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Why is the global warming proceeding much slower than expected?

L. Bengtsson, E. Roeckner, and M. Stendel
Max-Planck-Institut für Meteorologie, Hamburg, Germany

Abstract. Upper air observations from radiosondes and microwave satellite instruments does not indicate any global warming during the last 19 years, contrary to surface measurements, where a warming trend is supposedly being found. This result is somewhat difficult to reconcile, since climate model experiments do indicate a reverse trend, namely, that upper tropospheric air should warm faster than the surface. To contribute toward an understanding of this difficulty, we have here undertaken some specific experiments to study the effect on climate due to the decrease in stratospheric ozone and the Mount Pinatubo eruption in 1991. The associated forcing was added to the forcing from greenhouse gases, sulfate aerosols (direct and indirect effect), and tropospheric ozone, which was investigated in a separate series of experiments. Furthermore, we have undertaken an ensemble study in order to explore the natural variability of an advanced climate model exposed to such a forcing over 19 years. The result shows that the reduction of stratospheric ozone cools not only the lower stratosphere but also the troposphere, in particular, the upper and middle part. In the upper troposphere the cooling from stratospheric ozone leads to a significant reduction of greenhouse warming. The modeled stratospheric aerosols from Mount Pinatubo generate a climate response (stratospheric warming and tropospheric cooling) in good agreement with microwave satellite measurements. Finally, analysis of a series of experiments with both stratospheric ozone and the Mount Pinatubo effect shows considerable variability in climate response, suggesting that an evolution having no warming in the period is as likely as another evolution showing modest warming. However, the observed trend of no warming in the midtroposphere and clear warming at the surface is not found in the model simulations.

1. Introduction

Several papers [*Santer et al.*, 1996; *Hegerl et al.*, 1997; *North and Stevens*; 1998] have recently addressed the problem of whether climate warming caused by the ongoing increase in atmospheric concentration of greenhouse gases is detectable or not. The general conclusion, as summarized by the latest *Intergovernmental Panel on Climate Change* (*IPCC*) [1996] report, is that there are indications, that such a warming is under way. However, it appears that the warming is proceeding slower than expected and some data sets, such as the satellite microwave sounding data [*Christy*, 1995] and radiosonde observations [*Angell*, 1988; *Christy et al.*, 1998], do not show any warming at all for the time period 1979–1997, but in fact a slight cooling (Table 1). Other data sets, such as temperatures from surface weather stations and ocean ship and buoy data, show a warming trend of +0.15 K/decade [*Rayner et al.*, 1996]. The disagreement between the upper air and the surface observational records, on the one hand, and between the model calculations (showing a distinct warming) and upper air observations (showing a slight cooling), on the other hand, has caused some consternation, and from some quarters the accusation has been raised [*Singer*, 1996] that model results are unreliable in view of their inability to reproduce the temperature trend over the last two decades, a period which in fact is the only time with truly reliable global observations through the depth of the atmosphere.

It is not the intention in this paper to analyze in depth the apparent inconsistency between the surface temperature records and the microwave sounding data and radiosondes. Instead, we will describe a series of recent climate change experiments including the effect of ozone reduction in the stratosphere and the influence on climate of the Mount Pinatubo eruption, which we believe will contribute toward clarifying the issue raised in the previous paragraph.

The experiments reported here are part of a comprehensive climate change study carried out over the last 2 years at the Max-Planck-Institute for Meteorology in Hamburg. The main part of this investigation is being reported elsewhere [*Roeckner et al.*, 1998]. It consists of three transient integrations with the European Center/Hamburg (ECHAM4)/OPYC coupled model and an associated control integration considering the climate effect of greenhouse gases, sulfate aerosols, and tropospheric ozone. These integrations were started in 1860 and were exposed to successively increased concentrations of greenhouse gases, tropospheric ozone, and sulfate aerosols as determined from observed data. We will briefly summarize the result of these experiments in section 2. In section 3 we will describe the experiments with stratospheric ozone. We have then replaced the representation of stratospheric ozone in the control experiment, GSDIO (see Table 2), with the observed ozone values month by month for the years 1979–1997 [*de Winter-Sorkina*, 1997].

In section 4 we present the result from the simulation of the

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Table 1. Comparison of Decadal Temperature Trends Since 1979 for Three Simulation Experiments, for Radiosondes and MSU-Based Tropospheric Data Sets, and Surface Data Sets

	Experiment					
Level	GHG	GSD	GSDIO	Radiosondes[a]	T_{2LT}[b]	Synop[c]
500 hPa	+0.42	+0.22	+0.38	−0.06	−0.04	···
Surface	+0.35	+0.09	+0.27	···	···	+0.15

[a] *Angell* [1988] and updates [from *Christy et al.*, 1998], temperature 850–300 hPa.
[b] MSU data T_{2LT} [from *Christy et al.*, 1998].
[c] Surface data [*Rayner et al.*, 1996] (for the period 1979–1995 only).

Mount Pinatubo eruption. We have used the geographical distribution of aerosols monthly averaged according to *Stenchikov et al.* [1997]. Section 5 summarizes the results of a series of perturbation experiments investigating the combined effect of stratospheric ozone and the Mount Pinatubo eruption.

2. Control Experiment

For the experiments, we have used a coupled atmosphere-ocean general circulation model (GCM) [*Roeckner et al.*, 1996a, b]. The atmospheric and land surface component of the coupled model is the fourth-generation Max-Planck-Institut (MPI) model, ECHAM4. Prognostic variables are vorticity, divergence, surface pressure, temperature, water vapor, and cloud water. ECHAM4 is a spectral transform model with triangular truncation at wave number 42, equivalent to a horizontal resolution of 250–300 km. Advection of water vapor and cloud water is done with a semi-Lagrangian scheme [*Rasch and Williamson*, 1990]. The ECHAM4 model has been tested extensively and has been found to reproduce the atmospheric circulation with a high level of realism [e.g., *Chen and Roeckner*, 1996, 1997; *Tibaldi et al.*, 1997].

The ocean and sea ice is based on the OPYC model [*Oberhuber*, 1993a, b]. It is an isopycnal model and consists of three submodels for the interior ocean, the surface mixed layer and sea ice, respectively. The horizontal resolution of the ocean model is the same as that of the physical grid of the atmospheric model except in the longitudinal direction of the equatorial zone, where the resolution is increased to some 50 km. This was found to be required to realistically resolve the El Niño phenomenon [*Roeckner et al.*, 1996a].

As described by *Roeckner et al.* [1996a], the two model components are coupled through a mutual exchange of fluxes. Fluxes of momentum are unconstrained, while fluxes of heat and water vapor are flux adjusted, but only as annual averages. The purpose is to assure that the annual cycle of the model can interact freely with the coupled modes of the model such as El Niño–Southern Oscillation (ENSO).

