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Global Climate Models
Exploring the Reliability, Consistency, Limitations, Deficiencies, Uncertainties, and Methods of Global Climate Models in a Nonlinear and Chaotic Climate System

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Abstract

The current climate change dialogue revolves around many different climate elements and their processes but central to the anthropogenic warming hypothesis (some call it a theory but I'm not going to go there) is the development and enhancement of Global Climate Models (GCMs) that incorporate important climate components and their processes and use statistical and numerical mathematical methods to project future climates through a series of simulations. Notice I say project and not predict because there is a difference that I will explain later. Although climate models are based on scientific principles they do not embody traditional scientific methods. In climate science, and generally attributable to the long time periods required for validation, the climate model, represented by climate component inputs, has become the experiment and the analysis and confirmation are presented as projections and probabilities. I will discuss some factors adversely affecting climate models along with other factors that shape climate change models and research. While this paper mainly discusses model deficiencies, there are also many positive and useful aspects of climate modeling and many encouraging developments with the latest modeling techniques. The Intergovernmental Panel on Climate Change (IPCC) has addressed many of the areas discussed in this paper with their Assessment Reports (AR). Although I touch on a few specific areas of interest, any attempt to discuss and provide a detailed analysis on specific mathematical or climate processes for any particular model or models is not possible in a general scientific paper such as this one and is more suited for a specialized scientific paper with a focused analysis on the specific research subject matter.

Keywords: climate models, uncertainty, nonlinearity, chaos, parameterization, climate sensitivity

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What is a Climate Model?

General Circulation Models, which have more recently also become known as Global Climate Models (GCMs), are complex three dimensional mathematical numerical weather prediction models (NWP) designed to incorporate physical laws of thermodynamics and fluid dynamics to explain chemical, physical, and biological processes to predict weather and more recently to simulate climate and project climate changes. Global Climate Models normally incorporate the major components of the climate system. Originally designed as weather forecasting models they have been adapted and joined (more commonly referred to as coupled) to simulate and project the climate. Global Climate Models provide projections about future climate.

Climate models can be diagnostic (equilibrium based) or prognostic depending on the intended use. Either can project a future climate. Most climate models are diagnostic because they contain fewer complexities and produce faster output. Climate projections are different than predictions. Projections are based on changes in assumed conditions commonly known as scenarios. They state a possibility of what could happen given an assumed set of future conditions (i.e. such as a certain CO2 concentration level) set by the projector. Predictions are based on initial conditions and what we know today. They state a probability of what should happen based on what we currently know, not a variable set of future circumstances.

There are several basic types of models including atmospheric (AGCM), ocean (OGCM), and coupled atmospheric/ocean (AOGCM) that support global climate modeling. Global Climate Models include at least 10 and as many as 30 atmospheric layers at scales of 100-300 km (UCAR Center for Science Education, n.d.). Additional Regional Climate Models (RCMs), where appropriate, are embedded for high resolution on a spatial scale and a better representation of mesoscale variability. Various downscaling methods can also be used to represent processes and features on a finer scale.

Other models categorized in order of increasing complexity from simple to two dimensional are energy balance, radiative-convective, and statistical-dynamical models. Many other models and sub-models, both inductive and deductive, including land, sea ice, ice sheet, the bioclimatic envelope, atmospheric chemistry (chemical transport models), carbon cycle, to name a few, may be used to complement and enhance the GCMs.

Other complex two and three dimensional global and regional climate models are Earth System (ESM) models and earth system models of intermediate complexity (EMICs). ESMs include many chemical and biological processes and are often coupled with a chemical transport model but an instrumental part of an ESM is the representation of the carbon cycle (Geophysical Fluid Dynamics Library, n.d.). EMIC models are normally used for larger spatiotemporal scales (lower resolutions) and are more parameterized (a way to simplify complexities).

Complex scenarios of societal and scientific uncertainty can be incorporated into GCMs to reflect many possible future climates. Numerous simulations, ensembles, and multi-model ensembles including hundreds of global models and many more models and sub-models from private and governmental research labs are run to project climate outcomes. The IPCC is using ~20-30 Global Climate Models for climate projections.

Climate Models are Useful and Necessary Tools

Global Climate Models, despite their shortcomings, are incredible works of science and mathematics and provide meaningful and useful tools to look into the future climate. If you're not awed by a Global Climate Model or even one of the sub-models then you are a very hard person to impress. However, despite their complexity, GCMs are a greatly simplified replication of anticipated future reality. They are limited by their inability to identify and accurately represent important climate processes. They include a virtually limitless amount of variables, uncertainties, and numerical wizardry and as such there will always be those that question them, especially if and when they are used to confirm any extreme global warming hypothesis as 'settled science'.

Hind-casting, sometime called back-testing or back-casting, is the process of testing a model by comparing its output against observed data of the past to see if the model can recreate the past accurately. Hind-casting is a very good way to evaluate models and how they can represent known data from the past. The premise that hind-casting validates a model and its ability to project the future is unconfirmed and tenuous at best. Hind-casting merely allows a model to fit to the past and provides no assurances that it will also fit to the future as well.

