LETTERS

On Using Global Climate Model Simulations to Assess the Accuracy of MSU Retrieval Methods for Tropospheric Warming Trends

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ABSTRACT

Climate model simulations of the latter part of the twentieth century indicate a warming of the troposphere that is equal to or larger than the warming at the surface, while satellite observations from the Microwave Sounding Unit (MSU) indicate little warming of the troposphere relative to surface observations. Recently, Fu et al. proposed a new approach to retrieving free tropospheric temperature trends from MSU data that better accounts for stratospheric cooling, which contaminates the tropospheric signal and leads to a smaller trend in tropospheric warming. In this study, climate model simulations are used as a self-consistent dataset to test these retrieval algorithms. The two methods of retrieving tropospheric temperature trends are applied to three climate model simulations of the twentieth century. The Fu et al. algorithm is found to be in very good agreement with the model-simulated tropospheric warming, indicating that it accurately accounts for cooling from the lower stratosphere.

1. Introduction

Climate models simulating the climate of the twentieth century predict a warming of the surface and the troposphere and a cooling of the stratosphere. The tropospheric warming trends are of the same magnitude or larger than the warming trend at the surface. The simulated tropospheric trends, however, are not consistent with a much weaker trend for middle-tropospheric temperatures as retrieved from satellite platforms over the last 26 yr (Wallace et al. 2000). These satellite temperature retrievals have exploited the National Oceanic and Atmospheric Administration (NOAA) Microwave Sounding Unit (MSU; Spencer and Christy 1990), and a number of studies (Christy et al. 2003; Mears et al. 2003; Vinnikov and Grody 2003) find differing changes in tropospheric warming with results from some global climate models when subjected to anthropogenic and other natural forcing factors for the same period. There is a strong consensus among global climate models to project an increase in midtropospheric temperatures that is actually larger than the observed and simulated surface temperature increase.

The inconsistency of satellite-derived temperature trends and climate model simulations of temperature trends has been used to cast doubt on the veracity of our ability to correctly model the response of the climate system to increases in greenhouse gases. Much of the debate over these inconsistencies has focused on the difficulties associated with constructing reliable temperature trends from MSU, principally associated with changes in instruments, differences in orbital characteristics, and changes in retrieval algorithms (Wallace et al. 2000; Christy et al. 1998; Hurrell and Trenberth 1998). Recently, Fu et al. (2004a) proposed a new method to retrieve tropospheric temperatures that accounts for contamination by the cooling trend seen in stratospheric temperatures. They argue that this contamination offsets the true warming trend associated with the troposphere. To retrieve a more accurate measure of tropospheric temperature trends, Fu et al. used a linear combination of the channel-2 and channel-4

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brightness temperatures. The coefficients for this linear combination of brightness channels is obtained by least squares regression fits to observed global, hemispheric, and tropical monthly mean anomaly data from radiosonde stations from 1958 to 1997. They argue that the resulting trend of reconstructed tropospheric temperatures is more physically consistent with the observed surface temperature trend. In response to Fu et al.'s study, a series of brief communications debated the robustness of their approach (Tett and Thorne 2004; Gillett et al. 2004; Fu et al. 2004b). Fu and Johanson (2004) further explored the accuracy of their algorithm in accounting for the stratospheric cooling contamination of the tropospheric warming. They showed that their approach is more accurate than the T_{2LT} synthetic channel algorithm of Spencer and Christy (1992) and Christy et al. (1998, 2003). Most relevant to the present study, Gillett et al. (2004) used simulations from the Parallel Climate Model (PCM) in conjunction with the Fu et al. algorithm to show that this technique successfully retrieved the simulated tropospheric temperature trend. The Gillett et al. study used both Fu et al. retrieval coefficients and their own coefficients derived from the model simulation. The present study uses the regression coefficients derived by Fu et al. and expands the evaluation of the Fu et al. algorithm to a larger suite of climate model simulations, which have differing magnitudes of stratospheric cooling.

