On the Evaluation of Temperature Trends in the Tropical Troposphere.

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Abstract

A series of model experiments with the coupled Max-Planck-Institute ECHAM5/OM climate model have been investigated and compared with microwave measurements from the Microwave Sounding Unit (MSU) and re-analysis data for the period 1979-2008. The evaluation is carried out by computing the Temperature in the Lower Troposphere (TLT) and Temperature in the Middle Troposphere (TMT) using the MSU weights from both University of Alabama (UAH) and Remote Sensing Systems (RSS) and restricting the study to primarily the tropical oceans. When forced by analysed sea surface temperature the model reproduces accurately the time-evolution of the mean outgoing tropospheric microwave radiation especially over tropical oceans but with a minor bias towards higher temperatures in the upper troposphere.

The latest reanalyses data from the 25 year Japanese re-analysis (JRA25) and European Center for Medium Range Weather Forecasts (ECMWF) Interim Reanalysis are in very close agreement with the time-evolution of the MSU data with a correlation of 0.98 and 0.96 respectively. The re-analysis trends are similar to the trends obtained from UAH but smaller than the trends from RSS. Comparison of TLT, computed from observations from UAH and RSS, with Sea Surface Temperature (SST) indicates that RSS has a warm bias after 1993.

In order to identify the significance of the tropospheric linear temperature trends we determined the natural variability of 30-year trends from a 500 year control integration of the coupled ECHAM5 model. The model exhibits natural unforced variations of the 30 year tropospheric trend that vary within ±0.2K/decade for the tropical oceans. This general result is supported by similar results from the Geophysical Fluid Dynamics Laboratory (GFDL) coupled climate model. Present MSU observations from UAH for the period 1979-2008 are well within this range but RSS is close to the upper positive limit of this variability.

We have also compared the trend of the vertical lapse rate over the tropical oceans assuming that the difference between TLT and TMT is an approximate measure of the lapse rate. The TLT-TMT trend is larger in both the measurements and in the JRA25 than in the model runs by 0.04-0.06K/decade. Furthermore, a calculation of all 30 year TLT-TMT trends of the unforced 500-year integration vary between ±0.02K/decade suggesting that the models have a minor systematic warm bias in the upper troposphere.

1. Introduction

At higher surface temperatures, such as being projected in a future climate, the tropical upper troposphere is likely to warm proportionally more than the surface and the lower troposphere. This might be expected because the temperature of the upper troposphere is largely controlled by deep convection. At higher surface temperatures the moist adiabatic lapse rate diminishes leading to a reduced cooling in the upper troposphere. We might thus expect to find a larger warming trend in the upper troposphere than at the surface in a warming climate. This is also what is found in current climate models (Hegerl et al., 2007). However, whether this is correct or not is an open issue as the areas of deep convection are spatially confined and models have deficiencies including aliasing due to insufficient resolution. Consequently, an important question to explore is whether such a trend can be reliably determined from observations.

Estimates of temperature trends of the atmosphere are traditionally done from actual observations such as radiosondes and data from the Microwave Sounding Unit (MSU) onboard the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites (Spencer and Christy, 1990)). This includes the more recent Advanced Microwave Sounding Unit (AMSU) on the NOAA KLM satellites. Because of the scarcity of radiosondes in the tropics, tropospheric temperature trends are mainly based on MSU data. The MSU data have been available since 1979 and have by now provided measurements covering three decades. However, the MSU data are difficult to translate into temperature, and to determine its variation with height, since different frequencies and viewing angles represent different vertical layers in the atmosphere. The result of this is that the calculation of a representative temperature is obtained using empirical weights for the temperature at the different pressure levels. Moreover, surface temperatures and land surface conditions can significantly influence the outgoing microwave radiation (Christy et al., 2007, Mears and Wentz, 2009). Consequently trend calculations from the MSU data is delicate and open to different interpretations. The diurnal sampling from the space instruments varies with time and inconsistencies in the trend calculation also results from the use of different satellites over time. These problems are well documented (Lanzante et al., 2006; Randall and Herman, 2008). Because of the difficulties in determining a reliable observational database it is unsurprising that there are noticeable differences between the trend calculations from different research groups such as between University of Alabama in Huntsville (UAH) and Remote Sensing Systems (RSS) which we have used in this study (Christy et al., 2007, Mears and Wentz, 2009).

