Positive water vapour feedback in climate models confirmed by satellite data

D. Rind*, E.-W. Chiou†, W. Chu†, J. Larsen†, S. Oltmans‡, J. Lerner*, M. P. McCormick† & L. McMaster†

* NASA/Goddard Institute for Space Studies, New York, New York 10025, USA
† NASA/Langley Research Center, Hampton, Virginia 23665-5225, USA
‡ NOAA CMDL, Boulder, Colorado, 80302, USA

CHIEF among the mechanisms thought to amplify the global climate response to increased concentrations of trace gases is the atmospheric water vapour feedback. As the oceans and atmosphere warm, there is increased evaporation, and it has been generally thought that the additional moisture then adds to the greenhouse effect by trapping more infrared radiation. Recently, it has been suggested that general circulation models used for evaluating climate change overestimate this response, and that increased convection in a warmer climate would actually dry the middle and upper troposphere by means of associated compensatory subsidence[1]. We use some new satellite-generated water vapour data to investigate this question. From a comparison of summer and winter moisture values in regions of the middle and upper troposphere that have previously been difficult to observe with confidence, we find that, as the hemispheres warm, increased convection leads to increased water vapour above 500 mbar in approximate quantitative agreement with the results from current climate models. The same conclusion is reached by comparing the tropical western and eastern Pacific regions. Thus, we conclude that the water vapour feedback is not overestimated in models and should amplify the climate response to increased trace-gas concentrations.

Studies with the Goddard Institute for Space Studies (GISS) general circulation model (GCM) show that, of the 4.2 °C warming that results from doubling atmospheric CO_2, ~1.7 °C is contributed by the increase in water vapour[2]. In this regard, Lindzen[1] believes that the increased convection associated with the projected warming would act to dry the middle and upper troposphere. In his hypothesis, air rising in cumulus convective towers would cool and saturate, producing rain, which would fall out of the column. To balance the upward air-mass flux, there would have to be compensating downward motion, or subsidence, which would dry the atmosphere above ~5 km, thereby leading to a negative water vapour feedback.

In the vicinity of warmer sea surface temperatures, there will be greater convection; indeed, satellite observations have been used to verify that the greenhouse effect is larger over warmer ocean regions[3], suggesting that a positive feedback arises from increased convection. Here we address the question more directly by using satellite-derived water vapour observations to test the water vapour response to increased convection in regions of the middle and upper troposphere that have previously been difficult to observe with other methods.

The water vapour data set has been generated by the SAGE II (Stratospheric Aerosol and Gas Experiment) instrument aboard the Earth Radiation Budget Satellite[4] (ERBS). SAGE II has been collecting data continuously since its launch in October 1984. It is a solar occultation instrument measuring attenuated sunlight through the Earth's limb with a path length of ~200 km and a vertical resolution of 1 km. Each sunrise and sunset experienced by the spacecraft results in a solar occultation measurement yielding ~900 opportunities to retrieve gas-concentration profiles. The path length is small enough to isolate individual areas, but large enough to encompass most of the observed vertical motions associated with convection[10]. Water vapour is retrieved by determining the extinction of the solar signal at 0.94 μm. The instrument is self-calibrating as it observes the unattenuated sun above the atmosphere before or after each event. The water vapour observations have been validated by comparison with radiosonde data, frost point hygrometer, Lyman-α and LIMS satellite observations[5], and have been shown to produce realistic values, with an estimated accuracy of ~10%.

We compared the relative humidity calculated using the SAGE II water vapour data with that calculated using radiosonde observations with the Vaisala water vapour sensor, an instrument now in widespread use. The temperature data needed for the SAGE relative humidity calculations were provided by the National Weather Service of the National Oceanographic and Atmospheric Administration. The estimated radiosonde sensor accuracy is 2–3%, but this value becomes more uncertain with increasing altitude[6]. A comparison was made whenever the satellite and *in situ* measurements were within 250 km and 6 h during 1987.

