1. CLIMATE MODEL INADEQUACIES

Because the earth-ocean-atmosphere system is so vast and complex, it is impossible to conduct a small-scale experiment that reveals how the world's climate will change as the air's greenhouse gas concentrations continue to rise. As a result, scientists *estimate* its response using computer models that define a "virtual" earth-ocean-atmosphere system. To be of any validity, however, these models must incorporate all of the many physical, chemical and biological processes that influence climate in the real world. And they must do so *correctly*.

So how do the models perform in this regard? A review of the scientific literature reveals numerous deficiencies and shortcomings in today's state-of-the-art models, some of which deficiencies could even alter the *sign* of projected climate change. In this first chapter, we provide brief summaries of several studies that outline some of these deficiencies, arranged into three subsections of model inadequacies: radiation, clouds and precipitation.

Additional information on this topic, including reviews of climate model inadequacies not discussed here, can be found at http://www.co2science.org/subject/m/subject_m.php under the heading Models of Climate.

1.1. Radiation

One of the most challenging and important problems facing today's general circulation models of the atmosphere is how to accurately simulate the physics of earth's radiative energy balance. Of this task, Harries (2000) says "progress is excellent, on-going research is fascinating, but we have still a great deal to understand about the physics of climate."

Warning against excessive hubris, Harries says "we must exercise great caution over the true depth of our understanding, and our ability to forecast future climate trends." As an example, he states that our knowledge of high cirrus clouds is very poor, noting that "we could easily have uncertainties of many tens of W m^{-2} in our description of the radiative effect of such clouds, and how these properties may change under climate forcing." This state of affairs is extremely disconcerting, especially in light of the fact that the radiative effect of a doubling the air's CO_2 content is in the lower single-digit range of W m^{-2}, and, to quote Harries, that "uncertainties as large as, or larger than, the doubled CO_2 forcing could easily exist in our modeling of future climate trends, due to uncertainties in the feedback processes." Furthermore, because of the vast complexity of the subject, Harries rightly declares that "even if [our] understanding were perfect, our ability to describe the system sufficiently well in even the largest computer models is a problem."

Illustrative of a related problem is the work of Zender (1999), who characterized the spectral, vertical, regional and seasonal atmospheric heating caused by the oxygen collision pairs $O_2 \cdot O_2$ and $O_2 \cdot N_2$, which had earlier been discovered to absorb a small but significant fraction of the globally-incident solar radiation. This work revealed that these molecular collisions lead to the absorption of about 1 Wm^{-2} of solar radiation, globally and annually averaged. This discovery, in Zender's words, "alters the long-standing view that H_2O, O_3, O_2, CO_2 and NO_2 are the only significant gaseous solar absorbers in Earth's atmosphere," and he suggests that the phenomenon "should therefore be included in ... large-scale atmospheric models used to simulate climate and climate change." It also raises the possibility there are still other yet-to-be-discovered processes that should be included in the models that are used to simulate earth's climate, and that until we are confident there is little likelihood of further such surprises, we ought not rely too heavily on what the models of today are telling us about the climate of tomorrow.

In another revealing study, Wild (1999) compared the observed amount of solar radiation absorbed in the atmosphere over equatorial Africa with what was predicted by three general circulation models of the atmosphere, finding that the model predictions were much too small. Indeed, regional and seasonal model underestimation biases were as high as *30* Wm^{-2}, primarily because the models failed to properly account for spatial and temporal variations in atmospheric aerosol concentrations. In addition, Wild found that the models likely underestimated the amount of solar radiation absorbed by water vapor and clouds.

Similar large model underestimations were discovered by Wild and Ohmura (1999), who analyzed a comprehensive observational dataset consisting of solar radiation fluxes measured at 720 sites across the earth's surface and corresponding top-of-the-atmosphere locations to assess the true amount of solar radiation absorbed within the atmosphere. These results were compared with estimates of solar radiation absorption derived from four atmospheric general circulation models (GCMs); and, again, it was shown that "GCM atmospheres are generally too transparent for solar radiation," as they produce a rather substantial mean error close to 20% below actual observations.

Another solar-related deficiency of state-of-the-art GCMs is their failure to properly account for solar-driven variations in earth-atmosphere processes that operate over a range of timescales extending from the 11-year solar cycle to century- and millennial-scale cycles (see several of the subheadings under Solar Effects in our Subject Index). Although the absolute solar flux variations associated with these phenomena are rather small, there are a number of "multiplier effects" that may significantly amplify their impacts.

According to Chambers *et al*. (1999), most of the many nonlinear responses to solar activity variability are inadequately represented (in fact, they are essentially ignored) in the global climate models used by the Intergovernmental Panel on Climate Change (IPCC) to predict future greenhouse gas-induced global warming, while at the same time *other* amplifier effects are used to model past glacial/interglacial cycles and even the hypothesized CO_2-induced warming of the future, where CO_2 is *not* the major cause of the predicted temperature increase but rather an initial perturber of the climate system that according to the IPCC sets other more powerful forces in motion that produce the bulk of the ultimate warming. Hence, there appears to be a *double standard* within the climate modeling community that may best be described as an inherent reluctance to deal even-handedly with different aspects of climate change. When multiplier effects suit their purposes, they use them; but when they don't suit their purposes, they don't use them.

In setting the stage for the next study of climate model inadequacies related to radiative forcing, Ghan *et al*. (2001) state that "present-day radiative forcing by anthropogenic greenhouse gases is estimated to be 2.1 to 2.8 Wm^{-2}; the direct forcing by anthropogenic aerosols is estimated to be -0.3 to -1.5 Wm^{-2}, while the indirect forcing by anthropogenic aerosols is estimated to be 0 to -1.5 Wm^{-2}," so that "estimates of the total global mean present-day anthropogenic forcing range from 3 Wm^{-2} to -1 Wm^{-2}," which implies a climate change somewhere between a modest warming and a slight cooling, which would seem to be a rather shaky justification for mandating draconian measures to combat the first of these possibilities. Hence, they say that *clearly* "the great uncertainty in the radiative forcing must be reduced if the observed climate record is to be reconciled with model predictions and if estimates of future climate change are to be useful in formulating emission policies."

Pursuit of this goal, as they describe it, requires achieving "profound reductions in the uncertainties of direct and indirect forcing by anthropogenic aerosols," which is what they set out to do in their analysis of the situation, which consisted of "a combination of process studies designed to improve understanding of the key processes involved in the forcing, closure experiments designed to evaluate that understanding, and integrated models that treat all of the necessary processes together and estimate the forcing." At the conclusion of this laborious set of operations, Ghan *et al*. came up with some numbers that considerably reduced the range of uncertainty in the "total global mean present-day anthropogenic forcing," but that still implied a set of climate changes stretching from a small cooling to a modest warming. Hence, they provided a long list of *other* things that must be done in order to obtain a more definitive result, after which they acknowledged that even *this* list "is hardly complete." In fact, they concluded their analysis by saying "one could easily add the usual list of uncertainties in the representation of clouds, etc." Consequently, the bottom line, in their words, is that "much remains to be done before the estimates are reliable enough to base energy policy decisions upon."