The coupled MPI model has also been thoroughly evaluated in extensive control integrations [*Roeckner et al.*, 1996b; *Christoph et al.*, 1998]. The model simulates the ENSO phenomenon quite realistically and has, in fact, been successfully used as a forecasting model by dynamically adjusting the model toward a time sequence of observed sea surface temperatures (SSTs) [*Oberhuber et al.*, 1998]. It was found that the model predicted not only the 1997 El Niño phenomenon quite realistically, but also the corresponding climate response pattern (J. M. Oberhuber et al., personal communication, 1998).

As explained by *Roeckner et al.* [1998] and in Table 2, three major transient climate change experiments have been carried out. They all start in the year 1860. Estimated and observed concentrations of greenhouse gases and sulfate aerosols have been used until 1990 and thereafter changes according to the IPCC scenario IS92a. In this study, though, we will only concentrate on the time evolution until the present.

In the first simulation called GHG, the concentrations of the following greenhouse gases are prescribed as a function of time: CO_2, CH_4, N_2O, and also a series of industrial gases including CFCs and hydrochlorofluorocarbons (HCFCs). The absorptive properties of each gas constituent have been separately calculated, in contrast to the majority of previous climate change studies [*Cubasch et al.*, 1995; *Murphy and Mitchell*, 1995], where the minor greenhouse gases have been considered as proxy CO_2. Although the effect of treating the different greenhouse gases separately is minor, it nevertheless adds to the realism of this study. Furthermore, we have assured that the radiative forcing is practically identical to the narrowband calculations. This means here an increase in the radiative forcing by some 10% compared to the actual broadband calculation in the radiation code of the model.

In the second simulation, GSD, the greenhouse gases are treated as in GHG but with the additional incorporation of the tropospheric sulfur cycle as due to anthropogenic sources only. Natural biogenic and volcanic sulfur emissions are neglected, and the aerosol radiative forcing is generated through the anthropogenic part of the sulfur cycle only. The space/time evolution in the sulfur emissions has been derived from the work by *Örn et al.* [1996] and *Spiro et al.* [1992]. Previous studies [*Roeckner et al.*, 1995; *Mitchell et al.*, 1995] have mostly considered the effect of sulfate aerosols in a simplistic way by making use of an independent calculation of equilibrium distribution of sulfate aerosols and then, from this distribution, modified the surface albedo correspondingly. In this study we have integrated the full anthropogenic sulfur cycle in the atmospheric model including the actual geographical emission of SO_2, chemical transformation to sulfate, semi-Lagrangian transport of the sulfate aerosols, and finally, the dry and wet

Table 2. Reference Experiments

Acronym	Forcing	Simulation Period
GHG	CO_2 and other well-mixed greenhouse gases	1860–2100
GSD	GHG plus sulfate aerosols (direct effect only)	1860–2050
GSDIO	GHG plus sulfate aerosols (direct and indirect effect) plus tropospheric ozone	1860–2050

From *Roeckner et al.* [1998].

disposition of sulfate particles from the atmosphere [*Feichter et al.*, 1996]. A more comprehensive presentation is provided by *Roeckner et al.* [1998].

In the third simulation, GSDIO, we have additionally included the indirect aerosol effect on cloud albedo according to *Boucher and Lohmann* [1995] and *Lohmann and Feichter* [1997] as well as letting the tropospheric ozone distribution change as a result of the prescribed anthropogenic emission of precursor gases [*Roelofs and Lelieveld*, 1995]. The change in the radiative forcing for the period 1860–1990 is shown in Table 3.

The global annual mean temperature change from the three experiments, GHG, GSD, and GSDIO, is shown in Figure 1. As can be expected, the long-term warming is largest in experiment GHG and smallest in experiment GSDIO. Until 1980 or so, the fluctuations are more or less similar to the observed temperature variations. The simulated temperature patterns undergo large low-frequency variations on a multidecadal timescale in broad agreement with the estimated observed temperature pattern. In the model simulations there are pronounced ultralow fluctuations at higher latitudes of the southern hemisphere; it is not possible to say whether these fluctuations are realistic or simply an artefact of the coupled model.

Since in this study we will discuss the evolution of the global temperature during the last two decades, it is important to note that there are considerable natural variations in the global temperature trend over such a short time-space [*Manabe and Stouffer*, 1996; *Bengtsson*, 1997]. As can be seen from Plate 1, in the period 1979–1997 the warming in experiment GSD is actually less than in experiment GSDIO, while in the longer perspective (Figure 1), the trend follows broadly the radiative forcing. This makes it virtually impossible to make any firm statements of the size of global warming from observational records from the two decades we are investigating here. In section 5 we estimate the magnitude of the natural variability of the period 1979–1997 by means of an ensemble type experiment. Finally, there is also the problem of the reliability of the observational records themselves [*Hurrell and Trenberth*, 1996, 1998; *Christy et al.*, 1998].

However, there are several additional factors which are important. We will here describe some recent experiments to study the climate effect of the stratospheric ozone reduction in the last decades as well as the influence of the Mount Pinatubo eruption in 1991. This is a period for which we have excellent coverage of global observations through the depth of the atmosphere mainly due to quantitative measurements from satellite observing systems, which were not available before 1979. Of particular interest are here observations from microwave satellite data, microwave sounding unit (MSU), which have been carefully tested and evaluated [*Christy*, 1995]. In spite of some critical studies [*Hurrell and Trenberth*, 1997, 1998; *Wentz and Schabel*, 1998], we consider the thorough evaluation by *Christy et al.* [1998] as fully convincing. There is also an almost complete agreement between the MSU-data and radiosonde observations (Table 1). If both the upper air data and the surface data are correct, then there is a problem in explaining why the surface data and the SST data are characterized by a trend other than the data of the lower troposphere. In Table 1 we have compiled the surface and the 500 hPa temperature trend from the three experiments GHG, GSD, and GSDIO with the observations from MSU, radiosondes, and surface temperature data. The warming trend at 500 hPa is in all three experiments clearly positive, while both the radiosondes and the MSU T_{2LT} have a slightly negative trend, indicating a minor global tropospheric cooling since 1979. The surface temperature warming trend of the model experiments with greenhouse gases is slightly smaller than at 500 hPa, the enhanced warming with height being presumably caused by feedback through the moist adiabatic lapse rate [*Manabe and Wetherald*, 1975; *Manabe*, 1997; *Bengtsson*, 1997; *Tett et al.*, 1996].

