CLOUD COVER AND CLIMATE CHANGE

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Understanding how clouds respond to anthropogenic-induced perturbations of our planet's atmosphere is of paramount importance in determining the impact of the ongoing rise in the air's CO_2 content on global climate; for as Charlson *et al.* (2001) have noted, "man-made aerosols have a strong influence on cloud albedo, with a global mean forcing estimated to be of the same order (but opposite in sign) as that of greenhouse gases." And because of the great importance of this complex subject, this summary presents a brief review of a number of scientific papers that address various aspects of this crucial issue.

Ferek *et al.* (1998)[1] determined that cloud condensation nuclei in the airborne effluents of ships off the west coast of the United States were responsible for producing *ship tracks*, i.e., brighter and more persistent streaks in the overlying layer of natural and less-reflective cloud, both of which alterations create a cooling influence during daylight hours. Likewise, based on what is known about the properties of the aerosols responsible for *jet aircraft contrails*, Meerkotter *et al.* (1999)[2] suggested that the presence of such contrails tends to cool the earth's surface during daylight hours but warm it at night. And they also noted that aircraft emissions may cause *additional* indirect climate forcing by changing the particle size of natural cirrus clouds, concluding that "this indirect forcing may be comparable to the direct forcing due to additional contrail cloud cover."

The estimated cooling power of these aerosols – which they said was generally believed to be equivalent to the strength of the warming effect of all anthropogenic greenhouse gases – may actually be too conservative.

On the other hand, Boucher (1999)[3] and Nakanishi *et al.* (2001)[4] both noted that aircraft-induced increases in high-cloud amount may *also* have a *warming* effect, although Charlson *et*

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[1] http://www.co2science.org/articles/V1/N7/C1.php.
[2] http://www.co2science.org/articles/V3/N1/C2.php.
[3] http://www.co2science.org/articles/V2/N4/C1.php.
[4] http://www.co2science.org/articles/V4/N28/C2.php.

_al. (2001)_[5] have contended that the _net_ effect of _all_ anthropogenic-produced aerosols _averaged over the entire world_ is one of _cooling_. Furthermore, they noted that the estimated cooling power of these aerosols - which they said was generally believed to be equivalent to the strength of the warming effect of all anthropogenic greenhouse gases - may actually be too conservative.

During this same general time period, Facchini _et al._ (1999)[6] studied the effects of atmospheric solutes collected from cloud water in the Po Valley of Italy, finding that water vapor was more likely to form on its organic-solute-affected aerosols of lower surface tension - as opposed to the less-organic-solute-affected aerosols of the natural environment with their higher surface tension - creating more and smaller (and, therefore, more-highly-reflective) cloud droplets, which, of course, tend to cool the local environment. They also observed that the organic fractions and concentrations of the aerosols they studied were similar to those found in air downwind of other large agricultural/industrial regions, hinting at the likely widespread occurrence of this human-induced cooling influence.

Studying this phenomenon several years earlier, Kulmala _et al._ (1993) had additionally noted that "it is likely that the smaller droplet size will decrease precipitation so that the clouds will have a longer lifetime." In addition, their observation that "cloud formation can take place at smaller saturation ratios of water vapor" in the presence of organic-solute-affected aerosols suggests that clouds will be able to form at

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earlier times and in places where they would not otherwise form. In response to this particular type of anthropogenic effluent, therefore, cloud lifetimes expand at both ends of their existence spectrum - they are born earlier and die later (so to speak) - and, in imitation of the starship Enterprise, they are able to grow where no clouds have grown before.

How significant are these phenomena? Leaitch _et al._ (1992) concluded that the increased radiative cooling power due to just the increase in cloud albedo that results from pollution-

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[5] http://www.co2science.org/articles/V4/N31/EDIT.php.
[6] http://www.co2science.org/articles/V2/N19/C3.php.

induced increases in cloud droplet concentration averages about 2 Wm^{-2} over North America, which is about half the radiative warming power that is typically predicted to accompany a nominal doubling of the air's CO_2 content. Nowadays, therefore, and adding the impact of increased cloud cover, the overall effect would likely be considerably greater.