Also studying the aerosol-induced radiative forcing of climate were Vogelmann *et al*. (2003), who report that "mineral aerosols have complex, highly varied optical properties that, for equal loadings, can cause differences in the surface IR flux between 7 and 25 Wm^{-2} (Sokolik *et al*., 1998)," but who say that "only a few large-scale climate models currently consider aerosol IR effects (e.g., Tegen *et al*., 1996; Jacobson, 2001) despite their potentially large forcing." Because of these facts, and in an attempt to persuade climate modelers to rectify the situation, Vogelmann *et al*. used high-resolution spectra to calculate the surface IR radiative forcing created by aerosols encountered in the outflow of air from northeastern Asia, based on measurements made by the Marine-Atmospheric Emitted Radiance Interferometer aboard the NOAA Ship *Ronald H. Brown* during the Aerosol Characterization Experiment-Asia. In doing so, they determined, in their words, that "daytime surface IR forcings are often a few Wm^{-2} and can reach almost 10 Wm^{-2} for large aerosol loadings," which values they say "are comparable to or larger than the 1 to 2 Wm^{-2} change in the globally averaged surface IR forcing caused by greenhouse gas increases since pre-industrial times." In a massive understatement of fact, the researchers thus concluded that their results "highlight the importance of aerosol IR forcing which should be included in climate model simulations," causing us to wonder that if a forcing of this magnitude is not included in current state-of-the-art climate models, what other major forcings are they ignoring?

Shifting gears just a bit, two papers published one year earlier in the same issue of *Science* (Chen *et al*., 2002; Wielicki *et al*., 2002) revealed what Hartmann (2002) called a pair of "tropical surprises." The first of the seminal discoveries was the common finding of both groups of researchers that the amount of thermal radiation emitted to space at the top of the tropical atmosphere increased by about 4 Wm^{-2} between the 1980s and the 1990s, while the second was that the amount of reflected sunlight decreased by 1 to 2 Wm^{-2} over the same period, with the net result that more total radiant energy exited the tropics in the latter decade. In addition, the measured thermal radiative energy loss at the top of the tropical atmosphere was of the same magnitude as the thermal radiative energy gain that is generally predicted to result from an instantaneous doubling of the air's CO_2 content. Yet as Hartman correctly notes, "only very small changes in average tropical surface temperature were observed during this time." So what went wrong? Or, as we probably more correctly should phrase the question, what went *right*?

One thing was the change in solar radiation reception that was driven by changes in cloud cover, which allowed more solar radiation to reach the surface of the earth's tropical region and warm it. These changes were produced by what Chen *et al*. determined to be "a decadal-time-scale strengthening of the tropical Hadley and Walker circulations." Another helping-hand was likely provided by the past quarter-century's slowdown in the meridional overturning circulation of the upper 100 to 400 meters of the tropical Pacific Ocean (McPhaden and Zhang, 2002), which circulation slowdown also promotes tropical sea surface warming by reducing the rate-of-supply of relatively colder water to the region of equatorial upwelling.

So what do these observations have to do with evaluating the ability of climate models to correctly predict the future? For one thing, they provide several new phenomena for the models to replicate as a test of their ability to properly represent the real-world. In the words of McPhaden and Zhang, the time-varying meridional overturning circulation of the upper Pacific Ocean provides "an important dynamical constraint for model studies that attempt to simulate recent observed decadal changes in the Pacific." If the climate models can't reconstruct this simple wind-driven circulation, for example, why should we believe anything else they tell us?

In an eye-opening application of this principle, Wielicki *et al*. tested the ability of four state-of-the-art climate models and one weather assimilation model to reproduce the observed decadal changes in top-of-the-atmosphere thermal and solar radiative energy fluxes that occurred over the past two decades. The results were truly pathetic. No significant decadal variability was exhibited by *any* of the models; and they *all* failed to reproduce even the cyclical seasonal change in tropical albedo. The administrators of the test thus kindly concluded that "the missing variability in the models highlights the critical need to improve cloud modeling in the tropics so that prediction of tropical climate on interannual and decadal time scales can be improved." Hartmann, on the other hand, was considerably more candid in his scoring of the test, saying that the results indicated "the models are deficient." Expanding on this assessment, he further noted that "if the energy budget can vary substantially in the absence of obvious forcing," as it did over the past two decades, "then the climate of earth has modes of variability that are not yet fully understood and cannot yet be accurately represented in climate models," which leads us to wonder why anyone would put any faith in them. To do so is simply illogical.

Also concentrating on the tropics, Bellon *et al*. (2003) note that "observed tropical sea-surface temperatures (SSTs) exhibit a maximum around 30°C," and that "this maximum appears to be robust on various timescales, from intraseasonal to millennial." Hence, they say that "identifying the stabilizing feedback(s) that help(s) maintain this threshold is essential in order to understand how the tropical climate reacts to an external perturbation," which knowledge is needed for understanding how the *global* climate reacts to perturbations such as those produced by solar variability and the ongoing rise in the air's CO_2 content. This contention is further substantiated by the study of Pierrehumbert (1995), which "clearly demonstrates," in the words of Bellon *et al*., "that the tropical climate is not determined locally, but globally." Also, they note that Pierrehumbert's work demonstrates that interactions between moist and dry regions are an essential part of tropical climate stability, which hearkens back to the *adaptive infrared iris concept* of Lindzen *et al*. (2001).

Noting that previous box models of tropical climate have shown it to be rather sensitive to the relative areas of moist and dry regions of the tropics, Bellon *et al*. analyzed various feedbacks associated with this sensitivity in a four-box model of the tropical climate "to show how they modulate the response of the tropical temperature to a radiative perturbation." In addition, they investigated the influence of the model's surface-wind parameterization in an attempt to shed further light on the nature of the underlying feedbacks that help define the global climate system that is responsible for the tropical climate observations of constrained maximum SSTs.

Bellon *et al*.'s work, as they describe it, "suggests the presence of an important and as-yet-unexplored feedback in earth's tropical climate, that could contribute to maintain the 'lid' on tropical SSTs," much like the adaptive infrared iris concept of Lindzen *et al*. does. They also say that the demonstrated "dependence of the surface wind on the large-scale circulation has an important effect on the sensitivity of the tropical system," specifically stating that "this dependence reduces significantly the SST sensitivity to radiative perturbations by enhancing the evaporation feedback," which injects more heat into the atmosphere and allows the atmospheric circulation to export more energy to the subtropical free troposphere, where it can be radiated to space. Clearly, therefore, the case is not closed on either the *source* or the *significance* of the maximum "allowable" SSTs of tropical regions; and, hence, neither is the case closed on the degree to which the planet may warm in response to continued increases in the atmospheric concentrations of carbon dioxide and other greenhouse gases, in stark contrast to what is suggested by the climate models promoted by the IPCC.

In conclusion, there appear to be a number of major inadequacies in the ways in which several aspects of earth's radiative energy balance are treated in contemporary general circulation models of the atmosphere, as well as numerous other telling inadequacies stemming from the *non*-treatment of pertinent phenomena that are nowhere to be found in the models. Hence, there is no rational basis for any of the IPCC-inspired predictions of catastrophic climatic changes due to continued anthropogenic CO_2 emissions. The many scenarios they promulgate are simply unwarranted projections that have far outpaced what can be soundly supported by the current state of the climate modeling enterprise.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/m/inadeqradiation.php.

References

Bellon, G., Le Treut, H. and Ghil, M. 2003. Large-scale and evaporation-wind feedbacks in a box model of the tropical climate. *Geophysical Research Letters* **30**: 10.1029/2003GL017895.