In this paper, we will use results from multiple global climate model simulations to explore the accuracy of the retrieval approach proposed by Fu et al. (2004a) and will argue that global modeling tools should be more routinely used in quantifying the accuracy of satellite retrieval techniques.

2. Description of models and simulations

Climate models can be used to provide self-consistent datasets to explore satellite retrieval issues. They are self-consistent in that the data they produce come from the solution of four-dimensional systems of equations governing the energy, momentum, and mass budgets for the climate system. This does not mean that the solutions of these models are in perfect agreement with observational data. However, they are the most comprehensive means of studying the climate system and have shown success in simulating major features of the climate system (Stott et al. 2000).

A standard metric for climate system models is to attempt to simulate the climate of the twentieth century. To accomplish this, models must be supplied with various forcing factors, both natural and anthropogenic, for this time period. The forcings are usually calculated by the climate model with given inputs, for example, trace gas mixing ratio concentrations, aerosol mass concentration, and volcanic aerosol optical depth. Once the time evolution of these fields is specified, the fully coupled climate model simulations can be initialized in the late nineteenth century and run through the twentieth century. A number of fully coupled climate models have been used for this type of simulation (e.g., Stott et al. 2000). These models have been fairly successful in simulating the temporal evolution of global mean surface temperature, when compared to the observational records. The models can even capture regional characteristics of the twentieth-century climate. As an example, the simulation of the Community Climate System Model 3, version 3 (CCSM3), surface air temperature anomaly from 1979 to 1999 is shown in Fig. 1, which is the same period studied by Fu et al. As shown in this figure, the temporal evolution of the model is in very good agreement with the observational record.

For the present study we use three different model simulations of the twentieth century, the Climate System Model, version 1; the Parallel Climate Model; and the Community Climate System Model, version 3. All three of the models are fully coupled atmosphere–ocean–land–sea ice models, which include time-evolving natural and anthropogenic forcing factors. The forcing factors for the three simulations varied in the specification of anthropogenic sulfate concentration, tropospheric and stratospheric ozone, and solar variability. Thus, these three simulations can be viewed as including a measure of uncertainty in forcing factors. The models differ in their ocean, sea ice, and atmospheric components and are representative of fully coupled models used for climate simulations. The reason for using three different models with differences in forcing data is to include modeling uncertainty in applying the models to retrieval issues. The collection of models can be considered as representative of the larger community of models.

The first model is a version of the Climate System Model, version 1.4 (CSM1; Boville et al. 2001), which employs a spectral T31 (3.7° × 3.7°) 18-level atmospheric model, while the ocean model is nominally 2.4° reduced to 1.2° resolution in latitude near the equator. The forcing factors include time-evolving well-mixed greenhouse gases, specified time-evolving anthropogenic sulfate aerosols, time-evolving specified ozone, volcanic aerosols, and solar variability (Dai et al. 2001) for simulations of the twentieth century. The second model used is the PCM, which uses the T42 (2.8° × 2.8°) 18-level Community Climate Model version 3 (CCM3) atmospheric model and the Parallel Ocean Program (POP) with a nominal 2/3° resolution that is