In another study of the climatic implications of anthropogenic-produced aerosols, Satheesh and Ramanathan (2000)[7] measured the clear-sky radiative consequences of the December-to-April northeastern low-level monsoonal flow of air that transports sulphates, nitrates, organics, soot and fly ash (among other anthropogenically-produced substances) from the Indian sub-continent and southern Asia thousands of kilometers over the entire north Indian Ocean and as far south as 10°S latitude. And in doing so, they found that the "mean clear-sky solar radiative heating for the winters of 1998 and 1999 decreased at the ocean surface by 12 to 30 Wm^{-2}," which Schwartz and Buseck (2000) indicate is "three to seven times as great as global average longwave (infrared) radiative forcing by increases in greenhouse gases over the industrial period ... but opposite in sign."

This finding, however, was somewhat tempered by the study of Ackerman *et al*. (2000), who suggested that the large cooling effect was likely counterbalanced by a simultaneous reduction in cloud cover. But the very next year, in an analysis of a long-term study of real-world data, Norris (2001)[8] proved this suggestion to be wrong, thereby reaffirming the overall implications of the results of Satheesh and Ramanathan. Norris' reasoning was that if the conclusion of Ackerman *et al*. was correct, the great increase in anthropogenic aerosol emissions from southern and southeast Asia over the last half-century should have significantly decreased the low-level cloud cover over the northern Indian Ocean over this period. A test of this idea with data from the Extended Edited Cloud Report Archive, however, revealed that daytime low-level cloud cover over this part of the world not only did not decrease over the last half-century, it *increased* ... and it did so in both the Northern and Southern Hemispheric regions of the study area and at essentially all hours of the day.

In a somewhat similar study, Croke *et al*. (1999)[9] determined that the mean cloud cover of three regions of the United States (coastal southwest, coastal northeast and southern plains) rose from 35% to 47% from 1900 to 1987, while global mean air temperature rose by approximately 0.5°C. Likewise, Chernykh *et al*. (2001)[10] determined that global cloud cover rose by nearly 6% between 1964 and 1998; and these observations suggest that the earth's hydrologic cycle does indeed tend to moderate the thermal effects of any impetus for warming and, as noted by the latter authors, is "consistent with the decrease in diurnal temperature range evident over most of the globe," which tends to make for a more stable natural environment.

Another way by which clouds tend to stabilize earth's climate was suggested by Sud *et al*. (1999)[11]. Based on data from the Tropical Ocean Global Atmosphere Coupled Ocean-

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[7] http://www.co2science.org/articles/V3/N11/EDIT.php.
[8] http://www.co2science.org/articles/V4/N43/C3.php.
[9] http://www.co2science.org/articles/V2/N19/C2.php.
[10] http://www.co2science.org/articles/V4/N38/C1.php.
[11] http://www.co2science.org/articles/V2/N24/C2.php.

Atmosphere Response Experiment, these investigators found that deep convection in the tropics acts as a thermostat to keep sea surface temperature (SST) vacillating over a rather narrow range. Starting at the low end of the range, the tropical ocean acts as a net receiver of energy, and it warms. Soon thereafter, however, the cloud-base airmass is charged with the moist static energy needed for clouds to reach the upper troposphere; and the cloud cover thus formed reduces the amount of solar radiation received at the sea surface, while its cool and dry downdrafts also tend to promote surface cooling. And this "thermostat-like control," as Sud *et al*. put it, tends to "ventilate the tropical ocean efficiently and help contain the SST between 28-30°C." Presumably, it would also act to keep any CO_2-induced warming below the same upper bound.

Yet another way in which tropical ocean temperatures may be constrained by cloud-mediated phenomena has been described by Lindzen *et al*. (2001)[12]. Based on upper-level cloudiness data obtained from the Japanese Geostationary Meteorological Satellite and SST data obtained from the National Centers for Environmental Protection, these researchers determined that the cloudy moist region of the eastern part of the tropical western Pacific "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." Indeed, the strong inverse relationship they found between upper-level cloud area and mean SST was determined to be sufficient to "more than cancel all the positive feedbacks in the more sensitive current climate models," which, of course, are the ones that are used to predict the consequences of projected increases in the air's CO_2 content.