Chambers, F.M., Ogle, M.I. and Blackford, J.J. 1999. Palaeoenvironmental evidence for solar forcing of Holocene climate: linkages to solar science. *Progress in Physical Geography* **23**: 181-204.

Chen, J., Carlson, B.E. and Del Genio, A.D. 2002. Evidence for strengthening of the tropical general circulation in the 1990s. *Science* **295**: 838-841.

Ghan, S.J., Easter, R.C., Chapman, E.G., Abdul-Razzak, H., Zhang, Y., Leung, L.R., Laulainen, N.S., Saylor, R.D. and Zaveri, R.A. 2001. A physically based estimate of radiative forcing by anthropogenic sulfate aerosol. *Journal of Geophysical Research* **106**: 5279-5293.

Harries, J.E. 2000. Physics of the earth's radiative energy balance. *Contemporary Physics* **41**: 309-322.

Hartmann, D.L. 2002. Tropical surprises. *Science* **295**: 811-812.

Jacobson, M.Z. 2001. Global direct radiative forcing due to multicomponent anthropogenic and natural aerosols. *Journal of Geophysical Research* **106**: 1551-1568.

Lindzen, R.S., Chou, M.-D. and Hou, A.Y. 2001. Does the earth have an adaptive infrared iris? *Bulletin of the American Meteorological Society* **82**: 417-432.

McPhaden, M.J. and Zhang, D. 2002. Slowdown of the meridional overturning circulation in the upper Pacific Ocean. *Nature* **415**: 603-608.

Pierrehumbert, R.T. 1995. Thermostats, radiator fins, and the local runaway greenhouse. *Journal of the Atmospheric Sciences* **52**: 1784-1806.

Sokolik, I.N., Toon, O.B. and Bergstrom, R.W. 1998. Modeling the radiative characteristics of airborne mineral aerosols at infrared wavelengths. *Journal of Geophysical Research* **103**: 8813-8826.

Tegen, I., Lacis, A.A. and Fung, I. 1996. The influence on climate forcing of mineral aerosols from disturbed soils. *Nature* **380**: 419-422.

Vogelmann, A.M., Flatau, P.J., Szczodrak, M., Markowicz, K.M. and Minnett, P.J. 2003. Observations of large aerosol infrared forcing at the surface. *Geophysical Research Letters* **30**: 10.1029/2002GL016829.

Wielicki, B.A., Wong, T., Allan, R.P., Slingo, A., Kiehl, J.T., Soden, B.J., Gordon, C.T., Miller, A.J., Yang, S.-K., Randall, D.A., Robertson, F., Susskind, J. and Jacobowitz, H. 2002. Evidence for large decadal variability in the tropical mean radiative energy budget. *Science* **295**: 841-844.

Wild, M. 1999. Discrepancies between model-calculated and observed shortwave atmospheric absorption in areas with high aerosol loadings. *Journal of Geophysical Research* **104**: 27,361-27,371.

Wild, M. and Ohmura, A. 1999. The role of clouds and the cloud-free atmosphere in the problem of underestimated absorption of solar radiation in GCM atmospheres. *Physics and Chemistry of the Earth* **24B**: 261-268.

Zender, C.S. 1999. Global climatology of abundance and solar absorption of oxygen collision complexes. *Journal of Geophysical Research* **104**: 24,471-24,484.

1.2. Clouds

Correctly parameterizing the influence of clouds on climate is an elusive goal that the creators of atmospheric general circulation models (GCMs) have yet to achieve. One reason for their lack of success in this endeavor has to do with model resolution on both vertical and horizontal space scales. Lack of adequate resolution forces modelers to parameterize the ensemble large-scale effects of processes that occur on smaller scales than their models' are capable of handling. This is particularly true of physical processes such as cloud formation and cloud-radiation interactions. It is only natural to wonder, therefore, if the parameterizations used in the models that prompted calls for severe cuts in anthropogenic CO_2 emissions over the past decade or so adequately represented these processes and their interactions. The results of several studies conducted near the turn of the past century suggest that model parameterizations of that period did *not* succeed in this regard (Groisman *et al*., 2000); and subsequent studies suggest that they are *still* not succeeding.

Lane *et al*. (2000), for example, evaluated the sensitivities of the cloud-radiation parameterizations utilized in contemporary GCMs to changes in vertical model resolution, varying the latter from 16 to 60 layers in increments of four and comparing the results to observed values. This effort revealed that cloud fraction varied by approximately 10% over the range of resolutions tested, which corresponded to about 20% of the observed cloud cover fraction. Similarly, outgoing longwave radiation varied by 10 to 20 Wm^{-2} as model vertical resolution was varied, amounting to approximately 5 to 10% of observed values, while incoming solar radiation experienced similar significant variations across the range of resolutions tested. What is more, the model results did not converge, even at a resolution of 60 layers.

In an analysis of the multiple roles played by cloud microphysical processes in determining tropical climate, Grabowski (2000) found much the same thing, noting there were serious problems related to the degree to which computer models failed to correctly incorporate cloud microphysics. These observations led him to conclude that "it is unlikely that traditional convection parameterizations can be used to address this fundamental question in an effective way." He also became convinced that "classical convection parameterizations do not include realistic elements of cloud physics and they represent interactions among cloud physics, radiative processes, and surface processes within a very limited scope." Consequently, he but stated the obvious when he concluded that "model results must be treated as qualitative rather than quantitative."

Reaching rather similar conclusions were Gordon *et al*. (2000), who determined that many GCMs of the late 1990s tended to under predict the presence of subtropical marine stratocumulus clouds, and that they failed to simulate the seasonal cycle of the clouds. These deficiencies are extremely important, because these particular clouds exert a major cooling influence on the surface temperatures of the sea below them. In the situation investigated Gorden and his colleagues, for example, the removal of the low clouds, as occurred in the normal application of their model, led to sea surface temperature increases on the order of 5.5°C.

Further condemnation of turn-of-the-century model treatments of clouds came from Harries (2000), who wrote that our knowledge of high cirrus clouds is very poor and that "we could easily have uncertainties of many tens of Wm^{-2} in our description of the radiative effect of such clouds, and how these properties may change under climate forcing." This problem is particularly noteworthy in light of the fact that the radiative effect of a doubling of the air's CO_2 content is only on the order of low single-digit Wm^{-2}. It is, therefore, truly an understatement to say, as Harries did, that "uncertainties as large as, or larger than, the doubled CO_2 forcing could easily exist in our modeling of future climate trends, due to uncertainties in the feedback processes."

Moving into the 21st century, Lindzen *et al*. (2001) analyzed cloud cover and sea surface temperature (SST) data over a large portion of the Pacific Ocean, finding a strong inverse relationship between upper-level cloud area and mean SST, such that the area of cirrus cloud coverage normalized by a measure of the area of cumulus coverage decreased by about 22% for each degree C increase in cloudy region SST. *Essentially*, as the researchers described it, "the cloudy-moist region appears to act as an infrared adaptive iris that opens up and closes down the regions free of upper-level clouds, which more effectively permit infrared cooling, in such a manner as to resist changes in tropical surface temperature." The sensitivity of this negative feedback was calculated by Lindzen *et al*. to be substantial. In fact, they estimated it would "more than cancel all the positive feedbacks in the more sensitive current climate models" that were being used to predict the consequences of projected increases in atmospheric CO_2 concentration. And, as one might suppose, evidence of this potential impediment to global warming was nowhere to be seen *then*, and is nowhere to be seen *now*, even in today's most advanced GCMs.

