Warming maximum in the tropical upper troposphere deduced from thermal winds

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Published online: 25 May 2008; doi:10.1038/ngeo208

Climate models and theoretical expectations have predicted that the upper troposphere should be warming faster than the surface. Surprisingly, direct temperature observations from radiosonde and satellite data have often not shown this expected trend. However, non-climatic biases have been found in such measurements. Here we apply the thermal-wind equation to wind measurements from radiosonde data, which seem to be more stable than the temperature data. We derive estimates of temperature trends for the upper troposphere to the lower stratosphere since 1970. Over the period of observations, we find a maximum warming trend of 0.65 ± 0.47 K per decade near the 200 hPa pressure level, below the tropical tropopause. Warming patterns are consistent with model predictions except for small discrepancies close to the tropopause. Our findings are inconsistent with the trends derived from radiosonde temperature datasets and from NCEP reanalyses of temperature and wind fields. The agreement with models increases confidence in current model-based predictions of future climate change.

It has long been recognized that radiosonde temperature data are affected by non-climatic artifacts due to station relocations, observation time changes and radiosonde type or design changes[1]. Several investigators have attempted to detect and adjust (that is homogenize) these artefacts using a variety of tools, including statistical procedures, station metadata, various indicators of natural variability (such as volcanic eruptions, vertical coherence) and forecasts from a climate data assimilation system[2–6].

Despite these attempts, most analyses of radiosondes continue to show less warming of the tropical troposphere since 1979 than reported at the surface[1]. At least one satellite dataset also implies this[7]. By contrast, theoretical and model expectations[7,8] indicate that the troposphere should warm somewhat faster than the surface.

Recently, time-varying biases were shown to remain in the radiosonde temperature data, including a daytime cooling bias related to solar heating of the instrument (especially in the stratosphere)[9]. They were significantly larger than the average adjustments that had previously been made, and comparable to the above discrepancies, calling into question whether the adjustments had been adequate. A similar cooling bias was also found in night-time soundings[10,11]. Subsequent attempts to produce better homogenized records have yielded more warming than before[5,12,13], but only one has produced upper-tropospheric warming close to that expected[13].

Tropical warming rates shown by satellite data have similar problems. Although two research groups—Remote Sensing Systems and University of Maryland—found more tropical tropospheric warming than shown by radiosondes, a third group (University of Alabama in Huntsville) found little warming[1]. Interpretation of trends is complicated by the stratosphere's influence on the (nominally) tropospheric channel[14], and by errors in a previous version of the University of Alabama, Huntsville dataset, both of which have caused warming to be underestimated in some studies[15,16].

In each of the above cases, errors inherent in correction procedures (that is, structural uncertainty) could be sufficient to explain differences between expected and reported warming[17], but this has not been conclusively demonstrated[1]. Thus, doubts remain about whether the tropical atmosphere has behaved as predicted.

USING WINDS AS A PROXY FOR TEMPERATURE

We take an alternative approach by using trends in winds to infer those of temperature. Winds are observed by radiosonde tracking in a manner completely independent from temperature observations. While wind observations will undoubtedly have their own problems, artifacts seem to be significantly fewer and of smaller magnitude (relative to the trend) than those of temperature[5,18]. We report elsewhere[5] homogeneity adjustments to zonal winds since 1979 averaging $\sim -1\ \mathrm{cm\,s^{-1}}$ at tropical stations and less than $1\ \mathrm{mm\,s^{-1}}$ in northern hemisphere mid-latitudes. Another recent study found artifacts in the wind network, though in far smaller numbers (~10–15%) than found previously for temperature, and no systematic character to the adjustments was reported[18]. The zonal structure of wind-derived temperature trends in the western tropical Pacific agrees well with temperature trends from satellite measurements[19]. Furthermore, because our temperature trends are estimated from the vertical shear of the wind, errors that similarly affect all altitudes will not affect our results. Thus, the available evidence indicates that artifacts in radiosonde wind observations are only a small source of uncertainty in our results, although the issue deserves further attention[18].

