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Climate Models and Their Limitations

Introduction

To commemorate the publication of the 100th volume of the journal *Climatic Change*, Norman Rosenberg (Rosenberg, 2010) was asked to contribute an overview paper on progress that had occurred since the journal's inception in the interrelated areas of climate change, agriculture, and water resources. Rosenberg accepted, and at the valedictory age of 80, he did it quite admirably.

He began by noting the "overarching concern" of the volumes he edited was "to gain understanding of how climatic change affects agricultural production, unmanaged ecosystems and water resources; how farmers, foresters and water managers can strengthen these sectors against the negative impacts of climatic change and capitalize on positive impacts if any; how they can adapt to impacts that cannot be so modified or ameliorated and how they can contribute directly or indirectly to mitigation of anthropogenic climatic change—as, for example, through soil carbon sequestration and the production of biomass to substitute in part for the fossil fuels that are adding CO_2 to the atmosphere."

Rosenberg wrote in his closing paragraph, "it seems difficult to say with assurance that the 'state-of-the-art' in projecting climatic change impacts on agriculture and water resources and unmanaged ecosystems is, today, that much better than it was 30 years ago," noting that "the uncertainty and lack of agreement in GCMs [global climate models] is still too great." He reported, "much can and has been learned about *possible* outcomes," but "for actual planning and policy purposes we are still unable to assure those who need to know that we can forecast where, when and how much agriculture (as well as unmanaged ecosystems and water resources) will be affected by climatic change."

A similarly pessimistic commentary on the state of climate modeling appeared in 2010 in *Nature Reports Climate Change*. Kevin Trenberth, head of the Climate Analysis Section of the National Center for Atmospheric Research in Boulder, Colorado (USA), wrote that one of the major objectives of upcoming climate modeling efforts will be to develop "new and better representations of important climate processes and their feedbacks." The new work, Trenberth wrote, should increase "our understanding of factors we previously did not account for ... or even recognize."

In expressing these sentiments, Rosenberg and Trenberth gave voice to the concerns of many scientists who are skeptical of the reliability of GCMs. This is not "denial." Trenberth, at least, would deny being a "skeptic" of the theory of anthropogenic global warming. It is, rather, the humility of true scientists who—attempting to comprehend the complexity of the world of nature and its innermost workings—are well aware of their own limitations and those of all seekers of such truths. Although much has been learned, as Rosenberg and Trenberth outline in their respective essays, what is known pales in comparison to what is required "for actual planning and policy purposes," as Rosenberg describes it, or "certainty" as Trenberth puts it.

This sense of humility is no more, and no less, than what the authors of this chapter seek to communicate. The first section briefly describes problems that may be intrinsic to the global climate modeling exercise. It is followed by more detailed documentation of model shortcomings involving precipitation, temperature, El Niño/Southern Oscillation (ENSO), and soil moisture. We remind the reader that this is only a compilation of recent research on these topics, and little effort has been expended to make sustained arguments.

References

Rosenberg, N.J. 2010. Climate change, agriculture, water resources: what do we tell those that need to know? *Climatic Change* **100**: 113–117.

Trenberth, K. 2010. More knowledge, less certainty. *Nature Reports Climate Change*: 10.1038/climate.2010.06.

1.1 Intrinsic Problems with Models

To introduce the topic of intrinsic problems with GCMs, consider a paper that fails to recognize any such problems. Published in the *Proceedings of the National Academy of Sciences of the United States of America* and written by Susan Solomon (a cochair of the IPCC's Working Group 1 when AR4 was produced) and three coauthors, it claims to show that "climate change that takes place due to increases in carbon dioxide concentration is largely irreversible for 1,000 years after emissions stop" (Solomon et al., 2009). In the virtual world of computer-run climate models, that may be the case, but that need not be true of the real world.

The four scientists set forth three criteria they say should be met by the modeled climatic parameters they study: "(i) observed changes are already occurring and there is evidence for anthropogenic contributions to these changes, (ii) the phenomen[a] [are] based upon physical principles thought to be well understood, and (iii) projections are available and are broadly robust across models."

Real-world data provide little or no support for the first criterion. The global warming of the past few decades was part of a much longer warming trend that began in many places throughout the world a little over three centuries ago (about 1680) with the dramatic "beginning of the end" of the Little Ice Age (LIA, see Figure 1.1 below), well before there was any significant increase in the air's CO_2 content. This observation suggests a continuation of whatever phenomenon—or combination of phenomena—may have caused the greater initial warming may have caused the lesser final warming, the total effect of which has been to transport the Earth from the chilly depths of the Little Ice Age into the relative balminess of the Current Warm Period.

Climate history will be discussed in greater detail in Chapter 3, but it is useful to note here that Earth's current temperature is no higher now (and may be slightly less) than it was during the peak warmth of the Medieval Warm Period (MWP), when there was more than 100 ppm less CO_2 in the air than there is today. Consequently, since the great MWP-to-LIA cooling occurred without any significant change in the atmosphere's CO_2 concentration, the opposite could occur just as easily, and the planet could warm, and by an equal amount—just as it actually did over the past three centuries—without any help from an increase in the atmosphere's CO_2 content.

Regarding Solomon et al.'s second criterion, the studies reported in this chapter will show that there are non-modeled chemical and biological principles that may be equally as important as the physical principles employed in the models. The phenomena are simply not as "well understood" as Solomon et al. claim. A highly selective reading of the literature is required to miss the repeated admissions by leading researchers of the uncertainty and outright ignorance of underlying processes that undermine the reliability of GCMs.

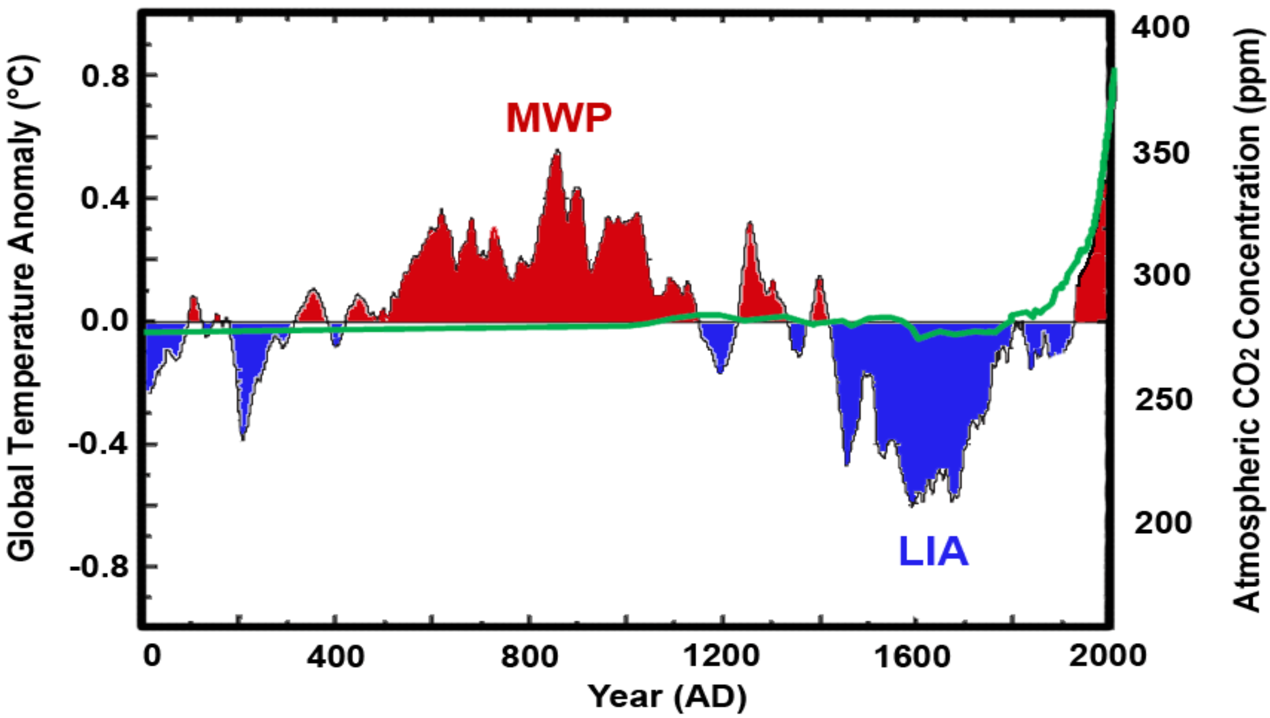

Figure 1.1. The mean relative temperature history of the Earth (blue, cool; red, warm) over the past two millennia—adapted from Loehle and McCulloch (2008)—highlighting the Medieval Warm Period (MWP) and Little Ice Age (LIA), together with a concomitant history of the atmosphere's CO_2 concentration (green).

Regarding Solomon et al.'s third criterion, many computer model projections are indeed "available and are broadly robust across models." But these models often diverge so greatly in their assumptions and in their specific spatial and temporal findings that they cannot be said to validate each other, nor can such discordant projections be combined to produce meaningful averages. Many studies have found that real-world data contradict what the models say should be occurring. To say such models are "robust" is wishful thinking.

A good example of an admission of the wide range of uncertainty that undermines GCMs appears in Woollings (2010):

> The spread between the projections of different models is particularly large over Europe, leading to a low signal-to-noise ratio. This is the first of two general reasons why European climate change must be considered especially uncertain. The other is the long list of physical processes which are very important for defining European climate in particular, but which are represented poorly in most, if not all, current climate models.

Woollings cites several examples of key atmospheric processes affecting the climate of Europe that models currently do not simulate well, noting that (1) the location of the jet stream over northern Europe in most models diverges from reality, (2) zonal flow is biased too far south in most models, (3) the models can't simulate or explain the North Atlantic Oscillation with sufficient magnitude to match historical data, and (4) heat waves and droughts, such as the summer 2010 Moscow heat wave and fires, are caused by blocking, which is a process the models are currently unable to simulate.

