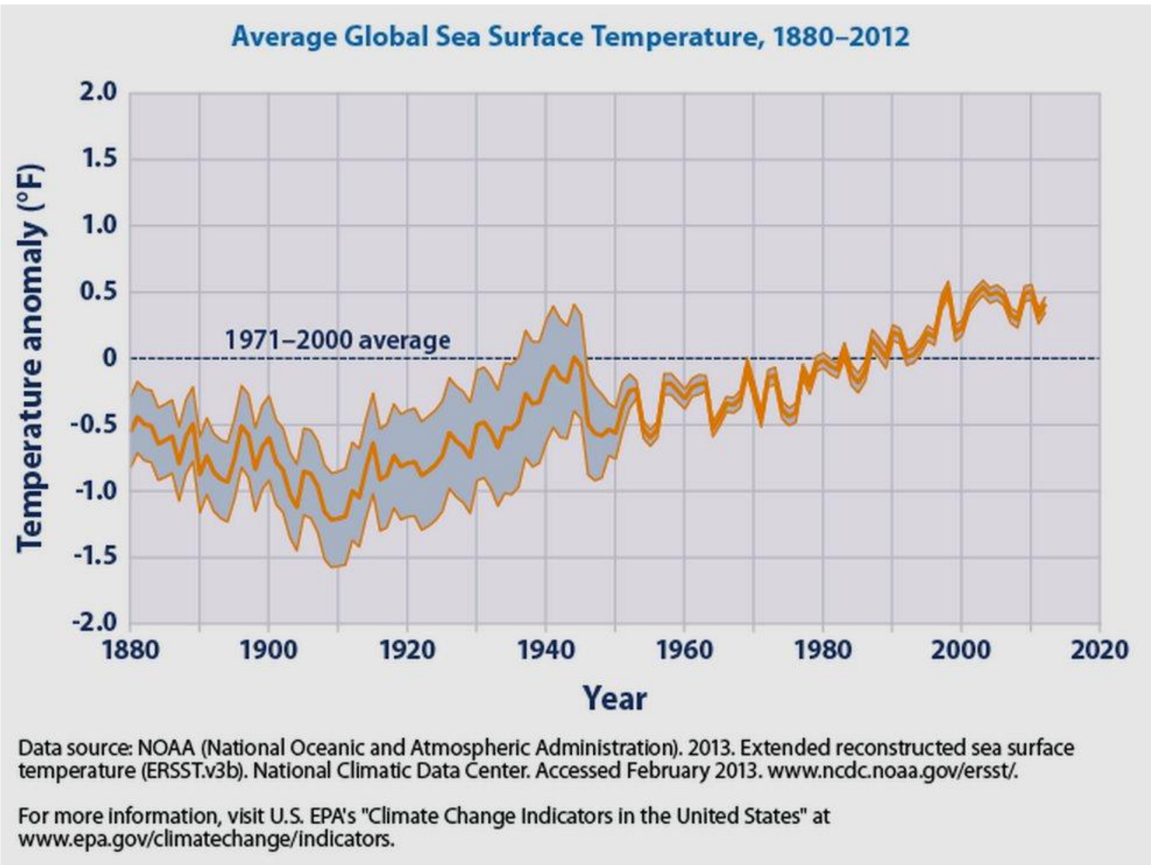
This is dramatically borne out by placing the temperature record in a historical perspective, Figure #7 (adapted from Markonis & Koutsoyiannis, *Surveys in Geophysics*, **34**, 181, 2013):



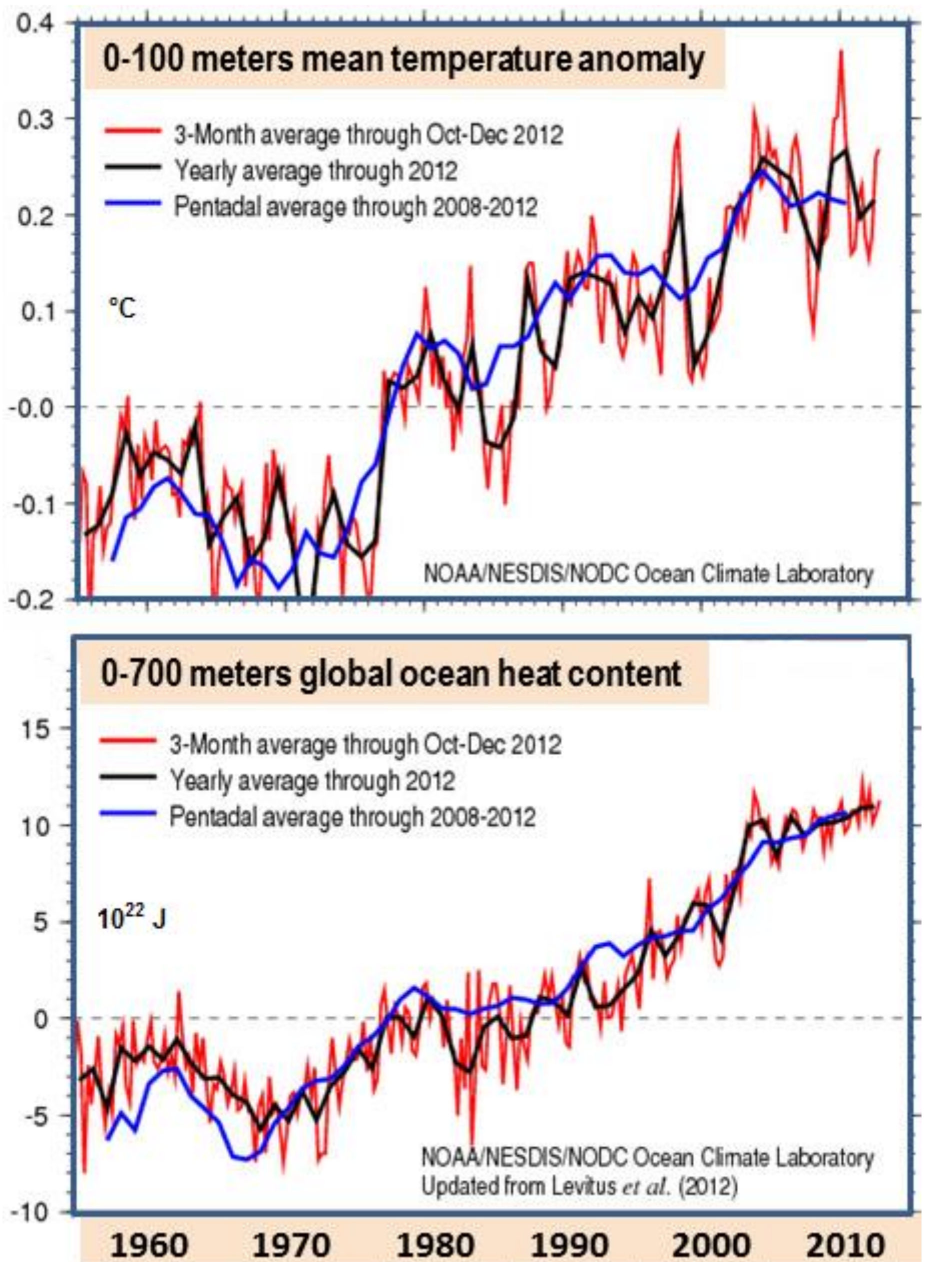

We should note that the Earth currently is in an ice age with periodic glaciations caused by changing orbital parameters (due to perturbations mainly by the planets Jupiter and Saturn) combined with suitable location of the land masses and ocean circulation, and that the Earth historically typically has been 5-10°C warmer than today.

**Temperatures over Oceans**

The oceans cover 71% of the Earth's surface and have a heat capacity several orders of magnitude higher than air and so contain (store) most of the heat received from the Sun for some period of time and are thus an important actor in climate change. Warming of the oceans accounts for more than 90% of the extra energy absorbed by Earth during 1971–2010. Systematic, direct measurements of Sea Surface Temperatures go back more than a century, Figure #8, but, of course have the same problems of coverage as the air temperatures, combined with a change of how the measurements were carried out. In the nineteenth century, measurements were obtained by dipping a thermometer into a bucket of water that was manually drawn from the sea surface, either a wood or an uninsulated canvas bucket (which cooled quicker than a wood bucket). Later, SST was measured as the temperature at the intake port of the seawater used to cool the engines in large ships. The sudden change in temperature in the 1940s is probably the result of an undocumented change in procedure. Today, extensive arrays of moored and drifting buoys measure seawater temperatures at the surface and at depth, beaming the measurements to satellites for processing and collection, and the coverage problem (while still somewhat with us) has become less serious.