Earth's plant life also plays an important role in stabilizing climate. The pioneering paper of Charlson *et al*. (1987), for example, describes how an initial SST increase leads to increased phytoplanktonic productivity in earth's oceans, which leads to a greater sea-to-air flux of dimethyl sulfide (DMS), which undergoes a gas-to-particle conversion that leads to greater numbers of cloud condensation nuclei that create more and brighter clouds that reflect more incoming solar radiation back to space, thereby countering the initial impetus for warming. Subsequently, Ayers and Gillett (2000)[13] reviewed what had been learned in the following years, concluding that "major links in the feedback chain proposed by Charlson *et al*. (1987) have a sound physical basis," additionally noting 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." And additional support for the powerful negative feedback loop has been provided by Simo and Pedros-Alio (1999)[14], who studied the effect of the depth of the surface mixing-layer on DMS production.

Although real-world studies thus continue to elucidate the workings of the planet's complex climate system and improve our understanding of it, there continue to be major problems with computer models that attempt to mimic it. Groisman *et al*. (2000)[15], for example, evaluated the ability of a number of climate models to reproduce mean daily cloud-temperature relations at

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[12] http://www.co2science.org/articles/V4/N12/C2.php.

[13] http://www.co2science.org/articles/V4/N7/C2.php.

[14] http://www.co2science.org/articles/V3/N2/C2.php.

[15] http://www.co2science.org/articles/V3/N14/C2.php.

different times of year. Although most models did a good job in the cold part of the year, they noted that "large discrepancies between empirical data and some models are found for summer conditions." In fact, the overall cloud effect on summer near-surface air temperature computed by one of the models was of even the wrong sign!

In another study, Gordon et al. (2000)[16] examined the response of a coupled general circulation model of the atmosphere to quasi-realistic specified marine stratocumulus clouds and compared the results to what they obtained from their model when operating in its normal mode, which fails to adequately express the presence of the clouds and their effects. And what were the consequences of this failure? When they removed the low clouds, *as occurs in the model's normal application*, the sea surface temperature warmed by fully 5.5°C.

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Two years later, two data-based studies published in *Science* - Chen *et al*. (2002) and 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 Chen *et al*. and Wielicki *et al*. 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; 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.

These changes were highly significant. The measured thermal radiative energy loss at the top of the tropical atmosphere, for example, was of the same magnitude as the thermal radiative energy gain that is generally predicted for an instantaneous doubling of the air's CO_2 content. Yet as Hartman correctly noted, "only very small changes in average tropical surface temperature were observed during this time." So what went wrong? Or as one could more correctly phrase the question, what went right?

One thing, of course, was the competing 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

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[16] http://www.co2science.org/articles/V3/N18/C2.php.

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, which was recently reported by McPhaden and Zhang (2002). This 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 all of these observations have to do with evaluating the ability of climate models to correctly predict the future? For one thing - and one very *important* 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, for example, 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, in other words, why should we believe anything else they tell us?

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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. And how did the models do? The results were absolutely *pathetic*. No significant decadal variability was exhibited by *any* of the models; and they *all* were unable to reproduce even the cyclical seasonal change in tropical albedo. Thus, the administrators of the test 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, however, was a little more candid in his scoring of the test, saying it simply indicated that "the models are deficient." And amplifying this assessment just a bit, he noted that "if the energy budget can vary substantially in the absence of obvious forcing," as it well did over the prior 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."