It has been suggested in some studies that a reduced warming trend in the upper tropical troposphere is neither seen in radiosonde observations nor in microwave soundings (MSU). Some investigations even suggest a *reduced warming* in the upper troposphere compared to the surface (Christy et al., 2007). The US Climate Change Science Program (CCSP) noted that *most observational datasets show more warming at the surface than in the troposphere, while most model runs have larger warming aloft than at the surface* (Karl et al., 2006, p.90). This might suggest that current climate models are suffering from a systematic error, casting some doubts as to the reliability of climate models (Douglass et al., 2007).

A common view is that differences between models and data can be caused by structural uncertainties, related to the way observations are controlled, corrected and processed. See paper by Santer et al., (2008 and references therein) for an extensive discussion of this aspect. Santer et al. (2008) have undertaken a comprehensive statistical analysis of the tropospheric temperature trends in the equatorial domain 20S-20N for the period 1979-1999 using surface data, available observations of radiosondes and MSU data. Their results show no apparent inconsistency between simulated temperature trends and of the trends found in the observational data but the many limitations of the observational database are highlighted.

Here we revisit this issue by bringing in two additional aspects namely the use of more recent re-analysis data for model evaluation as well as considering the general problem of whether tropical temperature trends for 30 year periods are at all robust enough to be suitable for evaluating the climate models used in Intergovernmental Panel on Climate Change (IPCC) assessments.

Needless to say, there are considerable difficulties in determining representative temperature trends directly from in-situ observations as these are both sparse and have a very irregular distribution. This is particularly the case in the tropics. Following the improvement of the upper air network at the time of the Global Weather Experiment in 1979 the in-situ observing system has in recent decades steadily deteriorated. On the other hand, aircraft data and many different types of satellite-based observations have improved steadily (Uppala et al., 2005) compensating for the loss but with observations with quite different characteristics and with a different distribution in time and space making validation with individual observations very difficult.

Fortunately, there have been major improvements in tropical predictive skill due to more reliable models and improved data-assimilation procedures (Simmons and Hollingsworth, 2002). This has made it possible to determine a more accurate initial state with better opportunities to identify observational errors and removing biases (Dee and Uppala, 2009). We believe in fact that recent data-assimilation has now reached a level where it might be appropriate to explore these data sets for trend calculation in the troposphere (Bengtsson et al., 2007). During the last decades there have been several efforts to reanalyze past observations using advanced data-assimilation procedures (e.g. Kalnay et al., 1996, Gibson et al., 1997, Uppala et al., 2005). However, due to recent progress in correcting biases in individual observations and in correcting systematic errors in observing systems the very latest reanalysis data sets are now becoming useful tools for investigating aspects of climate including troposphere temperature trends (Onogi et al., 2007; Simmons et al., 2009).

There are many advantages of using a re-analyses as they make use of available observations in a comprehensive way. Moreover, in the data-assimilation different sets of observations are systematically inter-compared both against each other and against an estimate of previous (and in the case of 4DVar also future) observations (and not necessarily for the same parameters) available to the assimilation system. In that respect we consider the control procedures that now also include observational biases (Dee and Uppala, 2009), are in several aspects superior to manual control procedures (e.g. Sherwood et al 2008). Because of the large number of observations from different observing systems there is a smaller risk that observational biases in individual observing systems will give rise to an integrated bias. Perhaps the most important aspect is the homogenous coverage of systematically analyzed fields making it possible to obtain representative mean values.

A serious concern when determining trends from the MSU measurements is the shortness of the data set as MSU measurements only exist for 30 years. Global warming is proceeding rather slowly over the tropical oceans and is furthermore characterized by large inter-annual variations associated with such events as El Niño-Southern Oscillation (ENSO). This is apparent in Figure 1a, which shows the observed Temperature in the Lower Troposphere (TLT) from RSS and UAH. We note that there is a significant difference between the trend estimates. It is important to clarify these differences and we will return to this question below.

To be able to better assess the significance of the trends we have determined the significance of 30-year trends from a 500 year pre-industrial integration with the ECHAM5/OM coupled model (Roeckner et al., 2006, Bengtsson et al., 2006)) without any changes in the external forcing. The purpose is to find out to what extent 30-year trends of the same magnitude as has been observed for the period 1979-2008 might develop by chance. The ECHAM5 model has been shown to generate ENSO mode fluctuations in broad statistical agreement with observations (Oldenborgh et al., 2005). There are no indications that the simulated variance is significantly different in the frequency of ENSO events from that observed (Guilyardi et al., 2009), but the amplitudes in ECHAM5 are generally larger by some 30%.