Clearly, this challenge to climatic *political* correctness could not go uncontested; and Hartmann and Michelsen (2002) quickly claimed that the correlation noted by Lindzen *et al*. resulted from variations in subtropical clouds that are not physically connected to deep convection near the equator, and that it was thus "unreasonable to interpret these changes as evidence that deep tropical convective anvils contract in response to SST increases." Fu *et al*. (2002) also chipped away at the adaptive infrared iris concept, arguing that "the contribution of tropical high clouds to the feedback process would be small since the radiative forcing over the tropical high cloud region is near zero and not strongly positive," while also claiming to show that water vapor and low cloud effects were overestimated by Lindzen *et al*. by at least 60% and 33%, respectively." As a result, they obtained a feedback factor in the range of -0.15 to -0.51, compared to Lindzen *et al*.'s much larger negative feedback factor of -0.45 to -1.03.

In a contemporaneously published reply to this critique, Chou *et al*. (2002) stated that Fu *et al*.'s approach of specifying longwave emission and cloud albedos "appears to be inappropriate for studying the iris effect," and that since "thin cirrus are widespread in the tropics and ... low boundary clouds are optically thick, the cloud albedo calculated by [Fu *et al*.] is too large for cirrus clouds and too small for boundary layer clouds," so that "the near-zero contrast in cloud albedos derived by [Fu *et al*.] has the effect of underestimating the iris effect." In the end, however, Chou *et al*. agreed that Lindzen *et al*. "may indeed have overestimated the iris effect somewhat, though hardly by as much as that suggested by [Fu *et al*.]."

Although there has thus been some convergence in the two extreme views of the subject, the debate over the reality and/or magnitude of the adaptive infrared iris effect continues apace; and when some of the meteorological community's best minds continue to clash over the nature and magnitude of the phenomenon, it is amazing that the EPA seeks to reduce anthropogenic CO_2 emissions via the Clean Air Act, as if the issue were settled when it clearly is not.

This situation is illustrative of the importance of the advice given two years earlier by Grassel (2000), who in a review of the then-current status of the climate modeling enterprise noted that changes in many climate-related phenomena, including cloud optical and precipitation properties caused by changes in the spectrum of cloud condensation nuclei, were insufficiently well known to provide useful insights into future conditions. His advice in the light of this knowledge gap was that "we must continuously evaluate and improve the GCMs we use," although he was forced to acknowledge that contemporary climate model results were already being "used by many decision-makers, including governments."

This state of affairs has continued to the present day and is very disturbing, as national and international policy is being made on the basis of vastly imperfect mathematical representations of a whole host of physical, chemical and biological phenomena, many of which involve clouds. Although some may think that what we currently know about the subject is sufficient for predictive purposes, a host of questions posed by Grassl - for which we *still* lack definitive answers - demonstrates that this assumption is erroneous.

As but a single example, Charlson *et al*. (1987) described a negative feedback process that links biologically-produced dimethyl sulfide (DMS) in the oceans with climate. The basic tenant of this hypothesis derives from the fact that the global radiation balance is significantly influenced by the albedo of marine stratus clouds, and that the albedo of these clouds is a function of cloud droplet concentration, which is dependent upon the availability of condensation nuclei that have their origin in the flux of DMS from the world's oceans to the atmosphere.

Acknowledging that the roles played by DMS oxidation products within the context described above are indeed "diverse and complex" and in many instances "not well understood," Ayers and Gillett (2000) summarized empirical evidence supporting Charlson *et al*.'s hypothesis that was derived from data collected at Cape Grim, Tasmania, and from reports of other pertinent studies in the peer-reviewed scientific literature. According to their findings, the "major links in the feedback chain proposed by Charlson *et al*. (1987) have a sound physical basis," and there is "compelling observational evidence to suggest that DMS and its atmospheric products participate significantly in processes of climate regulation and reactive atmospheric chemistry in the remote marine boundary layer of the Southern Hemisphere."

The empirical evidence analyzed by Ayers and Gillett (see also, in this regard, Dimethyl Sulfide in our Subject Index) highlights an important suite of negative feedback processes that act in opposition to model-predicted CO_2-induced global warming over the world's oceans; and these processes are not fully incorporated into even the very best of the current crop of climate models, nor are analogous phenomena that occur over land included in them, such as those discussed by Idso (1990).

Further to this point, O'Dowd *et al*. (2004) measured size-resolved physical and chemical properties of aerosols found in northeast Atlantic marine air arriving at the Mace Head Atmospheric Research station on the west coast of Ireland during phytoplanktonic blooms at various times of the year. In doing so, they found that in the winter, when biological activity was at its lowest, the organic fraction of the submicrometer aerosol mass was about 15%. During the spring through autumn, however, when biological activity was high, they found that "the organic fraction dominates and contributes 63% to the submicrometer aerosol mass (about 45% is water-insoluble and about 18% water-soluble)." Based on these findings, they performed model simulations that indicated that the marine-derived organic matter "can enhance the cloud droplet concentration by 15% to more than 100% and is therefore an important component of the aerosol-cloud-climate feedback system involving marine biota."

As for the significance of their findings, O'Dowd *et al*. state that their data "completely change the picture of what influences marine cloud condensation nuclei given that water-soluble organic carbon, water-insoluble organic carbon and surface-active properties, all of which influence the cloud condensation nuclei activation potential, are typically not parameterized in current climate models," or as they say in another place in their paper, "an important source of organic matter from the ocean is omitted from current climate-modeling predictions and should be taken into account."

Another perspective on the cloud-climate conundrum is 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." They report, however, that "despite the best efforts of [the climate modeling] community ... the problem remains largely unsolved." What is more, they say that "at the current rate of progress, cloud parameterization deficiencies will continue to plague us for many more decades into the future."

So what's the problem? "Clouds are complicated," Randall *et al*. declare, as they begin to describe what they call the "appalling complexity" of the cloud parameterization situation. For starters, they state that "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 that we also don't know all that much about *what comes down*, as they report that "downdrafts are either not parameterized or crudely parameterized in large-scale models."

With respect to stratiform clouds, the situation is no better, as their parameterizations are described by Randall *et al*. as "very rough caricatures of reality." As for *interactions* between convective and stratiform clouds, *forget about it* ... which is pretty much what scientists themselves did during the 1970s and 80s, when Randall *et al*. report that "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, in fact, they had to report that the concept of detrainment was "somewhat murky," and that the conditions that trigger detrainment were "imperfectly understood." Hence, it should again come as no surprise that "at this time," as they put it, "no existing GCM includes a satisfactory parameterization of the effects of mesoscale cloud circulations."

Randall *et al*. additionally say that "the large-scale effects of microphysics, turbulence, and radiation should be parameterized as closely coupled processes acting in concert," but they report that only a few GCMs have even *attempted* to do so. Why? Because, as they continue, "the cloud parameterization problem is overwhelmingly complicated," and "cloud parameterization developers," as they call them, are *still* "struggling to identify the most important processes on the basis of woefully incomplete observations." To drive this point home, they say "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 conclude that "a sober assessment suggests that with current approaches the cloud parameterization problem will not be 'solved' in any of our lifetimes."