In addition, for several key processes the models produce widely varying predictions. The atmospheric circulation response to warming in climate models, for example, is highly variable, as is the change in storm intensity, the projected change in the jet stream, and changes in temperature. And it is particularly noteworthy that Europe is predicted to warm less than most Northern Hemisphere sites due to the slowing of the Gulf Stream providing reduced northward heat transport. As a result of such findings it is easy to recognize that current climate models are unable to achieve the degree of accuracy in the details of atmospheric circulation that are critical to replicating current weather events, such as droughts, heat waves, and major storms in Europe. Thus, any assertion that these events can be forecast 100 years in the future under a changed climate is simply false, and claims about negative impacts of climate change in Europe are based upon no specific modeling skill.

The rest of this section presents four specific problems that may be intrinsic to GCMs: their treatment of aerosols, atmospheric blocking, chaotic systems, radiation, and tropospheric humidity, and how to reconcile divergent models.

References

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Loehle, C. and McCulloch, J.H. 2008. Correction to: A 2000-year global temperature reconstruction based on non-tree ring proxies. *Energy & Environment* **19**: 93–100.

Solomon, S., Plattner, G.-K., Knutti, R., and Friedlingstein, P. 2009. *Proceedings of the National Academy of Sciences USA* **106**: 1704–1709.

Woollings, T. 2010. Dynamical influences on European climate: an uncertain future. *Philosophical Transactions of the Royal Society A* **368**: 3733–3756.

1.1.1 Aerosols

The treatment of aerosols by GCMs is a major limitation on their reliability. Mishchenko et al. (2009) write, "because of the global nature of aerosol climate forcings, satellite observations have been and will be an indispensable source of information about aerosol characteristics for use in various assessments of climate and climate change," and "there have been parallel claims of unprecedented accuracy of aerosol retrievals with the moderate-resolution imaging spectroradiometer (MODIS) and multi-angle imaging spectroradiometer (MISR)."

If both aerosol retrieval systems are as good as they have been claimed to be, they should agree on a pixel-by-pixel basis as well as globally. Consequently, and noting that "both instruments have been flown for many years on the same Terra platform, which provides a unique opportunity to compare fully collocated pixel-level MODIS and MISR aerosol retrievals directly," Mishchenko et al. decided to see how they compare in this regard by analyzing eight years of such data.

The six scientists from NASA's Goddard Institute for Space Studies report finding what they describe as "unexpected significant disagreements at the pixel level as well as between long-term and spatially averaged aerosol properties." In fact, they write, "the only point on which both datasets seem to fully agree is that there may have been a weak increasing tendency in the globally averaged aerosol optical thickness (AOT) over the land and no long-term AOT tendency over the oceans." As a result, the bottom line for the NASA scientists is quite succinct: "Our new results suggest that the current knowledge of the global distribution of the AOT and, especially, aerosol microphysical characteristics remains unsatisfactory." And since this knowledge is indispensable "for use in various assessments of climate and climate change," it would appear that current assessments of greenhouse gas forcing of climate made by the very best models in use today are deficient.

In a contemporaneous study, Haerter et al. (2009) write that future projections of climate "have been—for a given climate model—derived using a 'standard' set of cloud parameters that produce realistic present-day climate." However, they write, "there may exist another set of parameters that produces a similar present-day climate but is more appropriate for the description of climate change," and, "due to the high sensitivity of aerosol forcing (F) to cloud parameters, the climate projection with this set of parameters could be notably different from that obtained from the standard set of parameters, even though the present-day climate is reproduced adequately." This state of affairs suggests that replication of the present-day climate is no assurance that a climate model will accurately portray Earth's climate at some future time.

To get a better idea of the magnitude of uncertainty associated with this conundrum, Haerter et al. used the ECHAM5 atmospheric general circulation model (GCM), which includes parameterizations of direct and first indirect aerosol effects, to determine what degree of variability in F results from reasonable uncertainties associated with seven different cloud parameters. These are the entrainment rate for shallow convection, the entrainment rate for penetrative convection, the cloud mass flux above the non-buoyancy level, the correction to asymmetry parameter for ice clouds, the inhomogeneity parameter for liquid clouds, the inhomogeneity parameter for ice clouds, and the conversion efficiency from cloud water to precipitation. When they had completed their analyses, the four researchers reported "the uncertainty due to a single one of these parameters can be as large as 0.5 W/m^2" and "the uncertainty due to combinations of these parameters can reach more than 1 W/m^2." As for the significance of their findings, they write, "these numbers should be compared with the sulfate aerosol forcing of -1.9 W/m^2 for the year 2000, obtained using the default values of the parameters."

Due to these large parametric uncertainties, we apparently do not know the mean sulfate aerosol forcing component of Earth's top-of-the-atmosphere radiative budget to within anything better than ± 50%. In addition, Haerter et al. note that structural uncertainties, such as "uncertainties in aerosol sources, representation of aerosols in models, parameterizations that relate aerosols and cloud droplets to simulate the indirect aerosol effect, and in cloud schemes" lead to an overall uncertainty in F of approximately ± 43%, as per the most recent IPCC estimates. In reality, therefore, we probably do not know the current atmosphere's aerosol radiative forcing to anything better than ± 100%, which does not engender confidence in our ability to simulate earth's climate very far into the future with state-of-the-art climate models.

References

Haerter, J.O., Roeckner, E., Tomassini, L., and von Storch, J.-S. 2009. Parametric uncertainty effects on aerosol radiative forcing. *Geophysical Research Letters* **36**: 10.1029/2009GL039050.

Mishchenko, M.I., Geogdzhayev, I.V., Liu, L., Lacis, A.A., Cairns, B., and Travis, L.D. 2009. Toward unified satellite climatology of aerosol properties: What do fully compatible MODIS and MISR aerosol pixels tell us? *Journal of Quantitative Spectroscopy & Radiative Transfer* **110**: 402–408.

1.1.2 Atmospheric Blocking

A phenomenon that is not often discussed in climate change studies is atmospheric blocking, a situation that develops when there is a stationary ridge of high pressure in the mid-latitude jet stream. This phenomenon is typically associated with unusually warm and dry weather in areas where these high-pressure ridges form, and cooler or wetter conditions upstream and downstream of where they occur. Some recent examples of blocking and its impact on regional weather are: (1) the Western European heat wave of 2003, (2) the extreme heat in Russia in 2010 and the downstream flooding in Pakistan, and (3) the cold temperatures over most of North America and Europe during December 2010.

In investigating this phenomenon, Kreienkamp et al. (2010) used National Centers for Atmospheric Research re-analyses to examine the occurrence of blocking events over Europe since the 1950s, using a well-known blocking index (Tibaldi and Molteni, 1990). They then employed the atmospheric general circulation model (ECHAM) used by the IPCC in an effort to determine how well the models were able to simulate such blocking. Lastly, they examined two climate warming scenarios (A1B and B1) for the twenty-first century in order to infer whether blocking will become more or less common in the twenty-first century based on model projections.

With respect to the re-analysis data, Kreienkamp et al. found little evidence of a statistically significant trend over the period 1951–2007 apart from a weak decrease in the European region, which decrease suggests extreme weather events caused by blocking events have probably also declined. With respect to model simulations, they found the models showed little change in the frequency, seasonality, or interannual variability of blocking for the Atlantic/ European region as a whole but a significant decrease in Central European region frequency.

Although we are cautious about placing too much emphasis on model projections, this finding is also good news, for it suggests the number of heat waves and/or cold waves that can be attributed to atmospheric blocking will not increase for the Atlantic/European region during the twenty-first century. In fact, the model output suggests fewer of these occurrences and/or a shorter duration of such events.

References

Kreienkamp, F., Spekat, A., and Enke, W. 2010. Stationarity of atmospheric waves and blocking over Europe—based on a reanalysis dataset and two climate scenarios. *Theory of Applied Climatology* **102**: 205–212.

Tibaldi, S. and Molteni, F. 1990. On the operational predictability of blocking. *Tellus* **42A**: 343–365.

1.1.3 Climate as a Chaotic System

The ability of atmosphere-ocean GCMs to predict the climatic effects of human alterations of greenhouse gases and other factors cannot be tested directly with respect to a point in time a hundred years in the future. However, it is still possible to ask—and determine—whether those models can in principle make such predictions to a reasonable degree of accuracy. One way to evaluate this ability is to consider the effects of errors in system initial values. If a system is well-behaved, small initial errors will lead to small future errors, or even damped responses. In a chaotic system, on the other hand, small initial errors will cause trajectories to diverge over time; and for such a system (or model), true predictability is low to nonexistent.

In a study addressing initial value errors, Collins (2002) used the HadCM3 model, the output of which at a given date was used as the initial condition for multiple runs in which slight perturbations of the initial data were used to assess the effect of a lack of perfect starting information, as can often occur in the real world. The results of the various experimental runs were then compared to those of the initial control run, assuming the degree of correlation of the results of each perturbed run with those of the initial run is a measure of predictability.

As a result of these operations, Collins found "annual mean global temperatures are potentially predictable one year in advance" and "longer time averages are also marginally predictable five to ten years in advance." In the case of ocean basin sea surface temperatures, it was additionally found that coarse-scale predictability ranges from one year to several years. But for land surface air temperature and precipitation, and for the highly populated northern land regions, Collin concludes, "there is very little sign of any average potential predictability beyond seasonal lead times."

Reference

Collins, M. 2002. Climate predictability on interannual to decadal time scales: the initial value problem. *Climate Dynamics* **19**: 671–692.

