Atmospheric science

Tropospheric temperature series from satellites

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There has been considerable debate about changes in the temperature of the troposphere[1] measured using the Microwave Sounding Unit (MSU) instrument[2,3] or radiosondes[4,5]. Fu *et al.*[6] linearly combine time series from two MSU channels to estimate vertically integrated 850–300-hPa temperatures and claim consistency between surface and free-troposphere warming for one MSU record. We believe that their approach overfits the data, produces trends that overestimate warming and gives overly optimistic uncertainty estimates. There still remain large differences between observed tropospheric temperature trends and those simulated by a climate model.

Fu *et al.*[6] linearly combine MSU channels 2 and 4 using coefficients estimated from linear regression on a single, monthly mean radiosonde data set to create an effective weighting function that minimizes the effect of the stratosphere. For this approach to be valid on all space and time scales, the structure of stratospheric temperature variability must be stationary; this is not the case in reality. For example, the quasi-biennial oscillation[7] has a temperature response of more than 1 K above pressures of 100 hPa, where the weightings of Fu *et al.*[6] are negative, but little signal below 100 hPa, where the weightings are positive. Fu *et al.*[6] will therefore alias an inverse quasi-biennial oscillation signal into the tropical tropospheric record — something not apparent in radiosonde observations.

Fu *et al.* trained and tested both their channel-2 and -4 coefficients on the same radiosonde data[5], which can give false agreement and overfitting[8]. They found a global-average trend difference between their estimated value and actual 850–300-hPa temperatures ($T_{850–300}$) of 0.001 K per decade. We believe that this result is misleading: their statistical model could have been independently confirmed by at least one other vertically resolved radiosonde data set[4], a reanalysis[9], a climate model forced with observed sea surface temperatures and anthropogenic and natural forcings[10] or a coupled climate model forced with anthropogenic and natural forcings[11]. We did this for tropical trends (Table 1). Discrepancies between tropical trends computed using the method of Fu *et al.*[6] (T_{fjws}) and tropical $T_{850–300}$ trends range from −0.02 to 0.06 K per decade, with root-mean-square values ranging from 0.03 to 0.09 K. Except for HadRT2.1s, the T_{2LT} trend (where T_{2LT} is a synthetic channel for lower-middle troposphere) is a better estimate of the $T_{850–300}$ trends than T_{fjws} trends. These T_{fjws} trends are generally larger than the $T_{850–300}$ trends, suggesting that the approach of Fu *et al.* has a warm bias.

Trend discrepancies, and root-mean-square values, are smaller when T_{fjws} is compared with 1,000–100-hPa temperatures ($T_{1,000–100}$), with less evidence of systematic bias (Table 1). This is probably because of the form of the effective weighting function. However, there still exist differences of −0.01 to 0.02 K per decade between $T_{1,000–100}$ and T_{fjws} trends — about 10% of the observed surface tropical warming.

Average tropospheric temperature trends derived from an ensemble of coupled atmosphere–ocean model simulations are similar to those in the atmosphere-only case (Table 1). However, tropospheric trend ranges in the coupled simulations are larger than the atmosphere-only case and so are consistent with that estimated from one processing of the MSU record[3]. This demonstrates that ignoring observed changes in sea surface temperature leads to a weaker test of model–data consistency.

We re-estimated the channel-2 and -4 coefficients of Fu *et al.*[6] using HadRT2.1s (ref. 4), rather than the radiosonde data set of ref. 5. Our coefficients differ from those of Fu *et al.* and are sensitive to the choice of training period, with a total uncertainty of the order of 10% for global and tropical coefficients, corresponding to a trend uncertainty of 0.01 to 0.02 K per decade.

Although the approach of Fu *et al.* is novel, independent data indicate that it contains significant uncertainty. HadAM3 and the GISS model[12] forced with observed sea surface temperatures and forcing reconstructions show significantly greater warming than all 'observed' data sets. To resolve differences between models and observations requires good experimental design and process-based studies using physical understanding.