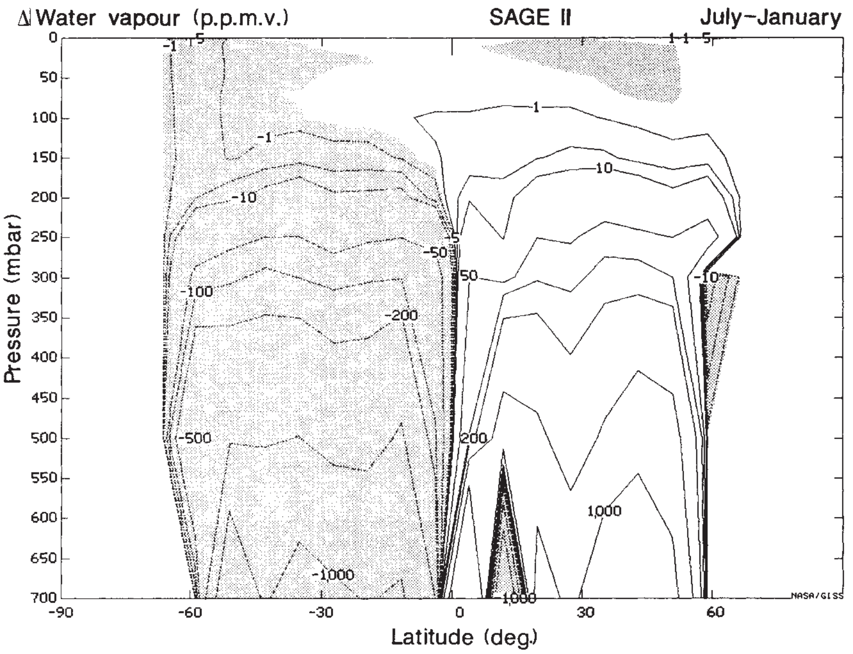

FIG. 1 Change in water vapour between July and January from SAGE II observations for January 1985 to July 1989.