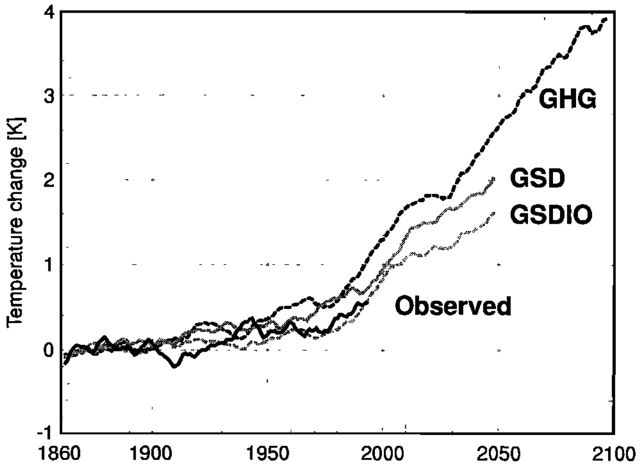

Figure 1. Decadal mean changes in the globally averaged surface temperature (K) in three different climate change experiments as described in Table 2. The observed surface temperature is indicated by a heavy solid line.

This is in disagreement with the observed data, where in fact, there is an opposite relation: the surface is warming and the lower troposphere is cooling. Before we start to question the reliability of the surface or, in fact, the upper air data, we will analyze the results from the experiments incorporating the effect of the reduction of stratospheric ozone and the effect of the Mount Pinatubo eruption.

Table 3. Changes in the Global Annual Mean Radiative Forcing

Forcing Experiments From Observed Data 1860–1990	Radiative Forcing, W m^{-2}
1. Well-mixed greenhouse gases (CO_2, CH_4, N_2O, CFCs, HCFs, etc.); same forcing as experiment GHG	2.11
2. Tropospheric ozone	0.39
3. Direct sulfate aerosols	−0.35
4. Indirect sulfate aerosols	−0.91
5. Experiments 1–4 included; same forcing as experiment GSDIO	1.24

3. Stratospheric Ozone

In situ observations as well as satellite measurements, Stratospheric Aerosol and Gas Experiment (SAGE) [*McCormick et al.*, 1992], and Total Ozone Mapping Spectrometer (TOMS) [*Stolarski et al.*, 1991] have clearly demonstrated the reduction in stratospheric ozone, in particular, during the last two decades. The adjusted radiative forcing for the period 1979–1994 [*Hansen et al.*, 1997, Figure 15] suggests a negative overall value of 0.20–0.28 W m^{-2}. The mechanisms by which the ozone depletion cools the surface is via reduction of longwave radiation to the surface due to cooling of the local atmospheric level. Of particular importance is the ozone reduction

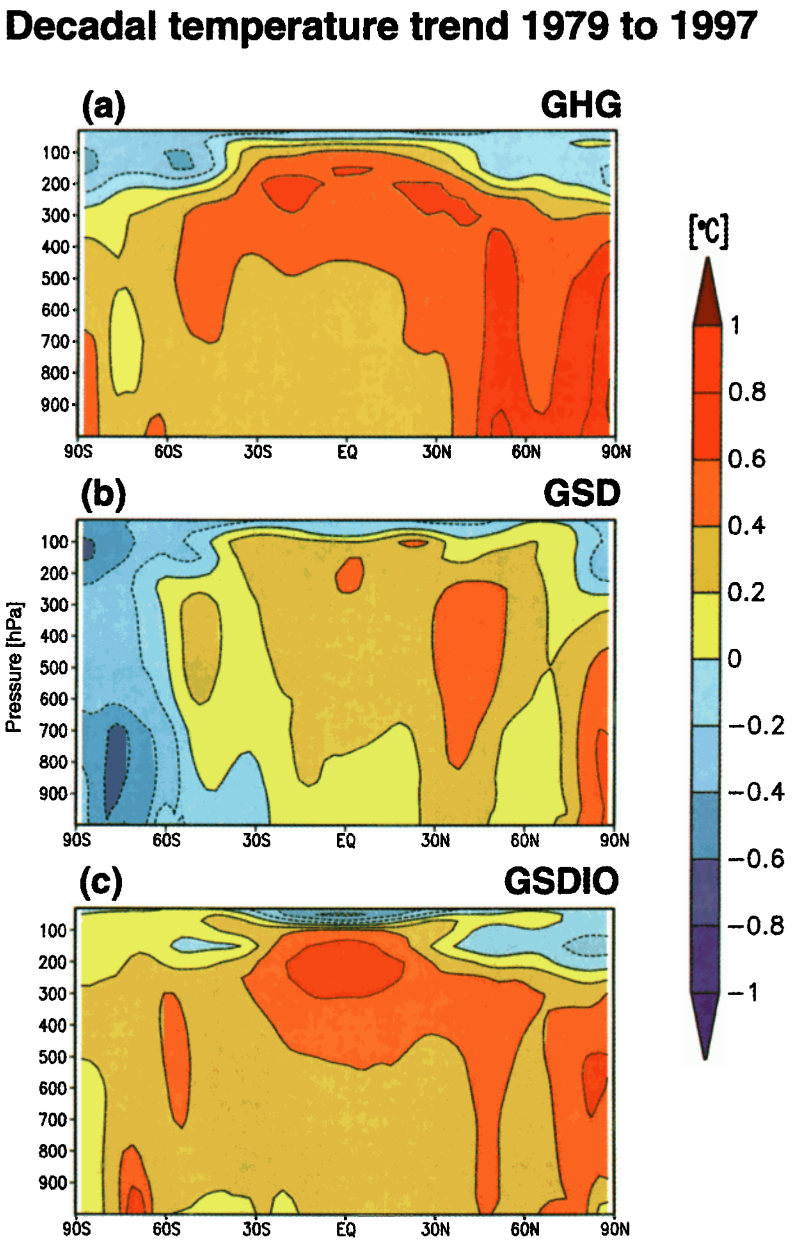

Plate 1. Zonally averaged cross sections of the decadal temperature trends for (a) GHG, (b) GSD, and (c) GSDIO, valid for the period 1979–1997. Note that due to natural variability, the warming in the GSD is less than that in GSDIO.

near the tropopause, where ozone absorption is still strong due to pressure broadening of the absorption bands. As *Hansen et al.* [1997] have pointed out, the specific vertical distribution of ozone is important and vertical redistribution can change the result significantly. We have here made use of a compiled data set produced month by month for the time period November 1978 to April 1993 [*de Winter-Sorkina*, 1997]. We have linearized the trend for each month and for each latitude band and extended it for the whole period 1979–1997. This data set thus includes the geographical variability, so the effect of the Antarctic ozone hole has been properly accounted for.