Contemporaneously, Fu *et al*. (2002)[17] - like Hartmann and Michelsen (2002) - continued to chip away at the *adaptive infrared iris* concept of Lindzen *et al*. (2001), 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 are overestimated by Lindzen *et al*. by at least 60% and 33%, respectively. And as a result, they obtained a feedback factor in the

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[17]   http://www.co2science.org/articles/V5/N44/C2.php.

range of -0.15 to -0.51, compared to Lindzen *et al*.'s larger negative feedback factor of -0.45 to -1.03." However, Chou *et al*. (2002) replied that Fu *et al*.'s approach of specifying longwave emission and cloud albedos "appears to be inappropriate for studying the iris effect," stating that from the point of view that "thin cirrus are widespread in the tropics and that 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." They ultimately agreed, however, that Lindzen *et al*. "may indeed have overestimated the iris effect somewhat, though hardly by as much as that suggested by [Fu *et al*.]."

Moving ahead another two years, Minnis *et al*. (2004)[18] analyzed surface-based measurements of cirrus coverage (CC) for different parts of the world for the period 1971-1995, while employing similar measurements obtained from the International Satellite Cloud Climatology Project (ISCCP) for 1984-1996 as a consistency check on them. The linear trends they derived from the data were then input to a relationship between changes in cirrus amount and surface temperature (derived from a general circulation model of the atmosphere) in order to calculate their climatic impact over the United States.

As a result of this exercise, Minnis *et al*. report that "values of CC increased over the United States, the North Atlantic and Pacific, and Japan, but dropped over most of Asia, Europe, Africa, and South America," making particular note of the fact that "the largest concentrated increases occurred over the northern Pacific and Atlantic and roughly correspond to the major air traffic routes." Their U.S. temperature assessment additionally indicated that "the cirrus trends over the United States are estimated to cause a tropospheric warming of 0.2°-0.3°C per decade, a range that includes the observed tropospheric temperature trend of 0.27°C per decade between 1975 and 1994." According to the researchers' results, therefore, it could be concluded that nearly all of the surface warming observed over the United States between 1975 and 1994, which they reported to be 0.54°C, may well have been due to aircraft-induced increases in cirrus cloud coverage over that period. And if true, this result would imply that *little to none* of the observed U.S. warming over that period could be attributed to the concomitant increase in the air's CO_2 content.

One year later, Harrison and Stephenson (2005)[19] reasoned that because the net global effect of cloud is cooling (Hartman, 1993), any widespread increase in the amount of overcast days could reduce air temperature globally, while local overcast conditions could do so locally. Thus, they compared the ratio of diffuse to total solar radiation - the *diffuse fraction* (DF) - which had been measured daily at 0900 UT at Whiteknights, Reading (UK) from 1997-2004, with the traditional subjective determination of cloud amount made simultaneously by a human observer, as well as with daily average temperature. Then, they compared the diffuse fraction measured at Jersey between 1968 and 1994 with corresponding daily mean neutron count rates measured at Climax, Colorado (USA), which provide a globally representative indicator of the galactic cosmic ray flux.

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[18]   http://www.co2science.org/articles/V7/N36/C1.php.
[19]   http://www.co2science.org/articles/V10/N2/C1.php.

This effort revealed that "across the UK, on days of high cosmic ray flux (above 3600×10^2 neutron counts per hour, which occur 87% of the time on average) compared with low cosmic ray flux, (i) the chance of an overcast day increases by 19% ± 4%, and (ii) the diffuse fraction increases by 2% ± 0.3%." In addition, they found that "during sudden transient reductions in cosmic rays (e.g. Forbush events), simultaneous decreases occur in the diffuse fraction," and they note that the latter of these observations indicates that diffuse radiation changes are, indeed, "unambiguously due to cosmic rays." They also report that "at Reading, the measured sensitivity of daily average temperatures to DF for overcast days is -0.2 K per 0.01 change in DR." And they thus suggest that the well-known inverse relationship between galactic cosmic rays and solar activity will lead to cooling at solar minima, and that "this might amplify the effect of the small solar cycle variation in total solar irradiance, believed to be underestimated by climate models (Stott *et al*., 2003) which neglect a cosmic ray effect." In addition, although the effect they detect is small, they say it is "statistically robust," and that the cosmic ray effect on clouds likely "will emerge on long time scales with less variability than the considerable variability of daily cloudiness."