Unfortunately, virtually all changes in climate and to be more precise all components, processes, and responses within the climate system, are variable and inherently nonlinear. Even processes thought to be linear may be nonlinear when combined with other ongoing dynamics at the time. Nonlinearity produces many disproportionate changes in the climate system where changes to an independent climate variable produce unexpected erratic changes to other dependent variables that are impossible to anticipate (GreenFacts, n.d.). Nonlinearity virtually ensures that future changes and outcomes from many climate variables will not conform to past changes. Nonlinearity does not mean you cannot project a future climate but it does ensure that a wide range of variability must not only be considered but expected. Dr. Edward Lorenz, an MIT professor, was instrumental in nonlinear dynamics and chaos theory and coined the term 'The Butterfly Effect'. The IPCC makes this statement on linearity.

> *Small changes in the climate system can be sufficiently understood by assuming linear relationships between variables. However, many climate processes are non-linear by nature, and conclusions based on linear models and processes may in these cases no longer be valid. Non-linearity is a prerequisite for the existence of thresholds in the climate system: small perturbations or changes in the forcing can trigger large reorganisations if thresholds are passed. The result is that atmospheric and oceanic circulations may change from one regime to another. This could possibly be manifested as rapid climate change.*
> (Stocker et al., 2001, pp. 455-456) IPCC Third Assessment Report, Physical Climate Processes and Feedbacks, (TAR, WG-1), Chapter 7.7, pp. 455-456

The following *Climatic Change* journal article stated: *"In sharp contrast to familiar linear physical processes, nonlinear behavior in the climate results in highly diverse, usually surprising and often counterintuitive observations"* (Rial, et al., 2004, p. 12).

In addition, and notwithstanding the numerous research studies, stationarity assumptions, and difficulty in replicating varying degrees of non-Gaussian characteristics of observed data also present further challenges for accurate future climate projections. Most hind-casting models fit to the past reasonably well, as they should, because they can be fine-tuned to 'known' data, even with the many uncertainties that pose difficulties for numerical model future projections. Projecting a future climate by using a model that was correct at some point in the past is a very daunting task and much more complex than hind-casting. Even if a model did perform well in projecting a future climate there can be no assurance that it will continue to perform well in the future.

Climate sensitivity, precipitation, and regional climates are also very problematic with hind-casting models. Despite disagreement over CO2 sensitivity issues, there are certainly some very successful hind-casting replications. Of course, Global Climate Models have accurately projected many general trends correctly. Some tropospheric warming has occurred, some stratospheric cooling has occurred (mostly before 1995), some geographical areas of warming have been identified, the top layer (~2 km) of the ocean has warmed, and possibly the earth's energy balance has been altered slightly.

Climate Models are Complex and Have Limitations

Uncertainties also abound within the mathematics and science of Global Climate Models. Parametric and structural uncertainties are inherent in all climate models (Webster & Sokolov, 1998, p. 1). Initial condition predictions using the laws of physics work well as a short-range weather forecasting tool but the additional mathematical and numerical analysis required to discretize and solve the complicated and recurrent nonlinear partial differential equations required for climate models are not always consistent, complete, appropriate, or true. Significant physical processes are only partially or implicitly resolved or may remain completely unresolved leading to additional parameterizations.

The weather and ultimately the climate is in a constant state of instability and highly nonlinear where multiple components are interacting with the environment and each other randomly and concurrently. Many components of the climate system are naturally chaotic (Iowa State University, Global Change Course, n.d.). The IPCC sums it up this way.

> *The climate system is particularly challenging since it is known that components in the system are inherently chaotic; there are feedbacks that could potentially switch sign, and there are central processes that affect the system in a complicated, non-linear manner. These complex, chaotic, non-linear dynamics are an inherent aspect of the climate system.*
> (Moore III, Gates, Mata, & Underdal, 2001, p. 773) IPCC Third Assessment Report, Advancing Our Understanding, (TAR, WG-1), Chapter 14.2.2, p. 773

Refer back to the Lorenz 'Butterfly Effect' where inaccuracies of data in initial conditions develops and grows over time into large inaccuracies and degrades future forecasts until eventually they become useless.

Global climate models are based on a set of boundary conditions (limitations) and forcings such as solar forcing or greenhouse gases. In addition to boundary conditions, initial condition processes throughout the climate system including decadal and multi-decadal changes and other slowly developing biospheric and cryospheric changes also influence future climate (Giorgi, 2005). These boundary condition models mostly assume linearity or eventually linearize any nonlinearities. Each climate model employs the vision of the modeler(s) on the amount of influence that any climate process will have on the climate and incorporates them into the climate model. Easterbrook (2010) stated that the errors in boundary climate models come primarily from the models themselves. Easterbrook goes on to explain that a small algorithmic error in a climate grid(s) will amplify itself over time and fail to represent a true picture of the earth's future climate. He concludes that for this reason climate models must conserve energy and mass over multi-decadal and centennial time scales.

Because of the complexity and unknowns of the climate system the models are simplified in various ways to facilitate computational problems. Attempting to model the complicated, interconnected, interdependent, and continually changing components of the atmosphere, hydrosphere and cryosphere, biosphere, and geosphere (including the lithosphere and pedosphere) with multiple external forces such as solar radiation and anthropogenic emissions requires that many exclusions, parameterizations, simplifications, and assumptions are applied while creating climate models.

