Likelihood of rapidly increasing surface temperatures unaccompanied by strong warming in the free troposphere

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ABSTRACT: Recent model simulations of the effects of increasing greenhouse gases combined with other anthropogenic effects predicted larger rates of warming in the mid and upper troposphere than near the Earth's surface. In multiple model comparisons we find that accelerated upper-level warming is simulated in all models for the greenhouse-gas/direct-aerosol forcing representative of 1979–2000. However, in a test of model predictive skill, a comparison with observations shows no warming of the free troposphere over this period. We assessed the likelihood that such a disparity between model projection and observations could be generated by forcing uncertainties or chance model fluctuations, by comparing all possible 22 yr temperature trends in a series of climate simulations. We find that it is extremely unlikely for near-surface air temperatures (surface temperatures) to increase at the magnitude observed since 1979 without a larger warming in the mid-troposphere. Warming of the surface relative to the mid-troposphere was also more likely in control simulations than under anthropogenic forcing. Because errors in the vertical temperature structure would be expected to create errors in water-vapor feedback, cloud cover and moisture content, these results suggest the need for great caution when applying the simulations to future climate predictions and to impact assessments.

KEY WORDS: Climate change · Model assessment · Vertical temperature structure

1. INTRODUCTION

An observed increase in global surface temperatures since 1979 has been most strongly tied to human activity by the IPCC (2001), and it is hypothesized to continue upwards as a result of increasing greenhouse-gas concentrations. Climate-model simulations indicate increasing surface temperatures in rough agreement with observations. An important test of model predictive ability and usefulness for impact studies is how well models simulate the observed vertical temperature structure of the troposphere under anthropogenically-induced-change scenarios.

Recent climate-model simulations produce a larger warming in the free troposphere than at the surface when forced by increasing atmospheric greenhouse-gas concentrations and the direct effect of sulfate aerosols (IPCC 1996, 2001). Fig. 1 shows example time series of global average surface temperature and 500 mb temperature changes resulting from CO_2 and aerosols simulated by a single realization from each of the 4 coupled atmosphere–ocean climate models: the CGCM1 and CGCM2 from the Canadian Centre for Climate Modelling and Analysis (CCCma; Flato et al. 2000; Flato and Boer, 2001), the Goddard Institute for Space Studies (GISS; Russel et al. 2000) coupled atmosphere-ocean model and the Geophysical Fluid Dynamics Laboratory (GFDL; Delworth et al., 2002) model. Each shows accelerated warming at 500 mb relative to the surface. Details of each simulation suite are given in Table 1. This pattern is a general feature of climate models and is also produced in more comprehen-
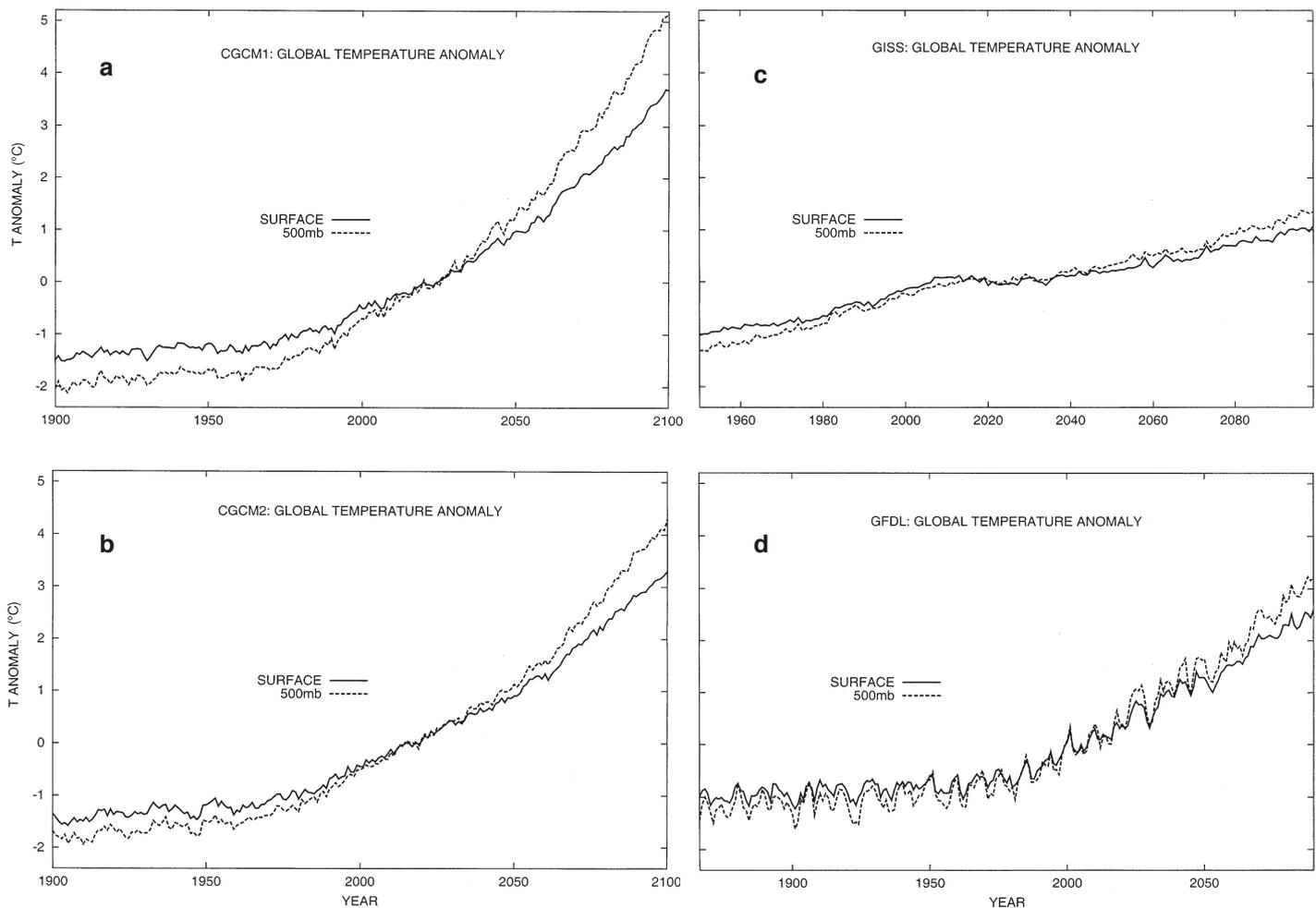
Fig. 1. Globally averaged surface and 500 mb temperature anomalies (relative to the 1979–2000 mean) for 1 realization of: (a) the Canadian Center for Climate Modelling and Analysis coupled model I (CGCM1) ensemble, (b) CGCM2, (c) the Goddard Institute for Space Studies (GISS) model, and (d) the Geophysical Fluid Dynamics Laboratory (GFDL) model