We exploit a dynamical relationship known as the thermal-wind equation[20,21], which relates horizontal temperature gradients to wind shear. This relation holds when inertia and frictional effects are small compared with the Coriolis and pressure gradient forces, as will tend to be the case from the free troposphere[6] to the lower stratosphere[22] except near the equator. To the extent that absolute temperature trends are

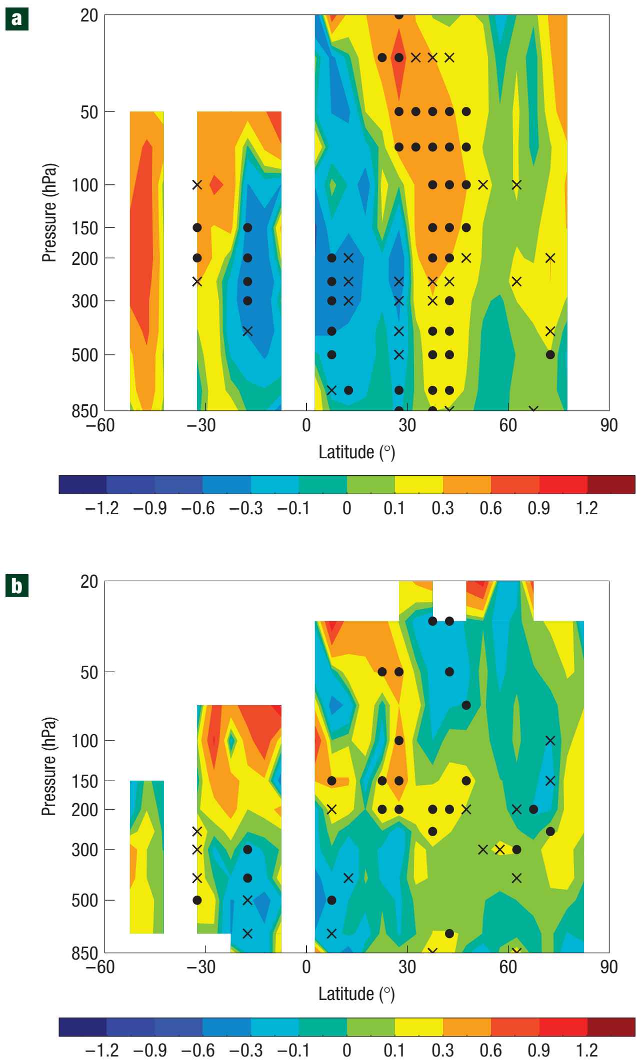

Figure 1 Radiosonde wind trends for 1979–2005. a, Trends in observed zonal mean westerly wind and **b**, shear. Symbols represent trend significance at the 95% (cross) and 99% (circle) confidence levels on the basis of a two-tailed Student *t*-distribution test with 26 degrees of freedom. Units are m (s-decade)$^{-1}$.

fairly well known at high northern latitudes[1], this technique enables recovery of trends at other latitudes, including the tropics. This method has recently been found to recover regional climatic temperature fluctuations accurately, even in the deep tropics, where the Coriolis force approaches zero[19], a finding we test further here using climate models. This characteristic, along with the relative homogeneity of radiosonde winds, makes the thermal wind equation a promising alternative for reconstructing patterns of temperature change above the planetary boundary layer.

We gridded wind data from 341 stations in the Integrated Global Radiosonde Archive[23] to monthly means at 5 × 10 degrees (see Supplementary Information, Methods). Only 38 stations were available in the southern hemisphere, and only half of these would have been available before 1970. We thus consider two time periods, 1970–2005 and 1979–2005; the latter comprises the period of satellite observations, and has been the focus of previously published temperature trend discrepancies[1].

We compare our results with those from three homogenized radiosonde temperature data sets: HadAT[4], Radiosonde Observation Correction using Reanalysis (RAOBCORE) v1.4[13] and the iteratively (universal) kriged (IUK)[5]. Other published radiosonde data sets[2,3,6], not shown, are similar to HadAT in that they show less-than-expected tropical tropospheric warming.