Parameterizations are an attempt to simplify and estimate complex and nonlinear processes and resolution issues with what amounts to basically an empirical probability estimate or maybe better described as a 'best guess'. The Li, (2005) tutorial further explains parameterizations. Parameterization is necessary in climate models to describe processes that are not fully understood, complex processes, and to account for micro-scale processes on sub-grid scales. Convection (vertical transport), cloud cover, and precipitation are three highly parameterized processes.

Many of the simplifying assumptions that are necessary, including the continuum assumption, and sometimes even required with numerical models are just not true. Simply, the First Law of Thermodynamics cannot be modeled without assumptions as to how the atmosphere behaves and parameterizations of those processes, including feedbacks. Other mathematical anomalies such as the Gibbs oscillations, also known as spurious numerical oscillations (SNOs), are mostly ignored despite recent findings of significant impacts in both spectral and non-spectral models (Geil & Zeng, 2015).

Many different advection (horizontal transport) methods are utilized in climate models including spectral, Lagrangian, semi-Lagrangian, and Eulerian. While no one method is perfect there is no agreement on a best way to represent advection so models implement these methods and a blend of these methods in various ways. Advection schemes use both interpolation and extrapolation techniques liberally.

While necessary and reasonably effective, the complexity of the climate system demands an extensive use of these mathematical tools that in my opinion tends to somewhat vitiate the result but it's the best and currently the only way we know how to create climate models that evaluate future climate change, and specifically, anthropogenic induced warming. For simplicity, many times nonlinearities are removed (i.e. made linear) thereby stabilizing chaos and reducing errors. Heteroscedastic errors, non-stationarity issues, systematic and unsystematic errors, and corrective methods and algorithms employed that may unintentionally modify other applied corrections are just a few of the problems that are inherent with numerical climate models. Stochastic methods, while not perfect, can improve small scale representation and otherwise provide process resolution and reduce systematic (bias) model errors (Franzke, O'Kane, Berner, Williams, & Lucarini, 2014). Additionally, Bayesian Model Averaging (BMA) using and weighting the best features of a variety of combined climate models can be useful (Min & Hense, 2006).

The transfer of energy is a dynamic process within the atmosphere and except for Regional Climate Models, smaller spatial scales tend to be ignored or minimized. Significant climate oscillations such as the North Atlantic Oscillation (NAO), Arctic Oscillation (AO), Pacific Decadal Oscillation (PDO), El Nino Southern Oscillation (ENSO) also known as El Nino (warm phase) and La Nina (cold phase), Atlantic Multidecadal Oscillation (AMO), Madden-Julian Oscillation(MJO), monsoon events, and other major weather events are either poorly represented or, in some cases, left out completely because they are difficult or nearly impossible to model due to a lack of understanding yet produce significant short term changes in the climate that could affect future climate. Great strides have been made over the last two decades and some recent improvements have been made to incorporate these important climate features into the Global Climate Models. Climate feedbacks and sensitivity are understood even less leading to many assumptions that increase uncertainty and further complicate the accuracy and ultimate reliability. Global Climate Models are so complex that it may take months for super computers to get a projection for just 100 years or less.

The aforementioned deficiencies are just the tip of the iceberg (no pun intended) on improvements needed to Global Climate Models. Much of the message of climate change by the scientific community that is conveyed to the public tends to ignore these deficiencies, and by deficiencies I mean the extreme difficulty of modeling the climate not the lack of scientific endeavor to do it, and take the model outputs as accurate, reliable, and trustworthy representations of our future climate. Again, they are remarkable and the best we have to date but they are still lacking and dare I say very flawed, not due to scientific excellence, but rather the difficulty of mathematically defining the climate, the lack of a complete knowledge and understanding of the climate system, countless uncertainties, and the relative significance of innumerable processes, transfers, exchanges, and interactions and their resultant effects on the climate.

Climate Model Temperature and Sea Level Projections Have Been Very Inconsistent

Commendably the IPCC recognizes trends and adjusts their projections about every six years with updated data and knowledge (including uncertainties, limitations, and deficiencies) known as Assessment Reports from their three Working Groups and issues a Synthesis Report that integrates the Working Group reports. Since inception in 1990 there have been large variations in the future IPCC sea level projections. The IPCC projections have varied greatly, most downward except for the most recent one (IPCC Fifth Assessment Report-AR5) in 2013/2014 which increases estimations by ~50% in low emission scenarios and ~80% in high emission scenarios over the previous projection in 2007 (IPCC Fourth Assessment Report-AR4), mainly because of concerns about ice sheet dynamics. There are many unknowns in these sea level projections and that is shown by the fluctuation and large uncertainty spans.

The IPCC Fifth Assessment Report-AR5 2013/2014 replaced the Special Report on Emissions Scenarios (SRES) and introduced the Representative Concentration Pathways (RCPs) depicting four scenarios of total radiative forcing and the expected CO2 concentration, temperature, and sea level rises. Without getting into specific details, the IPCC temperature ranges have generally expanded in uncertainty and official temperature projections have been higher than AR5 in all IPCC reports except for the Second Assessment Report (SAR) in 1995.

