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Vertical patterns of free and forced climate variations

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Abstract. Observations of the vertical structure of atmospheric temperature changes over the past three decades show that while the global-average lower atmosphere has warmed, the upper troposphere and lower stratosphere have cooled. While these changes may be due to observed anthropogenic increases of greenhouse gases, decreases of lower stratospheric ozone, and increases of tropospheric aerosols, the changes may also have been caused by natural unforced internal fluctuations of the climate system. Here we use the results of a 1000-year simulation from a mathematical model of the coupled ocean-atmosphere-land system performed without any changes in external forcing, so that we may consider its variations as a surrogate for free, internally-generated, natural fluctuations of the climate system. When the global mean surface air temperature is warm in the model, the lower troposphere, upper troposphere and lower stratosphere are also warm over most of the Earth, in contrast to the observations of the last three decades and to model simulations of the forced climate response due to increased greenhouse gases. The observed temperature change of the past three decades is therefore unlikely to have been caused solely by natural internal variations of the climate system, thereby strengthening the argument that these changes can at least partly be attributed to anthropogenic activities.

To assess if humans are having an impact on climate, it is necessary to show that the patterns of observed climate change result from anthropogenic forcing rather than from natural climate change. We must compare the observed patterns to those that would result from anthropogenic activities and from natural unforced variability.

Stouffer et al. [1994] indicated that, if the variability found in their coupled ocean-atmosphere climate model is realistic on time scales longer than 10 years, the rise of global average surface air temperature in the past century is highly likely to be due to external forcing. Using a "fingerprint" (the two- or three-dimensional pattern of response of a single variable to a particular cause of climate change) would be a very powerful method for solving the detection problem [*MacCracken and Moses*, 1982; *Robock*, 1983; *Barnett and Schlesinger*, 1987; *Karoly et al.*, 1994; *Karl*, 1994].

In this paper we examine the vertical structure of zonally-averaged temperature change. Earlier, *Karoly et al.* [1994] examined the vertical structure of the observed temperature change and concluded that there is a time-increasing correspondence between the pattern of observed changes in the vertical temperature structure and that forced by CO_2 doubling in GCMs. Here we build on that work by examining transient forcing and comparing the patterns of temperature caused by increased CO_2 to natural, internally-generated variations.

In our study we compare the vertical and latitudinal patterns of air temperature variations in three different data sets. The first is the radiosonde observations [*Oort and Liu*, 1993] for the period 1959-1989. We obtained gridded zonal-average annual average temperature observations from 88°N to 88°S and from 850 mb up to 50 mb. The global radiosonde network used to make the gridded data set does not have a uniform, high-density distribution, but is biased to land-based stations, with a much sparser network in the Southern Hemisphere, particularly at high altitudes, and there are gaps over oceans [*Oort and Liu*, 1993]. In addition, changes in the spatial coverage, type of instrumentation, and methods of processing the observations may introduce additional errors into this data set that may have an impact on the results [*Karoly et al.*, 1994; *Gaffen*, 1994].

The other data sets are simulations from the Geophysical Fluid Dynamics Laboratory coupled GCM, of the effects of a transient increase of CO_2 at a rate of 1% yr^{-1} for 140 years (integration 4XC of *Manabe and Stouffer* [1994]), and of the effects of natural variability simulated in a 1000-year calculation without changing external forcing [*Stouffer et al.*, 1994]. The 1% yr^{-1} increase in CO_2 represents an exponential increase in CO_2 concentration, but because the radiative forcing is proportional to the logarithm of the concentration change, the forcing varies linearly with time. At the end of 140 years, the CO_2 has reached 4 times its initial concentration. In the natural variability simulations, the El Niño/Southern Oscillation (ENSO) signal is slightly less than half the observed strength [*Knutson and Manabe*, 1994].

The coupled atmosphere-ocean GCM used for all these simulations is described in detail by *Manabe et al.* [1991]. The atmospheric component includes seasonally varying insolation with predicted cloud cover. It has 9 vertical finite-difference levels. The horizontal distribution of the predicted variables is represented by spherical harmonics (15 zonal waves and 15 associated Legendre functions) and by values at grid points with a 4.5° latitude by 7.5° longitude horizontal spacing. The ocean GCM has 12 vertical levels and horizontal spacing of 4.5° latitude by 3.75° longitude. Flux adjustment [*Manabe and Stouffer*, 1988; *Manabe et al.*, 1991] prevents long-term drift of the climate away from current conditions. This flux adjustment is predetermined and does not systematically amplify or dampen temperature fluctuations. The adjustments do not eliminate the shortcomings of the model dynamics which could distort the transients. But the adjustments do prevent the rapid drift of the model state from the realistic initial conditions, which could seriously distort the results of a numerical experiment.