Integration of the east–west component of the thermal-wind equation from pressure p_0 to p_1 yields a relationship between the meridional gradient of the mean virtual temperature ($\Delta \bar{T}_v$) and the vertical difference between the westerly geostrophic winds (S) at p_0 and p_1:

$$\Delta \bar{T}_v = -\frac{f}{R_d}\left[\ln\left(\frac{p_0}{p_1}\right)\right]^{-1} S, \qquad (1)$$

where R_d is the gas constant for dry air, f is the Coriolis parameter and $p_0 > p_1$. Integration of the zonal mean trend of (1) over latitude gives wind-derived estimates of the layer temperature trend, given a boundary value at some latitude. Tests of this method (see the Supplementary Information) show that it yields very accurate temperature trends, given good wind and boundary data, and that trends in actual and virtual temperature should not differ by more than 0.01 K decade^{-1}. For this reason we will henceforth ignore the distinction between virtual and actual temperature in discussing trends.

OBSERVED WIND TRENDS

Figure 1a shows the observed trends in the zonal mean westerly wind since 1979. Westerlies increased over much of the extratropical upper troposphere and lower stratosphere at rates of 0.1–1.0 m (s-decade)$^{-1}$. Many trends are significant at the 99% confidence level between 35 and 55° N, which may be related to a trend in the North Atlantic Oscillation[24,25]. The increases in upper-troposphere/lower-stratosphere zonal wind, relative to those at lower altitudes, imply an increase in vertical wind shear (Fig. 1b) and, according to thermal-wind balance, meridional temperature gradient at levels from 100 to 500 hPa. This is anticipated as a consequence of tropospheric warming and stratospheric cooling[26,27], because the tropopause height decreases from equator to pole. Trends computed for individual seasons are mostly similar to the annual mean, but not always, especially for 1979–2005 (see the Supplementary Information).

TEMPERATURE-GRADIENT TRENDS

Figure 2 shows how trends in the reported temperature gradient, $\Delta \bar{T}_t$, compare with those ($\Delta \hat{\bar{T}}_t$) estimated from winds via (1), for two atmospheric layers within the tropics and mid-latitudes of either hemisphere. Reported $\Delta \bar{T}_t$ values are taken from HadAT, with and without homogenization adjustments, and RAOBCORE v1.4. In the southern hemisphere, the two homogenized estimates of $\Delta \bar{T}_t$ are generally consistent with $\Delta \hat{\bar{T}}_t$; at 200–100 hPa, however, RAOBCORE $\Delta \bar{T}_t$ is too large, indicating too much southward reduction in warming compared with what winds imply. There is less agreement in the northern hemisphere, where the two HadAT estimates of $\Delta \bar{T}_t$ are of the opposite sign to $\Delta \hat{\bar{T}}_t$, with reported $\Delta \bar{T}_t$ implying decreasing wind shear, in contrast to Fig. 1. RAOBCORE shows better agreement with the winds, but still implies a smaller increase in wind shear than what is observed.

To help interpret these results, Fig. 2 also shows equivalent quantities from six climate models included in the World Climate Research Programme's Coupled Model Intercomparison Project Phase 3 (CMIP3) (see Supplementary Information, Methods). These six models were chosen because they include changes in greenhouse gases, sulfate aerosols, ozone and other forcings[1], and