We have further undertaken two independent integrations for the period 1979–1997 starting from slightly different initial states. The reference integration has been the experiment GSDIO, and in the following we will consider this as the control experiment.

Plate 2 shows the temperature trend of experiment GSO being the average of two realizations of GSDIO + stratospheric ozone (Table 4), as well as the difference between this experiment and GSDIO. The two experiments are rather similar at the southern hemisphere and in the tropics but differ substantially over the northern hemisphere. Major differences can be seen both in the troposphere and in the stratosphere, stressing the high level of internal dynamical variability not least in the stratosphere [e.g., *Manzini and Bengtsson*, 1996]. This is again an example of the sampling problem, highlighting the importance of undertaking ensemble calculations for climate change studies.

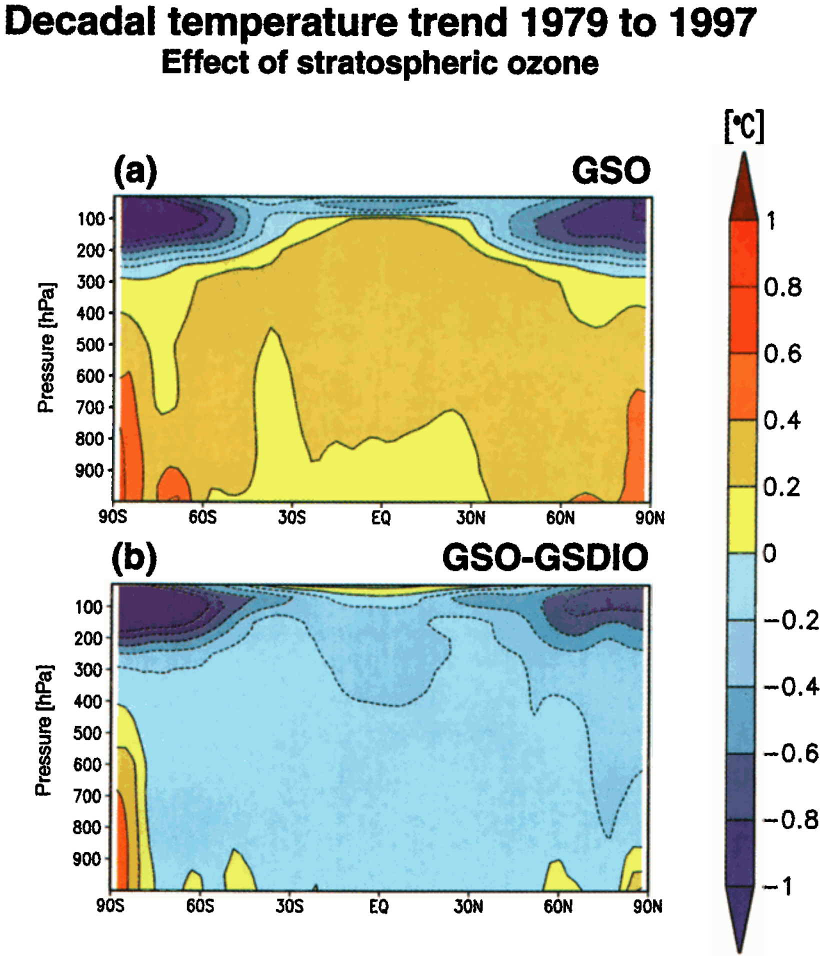

Plate 2. Zonally averaged cross sections of the decadal temperature trends for (a) GSO and the difference GSO − GSDIO for the period 1979–1997. Mean of two realizations. Note the major cooling in the lower stratosphere at high latitudes.

4. Mount Pinatubo Eruption

The volcanic eruption of Mount Pinatubo on the Philippine Island Luzon on June 15–16, 1991, was one of the largest in this century. It is estimated [*Krueger et al.*, 1995] that 14–21 million tons of SO_2 were injected into the stratosphere. The volcanic cloud moved eastward by some 20 m s^{-1}, thus encircling Earth in 3 weeks, whereby SO_2 was converted into sulfate aerosols [*Bluth et al.*, 1992].

In the first month, most of the aerosol mass was located in a band between 20°S and 30°N, and then gradually, the cloud spread to finally encircle the whole global stratosphere. Radiosonde observations as well as measurements from the MSU indicated a global stratospheric warming of about 2 K. The observations also suggested a cooling of the lower global troposphere and the surface of Earth by about 0.5 K [*Dutton and Christy*, 1992]. Whether the cooling of the troposphere was a consequence of the Mount Pinatubo eruption is not so easy to determine, since there are considerable temperature variations caused, for example, by large-scale air-sea interaction events such as the El Niño phenomenon. However, a cooling of the lower troposphere by about 0.5 K is actually calculated by the coupled MPI model.

There was also an extraordinarily high ozone reduction, which was detected in 1992 and 1993. We will not discuss this further here. At a later stage, we intend to carry through an experiment with this coupled model incorporating the chemical processes occurring at the surface of the aerosol particles leading to an increase in active chlorine species and thus to ozone losses [*Solomon et al.*, 1996]. In the experiment described in section 3, we used the observed ozone distribution, but only as a linear trend, so we have only partly incorporated the climate effect of this additional ozone destruction.

We carried through three specific experiments. Two of them used GSDIO as the reference integration. A third integration used the GSDIO with stratospheric ozone as the reference integration. Aerosol density, size distribution, and chemical composition and their three-dimensional distribution (monthly

Table 4. Experiments Carried Out in This Study

Acronym	Experiment and Forcing	Simulation Period
GSO	same as GSDIO but with the observed stratospheric ozone distribution; two experiments	1979–1999
GSP	same as GSDIO but with the added effect of the Mount Pinatubo eruption; two experiments	1991–1997
GSOP	same as GSDIO but with the observed stratospheric ozone distribution and the effect of the Mount Pinatubo eruption; one experiment	1979–1997