To assess how the vertical and latitudinal distribution of temperature change is related to the global mean surface temperature, a linear regression of the form

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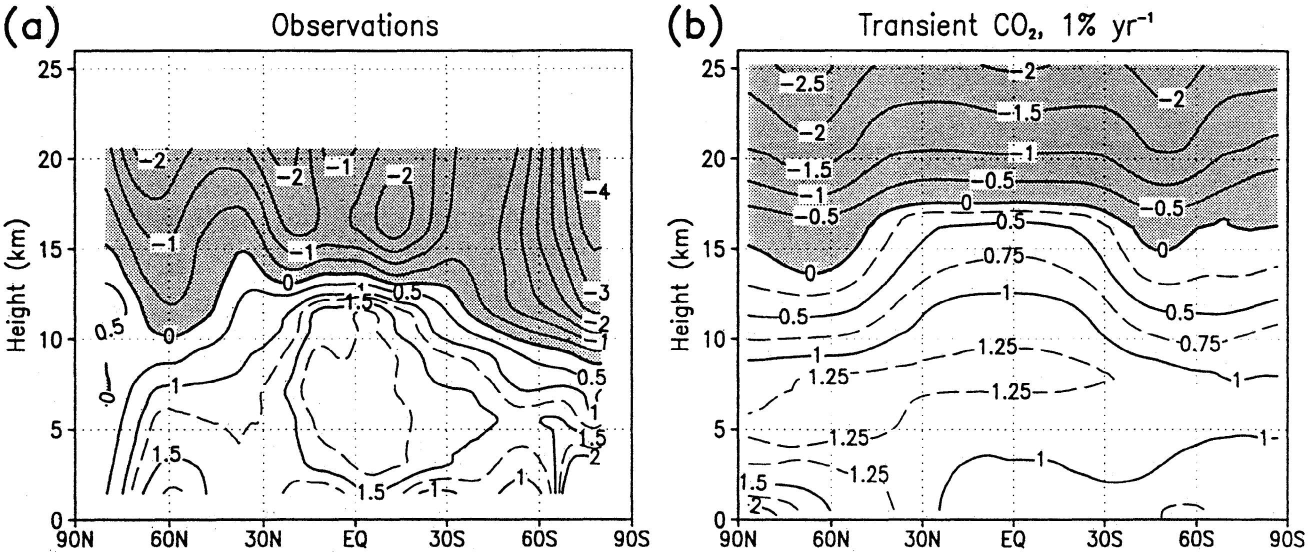
$$T = \alpha + \beta \overline{T}_S \qquad (1)$$

was performed, where T is the zonal average, annual average temperature at different altitudes, and $\overline{T}_S$ is the global average, annual average surface air temperature. This technique allows us to examine the relative changes of temperature from observations and model output, independent of the model sensitivity, and show that the patterns of temperature change associated with a unit change of global mean surface air temperature. Figure 1 shows the patterns of vertical and latitudinal temperature change. For Fig. 1a, T came from *Oort and Liu* [1993], while $\overline{T}_S$ was taken from a different data set [*Jones et al.*, 1994]. Figure 1b gives the pattern of β estimated from the 140 year transient CO_2 model simulation.

Figures 1a-b show that the patterns of temperature change in the observations and in the modeled climate with increasing CO_2 are quite similar. When the observed global mean surface air temperature is warm, there is also warming throughout the troposphere, slightly amplified at the North Pole near the surface, and cooling in the stratosphere. However, there are several important differences between the observed and modeled patterns: 1) the level at which the warming switches to cooling is lower in the observations (~8-12 km) as compared to the model (~14-18 km), 2) there is enhanced cooling in the observations in the Southern Hemisphere polar stratosphere as compared to the model, 3) the tropical middle tropospheric maximum is larger in the observations, and 4) the observations show a hemispheric asymmetry in the troposphere, with less warming in the