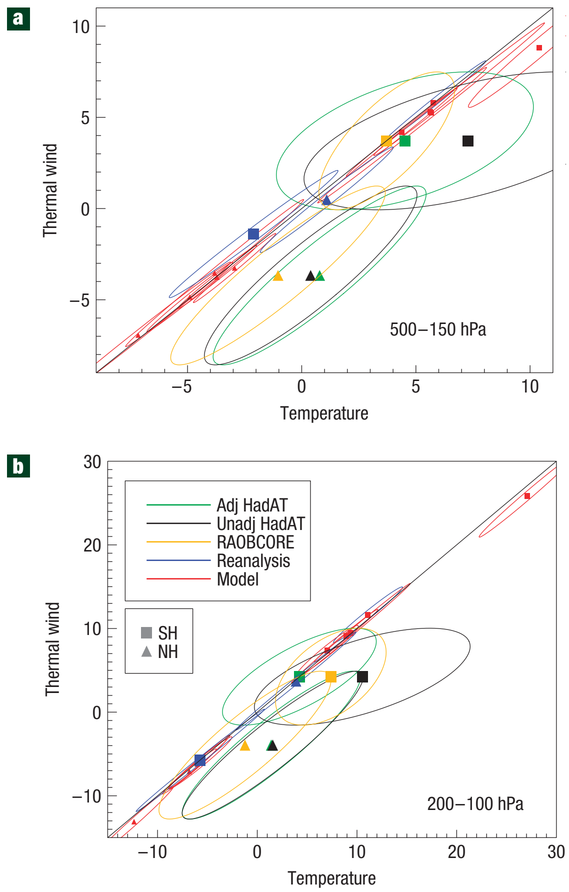

Figure 2 Trend in wind-estimated meridional temperature gradient versus the corresponding trend from temperature data for 1979–2005. Two layers are included, 500–150 hPa (**a**) and 200–100 hPa (**b**). Northern (triangle) and southern (square) hemispheres (2.5°–62.5°) are shown separately. Included are six climate models (red), NCEP/NCAR Reanalysis data (blue) and radiosonde observations (green for adjusted and black for unadjusted HadAT temperatures; yellow for adjusted RAOBCORE v1.4 temperatures). Ellipses indicate 95% confidence regions in the estimated linear trend, accounting for the correlation between temperature and thermal-wind residuals of fit. Units are deg (m-decade)$^{-1}$ $\times$ 10^{-8}.

predict surface warming in the tropics similar in magnitude to that observed[7]. Although $\Delta\bar{T}_t$ spans an order of magnitude among the simulations, all models show increasing meridional temperature gradients in both hemispheres, in agreement with sonde $\Delta\hat{\hat{T}}_t$ (from winds) but not sonde $\Delta\bar{T}_t$ (temperatures). The simulated pattern of wind trend also agrees roughly, though not exactly, with that observed (see Supplementary Information, Discussion). More importantly, all models fall very near the one-to-one line, indicating that their trends closely satisfy (1). The departures of the model points from this line indicates that small deviations from geostrophy are expected—but the departures implied by many of the observations are much too large. Models closely satisfy (1) even at much shorter space scales, including near the equator (see Supplementary Information, Discussion), despite the fact that all models solve the fully nonlinear momentum equations. Though thermal-wind balance becomes a poor approximation near the equator, $\Delta\bar{T}_v$ also becomes very small there and is thus known with sufficient absolute accuracy to reconstruct the temperature field itself with good absolute accuracy. In other words, the meridional gradient of temperature near the equator is unknown but is small enough not to matter.

Finally, equivalent quantities from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis[28] are included in the figure. Interestingly, these trends also obey thermal-wind balance, but show cooling of low latitudes relative to higher latitudes—that is, a decrease in zonal mean wind shear (see the Supplementary Information), opposite to the trends in radiosonde and model-simulated winds. This is probably due to the greater weight of temperature (particularly satellite) versus wind data going into the upper-air reanalyses. If wind data are indeed more homogeneous, but temperature data more plentiful, this poses an interesting dilemma for future reanalysis efforts.

TEMPERATURE DERIVED FROM THERMAL WINDS

Figure 3 shows meridional cross-sections of warming rate $\hat{\hat{T}}_v$ for each time period reconstructed by numerically integrating (1), using observed winds, from a boundary value at 62.5° N taken from adjusted HadAT data. The choice of 62.5° N is based on the maximum station coverage and, moreover, good agreement between several satellite and radiosonde data sets at this particular latitude[1]. For both time periods, a peak in warming is found near 200 hPa in the tropical upper troposphere. The magnitude $\hat{\hat{T}}_{tmax}$ of this peak is roughly 0.45 ± 0.29 K decade^{-1} for the satellite period and 0.65 ± 0.47 K decade^{-1} for the full period (uncertainties are two sigma and are discussed below). As can be inferred from Fig. 2 (see also Supplementary Information, Discussion), this warming maximum is either absent (HadAT) or weaker (IUK and RAOBCORE) in homogenized temperature datasets.

