2. FEEDBACK FACTORS

As reported in the Technical Support Document to the ANPR, the sensitivity of earth's climate system to a doubling of pre-industrial CO_2 is somewhere in the range of 1.5 to 4.5°C, with a most likely value of 3°C. However numerous scientific studies suggest this model-derived sensitivity is far too large and that feedbacks in the climate system reduce it to values that are an *order of magnitude* smaller. In this next chapter, we review some of those feedbacks predominately mentioned in the literature, some of which have the ability to *totally offset* the radiative forcing expected from the rise in atmospheric CO_2.

Additional information on this topic, including reviews of feedback factors not discussed here, can be found at http://www.co2science.org/subject/f/subject_f.php under the heading Feedback Factors.

2.1. Clouds

Based on data obtained from the Tropical Ocean Global Atmosphere - Coupled Ocean-Atmosphere Response Experiment, Sud *et al*. (1999) demonstrated that deep convection in the tropics acts as a thermostat to keep sea surface temperature (SST) vacillating between approximately 28 and 30°C. Their analysis suggests that as SSTs reach 28-29°C, the cloud-base airmass is charged with the moist static energy needed for clouds to reach the upper troposphere, at which point the cloud cover reduces the amount of solar radiation received at the surface of the sea, while cool and dry downdrafts promote ocean surface cooling by increasing sensible and latent heat fluxes there. This "thermostat-like control," as Sud *et al*. describe it, tends "to ventilate the tropical ocean efficiently and help contain the SST between 28-30°C." The phenomenon would also be expected to prevent SSTs from rising any higher in response to enhanced CO_2-induced radiative forcing.

Lindzen *et al*. (2001) used upper-level cloudiness data obtained from the Japanese Geostationary Meteorological Satellite and SST data obtained from the National Centers for Environmental Prediction to derive a strong inverse relationship between upper-level cloud area and the mean SST of cloudy regions of the eastern part of the western Pacific (30°S-30°N; 130°E-170°W), such that the area of cirrus cloud coverage normalized by a measure of the area of cumulus coverage decreases about 22% per degree C increase in the SST of the cloudy region. In describing this phenomenon, Lindzen *et al*. say "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." However, Hartmann and Michelsen (2002), in an analysis of spatial patterns of anomalous cloudiness and winds associated with the negative correlation between cloud-weighted SST and high-cloud fraction, claim that the correlation noted by Lindzen *et al*. results from variations in subtropical clouds that are not physically connected to deep convection near the equator, and that it is thus "unreasonable to interpret these changes as evidence that deep tropical convective anvils contract in response to SST increases."

In a contemporaneous study, Fu *et al*. (2002) continued to chip away at the *adaptive infrared iris* concept of Lindzen *et al*., 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." They also claim to show that "the water vapor and low cloud effects are overestimated [by Lindzen *et al*.] by at least 60% and 33%, respectively." As a result, they obtain a feedback factor "in the range of -0.15 to -0.51, compared to [Lindzen *et al*.'s] larger negative feedback factor of -0.45 to -1.03."

A year later, 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." Also, they say 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 agree that Lindzen *et al*. "may indeed have overestimated the iris effect somewhat, though hardly by as much as that suggested by [Fu *et al*.]."

The debate over the reality and/or magnitude of the *adaptive infrared iris effect* proposed by Lindzen *et al*. as a powerful means for thwarting CO_2-induced increases in the atmosphere's greenhouse effect continues apace. There has been some convergence in the two extreme views; but the controversy appears likely to continue for yet some time.

In a more straightforward study, Croke *et al*. (1999) used land-based observations of cloud cover for three regions of the United States (coastal southwest, coastal northeast, and southern plains) to demonstrate that, over the period 1900-1987, cloud cover had a high correlation with global air temperature, with mean cloud cover rising from an initial value of 35% to a final value of 47% as the mean global air temperature rose by 0.5°C. This phenomenon would again tend to counteract the effects of any impetus for warming.

In another study, Herman *et al*. (2001) used Total Ozone Mapping Spectrometer 380-nm reflectivity data to determine changes in radiation reflected back to space over the period 1979 to 1992, finding that "when the 11.3-year solar-cycle and ENSO effects are removed from the time series, the zonally averaged annual linear-fit trends show that there have been increases in reflectivity (cloudiness) poleward of 40°N and 30°S, with some smaller but significant changes occurring in the equatorial and lower middle latitudes." The overall long-term effect was an increase in radiation reflected back to space of 2.8 Wm^{-2} per decade, which represents a large cloud-induced cooling influence.

Last of all, Rosenfeld (2000) used satellite data obtained from the Tropical Rainfall Measuring Mission to look for terrestrial analogues of the cloud trails that form in the wakes of ships at sea as a consequence of their emissions of particulates that redistribute cloud-water into larger numbers of smaller droplets that do not rain out of the atmosphere as readily as they would in the absence of this phenomenon. Visualizations produced from the mission data clearly

revealed the existence of enhanced cloud trails downwind of urban and industrial complexes in Turkey, Canada and Australia, to which Rosenfeld gave the name *pollution tracks* in view of their similarity to *ship tracks*. Rosenfeld also demonstrated that the clouds comprising these pollution tracks were composed of droplets of reduced size that did indeed suppress precipitation by inhibiting further coalescence and ice precipitation formation. As Toon (2000) noted in a commentary on this study, these smaller droplets will not "rain out" as quickly and will therefore last longer and cover more of the earth, both of which effects tend to cool the globe.

In summation, as the earth warms, the atmosphere has a tendency to become more cloudy and exert a natural brake upon the rising temperature. Also, many of humanity's aerosol-producing activities tend to do the same thing. Hence, there appear to be a number of different ways in which cloud-mediated processes help the planet to "keep its cool," relatively speaking.

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

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2.2. Carbonyl Sulfide

Some time ago, Idso (1990) suggested that the volatilization of reduced sulfur gases from earth's soils may be just as important as dimethyl sulfide (DMS) emissions from the world's oceans in enhancing cloud albedo and thereby cooling the planet and providing a natural brake on the tendency for anthropogenically-enhanced greenhouse gases to drive global warming (see Dimethyl Sulfide above). On the basis of experiments that showed soil DMS emissions to be positively correlated with soil organic matter content, and noting that additions of organic matter to soils tend to increase the amount of sulfur gases they emit, Idso hypothesized that because atmospheric CO_2 enrichment augments plant growth and, as a result, vegetative inputs of organic matter to earth's soils, this phenomenon should produce an impetus for cooling, even in the absence of the surface warming that sets in motion the chain of events that produce the oceanic DMS-induced negative-feedback that tends to cool the planet.

Two years later, Idso (1992) expanded this concept to include another biologically-produced sulfur gas that is emitted from soils (carbonyl sulfide or OCS), noting that it too is likely to be emitted in increasingly greater quantities as earth's vegetation responds to the aerial fertilization effect of the ongoing rise in the air's CO_2 content, while pointing out that OCS is relatively inert in the troposphere, but that it eventually makes its way into the stratosphere, where it is transformed into solar-radiation-reflecting sulfate aerosol particles. He consequently concluded that the CO_2-induced augmentation of soil OCS emissions constitutes a mechanism that can cool the planet's surface (1) in the absence of an impetus for warming (2) without producing additional clouds or (3) making them any brighter.