With such a bleak assessment of where the climate-modeling community currently stands with respect to just *the single issue of cloud parameterization*, it might be well to pause and ask how anyone could possibly feel confident about what even the best climate models of the day are predicting about CO_2-induced global warming, *where proper cloud responses are critical to reaching a correct conclusion*. However, a shining hope of the climate-modeling community of tomorrow resides, according to Randall *et al*., in something called "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 that "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."

A few more decades, however, is a little long to wait to address an issue we are confronting now. Hence, Randall *et al*. say that an approach that could be used very soon (to possibly determine whether or not there even is a problem) is to "run a CSRM as a 'superparameterization' inside a GCM," which configuration they call a "super-GCM." Not wanting to be accused of impeding scientific progress, we say "go for it," but only with the proviso that if we are going to spend so much money on the project and devote so many scientific careers to it, we should admit up front that it is truly *needed* in order to obtain a definitive answer to the question of CO_2-induced "anthropogenic climate change." And admitting such, we should not do anything rash in the interim in an expensive and likely futile attempt to alter the course of future climate.

So it comes down to this: either we know enough about how the world's climate system works, so that we don't need the postulated super-GCMs, or we *don't* know enough about how it works and we *do* need them. We happen to believe with Randall *et al*. that our knowledge of *many* aspects of earth's climate system is *sadly* deficient. So let's own up to that fact and openly admit that we currently have *no rational basis* for implementing programs designed to restrict anthropogenic CO_2 emissions. The cloud parameterization problem *by itself* is so complex that no one can validly claim that humanity's continued utilization of fossil-fuel energy will result in massive counter-productive climatic changes. There is absolutely no justification for that conclusion in *reliable* theoretical models, simply because *there are none*.

That the basis for this conclusion is robust, and cannot be said to rest on the less-than-enthusiastic remarks of a handful of exasperated climate modelers, we report the results of additional studies of the subject that were published *subsequent* to the analysis of Randall *et* *al*., and which therefore could have readily refuted their assessment of the situation if they felt that such was appropriate.

In the first of these studies, which was conducted by *seventeen other climate modelers*, Siebesma *et al*. (2004) report that "simulations with nine large-scale models [were] carried out for June/July/August 1998 and the quality of the results [was] assessed along a cross-section in the subtropical and tropical North Pacific ranging from (235°E, 35°N) to (187.5°E, 1°S)," in order to "document the performance quality of state-of-the-art GCMs in modeling the first-order characteristics of subtropical and tropical cloud systems." The *main conclusions* of this study, according to Siebesma *et al*., were that "(1) almost all models strongly underpredicted both cloud cover and cloud amount in the stratocumulus regions while (2) the situation is opposite in the trade-wind region and the tropics where cloud cover and cloud amount are overpredicted by most models." In fact, they report that "these deficiencies result in an overprediction of the downwelling surface short-wave radiation of typically 60 W m^{-2} in the stratocumulus regimes and a similar underprediction of 60 W m^{-2} in the trade-wind regions and in the intertropical convergence zone (ITCZ)," which discrepancies are to be compared with a radiative forcing of only a couple of W m^{-2} for a 300-ppm increase in the atmosphere's CO_2 concentration. In addition, they state that "similar biases for the short-wave radiation were found at the top of the atmosphere, while discrepancies in the outgoing long-wave radiation are most pronounced in the ITCZ."

The seventeen scientists, who hail from nine different countries, also state that "the representation of clouds in general-circulation models remains one of the most important *as yet unresolved* [our italics] issues in atmospheric modeling." This is partially due, they continue, "to the overwhelming variety of clouds observed in the atmosphere, but even more so due to the large number of physical processes governing cloud formation and evolution as well as the great complexity of their interactions." Hence, they conclude that through repeated critical evaluations of the type they conducted, "the scientific community will be forced to develop further physically sound parameterizations that *ultimately* [our italics] result in models that are capable of simulating our climate system with increasing realism." Until that time (indeed, until climate simulations can be done, not with *increasing* realism, but with *true* realism), we suggest that it is not wise to put much credence in what these admittedly inadequate state-of-the-art GCMs suggest about the future; and to actually *mandate* drastic reductions in fossil-fuel energy use on the basis of what these models currently suggest can only be described as downright foolish.

In an effort to assess the status of state-of-the-art climate models in simulating cloud-related processes, Zhang *et al*. (2005) compared basic cloud climatologies derived from ten atmospheric GCMs with satellite measurements obtained from the International Satellite Cloud Climatology Project (ISCCP) and the Clouds and Earth's Radiant Energy System (CERES) program. ISCCP data were available from 1983 to 2001, while data from the CERES program were available for the winter months of 2001 and 2002 and for the summer months of 2000 and 2001. The purpose of their analysis was two-fold: (1) to assess the current status of climate models in simulating clouds so that future progress can be measured more objectively, and (2) to reveal serious deficiencies in the models so as to improve them.

The work of the *twenty additional climate modelers* involved in this exercise reveals a huge list of major model imperfections. First, Zhang *et al*. report a four-fold difference in high clouds among the models, and that the majority of the models only simulated 30-40% of the observed middle clouds, with some models simulating less than a quarter of observed middle clouds. For low clouds, they report that half the models underestimated them, such that the grand mean of low clouds from all models was only 70-80% of what was observed. Furthermore, when stratified in optical thickness ranges, the majority of the models simulated optically thick clouds more than twice as frequently as was found to be the case in the satellite observations, while the grand mean of all models simulated about 80% of optically intermediate clouds and 60% of optically thin clouds. And in the case of *individual* cloud types, the group of researchers reports that "differences of seasonal amplitudes among the models and satellite measurements can reach several hundred percent." As a result of these and other observations, Zhang *et al*. conclude that "much more needs to be done to fully understand the physical causes of model cloud biases presented here and to improve the models." We agree, especially since the deficiencies they discovered have relevance to model predictions of CO_2-induced global warming.

Next, L'Ecuyer and Stephens (2007) used multi-sensor observations of visible, infrared and microwave radiance obtained from the Tropical Rainfall Measuring Mission satellite for the period running from 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 sea surface temperature 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 Intergovernmental Panel on Climate Change's most recent Fourth Assessment Report. 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."

Results indicated that "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 found that "the intermodel variability in the responses of precipitation, total heating, and vertical motion is 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 reported that "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." As a result of these much-less-than-adequate findings, the two researchers from Colorado State University's Department of Atmospheric Science conclude that "deficiencies remain in the representation of relationships between radiation, clouds, and precipitation in current climate models," and they say that these deficiencies "cannot be ignored when interpreting their predictions of future climate."

In one final paper, published in the *Journal of the Atmospheric Sciences*, Zhou *et al*. (2007) state that "clouds and precipitation play key roles in linking the earth's energy cycle and water cycles," noting that "the sensitivity of deep convective cloud systems and their associated precipitation efficiency in response to climate change are key factors in predicting the future climate." They also report that *cloud resolving models* or CRMs "have become one of the primary tools to develop the physical parameterizations of moist and other subgrid-scale processes in global circulation and climate models," and that CRMs could someday be used in place of traditional cloud parameterizations in such models.