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Table 1 **Tropical trends for deep-layer temperatures for 1 December 1978 to 1 December 2002**

Data source	T_4	T_2	T_{fjws}	T_{2LT}	$T_{850–300}$	$T_{1,000–100}$	Surface
MSU (Remote Sensing Systems[3])	−0.35	0.12	0.18				0.13
MSU (University of Alabama, Huntsville[2])	−0.39	0.05	0.10	0.00			0.13
Radiosonde (HadRT2.1s[4])	−0.60	−0.08	−0.02	0.03	0.00 (0.09)	−0.03 (0.07)	0.13
ERA40 reanalysis (1 Dec 1978–1 Dec 2001)[9]	−0.20	0.06	0.09	0.02	0.03 (0.07)	0.10 (0.02)	0.10
HadAM3[10] Model average	−0.29	0.19	0.25	0.20	0.22 (0.03)	0.23 (0.02)	0.14
Smallest trend	−0.31	0.17	0.22	0.18	0.21	0.21	0.12
Largest trend	−0.26	0.22	0.29	0.23	0.25	0.27	0.15
HadCM3[11] Model average	−0.45	0.16	0.23	0.21	0.21 (0.03)	0.22 (0.01)	0.16
Smallest trend	−0.42	0.07	0.13	0.12	0.12	0.13	0.10
Largest trend	−0.51	0.24	0.32	0.28	0.30	0.30	0.21

Tropical (30° S–30° N) trends (K per decade) are shown for deep-layer temperatures for 1 December 1978 to 1 December 2002. For the non-satellite data sets, static weighting functions were used to estimate synthetic Microwave Sounding Unit (MSU) equivalents. T_{fjws} is derived for each data set by applying the Fu *et al.* published coefficients to the T_2 and T_4 data. All data were zonally averaged, then cosine-weighted and least-square estimates of the linear trends computed from annual-mean data. For HadRT2.1s, Indian data were removed from the analysis. Also shown are the logarithms of the pressure-weighted 850–300-hPa temperatures[1] ($T_{850–300}$) and of the pressure-weighted 1,000–100-hPa temperatures ($T_{1,000–100}$); the root-mean-square of the annual-mean differences between those and T_{fjws} is shown in brackets. Surface trends are from data averaged over land and ocean. For ERA40, we used two-metre temperatures over land and sea surface temperatures over the oceans. Surface temperatures from HadCRUT2v are used for RSS, UAH and HadRT2.1s. For the two model ensembles, the average, largest and smallest trends are shown. The difference between largest and smallest gives an indication of uncertainty in the ensemble average. The coupled (HadCM3) and atmosphere-only (HadAM3) simulations differ in their forcings, with the main differences being a correction of an error in ozone loss and changes to the sulphur cycle in the HadAM3 simulations. The HadAM3 (HadCM3) ensemble consists of six (four) simulations.

Atmospheric science

Stratospheric cooling and the troposphere

Satellite observations of tropospheric temperatures seem to show less warming than surface temperatures, contrary to physical predictions[1]. Fu *et al.*[2] show that statistical correction for the effect of stratospheric cooling brings the satellite-based estimates of tropospheric warming into closer agreement with observations of surface warming. Here we apply the method of Fu *et al.*[2] to output from a state-of-the-art coupled climate model and show that simulated tropospheric temperature trends are consistent with those observed and that their method is robust.

Tropospheric temperatures (T_2) monitored by channel 2 of the satellite-based Microwave Sounding Unit (MSU) include a contribution from temperatures in the cooling stratosphere[1,2] (T_4). Using radiosonde data, Fu *et al.*[2] apply a regression method to quantify the relative influences of T_4 and T_2 on the mean temperature of the 850–300-hPa layer ($T_{850\text{–}300}$). We apply the Fu *et al.* regression method to simulated 1958–97 monthly-mean global-mean T_4, T_2 and $T_{850\text{–}300}$ from a four-member ensemble of a climate-change experiment that was performed with the National Center for Atmospheric Research Parallel Climate Model (PCM)[3,4] with combined anthropogenic and natural forcing.