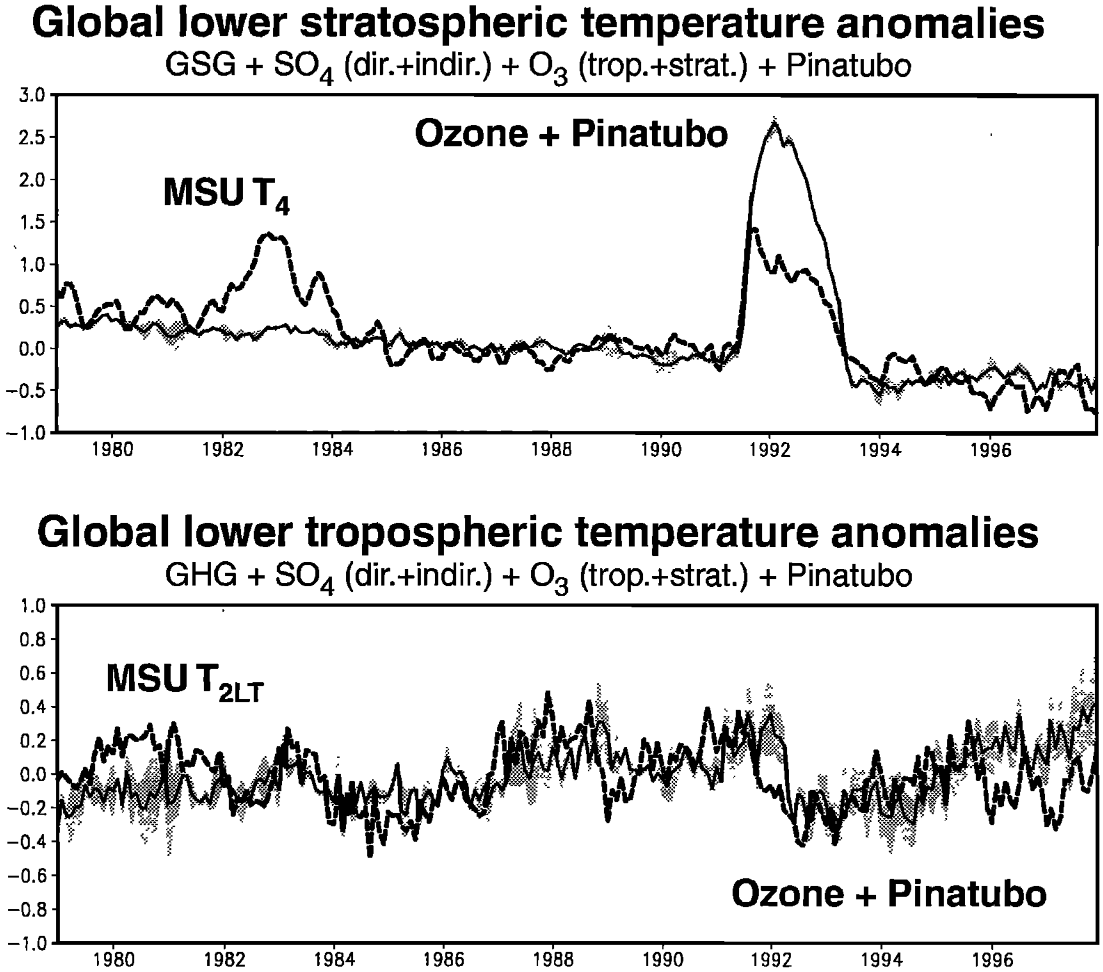

Figure 2. Observed microwave sounding unit (MSU) temperature, shown as dashed line, for channel 4 (top) for the period 1979–97 and the equivalent for the simulations with Mount Pinatubo and stratospheric ozone. The mean value obtained from the six realizations is denoted by the solid line, whereas the shaded area represents this value plus and minus one standard deviation of the individual simulations, respectively. (bottom) The same as Figure 2 (top) for channel 2_{LT}. Note the steady response in the stratosphere and the large variability in the lower troposphere.

averaged) were obtained from *Stenchikov et al.* [1997]. The volcanic aerosols were inserted during the period June 1991 until June 1993, but the integrations were continued until the end of 1997. All integrations (see Figure 2) demonstrate clearly a marked response of the Mount Pinatubo eruption, suggesting that the climate effect of a major volcanic eruption, such as Pinatubo, has a prolonged influence on the climate system due to the delayed influence of the oceans [*Robock and Mao*, 1995; *Lindzen and Giannitsis*, 1998].

5. Climate Change Evaluation

In order to obtain a preliminary estimate of an upper and lower bound of the temperature trend for the period, we have combined the stratospheric ozone and the Pinatubo run into six separate realizations. The number of experiments had to be restricted for computational reasons. The six realizations have been composed from the three independent Pinatubo experiments and two independent stratospheric ozone runs, all integrations initialized in 1979 from the reference experiment GSDIO. Figure 2 shows the results from the different integrations compared to the observed MSU data. The results of the experiments have been expressed in terms of equivalent MSU data [*Stendel and Bengtsson*, 1997].

The simulated stratospheric warming is higher than that observed; the differences are related to an equatorial cooling associated with an easterly phase of the quasi-biennial oscillation (QBO) (which is not (well) simulated by the model) and to the fact that stratospheric depletion of ozone due to the Mount Pinatubo eruption was not incorporated. The tropospheric cooling is in broad agreement with the satellite observations, suggesting the Mount Pinatubo eruption cooled the lower troposphere by some 0.5 K. The standard deviation of the experiments is indicated by shading. Note the stable response of the Mount Pinatubo eruption in the stratosphere.

It should be stressed that in this perturbation experiment, we have only perturbed the atmospheric initial state and not that of the oceans. A realistic perturbation of the state of the ocean circulation is likely to further increase the variance within the ensemble. In the following, we will show the mean of the six realizations as well as the cases with the largest and smallest warming trend.

Plate 3 shows three different zonally averaged cross sections of the different experiments including both Mount Pinatubo