In this regard, the authors note that "CRMs still need parameterizations on scales smaller than their grid resolutions and have many known and unknown deficiencies." To help stimulate progress in these areas, therefore, the nine scientists compared the cloud and precipitation properties observed from the Clouds and the Earth's Radiant Energy System (CERES) and Tropical Rainfall Measuring Mission (TRMM) instruments 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.

So what did the researchers learn from these efforts? Zhou *et al*. report that: (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, that (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 light of these several significant findings, it is clear that CRMs still have a long way to go before they are ready for "prime time" in the complex quest to properly assess the roles of *various types of clouds* and *forms of precipitation* in the future evolution of earth's climate in response to variations in numerous anthropogenic and background forcings. This evaluation is not meant to denigrate the CRMs in any way; it is merely done to indicate that the climate modeling enterprise is not yet at the stage where implicit faith should be placed in what it *currently* suggests about earth's climatic response to the ongoing rise in the air's CO_2 content.

In conclusion, there is absolutely no question but that the set of problems that currently restricts our ability to properly model a whole suite of cloud-related processes likewise restricts our ability to simulate future climate with any degree of confidence in the accuracy of the results.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/m/inadeqclouds.php.

References

Ayers, G.P. and Gillett, R.W. 2000. DMS and its oxidation products in the remote marine atmosphere: implications for climate and atmospheric chemistry. *Journal of Sea Research* **43**: 275-286.

Charlson, R.J., Lovelock, J.E., Andrea, M.O. and Warren, S.G. 1987. Oceanic phytoplankton, atmospheric sulfur, cloud albedo and climate. *Nature* **326**: 655-661.

Chou, M.-D., Lindzen, R.S. and Hou, A.Y. 2002. Reply to: "Tropical cirrus and water vapor: an effective Earth infrared iris feedback?" *Atmospheric Chemistry and Physics* **2**: 99-101.

Fu, Q., Baker, M. and Hartmann, D.L. 2002. Tropical cirrus and water vapor: an effective Earth infrared iris feedback? *Atmospheric Chemistry and Physics* **2**: 31-37.

Gordon, C.T., Rosati, A. and Gudgel, R. 2000. Tropical sensitivity of a coupled model to specified ISCCP low clouds. *Journal of Climate* **13**: 2239-2260.

Grabowski, W.W. 2000. Cloud microphysics and the tropical climate: Cloud-resolving model perspective. *Journal of Climate* **13**: 2306-2322.

Grassl, H. 2000. Status and improvements of coupled general circulation models. *Science* **288**: 1991-1997.

Groisman, P.Ya., Bradley, R.S. and Sun, B. 2000. The relationship of cloud cover to near-surface temperature and humidity: Comparison of GCM simulations with empirical data. *Journal of Climate* **13**: 1858-1878.

Harries, J.E. 2000. Physics of the earth's radiative energy balance. *Contemporary Physics* **41**: 309-322.

Hartmann, D.L. and Michelsen, M.L. 2002. No evidence for IRIS. *Bulletin of the American Meteorological Society* **83**: 249-254.

Idso, S.B. 1990. A role for soil microbes in moderating the carbon dioxide greenhouse effect? *Soil Science* **149**: 179-180.

Lane, D.E., Somerville, R.C.J. and Iacobellis, S.F. 2000. Sensitivity of cloud and radiation parameterizations to changes in vertical resolution. *Journal of Climate* **13**: 915-922.

L'Ecuyer, T.S. and Stephens, G.L. 2007. The tropical atmospheric energy budget from the TRMM perspective. Part II: Evaluating GCM representations of the sensitivity of regional energy and water cycles to the 1998-99 ENSO cycle. *Journal of Climate* **20**: 4548-4571.

Lindzen, R.S., Chou, M.-D. and Hou, A.Y. 2001. Does the earth have an adaptive infrared iris? *Bulletin of the American Meteorological Society* **82**: 417-432.

O'Dowd, C.D., Facchini, M.C., Cavalli, F., Ceburnis, D., Mircea, M., Decesari, S., Fuzzi, S., Yoon, Y.J. and Putaud, J.-P. 2004. Biogenically driven organic contribution to marine aerosol. *Nature* **431**: 676-680.

Randall, D., Khairoutdinov, M. Arakawa, A. and Grabowski, W. 2003. Breaking the cloud parameterization deadlock. *Bulletin of the American Meteorological Society* **84**: 1547-1564.

Siebesma, A.P., Jakob, C., Lenderink, G., Neggers, R.A.J., Teixeira, J., van Meijgaard, E., Calvo, J., Chlond, A., Grenier, H., Jones, C., Kohler, M., Kitagawa, H., Marquet, P., Lock, A.P., Muller, F., Olmeda, D. and Severijns, C. 2004. Cloud representation in general-circulation models over the northern Pacific Ocean: A EUROCS intercomparison study. *Quarterly Journal of the Royal Meteorological Society* **130**: 3245-3267.

Zhang, M.H., Lin, W.Y., Klein, S.A., Bacmeister, J.T., Bony, S., Cederwall, R.T., Del Genio, A.D., Hack, J.J., Loeb, N.G., Lohmann, U., Minnis, P., Musat, I., Pincus, R., Stier, P., Suarez, M.J., Webb, M.J., Wu, J.B., Xie, S.C., Yao, M.-S. and Yang, J.H. 2005. Comparing clouds and their seasonal variations in 10 atmospheric general circulation models with satellite measurements. *Journal of Geophysical Research* **110**: D15S02, doi:10.1029/2004JD005021.

Zhou, Y.P., Tao, W.-K., Hou, A.Y., Olson, W.S., Shie, C.-L., Lau, K.-M., Chou, M.-D., Lin, X. and Grecu, M. 2007. Use of high-resolution satellite observations to evaluate cloud and precipitation statistics from cloud-resolving model simulations. Part I: South China Sea monsoon experiment. *Journal of the Atmospheric Sciences* **64**: 4309-4329.

1.3. Precipitation

One of the basic predictions of atmospheric general circulation models (GCMs) is that the planet's hydrologic cycle will intensify as the world warms, leading to an increase in both the frequency and intensity of extreme precipitation events. In an early review of the subject, Walsh and Pittock (1998) reported "there is some evidence from climate model studies that, in a warmer climate, rainfall events will be more intense," and that "there is considerable evidence that the frequency of extreme rainfall events may increase in the tropics." Upon further study, however, they were forced to conclude that "because of the insufficient resolution of climate models and their generally crude representation of sub-grid scale and convective processes, little confidence can be placed in any definite predictions of such effects."

Two years later, Lebel *et al*. (2000) compared rainfall simulations produced by a GCM with real-world observations from West Africa for the period 1960-1990. Their analysis revealed that the model output was affected by a number of temporal and spatial biases that led to significant differences between observed and modeled data. The simulated rainfall totals, for example, were significantly greater than what was typically observed, exceeding real-world values by 25% during the dry season and 75% during the rainy season. In addition, the seasonal cycle of precipitation was not well simulated, as the researchers found that the simulated rainy season began too early and that the increase in precipitation was not rapid enough. Shortcomings were also evident in the GCM's inability to accurately simulate convective rainfall events, as it typically predicted far too much precipitation. Furthermore, it was found that "interannual variability [was] seriously disturbed in the GCM as compared to what it [was] in the observations." As for *why* the GCM performed so poorly in these several respects, Lebel *et al*. gave two main reasons. They said the parameterization of rainfall processes in the GCM was much too simple and that the spatial resolution was much too coarse.