In this paper we concentrate the examination on the ocean areas of the tropical belt between 20^0S and 20^0N, covering some 27% of the globe. We decided to avoid tropical land areas as we intend to use observed MSU data and compare these with calculated MSU emission from re-analysis data and model simulations. Using MSU data over land implies an additional complication due to the difficulties to correctly represent land surfaces and orography (e.g. Randall and Herman, 2008; their Figure 2). Since our main interest is to investigate the temperature trends in the troposphere we will use TLT representing the temperature of the lower troposphere and Temperature in the Middle Troposphere (TMT) that is a broad measure of the temperature of the upper troposphere (Christy et al., 2007, Mears and Wentz, 2009) but including a stratospheric contribution. In the tropics this is minor and estimated at some 5%.

The paper continues in section 2 with a description of the data and methodology that is used in the study. In section 3 results from observations and the reanalyses are presented and in section 4 results from the model integrations covering the same period as the observations are presented. In section 5 we discuss the significance problem towards the long-term natural variability and in 6 we try to draw some general conclusions from the results.

2. Data and Methodology

Suitable weighting curves to calculate the TLT and TMT from re-analysis and General Circulation Model (GCM) data have been kindly provided by RSS (personnel communication C. Mears, 2009) and the atmospheric science department of UAH (personnel communication J. Christy, 2009). The TLT and TMT are obtained by the weighted sum of the temperature on pressure levels between the surface and stratosphere, land areas are masked so as to concentrate on the ocean only. For studies such as this, the static weighting function used here is sufficient to capture the anomalies and trends with fidelity as opposed to using the full radiation code, which takes into account such subtleties as the emission and reflection of radiation from the surface. Since this is ocean-only, the variation of surface emission is small over long time periods and will not materially impact the result. Before analysing the TLT and TMT the seasonal cycle is removed and all results in this paper will be in terms of these anomalies. The TLT is a measure of the temperature of the lower troposphere, with some 85 % of the radiation coming from below 500 hPa. The TMT represents rather the temperature of the whole troposphere with the main part of the radiation, some 55%, coming from the region between 300-700 hPa. The proportion coming from the stratosphere is ~5% and will be discussed separately below. For the reanalyses we have decided to use temperature data from the 25 year Japanese re-analysis (JRA25) (Onogi et al., 2005, Onogi et al., 2007) and the European Center for Medium Range Weather Forecasts (ECMWF) Interim re-analysis (ERA-Interim) (Dee and Uppala, 2009). The JRA25 covers the period 1979-2008 and ERA interim 1989 – 2008.

We decided against using data from the National Center for Atmospheric Research/National Center for Atmospheric (NCEP/NCAR) and from ECMWF 40 year reanalysis (ERA-40). Preliminary tests have confirmed reported deficiencies which make them less suitable for tropical trend calculations (Bengtsson et al., 2004a; Trenberth et al., 2001). Sakamoto and Christy (2009) have also reported problems with JRA25, although these are less likely to affect the tropospheric trends. ERA-Interim has not yet been systematically evaluated but the problem with excessive tropical ocean precipitation found in ERA-40 (Bengtsson et al., 2004b) has essentially been significantly reduced (personal communication S. Uppala, 2008) and is not judged to affect the result here. Since the JRA25 and ERA-Interim re-analyses cover different periods we will use the shorter ERA-Interim period when contrasting them both.

For the GCM data we use integrations obtained with the Max-Planck-Institute (MPI) climate model, ECHAM5 (Roeckner et al., 2006, Jungclaus et al., 2006). The first integration considered is an atmosphere only simulation forced with observed SST's for the period 1979-1999, to allow an assessment of the models ability to reproduce the observed temperature trends. A second set of integrations consists of three simulations with the coupled MPI, ECHAM5/OM model at T63 resolution for the period 1979-2008. The coupled model uses observed or estimated greenhouse gases or aerosols until the year 2000. After this year data is taken from the simulations which extend these integrations following the IPCC A1B scenario until 2008.

In order to get a better understanding of the obtained results we have also made use of a pre-industrial 500-year control integration with the coupled ECHAM5/OM model at T63 resolution, (Bengtsson et al., 2006) as well as data from an integration of the Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1 coupled model at resolution 2.5^0x2^0, obtained from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset archive (Meehl et al., 2007).

3. Results From Observations and Re-analyses

Results are here presented for the TLT and TMT determined from observations and reanalyses. Because of the large inter-annual variations, that are almost an order of magnitude larger than the decadal trend, considerable care must be exercised in interpreting the trends. We will support the presentation by evaluating maps of the trend as well as the temporal evolution of TLT and TMT as obtained from re-analyses and model calculations. As will be shown there are comparatively large differences between the TLT and the TMT data from UAH and RSS, where the data from RSS show a clearly larger warming trend both for TLT and TMT. Christy et al. (2007) pointed to a warming shift in the RSS data occurring in 1992 of between + 0.07 K and + 0.13 K. They further suggest that the shift occurs at the time when the data streams from NOAA-11 and NOAA-12 were adjusted to each other.