Also, in the latest report the Equilibrium Climate Sensitivity (ECS) lower boundary has been lowered and the complete range of the Transient Climate Response (TCR) indicator has been lowered in AR5. In my opinion the .3-.7 °C IPCC warming projection in AR5 through 2035, relative to 1986-2005 baseline, (Cubasch et al., 2013, Figure 1.4, p. 131) is not unreasonable although I favor the lower end of that range as that has been the general long range trend although the last several years that has been somewhat higher. The trend for climate sensitivity and projected temperatures by the IPCC reports is unquestionably downward. Also notice that this final range in the AR5 projection through 2035 is based on ‘expert assessment’ and not a model projection.

> *Future climate will depend on committed warming caused by past anthropogenic emissions, as well as future anthropogenic emissions and natural climate variability. The global mean surface temperature change for the period 2016–2035 relative to 1986–2005 is similar for the four RCPs and will likely be in the range 0.3°C to 0.7°C (medium confidence). This assumes that there will be no major volcanic eruptions or changes in some natural sources (e.g., CH4 and N2O), or unexpected changes in total solar irradiance. By mid-21st century, the magnitude of the projected climate change is substantially affected by the choice of emissions scenario. {2.2.1, Table 2.1}.*
> (Intergovernmental Panel on Climate Change [IPCC], 2014, p. 10) IPCC Fifth Assessment Report, Climate Change 2014: Synthesis Report, SPM 2.2, Projected changes in the climate system, p. 10

We have been warming for nearly 12,000 years and sea levels have been rising rapidly, helped by several major Meltwater Pulses since the Bolling-Allerod interstadial nearly 15,000 years ago. That level of rise has dramatically reduced over the last 6,000-7,000 years and even less (~.7 mm/yr) over the last 4,000 years, although there has been an increase in the velocity since the mid 1800's, especially since 1993, that is of some concern. I don't see many of the projected extreme sea level and temperatures rises projected by most models occurring and neither does the IPCC if you read further into their reports but an increase of .08-.1 meters through 2035 and .3-.5 meters by 2100 is certainly possible and within the lower to mid range of IPCC projections (Cubasch et al., 2013, Figure 1.10, p. 137). Their official estimates tend to run in the low to mid ranges of the models. At this time, in the absence of another highly unlikely major Meltwater Pulse, I anticipate that in most cases and until the models display acceptable uniformity, the more conservative values of the GCM simulations that the IPCC has acknowledged as possible. Even disregarding climate model scenarios there is certainly proxy and empirical paleoclimatological evidence to warrant these values and possibly even higher values with or without elevated CO2 levels.

Weather Observations and Satellite Data for Climate Studies

Although I recognize that anthropogenic forcing is likely causing warming, I currently tend to agree with lower to mid range of the IPCC scenarios (.1-.15 °C /decade) for surface temperature in the immediate future, which matches well with the satellite observations since 1979, with continued interruptions caused mostly by climate oscillations or other natural causes.

Now that many, but certainly not all, of the satellite data inaccuracies have been mostly resolved, I prefer to use the satellite data (RSS/UAH) of lower tropospheric (TLT) and mid tropospheric (TMT) temperature (lower atmospheric temperature from ~1-10 km) for climatic temperature trends. I prefer TLT, which eliminates any stratospheric influence, or the adjusted TMT, which removes the stratospheric influence. I realize that is not where we live but there are numerous faults with surface observations that I will expound upon later.

Overall the UAH and RSS TLT temperature data is remarkably similar with RSS being, on average just slightly cooler than UAH data before the most recent version. Recent versions of UAH V6 (Mar 2015) and RSS 4 (Jun 2016) of TLT data now show that RSS V4 TLT is slightly warmer than UAH V6 TLT. These differences are driven mostly by satellite orbit and diurnal drift corrections. Before the latest versions, the UAH data had been slightly warmer in the TLT while the RSS data has been slightly warmer in the TMT. It's somewhat ironic that they have virtually changed trends over the last decade displayed by this graph (Stokes, 2017), Now, the UAH is becoming cooler and the RSS warmer. The new UAH V6 is more similar to the older RSS V3.3 while the older UAH V5.6 is now more similar but not as high as RSS V4. The GCMs are particularly aggressive with temperature increases when compared to observed satellite and balloon data of the lower troposphere.

Recent adjustments (UAH V6 Mar 2015) to satellite data show a slightly lower tropospheric temperature (TLT) reducing the decadal trend from .14 °C /decade to .114 °C /decade (Spencer, Christy, & Braswell, 2015) mainly due to high spatial resolution and drift corrections. UAH V6 (vs. V5.6) regional temperature trends (Christy & Spencer, 2015) increased warming slightly in the tropics and Southern Hemisphere while decreasing warming slightly over the Northern Hemisphere including the Arctic. The Antarctic remained virtually unchanged.

Currently, satellite data (RSS/UAH) from 2016 indicates a trend (National Oceanic and Atmospheric Administration [NOAA], 2016) of .14-.16 °C /decade when including the recent El Nino; otherwise, the previous trend (NOAA, 2015) is .12-.14 °C /decade. UAH and RSS TLT satellite measurements since 1979 indicate warming of ~.114-.135 °C/decade while surface datasets (Simmons et al., 2017, p. 5) indicate warming of ~.16-.18 °C/decade over that time, thus ~25% less warming than surface temperature datasets. From 1998-2014 the satellite data was fairly flat.