So what have we subsequently learned about the latter of these two natural cooling phenomena, i.e., the one that involves biologically-mediated increases in carbonyl sulfide emissions? One important thing is that the OCS-induced cooling mechanism also operates at sea, just as the DMS-induced cooling mechanism does, and that it too possesses a warming-induced component in addition to its CO_2-induced component.

In a study contemporary with that of Idso (1992), ocean-surface OCS concentrations were demonstrated by Andreae and Ferek (1992) to be highly correlated with surface-water primary productivity. So strong is this correlation, in fact, that Erickson and Eaton (1993) developed an empirical model for computing ocean-surface OCS concentrations based solely on surface-water chlorophyll concentrations and values of incoming solar radiation. It has also been learned that an even greater portion of naturally-produced OCS is created in the atmosphere, where carbon disulfide and dimethyl sulfide - also largely of oceanic origin (Aydin *et al*., 2002) - undergo photochemical oxidation (Khalil and Rasmussen, 1984; Barnes *et al*., 1994). Hence, the majority of the tropospheric burden of OCS is ultimately dependent upon photosynthetic activity occurring near the surface of the world's oceans.

Why is this important? It is important because the tropospheric OCS concentration has risen by approximately 30% since the 1600s, from a mean value of 373 ppt over the period 1616-1694

to something on the order of 485 ppt today. This is a sizeable increase; and Aydin *et al*. (2002) note that only a fourth of it can be attributed to anthropogenic sources. Consequently, the rest of the observed OCS increase must have had a natural origin, a large portion of which must have ultimately been derived from the products and byproducts of marine photosynthetic activity, which must have increased substantially over the last three centuries. What is more, a solid case can be made for the proposition that both the increase in atmospheric CO_2 concentration and the increase in temperature experienced over this period were the driving forces for the concomitant increase in tropospheric OCS concentration and its likely subsequent transport to the stratosphere, where it could exert a cooling influence on the earth and that may have kept the warming of the globe considerably below what it might otherwise have been in the absence of this chain of events.

Another fascinating aspect of this multifaceted global "biothermostat" was revealed in a laboratory study of samples of the lichen *Ramalina menziesii*, which were collected from an open oak woodland in central California, USA, by Kuhn and Kesselmeier (2000). They found that when the lichens were optimally hydrated, they *absorbed* OCS from the air at a rate that gradually doubled as air temperature rose from approximately 3 to 25°C, whereupon their rate of OCS absorption began a precipitous decline that led to zero OCS absorption at 35°C.

The first portion of this response can be explained by the fact that most terrestrial plants prefer much warmer temperatures than a mere 3°C, so that as their surroundings warm and they grow better, they extract more OCS from the atmosphere in an attempt to promote even more warming and grow better still. At the point where warming becomes a detriment to them, however, they reverse this course of action and begin to rapidly *reduce* their rates of OCS absorption in an attempt to forestall warming-induced death. And since the consumption of OCS by lichens is under the physiological control of carbonic anhydrase - which is the key enzyme for OCS uptake in all higher plants, algae and soil organisms - we could expect this phenomenon to be generally operative over most of the earth. Hence, this *thermoregulatory function of the biosphere* may well be powerful enough to define an upper limit above which the surface air temperature of the planet may be restricted from rising, even when changes in other forcing factors, such as increases in greenhouse gas concentrations, produce an impetus for it to do so.

Clearly, this multifaceted phenomenon is extremely complex, with different biological entities tending to both increase and decrease atmospheric OCS concentrations at one and the same time, while periodically reversing directions in this regard in response to climate changes that push the temperatures of their respective environments either above or below the various thermal optima at which they function best. This being the case, there is obviously much more we need to learn about the many plant physiological mechanisms that may be involved. Nevertheless, state-of-the-art climate models *totally neglect* these and many other vital biological processes (some of which may yet be undiscovered) that combine to determine the mean state of earth's climate.

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

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2.3. Diffuse Light

The initial impetus for the increase in surface air temperature in the negative feedback phenomenon we describe here focuses exclusively on the incremental enhancement of the atmosphere's greenhouse effect that is produced by an increase in the air's CO_2 content; and from this starting point we identify a chain of events that ultimately counteracts this impetus for warming by the incremental enhancement of the planet's natural rate of CO_2 removal from the air.

The first of the linkages in this negative feedback loop is the proven propensity for higher levels of atmospheric CO_2 to enhance vegetative productivity, which phenomena are themselves powerful negative feedback mechanisms of the type we envision. Greater CO_2-enhanced photosynthetic rates, for example, enable plants to remove considerably more CO_2 from the air than they do under current conditions; while CO_2-induced increases in plant water use efficiency allow plants to grow where it was previously too dry for them. This latter

consequence of atmospheric CO_2 enrichment establishes a potential for more CO_2 to be removed from the atmosphere by increasing the *abundance* of earth's plants, whereas the former phenomenon does so by increasing their *robustness*.

The second of the linkages of the new feedback loop is the ability of plants to emit gases to the atmosphere that are ultimately converted into "biosols," i.e., aerosols that owe their existence to the biological activities of earth's vegetation, many of which function as cloud condensation nuclei. It takes little imagination to realize that since the existence of these atmospheric particles is dependent upon the physiological activities of plants and their associated soil biota, the CO_2-induced presence of more and more-highly-productive plants will lead to the production of more of these cloud-mediating particles, which can then act to cool the planet. But this two-linkage-long negative feedback effect, like the one-linkage-long dual cooling mechanism described in the previous paragraph, is still not the endpoint of the new feedback loop we are describing.

The third linkage of the new scenario is the observed propensity for increases in aerosols and cloud particles to enhance the amount of diffuse solar radiation reaching the earth's surface. The fourth linkage is the ability of enhanced diffuse lighting to reduce the volume of shade within vegetative canopies. The fifth linkage is the tendency for less internal canopy shading to enhance whole-canopy photosynthesis, which finally produces the end result: a greater biological extraction of CO_2 from the air and the subsequent sequestration of its carbon, compliments of the intensified diffuse-light-driven increase in total canopy photosynthesis and subsequent transfers of the extra fixed carbon to plant and soil storage reservoirs.

How significant is this multi-link process? Roderick *et al*. (2001) provide a good estimate based on the utilization of a unique "natural experiment," a technique that has been used extensively by Idso (1998) to evaluate the climatic sensitivity of the entire planet. Specifically, Roderick and his colleagues considered the volcanic eruption of Mt. Pinatubo in June of 1991, which ejected enough gases and fine materials into the atmosphere to produce sufficient aerosol particles to greatly increase the diffuse component of the solar radiation reaching the surface of the earth from that point in time through much of 1993, while only slightly reducing the receipt of total solar radiation. Based on a set of lengthy calculations, they concluded that the Mt. Pinatubo eruption may well have resulted in the removal of an extra 2.5 Gt of carbon from the atmosphere due to its diffuse-light-enhancing stimulation of terrestrial vegetation in the year following the eruption, which would have reduced the ongoing rise in the air's CO_2 concentration that year by about 1.2 ppm.