The model-derived regression coefficients of $T_{850\text{–}300}$ against T_2 and T_4 are $a_2 = 1.106 \pm 0.026$ and $a_4 = -0.157 \pm 0.019$, with 5–95% uncertainty ranges derived from intra-ensemble variability. Results are in close agreement with the coefficients estimated by Fu *et al.*[2] from radiosonde data ($a_2 = 1.156$, $a_4 = -0.153$). To assess the contribution to these coefficients of the overlap between the T_2 and T_4 weighting functions, we derive a weighting function for $T_{850\text{–}300}$ and regress this directly against the mass-based weighting functions[5] of T_2 and T_4. This yields $a_2 = 1.089$ and $a_4 = -0.129$, implying that the regression relation derived by Fu *et al.* arises largely from the overlap of the weighting functions, rather than from physical coupling between tropospheric and stratospheric temperatures.

Because we know the actual $T_{850\text{–}300}$ trends over 1979–99 in PCM, we can evaluate the reliability of the statistical method of Fu *et al.*[2] for reconstructing these trends. For each ensemble member, trend reconstructions were produced with the Fu *et al.* and PCM-derived regression coefficients. Reconstructed trends agree with the actual PCM $T_{850\text{–}300}$ trends to within 0.016 K per decade on average (Fig. 1). We find a similar level of agreement between PCM's reconstructed and actual $T_{850\text{–}300}$ trends for the Northern and Southern Hemispheres and the tropics. Note that although simulated trends in T_{2LT} (where T_{2LT} is a synthetic channel for lower-middle troposphere) and $T_{850\text{–}300}$ are in close correspondence, PCM's T_{2LT} trends are not subject to problems that affect the observed T_{2LT} product, such as changes in surface emissivity, intersatellite calibration biases, and noise amplification[2].

Our model-based $T_{850\text{–}300}$ trends shown in Fig. 1 are consistent with the free tropospheric temperature trends that Fu *et al.* reconstructed from MSU observations for the period 1979–2001 (refs 2, 6; 0.09 and 0.18 K per decade for the UAH (University of Alabama at Huntsville) and RSS (Remote Sensing Systems) reconstructions, respectively). Overall, we find that the analysis method of Fu *et al.*[2] is robust, and that their radiosonde-based regression relationships between T_4, T_2 and $T_{850\text{–}300}$ are in good agreement with those independently derived from climate-model output.

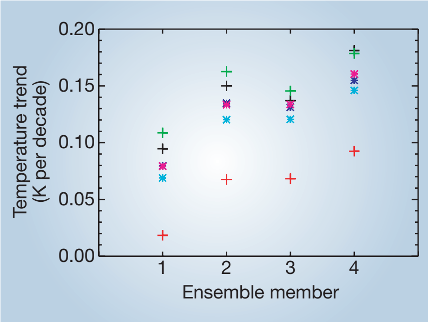

Figure 1 Simulated trends in global-mean free-tropospheric temperature. Black crosses, trends in $T_{850\text{–}300}$ over the period 1979–99, as simulated by the National Center for Atmospheric Research Parallel Climate Model (PCM) in each of four realizations of an experiment with anthropogenic and natural forcing[3,4]. Asterisks indicate free-tropospheric temperature trends reconstructed from synthetic T_2 and T_4 trends using the method of Fu *et al.*[2]. These are calculated using three different sets of regression coefficients, which are derived from radiosonde observations by Fu *et al.*[2] (pink asterisks), estimated from the PCM experiments (dark blue asterisks), and obtained directly from the T_2 and T_4 weighting functions (light blue asterisks). Red crosses, simulated trends in T_2; green crosses, simulated trends in T_{2LT}. The simulated trend in T_4 is -0.36 ± 0.03 K per decade. The model's surface warming over 1890–1999 (0.62 °C) is consistent with that observed.

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Fu et al. *reply* — The success of our method[1] for reconstructing tropospheric temperature trends is reinforced by Gillett *et al.*[2], who show that our method is robust for reconstructing the tropospheric temperature trends, and that the statistical relationships between our T_4, T_2 and $T_{850\text{–}300}$ estimates are in agreement with those independently derived from climate-model output. But Tett and Thorne[3] use different data sets in the tropical region and suggest that our approach produces tropospheric temperature trends that are biased to warm and that it overfits the data. We argue that the differences in tropical tropospheric temperature trends between our estimate of T (T_{fjws}) and the $T_{850\text{–}300}$ of Tett and Thorne do not invalidate our method. We also question their interpretation of the comparison between global climate model results and satellite observations.