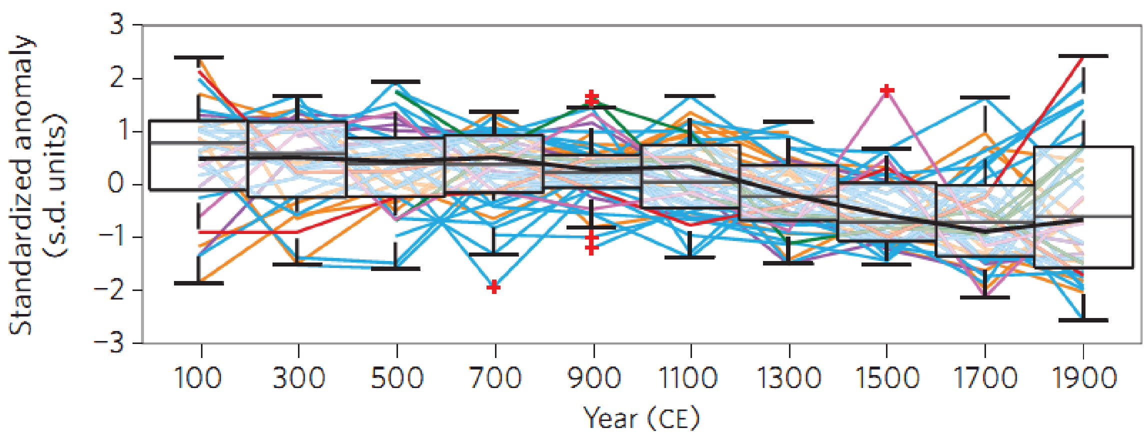

Since the 1950s it has been possible to estimate the Heat Content of the upper 700 meter of the Ocean and also the temperature anomaly in the uppermost 100 m, Figure #8, being very similar to the surface anomaly, but (understandably) of only half the amplitude:




The Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC-AR5), authored by 209 lead authors, 50 review editors from 39 countries, and more than 600 contributing authors from 32 countries, with feedback from many hundreds of reviewers and vetted (and suitably altered) for political adherence to policy by numerous Governmental reviewers, explains that "A combination of rising Sulfur aerosol emissions from around 2001, a decline in sunspot activity and La Niña events resulted in a relative lull in warming, while peak temperatures were reached in 2005 and 2010 and warming of the oceans continues", while other researchers contradict the IPCC by claiming that no such lull, or pause, or hiatus exists at all and thus need no explanation:
( http://news.stanford.edu/news/2015/september/global-warming-hiatus-091715.html ).

The pause (or even decline) from 1945-1975 was also blamed on rising aerosol emissions, that at that time apparently overwhelmed both high sunspot activity and increasing emission of greenhouse gases. With our poor understanding of the climate system, such post-hoc 'explanations' come easily, almost as knee-jerk reactions to any change whatsoever, especially if they fit in the current paradigm (back then global cooling, now global warming).

Reconstructions of ocean paleo-temperature anomalies over longer time spans put the above 'instrumental' record in perspective. The long-awaited (and long overdue) PAGES2K synthesis of 57 high-resolution ocean sediment series (OCEAN2K) was recently published [McGregor et al., *Nature Geoscience*, **8**, 671-677, September 2015, http://www.nature.com/ngeo/journal/v8/n9/pdf/ngeo2510.pdf ], Figure #10 (the lines are color-coded for each ocean basin around the 200-year wide box containing the medians of the values in that box [encompassing the 25% and 75% quartiles]; the thick black line is a weighted median of these values):

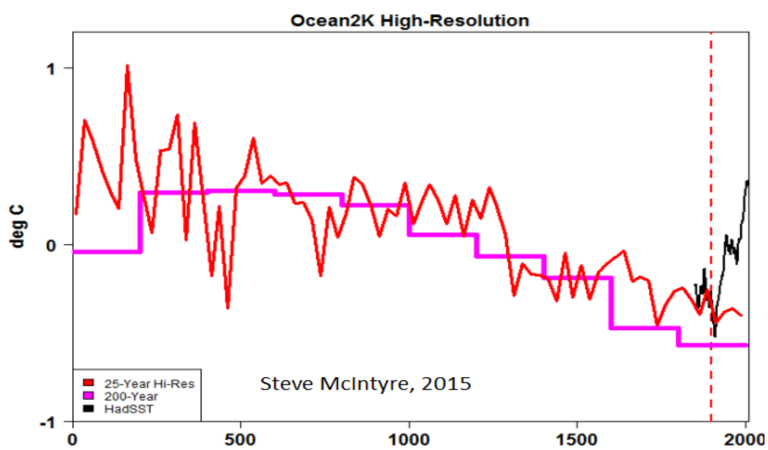



The reconstruction relies heavily on the fact that certain species of ocean-living coccolithophores produce unique organic compounds [biomarkers]. The coccolithophores *Emiliana huxleyi* and the closely related *Gephyrocapsa oceanica* produce a suite of long-chain (C37-C39) unsaturated ethyl and methyl ketones known as alkenones. Alkenones are resistant to degradation and preserve well in ocean sediments. Alkenone undersaturation is an indicator of sea surface temperature. In the 1980s, researchers discovered that in C37 methyl ketones the ratio of diunsaturated ($C_{37:2}$) and triunsaturated ($C_{37:3}$) methyl ketones reflects the growth temperature of the alkenone producers (e.g. Marlowe et al. 1984). The ratio is typically expressed as $U_{37}^K = [C_{37:2}]/[C_{37:2} + C_{37:3}]$. Several studies of laboratory cultures have provided a direct calibration between sea surface temperatures and $U_{37}^K$ (Eglinton et al. 2001) and established a universal calibration between the mean annual sea surface temperature (SST in °C) and alkenone undersaturation: $U_{37}^K = (0.044 \pm 0.016) + (0.033 \pm 0.001)$ SST. See also Conte et al., *G-Cubed*, **7**(2), 2006.

Temperature seems to be the dominant control element of Mg/Ca ratios in foraminifera, and foraminiferal Mg/Ca is emerging as a widely applied paleothermometer (e.g. Nuernberg et al. 1996). The alkenone and Mg/Ca ratio are directly calibrated in degrees C according to standard equations (not ex-post correlations). During the past 25 years and especially the past 10 years, alkenone samples have been widely collected throughout world oceans and sediment data yield reliable maps of ocean temperature without post-hoc adjusting or curve fitting.

Alkenone series constitute 15 of 21 the high-resolution series of the OCEAN2K dataset (26 of 57 overall) and are also the majority (31 of 60) of another recent reconstruction (http://www.sciencemag.org/content/339/6124/1198.abstract, Marcott et al., 2013) of ocean temperature data, with foraminifera Mg/Ca being the second-largest fraction. Alkenone and Mg/Ca series have been sampled at sufficiently high-resolution to reconstruct climate change the past two millennia.