Interestingly, this reduction is about the magnitude of the real-world perturbation that was actually observed (Sarmiento, 1993). What makes this observation even more impressive is the fact that the CO_2 reduction was coincident with an El Niño event; because, in the words of Roderick et al., "previous and subsequent such events have been associated with *increases* in atmospheric CO_2." In addition, the observed reduction in total solar radiation received at the earth's surface during this period would have had a tendency to reduce the amount of photosynthetically active radiation incident upon earth's plants, which would also have had a

tendency to cause the air's CO_2 content to rise, as it would tend to lessen global photosynthetic activity.

Significant support for the new negative feedback phenomenon was swift in coming, as the very next year a team of 33 researchers published the results of a comprehensive study (Law *et al*., 2002) that compared seasonal and annual values of CO_2 and water vapor exchange across sites in forests, grasslands, crops and tundra -- which are part of an international network called FLUXNET -- investigating the responses of these exchanges to variations in a number of environmental factors, including direct and diffuse solar radiation. As for their findings, the huge group of researchers reported that "net carbon uptake (net ecosystem exchange, the net of photosynthesis and respiration) was greater under diffuse than under direct radiation conditions," and in discussing this finding, which is the centerpiece of the negative feedback phenomenon we describe, they noted that "cloud-cover results in a greater proportion of diffuse radiation and constitutes a higher fraction of light penetrating to lower depths of the canopy (Oechel and Lawrence, 1985)." More importantly, they also reported that "Goulden *et al*. (1997), Fitzjarrald *et al*. (1995), and Sakai *et al*. (1996) showed that net carbon uptake was consistently higher during cloudy periods in a boreal coniferous forest than during sunny periods with the same PPFD [photosynthetic photon flux density]." In fact, they wrote that "Hollinger *et al*. (1994) found that daily net CO_2 uptake was greater on cloudy days, *even though total PPFD was 21-45% lower on cloudy days than on clear days* [our italics]."

One year later, Gu *et al*. (2003) reported that they "used two independent and direct methods to examine the photosynthetic response of a northern hardwood forest (Harvard Forest, 42.5°N, 72.2°W) to changes in diffuse radiation caused by Mount Pinatubo's volcanic aerosols," finding that in the eruption year of 1991, "around noontime in the mid-growing season, the gross photosynthetic rate under the perturbed *cloudless* [our italics] solar radiation regime was 23, 8, and 4% higher than that under the normal *cloudless* [our italics] solar radiation regime in 1992, 1993, and 1994, respectively," and that "integrated over a day, the enhancement for canopy gross photosynthesis by the volcanic *aerosols* [our italics] was 21% in 1992, 6% in 1993 and 3% in 1994." Commenting on the significance of these observations, Gu *et al*. noted that "because of substantial increases in diffuse radiation world-wide after the eruption and strong positive effects of diffuse radiation for a variety of vegetation types, it is likely that our findings at Harvard Forest represent a *global* [our italics] phenomenon."

In the preceding paragraph, we have highlighted the fact that the diffuse-light-induced photosynthetic enhancement observed by Gu *et al*., in addition to likely being global in scope, was caused by volcanic *aerosols* under acting under *cloudless* conditions. Our reason for calling attention to these two italicized words is to clearly distinguish this phenomenon from a closely related one that is also described by Gu *et al*., i.e., the propensity for the extra diffuse light created by *increased cloud cover* to further enhance photosynthesis, *even though the total flux of solar radiation received at the earth's surface may be reduced under such conditions*. Based on still more real-world data, for example, Gu *et al*. note that "Harvard Forest photosynthesis also increases with cloud cover, with a peak at about 50% cloud cover."

Although very impressive, in all of the situations discussed above the source of the enhanced atmospheric aerosol concentration was a singular significant event -- specifically, a massive volcanic eruption -- but what we really need to know is what happens under more normal conditions. This was the new and important question that was addressed the following year in the study of Niyogi *et al*. (2004): "Can we detect the effect of relatively routine aerosol variability on field measurements of CO_2 fluxes, and if so, how does the variability in aerosol loading affect CO_2 fluxes over different landscapes?"

To answer this question, the group of sixteen researchers used CO_2 flux data from the AmeriFlux network (Baldocchi *et al*., 2001) together with cloud-free aerosol optical depth data from the NASA Robotic Network (AERONET; Holben *et al*., 2001) to assess the effect of aerosol loading on the net assimilation of CO_2 by three types of vegetation: trees (broadleaf deciduous forest and mixed forest), crops (winter wheat, soybeans and corn) and grasslands. Their work revealed that an aerosol-induced increase in *diffuse radiative-flux fraction* [DRF = ratio of diffuse (Rd) to total or global (Rg) solar irradiance] increased the net CO_2 assimilation of trees and crops, making them larger carbon sinks, but that it decreased the net CO_2 assimilation of grasslands, making them smaller carbon sinks.

How significant were the effects observed by Niyogi *et al*.? For a summer mid-range Rg flux of 500 W m^{-2}, going from the set of all DRF values between 0.0 and 0.4 to the set of all DRF values between 0.6 and 1.0 resulted in an approximate 50% increase in net CO_2 assimilation by a broadleaf deciduous forest located in Tennessee, USA. Averaged over the entire daylight period, they further determined that the shift from the lower to the higher set of DRF values "enhances photosynthetic fluxes by about 30% at this study site." Similar results were obtained for the mixed forest and the conglomerate of crops studied. Hence, they concluded that natural variability among commonly-present aerosols can "routinely influence surface irradiance and hence the terrestrial CO_2 flux and regional carbon cycle." And for these types of land-cover (forests and agricultural crops), that influence is to significantly *increase* the assimilation of CO_2 from the atmosphere.

In the case of grasslands, however, the effect was found to be just the opposite, with greater aerosol loading of the atmosphere leading to *less* CO_2 assimilation, due most likely, in the estimation of Niyogi *et al*., to grasslands' significantly different canopy architecture. With respect to the planet as a whole, however, the net effect is decidedly positive, as earth's trees are the primary planetary players in the sequestration of carbon. Post *et al*. (1990), for example, noted that woody plants account for approximately 75% of terrestrial photosynthesis, which comprises about 90% of the global total (Sellers and McCarthy, 1990); and those numbers make earth's trees and shrubs responsible for fully two thirds (0.75 x 90% = 67.5%) of the planet's net primary production.

What is especially exciting about these real-world observations is that much of the commonly-present aerosol burden of the atmosphere is plant-derived. Hence, it can be appreciated that earth's woody plants are themselves responsible for emitting to the air that which ultimately enhances their own photosynthetic prowess. In other words, earth's trees significantly control

their own destiny, i.e., they alter the atmospheric environment in a way that directly enhances their opportunities for greater growth.