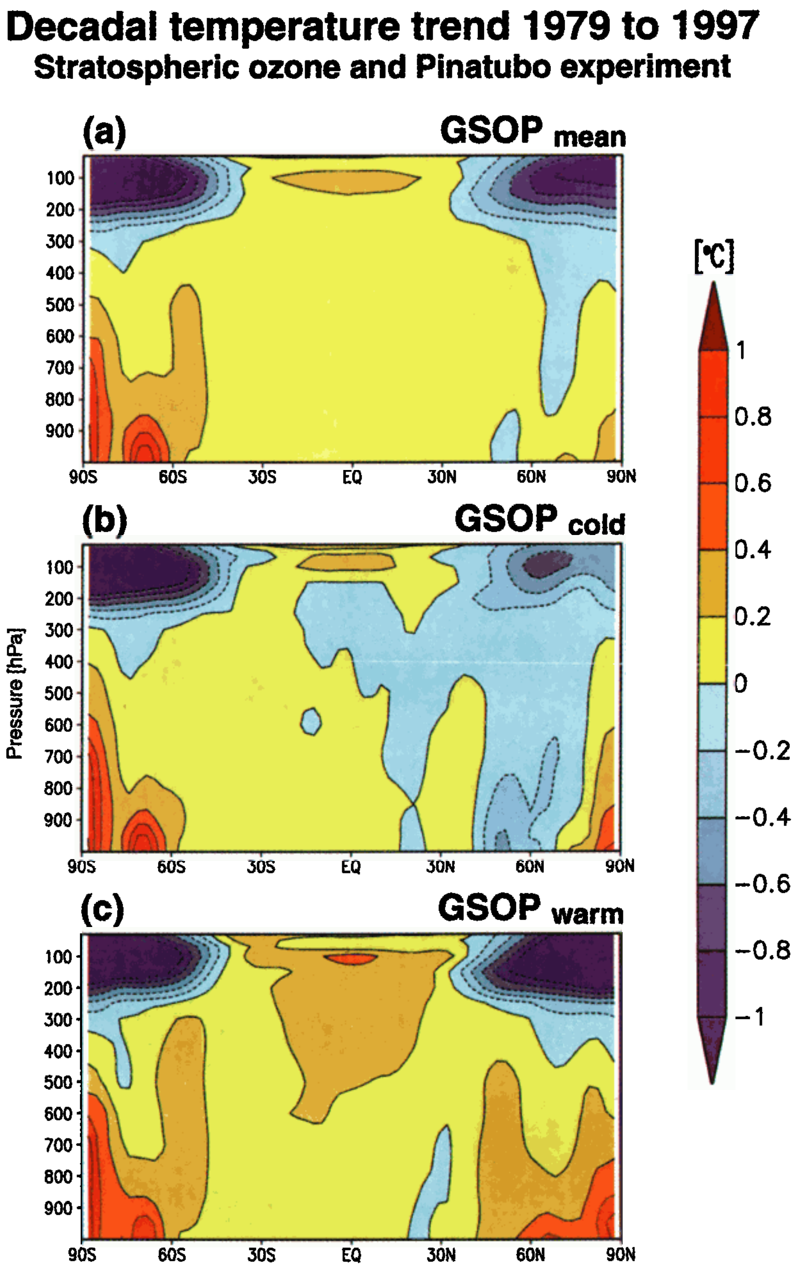

Plate 3. Zonally averaged cross sections of the decadal temperature trend 1979–1997 for the (a) averaged stratospheric ozone and Mount Pinatubo run, GSOP, and for the case with (b) minimum tropospheric warming and (c) maximum tropospheric warming.

Table 5. Comparison of Decadal Temperature Trends Since 1979 for the GSOP Experiment "Mean" column gives the mean of six realizations; "minimum" and "maximum" columns give the case with the smallest and largest decadal trend, respectively. GSOP is the same as GSDIO but with the added effect of stratospheric ozone and the Mount Pinatubo eruption.

Level, hPa	GSOP Experiment		
	Mean	Minimum	Maximum
50	−0.17	−0.15	−0.17
500	+0.10	+0.02	+0.16
850	+0.10	+0.03	+0.15
Surface	+0.12	+0.04	+0.19

and stratospheric ozone (mean, maximum and minimum trends). In Table 5 we provide similar information but for 50 hPa, 500 hPa, and the surface.

GHG and GSDIO have rather similar patterns but with a reduced warming in GSDIO. The largest warming occurs in the upper tropical troposphere and in the lower troposphere at high latitudes, particularly, of the northern hemisphere. A cooling takes place in the stratosphere. The reduced stratosphere cooling in GSDIO is atypical and happens only during these two decades. The effect of stratospheric ozone is to reduce warming significantly, in particular, in the stratosphere and upper troposphere. The pattern changes similarly. The three cross sections now also incorporate the effect of the Mount Pinatubo eruption. We also show here the two extreme

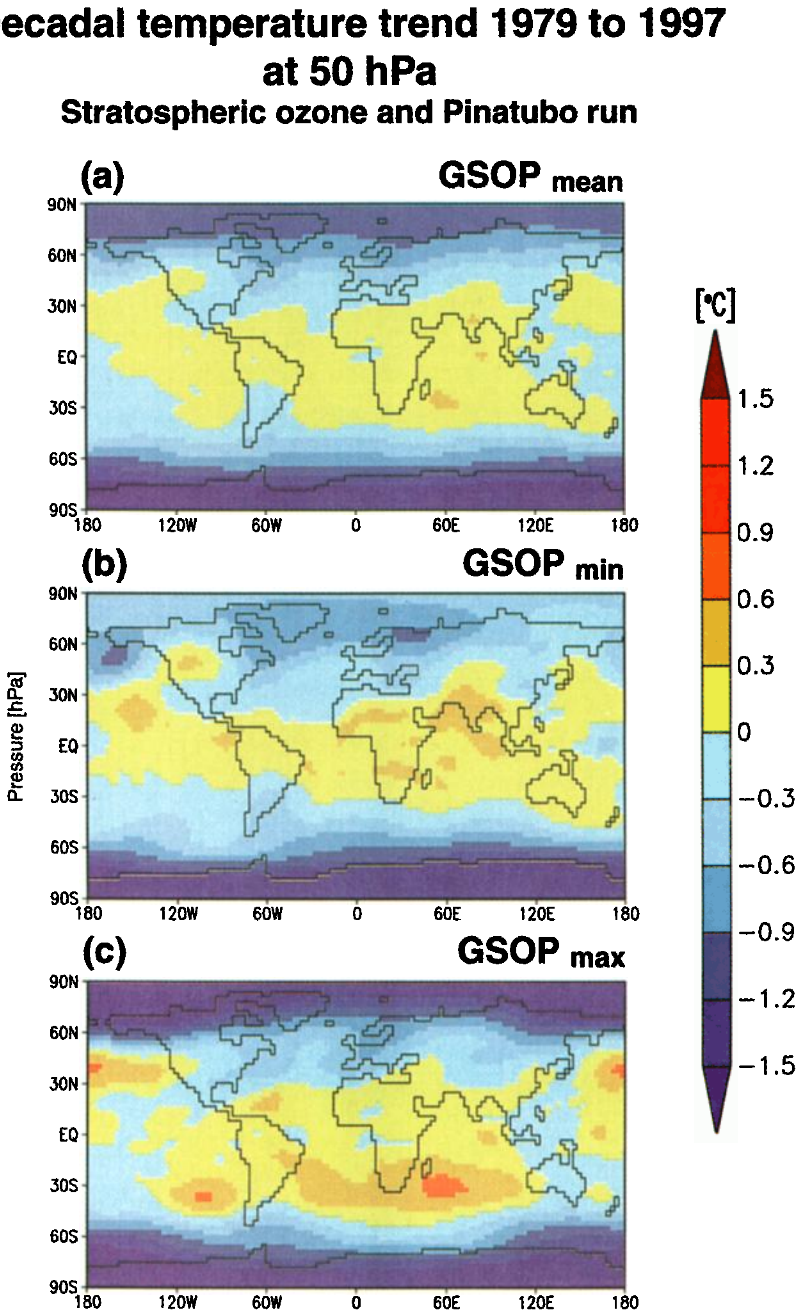

Plate 4. Decadal temperature trend for the period 1979–1997 at 50 hPa and for the (a) averaged stratospheric and Mt. Pinatubo run and for the case with (b) minimum warming trend and (c) maximum warming trend.

realizations. In the one with the minimum trend, the global trend is close to zero and the northern hemisphere is actually cooling (see Table 5).