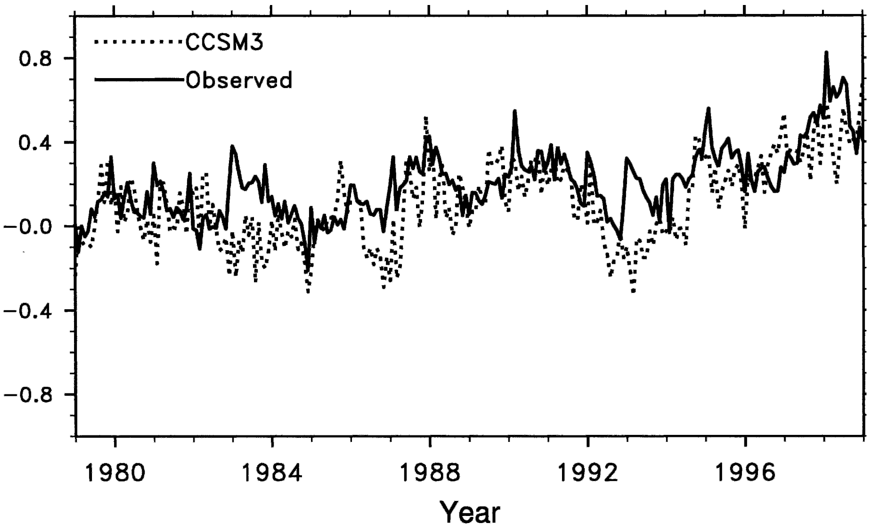

FIG. 1. Monthly mean anomalies in surface air temperature (°C) from the CCSM3 simulation and observations (Jones and Moberg 2003) from 1979 to 1999. Anomalies are calculated relative to the time period 1961–90.

reduced to ½° near the equator (Washington et al. 2000). The simulation employs similar forcings as in CSM1 (Meehl et al. 2004). The third model is CCSM3 (Collins et al. 2005, manuscript submitted to *J. Climate*), which uses the Community Atmosphere Model (CAM3), the Community Land Model, the Parallel Ocean Program, and a new sea ice model. The atmospheric component of the CCSM3 model employs a 26-level spectral T85 ($\sim$1.4° $\times$ 1.4°) truncation and a nominal 1° resolution for both the ocean and sea ice components, with higher resolution at the poles and the equator. The forcing factors used in the CCSM3 simulation include fully prognostic sulfate, carbonaceous, mineral dust and sea salt aerosols, specified time-varying ozone concentrations calculated from an offline chemical transport model, specified well-mixed greenhouse gases, volcanic aerosol optical depths, and the solar variability of Lean et al. (1995), whereas the CSM1 and PCM simulations employed the solar variability of Hoyt and Shatten (1993) and the ozone data described in Kiehl et al. (1999).

This study uses one realization for the CSM1 and CCSM3 models and an ensemble mean of four PCM simulations. Qualitatively, all three models capture important features of the observed changes in surface air temperature, such as the temperature increase over the twentieth century, the episodic volcanically induced cooling, and the rapid warming over the last two decades (e.g., Jones and Moberg 2003). The climate sensitivity of the various models is 1.9° for CSM1, 2.0° for PCM, and 2.7°C for CCSM3. The stratospheric cooling simulated by these various models is different depending on model resolution, physics, and forcings, and all three models underestimate the observed stratospheric cooling, similar to other models (e.g., Shine et al. 2003).

The focus of the present study is on the time period from 1979 to 1999, similar to that of Fu et al. (2004a). We use the three-dimensional monthly mean temperature data from the three models and apply various retrieval algorithms described in Fu et al. (2004a) to the model temperature data. The regression coefficients are those obtained by Fu et al. and are applied as a static mean weighting function to the model temperature data.

3. Analysis of results

The advantage of using the coupled model simulations is that we can explicitly calculate simulated surface, tropospheric, and stratospheric temperature trends. We can then apply the MSU satellite retrieval algorithms to the climate model temperature data to evaluate the accuracy of these various algorithms. Note that this approach to testing the accuracy of the algorithms is independent of the models' ability to accurately simulate climate change. In fact, all three models perform reasonably well in simulating the observed trend in global surface temperature change. Independent of this agreement, the model simulations are an ideal dataset to test satellite retrieval methods, since they provide a "truth" for validation where the explicitly simulated thermal structure is known.