Society helps too, in this regard; for as we pump ever more CO_2 into the atmosphere, the globe's woody plants quickly respond to its *aerial fertilization effect*, becoming ever more productive, which leads to even more plant-derived aerosols being released to the atmosphere, which stimulates this positive feedback cycle to a still greater degree. Stated another way, earth's trees use some of the CO_2 emitted to the atmosphere by society to alter the aerial environment so as to enable them to remove even more CO_2 from the air. The end result is that earth's trees and humanity are working *hand-in-hand* to significantly increase the productivity of the biosphere; and it is happening in spite of all other insults to the environment that work in opposition to enhanced biological activity.

In light of these several observations, it should be obvious that the historical and still-ongoing CO_2-induced increase in atmospheric *biosols* should have had, and should be continuing to have, a significant cooling effect on the planet that exerts itself by both slowing the rate of rise of the air's CO_2 content and reducing the receipt of solar radiation at the earth's surface, neither of which effects is fully and adequately included in any general circulation model of the atmosphere of which we are aware.

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

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2.4. Iodocompounds

The climatic significance of iodinated compounds or *iodocompounds* was first described in the pages of *Nature* by O'Dowd *et al*. (2002). As related by Kolb (2002) in an accompanying perspective on their work, the ten-member research team discovered "a previously unrecognized source of aerosol particles" by unraveling "a photochemical phenomenon that occurs in sea air and produces aerosol particles composed largely of iodine oxides." Specifically, the team used a smog chamber operated under coastal atmospheric conditions to demonstrate, as they report, that "new particles can form from condensable iodine-containing vapors, which are the photolysis products of biogenic iodocarbons emitted from marine algae." With the help of aerosol formation models, they also demonstrated that concentrations of condensable iodine-containing vapors over the open ocean "are sufficient to influence marine particle formation."

The significance of this work, of course, is that the aerosol particles O'Dowd et al. discovered can function as cloud condensation nuclei (CCN), helping to create new clouds that reflect more incoming solar radiation back to space and thereby cool the planet. With respect to the negative feedback nature of this phenomenon, O'Dowd et al. cite the work of Laturnus *et al*. (2000), which demonstrates that emissions of iodocarbons from marine biota "can increase by up to 5 times as a result of changes in environmental conditions associated with global change." Therefore, as O'Dowd *et al*. continue, "increasing the source rate of condensable iodine vapors will result in an increase in marine aerosol and CCN concentrations of the order of 20 - 60%." Furthermore, they note that "changes in cloud albedo resulting from changes in CCN concentrations of this magnitude can lead to an increase in global raidative forcing *similar in magnitude, but opposite in sign* [our italics], to the forcing induced by greenhouse gases."

Four years later, Smythe-Wright *et al*. (2006) measured trace gas and pigment concentrations in seawater, while identifying and enumerating picophytoprokaryotes during two ship cruises in the Atlantic Ocean and one in the Indian Ocean, where they focused "on methyl iodide production and the importance of a biologically related source." In doing so, they encountered methyl iodide concentrations as great as 45 pmol per liter in the top 150 meters of the oceanic water column that correlated well with the abundance of *Prochlorococcus*, which they report "can account for >80% of the variability in the methyl iodide concentrations," they add that they "have confirmed the release of methyl iodide by this species in laboratory culture experiments."

Extrapolating their findings to the globe as a whole, the six researchers "estimate the global ocean flux of iodine [I] to the marine boundary layer from this single source to be 5.3×10^{11} g I $year^{-1}$," which they say "is a large fraction of the total estimated global flux of iodine (10^{11}-10^{12} g I $year^{-1}$)." This observation is extremely important, because volatile iodinated compounds, in Smythe-Wright *et al*.'s words, "play a part in the formation of new particles and cloud condensation nuclei (CCN)," and because "an increase in the production of iodocompounds and the subsequent production of CCN would potentially result in a net cooling of the earth system

and hence in a negative climate feedback mechanism, mitigating global warming." More specifically, they suggest that "as ocean waters become warmer and more stratified, nutrient concentrations will fall and there will likely be a regime shift away from microalgae toward *Prochlorococcus*," such that "colonization within the <50° latitude band will result in a ~15% increase in the release of iodine to the atmosphere," with consequent "important implications for global climate change," which, as previously noted, tend to counteract global warming.

Most recently, as part of the Third Pelagic Ecosystem CO_2 Enrichment Study, Wingenter *et al*. (2007) investigated the effects of atmospheric CO_2 enrichment on marine microorganisms in nine marine mesocosms maintained within two-meter-diameter polyethylene bags submerged to a depth of ten meters in a fjord at the Large-Scale Facilities of the Biological Station of the University of Bergen in Espegrend, Norway. Three of these mesocosms were maintained at ambient levels of CO_2 (~375 ppm or base CO_2), three were maintained at levels expected to prevail at the end of the current century (760 ppm or 2xCO_2), and three were maintained at levels predicted for the middle of the next century (1150 ppm or 3xCO_2). During the 25 days of this experiment, the twelve researchers followed the development and subsequent decline of an induced bloom of the coccolithophorid *Emiliania huxleyi*, carefully measuring several physical, chemical and biological parameters along the way. This work revealed that the iodocarbon chloroiodomethane (CH_2ClI) experienced its peak concentration about six to ten days after the coccolithophorid's chlorophyll-a maximum, and that its estimated abundance was 46% higher in the 2xCO_2 mesocosms and 131% higher in the 3xCO_2 mesocosms.

The international team of scientists concluded that the differences in the CH_2ClI concentrations "may be viewed as a result of changes to the ecosystems as a whole brought on by the CO_2 perturbations." And because emissions of various iodocarbons have been found to lead to an enhancement of cloud condensation nuclei in the marine atmosphere, as demonstrated by O'Dowd *et al*. (2002) and Jimenez *et al*. (2003), it can be appreciated that the CO_2-induced stimulation of the marine emissions of these substances provides a *natural brake* on the tendency for global warming to occur as a consequence of *any* forcing, as iodocarbons lead to the creation of more-highly-reflective clouds over greater areas of the world's oceans.

In conclusion, as Wingenter *et al*. sum things up, the processes described above "may help contribute to the homeostasis of the planet." And the finding of O'Dowd *et al*. that changes in cloud albedo "associated with global change" can lead to an increase in global radiative forcing that is "similar in magnitude, but opposite in sign, to the forcing induced by greenhouse gases," suggests that CO_2-induced increases in marine iodocarbon emissions likely contribute to maintaining that homeostasis in a really big way.

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

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2.5. Nitrous Oxide

One of the main sources of N_2O is *agriculture*, which in some countries accounts for almost half of a nations' N_2O emissions (Pipatti, 1997). Moreover, with N_2O originating from microbial N cycling in soil -- mostly from aerobic nitrification or from anaerobic denitrification (Firestone and Davidson, 1989) -- there is a concern that CO_2-induced increases in carbon input to soil, together with increasing N input from other sources, will increase substrate availability for denitrifying bacteria and may result in higher N_2O emissions from agricultural soils as the air's CO_2 content continues to rise.