In Plates 4–6 we show the geographical patterns for the mean and the two extreme Mount Pinatubo runs for 50 hPa, 500 hPa, and the surface. The stratospheric cooling at high latitudes of both hemispheres is strongly pronounced, and the warming trend in the tropics is due to the Mount Pinatubo eruption. At 500 hPa there are marked pattern variations between the different realizations due to the strong internal variability of the coupled system. The surface shows similar very strong variations between the different realizations, in particular, at the surface. Over the Eurasian region (40°N–70°N; 10°W–135°E) the difference in decadal trend between the warmest and the coldest realization is as high as 0.88 K. Assuming now that the real atmosphere behaves in a similar way (and we have no reason to believe otherwise), it is hardly possible to make any statements about climate warming by inspection of atmospheric global temperature records of this length and even less possible if we restrict the evaluation to certain regions.

In fact, we have good reasons to believe that the variability is even larger. We have here used GSDIO as a reference case. The period 1979–1997 is a period of rapid warming in the GSDIO run; in fact, it is significantly stronger than GSD, which over a longer time, consistent with the stronger positive forc-

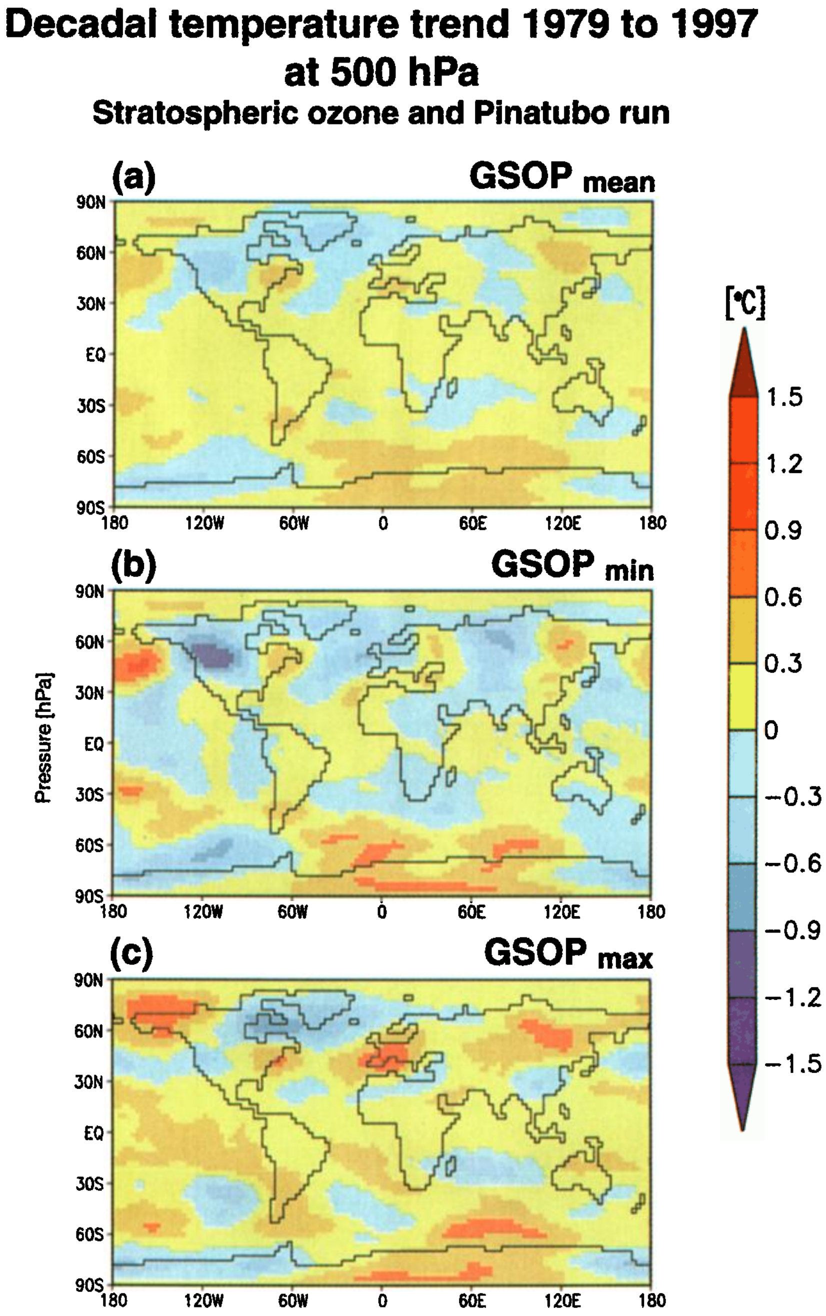

Plate 5. Same as Plate 4 but for 500 hPa.

ing, is warming more rapidly. If we only assume that GSDIO would behave in the same way as GSD over the period 1979–1997, we might expect that this would also affect the stratosphere ozone and the Mount Pinatubo run in a similar direction. In such a situation, the stratospheric and Mount Pinatubo run could then have resulted in an overall cooling trend.

6. Discussion

We have described here a series of climate change experiments with the coupled ECHAM4/OPYC model of the Max-Planck-Institute for Meteorology in Hamburg. The purpose of the experiment was to clarify some of the perceived inconsistencies between global temperature observations over the last two decades and results from climate simulations with a high-resolution, state-of-the-art global coupled model.

First, it is a common result from available general circulation coupled models that they show a considerable variability on timescales less than 50 years or so. This variability is due to internal dynamic processes and is, in essence, not possible to predict. Identical climate change integrations differing only slightly in the initial state (well within the observational accuracy) generate patterns which after some time of integration are quite different from each other. A typical standard deviation in globally averaged decadal trends for a 20-year time interval is of the order of 0.2–0.3 K.