A much maligned bulk atmospheric comparison (Christy, 2017), p. 5 Figure 2, p. 6 Figure 3, of satellite and balloon datasets shows a significantly less rate of total tropospheric warming relative to the rate of model projected surface warming. As you can see from the graphs on this page (Remote Sensing Systems, n.d.) the lower tropospheric temperature (TLT) from RSS, Fig. 1., identified by the thick black line continues to remain fairly steady or increasing just slightly over the last 15-20 years while the cumulative model simulation (33 CMIP-5 simulations in his case), identified by the yellow uncertainty band continues to escalate. By 2015 the satellite data is just barely within the very lowest part of the simulated uncertainty band. The difference was even greater with RSS 3.3 before the adjustments Fig. 1. (Remote Sensing Systems [Archives], n.d.). These figures from RSS seem to somewhat confirm the bulk atmospheric temperature graph by Christy above. The balloon datasets trend is even lower than the satellite thick black line in Fig. 1. RSS issued the following statement on the graph in Fig. 1.

> *The troposphere has not warmed quite as fast as most climate models predict. Note that this problem has been reduced by the large 2015-2016 El Nino Event and the updated version of the RSS tropospheric datasets.* (Remote Sensing Systems, n.d.)

Stratospheric cooling and ozone depletion is another area where models have significant problems. Lower stratospheric cooling (TLS) has actually been more pronounced in observations than model projections, partially attributed to the Mt. Pinatubo eruption in 1991 (Arblaster et al., 2014; Remote Sensing Systems, n.d.). After a decrease of ~1 °C from 1979-1995 there has been virtually no stratospheric cooling since 1995, RSS Fig. 4. (Remote Sensing Systems, n.d.; Arblaster et al., 2014). It could even be argued that the lower stratosphere has warmed slightly since 1995.

Generally, it is expected that the stratosphere should cool as the troposphere warms, but lack of stratospheric cooling since 1996 has generated more research in this area. Stratospheric variability and stratospheric-tropospheric coupling is vital to understanding and projecting climate change. Stratospheric cooling is mainly caused by reduced ozone as a result of CFCs, and volcanic eruptions. It is also widely accepted that CO2 and other gases, including anthropogenic greenhouse gasses, cool the stratosphere but a complete understanding of the processes involved and the extent of their involvement has been elusive.

As far as surface weather measurements are concerned, certain areas of the globe known to have unreliable information such as Southeastern Asia, Siberia, areas in South America along with many ocean locations do not correspond well with satellite data while known reliable data from North America, most of Europe, and Australia does correlate well with the satellite data.

Ships have a whole different way of reporting temperature data over the oceans (SSTs) and we know the oceans cover more than 70% of the earth's surface. The general assumption for the Sea Surface Temperature (SST) is that the surface temperature one to two meters above the sea corresponds to that of the temperature roughly one meter below the sea surface. Satellites measure at or above the surface and other data is gathered from moored and drifting buoys or other devices with sensors below the surface. The one meter depth eliminates most diurnal variation except on calm days when a diurnal thermocline may develop and persist. A diurnal thermocline is the process of heating the upper layer of water, possibly in the first several meters, into a warm stratified layer due to shortwave (solar) radiation during calm conditions resulting in weak mixing. Buoy and ship temperature measurements under these conditions are mostly unusable. Due to standard navigation lanes and known safe routes there are many areas that ships never measure and the data is affected by salt, direction of movement, wind direction, and other variables. Fixed and drifting buoys help to fill in data from some ocean areas but most of the southern hemisphere is woefully lacking in manual and instrumented records and is unmonitored not only in the oceans but also on vast areas of land. Recent ship data has been analyzed and is warmer than buoy data so additional corrections for this bias are now being considered.

Lastly, the dynamics of sea temperatures are such that the forcing processes affecting the lower atmosphere do not correlate to the processes controlling the Sea Surface Temperatures (SSTs), especially as it relates to atmospheric radiative forcing and CO2 warming. SST, the water temperature taken near the surface, is more adversely affected by wind driven upwelling or lack thereof, and locally occurring currents known as mesoscale eddies. The thermohaline circulation (THC) and multi-decadal oscillations such as the AMO, ENSO, and other climate oscillations also affect SSTs. In summary, different processes are driving the Sea Surface Temperature (SST) and Surface Air Temperature (SAT) data yet they are deemed compatible and used to determine global temperature changes despite the oceans dominating the coverage area.

Another important point regarding surface temperature measurements is the competency and commitment of those taking the observations in various economic and political environments around the globe. The surface observational data quality that is vital to climate research is not and cannot be guaranteed over some large areas as to the integrity, accuracy, and viability of that data being provided. Since the 1970's the number of stations providing data used in surface datasets has severely declined leaving large areas of South America, Africa, and the Soviet Union sparsely represented. Some countries even consider their climate data to be proprietary.