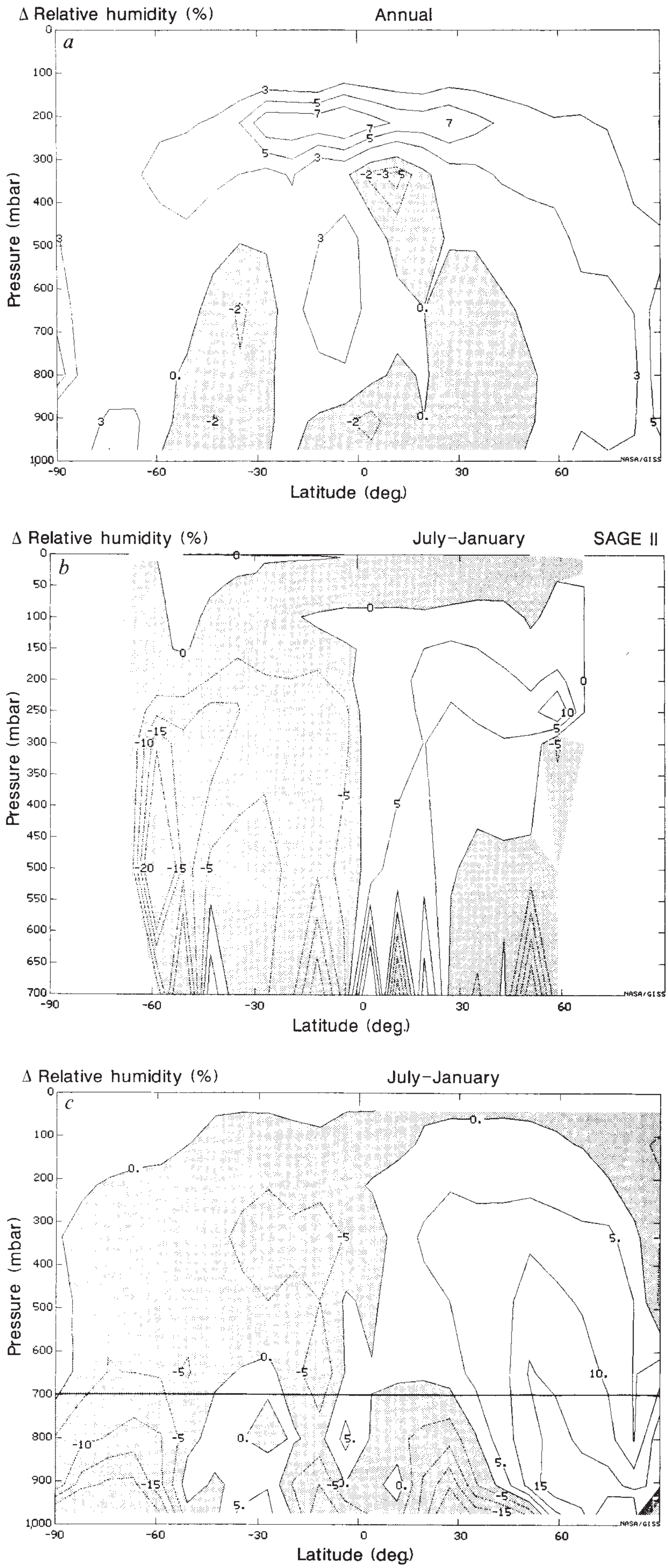

FIG. 2 Change of relative humidity *a*, between the doubled-CO_2 climate and the current climate in the GISS model; *b*, between July and January, SAGE II observations, January 1985 to July 1989; *c*, between July and January in the GISS GCM, for which three July and three January months were used from different years of a five-year simulation of the present climate. For comparison between model and observations, the levels above 700 mbar (solid line) should be considered.

TABLE 1 Comparison of SAGE II and radiosonde relative humidity

Altitude (km)	Number of comparisons	Average difference (%) SAGE II – sonde	Absolute difference (%) |SAGE II – sonde|
5.5	76	−4.3	14.1
6.5	119	−2.4	16.2
7.5	143	3.1	16.1
8.5	174	5.8	14.8
9.5	178	6.7	14.0
10.5	201	4.3	8.6
11.5	216	1.7	5.5
12.5	182	0.5	3.1

The results are shown in Table 1. The average difference between the two data sets is within the instrument uncertainties, and the SAGE data show no obvious bias. The slightly higher SAGE relative humidities in the upper troposphere may be the result of a systematic difference in the calculation of relative humidity at sub-freezing temperatures—with respect to ice in the satellite data set, and with respect to water in the radiosonde retrievals. For example, using global average values, this difference would artificially increase SAGE relative humidities by ~9% at 9.5 km. The absolute differences between the techniques are somewhat larger, possibly due to spatial and temporal heterogeneities that could not be removed.

To test the effects of convection on the atmospheric water vapour profile, we first examine the seasonal variation in troposphere moisture. As each hemisphere in summer experiences greater convection than in winter, we compared the SAGE II retrievals for each July and January for five years of data (Fig. 1). The specific humidity (mass of water vapour per unit mass of moist air) is consistently higher in July in the Northern Hemisphere, and January in the Southern Hemisphere, and there is clearly more water vapour in the middle and upper troposphere (~5–15 km) when there is increased convection. Latitude–longitude plots of specific humidity using the SAGE II data confirm that the specific humidity values are largest in the convective regions[5].

It is also important to investigate the variation of specific humidity with temperature. Compared with the current climate, the GISS model calculates that in a climate with doubled CO_2, the relative humidity will remain approximately constant, with slight increases in the upper troposphere (Fig. 2*a*). Given that the model also predicts considerable temperature increases, of up to 8 °C in the upper troposphere, constant relative humidity implies a large increase in specific humidity, averaging ~33% with a 4 °C global warming.

To determine if the model is producing the proper quantitative water vapour change as a function of temperature under warming conditions, we compared the difference in relative humidity between summer and winter in the SAGE II observations to the results from the model simulation of the present climate (Fig. 2*b*, *c*). The SAGE II retrievals cannot be made through cloud cover, and so to allow the model to duplicate satellite-observing conditions, we reran three Januarys and three Julys from different years of the model simulations of the present climate. We then saved only the data that would have been observed by satellite (that is, we removed data below clouds). In both model and observations, data were available down to 5 km for ~50% of the time.

Both the SAGE II data and the model show that relative humidity does not change much between summer and winter in either hemisphere. There is a slight increase of ~5–10% in the convective (summer) hemisphere above 500 mbar in both the satellite data and the model, which is broadly similar to that forecast for the warmer climate (Fig. 2*a*). Although the differences between summer and winter are not precisely equivalent to the difference between the doubled-CO_2 climate and that of today, both summer and the doubled-CO_2 climate feature warming and increased convection. For example, in the GISS GCM, the convective mass flux passing through 300 mbar in the Northern Hemisphere increases by 28% from winter to summer, whereas, by comparison, the global annual average convective mass flux through the same level increases by 10% in the doubled-CO_2 climate. The seasonal climate change is thus a more severe test for the effects of increased convection, which apparently does not result in drying of the middle and upper troposphere in either the SAGE II data or the model.