1.1.4 Radiation

Eisenman et al. (2007) used two standard thermodynamic models of sea ice to calculate equilibrium Arctic ice thickness based on simulated Arctic cloud cover derived from 16 different general circulation models (GCMs) that were evaluated for the IPCC's Fourth Assessment Report. Their results indicated there was a 40 Wm^{-2} spread among the 16 models in terms of their calculated downward long-wave radiation, for which both sea ice models calculated an equilibrium ice thickness ranging from 1.0 to more than 10.0 meters. However, they note that the mean 1980–1999 Arctic sea ice thickness simulated by the 16 GCMs ranged from only 1.0 to 3.9 meters, a far smaller inter-model spread. Hence, they say they were "forced to ask how the GCM simulations produce such similar present-day ice conditions in spite of the differences in simulated downward longwave radiative fluxes."

Answering their own question, the three researchers observe that "a frequently used approach" to resolving this problem "is to tune the parameters associated with the ice surface albedo" to get a more realistic answer. "In other words," they continue, "errors in parameter values are being introduced to the GCM sea ice components to compensate simulation errors in the atmospheric components."

In consequence of the above findings, the three researchers conclude, "the thinning of Arctic sea ice over the past half-century can be explained by minuscule changes of the radiative forcing that cannot be detected by current observing systems and require only exceedingly small adjustments of the model-generated radiation fields" and, therefore, "the results of current GCMs cannot be relied upon at face value for credible predictions of future Arctic sea ice."

In another pertinent study, Andronova et al. (2009) "used satellite-based broadband radiation observations to construct a continuous 1985–2005 record of the radiative budget components at the top of the atmosphere (TOA) for the tropical region (20°S–20°N)" and then (1) "derived the most conservative estimate of their trends" and (2) "compared the interannual variability of the net radiative fluxes at the top of the tropical atmosphere with model simulations from the Intergovernmental Panel on Climate Change fourth assessment report (AR4) archive available up to 2000."

The three researchers found "the tropical system became both less reflective and more absorbing at the TOA" and, "combined with a reduction in total cloudiness (Norris, 2007), this would mean the tropical atmosphere had recently become more transparent to incoming solar radiation, which would allow more shortwave energy to reach earth's surface." Second, they found "none of the models simulates the overall 'net radiative heating' signature of the earth's radiative budget over the time period from 1985–2000."

With respect to the first of their findings and the associated finding of Norris (2007), Andronova et al. state these observations "are consistent with the observed near-surface temperature increase in recent years," which provides an independent validation of the TOA radiation measurements. With respect to their second finding, however, the failure of all of the AR4 climate models to adequately simulate the TOA radiation measurements discredits the models. The combination of these two conclusions suggests the historical rise in the air's CO_2 content has likely played a next-to-negligible role in the post-Little Ice Age warming of the world.

References

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Norris, J.R. 2007. Observed interdecadal changes in cloudiness: Real or spurious? In *Climate Variability and Extremes During the Past 100 Years*, edited by S. Broennimann et al., 169–178. New York, NY: Springer.

1.1.5 Tropospheric Humidity

Paltridge et al. (2009) write, "water vapor feedback in climate models is large and positive" and "the various model representations and parameterizations of convection, turbulent transfer, and deposition of latent heat generally maintain a more-or-less constant relative humidity (i.e., an increasing specific humidity *q*) at all levels in the troposphere as the planet warms," and that this "increasing *q* amplifies the response of surface temperature to increasing CO_2 by a factor or 2 or more." Consequently, knowledge of how *q* responds to atmospheric warming is of paramount importance to the task of correctly predicting how air temperatures respond to increasing CO_2 concentrations. Paltridge et al. explored this important subject by determining trends in relative and specific humidity at various levels in the atmosphere based on reanalysis data of the National Centers for Environmental Prediction (NCEP) for the period 1973–2007.

The three researchers report, "the face-value 35-year trend in zonal-average annual-average specific humidity *q* is significantly negative at all altitudes above 850 hPa (roughly the top of the convective boundary layer) in the tropics and southern midlatitudes and at altitudes above 600 hPa in the northern midlatitudes." Given these findings, Paltridge et al. conclude "negative trends in *q* as found in the NCEP data would imply that long-term water vapor feedback is negative—that it would reduce rather than amplify the response of the climate system to external forcing such as that from increasing atmospheric CO_2."

Reference

Paltridge, G., Arking, A. and Pook, M. 2009. Trends in middle- and upper-level tropospheric humidity from NCEP reanalysis data. *Theoretical and Applied Climatology* **98**: 351–359.

1.1.6 Reconciling Divergent Models

Reifen and Toumi (2009) note, "with the ever increasing number of models, the question arises of how to make a best estimate prediction of future temperature change." That is to say, which model should one use? With respect to this question, they note, "one key assumption, on which the principle of performance-based selection rests, is that a model which performs better in one time period will continue to perform better in the future." In other words, if a model predicts past climate fairly well, it should predict future climate fairly well. The principle sounds reasonable enough, but is it true?

Reifen and Toumi examined this question "in an observational context" for what they describe as "the first time." Working with the 17 climate models employed by the IPCC in its Fourth Assessment Report, they determined how accurately individual models, as well as various subsets of the 17 models, simulated the temperature history of Europe, Siberia, and the entire globe over a selection period (such as 1900–1919) and a subsequent test period (such as 1920–1939), asking whether the results for the test period are as good as those of the selection period. They followed this procedure while working their way through the entire twentieth century at one-year time-steps for not only 20-year selection and test intervals but also for 10- and 30-year intervals.

The two researchers could find "no evidence of future prediction skill delivered by past performance-based model selection," noting, "there seems to be little persistence in relative model skill." As for why this was so, they speculated, "the cause of this behavior is the non-stationarity of climate feedback strengths," which they explain by stating "models that respond accurately in one period are likely to have the correct feedback strength at that time," but "the feedback strength and forcing is not stationary, favoring no particular model or groups of models consistently."

Given such findings, the U.K. physicists conclude their analysis of the subject by stating, "the common investment advice that 'past performance is no guarantee of future returns' and to 'own a portfolio' appears also to be relevant to climate projections."

Reference

Reifen, C. and Toumi, R. 2009. Climate projections: Past performance no guarantee of future skill? *Geophysical Research Letters* **36**: 10.1029/2009GL038082.

1.2. Precipitation

Correctly simulating future precipitation has proved an extremely difficult task for modelers. One reason for the lack of success in this area is inadequate model resolution on both vertical and horizontal spatial scales, a limitation that forces climate modelers to parameterize the large-scale effects of processes that occur on smaller scales than their models are capable of simulating. This is particularly true of physical processes such as cloud formation and cloud-radiation interactions.

A good perspective on the cloud-climate conundrum was provided by Randall et al. (2003), who state at the outset of their review of the subject that "the representation of cloud processes in global atmospheric models has been recognized for decades as the source of much of the uncertainty surrounding predictions of climate variability." Yet despite what they called the "best efforts" of the climate modeling community, they had to acknowledge that "the problem remains largely unsolved." What is more, they suggested that "at the current rate of progress, cloud parameterization deficiencies will continue to plague us for many more decades into the future," which has important implications for predicting precipitation-related events such as floods and droughts.

In describing some of these deficiencies, Randall et al. stated, "our understanding of the interactions of the hot towers [of cumulus convection] with the global circulation is still in a fairly primitive state," and not knowing all that much about what goes up, it's not surprising the climate modelers don't know much about what comes down, as they report "downdrafts are either not parameterized or crudely parameterized in large-scale models."

The situation is no better with respect to stratiform clouds. Randall et al. describe the modelers' parameterizations as "very rough caricatures of reality." The models do not account for interactions between convective and stratiform clouds. During the 1970s and '80s, Randall et al. report, "cumulus parameterizations were extensively tested against observations without even accounting for the effects of the attendant stratiform clouds." Even at the time of their study (2003), in fact, they had to report that the concept of cloud detrainment was "somewhat murky" and that conditions that trigger detrainment are "imperfectly understood." Hence it should come as no surprise that at the time of their review they had to admit that "no existing GCM [includes] a satisfactory parameterization of the effects of mesoscale cloud circulations."

Randall et al. additionally noted, "the large-scale effects of microphysics, turbulence, and radiation should be parameterized as closely coupled processes acting in concert," but they reported only a few GCMs had attempted to do so. As they described it, "the cloud parameterization problem is overwhelmingly complicated," and "cloud parameterization developers," as they referred to them, were still "struggling to identify the most important processes on the basis of woefully incomplete observations." To drive this point home, they wrote, "there is little question why the cloud parameterization problem is taking a long time to solve: It is very, very hard." In fact, the four scientists concluded that "a sober assessment suggests that with current approaches the cloud parameterization problem will not be 'solved' in any of our lifetimes."

In spite of such a sobering assessment, the climate-modeling community places hope in what Randall et al. call "cloud system-resolving models," or CSRMs, which can be compared with single-column models or SCMs that can be "surgically extracted from their host GCMs." These advanced models, as they describe them, "have resolutions fine enough to represent individual cloud elements, and space-time domains large enough to encompass many clouds over many cloud lifetimes." Of course, these improvements mean "the computational cost of running a CSRM is hundreds or thousands of times greater than that of running an SCM." Nevertheless, in a few more decades, according to Randall et al., "it will become possible to use such global CSRMs to perform century-scale climate simulations, relevant to such problems as anthropogenic climate change." In the interim, they remain far from ready for prime time, as evidenced in a study conducted four years later by Zhou et al. (2007) and one three years later by Schliep et al. (2010).