Figure #10 showed the 'standardized changes' (not the actual 'sea surface temperatures'). The original proxies were expressed in degrees of temperature, and the supplemental information of the paper contains the temperature data and with higher time resolution than 200 years, so it is possible (and trivial) to obtain a much more meaningful representation of the data, Figure #11, with time resolution of 25 years:

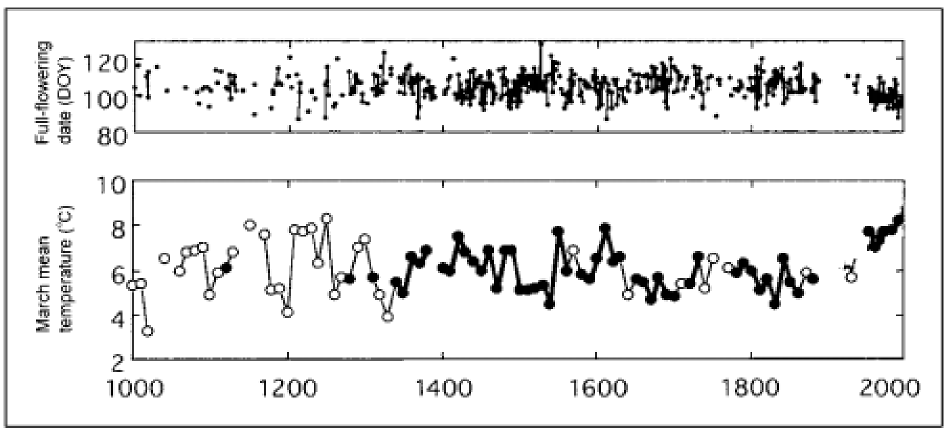



The thin black graph shows the instrumental record since 1850 [HadSST: http://www.metoffice.gov.uk/hadobs/hadsst3/data/download.html ]. The divergence between the poorly calibrated instrumental record and the well-calibrated reconstruction visible in the higher time resolution (perhaps reminiscent of the infamous 'hide-the-decline' Nature-trick in order not to "dilute the message") is disconcerting, but may be a reflection on how much to trust either record. The large scatter in the 1801-2000 box of Figure #7 may be part of the problem. The discrepancy between the ocean-record and the instrumental record is a serious puzzle and needs to be resolved.

The decrease during years 800-1800 is ascribed by McGregor et al. to increasing (but also uncertain) volcanic forcing rather than to changes in Earth-orientation and orbital changes. The Holocene's comparatively warm climate has been the exception more than the rule during the last 500,000 years or more. Berger and Loutre argue (*Science*, **297**, 1287, 2002) that with or without human perturbations, the current warm climate may last another 50,000 years. The reason is a minimum in the eccentricity of Earth's orbit around the Sun, but eventually, the current interglacial will come to an end, and we resume the slow decline towards the next glaciation many tens of thousands of years in the future, and thus of relatively little concern today.

## A Cherry Blossom Record

A unique data set that can potentially be used as a reliable proxy of temperature is the record of annual cherry blossom festivals in Japan. Cherry blossom festivals are a special feature of Japanese life that really has no equivalent in other countries. During festivals, all ages spend time outdoors, enjoying the beauty of the cherry blossoms by day and by night. The festivals have been the subject of numerous poems and songs and have been depicted in paintings, pottery, and textiles for hundreds of years. Because of their great popularity and cultural significance, local governments, meteorologists, botanists, and newspapers have recorded the flowering date of cherry blossoms for an extraordinarily long time. Researchers have been able to estimate March temperatures in the beautiful city of Kyoto going back to the 11th century, Figure #12, showing that during the 11th through the 13th centuries, average temperatures were at their warmest averages, often as high as 8°C, as indicated by early dates of the cherry blossom festival:




COURTESY OF DR. YASUYUKI AONO AND YUKIO OMOTO, 1994

*Upper figure. Known dates of the cherry blossom festival (full flowering of* P. jamasakura*) in Kyoto from the 11th century to the present time. April 1 is the 91st day of the year (in years without a Leap Year); May 1 is the 122nd day of the year. In recent decades, flowering times have become earlier than in the past.*

*Lower figure. Estimated March mean temperature in each decade, as calculated from flowering dates. Means calculated from 5 or more years are shown as solid dots. Decades with less than 5 years of data are shown as open circles. While temperatures have varied over this period, recent decades have been warmer on average than any time during the past 1000 years.*

There were occasionally very cold years, as indicated by late flowering years, but on the whole this was the warmest average period. From 1400 to the mid 1500s, temperatures were variable, but they appear to have declined slightly on average. Certain decades, both before and after 1600, were noticeably warmer. In the following centuries, temperatures generally declined to 6°C, with particularly low temperatures in the periods from 1690 to the 1710s, and from 1810 to the 1830s, e.g. the *year without a summer*, 1816, likely caused by the massive 1815 eruption of Mount Tambora in Indonesia. The recent rise of temperatures is attributed, **primarily** to the warming associated with the urbanization of the Kyoto area (estimated to be of the order of 3°C), and secondarily with the general global climate warming of Japan.

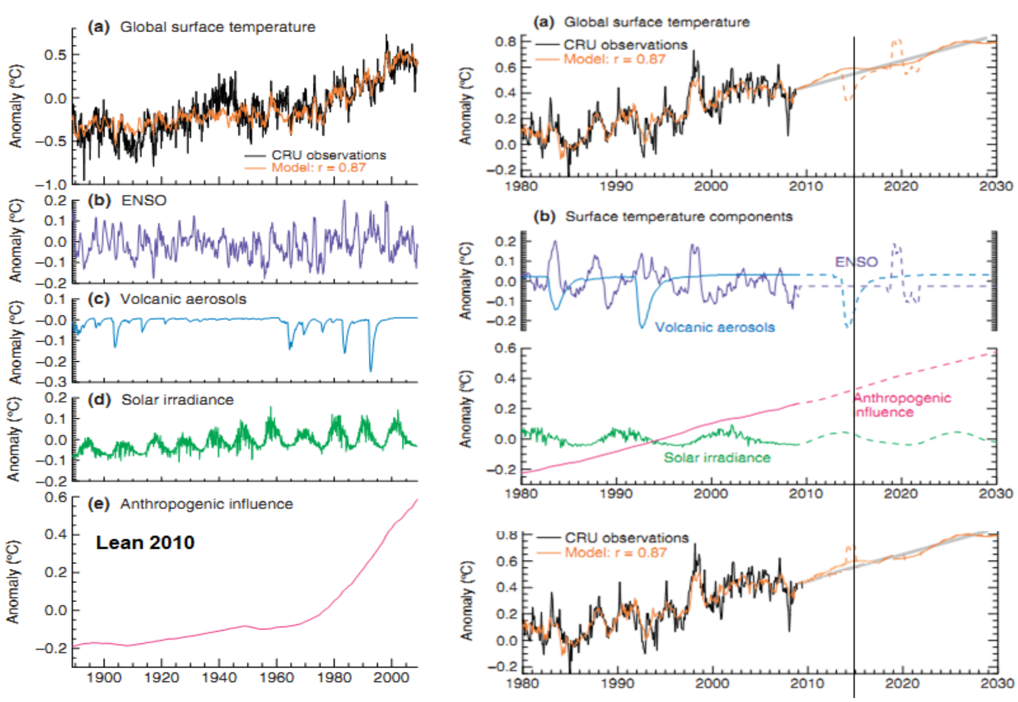
## Climate Variables and Models

As far as we know there are the following parameters or variables influencing our climate on time scales less than a million years (thus excluding the slow evolution of the Sun):

1) Earth orbital and orientation variations
2) Changes in ocean circulation, ENSO and others
3) Solar Irradiance and activity
4) Volcanic aerosol emissions
5) Greenhouse gas emissions
6) Land use (cities, logging, crops, grazing…)
7) Regional differences
8) Stochastic variations of a complex, non-linear system
9) Diverse unpredictable catastrophes