In a study designed to investigate this possibility, Kettunen *et al*. (2007a) grew mixed stands of timothy (*Phleum pratense*) and red clover (*Trifolium pratense*) in sandy-loam-filled mesocosms at low and moderate soil nitrogen levels within greenhouses maintained at either 360 or 720 ppm CO_2, while measuring harvestable biomass production and N_2O evolution from the mesocosm soils over the course of three crop cuttings. This work revealed that the total harvestable biomass production of *P. pratense* was enhanced by the experimental doubling of the air's CO_2 concentration by 21 and 26%, respectively, in the low and moderate soil N treatments, while corresponding biomass enhancements for *T. pratense* were 22 and 18%. In addition, the researchers found that after emergence of the mixed stand and during vegetative growth before the first harvest and N fertilization, N_2O fluxes were higher under *ambient* CO_2 in both the low and moderate soil N treatments. In fact, it was not until the water table had been raised and extra fertilization given after the first harvest that the elevated CO_2 seemed to increase N_2O fluxes. The four Finnish researchers thus concluded that the mixed stand of *P.*

pratense and *T. pratense* was "able to utilize the increased supply of atmospheric CO_2 for enhanced biomass production without a simultaneous increase in the N_2O fluxes," thereby raising "the possibility of maintaining N_2O emissions at their current level, while still enhancing the yield production [via the *aerial fertilization effect* of elevated CO_2] even under low N fertilizer additions."

In a similar study, Kettunen *et al*. (2007b) grew timothy (*Phleum pratense*) in monoculture within sandy-soil-filled mesocosms located within greenhouses maintained at atmospheric CO_2 concentrations of either 360 or 720 ppm for a period of 3.5 months at *moderate* (standard), *low* (half-standard) and *high* (1.5 times standard) soil N supply, while they measured the evolution of N_2O from the mesocosms, vegetative net CO_2 exchange, and final above- and below-ground biomass production over the course of three harvests. In this experiment the elevated CO_2 concentration increased the net CO_2 exchange of the ecosystems (which phenomenon was primarily driven by CO_2-induced increases in photosynthesis) by about 30%, 46% and 34% at the low, moderate and high soil N levels, respectively, while it increased the above-ground biomass of the crop by about 8%, 14% and 8% at the low, moderate and high soil N levels, and its below-ground biomass by 28%, 27% and 41% at the same respective soil N levels. And once again, Kettunen *et al*. report that "an explicit increase in N_2O fluxes due to the elevated atmospheric CO_2 concentration was not found."

One year later, Welzmiller *et al*. measured N_2O and denitrification emission rates in a C_4 sorghum [*Sorghum bicolor* (L.) Moench] production system with ample and limited flood irrigation rates under Free-Air CO_2 Enrichment (seasonal mean = 579 ppm) and control (seasonal mean = 396 ppm) CO_2 during the 1998 and 1999 summer growing seasons at the experimental FACE site near Maricopa, Arizona (USA). Results of the study indicated that "elevated CO_2 did not result in increased N_2O or N-gas emissions with either ample or limited irrigation," which findings they describe as being "consistent with findings for unirrigated western U.S. ecosystems reported by Billings *et al*. (2002) for Mojave Desert soils and by Mosier *et al*. (2002) for Colorado shortgrass steppe."

In discussing the implications of their findings, Welzmiller *et al*. say their results suggest that "as CO_2 concentrations increase, there will not be major increases in denitrification in C_4 cropping environments such as irrigated sorghum in the desert southwestern United States," which further suggests there will not be an increased impetus for global warming due to this phenomenon.

In a different type of study -- driven by the possibility that the climate of the Amazon Basin may gradually become drier due to a warming-induced increase in the frequency and/or intensity of El Niño events that have historically brought severe drought to the region -- Davidson *et al*. (2004) devised an experiment to determine the consequences of the drying of the soil of an Amazonian moist tropical forest for the net surface-to-air fluxes of both N_2O and methane (CH_4). This they did in the Tapajos National Forest near Santarem, Brazil, by modifying a one-hectare plot of land covered by mature evergreen trees so as to dramatically reduce the

amount of rain that reached the forest floor (throughfall), while maintaining an otherwise similar one-hectare plot of land as a control for comparison.

Prior to making this modification, the three researchers measured the gas exchange characteristics of the two plots for a period of 18 months; then, after initiating the throughfall-exclusion treatment, they continued their measurements for an additional three years. This work revealed that the "drier soil conditions caused by throughfall exclusion inhibited N_2O and CH_4 production and promoted CH_4 consumption." In fact, they report that "the exclusion manipulation lowered annual N_2O emissions by >40% and increased rates of consumption of atmospheric CH_4 by a factor of >4," which results they attributed to the "direct effect of soil aeration on denitrification, methanogenesis, and methanotrophy."

Consequently, if global warming would indeed increase the frequency and/or intensity of El Niño events as some claim it will, the results of this study suggest that the anticipated drying of the Amazon Basin would initiate a strong *negative* feedback via (1) large drying-induced reductions in the evolution of both N_2O and CH_4 from its soils, and (2) a huge drying-induced increase in the consumption of CH_4 by its soils. Although Davidson et al. envisage a more extreme *second phase response* "in which drought-induced plant mortality is followed by increased mineralization of C and N substrates from dead fine roots and by increased foraging of termites on dead coarse roots" (an extreme response that would be expected to *increase* N_2O and CH_4 emissions), we note that the projected rise in the air's CO_2 content would likely prohibit such a thing from ever occurring, due to the documented tendency for atmospheric CO_2 enrichment to greatly increase the water use efficiency of essentially all plants, which would enable the forest to continue to flourish under significantly drier conditions than those of the present.

In summation, it would appear that concerns about additional global warming arising from enhanced N_2O emissions from agricultural soils in a CO_2-enriched atmosphere of the future are not well founded.

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

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2.6. Methane

What impact do global warming, the ongoing rise in the air's carbon dioxide (CO_2) content and a number of other contemporary environmental trends have on the atmosphere's methane (CH_4) concentration? The implications of this question are huge, in light of the fact that methane is a more powerful greenhouse gas, molecule for molecule, than is carbon dioxide. Its atmospheric concentration is determined by the difference between how much CH_4 goes into the air (emissions) and how much comes out of it (extractions) over the same time period. And as indicated in the literature below, there are significant forces at play that will likely produce a large negative feedback toward the future warming potential of this powerful greenhouse gas, nearly all of which forces are not presently included in model projections of future climate. We begin with a discussion of methane emissions associated with agricultural operations.