Because the net global effect of cloud is cooling, any widespread increase in the amount of overcast days could reduce air temperature globally, while local overcast conditions could do so locally.

Inching yet another year closer to the present, the study of Palle *et al*. (2006)[20] made its appearance in the scientific literature. Using the most up-to-date cloud amount data from the International Satellite Cloud Climatology Project, and following the protocols of Palle *et al*. (2004), the four researchers derived globally-averaged albedo anomalies and related solar radiative forcing anomalies that were supposedly experienced by the earth over the prior two decades. In addition, they explored the impacts of observed changes in the amounts of low clouds and high plus mid-level clouds that occurred between 2000 and 2004 on *total* radiative forcing (solar plus thermal). Between 1985 and 2000, therefore, Palle *et al*. calculated that the flux of solar radiation absorbed by the earth-atmosphere system rose by about 8 Wm^{-2} in response to an observed decline in total cloud amount.

Thereafter, however, total cloud amount began to *rise*; but because of a concomitant redistribution of cloud types (an increase in high and mid-level clouds that tend to warm the planet, and a decrease in low level clouds that tend to cool the planet), they concluded that the positive radiative forcing trend experienced between 1985 and 2000 may have continued to the time of the writing of their paper, even in the face of an increasing total cloud amount. And if it

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[20]   http://www.co2science.org/articles/V9/N5/C2.php.

had so contributed, and if it had continued at the rate established between 1985 and 2000, it could well have added another 3 Wm^{-2} to the total increase in radiative forcing experienced between 1985 and 2000.

Finally, Palle *et al*. note that the increase in radiative forcing produced by the concentration increases experienced by *all greenhouse gases since 1850* was something on the order of only 2.5 Wm^{-2}. Compared to the increase in radiative forcing that may have been experienced between 1985 and 2005 as a result of observed changes in total cloud amount and the fractions of clouds located at different elevations (~11 Wm^{-2}, according to the data and analyses of Palle *et al*.), the concomitant *20-year* change in radiative forcing due to *CO_2 alone* would have had to have been truly *miniscule*, which suggests that all of the angst manifest by climate alarmists over anthropogenic CO_2 emissions may be *wholly misplaced*. And if a radiative forcing on the order of 11 Wm^{-2} only raised mean global air temperature by *a fraction of a degree*, as occurred between 1985 and 2005, it would appear that earth's climate is *much* less responsive to changes in radiative forcing than the world's climate alarmists and most climate modelers claim it to be.

Last of all, and based on approximately 185 million synoptic weather observations obtained from some 5400 stations worldwide, covering all continents and many islands, Warren *et al*. (2007)[21] developed separate day and night histories of cloud amount for nine different cloud types for the 26-year period 1971-1996. This work revealed, in their words, that "there are large regional changes in cloud-type amounts, and significant changes in the global averages of some cloud types." More specifically, they say that "the time series of total-cloud-cover anomalies for individual continents show a large decrease for South America, small decreases for Eurasia and Africa, and no trend for North America." They also state that "the zonal average trends of total cloud cover are positive in the Arctic winter and spring, 60°-80°N, but negative in all seasons at most other latitudes." In addition, they state that "night trends agree with day trends for total cloud cover and for all cloud types except cumulus," and that "cirrus trends are generally negative over all continents." *However*, they find that all of these changes "compensate each other to result in only a small trend of global average land cloud cover, -0.7% decade^{-1}." What is more, they note that "this small negative trend is further compensated by a small positive trend over the ocean of +0.4% decade^{-1} (Norris, 1999), resulting in almost no trend for global average cloud cover over the past few decades."

Although Warren *et al*. readily acknowledge the great significance of changes in cloud type and amount for global and regional climate change and vice versa, they do not speculate on the climatic implications of their specific findings, noting that "it will be important to prepare cloud datasets for the more recent years [post 1996], when changes may become more noticeable with increased global warming." But, as is now known, there has been no net warming of the planet since about 1998.

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[21] http://www.co2science.org/articles/V10/N17/C1.php.

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