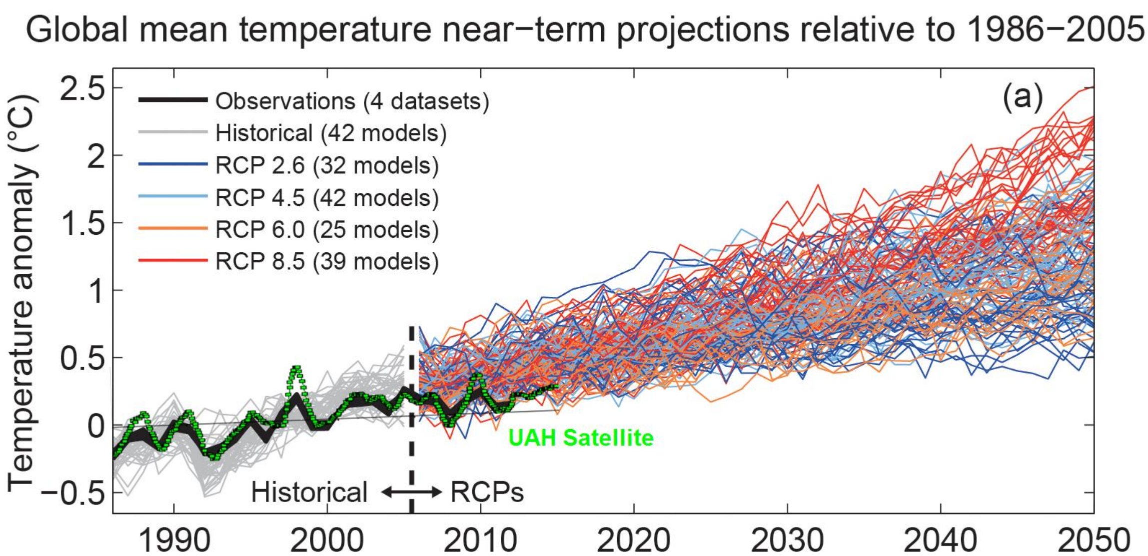
The parameters are not all independent and couplings and feedback make for intricate interplays and confounding correlations. With so many parameters in play, one can usually (and easily) find some combination that 'models' or mimics the (uncertain) variations of global temperatures over a cherry-picked time interval of choice. Von Neumann's quip that "with four parameters I can fit an elephant, and with five I can make him wiggle his trunk" comes to mind. Some parameters may convolve to form intermediate ones, e.g. the albedo, depending on cloud cover (controlled by evaporation, thus on solar insolation) and aerosols.

Figure #13 shows an attempt to model the global temperature anomaly from a linear combination of Total Solar Irradiance, ENSO, Volcanic aerosols, and an assumed Anthropogenic influence (Lean, Clim. Change 2010, 1, 111–122):



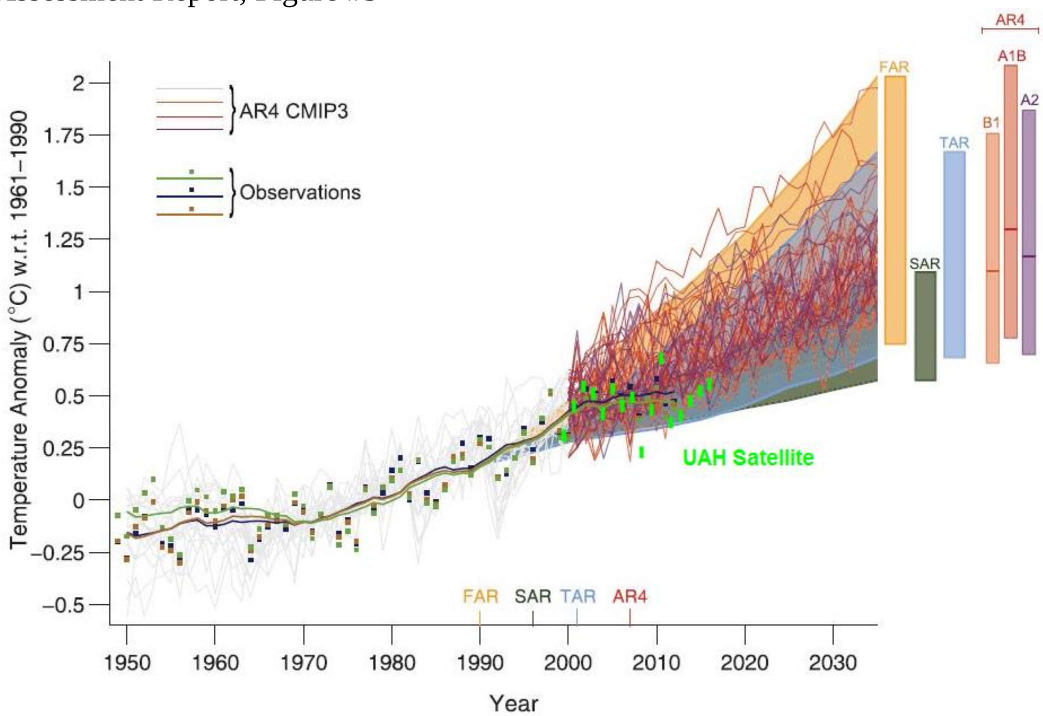

The anthropogenic influence was the net effect of eight different components, including greenhouse gases, land use and snow albedo changes, and (uncertain) tropospheric aerosols. The combination of natural and anthropogenic influences (at appropriate lags, a set of yet more free parameters) in the empirical phenomenological model captures 76% of the variance in the monthly global surface temperature record, and the Figure illustrates that this statistical model tracks closely the observed global surface temperatures from 1980 to 2008 (on which it was trained), including the lack of overall warming during the past decade (which some researchers claim did not even happen). But it is also clear that the model fails to account for the increase of the anomaly during 1910-1945, where the anthropogenic influence was negligible, as it also was before 1900.

A different approach is to model the climate using supercomputers to perform forward modeling, solving a set of equations believed to govern the evolution of the climate system, using the current state as initial conditions and projecting into the future various assumed scenarios about the anthropogenic contributions ('what-if' analysis). Scores of such models exist, but have generally been unsuccessful in predicting the near-term climate evolution, and hence doubtful as regards the longer-term changes, e.g. a century out, Figure #14 (from the recent IPCC-AR5, Figure TS.14, updated with Satellite Observations by UAH, http://www.drroyspencer.com/2015/04/version-6-0-of-the-uah-temperature-dataset-released-new-lt-trend-0-11-cdecade/) documents the failure of the models to match recent observations:




The RCPs are Representative Concentration Pathways chosen by IPCC (for a tutorial see e.g. http://www.leif.org/research/RCP_Guide.pdf). Four RCPs were selected and defined by their total radiative forcing (assumed cumulative measure of human emissions of Green House Gases (GHGs) from all sources). The RCPs were chosen to represent a broad range of climate *outcomes*; each single RCP is based on an internally consistent set of socioeconomic assumptions. Higher RCP numbers correspond to stronger assumed GHG forcings. An RCP = *x.y* means an evolution of the forcing from the base level in the year 2005 reaching *x.y* $W/m^2$ by the year 2100. Each RCP results from different combinations of economic, technological, demographic, policy, and institutional futures. Even though all the models predict more warming than is observed, one could perhaps assume that the physics behind the models is understood well enough (the infamous 'science is settled' assumption) to lend some credibility to the predictions as such, but that the error is in the climate (or model!) sensitivity to the assumed forcings of the RCPs. Regardless of which approach is believed, the failure of the models so far would seem to seriously undermine their support for extrapolations leading to a large temperature increase (e.g. 5°C or more) by 2100. The IPCC AR5 concludes that "Equilibrium climate sensitivity is likely in the range 1.5°C to 4.5°C (high confidence), extremely unlikely less than 1°C (high confidence), and very unlikely greater than 6°C (medium confidence), but admits in a footnote that "No best estimate for equilibrium climate sensitivity can now be given because of a lack of agreement on values across assessed lines of evidence and studies."

The IPCC AR5 also reminds us of the state of the model projections from the previous Assessment Report, Figure #5



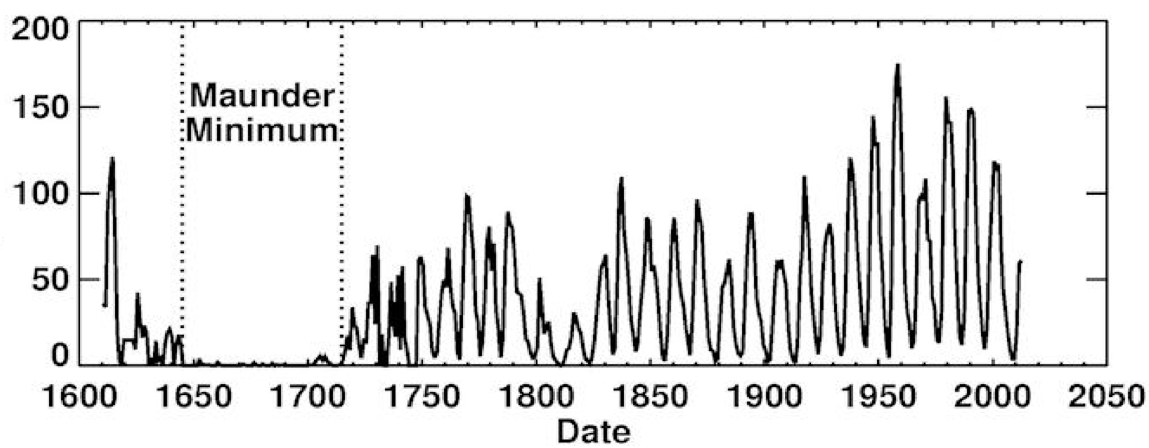

As before, we have updated the Figure to include the latest UAH Satellite data (light green rectangles). And as before, the models run too hot. The AR5 describes the models as "the simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases and aerosols". The models do not predict $CO_2$ emissions, which are an input to the models.