sive climate-change simulations (Roeckner et al. 1999). Though many climate forcings and feedbacks are not accounted for in these simulations, similar forcing assumptions are the basis of both the IPCC (2001) report and the US National Assessment (National Assessment Synthesis Team 2001), making a comprehensive examination of performance under these assumptions imperative.

In comparison, a comprehensive analysis of observed temperature changes during 1979–2000 has been provided by the IPCC (2001) assessment report (their Table 2.3). This analysis indicates a strong and significant surface warming of 0.14 to 0.16°C decade^{-1} since 1979 in observational data. However, observed temperature trends in the lower troposphere from 5 different data sets range from –0.03 to +0.04°C decade^{-1}, are

Table 1. Summary of model simulations

Model	Duration	Realizations	CO_2	Aerosol source
CGCM1	1900–2100	3	OBS to 1996, 1% yr^{-1} after	Langner & Rodhe (1991)
CGCM2	1900–2100	3	OBS to 1996, 1% yr^{-1} after	Langner & Rodhe (1991)
GISS	1950–2100	2	OBS to 1990, 0.5% yr^{-1} after	Mitchell et al. (1995)
GFDL	1866–2090	3	IS92a to 1990, 1% yr^{-1} after	Haywood et al. (1997)

statistically indistinguishable from zero in each measure, and give no indication of warming whatsoever. A revised version of the Microwave Sounding Unit (MSU) satellite data (Mears et al. 2003) indicates a larger tropospheric warming than the original version (Christy et al. 2000) or any of the other datasets discussed in IPCC (2001); reasons for this difference are the subject of vigorous debate (Santer et al. 2003). Recently, Christy et al. (2003) demonstrated a strong correspondence between their version of the MSU time series and several other independent measures of tropospheric temperature trends, and they conclude that the Mears et al. (2003) trend is likely too strong. We address the implications of this alternate satellite data further in the conclusions.

For comparison with trends presented later, Fig. 2 shows the time series for some of these observational data, while Table 2 provides estimated linear trends and significance values. Autocorrelation is corrected for in the estimated trends using an autoregressive error model for up to 4 time lags using a stepwise procedure testing for autocorrelation at each lag. When the strong El Niño year of 1998 is removed from near the end of the time series, all upper-level air-temperature measurements show weak and insignificant cooling during 1979–2000 (Table 2). There appears to be little evidence for a progressive warming above the surface since 1979.