We wish to test three issues related to retrieval of tropospheric warming from MSU data and raised by Fu et al. (2004a): 1) Using models, can we verify that the

MSU channel-2 retrievals are sensitive to a stratospheric cooling trend? 2) does Fu et al.'s method of retrieving tropospheric warming eliminate the contamination by stratospheric cooling? 3) What is the relative warming of the tropical troposphere to the surface? To answer the first question, we apply the MSU channel-2 weighting function (Christy et al. 1998) to the CSM1, PCM, and CCSM3 twentieth-century simulations. This algorithm produces a brightness temperature, T_2, that represents a mean layer temperature centered in the midtroposphere, which is used to calculate the middle-tropospheric temperature trend for the time period from 1979 to 1999. To answer the second question, we apply the algorithm developed by Fu et al. (2004a), that is, his regression coefficients, to the same model data and calculate a tropospheric temperature trend using the base period 1985–94, which is the climatological period used in Fu et al. (2004a), to create monthly mean anomalies. To evaluate the accuracy of the retrieval approaches, we compare the two retrieved trends to the exact trend in layer-averaged 850- to 300-hPa tropospheric temperature as simulated by the models. The results of this process for the three models are shown in Figs. 2a–c.

As in Fu et al. (2004a), we show temperature trends averaged globally for the Northern and Southern Hemispheres and Tropics separately. The analysis using CSM1 simulations is shown in Fig. 2a. For all three spatial averages, the channel-2 trend underestimates the explicitly simulated tropospheric trend, while the Fu et al. method agrees very well with the simulated trend, except for the CSM1 Southern Hemisphere results. The analysis using the PCM ensemble model simulations is shown in Fig. 2b. Once again the channel-2 retrieved trend in tropospheric warming severely underestimates the explicit simulation, and the Fu et al. algorithm provides a much better approximation. Note that the bias in the channel-2 method is larger than when the CSM1 data are used. This is because the stratospheric cooling in the PCM simulation is -0.39 K decade^{-1} compared to that simulated by CSM1 (-0.17 K decade^{-1}). The cooling trend simulated by PCM is closer to the observed trend of ~ -0.5 K decade^{-1} (Houghton et al. 2001) but is still an underestimate. The results for the analysis of CCSM3 are shown in Fig. 2c. This model produces a stratospheric cooling of -0.31 K decade^{-1}, which is less than that simulated by PCM and derived from observations. The conclusion again indicates that the Fu et al. method accurately represents the simulated trend in tropospheric warming compared to the channel-2 method. There is a strong correlation between the bias in channel 2 and the simulated stratospheric cooling (Fig. 3), which illustrates the magnitude of the sensitivity of the channel-2 radiance to cooling in the stratosphere, while the Fu et al. method does not.

Next, we determine whether or not the resulting tropospheric temperature trends computed using the technique devised by Fu et al. (2004a) are significantly different from the actual 850–300-hPa layer temperature trends by computing the difference of the two time series,

$$T_d = T_{850-300} - T_{\mathrm{Fu}},$$

and assuming a null hypothesis that the trend of T_d is not significantly different from zero at the 95% level. We then compute the ratio between the trend, T_d, and its error, s_b, using the effective sample size n_e to adjust s_b for temporal autocorrelation in the difference series. The trend significance testing follows Santer et al. (2000). We find that for the CSM1 and CCSM3 models, we cannot reject the null hypothesis, and therefore the tropospheric temperature trend from Fu et al. is indistinguishable from the $T_{850–300}$ trend at the 95% level, whereas for the PCM, the trends fall outside the 95% confidence level. Note that we have also applied the retrieval algorithm to individual members of the PCM ensemble, and this conclusion remains unchanged. The same test is applied to the original MSU T_2 method of computing the tropospheric temperature, where $T_d = T_{850-300} - T_2$. We find that for the CSM1, PCM, and CCSM3 models, the trend of T_d is significantly different from zero, and thus the trend of T_2 is distinguishable from that of $T_{850–300}$ at the 95% level.

To answer the third question (What is the relative warming of the tropical troposphere to the surface?), we calculate the ratio of the mean tropical tropospheric warming trend to that of the simulated surface trend. The results from the model and the ratio deduced from using Fu et al.'s retrieved tropospheric temperature trend and model surface trend are shown in Table 1. We see that this ratio for the tropical region (30°S–30°N) is greater than unity, indicating that the trend in tropospheric warming is ~1.5 times greater than that at the surface for the tropical region, which agrees with the conclusion of Fu et al. (2004a). The reason that the ratio of Fu et al. retrieved tropical trends is larger than the ratio of model tropical trends is due to the fact that the Fu et al. method includes a contribution from the layer between 300 and 100 hPa, where the temperature trends are larger than the layers below this region.