## The Solar Connection, if Any

Because the anthropogenic influences were insignificant before, say, the 1940s, other causes or drivers of the observed (and real and large) climate changes must be sought for earlier times (and thus also for current and future times). A popular (and obvious) choice is variation of the Sun's output of various kinds; after all, the Sun provides and regulates almost all the energy entering the Earth system and the Sun is known to be an, albeit weakly, variable star. The sunspot number is found to be a good proxy, either direct or inversed, for all variations of solar output and the number of papers claiming relationships between the sunspot number (or other solar parameter varying phased with the sunspot number) runs in the thousands (Hoyt & Schatten, *The Role of the Sun in Climate Change*, 1997) starting with Riccioli (*Almagestum Novum*, 1651) and the influential investigation by William Herschel (*Phil. Trans. R. Soc. London*, **91**, 265, 1801, debunked by Love, *Geo. Res. Lett*, **40**, 4171, 2013, but occasionally still quoted today, e.g. Clark, *The Sun Kings*, 2007, as being essentially factual). Herschel acknowledged with a caution that is sorely lacking from so many other papers on the solar connection that predictions based on his hypothesis "ought not be relied on by any one, with more confidence than the arguments ... may appear to deserve".

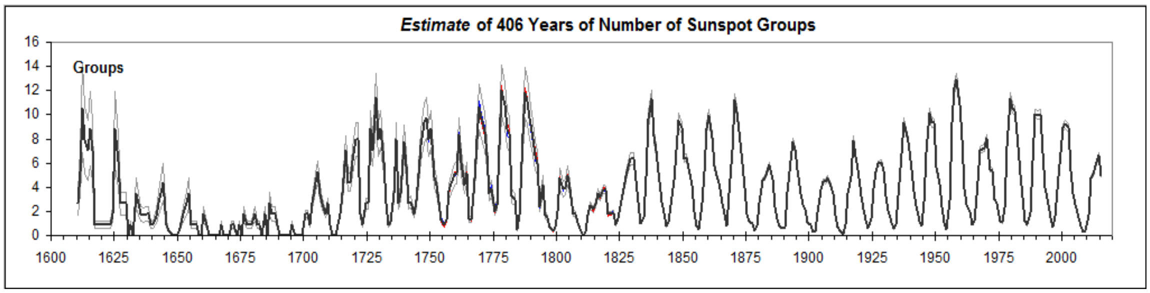
Reports of the appearance of sunspots go back to antiquity, but the sunspot record begins in and about 1610 with the first telescopic observations of sunspots by Harriot, Scheiner, Galileo, and others and continues to the present day. Rudolf Wolf (1816-1893) collected much of the earlier observational data and provided 45 years of observations of his own, constructing his celebrated Relative Sunspot Number (SSN), which we still use today (http://www.sidc.be/silso/home). As the small spots were more difficult to observe with telescope technology of the 17th and early 18th centuries (with chromatic and spherical aberration), Hoyt and Schatten (*Solar. Phys.*, **181**, 491, 1998) suggested using instead the count of sunspot groups (active regions) as a measure of solar activity, based on the notion that groups were easier to see and fewer would be missed. Hoyt and Schatten found and digitized many sunspot observations not known or used by Wolf and his successors, effectively doubling the amount of data available before Wolf's tabulations. The resulting Group Sunspot Number (GSN) was made compatible with the SSN by scaling the number of groups (GN) by a factor (12.08) to make it match the modern SSN.

Figure #16 shows the GSN proposed by Hoyt and Schatten. It has the alluring property of displaying a Modern Grand Maximum in the latter part of the 20th century ("the highest in 10,000 years" is an often cited claim) and thus may explain recent global warming as solar irradiance (and output of other kinds) would then, eventually helped by a variety of vaguely defined feedbacks and amplification processes, supply the additional energy input to the climate system needed to account for the warming.




The amplification processes are needed because the Total Solar Irradiance (TSI) varies only 0.1% from sunspot minimum to sunspot maximum, corresponding to a temperature variation of only 0.07°C.

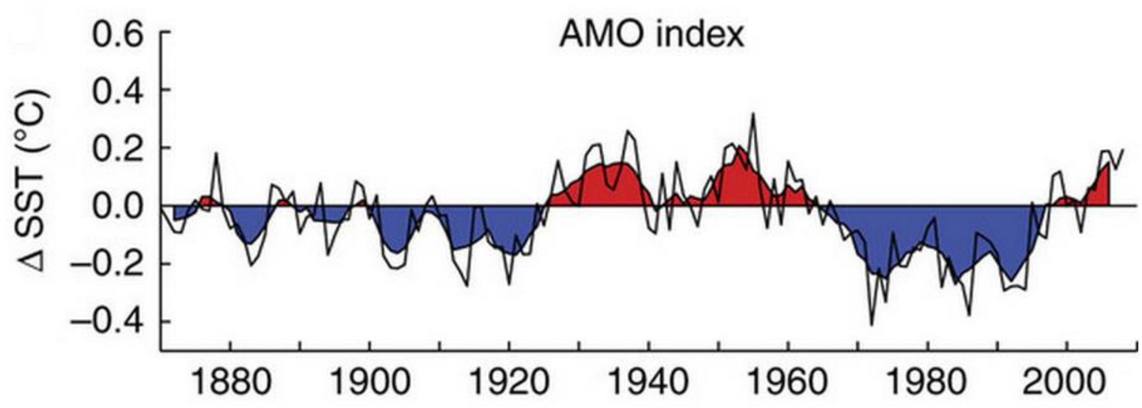
The GSN differs from the 'official' SSN by being some 40% lower before about 1880 which immediately gives the GSN an edge over the SSN in 'explaining' the recent warming. Having two significantly different sunspot number series is unsatisfactory, basically making the solar influence a free parameter: prefer the one that best matches the speculation you are peddling. A number of Workshops have recently been held by a solar physics community with the aim of resolving the discrepancy between the two sunspot number series. The main finding of the Workshop researchers was that both the GSN and the SSN had errors, artifacts, and inhomogeneities. Correcting those, revised (and reconciled) series are now replacing the earlier versions. The findings were released at a press conference at the recent 2015 International Astronomical Union General Assembly in Hawaii (http://www.iau.org/news/pressreleases/detail/iau1508/). A surprising outcome of the work was the realization that there has been no long-term trend in solar activity since 1700 AD, Figure #17:




The absence of the Modern Grand Maximum in the revised series suggests that rising global temperatures since the industrial revolution cannot be attributed mainly to increased solar activity or to processes that vary with solar activity such as the flux of Galactic Cosmic Rays, which often are claimed to modulate or control the amount of cloudiness and hence the amount of sunlight reflected back to space.