It is unclear from IPCC (2001) and from Fig. 1 whether model-projected accelerated warming aloft should be detectable at the present time. Therefore, our first objective was to assess whether any simulated accelerated warming aloft was of sufficient magnitude to be presently detectable.
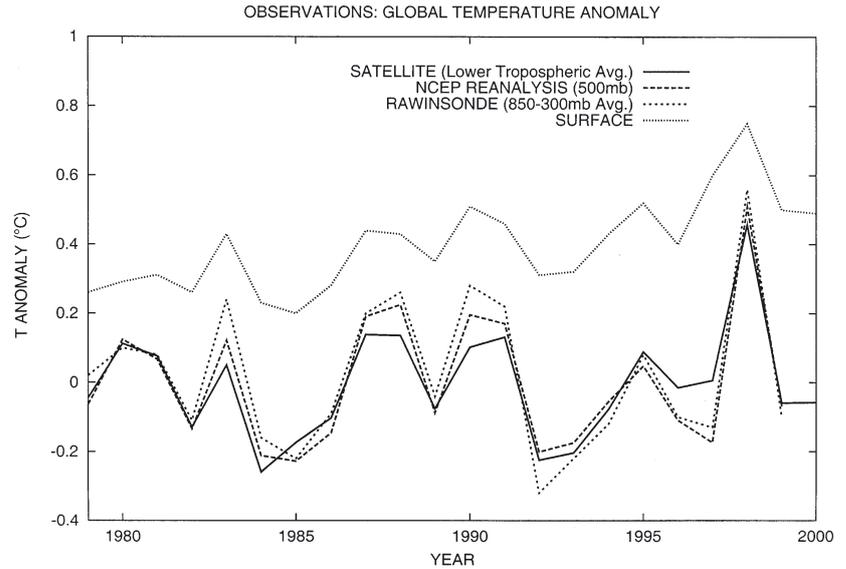

Fig. 2. Observed globally averaged temperature anomalies (relative to the 1979–2000 mean) for 3 upper-level air-temperature measures and the surface for 1979–2000

Our second objective was to examine all possible 22 yr time series in the climate-change and control simulations and assess the likelihood that such a disparity between predicted and observed patterns of warming could result from model variability or small uncertainties in forcing rates.

2. SIMULATED SURFACE VERSUS TROPOSPHERIC TEMPERATURE, 1979–2000

Table 3 gives the 1979–2000 surface and 500 mb temperature trends for each model realization calculated from linear regression model corrected for autocorrelation. We chose 1979–2000 to examine in detail for several reasons. Satellite observations became available in 1979, allowing a comprehensive picture of free troposphere temperature changes. It is unclear whether trends from the NCEP Reanalysis prior to 1979 are homogeneous (Santer et al. 1998). The very large observed surface warming beginning in the late 1970s has been tied, in large part, to anthropogenic causes by the IPCC (2001) report. This is therefore the period when comparisons with model simulations of anthropogenically induced effects should be most informative.

For the simulated period, 1979–2000, all models exhibited a significant (p < 0.001) warming at the

Table 2. Linear regression trends (°C decade^{-1}) and significance p values in parentheses for 3 upper-level air-temperature datasets and the surface for 1979–2000 and with the strong El Niño year of 1998 removed. SFC: Jones et al. (2001); NCEP: Kalnay et al. (1996); MSU: Christy et al. (2000); RAWINSONDE: Sterin (2001)

SFC	NCEP (500 mb)	MSU 2LT-d	RAWINSONDE (850–300 mb)
All data			
0.16 (<0.01)	0.01 (0.85)	0.04 (0.51)	−0.00 (0.92)
1998 removed			
0.14 (<0.01)	−0.04 (0.43)	−0.01 (0.81)	−0.04 (0.24)

Table 3. Linear regression trends (°C decade^{-1}) for model simulations over 1979–2000. p < 0.01 for all trends

	CGCM1			CGCM2			GISS		GFDL		
Realization	1	2	3	1	2	3	1	2	1	2	3
Surface	0.25	0.25	0.26	0.29	0.27	0.24	0.22	0.20	0.28	0.23	0.20
500 mb	0.31	0.37	0.35	0.35	0.37	0.32	0.26	0.25	0.28	0.24	0.27
Ratio	1.24	1.48	1.36	1.22	1.36	1.35	1.19	1.26	0.98	1.05	1.35

surface ranging from 0.20 to 0.29°C decade^{-1}. All models also simulate a significant (p < 0.001) 500 mb warming (from 0.29–0.37°C decade^{-1}) which exceeded the trend at the surface in all except 1 realization of the GFDL model, where the trends were comparable. On average, the surface trend among the 11 model realizations considered here was 0.24°C decade^{-1}, while the average 500 mb temperatures increased 0.06°C decade^{-1} (or 25%) faster than at the surface. This difference is more than one-third the total observed surface trend and should be detectable.