4. Conclusions

We have applied the MSU channel-2 (Christy et al. 1998) temperature retrieval technique and the Fu et al.

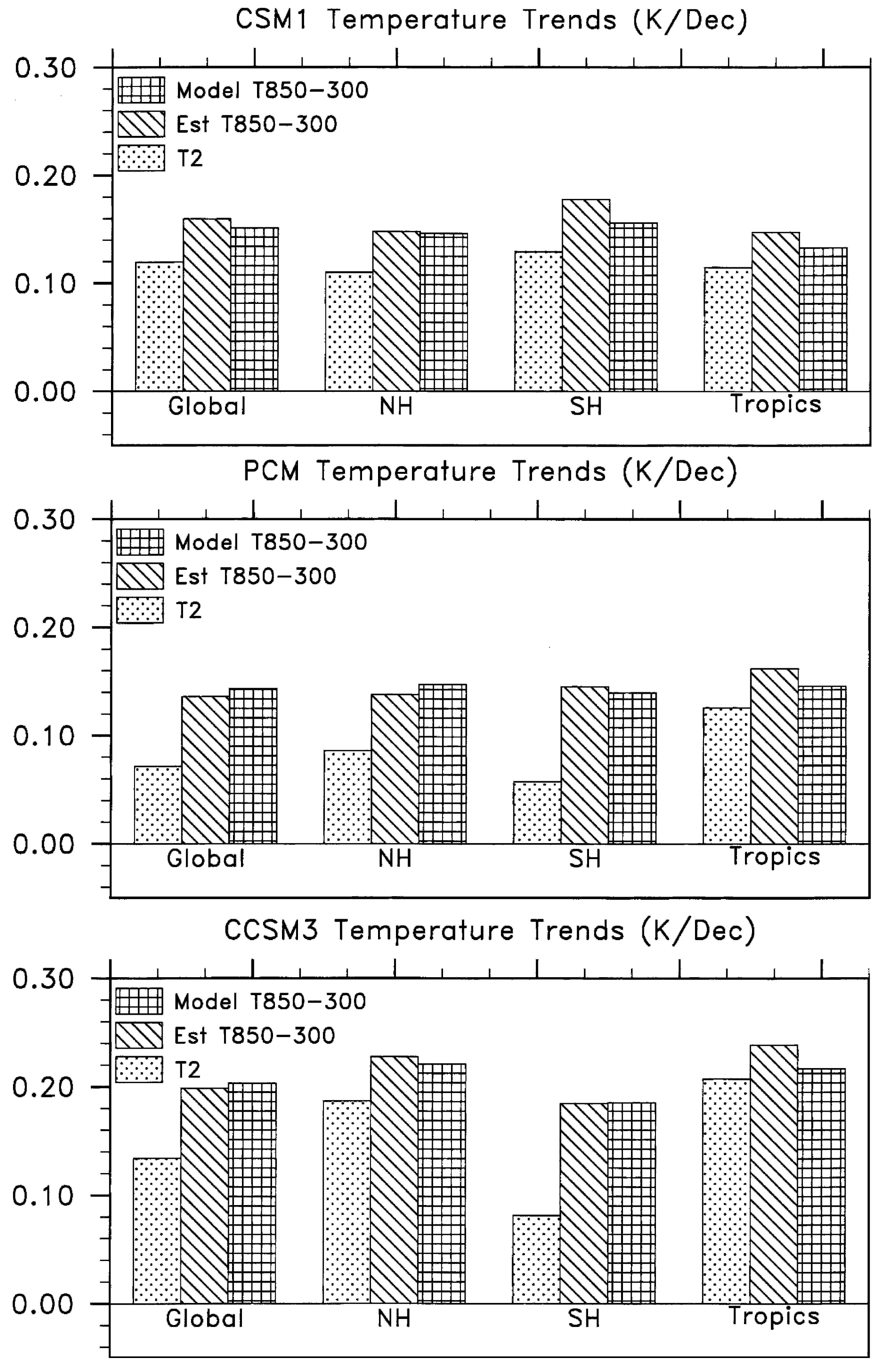

FIG. 2. Tropospheric temperature trends (°C decade^{-1}) from the (a) CSM1, (b) PCM, and (c) CCSM3 models compared to the trends from applying the MSU channel 2 and Fu et al. retrieval algorithms to the climate model temperature data.

retrieval technique to three different global climate models—CSM1, PCM, and CCSM3—to determine if the Fu et al. approach successfully removes the contamination of the stratospheric cooling trend from retrieved tropospheric temperature trends. These models differ in their treatment of parameterized physics, in their vertical and horizontal resolutions, and in the specification of stratospheric ozone and tropospheric aerosols. All of the models produce similar realistic warming trends in surface temperature for 1979–99. Stratospheric temperature cooling trends are most realistic for the PCM and CCSM3 models, although still

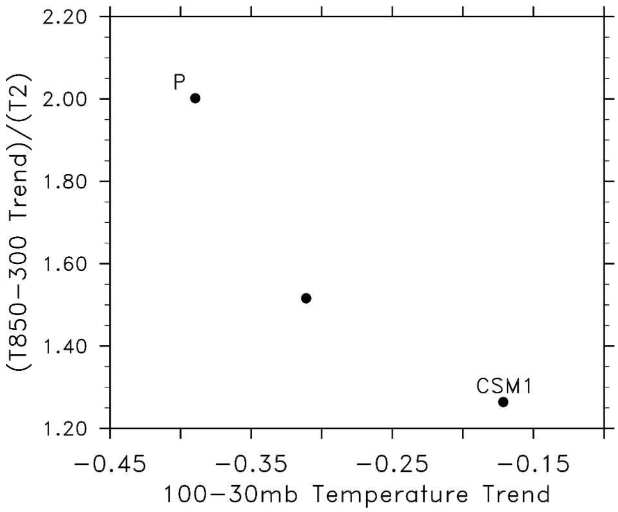

FIG. 3. Model tropospheric temperature trends (°C decade^{-1}) as calculated from the MSU channel-2 algorithm vs the model-simulated stratospheric cooling trend (°C decade^{-1}).

weaker than observed. The CSM1 stratospheric cooling trend is approximately half of what is simulated by PCM and is partially attributable to the treatment of stratospheric ozone in the two models. The channel-2 retrieval of middle-tropospheric temperature trends, however, is significantly weaker than what is simulated by all three models. The magnitude of the error is directly related to the magnitude of the stratospheric cooling in each of the model simulations.

Our modeling results confirm earlier hypotheses that the channel-2 MSU retrieval of tropospheric temperature trends is likely to be significantly contaminated by the stratospheric cooling trends, a signature of global warming in response to increasing levels of greenhouse gases. Our results also indicate that the Fu et al. (2004a) retrieval algorithm does a very good job of reducing this contamination and accurately capturing the true middle-tropospheric temperature trend. Our results suggest that the technique is quite robust and produces similar ratios of tropospheric warming to surface warming as compared with what has been derived from the observational record by Fu and colleagues. These results also demonstrate the value of using global numerical models of the climate system as test vehicles for remote sensing retrieval techniques.

TABLE 1. Ratio of model and retrieved tropical tropospheric warming trend to model surface trend for the three coupled model simulations of the twentieth century. The trend is calculated for the time period of 1979–99.

Model version	Ratio of model tropical tropospheric trend to model surface trend	Ratio of Fu et al. retrieved tropical tropospheric trend to model surface trend
CSM1	1.28	1.42
PCM	1.37	1.52
CCSM3	1.41	1.55

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