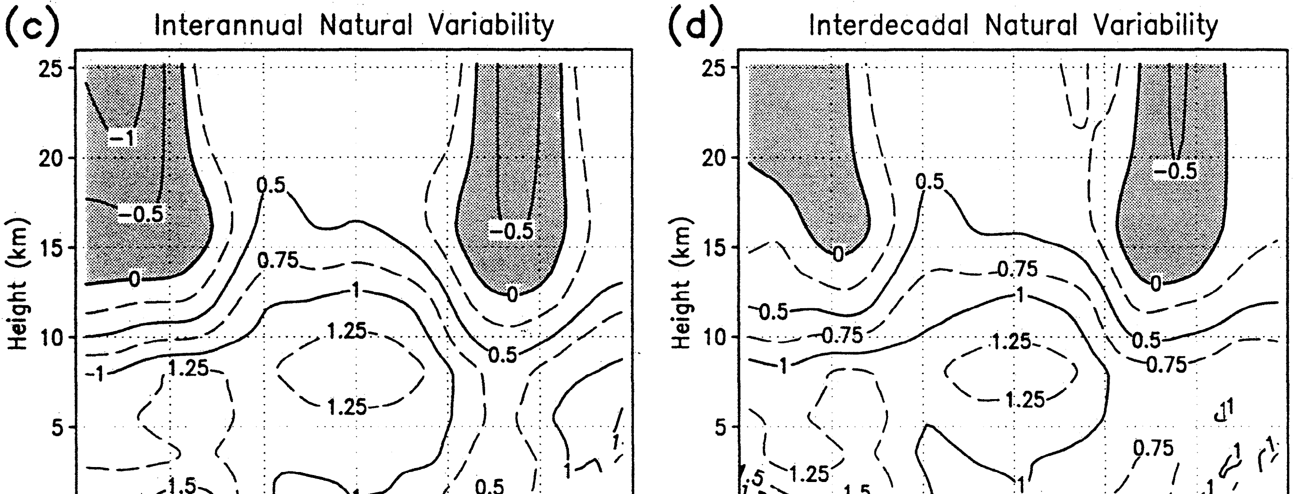


Fig. 1. Patterns of vertical and latitudinal temperature change, showing the linear regression coefficient β (Eq. 1) between the annual mean, zonally-averaged air temperature in the free atmosphere and the annual mean, global mean surface air temperature. The value at any point in each panel represents the zonal mean temperature change (°C) given a simultaneous 1°C increase in annual mean, global mean surface air temperature. (a) From upper-air [*Oort and Liu*, 1993] and surface [*Jones et al.*, 1994] observations for the period 1959-1989, with regression coefficients smoothed with a 1-2-3-2-1 smoothing on the original 2° grid. (b) From the 140-year transient CO_2 simulation [*Manabe et al.*, 1991; *Manabe and Stouffer*, 1994]. (c) Annual averages from the 1000-year internally-generated variability simulation [*Stouffer et al.*, 1994; *Manabe and Stouffer*, 1996]. (d) As in (c), but for decadal-averages.

Northern Hemisphere, while the model shows the opposite, with a larger signal in the Northern Hemisphere.

The first two points may both be caused by ozone effects not included in the model simulations, lower stratospheric ozone reductions [*Ramaswamy et al.*, 1992; *Karoly et al.*, 1994; *Hansen et al.*, 1993, 1995] and the Antarctic "ozone hole" [*Mahlman et al.*, 1994]. The middle tropospheric maximum in the observations (Fig. 1a) may be partly due to the predominance of radiosonde stations over land, while the surface observations include a larger fraction of ocean data. The free atmosphere temperature over land would be expected to have a larger response, due to the lower thermal inertia of the land as compared to the ocean. As for the hemispheric asymmetry, the lag in warming around Antarctica in the coupled model is due to deep ocean mixing that prevent warming there [*Manabe et al.*, 1991], while the smaller warming in the Northern Hemispheric troposphere in the observations may be due to tropospheric aerosols [*Santer et al.*, A search for human influences on the thermal structure of the atmosphere, submitted to *Nature*, 1996], again which are not included in the coupled model simulation.

We also examined the pattern of β found in the 1000-year simulation of the coupled model, which has only internally-generated variability and no changes of greenhouse gases, solar constant, or aerosols (Fig. 1c). The pattern shown here is very different from that in Figs. 1a-b. While the tropospheric pattern is similar to that found in Fig. 1b, the stratospheric pattern has the same sign as that in the troposphere, except for a small region centered at 60°S. This means that in the coupled model when the surface and troposphere warm, the stratosphere also warms slightly, in sharp contrast to the cooling forced by enhanced longwave radiation emission in the experiment with increased CO_2 (Fig. 1b). The smaller value of the regression coefficient from 30°-60°S throughout the troposphere in Fig. 1c is mainly due to the large oceanic fraction at these latitudes. Because of the low stratospheric vertical resolution of this model, important processes may not be well simulated. However, we do not believe that these missing processes in the model would change the sign of the signal.