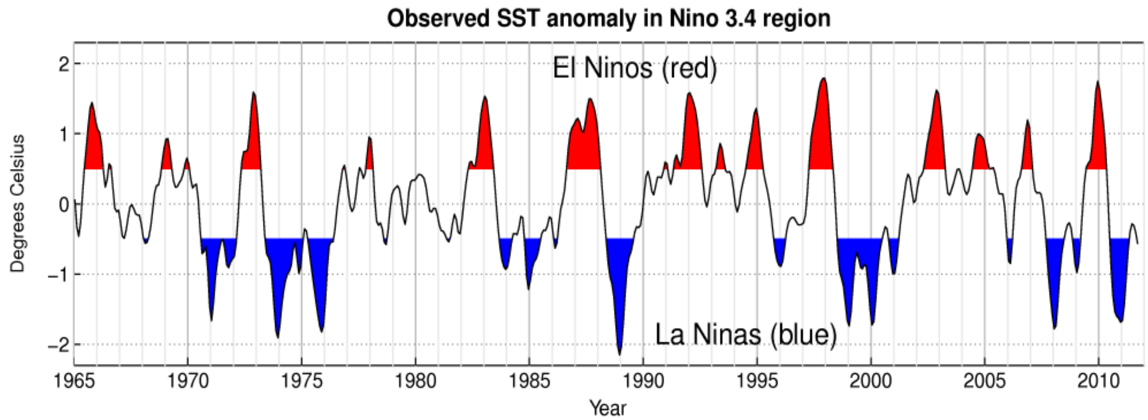
**Ocean Circulations**

The idea that slow changes in ocean circulation influence climate variability in the North Atlantic region goes back half a century. The Atlantic Multi-decadal Oscillation (AMO) is an ongoing series of long-duration changes in the sea surface temperature of the North Atlantic Ocean, with cool and warm phases that may last for 20-40 years at a time and a difference of about 0.6°C between extremes. These changes are natural and have been occurring for at least the last 1,000 years (Faurschau Knudsen et al., *Nature Comm.*, **2**, A#178, 2011). There are several lines of evidence suggesting that SST variations related to the AMO drive climate and precipitation patterns over North America, droughts in the Sahel region of Africa, variability in Northeast Brazilian rainfall, and tropical hurricane frequency and intensity. The AMO is also believed to influence regional to hemispheric-scale climate trends as far away as the Tibetan Plateau and India, possibly through changes in the inter-hemispheric redistribution of heat. The modern AMO index is defined by subtracting the global mean SST anomalies from the North Atlantic SST anomalies, Figure #18.

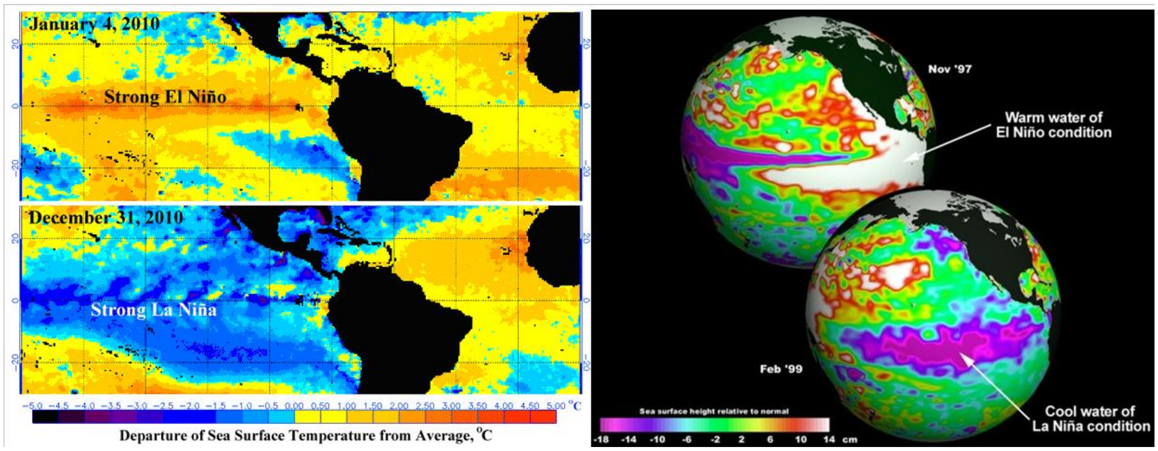



The nature and origin of the AMO is uncertain, and it remains unknown whether it represents a persistent periodic driver in the climate system, e.g. related to the Atlantic branch of the Thermohaline Circulation, or merely a transient feature. Faurschau Knudsen et al. show that distinct, ~55- to 70-year oscillations characterized the North Atlantic ocean-atmosphere variability over the past 8,000 years. They test and reject the hypothesis that this climate oscillation was directly forced by periodic changes in solar activity. They therefore conjecture that a quasi-persistent ~55- to 70-year AMO, linked to internal ocean-atmosphere variability, existed during large parts of the Holocene. In addition, their analyses suggest that the coupling from the AMO to regional climate conditions is modulated by orbitally induced shifts in large-scale ocean-atmosphere circulation.

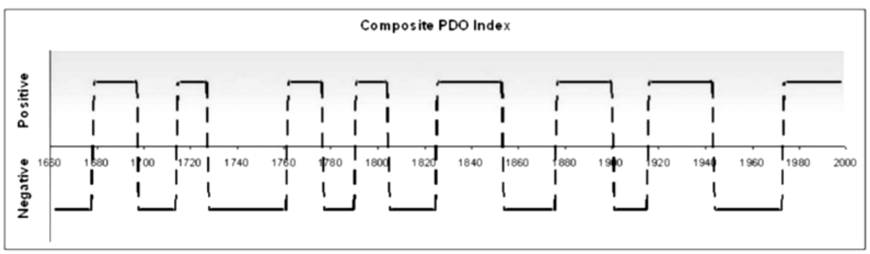
*El Niño* and *La Niña* are natural oscillations of the ocean-atmosphere system in the tropical Pacific that have important consequences for weather around the globe. They are part of a phenomenon known as El Niño-Southern Oscillation (ENSO), a continual but irregular cycle (of about 3 to 7 years that we can detect, but not predict) of shifts in ocean and atmospheric conditions that affect the global climate, Figure #19.




El Niño is characterized by unusually warm ocean temperatures in the Equatorial Pacific, as opposed to La Niña, which is characterized by unusually cold ocean temperatures in the Equatorial Pacific, Figure #20:




El Niño events tend to suppress Atlantic hurricane activity, while La Niña events tend to enhance it. The El Niño-La Niña conditions are revealed in the monthly Multivariate ENSO Index (MEI) which is also related to the Pacific Decadal Oscillation (PDO). The PDO is a natural, long-term temperature fluctuation of the Pacific Ocean, Figure #21:

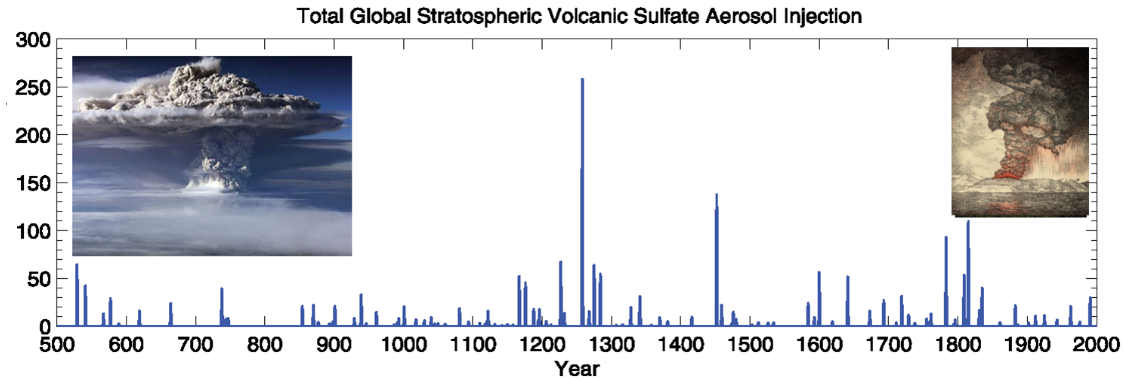



The PDO waxes and wanes approximately every 20 to 30 years, has a dominant impact on hurricane variability in the Pacific and is probably influenced by the ENSO or is perhaps a low-frequency modulation of El Niño and La Niña activity. At the time of writing (Sept. 2015) a powerful El Niño is building and the expected (temporary) increase of global temperature will certainly be played to the hilt by the various blocs that (falsely) see every little fluctuation as 'climate change'.

And then there are the North Atlantic Oscillation (NAO), the Madden-Julian Oscillation (MJO), the Arctic Oscillation (AO), the Pacific North American Pattern (PNA), and the Antarctic Oscillation (AAO), all contributing to natural global climate variability and not predictable by current models. There are plenty of oscillations and circulations to go around and complicate a modeler's life.