In the first of these two studies, Zhou et al. acknowledged CSRMs "still need parameterizations on scales smaller than their grid resolutions and have many known and unknown deficiencies." To stimulate progress in these areas, they compared the cloud and precipitation properties observed by instruments deployed in the Clouds and Earth's Radiant Energy System (CERES) and Tropical Rainfall Measuring Mission (TRMM) systems against simulations obtained from the three-dimensional Goddard Cumulus Ensemble (GCE) model during the South China Sea Monsoon Experiment (SCSMEX) field campaign of 18 May–18 June 1998. As a result of that analysis, the nine researchers reported the following: (1) "the GCE rainfall spectrum includes a greater proportion of heavy rains than PR (Precipitation Radar) or TMI (TRMM Microwave Imager) observations," (2) "the GCE model produces excessive condensed water loading in the column, especially the amount of graupel as indicated by both TMI and PR observations," (3) "the model also cannot simulate the bright band and the sharp decrease of radar reflectivity above the freezing level in stratiform rain as seen from PR," (4) "the model has much higher domain-averaged OLR (outgoing longwave radiation) due to smaller total cloud fraction," (5) "the model has a more skewed distribution of OLR and effective cloud top than CERES observations, indicating that the model's cloud field is insufficient in area extent," (6) "the GCE is ... not very efficient in stratiform rain conditions because of the large amounts of slowly falling snow and graupel that are simulated," and finally, in summation, (7) "large differences between model and observations exist in the rain spectrum and the vertical hydrometeor profiles that contribute to the associated cloud field."

In the second of the two studies, Schleip et al. (2010) compared the results of six regional climate models (RCMs) that were forced with a common set of reanalysis data, which was created by running a climate model that was fed real-world data for a 20-year simulation period. The area analyzed was North America, where winter precipitation was the response variable and the 100-year extremum of daily winter precipitation was the test statistic, extreme values of which were estimated by fitting a tailed distribution to the data, taking into account their spatial aspects.

The results of this exercise indicated the six RCMs maintained similar general spatial patterns of extrema across North America, with the highest extremes in the Southeast and along the West Coast. However, when comparing absolute levels, which are most relevant to risk forecasts, the models exhibited strong disagreement. The lowest-predicting model was low almost everywhere in North America compared to the mean of the six models; and, similarly, the highest-predicting model was above the mean almost everywhere. In fact, the difference between the two models was almost 60mm of daily precipitation (for the 100-year extreme event) over much of the United States. The other four models showed greatly differing spatial patterns of extremes from each other, which differences were found to be statistically significant by an F-test. The researchers speculate that when driven by multiple GCMs rather than reanalysis data, the range of extreme outcomes would only increase.

Other studies have continued to demonstrate the difficulties models have in simulating precipitation properties and trends. Kiktev et al. (2007), for example, analyzed the abilities of five global coupled climate models that played important roles in the IPCC's Fourth Assessment Report to simulate temporal trends over the second half of the twentieth century for five annual indices of precipitation extremes. Their results revealed "low skill" or an "absence" of model skill.

Two years later, Lavers et al. (2009) examined the predictive skill of eight seasonal climate forecast models developed at various European climate centers. Specifically, they assessed the predictability of monthly precipitation "retrospective forecasts" or hindcasts, which were composed of multiple nine-month projections initialized during each month of the year over the period 1981–2001. They compared the projections against real-world precipitation values obtained from Global Precipitation Climatology Center data. In addition, they conducted a virtual-world analysis, where the output of one of the models was arbitrarily assumed to be the truth and the average of the rest of the models was assumed to be the predictor.

The results of these exercises indicated that in the virtual world of the climate models, there was quite good skill over the first two weeks of the forecast, when the spread of ensemble model members was small, but that there was a large drop off in predictive skill in the second 15-day period. Things were even worse in the real world, where they say the models had negligible skill over land at a 31-day lead time, which they described as being "a relatively short lead time in terms of seasonal climate prediction." In light of these findings, therefore, the three researchers concluded that given the lack of real-world skill demonstrated by state-of-the-art models, "it appears that only through significant model improvements can useful long-lead forecasts be provided that would be useful for decision makers," a quest they frankly state "may prove to be elusive."

More of the same was reported by O'Gorman and Schneider (2009), who assessed "how precipitation extremes change in simulations with 11 different climate models in the World Climate Research Program's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) archive." Based on their findings, as well as those of others, O'Gorman and Schneider report, "in simulations with comprehensive climate models, the rate of increase in precipitation extremes varies widely among models, especially in the tropics (Kharin et al., 2007)." They also note, in this regard, "the variations among models in the tropics indicate that simulated precipitation extremes may depend sensitively on the parameterization of unresolved and poorly understood processes," citing the work of Wilcox and Donner (2007). In fact, they state, "climate models do not correctly reproduce the interannual variability of precipitation extremes in the tropics (Allan and Soden, 2008), or the frequency and intensity distribution of precipitation generally (Wilcox and Donner, 2007; Dai, 2006; Sun et al., 2006)." Thus the two researchers concluded, "current climate models cannot reliably predict changes in tropical precipitation extremes," noting "inaccurate simulation of the upward velocities may explain not only the intermodal scatter in changes in tropical precipitation extremes but also the inability of models to reproduce observed interannual variability."

In another study, based on real-world data pertaining to the onset, end, and total rainfall of the South American Monsoon System (SAMS)—as characterized by precipitation data for the period 1979–2006, which they derived from the Global Precipitation Climatology Project—Bombardi and Carvalho (2009) evaluated the ability of ten IPCC global coupled climate models (with distinct physics and resolutions) to simulate real-world SAMS characteristics. They report that over northern South America the annual precipitation cycle "is poorly represented by most models," and more specifically, "most models tend to underestimate precipitation during the peak of the rainy season." In addition, they say "the misrepresentation of the Inter-Tropical Convergence Zone and its seasonal cycle seems to be one of the main reasons for the unrealistic out-of-phase annual cycles simulated near the equator by many GCMs" and "poor representation of the total monsoonal precipitation over the Amazon and northeast Brazil is observed in a large majority of the models." As a consequence, they note, "simulations of the total seasonal precipitation, onset and end of the rainy season diverge among models and are notoriously unrealistic over [the] north and northwest Amazon for most models."

Roesler and Penner (2010) used a microphysical model to explore the impact of the chemical composition and size of aerosols on the concentration of cloud droplets over the United States, noting aerosols are important because they can affect energy budgets in the atmosphere and because they also serve as condensation nuclei for cloud formation. Clouds, as we know, affect Earth's energy budget through their ability to reflect and scatter light and to absorb and reradiate long-wave radiation.

The results Roesler and Penner obtained by this approach indicate that as vertical motion increased in their model, the number of cloud droplets increased. They also found that larger aerosols, though fewer in number, were more soluble as they formed cloud droplets, as opposed to smaller, less-soluble aerosols that were more numerous. Thus the larger aerosols were found to be better at producing cloud droplets. In addition, they found that the size of the aerosols depended on their chemical composition, which could vary by region across the United States, and by season.

Considering these results, it is clear that in order to model cloud forcing in a GCM, which ultimately impacts the ability of the model to capture climate or climate change, the chemical composition of the condensation nuclei that form the clouds must be known. And in this regard, Roesler and Penner state in closing, "A global model using an empirical relationship based on regional measurements could over or under predict droplet concentrations when applied to other regions depending on differences in composition."

Also in 2010, Zhang et al. wrote as background for their study that different representations of clouds and their feedback processes in Global Climate Models (GCMs) have been identified as major sources of differences in model climate sensitivities, stating, "contemporary GCMs cannot resolve clouds and highly simplified parameterizations are used to represent the interactions between clouds and radiation." In conducting their own study of the subject, therefore, they combined cloud profiling radar data from the CloudSat satellite with lidar data from the CALIPSO satellite to obtain 3D profiles of clouds and precipitation regimes across the tropics. Some of these profiles corresponded to well-known weather features, such as low clouds, thin cirrus, cirrus anvils, etc., and they were compared to output obtained from the Community Atmosphere Model version 3 (CAM3.1).

The results of this exercise revealed the model "overestimates the area coverage of high clouds and underestimates the area coverage of low clouds in subsidence regions." And what was particularly striking, in the words of Zhang et al., was "the model overestimate of the occurrence frequency of deep convection and the complete absence of cirrus anvils," plus the fact that "the modeled clouds are too reflective in all regimes."

Since incoming and outgoing radiation are strongly affected by the 3D spatial pattern of clouds of various types, a model that gets the "right" current global temperature with the wrong pattern of clouds must have errors in its radiation and/or heat transfer parameterizations. In addition, the manner in which future climate scenarios achieve amplification of the direct radiative effect of increased greenhouse gases (the assumed positive feedback) is also not likely to be correct if the 3D pattern of simulated clouds is as far off as shown in this study. What is more, the pattern of clouds also reflects convective processes that distribute heat and water vapor in the atmosphere, and the results of Zhang et al. point to deficiencies in the handling of this aspect of atmospheric dynamics as well. Climate modelers' claims of physical realism in their models are not supported by detailed comparisons with the real world, and the basic radiative physics they employ, as parameterized at the grid scale, is probably faulty.

In another study, Anagnostopoulos et al. (2010) compared observed versus modeled precipitation values over the twentieth century for 55 locations across the globe. Their results indicated the six models investigated (three from the IPCC's Third Assessment and three from its most recent Fourth Assessment) reproduce only poorly the observed precipitation values over the period of study, and in far too many instances the models showed a rise in precipitation when observed values actually fell, or vice versa. The models fared worse when a similar analysis was conducted in the aggregate for the entire conterminous United States. Model output differed "substantially" from the observed time series, with annual precipitation values overestimating observed values by up to 300 mm, or 40 percent. What is more, the authors indicate the results from the three models used in the IPCC's Fourth Assessment Report were "no better" than the three models used in the IPCC's Third Assessment Report.

In one final study comparing model observations with real-world observations, Stephens et al. (2010) write in introducing their work that in prior studies of the subject "land surface observations of the daily-accumulated rainfall intensities of rates >1 mm/day were compiled from the Global Historical Climatology Network by Sun et al. (2006) and compared to analogous model accumulated precipitation," and they report that "as in other studies (e.g., Dai and Trenberth, 2004), the Sun et al. comparison revealed a general overestimate in the frequency of modeled precipitation and an associated underestimate of intensity," while noting that "Wilcox and Donner (2007) reached a similar conclusion."