Figure 3 also includes the model-mean warming patterns for the two periods, which are qualitatively consistent with those observed here. Although the 1970–2005 $\hat{\hat{T}}_{tmax}$ is stronger in the observations than the model average, it is within the range of individual model simulations (see the Supplementary Information). Model–data discrepancies are highly significant only near the tropopause, with model warming decreasing more gradually above 200 hPa whereas observed trends drop rapidly and reach stronger negative values in the lower stratosphere. This may be due to errors in some models' stratospheric cooling trends[29] (due for example to incorrect ozone trend specification) and/or tropopause height[30]. We find a warming maximum in all four seasons, but it is considerably stronger in December–January–February (see the Supplementary Information), suggesting a role for atmospheric variability in altering the lapse rates on decadal timescales. We conclude that, although problems in model physics or applied forcings may be affecting temperature trends in the lower stratosphere and near the tropopause, at levels dominated by convective heating the models as a group seem to be roughly consistent with observations, given uncertainties and intermodel variability.

On the basis of our earlier discussion of errors (and further information in the Supplementary Information), ageostrophic and moisture effects should not be significant sources of uncertainty, and wind heterogeneities do not look like a serious problem, although this is harder to verify. Remaining sources of uncertainty in our warming estimates are that associated with the high-latitude boundary condition, and those due to incomplete station sampling in space and time.

We quantified uncertainty in the boundary condition by varying the choice of data set and boundary latitude (see the Supplementary Information). Although these variations can change $\hat{\hat{T}}_{tmax}$ by up to ~0.3 K decade^{-1}, the presence and location of this warming maximum remain robust.