Early indications that atmospheric CO_2 enrichment might significantly reduce methane emissions associated with the production of rice were provided by Schrope *et al*. (1999), who studied batches of rice growing in large vats filled with topsoil and placed within greenhouse tunnels maintained at atmospheric CO_2 concentrations of 350 and 700 ppm, each of which tunnels was further subdivided into four sections that provided temperature treatments ranging from ambient to as much as 5°C above ambient. As would be expected, doubling the air's CO_2 content significantly enhanced rice biomass production in this system, increasing it by up to 35% above-ground and by up to 83% below-ground. However, in a truly unanticipated development, methane emissions from the rice grown at 700 ppm CO_2 were found to be 10 to 45 times less than emissions from the plants grown at 350 ppm. As Schrope *et al*. describe it, "the results of this study did not support our hypothesis that an effect of both increased carbon

dioxide and temperature would be an increase in methane emissions." Indeed, they report that "both increased carbon dioxide and increased temperatures were observed to produce decreased methane emissions," except for the first 2°C increase above ambient, which produced a slight increase in methane evolution from the plant-soil system.

In checking for potential problems with their experiment, Schrope *et al*. could find none. They thus stated that their results "unequivocally support the conclusion that, during this study, methane emissions from *Oryza sativa* [rice] plants grown under conditions of elevated CO_2 were dramatically reduced relative to plants gown in comparable conditions under ambient levels of CO_2," and to be doubly sure of this fact, they went on to replicate their experiment in a second year of sampling and obtained essentially the same results. Four years later, however, a study of the same phenomenon by a different set of scientists yielded a far different result in a different set of circumstances.

Inubushi *et al*. (2003) grew a different cultivar of rice in 1999 and 2000 in paddy culture at Shizukuishi, Iwate, Japan in a FACE study where the air's CO_2 concentration was increased 200 ppm above ambient. They found that the extra CO_2 "significantly increased the CH_4 [methane] emissions by 38% in 1999 and 51% in 2000," which phenomenon they attributed to "accelerated CH_4 production as a result of increased root exudates and root autolysis products and to the increased plant-mediated CH_4 emission because of the higher rice tiller numbers under FACE conditions." With such a dramatically different result from that of Schrope *et al*., many more studies likely will be required to clarify this issue and determine which of these two contrasting results is the more typical of rice culture around the world.

A somewhat related study was conducted by Kruger and Frenzel (2003), who note that "rice paddies contribute approximately 10-13% to the global CH_4 emission (Neue, 1997; Crutzen and Lelieveld, 2001)," and that "during the next 30 years rice production has to be increased by at least 60% to meet the demands of the growing human population (Cassman *et al*., 1998)." Because of these facts they further note that "increasing amounts of fertilizer will have to be applied to maximize yields [and] there is ongoing discussion on the possible effects of fertilization on CH_4 emissions."

To help promote that discussion, Kruger and Frenzel investigated the effects of N-fertiliser (urea) on CH_4 emission, production and oxidation in rice culture in laboratory, microcosm and field experiments they conducted at the Italian Rice Research Institute in northern Italy. They report that in some prior studies "N-fertilisation stimulated CH_4 emissions (Cicerone and Shetter, 1981; Banik *et al*., 1996; Singh *et al*., 1996)," while "methanogenesis and CH_4 emission was found to be inhibited in others (Cai *et al*., 1997; Schutz *et al*., 1989; Lindau *et al*., 1990)," similar to the polarized findings of Schrope *et al*. and Inubushi *et al*. with respect to the effects of elevated CO_2 on methane emissions. In the mean, therefore, there may well be little to no change in overall CH_4 emissions from rice fields in response to both elevated CO_2 and increased N-fertilization. With respect to their own study, for example, Kruger and Frenzel say that "combining our field, microcosm and laboratory experiments we conclude that any agricultural praxis improving the N-supply to the rice plants will also be favourable for the CH_4 oxidising

bacteria," noting that "N-fertilisation had only a transient influence and was counter-balanced in the field by an elevated CH_4 production." The implication of these findings is well articulated in the concluding sentence of their paper: "neither positive nor negative consequences for the overall global warming potential could be found."

Another agricultural source of methane is the fermentation of feed in the rumen of cattle and sheep. Fievez *et al*. (2003) studied the effects of various types and levels of fish-oil feed additives on this process by means of both *in vitro* and *in vivo* experiments with sheep, observing a maximal 80% decline in the ruminants' production of methane when using fish-oil additives containing n-3-eicosapentanoic acid. With respect to cattle, Boadi et al. (2004) report that existing mitigation strategies for reducing CH_4 emissions from dairy cows include the addition of ionophores and fats to their food, as well as the use of high-quality forages and grains in their diet, while newer mitigation strategies include "the addition of probiotics, acetogens, bacteriocins, archaeal viruses, organic acids, [and] plant extracts (e.g., essential oils) to the diet, as well as immunization, and genetic selection of cows." To this end, they provide a table of 20 such strategies, where the average *maximum potential* CH_4 reduction that may result from the implementation of *each* strategy is 30% *or more*.

With as many as 20 different mitigation strategies from which to choose, each one of which (on average) has the potential to reduce CH_4 emissions from dairy cows by as much as a third, it would appear there is a tremendous potential to dramatically curtail the amount of CH_4 released to the atmosphere by these ruminants and, by implication, the host of other ruminants that mankind raises and uses for various purposes around the world. Such high-efficiency approaches to reducing the strength of the atmosphere's greenhouse effect, while not reducing the biological benefits of elevated atmospheric CO_2 concentrations in the process, should be at the top of any program designed to achieve that difficult (but still highly questionable) objective.

In view of these several observations, we can be cautiously optimistic about our agricultural intervention capabilities and their capacity to help stem the tide of earth's historically-rising atmospheric methane concentration, which could take a huge bite out of methane-induced global warming. But what about methane emissions from natural vegetation, do they respond in a similar way?

With respect to methane emissions associated with natural vegetation, we have already discussed the results of Davidson *et al*. (2004) in our *Nitrous Oxide* section, which results suggest that a global warming-induced drying of the Amazon Basin would initiate a strong negative feedback to warming via (1) large drying-induced reductions in the evolution of N_2O and CH_4 from its soils and (2) a huge drying-induced increase in the consumption of CH_4 by its soils. In a contemporaneous study, Strack *et al*. (2004) also reported that climate models predict increases in evapotranspiration that could lead to drying in a warming world and a subsequent lowering of water tables in high northern latitudes. This prediction literally cries out for an analysis of how lowered water tables will impact peatland emissions of CH_4; and in a *theoretical* study of the subject, Roulet *et al*. (1992) calculated that for a decline of 14 cm in the

water tables of northern Canadian peatlands, due to climate-model-derived increases in temperature (3°C) and precipitation (1mm/day) predicted for a doubling of the air's CO_2 content, CH_4 emissions would decline by 74-81%. Hence, in an attempt to obtain some *experimental* data on the subject, at various times over the period 2001-2003 Strack *et al*. measured CH_4 fluxes to the atmosphere at different locations that varied in depth-to-water table within natural portions of a poor fen in central Quebec, Canada, as well as within control portions of the fen that had been drained eight years earlier.