To further examine the issue—and to extend the scope of its relevance—Stephens et al. focused on the much larger portion of the planet that is occupied by oceans, where they used "new and definitive measures of precipitation frequency provided by CloudSat [e.g., Haynes et al., 2009]" to assess the realism of global model precipitation via an analysis that employed five different computational techniques representing "state-of-the-art weather prediction models, state-of-the-art climate models, and the emerging high-resolution global cloud 'resolving' models."

Stephens et al. determined "the character of liquid precipitation (defined as a combination of accumulation, frequency, and intensity) over the global oceans is significantly different from the character of liquid precipitation produced by global weather and climate models," noting "the differences between observed and modeled precipitation are larger than can be explained by observational retrieval errors or by the inherent sampling differences between observations and models." More specifically, they say for the oceans as a whole, "the mean model intensity lies between 1.3 and 1.9 times less than the averaged observations" and occurrences "are approximately twice the frequency of observations." They also say the models "produce too much precipitation over the tropical oceans" and "too little mid-latitude precipitation." And they indicate the large model errors "are not merely a consequence of inadequate upscaling of observations but indicative of a systemic problem of models more generally."

In concluding their study, the nine U.S., U.K., and Australian researchers say their results imply that state-of-the-art weather and climate models have "little skill in precipitation calculated at individual grid points" and "applications involving downscaling of grid point precipitation to yet even finer-scale resolution has little foundation and relevance to the real earth system." That is not too encouraging a result, considering it is the "real earth system" in which we live and for which we have great concern. Given these findings and the many others previously cited, it is difficult to conceive how today's state-of-the-art computer models can be claimed to produce reliable precipitation forecasts decades and centuries into the future.

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1.3 Temperature

How much of the warming of the past 100 years is due to human activity? When multiple forcings are varying and poorly characterized, and there is also internal variation, this question becomes even more difficult to answer. Nevertheless, several studies have attempted to do so, including DelSole et al. (2010), who began by using a set of climate models run in "control" or unforced mode to develop a 300-year dataset of spatial ocean temperature data, where it was found that an internal pattern, detectable using a spatial fingerprinting technique, could be identified in the simulated data. This spatial pattern of ocean temperature anomalies was labeled the Internal Multidecadal Pattern (IMP); it was found to be highly coherent with the Atlantic Multidecadal Oscillation (AMO), suggesting the models were able to match the internal dynamics of the real-earth system reasonably well.

Proceeding from this point, the researchers next extracted, also by means of discriminant fingerprinting, the forced component of the spatial patterns produced in the absence of the IMP as an orthogonal function, which they demonstrated has only a minor effect (less than 1/7 the amplitude) on the IMP, after which they used historical sea surface temperature data to evaluate the relative importance of the forced vs. IMP components of change from 1850.

In considering the latter portion of the record (1946–2008), the researchers' results indicated the internal variability component of climate change (the IMP) operated in a cooling mode between 1946 and 1977, but switched to a warming mode thereafter (between 1977 and 2008), suggesting the IMP is strong enough to overwhelm any anthropogenic signal. That led them to state, "the trend due to only the forced component is statistically the same in the two 32-year periods and in the 63-year period." That is to say, the forced part was not accelerating. Taken together, these results imply that the observed trend differs between the periods 1946–1977 and 1977–2008 not because the forced response accelerated but because "internal variability led to relative cooling in the earlier period and relative warming in the later period." Thus their results suggest that simple extrapolations of rates of warming from 1980 onward overestimate the forced component of warming, and that using this period without factoring out internal variability will likely lead to unrealistic values of climate sensitivity.

In an earlier study, Lean and Rind (2008) performed "a robust multivariate analysis using the best available estimates of each together with the observed surface temperature record from 1889 to 2006" in an effort "to distinguish between simultaneous natural and anthropogenic impacts on surface temperature, regionally as well as globally." Their results indicated that "contrary to recent assessments based on theoretical models (IPCC, 2007) the anthropogenic warming estimated directly from the historical observations is more pronounced between 45°S and 50°N than at higher latitudes," which finding, in their words, "is the approximate inverse of the model-simulated anthropogenic plus natural temperature trends ... which have minimum values in the tropics and increase steadily from 30 to 70°N." Furthermore, as they continue, "the empirically-derived zonal mean anthropogenic changes have approximate hemispheric symmetry whereas the mid-to-high latitude modeled changes are larger in the Northern Hemisphere." And as a result, the two researchers concluded that "climate models may therefore lack—or incorrectly parameterize—

fundamental processes by which surface temperatures respond to radiative forcings."

Lavers et al. (2009), in a study also described previously in Section 1.2, assessed the predictability of monthly "retrospective forecasts," or hindcasts, which were composed of multiple nine-month projections initialized during each month of the year over the period 1981-2001, comparing the projections against real-world air temperatures obtained from ERA-40 reanalysis data. In addition, they conducted a virtual-world analysis where the output of one of the models was arbitrarily assumed to be the truth and the average of the rest of the models was assumed to be the predictor.

Lavers et al. report that in the virtual world of the climate models, there was quite good skill over the first two weeks of the forecast, when the spread of ensemble model members was small, but that there was a large drop off in predictive skill in the second 15-day period. Things were even worse in the real world, where they say the models had negligible skill over land at a 31-day lead time, which they described as being "a relatively short lead time in terms of seasonal climate prediction." Based on these results, the three researchers concluded that given the real-world skill demonstrated by the state-of-the-art models, "it appears that only through significant model improvements can useful long-lead forecasts be provided that would be useful for decision makers," a quest they state "may prove to be elusive."

Chylek et al. (2009) state, "one of the robust features of the AOGCMs [Atmosphere-Ocean General Circulation Models] is the finding that the temperature increase in the Arctic is larger than the global average, which is attributed in part to the ice/snow-albedo temperature feedback." More specifically, they say "the surface air temperature change in the Arctic is predicted to be about two to three times the global mean," citing the IPCC (2007). In conducting their own study of this feature, the authors utilized Arctic surface air temperature data from 37 meteorological stations north of 64°N in an effort to explore the latitudinal variability in Arctic temperatures within two belts—the low Arctic (64°N-70°N) and the high Arctic (70°N-90°N)—comparing them with mean global air temperatures over three sequential periods: 1910–1940 (warming), 1940–1970 (cooling), and 1970–2008 (warming).

In harmony with state-of-the-art AOGCM simulations, the five researchers report "the Arctic has indeed warmed during the 1970–2008 period by a factor of two to three faster than the global mean." More precisely, the Arctic amplification factor was 2.0 for the low Arctic and 2.9 for the high Arctic. But that is the end of the real world's climate-change agreement with theory. During the 1910–1940 warming, for example, the low Arctic warmed 5.4 times faster than the global mean, while the high Arctic warmed 6.9 times faster. Even more out of line with climate model simulations were the real-world Arctic amplification factors for the 1940–1970 cooling: 9.0 for the low Arctic and 12.5 for the high Arctic. Such findings constitute another important example of the principle described (and proven to be correct) by Reifen and Toumi (2009), that a model that performs well in one time period will not necessarily perform well in another period.

Also studying the Arctic, Liu et al. (2008) "assessed how well the current day state-of-the-art reanalyses and CGCMs [coupled global climate models] are reproducing the annual mean, seasonal cycle, variability and trend of the observed SAT [surface air temperature] over the Arctic Ocean for the late twentieth century (where sea ice changes are largest)." According to the authors, the results indicate that "large uncertainties are still found in simulating the climate of the twentieth century," and on an annual basis, "almost two thirds of the IPCC AR4 [Fourth Assessment Report] models have biases that [are] greater than the standard deviation of the observed SAT variability." What is more, Liu et al. additionally note (1) the models "can not capture the observed dominant SAT mode variability in winter and seasonality of SAT trends," (2) "the majority of the models show an out-of-phase relationship between the sea ice area and SAT biases," and (3) "there is no obvious improvement since the IPCC Third Assessment Report."

Anagnostopoulos et al. (2010) compared observed versus modeled temperature values over the twentieth century for 55 locations across the globe, finding that although the six models (three from the IPCC's Third Assessment and three from its most recent Fourth Assessment) could reproduce the seasonal variations in temperature fairly well, they fared far worse, or "poor," at the annual time scale, where "some model outputs [had] enormous differences from reality (up to 6 °C in temperature)." What is more, the authors note, there were many instances where the models showed a rise in temperature when observed values actually fell, or vice versa.

Not much changed when the five researchers conducted a similar analysis in the aggregate for the conterminous United States. Model output differed "substantially" from the observed time series. For example, the observed annual mean temperature of the conterminous USA "gradually rose between 1890 and 1940, then had a falling trend until 1970, and from 1970 until today it had a slight upward trend." Yet "none of the model outputs fit these fluctuations of the annual mean temperature; most indicate a constant increase that becomes steeper in the last decades of the twentieth century." What is more, the authors indicate the results from the three models used in the IPCC's Fourth Assessment Report were "no better" than the three models used in the IPCC's Third Assessment Report, noting that in some, "the annual mean temperature of the USA is overestimated by about 4–5 °C." Given such findings, they conclude by stating, "we think that the most important question is not whether GCMs can produce credible estimates of future climate, but whether climate is at all predictable in deterministic terms."

Christy et al. (2010) focused on the upper atmosphere, where models suggest the presence of a tropical tropospheric "hotspot" that warms faster than the surface under conditions of enhanced greenhouse gas forcing, and where previous studies had produced disagreement over whether data were consistent with models on this question. In conducting their analysis, Christy et al. (2010) made several advances by doing the following: (1) enhancing the data for surface trends, (2) extending the data to a 31-year period, (3) evaluating the wind-based temperature estimates, and (4) clarifying the meaning of "best estimate" multi-data warming trends from data and models.