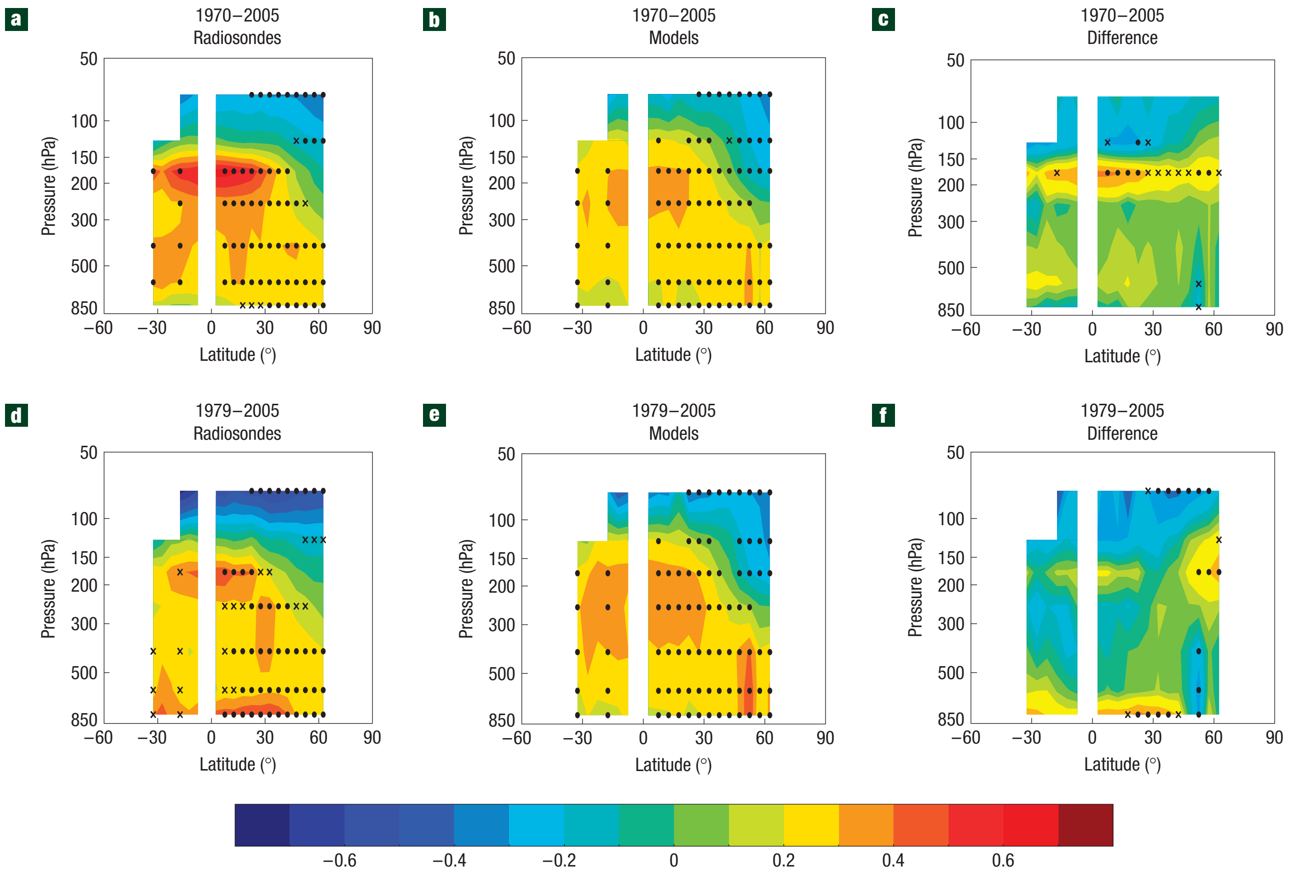

Figure 3 Meridional sections of atmospheric temperature trends. a,**d**, Trends estimated via (1) on the basis of winds from radiosondes; **b**,**e**, temperature from the ensemble mean of the six climate models; **c**,**f**, the difference (radiosonde − model) for 1970–2005 (**a**–**c**) and 1979–2005 (**d**–**f**). Models have been masked with the same missing monthly data as the gridded radiosonde winds. Symbols represent trend significance at the 95% (cross) and 99% (circle) confidence levels. Units are K decade^{-1}.

We quantified sampling and instrument error at each latitude via the spread of trends among individual stations near that latitude (via the standard error). This uncertainty estimate includes errors (among them any bias heterogeneities) that vary randomly among stations, but not systematic trend errors biasing all stations at a given latitude in a certain direction (which, fortunately, have not been detected in other studies). Propagating this error southward yields a 2σ sampling uncertainty in $\hat{T}_{\mathrm{tmax}}$ of 0.25 K decade^{-1} for 1979–2005 and 0.20 K decade^{-1} for 1970–2005. Combining this with the boundary condition uncertainty, we estimate an overall 2σ uncertainty in $\hat{T}_{\mathrm{tmax}}$ of 0.29(0.47) K decade^{-1} for 1979–2005 (1970–2005), or 95% confidence intervals of 0.16–0.74 (0.18–1.12) K decade^{-1}.

CONCLUSIONS

We conclude that the peak warming in the upper troposphere is highly significant for both time periods, and that our data do not seem to be consistent with a lack of upper-tropospheric warming in the tropics. The degree of warming remains fairly uncertain, but is within the range simulated by climate models, albeit with some discrepancies near the tropopause. This analysis reveals the importance of remembering dynamics in monitoring atmospheric change. Results indicate that, although past attempts to remove artifacts from the radiosonde temperature record have been beneficial, artifacts probably still remain and further work is warranted. Our results also suggest that the development of a climate-quality reanalysis will not be easy, and may fail if anchored to current temperature datasets.

Attention should also be paid to current observing systems so that problems of this sort can be avoided in the future. Specifically, it is important to implement the Global Climate Observing System reference upper-air network[31]; maintain the Global Climate Observing System Upper Air Network; support the Global Space-Based Intercalibration System and follow the climate-monitoring principles for all meteorological observations[32].

Most importantly, we conclude that observed changes in wind seem to be consistent with those predicted by models given sampling and other uncertainties, supporting previous suggestions that discrepancies between predicted and observed upper-tropospheric warming are due to problems remaining in the temperature records[1].

Received 13 September 2007; accepted 25 April 2008; published 25 May 2008.

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Supplementary Information accompanies this paper on www.nature.com/naturegeoscience.

Acknowledgements

We acknowledge the individual modelling groups, the Program for Climate Model Diagnosis and Intercomparison and the WCRP's Working Group on Coupled Modeling for their roles in making available the WCRP CMIP3 multimodel dataset. Support of this dataset is provided by the Office of Science, US Department of Energy. We also thank P. Thorne and L. Haimberger for providing key datasets.

Author contributions

R.J.A. initiated and conducted the project, carried out all data analysis and led the writing of the manuscript as part of his PhD thesis. S.C.S. advised on methods and interpretation.

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