At the conclusion of their study, the Canadian scientists reported that "methane emissions and storage were lower in the drained fen." The greatest reductions (up to 97%) were measured at the higher locations, while at the lower locations there was little change in CH_4 flux. Averaged over all locations, they determined that the "growing season CH_4 emissions at the drained site were 55% lower than the control site," indicative of the fact that the biosphere appears to be organized to resist warming influences that could push it into a thermal regime that might otherwise prove detrimental to its health.

In another experimental study, Garnet *et al*. (2005) grew seedlings of three emergent aquatic macrophytes (*Orontium aquaticum* L., *Peltandra virginica* L. and *Juncus effusus* L.) plus one coniferous tree (*Taxodium distichum* L.), all of which are native to eastern North America, in a five-to-one mixture of well-fertilized mineral soil and peat moss in pots submerged in water in tubs located within controlled environment chambers for a period of eight weeks. Concomitantly, they measured the amount of CH_4 emitted by the plant foliage, along with net CO_2 assimilation rate and stomatal conductance, which were made to vary by changing the CO_2 concentration of the air surrounding the plants and the density of the photosynthetic photon flux impinging on them.

Methane emissions from the four wetland species increased linearly with increases in both stomatal conductance and net CO_2 assimilation rate; but the researchers found that changes in stomatal conductance affected foliage methane flux "three times more than equivalent changes in net CO_2 assimilation," making stomatal conductance the more significant of the two CH_4 emission-controllers. In addition, they note that evidence of stomatal control of CH_4 emission has also been reported for *Typha latifolia* (Knapp and Yavitt, 1995) and *Carex* (Morrissey *et al*., 1993), two other important wetland plants. Hence, since atmospheric CO_2 enrichment leads to approximately equivalent - but oppositely directed - changes in foliar net CO_2 assimilation (which is increased) and stomatal conductance (which is reduced) in most herbaceous plants (which are the type that comprise most wetlands), it can be appreciated that the ongoing rise in the air's CO_2 content should be acting to *reduce* methane emissions from earth's wetland vegetation, because of the three-times-greater negative CH_4 emission impact of the decrease in stomatal conductance compared to the positive CH_4 emission impact of the equivalent increase in net CO_2 assimilation.

In light of the above findings, it would appear that current environmental trends that may impact methane emissions from natural vegetation, including the ongoing rise in the air's CO_2 content, primarily tend to *reduce* this flux; and perhaps that is why the rate-of-rise of the

atmosphere's methane concentration has been steadily declining over the last several years to the point that it is now nearly nil. Still, there are other relevant ways by which methane is also removed from the atmosphere.

According to Prinn *et al*. (1992), one of the major means by which methane is removed from the atmosphere is via oxidation by methanotrophic bacteria in the aerobic zones of soils, the magnitude of which phenomenon is believed to be equivalent to the annual input of methane to the atmosphere (Watson *et al*., 1992). This soil sink for methane appears to be ubiquitous, as methane uptake has been observed in soils of tundra (Whalen and Reeburgh, 1990), boreal forests (Whalen *et al*., 1992), temperate forests (Steudler *et al*., 1989; Yavitt *et al*., 1990), grasslands (Mosier *et al*., 1997), arable lands (Jensen and Olsen, 1998), tropical forests (Keller, 1986; Singh *et al*., 1997), and deserts (Striegl *et al*., 1992), with forest soils - especially boreal and temperate forest upland soils (Wahlen and Reeburgh, 1996) - appearing to be the most efficient in this regard (Le Mer and Roger, 2001).

In an attempt to learn more about this subject, Tamai *et al*. (2003) studied methane uptake rates by the soils of three Japanese cypress plantations composed of 30- to 40-year-old trees. Through all seasons of the year, they found that methane was absorbed by the soils of all three sites, being positively correlated with temperature, as has also been observed in several other studies (Peterjohn *et al*., 1994; Dobbie and Smith, 1996); Prieme and Christensen, 1997; Saari *et al*., 1998). Methane absorption was additionally - and even more strongly - positively correlated with the C/N ratio of the cypress plantations' soil organic matter. Based on these results, it can be appreciated that CO_2-induced global warming, if real, would produce two biologically-mediated negative feedbacks to counter the increase in temperature: (1) a warming-induced increase in methane uptake from the atmosphere that is experienced by essentially all soils, and (2) an increase in soil methane uptake from the atmosphere that is produced by the increase in plant-litter C/N ratio that typically results from atmospheric CO_2 enrichment.

Another study that deals with this topic is that of Menyailo and Hungate (2003), who assessed the influence of six boreal forest species -- spruce, birch, Scots pine, aspen, larch and Arolla pine -- on soil CH_4 consumption in the Siberian artificial afforestation experiment, in which the six common boreal tree species had been grown under common garden conditions for the past 30 years under the watchful eye of the staff of the Laboratory of Soil Science of the Institute of Forest, Siberian Branch of the Russian Academy of Sciences (Menyailo *et al*., 2002). They determined, in their words, that "soils under hardwood species (aspen and birch) consumed CH_4 at higher rates than soils under coniferous species and grassland." Under low soil moisture conditions, for example, the soils under the two hardwood species consumed 35% more CH_4 than the soils under the four conifers; while under high soil moisture conditions they consumed 65% more. As for the implications of these findings, Pastor and Post (1988) have suggested, in the words of Menyailo and Hungate, that "changes in temperature and precipitation resulting from increasing atmospheric CO_2 concentrations will cause a northward migration of the hardwood-conifer forest border in North America." Consequently, if such a shifting of species does indeed occur, it will likely lead to an increase in methane consumption by soils and a

reduction in methane-induced global warming potential, thereby providing yet another biologically-mediated negative feedback factor that has yet to be incorporated into models of global climate change.

Last of all, we note that increases in the air's CO_2 concentration will likely lead to a net reduction in vegetative isoprene emissions, which, as explained elsewhere in this document under the heading of Isoprene, should also lead to a significant removal of methane from the atmosphere. Hence, as the air's CO_2 content -- and possibly its temperature -- continues to rise, we can expect to see a significant increase in the rate of methane removal from earth's atmosphere, which should help to reduce the potential for further global warming.

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

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2.7. Dimethyl Sulfide

Several years ago, Charlson *et al*. (1987) discussed the plausibility of a multi-stage negative feedback process, whereby warming-induced increases in the emission of dimethyl sulfide

(DMS) from the world's oceans tend to counteract any initial impetus for warming. The basic tenant of their hypothesis was that the global radiation balance is significantly influenced by the albedo of marine stratus clouds (the greater the cloud albedo, the less the input of solar radiation to the earth's surface). The albedo of these clouds, in turn, is known to be a function of cloud droplet concentration (the more and smaller the cloud droplets, the greater the cloud albedo and the reflection of solar radiation), which is dependent upon the availability of cloud condensation nuclei on which the droplets form (the more cloud condensation nuclei, the more and smaller the cloud droplets). And in completing the negative feedback loop, Charlson *et al*. noted that the cloud condensation nuclei concentration often depends upon the flux of biologically-produced DMS from the world's oceans (the higher the sea surface temperature, the greater the sea-to-air flux of DMS).