3. COMPARISON OF SURFACE AND 500 mb TRENDS IN CLIMATE-CHANGE SIMULATIONS

While the model evidence in the preceding section indicates that it is highly unlikely for a climate dominated by increasing greenhouse gases and the direct aerosol effect to warm at the surface and not warm at a faster (or at least comparable) rate aloft, it is possible that such a situation may occur at times due to some combination of internal model variability or variations in forcing. We therefore examined all possible 22 yr surface trends using a simple linear regression model in each of the simulations for a warming rate which is at least that observed (0.16°C decade^{-1}) and compared with the corresponding trend at 500 mb. We searched for evidence that it is possible, under some circumstances, for a model to warm quickly at the surface but not at 500 mb. We maximized the chance that a warming is statistically significant and therefore detectable by using a simple linear regression model for this analysis.

A total of 1018 periods of 22 yr across all realizations of all 4 models met the surface warming criterion of a 0.16°C decade^{-1} warming. Of these periods, 987 (97%) had a larger warming at 500 mb than at the surface (Table 4). While all models had a large proportion of periods with larger warming aloft than at the surface, there are also clear differences in the statistics between models. For example, both CCCma models had 500 mb-level warming faster than at the surface in every 22 yr period, while the GFDL simulations had the largest proportion of surface trends exceeding the 500 mb-level trends (23% of the cases).

Table 4. Fraction of simulated 22 yr periods with strong surface warming where the 500 mb temperature trend exceeded the surface temperature trend

	CGCM1	CGCM2	GISS	GFDL
Surface	338/338	336/336	86/111	290/312

Of the 3% of cases where the surface warmed faster than at 500 mb, there was most often a comparable warming at 500 mb. However, 3 instances where the surface warmed significantly (p < 0.1) and substantially (defined here as >1.3 times the 500 mb warming) were recorded with the maximum ratio of surface-to-500 mb-level warming at 1.37, as compared to the observed ratio of at least 4.0 times faster warming at the surface than aloft. There was no indication of significantly increased probability of accelerated surface warming late in a simulation under stronger forcing.

4. COMPARISON OF SURFACE AND 500 mb TRENDS IN CONTROL SIMULATIONS

Though we found little evidence that greatly accelerated surface warming is more likely early in climate-change simulations (i.e. in more control-like situations), it is possible that such a situation is more representative of an unforced climate system. Control simulations allow no changes in atmospheric or other forcings over time and give some indication of natural climate variability in the absence of other influences. Control simulations were available for CGCM1, GISS and GFDL, and we examined these for signs that accelerated trends at the surface relative to at 500 mb are possible or become more likely under naturally varying conditions. We began again with any periods with a 0.16°C decade^{-1} surface warming and compared to corresponding 500 mb trends. In 9 cases, the 22 yr surface trend exceeded 0.16°C decade^{-1}; 8 of these 9 cases occured in the GISS model, a manifestation of a warming drift in the control simulation (Russell et al. 2000). All 8 trends in the GISS model, warmed more at the surface than the 500 mb level, with a maximum ratio of 1.2.

We also compared all surface trends exceeding 0.08°C decade^{-1} with 500 mb-level trends. All 3 models had surface trends of this magnitude, so this is a more representative sample. Of 84 trends recorded at the surface which exceeded 0.08°C decade^{-1}, 37 of them warmed faster at 500 mb (44%). Of the 47 periods where the surface warmed faster than at 500 mb, in 6 of these the trends at the surface were more than 1.3 times larger than at 500 mb and the maximum ratio of surface-to-500 mb-level trends was 1.7. There appears to be some evidence that surface trends exceeding those in the mid-troposphere are more likely under unforced conditions in these models.