### Volcanic Aerosol Emissions

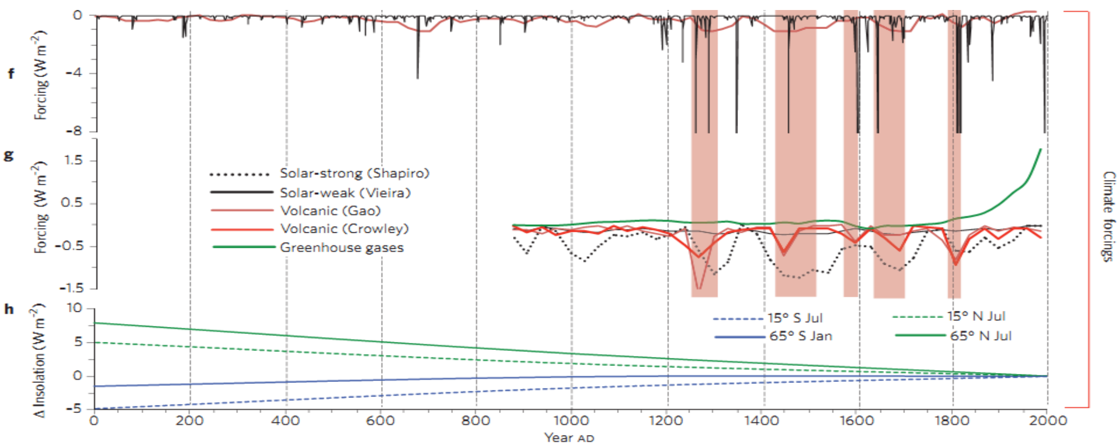
One of the more important natural causes of climate change is volcanic eruptions. The impact on climate induced by volcanic ''dust veils'' has long been recognized, in particular, volcanic sulfates that form in the stratosphere have been identified as the main cause of large-scale climate perturbations. The sulfate loading (Mega tons or Tg) can be estimated from deposits in ice cores (http://climate.envsci.rutgers.edu/IVI2/), Figure #22:




Miller et al. (*Geophys. Res. Lett.*, **39**, L02708, 2012) link the Little Ice Age to an "unusual 50-year-long episode with four large sulfur-rich explosive eruptions, each with global sulfate loading >60 Tg," and note that "large changes in solar irradiance are not required." Throughout the Little Ice Age, the world experienced heightened volcanic activity. When a volcano erupts, its ash reaches high into the atmosphere and can spread to cover the whole earth. This ash cloud blocks out some of the incoming solar radiation, leading to worldwide cooling that can last up to two years after an eruption. Also emitted by eruptions is sulfur in the form of sulfur dioxide gas. When this gas reaches the stratosphere, it turns into sulfuric acid particles, which reflect the sun's rays, further reducing the amount of radiation reaching Earth's surface.

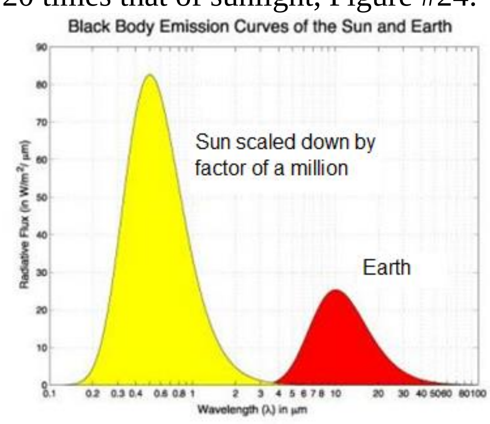
The massive tropical volcanic eruption in 1258, possibly of Mount Rinjani, followed by three smaller eruptions in 1268, 1275, and 1284 that did not allow the climate to recover, may have caused the initial cooling, and the 1452–53 eruption of Kuwae in Vanuatu triggered a second pulse of cooling. The cold summers can be maintained by sea-ice/ocean feedbacks long after volcanic aerosols are removed. Other volcanoes that erupted during that era and may have contributed to the cooling include Billy Mitchell (ca. 1580), Huaynaputina (1600), Mount Parker (1641), Long Island (Papua New Guinea, ca. 1660), and Hekla (1693). There were also strong eruptions during the Dalton Solar Minimum in 1809 (unnamed, see Dai, JGR **96**, 1991), 1814 (Mayon), and 1815 (Tambora).The 1815 eruption of Tambora in Indonesia blanketed the atmosphere with ash; the following year, 1816, came to be known as the Year Without a Summer. A common problem is that of statistical degeneracy of correlations: if by coincidence some segments of two time series have similar variations a strong (but false) relationship emerges which can be mistaken as causal. E.g. Crowley and Hegerl (SORCE 2008 Science Meeting) note a somewhat disconcerting apparent correlation between pulses of volcanism with the Dalton, Maunder, Spörer, and Wolf Minima. Given the unlikely physically significant correlations between the two, perhaps the cosmogenic records have an uncorrected overprint from volcanically driven climate change.

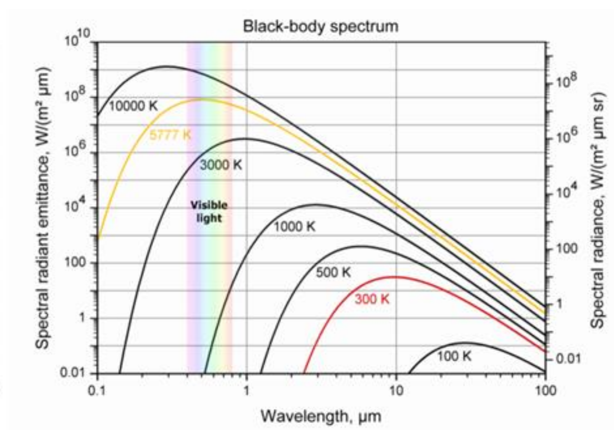
The PAGES 2k Consortium (*Nature Geoscience,* **6**, 339, 2013) in their study of continental-scale temperature variability during the past two millennia came to the same conclusion that volcanic eruptions were the main driver of little ice age conditions and note the uncanny coincidence of volcanic and solar forcings, Figure #23:



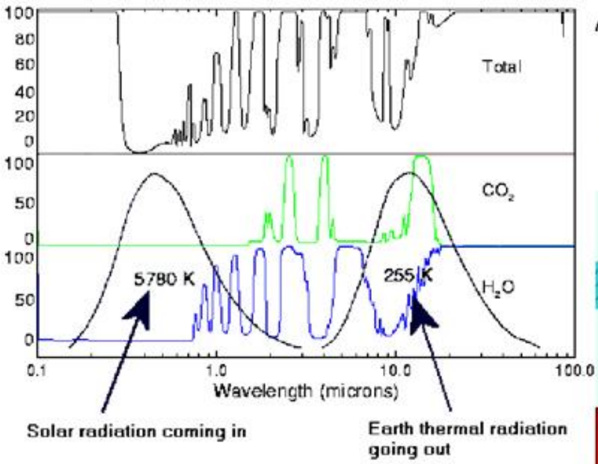

## Greenhouse Gases

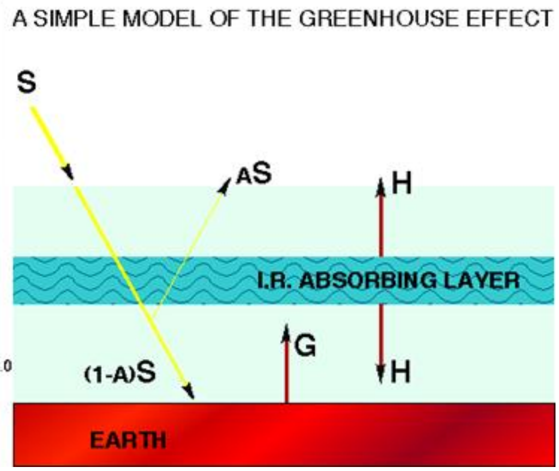
The climate of the Earth is controlled by two competing processes: the greenhouse effect, which acts to warm the lower atmosphere and cool the upper atmosphere, and atmospheric convection (thermals, clouds, precipitation) which does just the opposite: cools the lower atmosphere and warms the upper atmosphere. Roy Spencer, (http://www.drroyspencer.com/2009/12/what-if-there-was-no-greenhouse-effect/) points out that the greenhouse effect which is due to molecules with more than two atoms ($H_2O$, $CO_2$, $CH_4$, etc) has a rather fundamental role: there would be no weather on Earth without the greenhouse effect. Most of the energy of sunlight is in the visible and near infrared wavelengths. Since the atmosphere is basically transparent at these wavelengths, the major constituents being $N_2$ and $O_2$ that do not absorb or emit at those short wavelengths, the sunlight energy reaches and heats the surface to a temperature that is 1/20$^{th}$ of that of the source of the sunlight, and so the surface emits infrared radiation with a wavelength 20 times that of sunlight, Figure #24:




At wavelengths at or above 10 μm most of the outgoing radiation is absorbed by the GHGs diHydrogen oxide (Water) and Carbon dioxide, Figure #25 (left), If the outgoing radiation is absorbed in a layer (for simplicity) at some effective height, the outer surface of the absorbing layer becomes the outer surface of the planet radiating H and must come to radiative balance with the fraction (1-A) S of the incoming radiation, S, absorbed by the spherical, rotating planet with albedo A, so H = (1-A) S/4, and G = 2 (1-A) S/4.