Two prior studies had derived tropospheric temperature trends from the Thermal Wind Equation (TWE)—which uses radiosonde measurements of wind speed to calculate temperature—on the theoretical basis that warmer air should move faster than cooler air. They found there were biases in the data for this type of calculation. For example, particularly for older radiosonde observations, on days when the upper wind was stronger, the balloons would tend to blow out of receiver range. This created a bias by causing missing data for high winds for older observations, leading to a spurious warm trend over time. Overall, the TWE-based trends were three times greater than trends derived from all other types of data. In addition, they did not agree with other wind data and were based on much sparser data. This type of data was therefore not used in the authors' analysis, which also identified a small warm bias in the RSS satellite data that was explained by Christy and his colleagues.

The next innovation was to use the Scaling Ratio (SR), which is the ratio of atmospheric temperature trend to surface temperature trend. The SR attempts to factor out the effect of the lack of actual (historic) El Niños or other oscillations in climate model runs, and such simulated events in different computer runs. In doing so, the nine researchers found that the SR for real-world data was 0.8 ± 0.3, whereas the model simulations had a SR of 1.38 ± 0.08 (a significant difference). That is, the data show a lower rate of warming for the lower troposphere than for the surface (though not statistically different), whereas the models show amplification. The SR value for the middle troposphere data was 0.4, which is even more different from the model predictions. Only the SR for RSS data, which has a documented warming bias, overlaps with any model SR results. Given these findings, this study suggests that current state-of-the-art climate models have something fundamentally wrong with how they represent Earth's atmosphere.

Solomon et al. (2010) write "the trend in global surface temperatures has been nearly flat since the late 1990s despite continuing increases in the forcing due to the sum of the well-mixed greenhouse gases (CO_2, CH_4, halocarbons, and N_2O), raising questions regarding the understanding of forced climate change, its drivers, the parameters that define natural internal variability, and how fully these terms are represented in climate models." Therefore, in an effort to better our understanding of climate forcing, Solomon et al. used observations of stratospheric water vapor concentration obtained over the period 1980–2008, together with detailed radiative transfer and modeling information, in order to calculate the global climatic impact of this important greenhouse gas and compare it with trends in mean global near-surface air temperature observed over the same time period.

According to the seven scientists, stratospheric water vapor concentrations decreased by about 10 percent after the year 2000; and their analysis indicates this decrease should have slowed the rate of increase in global near-surface air temperature between 2000 and 2009 by about 25 percent compared to what would have been expected (on the basis of climate model calculations) due to measured increases in carbon dioxide and other greenhouse gases over the same time period. In addition, they found "more limited data suggest that stratospheric water vapor probably increased between 1980 and 2000, which would have enhanced the decadal rate of surface warming during the 1990s by about 30% [above what it would have been without the stratospheric water vapor increase]."

In their concluding paragraph, Solomon et al. thus write it is "not clear whether the stratospheric water vapor changes represent a feedback to global average climate change or a source of decadal variability." In either case, their findings elucidate an important phenomenon that was not included in any prior analyses of global climate change. They also write that current climate models do not "completely represent the Quasi Biennial Oscillation [which has a significant impact on stratospheric water vapor content], deep convective transport [of water vapor] and its linkages to sea surface temperatures, or the impact of aerosol heating on water input to the stratosphere."

In light of Solomon et al.'s specific findings, their listing of what current climate models do not do (which they should do), and the questions they say are raised by the flat-lining of mean global near-surface air temperature since the late 1990s, it is premature to conclude that current climate models correctly simulate the intricate workings of Earth's climate regulatory system.

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1.4 El Niño/Southern Oscillation

Computer model simulations have given rise to three claims regarding the influence of global warming on El Niño/Southern Oscillation (ENSO) events: (1) global warming will increase the *frequency* of ENSO events, (2) global warming will increase the *intensity* of ENSO events, and (3) weather-related disasters will be exacerbated under El Niño conditions. In this section we highlight findings that suggest the virtual world of ENSO, as simulated by state-of-the-art climate models, is at variance with reality, beginning with several studies that described the status of the problem a decade ago.

In a comparison of 24 coupled ocean-atmosphere climate models, Latif et al. (2001) reported, "almost all models (even those employing flux corrections) still have problems in simulating the SST [sea surface temperature] climatology." They also noted "only a few of the coupled models simulate the El Niño/Southern Oscillation in terms of gross equatorial SST anomalies realistically." And they stated, "no model has been found that simulates realistically all aspects of the interannual SST variability." Consequently, because "changes in sea surface temperature are both the cause and consequence of wind fluctuations," according to Fedorov and Philander (2000), and because these phenomena figure prominently in the El Niño-La Niña oscillation, it is not surprising that the latter researchers concluded climate models near the turn of the century did not do a good job of determining the potential effects of global warming on ENSO.

Human ignorance likely also played a role in those models' failure to simulate ENSO. According to Overpeck and Webb (2000), there was evidence that "ENSO may change in ways that we do not yet understand," which "ways" had clearly not yet been modeled. White et al. (2001), for example, found that "global warming and cooling during earth's internal mode of interannual climate variability [the ENSO cycle] arise from fluctuations in the global hydrological balance, not the global radiation balance," and they noted that these fluctuations are the result of no known forcing of either anthropogenic or extraterrestrial origin, although Cerveny and Shaffer (2001) made a case for a lunar forcing of ENSO activity, which also was not included in any climate model of that time.

Another example of the inability of the most sophisticated of late twentieth-century climate models to properly describe El Niño events was provided by Landsea and Knaff (2000), who employed a simple statistical tool to evaluate the skill of 12 state-of-the-art climate models in real-time predictions of the development of the 1997–98 El Niño. In doing so, they found the models exhibited essentially no skill in forecasting this very strong event at lead times ranging from zero to eight months. They also determined no models were able to anticipate even one-half of the actual amplitude of the El Niño's peak at a medium-range lead time of six to 11 months. Hence, they stated, "since no models were able to provide useful predictions at the medium and long ranges, there were no models that provided both useful and skillful forecasts for the entirety of the 1997–98 El Niño."

Given the inadequacies listed above, it is little wonder that several scientists criticized model simulations of ENSO behavior at the turn of the century, including Walsh and Pittock (1998), who concluded, "there is insufficient confidence in the predictions of current models regarding any changes in ENSO," and Fedorov and Philander (2000), who wrote, "at this time, it is impossible to decide which, if any, are correct."

So what's happened subsequently? Have things improved since then?

Huber and Caballero (2003) introduced their contribution to the subject by stating, "studies of future transient global warming with coupled ocean-atmosphere models find a shift to a more El Niño-like state," although they also reported the "permanent El Niño state"—which has been hyped by some climate alarmists—"is by no means uniformly predicted by a majority of models." To help resolve this battle of the models, they worked with still another model, plus real-world data pertaining to the Eocene, which past geologic epoch—having been much warmer than the recent past—provided, in their words, "a particularly exacting test of the robustness of ENSO." More specifically, they used the Community Climate System Model of the National Center for Atmospheric Research, which they said yielded "a faithful reproduction of modern-day ENSO variability," to "simulate the Eocene climate and determine whether the model predicts significant ENSO variability." In addition, they compared the model results against middle Eocene lake-sediment records from two different regions: the Lake Gosiute complex in Wyoming and Eckfield Maar in Germany.

In describing their findings, Huber and Caballero report the model simulations showed "little change in ... ENSO, in agreement with proxies." They also note other studies "indicate an ENSO shutdown as recently as ~6000 years ago, a period only slightly warmer than the present." Hence, they concluded, "this result contrasts with theories linking past and future 'hothouse' climates with a shift toward a permanent El Niño-like state." This conclusion represents a significant setback to climate alarmists who have used this unsubstantiated (and now invalidated) theory to induce unwarranted fear of global warming among the general public.

Three years later, Joseph and Nigam (2006) evaluated several climate models "by examining the extent to which they simulated key features of the leading mode of interannual climate variability: El Niño -Southern Oscillation (ENSO)"—which they described as "a dominant pattern of ocean-atmosphere variability with substantial global climate impact"—based on "the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4) simulations of twentieth-century climate." This evaluation indicated that different models were found to do well in some respects but not so well in many others. For example, they found climate models "are still unable to simulate many features of ENSO variability and its circulation and hydroclimate teleconnections." In fact, they found the models had only "begun to make inroads in simulating key features of ENSO variability."

According to Joseph and Nigam, "climate system models are not quite ready for making projections of regional-to-continental scale hydroclimate variability and change." Indeed, the study raises the question of whether they are ready to make any valid projections about anything. As Joseph and Nigam conclude, "predicting regional climate variability/change remains an onerous burden on models."

One year later, L'Ecuyer and Stephens (2007) asked how well state-of-the-art climate models reproduced the workings of real-world energy and water cycles, noting "our ability to model the climate system and its response to natural and anthropogenic forcings requires a faithful representation of the complex interactions that exist between radiation, clouds, and precipitation and their influence on the large-scale energy balance and heat transport in the atmosphere," while further stating "it is also critical to assess [model] response to shorter-term natural variability in environmental forcings using observations."

The two researchers used multi-sensor observations of visible, infrared, and microwave radiance obtained from the Tropical Rainfall Measuring Mission satellite for the period January 1998 through December 1999, in order to evaluate the sensitivity of atmospheric heating (and the factors that modify it) to changes in east-west SST gradients associated with the strong 1998 El Niño event in the tropical Pacific, as expressed by the simulations of nine general circulation models of the atmosphere that were utilized in the IPCC's AR4. This protocol, in their words, "provides a natural example of a short-term climate change scenario in which clouds, precipitation, and regional energy budgets in the east and west Pacific are observed to respond to the eastward migration of warm sea surface temperatures."