This variability seems to be somewhat larger in comparison

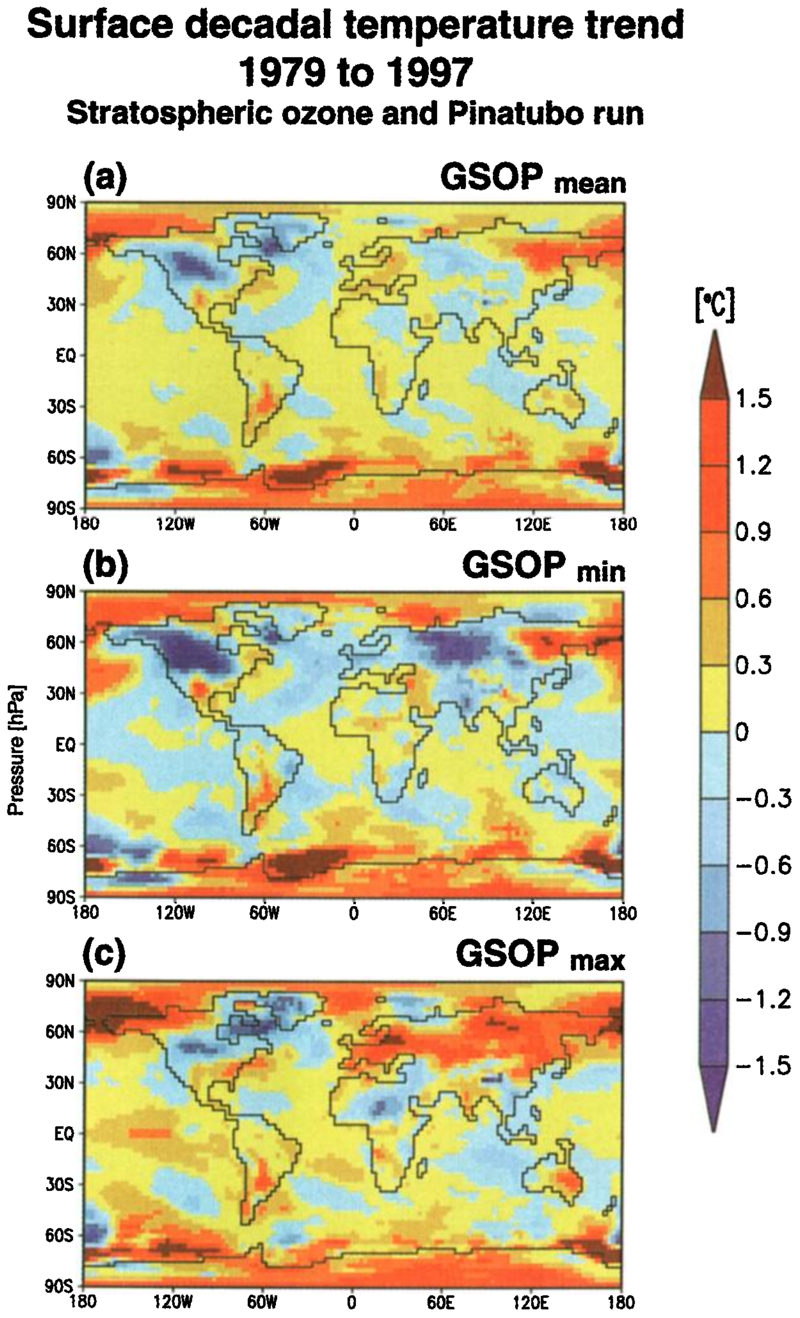

Plate 6. Same as Plate 4 but for the surface.

to some other coupled models. A possible explanation could be that the model used here has a comparatively high horizontal resolution and also has the capability to resolve El Niño and La Niña events with realistic amplitudes [*Roeckner et al.*, 1996a] and with associated superimposed decadal type fluctuations.

Second, we have explored the climate effect of the ongoing reduction of stratospheric ozone. With the data set we have used here, there is a clear cooling effect not only in the lower stratosphere but also in the troposphere. The result is strongly dependent on the vertical distribution of the ozone reduction, so more studies are required [*Hansen et al.*, 1997]. It seems nevertheless that it is highly important to include the stratospheric ozone change in climate change experiments. Owing to the fact that the relative cooling effect of stratospheric ozone is larger in the upper troposphere than in the lower part (see Plate 2b), it consequently reduces the strong upper air warming by the greenhouse gases, in better agreement with observations.

Major volcanic eruptions such as Mount Pinatubo have a recognizable effect on climate. Although the direct forcing may be limited in duration to a few years at most, the effect on climate is longer due to the cooling of the oceans. In our experiments it appears that the effect of Mount Pinatubo lasted for 5–7 years. The maximum tropospheric cooling amounts to about 0.5 K, in agreement with previous estimates.

Based on six realizations, we calculated the decadal global averaged surface temperature trend during 1979–1997 to be between +0.19 and +0.04 K when we used experiment GSDIO as the reference. It is not unlikely that if we had instead used the GSD experiment, the values would have been further reduced. In conclusion therefore, it is certainly not unlikely that even a slight cooling could have taken place during 1979–1997, in agreement with some of the model integrations we have undertaken here. The inconsistency we have noted, though, is that the surface warming as assessed from surface synoptic records is in all likelihood on the warm side or, alternatively, the MSU data and the radiosondes observations are on the cold side. To clarify which of the data sets is most reliable is the purpose of another study. As discussed above, the vertical gradient of the temperature trend in the model integrations is slightly reduced with height when we incorporate the effect of stratospheric ozone, but significantly less than for the observations: 0.02 K compared to 0.19 K per decade.

The result of this study further depends on the implicit forcing assumptions in the reference transient experiment, GSDIO. While the forcing from the greenhouse gases varies only within a small range, the effect of aerosols is less well known. The forcing used in this experiment for both the direct and indirect effect of sulfate aerosols is close to the middle within the range of possible values given by IPCC [*Roeckner et al.*, 1998].

The model's response to forcing is another important factor. Mixed layer modeling experiments have shown that a doubling of CO_2 leads to an average equilibrium surface warming of 3.6 K, which is close to the average for the coupled models summarized by *IPCC* [1996, Table 6.3].

It must finally be stressed that the fact that no warming may have taken place during the last two decades can in no way be interpreted as evidence that there is no anthropogenic climate warming. In fact, we may expect a recovery of the stratospheric ozone during the beginning of the next century, which will reduce or eliminate the compensatory cooling effect. Volcanic eruptions are not predictable, but their effect is limited in time. Perhaps the most difficult factors to consider are the aerosol effects, their scattering albedo, or even more the indirect effects such as the interaction with cloud albedo and possible influence on cloud lifetime.

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L. Bengtsson, E. Roeckner, and M. Stendel, Max-Planck-Institut für Meteorologie, Bundesstraße 5, D 20146 Hamburg, Germany. (bengtsson@dkrz.de, roeckner@dkrz.de, mas@dmi.dk)

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