An additional test of the effects of convection can be made by investigating the humidity profiles in individual regions. Figure 3 shows the difference in relative humidity, calculated from the SAGE II data, between areas in the convective western Pacific and the largely non-convective eastern Pacific for the altitudes in question, between 5.5 and 11.5 km (~500–200 mbar). Results are shown for the two solstice seasons, when the two regions differ in precipitation by nearly 80% (ref. 7), almost all of which is convective in origin. The west Pacific has higher relative humidity throughout most of the altitude range, although the differences are small. At 400 mbar (~7.5 km), the observed temperatures in the western Pacific are nearly 2 °C warmer[7], so that even if relative humidities were the same, the western Pacific would have ~20% greater specific humidity. Again, there is no indication of drying associated with increased convection. Shown for comparison are the model results, which also indicate a small increase in relative humidity. The model-generated change occurs with a somewhat different vertical profile. Although a detailed extrapolation is probably not warranted, it would appear that the model is underestimating the greenhouse effect of increased convection, as the predicted water vapour increase peaks at a lower altitude than in the SAGE II observations.

The observed moistening in both the seasonal and regional comparisons is apparently associated with increased convection, as it is most evident in the known convective regions of the western Pacific, and the Amazon and African rainforests during their rainy seasons[5]. Although increased subsidence would probably produce a drying tendency, other processes are affecting the moisture distribution, such as detrainment of water vapour at cloud top, and re-evaporation of moisture blown out of the convective plume. Furthermore, the large-scale circulation can respond to the convective heating with its own vertical transport mechanisms. In total, these other processes seem to offset the effects of drying due to subsidence.

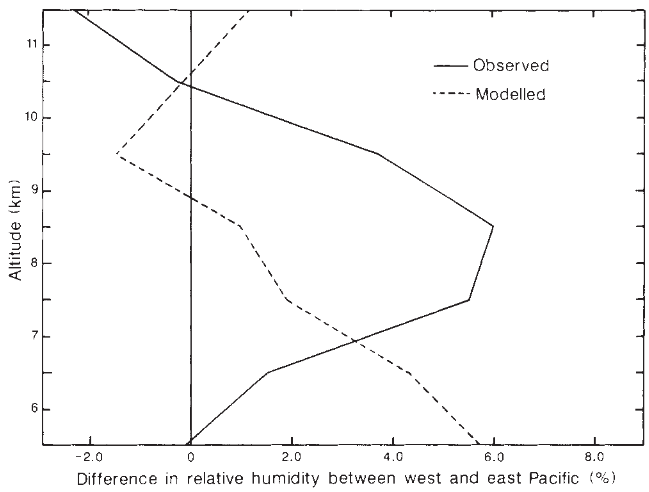

FIG. 3 Difference in relative humidity between the east Pacific (90°–120° W, 0°–30° N) and west Pacific (120°–150° E, 0°–30° N) for the two solstice seasons from the SAGE II data (observed) and the GISS GCM (modelled).

As noted by Cess[8], the various GCMs agree remarkably well concerning clear-sky long-wave feedback, and the results of our study and that of Raval and Ramanathan[3] indicate that GCMs appear to be consistent with two independent clear-sky data sets. The similarity of modelled and observed relative humidity variations under warming conditions is a first-order validation of the model's water vapour response, and does suggest that the models are not overestimating the water vapour feedback. The predicted 1.7 °C warming from this process, in combination with the 1.2 °C warming from doubled CO_2, brings the system response close to 3 °C. The ice-albedo feedback, due to decreased snow cover and sea ice, is also likely to be positive, with a magnitude, in the GISS GCM, of nearly 0.4 °C[2]. That leaves only cloud properties as an obvious possible mitigating (or amplifying) factor. Given the potential impact of a 3-4 °C warming on droughts and ecosystems[9], our results re-emphasize the importance of reducing trace-gas emissions. □

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Could reducing fossil-fuel emissions cause global warming?

T. M. L. Wigley

Climatic Research Unit, University of East Anglia, Norwich NR4 7TJ, UK

WHEN fossil fuel is burned, both carbon dioxide and sulphur dioxide are added to the atmosphere. The former should cause warming of the lower atmosphere by enhancing the greenhouse effect, whereas the latter, by producing sulphate aerosols, may cause a cooling effect. The possibility that these two processes could offset each other was suggested many years ago (see, for example, ref. 1), but during most of the intervening period, attention has focused on the greenhouse effect. Interest in tropospheric aerosols has, however, recently been rekindled by the realization that they may influence climate, not only through clear-sky radiative effects[2–5], but also by modifying cloud albedo[6–8]. Here I examine the sensitivity of the climate system to simultaneous changes in SO_2 and CO_2 emissions, as might occur if controls were imposed on fossil-fuel use. Over the next 10–30 years, it is conceivable that the increased radiative forcing due to SO_2 concentration changes could more than offset reductions in radiative forcing due to reduced CO_2 emissions.