Following the passage of an additional three years, Woodhouse (2003) generated a tree-ring-based history of snow water equivalent (SWE) characteristic of the first day of April for each year of the period 1569-1999 for the drainage basin of the Gunnison River of western Colorado, USA. Then, because "an understanding of the long-term characteristics of snowpack variability is useful for guiding expectations for future variability," as she phrased it, she analyzed the reconstructed SWE data in such a way as to determine if there was there anything unusual about the SWE record of the 20th century, which hundred-year period is claimed by climate alarmists to have experienced a warming that was *unprecedented over the past two millennia*.

So did Woodhouse find anything unusual? Yes, she did. She found that "the twentieth century is notable for several periods that *lack* [our italics] extreme years." Specifically, she determined that "the twentieth century is notable for several periods that contain few or no extreme years, for both low and high SWE extremes," and she reports that "the twentieth century also contains the lowest percent of extreme low SWE years." These results, of course, are in direct contradiction of what state-of-the-art GCMs typically predict should occur in response to global warming; and their failure in this regard is especially damning, knowing it occurred during a period of global warming that is said by many have been the most significant of the past 20 centuries.

Two years later, and as a result of the fact that the 2004 summer monsoon season of India experienced a 13% precipitation deficit that was not predicted by any of the empirical or dynamical models regularly used in making rainfall forecasts, Gadgil *et al*. (2005) performed an historical analysis of the models' forecast skill over the period 1932-2004. Interestingly, and despite numerous model advancements and an ever-improving understanding of monsoon variability, they found that the models' skill in forecasting the Indian monsoon's characteristics had not improved since the very first versions of the models were applied to the task some seven decades earlier.

In the case of the empirical models Gadgil *et al*. evaluated, large differences were generally observed between monsoon rainfall measurements and model predictions. In addition, the models often failed to correctly predict even the *sign* of the precipitation anomaly, frequently predicting excess rainfall when drought occurred and drought when excess rainfall was received.

The dynamical models fared even worse. In comparing observed monsoon rainfall totals with simulated values obtained from 20 state-of-the-art GCMs and a supposedly superior coupled atmosphere-ocean model, Gadgil *et al*. report that not a single one of these many models was able "to simulate correctly the interannual variation of the summer monsoon rainfall over the Indian region." And as with the empirical models, the dynamical models also frequently failed to correctly capture even the *sign* of the observed rainfall anomalies. In addition, the researchers report that Brankovic and Molteni (2004) attempted to model the Indian monsoon with a much higher-resolution GCM, but that its output *also* proved to be "not realistic."

Consequently, and in spite of the *billions of dollars* that have been spent by the United States alone on developing and improving climate models, taxpayers have achieved essentially *no return on their investment* in terms of the models' ability to correctly simulate one of the largest and most regionally-important of earth's atmospheric phenomena -- the tropical Indian monsoon. After more than *70 years* of trying to remake the models into better predictive tools, one would surely have expected *some* improvement in this regard, even if only by *accident*. That there has been absolutely *none* is a sad commentary indeed on the state of the climate modeling enterprise.

Advancing one more year in time, Lau *et al*. (2006) considered the Sahel drought of the 1970s-90s to provide "an ideal test bed for evaluating the capability of CGCMs [coupled general circulation models] in simulating long-term drought, and the veracity of the models' representation of coupled atmosphere-ocean-land processes and their interactions." Hence, they decided to "explore the roles of sea surface temperature coupling and land surface processes in producing the Sahel drought in CGCMs that participated in the twentieth-century coupled climate simulations of the Intergovernmental Panel on Climate Change [IPCC] Assessment Report 4," in which the 19 CGCMs "are driven by combinations of realistic prescribed external forcing, including anthropogenic increase in greenhouse gases and sulfate aerosols, long-term variation in solar radiation, and volcanic eruptions."

In performing this analysis, the climate scientists found, in their words, that "only eight models produce a reasonable Sahel drought signal, seven models produce excessive rainfall over [the] Sahel during the observed drought period, and four models show no significant deviation from normal." In addition, they report that "even the model with the highest skill for the Sahel drought could only simulate the increasing trend of severe drought events but not the magnitude, nor the beginning time and duration of the events." Consequently, since all 19 of the CGCMs employed in the IPCC's Fourth Assessment Report failed to adequately simulate the basic characteristics of "one of the most pronounced signals of climate change" of the past century -- as defined by its start date, severity and duration -- the results of this "ideal test" for evaluating the models' capacity for accurately simulating "long-term drought" and "coupled atmosphere-ocean-land processes and their interactions" would almost *mandate* that it would be unwise to rely on their output as a guide to the future, especially when the tested models were "driven by combinations of realistic prescribed external forcing" and they *still* could not properly simulate the past.

During the following year of 2007, a number of other pertinent papers appeared. In an intriguing report in *Science*, Wentz *et al*. (2007) noted that the Coupled Model Intercomparison Project, as well as various climate modeling analyses, predicted an increase in precipitation on the order of one to three percent per °C of surface global warming. Hence, they decided to see what had happened in the real world in this regard over the prior 19 years (1987-2006) of supposedly *unprecedented global warming*, when data from the Global Historical Climatology Network and satellite measurements of the lower troposphere indicated there had been a global temperature rise on the order of 0.20°C per decade.

Using satellite observations obtained from the Special Sensor Microwave Imager (SSM/I), the four *Remote Sensing Systems* scientists derived precipitation trends for the world's oceans over this period; and using data obtained from the Global Precipitation Climatology Project that were acquired from both satellite and rain gauge measurements, they derived precipitation trends for earth's continents. Appropriately combining the results of these two endeavors, they derived a real-world increase in precipitation on the order of 7% per °C of surface global warming, which is somewhere between 2.3 and 7 times *larger* than what is predicted by state-of-the-art climate models.

How was this horrendous discrepancy to be resolved?

Based on theoretical considerations, Wentz *et al*. concluded that the only way to bring the two results into harmony with each other was for there to have been a 19-year *decline* in global wind speeds. But when looking at the past 19 years of SSM/I wind retrievals, they found just the *opposite*, i.e., an *increase* in global wind speeds. In quantitative terms, in fact, the two results were about *as opposite as they could possibly be*, as they report that "when averaged over the tropics from 30°S to 30°N, the winds increased by 0.04 m s^{-1} (0.6%) $decade^{-1}$, and over all oceans the increase was 0.08 m s^{-1} (1.0%) $decade^{-1}$," while global coupled ocean-atmosphere models or GCMs, in their words, "predict that the 1987-to-2006 warming should have been accompanied by a decrease in winds on the order of 0.8% $decade^{-1}$."

In discussing these results, Wentz *et al*. correctly state that "the reason for the discrepancy between the observational data and the GCMs is not clear." They also rightly state that this dramatic difference between the real world of nature and the virtual world of climate modeling "has enormous impact," concluding that the questions raised by the discrepancy "are far from being settled."