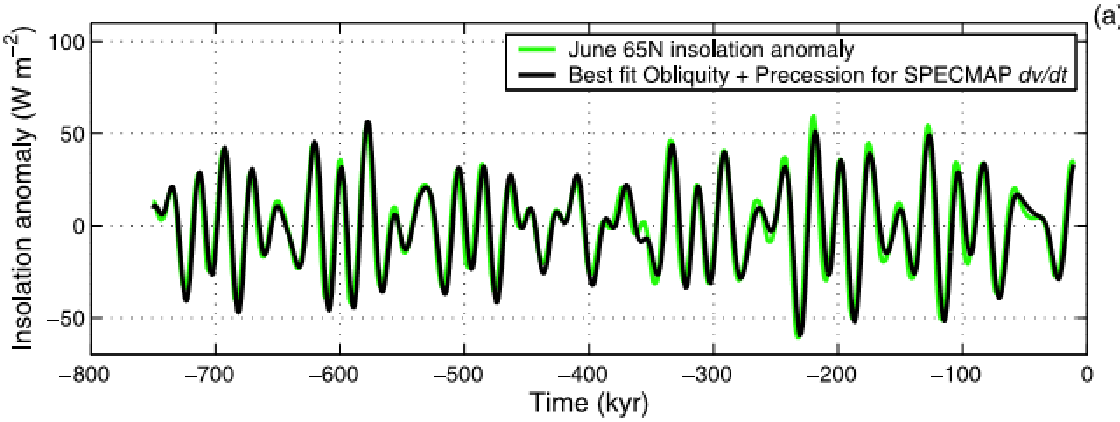




If all of the outgoing radiation were absorbed (heating the atmosphere), the temperature at the surface $T_G$, calculated from the Stefan-Boltzmann law, $G = \sigma T_G^4$, would increase by a factor 1.19, equal to the fourth root of 2, i.e. to 1.19 (255K) = 303K, which is more than the 288K observed, because *some* fraction of the longwave infrared radiation does escape to space without being absorbed. So, the (misnamed) greenhouse effect arises because the surface now receives energy from *two* sources, the Sun and the heated atmosphere. Without the GHGs (mostly $H_2O$ that is up to two orders of magnitude more abundant than $CO_2$) the surface temperature would be a brutal 255K = -18°C, instead of the balmy 288K = 15°C we presently enjoy. It would seem that we should be able to compute from first principles what the amplification should be, but in practice that turns out to be impossible because the atmosphere is much more complicated than the simple model used above and while the CO2 content is only varying slowly and is measured with good accuracy, the water vapor content is highly variable in time and space with intractable feedbacks from other GHGs and climate variables and is beyond the capability of current physical models to cope with, so the effect of GHGs must be assessed empirically with attendant very large uncertainty, as reflected in the IPCC statement referred to earlier that bears be repeated "No best estimate for equilibrium climate sensitivity can now be given because of a lack of agreement on values across assessed lines of evidence and studies".

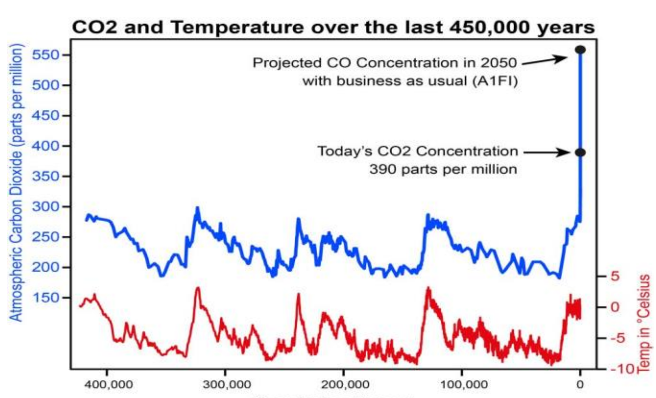
## Earth Orbital and Orientation Variations

Milutin Milankovitch (in 1941) was among the first to highlight the role that periodic variations in the Earth's orbit might play in climate. He computed time series of solar insolation as a function of latitude and season, and also undertook basic energy balance studies to estimate the temperature changes that might result. He further argued that periods of minima in summertime insolation in the northern high latitudes coincided with the half-dozen then-known glacial advances in Europe. Three main orbital parameters induce insolation variations: eccentricity (~100 and ~400 kyr periods), obliquity (41 kyr), and climatic precession (~19 kyr and ~23 kyr). With so many periods to choose from, the usual problems of statistical degeneracy and wiggling-the-elephant-trunk crop up.

Nevertheless, the Milankowitch Cycles are widely accepted as a basically valid explanation of glaciations, although some observational details are still troubling, perhaps because the details have not been sufficiently worked out from the theory. In a recent paper (G. Roe, *Geophys. Res. Lett.*, **33**, L24703, 2006), a specific formulation of the Milankovitch hypothesis is suggested and defended: instead of focusing on the absolute global ice volume, it is much more informative to consider the time rate of change of global ice volume, *dV/dt*. The orbitally-induced variations in summertime insolation in the northern high latitudes are in antiphase with the time rate of change of ice sheet volume. This simple and dynamically-logical change in perspective is used to show that the available records support a direct, zero-lag, antiphased relationship between the rate of change of global ice volume and summertime insolation in the northern high latitudes, Figure #26 (Roe, 2006):




[10] Atmospheric $CO_2$ has also been suggested as driving changes in global ice volume. The concentration of $CO_2$ varied between about 200 and 280 ppmv over the last several ice age cycles. Comparisons of the impacts of shortwave and longwave radiative forcing appropriate over the ice sheets are not straightforward, but taking summer half-year insolation variations in shortwave, and assuming an albedo of 0.5 for melting ice, variations in summertime shortwave forcing exceed the direct $CO_2$ radiative forcing by about a factor of five. Cross-spectral analyses and lag correlations show that, at frequencies where there is significant coherence between the records, atmospheric $CO_2$ lags, or is at most synchronous with *dV/dt*. In other words, variations in melting precede variations in $CO_2$. Thus, the relatively small amplitude of the $CO_2$ radiative forcing and the absence of a lead over *dV/dt* both suggest that $CO_2$ variations play a relatively weak role in driving changes in global ice volume compared to insolation variations, Figure #27:



**Diverse unpredictable catastrophes**

Although a fascinating and important subject leading to mass extinctions and extreme environmental stresses, we consider it to be outside of the scope of this overview.

**Conclusion**

Global Warming, or Climate Change, or Climate Disruption, just to mention some of the (increasingly scary) monikers that are being deployed these days have become a divisive political issue, seemingly divorced from scientific discourse. If it were not for the high-jacking of the subject by politicians, environmental pressure groups, and plain wishful eco-thinking, one would conclude from the present overview that Climate Science is a vigorous field with healthy debate and exciting interdisciplinary facets rather than a moribund body of ‘Settled Science’ without prospects for further progress, perhaps like Physics at the end of the 19$^{th}$ century. However, science is ultimately a self-correcting process where the scientific community plays a crucial and collective role, so we will eventually get it right, with or without political and societal interference, if the last two millennia are any guide. In the meantime we “may hope to enjoy future ages with more equable and better climates”, Svante Arrhenius [the originator of the GHG theory, 1896].