Many adjustments are applied to surface measurements including time of observation, poor station sites, types of instrumentation used, different ways of measuring SSTs, station relocations, missing data, eliminating local station data that 'seems' erroneous, and many more. Finally, the surface temperature data is then amalgamated to fit a grid used by climate models. Many of these 'adjustments' are altering data and trends already established by respected, trusted, and accredited meteorological organizations. As one who has intimately dealt with climate data in the past, many times data quality control eliminated anomalies and interpolated and extrapolated missing data which can lead to substantial multicollinearity. Interpolation and extrapolation methods are very comprehensive and are not necessarily right or wrong they're just not real, not verifiable, and possibly deceptive. We already have enough uncertainty in climate data; we don't need added illusory data.

Surface observation data is collected in a myriad of ways, uses a wide array of instrumentation, is dependent on continuous calibration and maintenance procedures that differ widely, and uses numerous mathematical methods to apply corrections. Satellite measurements have unique maintenance, calibration, and diurnal and orbital correction complications and the measurements are inferred and computed through a model, however, they use the same or congruent equipment and methods to determine data values.

The satellite data, though not perfect, reduces individual station anomalies such as sensor placement, locality inconsistencies such as geographical, environmental and ecological impacts including any urban heat island effect, varying procedures used for measurement, station relocations, statistical errors in data correction, equipment differences and faults including maintenance and calibration, and large areas of land and ocean surfaces that are unobserved where data is interpolated or extrapolated with many different methods and assumptions. Radiosonde measurements of the troposphere are also suspect in some areas, especially near the tropics, but generally correlate well with satellite data trends.

In addition, many sea surface temperature datasets are using satellites to contribute as well as in situ to gather SST data while abundant research has been done with blended satellite and in situ data. Instrumentation on NASA's Terra and Aqua satellites has provided SST data since 2000 through the Moderate Resolution Imaging Spectroradiometer (MODIS) and other instrumentation. The Advanced Very High Resolution Radiometer (AVHRR) on the NOAA Polar Orbiting Environmental Satellites (POES) contributes to measuring ocean temperature, SST, and are closely aligned and compared to buoy data gathered through the Argos Data Collection System (DCS) that can be used to calibrate algorithms for AVHRR data.

Considering the above information I find a .1-.15 °C/decade increase in a theoretical GLOBAL mean or average temperature to be quite possible but at the same time questionable as well. This does not mean that there are no other indicators that some warming has been occurring, just that both the SAT and SST data are not an ideal, comprehensive or conclusive measurement for the determination of atmospheric anthropogenic warming. In fact, all things considered the global temperature could be somewhat lower or possibly even slightly higher than measured by SAT and SST, which is why I prefer the relative objectivity of satellite measurements. Of course I realize that we don't live at these higher altitudes and the surface temperature is more relevant to us for day to day living. Satellite data, however, samples more lower atmospheric temperature (TLT), which I consider more significant for gaining a better understanding of the comprehensive atmospheric changes occurring rather than just the surface data alone, especially when reports of multiple questionable adjustments to surface data are considered. Here is what the IPCC says about observation records:

The following is a condensed version with highlights of 'Uncertainty in Observational Records' from the Fifth Assessment IPCC Report.

> *IPCC FIFTH ASSESSMENT REPORT CLIMATE CHANGE 2013*
> *Box 2.1: Uncertainty in Observational Records*
>
> *The vast majority of historical (and modern) weather observations were not made explicitly for climate monitoring purposes. Measurements have changed in nature as demands on the data, observing practices and technologies have evolved. These changes almost always alter the characteristics of observational records, changing their mean, their variability or both, such that it is necessary to process the raw measurements before they can be considered useful for assessing the true climate evolution. This is true of all observing techniques that measure physical atmospheric quantities. The uncertainty in observational records encompasses instrumental / recording errors, effects of representation (e.g., exposure, observing frequency or timing), as well as effects due to physical changes in the instrumentation (such as station relocations or new satellites). All further processing steps (transmission, storage, gridding, interpolating, averaging) also have their own particular uncertainties. Since there is no unique, unambiguous, way to identify and account for non-climatic artifacts in the vast majority of records, there must be a degree of uncertainty as to how the climate system has changed…. To conclude, the vast majority of the raw observations used to monitor the state of the climate contain residual non-climatic influences. Removal of these influences cannot be done definitively and neither can the uncertainties be unambiguously assessed.*
> (Hartmann et al., 2013, p. 165) IPCC Fifth Assessment Report, Box 2.1 | Uncertainty in Observational Records, (AR5, WG-1), Chapter 2.2, p. 165

Improvements in Climate Models Are Needed To Better Represent Our Climate

Upon review and examination, Global Climate Models need to reduce assumptions wherever possible, including radiative forcing and equilibrium assumptions, improve upon representation of spacial scales, incorporate a more vigorous atmospheric chemistry simulation, a more robust representation of biological processes, incorporate better cloud (especially tropical), water vapor, and radiation simulation and feedbacks resulting in climate sensitivity uncertainty, improve cryospheric feedback representation (albedo, sea ice, absorbed solar radiation, and other glacial phenomena), better represent ocean circulations, reduce 'climate drift' errors (especially ocean), correct polar jet misrepresentation, continue to resolve local atmospheric blocking anomalies and somehow try to better account for monsoons and significant climate oscillations, among many other deficiencies.