In another intriguing bit of research, Allan and Soden (2007) quantified trends in precipitation within ascending and descending branches of the planet's tropical circulation and compared their results with simulations of the present day and projections of future changes provided by up to 16 state-of-the-art climate models. The precipitation data for this analysis came from the Global Precipitation Climatology Project (GPCP) of Adler *et al*. (2003) and the Climate Prediction Center Merged Analysis of Precipitation (CMAP) data of Xie and Arkin (1998) for the period 1979-2006, while for the period 1987-2006 they came from the monthly mean intercalibrated Version 6 Special Sensor Microwave Imager (SSM/I) precipitation data described by Wentz *et al*. (2007).

So what did the researchers learn?

Allan and Soden report that "an emerging signal of rising precipitation trends in the ascending regions and decreasing trends in the descending regions are detected in the observational datasets," but that "these trends are substantially larger in magnitude than present-day simulations and projections into the 21st century," especially in the case of the descending regions. More specifically, they state that, for the tropics, "the GPCP trend is about 2-3 times larger than the model ensemble mean trend, consistent with previous findings (Wentz *et al*., 2007) and also supported by the analysis of Yu and Weller (2007)," who additionally contend that "observed increases of evaporation over the ocean are substantially greater than those simulated by climate models." What is more, Allan and Soden note that "observed precipitation changes over land also appear larger than model simulations over the 20th century (Zhang *et al*., 2007)."

What is one to make of this conflict between models and measurements?

Noting that the difference between the two "has important implications for future predictions of climate change," Allan and Soden say "the discrepancy cannot be explained by changes in the reanalysis fields used to subsample the observations but instead must relate to errors in the satellite data *or in the model parameterizations* [our italics]." This same dilemma was also faced by Wentz *et al*. (2007); and they too stated that the resolution of the issue "has enormous impact," but likewise concluded that the questions raised by the discrepancy "are far from being settled."

To us, the issue seems a bit less difficult. Given a choice between *model* ***simulations*** and *observational* ***reality***, we will cast our lot with the latter every chance we get. Granted, this choice implies a huge problem with the former. But why should that be a surprise to anyone? The earth, with its oceans and atmosphere, and its myriad life forms, is a most complex place; and to believe that we have condensed all of its many climate-related phenomena -- many of which are shrouded in mystery, and some of which may even remain undetected -- to a set of equations that rigorously define our climatic future in response to an increase in anthropogenic CO_2 emissions, seems to us to be irrational.

In one final paper from the same year, Lin (2007) states that "a good simulation of tropical mean climate by the climate models is a *prerequisite* [our italics] for their good simulations/predictions of tropical variabilities and global teleconnections," but that "unfortunately, the tropical mean climate has not been well simulated by the coupled general circulation models (CGCMs) *used for climate predictions and projections* [our italics]," noting that "most of the CGCMs produce a double-intertropical convergence zone (ITCZ) pattern," and acknowledging that "a synthetic view of the double-ITCZ problem is still elusive."

To explore the nature of this problem in greater depth, and to hopefully make some progress in resolving it, Lin analyzed tropical mean climate simulations of the 20-year period 1979-99 provided by 22 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) CGCMs, together with concurrent Atmospheric Model Intercomparison Project (AMIP) runs from 12 of them.

This work revealed, in Lin's words, that "most of the current state-of-the-art CGCMs have some degree of the double-ITCZ problem, which is characterized by excessive precipitation over much of the Tropics (e.g., Northern Hemisphere ITCZ, Southern Hemisphere SPCZ [South Pacific Convergence Zone], Maritime Continent, and equatorial Indian Ocean), and often associated with insufficient precipitation over the equatorial Pacific," as well as "overly strong trade winds, excessive LHF [latent heat flux], and insufficient SWF [shortwave flux], leading to significant cold SST (sea surface temperature) bias in much of the tropical oceans," while additionally noting that "most of the models also simulate insufficient latitudinal asymmetry in precipitation and SST over the eastern Pacific and Atlantic Oceans," *further* stating that "the AMIP runs also produce excessive precipitation over much of the Tropics including the equatorial Pacific, which also leads to overly strong trade winds, excessive LHF, and insufficient SWF," which suggests that "the excessive tropical precipitation is an intrinsic error of the atmospheric models." And if that is not enough, Lin adds that "over the eastern Pacific stratus region, most of the models produce insufficient stratus-SST feedback associated with insufficient sensitivity of stratus cloud amount to SST."

With the solutions to *all* of these long-standing problems continuing to remain "elusive," and with Lin suggesting that the sought-for solutions are in fact *prerequisites* for "good simulations/predictions" of future climate, there is significant reason to conclude that current state-of-the-art CGCM predictions of CO_2-induced global warming ought not be considered all that reliable.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/p/precipmodelinadeq.php.

References

Adler, R.F. *et al*. 2003. The version-2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979-present). *Journal of Hydrometeorology* **4**: 1147-1167.

Allan, R.P. and Soden, B.J. 2007. Large discrepancy between observed and simulated precipitation trends in the ascending and descending branches of the tropical circulation. *Geophysical Research Letters* **34**: 10.1029/2007GL031460.

Brankovic, C. and Molteni, F. 2004. Seasonal climate and variability of the ECMWF ERA-40 model. *Climate Dynamics* **22**: 139-155.

Gadgil, S., Rajeevan, M. and Nanjundiah, R. 2005. Monsoon prediction - Why yet another failure? *Current Science* **88**: 1389-1400.

Idso, S.B. 1998. CO_2-induced global warming: a skeptic's view of potential climate change. *Climate Research* **10**: 69-82.

Lau, K.M., Shen, S.S.P., Kim, K.-M. and Wang, H. 2006. A multimodel study of the twentieth-century simulations of Sahel drought from the 1970s to 1990s. *Journal of Geophysical Research* **111**: 10.1029/2005JD006281.

Lebel, T., Delclaux, F., Le Barbé and Polcher, J. 2000. From GCM scales to hydrological scales: rainfall variability in West Africa. *Stochastic Environmental Research and Risk Assessment* **14**: 275-295.

L'Ecuyer, T.S. and Stephens, G.L. 2007. The tropical atmospheric energy budget from the TRMM perspective. Part II: Evaluating GCM representations of the sensitivity of regional energy and water cycles to the 1998-99 ENSO cycle. *Journal of Climate* **20**: 4548-4571.

Lin, J.-L. 2007. The double-ITCZ problem in IPCC AR4 coupled GCMs: Ocean-atmosphere feedback analysis. *Journal of Climate* **20**: 4497-4525.

Walsh, K. and Pittock, A.B. 1998. Potential changes in tropical storms, hurricanes, and extreme rainfall events as a result of climate change. *Climatic Change* **39**: 199-213.

Wentz, F.J., Ricciardulli, L., Hilburn, K. and Mears, C. 2007. How much more rain will global warming bring? *Science* **317**: 233-235.

Woodhouse, C.A. 2003. A 431-yr reconstruction of western Colorado snowpack from tree rings. *Journal of Climate* **16**: 1551-1561.

Xie, P. and Arkin, P.A. 1998. Global monthly precipitation estimates from satellite-observed outgoing longwave radiation. *Journal of Climate* **11**: 137-164.

Yu, L. and Weller, R.A. 2007. Objectively analyzed air-sea heat fluxes for the global ice-free oceans (1981-2005). *Bulletin of the American Meteorological Society* **88**: 527-539.

Zhang, X. *et al*. 2007. Detection of human influence on twentieth-century precipitation trends. *Nature* **448**: 461-465.