We first clarify that the quasi-biennial oscillation (QBO) issue that they raise is irrelevant to the trend analyses because the QBO signal is periodic. It is also incorrect that our weightings were negative above 100 hPa in the tropics. In reality, T_2 still has a significant weight above 100 hPa (ref. 4) and so should experience QBO effects. By contrast, our weighting function changes sign from positive to negative at about 75 hPa and has much smaller absolute values than the T_2 weighting function throughout the tropical stratosphere (see Fig. 3 of ref. 5).

Tett and Thorne show discrepancies between T_{fjws} and $T_{850\text{–}300}$ trends ranging from -0.02 to 0.06 K per decade for different data sets applied to the tropics, and so claim that our approach is biased to warm. We have shown that our weighting function is largely free of the stratospheric influence (Fig. 3 of ref. 5). However, these large trend differences arise because, in the tropical region, our weighting function is attributed to the whole troposphere from the surface to the tropopause (about 100 hPa), including a significant contribution from the layer between 300 hPa and 100 hPa, where the temperature trends are poorly characterized but might be very different from those below[6].

For the tropical region, where the tropospheric temperature trends have significant height dependence, we argue that the T_{fjws} trend is more representative of the entire troposphere than of the $T_{850\text{–}300}$ layer. For example, for the ERA40 data for 1979–2001 in the tropics, there is a moderate positive temperature trend below 775 hPa, a moderate negative trend between 700 and 400 hPa, and a very strong positive trend between 300 hPa and tropopause. The $T_{850\text{–}300}$ trend excludes the large positive contribution from the upper troposphere, which leads to a much smaller trend for $T_{850\text{–}300}$ than for T_{fjws}. The large discrepancy with ERA40 data therefore arises owing to its very complex vertical structure of trends, which has not been shown to be realistic. If it is real, it indicates that the $T_{850\text{–}300}$ trend does not represent the layer-mean trend of the entire tropical troposphere but that the T_{fjws} trend does. The trend comparison, which shows a mean difference of 0.01 K per decade between T_{fjws} and $T_{1,000–100}$ (mass-weighted temperatures from 1,000 to 100 hPa) in Table 1, supports our argument.

Tett and Thorne assert[3] that the average tropospheric temperature trends from an ensemble of coupled atmospheric–ocean model simulations are similar to those in the atmosphere-only case. However, we notice that the average ratio of T_{fjws} to surface-temperature trends is about 1.4 from the coupled model, which is different from the atmospheric-only result (about 1.8); the former is consistent with the trend ratio derived from the RSS (Remote Sensing Systems) data (about 1.4) (Table 1). Understanding the differences between the HadAM and HadCM results are outside the scope of our study[1], but we notice that the global climate simulation with prescribed sea surface temperature does not conserve energy.

We performed tests, similar to those done by Tett and Thorne[3], to check the sensitivity of the regression coefficients to different data sets[6] and to the choice of training periods. The scatter in derived coefficients was within 10%, in agreement with their findings. Using the observed Microwave Sounding Unit T_2 and T_4, this leads to an uncertainty of, at most, 0.01 K per decade in the derived tropospheric temperature trends. Our more recent analysis[5], in which we directly apply our effective weighting function[1] to observed profiles of stratospheric temperature trend, reveals that our approach does remove the stratospheric influence effectively, leaving a residual influence of less than 0.01 K per decade[5]. Furthermore, by comparing T_2 and T_{fjws} in Table 1, we notice a robust stratospheric contamination in tropical T_2 trend, insofar as it depicts the tropospheric trend: it is about -0.06 K per decade from both satellite Microwave Sounding Unit data sets, radiosonde, and both global climate model outputs (only ERA40 reanalysis shows a smaller stratospheric influence in T_2).

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