While much progress in climate modeling has been made in many areas, there is still a long way to go before we can produce a reasonable numerical climate model that effectively integrates a seemingly endless amount of processes with the laws of physics to project a future climate with complete confidence. Although global trends and some specifics can be determined to some extent in various models and improvements to models are helping with local and regional projections much uncertainty and bias remains at those levels.

Climate Sensitivity and Risk Assessment

There is little doubt that anthropogenic warming has affected our climate and a doubling of CO_2 itself may cause temperatures to rise by as much as 1 °C excluding climate sensitivity and ~3.0±1.5 °C including sensitivity according to the IPCC. While AR5 has lowered the climate sensitivity floor to 1.5 °C attributable to 'new understanding', some studies since 2011 have put ECS at 1.6-2.0 °C with a range of 1.3-2.8 °C. This is significantly lower than previously estimated by 30-50%, a downward trend that must be seriously and thoughtfully considered. There is also information and research showing confidence that the current ECS is accurate and maybe even too low (Tan, Storelvmo, & Zelinka, 2016). Clearly the jury is still out and will be for the foreseeable future because of the great amount of uncertainty associated with climate sensitivity.

Additionally, as a result of additional water vapor in the atmosphere from our current warming since the end of the Little Ice Age, the effects of the added water vapor and changes in cloud cover in the atmosphere are currently unknown and could alter the future climate in a number of different ways. There are many feedbacks such as clouds and water vapor that are vital to the climate and to future climate projections for which we have very little understanding and the full efficacy of climate models has yet to be determined as more understanding, adjustments, and time are needed to develop methods to fully incorporate them into future climate models.

Risk assessment is another area of high uncertainty. The IPCC prefers to present probabilities for determining risk assessment. According to (Dessai and Hulme, 2004, abstract)…

> *Probability assessment in the context of climate change is always subjective, conditional and provisional. There are various problems in estimating the probability of future climate change, but reflexive human behaviour (i.e. actions explicitly influenced by information) is largely intractable in the context of prediction. Nonetheless, there is considerable scope to develop novel methodologies that combine conditional probabilities with scenarios and which are relevant for climate decision-making.*

Subsequently, (Dessai & Hulme, 2004) went on to explain the cause of the range of temperature projection uncertainty, and finally the types of uncertainty and give examples of those how uncertainties create unpredictability, volatility, and ultimately chaos in the climate.

In climate model evaluations and validations using Bayesian methods the probability density functions (PDFs) of climate variables show a wide range of probability distribution divergence (relative entropy or Kullback-Leibler divergence) even when using many assumptions such as stationarity, linearity, and normality. In a 2003 Newsletter of the Center for Science and Technology Policy Research, Clark & Pulwarty (2003) stated that probabilities could imply that uncertainty is less than it really is and the improvements in modeling have expanded, not contracted uncertainty. In that newsletter you can also read Rob Wilby's response to Clark and Pulwarty's article (Wilby, 2013). Stainforth, Allen, Tredger, and Smith (2007) similarly concluded that the reasons for model deficiencies are mostly known and questioned the ability to make decisions based on tentative PDFs. (p. 2158)

Paradoxically, the more we understand about the climate system and the more we attempt to make models more realistic and comprehensive, the more uncertainty is also introduced into the models. In addition, bias corrections for systematic errors are used to smooth model output. A 2012 Hydrology and Earth System Sciences (HESS) Opinions article stated that bias corrections decrease model uncertainty, are typically inconspicuous, and provide the appearance of an improved climate model without a valid rationalization. The article goes on to say *"We argue that this hides rather than reduces uncertainty, which may lead to avoidable forejudging of end users and decision makers."* (Ehret, Zehe, Wulfmeyer, Warrach-Sagi, & Liebert, 2012, p. 3391)

Climate models are run with single simulations, ensembles, or multi-model ensembles. Ensembles run with a single model using a variety of initial condition variables are called initial condition ensembles. Perturbed physic models are run by changing 20-30 parameters (climate process variables) and varying their values. Forcing ensembles measure how the climate system reacts to forcing (natural and anthropogenic) such as aerosols, CO2, solar activity and variability, and volcanic activity.

Most of these simulations use a Bayesian approach to compute probability density functions. These ensembles can compute the mean and average of the ensemble(s) and define ranges of uncertainty. However, a mean or average of an ensemble(s) uncertain outcome doesn't create a more certain outcome, it merely creates an average of uncertain outcomes. Ensembles don't reduce uncertainty but expand uncertainty. Their real value is to illustrate wider ranges of uncertainty that may be useful for probability predictions. Finally, uncertainty does not mean do nothing. Uncertainty further enhances the need for a realistic risk assessment climate policy that is sensible, flexible and progressive but not oblivious to current and future reality either socially, economically, politically, or scientifically.

Should We Let Climate Model Projections Dictate Our Current and Future Actions?