To examine whether the difference between the pattern of natural variability in Fig 1c and the pattern of forced variation in Fig. 1b could have happened as a result of different time scales of the processes we produced Fig. 1d, showing the pattern of β for the interdecadal variability (by smoothing the annual time series with an 11-point binomial filter before calculating the regression) from the same 1000-year model run as Fig. 1c. It shows virtually the same pattern, demonstrating that this pattern of natural variability is independent of time scale.

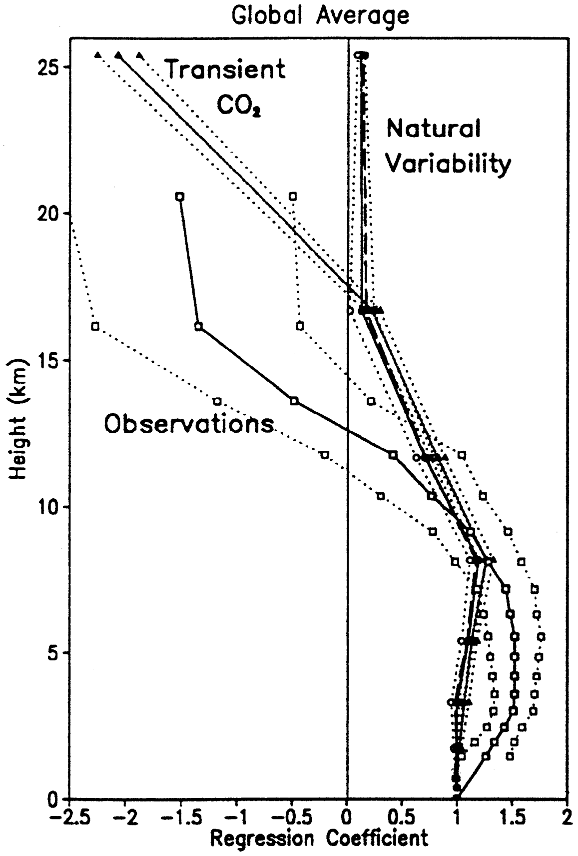


Fig. 2. Global-average vertical profiles corresponding to the plots in Fig. 1. The solid natural variability curve corresponds to the annual results in Fig. 1c, and the dashed one corresponds to the decadal results in Fig. 1d. All values of the regression coefficients with absolute value > 0.5 are significantly different from 0. The dotted lines give the 95% confidence intervals for the estimates of β, using a Student's t-test, accounting for autocorrelation in the time series.

The regression between the global-mean temperatures at each altitude and the global-mean surface air temperature (Fig. 2) clearly show that the observed vertical structure of temperature change disagrees with both the modeled CO_2-forced pattern and the modeled pattern of internally-generated natural variability. The observed estimates of β more closely resemble the CO_2-forced estimates, but change sign at a lower level than the CO_2 curves. Consideration of other important climatic forcings during this period can help to reconcile the CO_2 and observed patterns. As noted earlier, the observed lower stratospheric ozone depletion that has occurred in the past 3 decades and which is not included in the model would produce added cooling in the 10-20 km levels [*Hansen et al.*, 1995]. Volcanic eruptions tend to cool the surface while warming the stratosphere [*Hansen et al.*, 1978], and would therefore produce the same shaped pattern as the observed and CO_2 curves. There were 2 large eruptions during the period studied, Agung in 1963 and El Chichón in 1982, so potentially part of the observed pattern is due to them. However, observations of the trend of surface and upper atmosphere temperatures during the past three decades [*Angell*, 1991; *Oort and Liu*, 1993] show that there has been a strong cooling trend in the stratosphere at the same time as warming at the surface. Therefore, the volcanic pattern, which lasts for only a few years in each case, can only have contributed to a small part of the observed curve.

All of the potentially important anthropogenic forcings of global climate change during the period studied would tend to make the pattern of vertical temperature change look much like the observed pattern, while the pattern of natural variability clearly differs from the observed in the stratosphere above 10 km. Therefore, assuming that the model patterns of variability are a good representation of the natural internal fluctuations of the climate system, the present results suggest that the climate change of the past three decades cannot be attributed solely to natural internal climatic variability, and is likely to have been caused at least partly by human activities.

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