L'Ecuyer and Stephens report "a majority of the models examined do not reproduce the apparent westward transport of energy in the equatorial Pacific during the 1998 El Niño event." They also discovered "the intermodel variability in the responses of precipitation, total heating, and vertical motion [was] often larger than the intrinsic ENSO signal itself, implying an inherent lack of predictive capability in the ensemble with regard to the response of the mean zonal atmospheric circulation in the tropical Pacific to ENSO." In addition, they found "many models also misrepresent the radiative impacts of clouds in both regions [the east and west Pacific], implying errors in total cloudiness, cloud thickness, and the relative frequency of occurrence of high and low clouds." In light of these much-less-than-adequate findings, they conclude, "deficiencies remain in the representation of relationships between radiation, clouds, and precipitation in current climate models," while further stating these deficiencies "cannot be ignored when interpreting their predictions of future climate."

Paeth et al. (2008) compared 79 coupled ocean-atmosphere climate simulations derived from 12 different state-of-the-art climate models forced by six different IPCC emission scenarios with observational data in order to evaluate how well they reproduced the spatio-temporal characteristics of ENSO over the twentieth century, after which they compared the various models' twenty-first-century simulations of ENSO and the Indian and West African monsoons to one another. With respect to the twentieth century, this work revealed that "all considered climate models draw a reasonable picture of the key features of ENSO." With respect to the twenty-first century, on the other hand, they say that "the differences between the models are stronger than between the emission scenarios," while "the atmospheric component of ENSO and the West African monsoon are barely affected." Their "overall conclusion" was that "we still cannot say much about the future behavior of tropical climate." Indeed, they considered their study to be merely "a benchmark for further investigations with more recent models in order to document a gain in knowledge or a stagnation over the past five years."

Jin et al. (2008) investigated the overall skill of ENSO prediction in retrospective forecasts made with ten different state-of-the-art ocean-atmosphere coupled general circulation models with respect to their ability to hindcast real-world observations for the 22 years from 1980 to 2001. They found almost all models have problems simulating the mean equatorial SST and its annual cycle. They write, "none of the models we examined attain good performance in simulating the mean annual cycle of SST, even with the advantage of starting from realistic initial conditions." They also note that "with increasing lead time, this discrepancy gets worse," and that "the phase and peak amplitude of westward propagation of the annual cycle in the eastern and central equatorial Pacific are different from those observed." What is more, they found, "ENSO-neutral years are far worse predicted than growing warm and cold events," and "the skill of forecasts that start in February or May drops faster than that of forecasts that start in August or November." They and others call this behavior "the spring predictability barrier," which gives an indication of the difficulty of what they were attempting to do. Jin et al. conclude that "accurately predicting the strength and timing of ENSO events continues to be a critical challenge for dynamical models of all levels of complexity."

McLean et al. (2009) quantified "the effect of possible ENSO forcing on mean global temperature, both short-term and long-term," using Southern Oscillation Index (SOI) data provided by the Australian government's Bureau of Meteorology. This parameter is defined as "the standardized anomaly of the seasonal mean sea level pressure difference between Tahiti and Darwin, divided by the standard deviation of the difference and multiplied by 10." The temperature data employed in this endeavor were "the University of Alabama in Huntsville lower-tropospheric (LT) temperature data based on measurements from selected view angles of Microwave Sounding Unit (MSU) channel LT 2" for the period December 1979 to June 2008, supplemented by "balloon-based instrumentation (radiosondes)." More specifically, in the case of the latter data going back in time to 1958, they employed the Radiosonde Atmospheric Temperature Products for Assessing Climate (RATPAC) product (A) of the U.S. National Climatic Data Center, which represents the atmospheric layer between approximately 1500 and 9000 meters altitude.

When their work was completed, McLean et al. found "change in SOI accounts for 72% of the variance in GTTA [Global Tropospheric Temperature Anomalies] for the 29-year-long MSU record and 68% of the variance in GTTA for the longer 50-year RATPAC record," as well as "81% of the variance in tropospheric temperature anomalies in the tropics," where they say ENSO "is known to exercise a particularly strong influence." In addition, they determined that "shifts in temperature are consistent with shifts in the SOI that occur about 7 months earlier." Consequently, the three researchers state as their final conclusion, "natural climate forcing associated with ENSO is a major contributor to variability and perhaps recent trends in global temperature, a relationship that is not included in current global climate models."

Noting that "coral records closely track tropical Indo-Pacific variability on interannual to decadal timescales," Ault et al. (2009) employed 23 coral δ^{18}O records from the Indian and Pacific Oceans to extend the observational record of decadal climate variability back in time to cover the period of AD 1850–1990. In so doing they identified "a strong decadal component of climate variability" that "closely matches instrumental results from the twentieth century." In addition, they report the decadal variance they uncovered was much greater between 1850 and 1920 than it was between 1920 and 1990. As for what this observation means, the researchers say they "infer that this decadal signal represents a fundamental timescale of ENSO variability," which has an enhanced variance in the early half of the record that "remains to be explained."

In conclusion, there remain multiple unknowns with respect to ENSO and long-term climate change, and many of these unknowns raise serious questions about the ability of current climate models to adequately anticipate the multiplicity of climatic effects that the ongoing rise in the air's CO_2 content may or may not impose on Earth's atmospheric and oceanic environments.

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1.5 Soil Moisture

Climate models have long indicated that CO_2-induced global warming will increase evapotranspiration, causing decreases in soil moisture content that may offset modest increases in continental precipitation and lead to greater aridity in water-limited natural ecosystems and lands devoted to agriculture (Manabe and Wetherald, 1986; Rind, 1988; Gleick, 1989; Vlades et al., 1994; Gregory et al., 1997; Komescu et al., 1998). In the following pages we examine this model-based claim.

In a turn-of-the century evaluation of how climate modelers had progressed in their efforts to improve simulations of soil moisture content over the prior few years, Srinivasan et al. (2000) examined "the impacts of model revisions, particularly the land surface representations, on soil moisture simulations, by comparing the simulations to actual soil moisture observations." In summarizing their findings, they stated, "the revised models do not show any systematic improvement in their ability to simulate observed seasonal variations of soil moisture over the regions studied." They also concluded, "there are no indications of conceptually more realistic land surface representations producing better soil moisture simulations in the revised climate models." In addition, they reported a "tendency toward unrealistic summer drying in several models," which they noted was "particularly relevant in view of the summer desiccation projected by GCMs considered in future assessments of climate change."

Although Srinivasan et al. note that "simpler land-surface parameterization schemes are being replaced by conceptually realistic treatments" as the climate-modeling enterprise moves ever forward, they state that "improvements gained by such changes are ... not very apparent." Thus at the time of their study there had been no real progress in this area, only attempted progress.

Robock et al. (2000) developed a massive collection of soil moisture data for more than 600 stations from a wide variety of climatic regimes within the former Soviet Union, China, Mongolia, India, and the United States. In describing these datasets they also stated an important ground rule. Sometimes, they said, "the word 'data' is used to describe output from theoretical model calculations, or values derived from theoretical analysis of radiances from remote sensing." However, as they put it, "we prefer to reserve this word for actual physical observations," noting that "all the data in our data bank are actual *in situ* observations."

This distinction is important, for one of the illuminating analyses Robock et al. performed with their data was to check summer soil moisture trends simulated by the Geophysical Fluid Dynamics Laboratory's general circulation model of the atmosphere as forced by transient CO_2 and tropospheric sulfate aerosols for specific periods and regions for which they had actual soil moisture data.

What they learned from this exercise, in their words, was that "although this model predicts summer desiccation in the next century, it does not in general reproduce the observed upward trends in soil moisture very well." That is an understatement, when one considers that the predictions and observations go in opposite directions.

Robock et al. add, "in contrast to predictions of summer desiccation with increasing temperatures, for the stations with the longest records, summer soil moisture in the top 1 m has increased while temperatures have risen." Given that the model predictions and actual measurements failed to coincide, or actually diverged, Robock et al. offer their hope that the real-world data they assembled in their databank might help "improve simulations of the recent past so we may have more confidence in predictions for the next century."

Five years later, Robock et al. (2005) noted "most global climate model simulations of the future, when forced with increasing greenhouse gases and anthropogenic aerosols, predict summer desiccation in the midlatitudes of the Northern Hemisphere (e.g., Gregory et al., 1997; Wetherald and Manabe, 1999; Cubasch et al., 2001)," and they stated, "this predicted soil moisture reduction, the product of increased evaporative demand with higher temperatures overwhelming any increased precipitation, is one of the gravest threats of global warming, potentially having large impacts on our food supply."

Therefore, with the explicit purpose "to evaluate these model simulations," the three American and two Ukrainian scientists presented "the longest data set of observed soil moisture available in the world, 45 years of gravimetrically-observed plant available soil moisture for the top 1 m of soil, observed every 10 days for April-October for 141 stations from fields with either winter or spring cereals from the Ukraine for 1958–2002." And as they described it, "the observations show a positive soil moisture trend for the entire period of observation, with the trend leveling off in the last two decades," noting that "even though for the entire period there is a small upward trend in temperature and a downward trend in summer precipitation, the soil moisture still has an upward trend for both winter and summer cereals."

As a result of these real-world observations, Robock et al. noted that "although models of global warming predict summer desiccation in a greenhouse-warmed world, there is no evidence for this in the observations yet, even though the region has been warming for the entire period." In attempting to explain this dichotomy, they say the real-world increase in soil moisture content possibly may have been driven by a downward trend in evaporation caused by the controversial "global dimming" hypothesis (Liepert et al., 2004). Alternatively, it may have been driven by the well-known anti-transpirant effect of atmospheric CO_2 enrichment, which tends to conserve water in the soils beneath crops and thereby leads to enhanced soil moisture contents, as has been demonstrated in a host of experiments conducted in real-world field situations.