Currently model projections are not yet capable enough to specifically identify, analyze, and project with confidence a multifaceted and constantly changing climate system that is always in a state of flux with unpredictable dynamic, chemical, physical, and organic processes that can only be simulated in climate models through a series of mathematical assumptions and parameterizations that minimize or even ignore important climate factors and events. Nevertheless, paleoclimate proxies and empirical data also support rapid climate changes due to a number of factors and anthropogenic warming will likely prove to be a another transitory climate modifier with an as yet to be determined duration and impact on future climate. A multi-centennial or even multi-millennial time span is not only probable, but likely, to rid ourselves of all human generated CO2. The oceans will likely absorb the majority but traces will linger for thousands if not tens of thousands of years or more. The following is from the IPCC's Fourth Assessment Report.

> *Carbon dioxide cycles between the atmosphere, oceans and land biosphere. Its removal from the atmosphere involves a range of processes with different time scales. About 50% of a CO2 increase will be removed from the atmosphere within 30 years, and a further 30% will be removed within a few centuries. The remaining 20% may stay in the atmosphere for many thousands of years.*
> (Denman et al., 2007, p. 501) IPCC Fourth Assessment Report, Couplings Between Changes in the Climate System and Biogeochemistry, (AR4, WG-1), Chapter 7, p. 501

I'm not saying that warming isn't a problem or a potential problem in the future, however, I'm not yet ready to "baton down the hatches" and call for drastic socio-economic, political, and fiscal policies that are based on a plethora of unspecific, tentative model projections that vary widely even amongst themselves for many reasons and with regards to reliable empirical data. Undoubtedly there is anthropogenic involvement with our current warming and reasonable means should be employed to limit greenhouse gases and pollutants. Once again this emphasizes the need for a reasonable, responsible, well crafted climate policy that realizes and understands the needs of today and the immediate future as well as preparing us for the uncertainties of the distant future.

One Final Note - Concluding Discussion

Global Climate Models have definitely shown us trends and even some possible outcomes. Despite enormous advances in climate modeling and even though the complexities of modeling the climate are immense and the mathematical methods and physical processes used to represent it are becoming more robust, they are still relatively fragile when trying to represent climate reality. (Smith, 2002, p. 2491) states…

> *The perfect model scenario is a useful but misleading fiction. And there is no simple stochastic fix. This does not imply that increasing resolution, improving parameterizations, introducing stochastic physics, and the like, will not significantly improve our current models but it does suggest that careful thought is required in quantifying exactly what we mean by ''improve.''*

To be clear, I am *NOT* in any way disparaging the science and mathematics used in climate modeling, I am just being realistic as to the accuracy and reliance on models when there are so many unanswered questions. Quite the opposite, I am simply amazed by the sophistication of climate modeling and the incredible details of the climate system that are included in models and sub-models. The IPCC stated the following in the Executive Summary of the Third Assessment Report (TAR)…

> *The climate system is a coupled non-linear chaotic system, and therefore the long-term prediction of future climate states is not possible. Rather the focus must be upon the prediction of the probability distribution of the systems future possible states by the generation of ensembles of model solutions. Addressing adequately the statistical nature of climate is computationally intensive and requires the application of new methods of model diagnosis, but such statistical information is essential.*

(Moore III, Gates, Mata, & Underdal, 2001, p. 771) IPCC Third Assessment Report, Advancing Our Understanding, Chapter 14 Executive Summary, p. 771

If we are going to 'predict' future climate states through probability we have not confirmed the global warming hypothesis scientifically we have merely surmised that one or several of the many Global Climate Models, notwithstanding the uncertainties and flaws, will eventually resemble a future climate state. Until much more of every type of uncertainty is resolved, the chance is small that the science alone of a climate model and its integrated biases will 'predict' a future climate state and more likely a function of the number of models used to 'predict' it.

Global Climate Models are trying to predict an uncertainty, the future climate, while having numerous uncertainties themselves. I have tried to delineate some of the areas of uncertainty. Unquestionably there are many more. Uncertainty quantification is a very complex process and climate science has every possible source of uncertainty that is trying to be quantified in a meaningful way with a variety of methods. Numerous uncertainties, including a vast amount of climate sensitivity and feedback uncertainty, are propagated in climate models ultimately casting doubts on specificity, accuracy, reliability, and credibility of climate projection outputs.

The key to accepting and having confidence in future climate models and their projections is to continue to improve models by further enhancing our knowledge of how the climate system functions and reducing uncertainty wherever possible while recognizing the limiting factors of models by continuing to minimize errors and bias corrections, where appropriate, into meaningful while not perfect models with a tolerable amount of inaccuracy, inconsistency, and uncertainty. Global Climate Models will never be perfect or even near perfect but they are tools that, in my opinion, will eventually be reliable enough to guide future global interest decisions regarding climate change.

Finally, Global Climate Models and climate modeling in general are extraordinary, important, and useful tools with an incredible amount mathematical complexity. However, they currently lack the required precision, specificity and conformity to warrant taking extreme actions that could cause financial and economic hardships when our current knowledge and understanding of how the climate system functions is still lacking, our assessment of how future human behavior could change the climate is speculation, and our attempt to model it through mathematics is encumbered with numerous exclusions, parameterizations, presumptions, assumptions, simplifications, uncertainties, inconsistencies, and complexities while the most recent attempts to model the climate in new and meaningful ways are in their relative infancy.

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Global Climate Models: Exploring the Reliability, Consistency, Limitations, Deficiencies, Uncertainties, and Methods of Global Climate Models in a Nonlinear and Chaotic Climate System
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