5. DISCUSSION AND CONCLUSIONS

Because there are claims that the anthropogenic greenhouse-gas warming signal has been detected since the mid-1970s (IPCC 2001), it is important to critically assess model performance and predictive ability as to tropospheric temperature structure during this time period despite its short duration. IPCC (2001) indicated that observed trends for 1979–2000 show no evidence of significant warming in the free troposphere in conjunction with a very large observed warming at the surface. The difference between a troposphere that warms increasingly with height through a deep layer, as in model simulations, and one where warming is confined to a shallow layer near the surface, as in observations, has large implications for atmospheric moisture content, water-vapor feedback, thickness gradients and convection-initiated circulation responses. To determine whether such a disparity could be explained by natural model variability or small changes in forcing, we examined realizations from 4 climate models in both unforced control scenarios and scenarios forced with increased atmospheric greenhouse gasses and the direct aerosol effect. These comparisons indicate the following:

- Model simulations of the period representative of the greenhouse-gas and aerosol forcing for 1979–2000 generally show a greatly accelerated and detectable warming at 500 mb relative to the surface (a 0.06°C decade^{-1} increase).
- Considering all possible simulated 22 yr trends under anthropogenic forcing, a strong surface warming was highly likely to be accompanied by accelerated warming at 500 mb with no change in likelihood as forcings increased over time.
- In simulated periods where the surface warmed more quickly than 500 mb, there was never a case in which the 500 mb temperatures did not also warm at a large fraction of the surface warming. A 30% acceleration at the surface was the maximum simu-

lated as compared with an observed acceleration factor of at least 400% the mid-troposphere trend.

- In cases where there was a strong surface warming and the surface warmed more quickly than at 500 mb in the forced experiments, there was never a case in which the 500 mb-level temperatures did not register a statistically significant ($p < 0.1$) trend (i.e. a trend detectable with a simple linear regression model). The minimum p value of approximately 0.08 occurred in the single case in which the significance was not greater than 99%.
- It was more likely that the surface warmed relative to the mid-troposphere under control simulations than under forced simulations.
- At no time, in any model realization, forced or unforced, did any model simulate the presently observed situation of a large and highly significant surface warming accompanied with no warming whatsoever aloft.

A revised estimate of tropospheric temperature trends (Mears et al. 2003), if robust, serves to reduce the magnitude of the discrepancy, but it does not change the overall conclusions of this study. However, Christy et al. (2003) have argued through a detailed error analysis that the Mears et al. (2003) warming trend is likely too large. Such a conclusion mirrors that of Pielke et al. (1998a,b). Conversely, Santer et al. (2003) indicate that the spatial pattern of warming in the Mears et al. (2003) time series is more consistent with model simulations. However, we believe caution is in order when assessing regional patterns of climate change in models which neglect some processes, such as land-cover change, which can have large regional effects (Chase et al. 2001, Pielke et al. 2002) and are forced by other processes, such as the effect of sulfate aerosols, which are described as having 'low' levels of scientific understanding (IPCC 2001) and which are possibly quite erroneous (Anderson et al. 2003). A National Academy Report (2001) also indicated that at least part of the disparity between surface and free troposphere was likely to be real and suggested that uncertainties in forcing might be responsible for some of the remainder. This does not appear to be the case.

These results imply that model variability and uncertainty in applied forcings cannot produce the recently observed tropospheric temperature characteristics. This interpretation is consistent with Santer et al. (1998), who used more comprehensive but more uncertain forcings, and with Hegerl & Wallace (2002), who found that observed changes in lapse rate cannot be attributed to natural variability and that such changes were highly unlikely in a single coupled model with more comprehensive estimates of human climatic forcing.

The disparity between model simulations under these assumptions and observed climatic shifts may be

an indication that additional forcing combinations are necessary, that internal variability is improperly simulated or that inadequately simulated feedback mechanisms (perhaps in the vertical distribution of cloud or water vapor) are at work. Because accelerated warming aloft, particularly in the tropics, is intimately tied with convective processes, such a discrepancy might also result from the systematic overestimation of energy transfer aloft by convective parametrizations.

While we cannot assess here the degree to which the above possibilities are responsible for the inability of recent climate-change simulations to reproduce recent observations, it is important to note that many of the conclusions from the IPCC (2001) and the National Assessment Synthesis Team (2001) are derived from similar models and forcing assumptions as those discussed here. Significant errors in the simulations of globally averaged tropospheric temperature structure indicate likely errors in tropospheric water-vapor content and therefore total greenhouse-gas forcing, precipitable water and convectively forced large-scale circulations. Such errors argue for extreme caution in applying simulation results to future climate-change assessment activities and to attribution studies (e.g. Zwiers & Zhang 2003) and call into question the predictive ability of recent generation model simulations, the most rigorous test of any hypothesis.

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