One especially outstanding study in this regard was that of Zaveleta et al. (2003), who tested the hypothesis that soil moisture contents may decline in a CO_2-enriched and warmer world, in a two-year study of an annual-dominated California grassland at the Jasper Ridge Biological Preserve, Stanford, California, USA. They delivered extra heating to a number of free-air CO_2-enriched (FACE) plots (enriched with an extra 300 ppm of CO_2) via infrared heat lamps suspended over the plots, which warmed the surface of the soil beneath them by 0.8–1.0°C.

The individual effects of atmospheric CO_2 enrichment and soil warming were of similar magnitude, and acting together they enhanced mean spring soil moisture content by about 15 percent over that of the control treatment. The effect of CO_2 was produced primarily as a consequence of its ability to cause partial stomatal closure and thereby reduce season-long plant water loss via transpiration. In the case of warming, there was an acceleration of canopy senescence, which further increased soil moisture by reducing the period of time over which transpiration losses occur, all without any decrease in total plant production.

Zaveleta et al. note their findings "illustrate the potential for organism-environment interactions to modify the direction as well as the magnitude of global change effects on ecosystem functioning." Indeed, whereas for the past two decades climate alarmists have predicted that vast reaches of agricultural land will dry up and be lost to profitable production in a CO_2-enriched world of the future, this study suggests just the opposite could occur. As the six researchers describe it, "we suggest that in at least some ecosystems, declines in plant transpiration mediated by changes in phenology can offset direct increases in evaporative water losses under future warming."

Guo and Dirmeyer (2006) compared soil moisture simulations made by 11 different models within the context of the Second Global Soil Wetness Project (a multi-institutional modeling research activity intended to produce a complete multi-model set of land surface state variables and fluxes by using current state-of-the-art land surface models driven by the ten-year period of data provided by the International Satellite Land Surface Climatology Project Initiative II) against real-world observations made on the top meter of grassland and agricultural soils located within parts of the former Soviet Union, the United States (Illinois), China, and Mongolia that are archived in the Global Soil Moisture Data Bank.

According to the two researchers, "simulating the actual values of observed soil moisture is still a challenging task for all models" and "both the root mean square of errors (RMSE) and the spread of RMSE across models are large." They conclude "the absolute values of soil moisture are poorly simulated by most models," and they find that "within regions there can be tremendous variations of any model to simulate the time series of soil moisture at different stations."

How serious are these large errors and tremendous variations? It would appear they are very serious, based on a number of explanatory statements made by Guo and Dirmeyer. First, the two researchers say "the land surface plays a vital role in the global climate system through interactions with the atmosphere." Second, they state that "accurate simulation of land surface states is critical to the skill of weather and climate forecasts." Third, they write that soil moisture "is the definitive land surface state variable; key for model initial conditions from which the global weather and climate forecasts begin integrations, and a vital factor affecting surface heat fluxes and land surface temperature."

Lastly, Li et al. (2007) compared soil moisture simulations derived from the IPCC's Fourth Assessment climate models (which were driven by observed climate forcings) for the period 1958–1999 with actual measurements of soil moisture made at more than 140 stations or districts in the mid-latitudes of the Northern Hemisphere, which were averaged in such a way as to yield six regional results: one each for the Ukraine, Russia, Mongolia, Northern China, Central China, and Illinois (USA).

According to the three researchers, the models showed realistic seasonal cycles for the Ukraine, Russia, and Illinois but "generally poor seasonal cycles for Mongolia and China." In addition, they report that the Ukraine and Russia experienced soil moisture increases in summer "that were larger than most trends in the model simulations." They write, "only two out of 25 model realizations show trends comparable to those observations," and they note the two realistic model-derived trends were "due to internal model variability rather than a result of external forcing," which means the two reasonable matches were actually accidental. Noting further that "changes in precipitation and temperature cannot fully explain soil moisture increases for [the] Ukraine and Russia," Li et al. write, "other factors might have played a dominant role on the observed patterns for soil moisture." In this regard they mention solar dimming as well as the fact that in response to elevated atmospheric CO_2 concentrations, "many plant species reduce their stomatal openings, leading to a reduction in evaporation to the atmosphere," so that "more water is likely to be stored in the soil or [diverted to] runoff," reporting that this phenomenon was detected by Gedney et al. (2006) in continental river runoff data.

Given these findings, the climate models employed in the IPCC's AR4 appear to be deficient in their ability to correctly simulate soil moisture trends, even when applied to the past and when driven by observed climate forcings. In the words of Li et al., "global climate models should better integrate the biological, chemical, and physical components of the earth system." Essentially all climate models employed to date have erred with respect to what Robock et al. (2005) describe as "one of the gravest threats of global warming."

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1.6. Climate Sensitivity

"We still can't predict future climate responses at low and high latitudes, which constrains our ability to forecast changes in atmospheric dynamics and regional climate." Thus states the subtitle of a paper by NASA Senior Scientist David Rind of the Goddard Institute for Space Studies (Rind, 2008). Rind begins his review and analysis of this important subject by noting Charney et al. (1979) concluded global temperature sensitivity to a doubling of the atmosphere's CO_2 concentration was "between 1.5° and 4.5°C," while noting since that time "we have not moved very far from that range." In addition, he reports uncertainty in our assessment of high- and low-latitude climate sensitivity "is also still as great as ever, with a factor of 2 at both high and low latitudes."

Rind lists a number of separate problems. For one thing, whether the water vapor response to warming employed by climate models "is realistic is hard to assess," as he puts it, "because we have not had recent climate changes of the magnitude forecast for the rest of this century" to test against. Closely associated are low-latitude difficulties related to modeling both low- and high-level clouds in the tropics and the physics and dynamics associated with them, plus high-latitude difficulties associated with cryosphere feedbacks related to sea ice and snow cover.

One approach to dealing with these uncertainties has been to suggest, in Rind's words, that "we can have greater confidence in the multi-model mean changes than in that of any individual model for climate change assessments." However, he writes, "it is doubtful that averaging different formulations together will end up giving the 'right' result," because "model responses (e.g., tropical land precipitation) can often be of different signs, and there can be little confidence that averaging them together will produce a better result."

Rind thus concludes, "at this point, we cannot determine the low- and high-latitude sensitivities, and we have no real way of obtaining them." These unknowns, in his opinion, "affect the confidence we can have in many of our projections of atmospheric dynamic and hydrologic responses to global warming."

Rind states, "forecasting even the large-scale response to climate change is not easy given the current uncertainties," and "regional responses may be the end result of varying influences in part due to warming in different tropical and high-latitude regions."

As to what Rind's analysis of the climate-modeling enterprise suggests about the future, he writes, "real progress will be the result of continued and newer observations along with modeling improvements based on these observations," which observations must provide the basis for evaluating all model implications. So difficult will this task be, however, that he says "there is no guarantee that these issues will be resolved before a substantial global warming impact is upon us." However, because of the large uncertainties—and unknowns—that surround many aspects of Earth's complex climate system, there is also no guarantee there even will be any "substantial global warming impact" from a doubling or more of the air's CO_2 content.

Lindzen and Choi (2009), two Massachusetts Institute of Technology scientists, used the National Centers for Environmental Prediction's 16-year (1985–1999) monthly record of sea surface temperature (SST), together with corresponding radiation data from the Earth Radiation Budget Experiment, to estimate the sign and magnitude of climate feedback over the oceanic portion of the tropics and thus obtain an empirical evaluation of Earth's thermal sensitivity, as opposed to the model-based evaluation employed by the IPCC.

According to Lindzen and Choi, all 11 models employed in the IPCC's analysis "agree as to positive feedback," but they find that they all *disagree*—and disagree "very sharply"—with the real-world observations that Lindzen and Choi utilized, which imply that negative feedback actually prevails. Moreover, the presence of that negative feedback reduces the CO_2-induced propensity for warming to the extent that their analysis of the real-world observational data yields only a mean SST increase "of ~0.5°C for a doubling of CO_2."

How does one decide which of the two results is closer to the truth? Real-world data would be the obvious standard against which to compare model-derived results, but since Lindzen and Choi's results are indeed based on real-world measurements, the only alternative we have is to seek other real-world results. Fortunately, there are several such findings, many of which are summarized by in Idso (1998), who describes eight "natural experiments" that he personally employed in prior studies to determine "how earth's near-surface air temperature responds to surface radiative perturbations."

The eight natural experiments used by Idso were (1) the change in the air's water vapor content that occurs at Phoenix, Arizona with the advent of the summer monsoon, (2) the naturally occurring vertical redistribution of dust that occurs at Phoenix between summer and winter, (3) the annual cycle of surface air temperature caused by the annual cycle of solar radiation absorption at the Earth's surface, (4) the warming effect of the entire atmosphere caused by its mean flux of thermal radiation to the surface of the Earth, (5) the annually averaged equator-to-pole air temperature gradient that is sustained by the annually averaged equator-to-pole gradient of total surface-absorbed radiant energy, (6) the mean surface temperatures of Earth, Mars, and Venus relative to the amounts of CO_2 contained in their atmospheres, (7) the paradox of the faint early sun and its implications for Earth's thermal history, and (8) the greenhouse effect of water vapor over the tropical oceans and its impact on sea surface temperatures.

These eight analyses, in the words of Idso, "suggest that a 300 to 600 ppm doubling of the atmosphere's CO_2 concentration could raise the planet's mean surface air temperature by only about 0.4°C," which is right in line with Lindzen and Choi's deduced warming of ~0.5°C for a nominal doubling of the air's CO_2 content. Hence, there would appear to be strong real-world data that argue against the overinflated CO_2-induced global warming predicted by state-of-the-art climate models.

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