The relative emissions of SO_2 and CO_2 from fossil-fuel combustion depend on fuel type and emissions-control technologies, and so could change in the future. As a baseline case, however, I assume that emissions of both gases will parallel total fuel use, and consider total fossil-fuel use to change with a constant growth rate. Future SO_2 and CO_2 emissions are therefore both

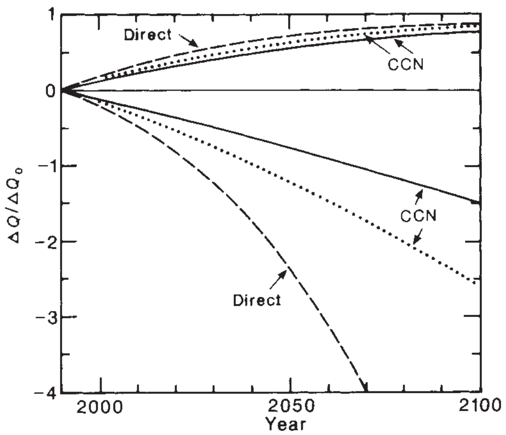

FIG. 1 Northern Hemisphere SO_2-related radiative-forcing changes (W m^{-2}) for emissions growth rates of +2% yr^{-1} (lower curves) and −2% yr^{-1} (upper curves). The values are expressed relative to the appropriate forcing increment to 1990 ($\Delta Q_{0,dir}$ or $\Delta Q_{0,indir}$) with the sign changed so that the results reflect the sign of future changes (that is, a positive forcing effect for −2% yr^{-1} growth rate). The uppermost and lowermost curves (long dashes) show the direct effect of changes in clear-sky sulphate aerosol. The innermost curves (full lines) show the indirect (CCN) effect for a present to pre-industrial SO_2 emissions ratio (E_1/E_0) of 3.6, as suggested by the modelling study of Charlson *et al.* (ref. 5). The short dashed curves show the indirect (CCN) effect for $E_1/E_0=1.8$. Note that the apparently larger CCN effect for smaller E_1/E_0 is only relative to $\Delta Q_{0,indir}$.

determined by an equation of the form

$$E = E_0 + (E_1 - E_0)\,e^{\alpha t} \qquad (1)$$

where E_0 is the natural background emission rate, E_1 is the current total emission rate (at time $t=0$) and α is the growth rate. To determine the possible effect of reductions in fossil-fuel use on climate, I will compare the SO_2- and CO_2-derived changes in radiative forcing for three scenarios: growth rates of zero and ±2% yr^{-1}.

Consider the direct SO_2 effect first. The forcing change, dQ_{dir}, is approximately proportional to the change in the integrated column burden of sulphate aerosol, which in turn is approximately proportional to the change in mean-column SO_2 concentration[5]. As the lifetime for SO_2 is much less than a year, changes in SO_2 concentration must parallel emission changes. The direct radiative forcing may therefore be considered as linearly related to changes in emissions:

$$dQ_{dir} = a\,dE \qquad (2)$$

For the indirect SO_2 effect through changes in cloud albedo, $dQ_{indir} \propto dC/C$, where C denotes the cloud-condensation-nuclei (CCN) concentration[6,7]. If changes in C are linearly related to changes in aerosol concentration (as assumed, for example, in refs 8 and 9) then, as changes in aerosol concentration should be approximately linearly related to changes in SO_2 emissions (see above), we obtain

$$dQ_{indir} \propto dE/E = b\,dE/E \qquad (3)$$

for the indirect forcing change. The C–A link (A denotes aerosol concentration) is known to be nonlinear[10,11], but equation (3) still applies provided that the relationship can be expressed in the form $C \propto A^n$.

The above relationships between emissions and forcing are only approximate, and the constants a and, in particular, b are of uncertain magnitude. These uncertainties can be circumvented by expressing future forcing changes in terms of the present man-made SO_2-related forcing (denoted by ΔQ_0). ΔQ_0 is not known, but the range of possible values can be estimated by noting that the preponderance of SO_2 emissions in the Northern Hemisphere should have led to a difference in the temperature record of the two hemispheres. As no striking difference is