Since the publication of Charlson *et al*.'s initial hypothesis, much empirical evidence has been gathered in support of its several tenants. One review, for example, states that "major links in the feedback chain proposed by Charlson *et al*. (1987) have a sound physical basis," and that 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" (Ayers and Gillett, 2000).

But just how strong is the negative feedback phenomenon proposed by Charlson *et al*.? Is it powerful enough to counter the threat of greenhouse gas-induced global warming? According to the findings of Sciare *et al*. (2000), it may well be able to do just that, for in examining ten years of DMS data from Amsterdam Island in the southern Indian Ocean, these researchers found that a sea surface temperature increase of only 1°C was sufficient to increase the atmospheric DMS concentration by as much as 50%. This finding suggests that the degree of warming typically predicted to accompany a doubling of the air's CO_2 content would increase the atmosphere's DMS concentration by a factor of three or more, providing what they call a "very important" negative feedback that could potentially offset the original impetus for warming.

Other research has shown that this same chain of events can be set in motion by means of phenomena not discussed in Charlson *et al*.'s original hypothesis. Simo and Pedros-Alio (1999), for example, discovered that the depth of the surface mixing-layer has a substantial influence on DMS yield in the short term, via a number of photo-induced (and thereby mixing-depth mediated) influences on several complex physiological phenomena, as do longer-term seasonal variations in vertical mixing, via their influence on seasonal planktonic succession scenarios and food-web structure.

More directly supportive of Charlson *et al*.'s hypothesis was the study of Kouvarakis and Mihalopoulos (2002), who measured seasonal variations of gaseous DMS and its oxidation products - non-sea-salt sulfate (nss-SO_4^{2-}) and methanesulfonic acid (MSA) - at a remote coastal location in the Eastern Mediterranean Sea from May 1997 through October 1999, as well as the diurnal variation of DMS during two intensive measurement campaigns conducted in September 1997. In the seasonal investigation, DMS concentrations tracked sea surface

temperature (SST) almost perfectly, going from a low of 0.87 nmol m^{-3} in the winter to a high of 3.74 nmol m^{-3} in the summer. Such was also the case in the diurnal studies: DMS concentrations were lowest when it was coldest (just before sunrise), rose rapidly as it warmed thereafter to about 1100, after which they dipped slightly and then experienced a further rise to the time of maximum temperature at 2000, whereupon a decline in both temperature and DMS concentration set in that continued until just before sunrise. Consequently, because concentrations of DMS and its oxidation products (MSA and nss-SO_4^{2-}) rise dramatically in response to both diurnal and seasonal increases in SST, there is every reason to believe that the same negative feedback phenomenon would operate in the case of the long-term warming that could arise from increasing greenhouse gas concentrations, and that it could substantially mute the climatic impacts of those gases.

Also of note in this regard, Baboukas *et al*. (2002) report the results of nine years of measurements of methanesulfonate (MS-), an exclusive oxidation product of DMS, in *rainwater* at Amsterdam Island. Their data, too, revealed "a well distinguished seasonal variation with higher values in summer, in line with the seasonal variation of its gaseous precursor (DMS)," which, in their words, "further confirms the findings of Sciare *et al*. (2000)." In addition, the MS- anomalies in the rainwater were found to be closely related to SST anomalies; and Baboukas *et al*. say that this observation provides even more support for "the existence of a positive ocean-atmosphere feedback on the biogenic sulfur cycle above the Austral Ocean, one of the most important DMS sources of the world."

In a newer study of this phenomenon, Toole and Siegel (2004) note that it has been shown to operate as described above in the 15% of the world's oceans "consisting primarily of high latitude, continental shelf, and equatorial upwelling regions," where DMS may be accurately predicted as a function of the ratio of the amount of surface chlorophyll derived from satellite observations to the depth of the climatological mixed layer, which they refer to as the "bloom-forced regime." For the other 85% of the world's marine waters, they demonstrate that modeled surface DMS concentrations are independent of chlorophyll and are a function of the mixed layer depth alone, which they call the "stress-forced regime." So how does the warming-induced DMS negative feedback cycle operate in these waters?

For oligotrophic regimes, Toole and Siegel find that "DMS biological production rates are negatively or insignificantly correlated with phytoplankton and bacterial indices for abundance and productivity while more than 82% of the variability is explained by UVR(325) [ultraviolet radiation at 325 nm]." This relationship, in their words, is "consistent with recent laboratory results (e.g., Sunda *et al*., 2002)," who demonstrated that intracellular DMS concentration and its biological precursors (particulate and dissolved dimethylsulfoniopropionate) "dramatically increase under conditions of acute oxidative stress such as exposure to high levels of UVR," which "are a function of mixed layer depth."

These results -- which Toole and Siegel confirmed via an analysis of the Dacey *et al*. (1998) 1992-1994 organic sulfur time-series that was sampled in concert with the U.S. JGOFS Bermuda Atlantic Time-Series Study (Steinberg *et al*., 2001) -- suggest, in their words, "the potential of a

global change-DMS-climate feedback." Specifically, they say that "UVR doses will increase as a result of observed decreases in stratospheric ozone and the shoaling of ocean mixed layers as a result of global warming (e.g., Boyd and Doney, 2002)," and that "in response, open-ocean phytoplankton communities should increase their DMS production and ventilation to the atmosphere, increasing cloud condensing nuclei, and potentially playing out a coupled global change-DMS-climate feedback."

This second DMS-induced negative-feedback cycle, which operates over 85% of the world's marine waters and complements the first DMS-induced negative-feedback cycle, which operates over the other 15%, is but another manifestation of the wonderful capacity of earth's biosphere to regulate its affairs in such a way as to maintain climatic conditions over the vast majority of the planet's surface within bounds conducive to the continued existence of life, in all its variety and richness. In addition, it has been suggested that a DMS-induced negative climate feedback phenomenon also operates over the *terrestrial* surface of the globe, where the volatilization of reduced sulfur gases from soils may be just as important as marine DMS emissions in enhancing cloud albedo (Idso, 1990). On the basis of experiments that showed soil DMS emissions to be positively correlated with soil organic matter content, for example, and noting that additions of organic matter to a soil tend to increase the amount of sulfur gases emitted therefrom, Idso (1990) hypothesized that because atmospheric CO_2 is an effective aerial fertilizer, augmenting its atmospheric concentration and thereby increasing vegetative inputs of organic matter to earth's soils should also produce an impetus for cooling, even in the *absence* of surface warming.

Nevertheless, and in spite of the overwhelming empirical evidence for both land- and ocean-based DMS-driven negative feedbacks to global warming, the effects of these processes have not been fully incorporated into today's state-of-the-art climate models. Hence, the warming they predict in response to future anthropogenic CO_2 emissions must be considerably larger than what could actually occur in the real world. In fact, it is very possible these biologically-driven phenomena could totally compensate for the warming influence of all greenhouse gas emissions experienced to date, as well as all those that are anticipated to occur in the future.

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

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