Over decadal and longer periods we would expect that the difference between the anomalies of TLT and SST will be small and not likely to change in time. For individual months, as shown in Figure 1b, the difference can be as high as 0.75K as happened during the 1997/98 El Nino event. As can be seen from Figure 1b the RSS TLT-SST is becoming systematically larger from roughly 1993 onwards. This is not the case with UAH, nor is it the case with the JRA25 reanalysis (not shown). In Table 1 we have summarized the mean difference for the years 1979-1992 and for 1993-2008 for the observations and for the re-analysis. *This clearly shows that the RSS after 1992 has a marked warm bias relative to SST*.

3.1. Global ocean areas

To put our study on tropical tropospheric trends in an overall context we present here some general results for global ocean areas. Because of the comparatively large stratospheric contribution to TMT at higher latitudes we consider the difference TLT-TMT as ambiguous on a global scale and a detailed assessment will not be carried out.

In Figure 2 the spatial variation of the decadal trend is shown for TLT and TMT restricted to the global oceans both for RSS and UAH, i.e. calculated directly from MSU observations, and for JRA25 for the period of 1979-2008 using the RSS and UAH weights. The trend in RSS is larger than in UAH, a discussion on this can be found in (Lanzante et al., 2006), see also comments above. The warming trend in JRA25 is probably underestimated (Sakamoto and Christy, 2009). The trend in the SST anomaly, globally averaged, amounts to 0.08 K/decade as calculated from the HadISST SST (Version 1.1) (Rayner et al., 2003). This is close to the global TLT trend from UAH (0.11K/decade) but much smaller than RSS (0.16K/decade). There are considerable geographical differences in both the TLT and TMT trends with in fact a cooling over the major area south of 50^0S, where significant stratospheric cooling has been observed that has influenced TMT. Other areas having a minor cooling or reduced warming trend (depending on the data sets) are in parts of the eastern Pacific.

For the shorter and later period of 1989-2008 (Figure 3) we also include the results from ERA-Interim. These trends are larger but less representative since they are strongly influenced by the extreme ENSO in 1998 and the global cooling due to Mt. Pinatubo in 1991-1992. The patterns are similar in their broad features although the high latitude cooling of the Southern Hemisphere is larger in JRA25. The TLT trend in ERA-Interim and JRA25 are both closer to UAH than to RSS.

3.2. Tropical ocean areas

In Figure 4, the time evolution of TLT and TMT is shown, averaged over the tropical oceans, for the period 1979-2008 for the UAH observations and the JRA25 re-analysis. The corresponding results for ERA Interim (not shown) for the period 1989-2008 are almost identical to the JRA25. The temperature variation is dominated by ENSO events with a range of almost 2K. The temperature changes are also rather rapid on these occasions with a change (both warming and cooling) of around 1K in a couple of months. The strong ENSO event in 1997/98 stands out. The dominant inter-annual variability requires longer periods than 30 years for robust trend calculations, which is why calculated values for shorter periods can only be considered as tentative. Below we compare these trends with stochastic trends occurring in a 500 year pre-industrial integration with constant external forcing.

As the tropical tropopause is around 100 hPa we can at first approximation consider TLT to represent the lower troposphere and TMT the temperature of the upper troposphere. Dividing the atmospheric into three vertical layers of 1000-700hPa, 700-350hPa and 350-50hPa the corresponding weights for TLT is 0.55, 0.37 and 0.08, respectively and for TMT 0.28, 0.35 and 0.37, respectively. With some minor simplification it follows that if TLT is larger than TMT then the low level warming trend, to be represented by a layer centered around 850hPa is larger than the upper level warming to be represented by a layer around 200hPa. Consequently the difference between the two is an approximate value for the trend in the tropospheric lapse rate. There is a minor stratospheric contribution of ~5% consisting of the contribution above 100 hPa. We have recalculated TLT and TMT with the stratospheric weights removed leading to an increase in TMT by between 0.01 and 0.005 K/decade and a corresponding decrease in TLT-TMT indicating that the contribution from the stratosphere is minimal in the tropics.

Generally, both the re-analyses and the observations indicate that the TLT warming trend is larger than the TMT trend (Table 2 and Table 3). There are differences in the overall warming trend as RSS is warming more than UAH, but both re-analyses are closer to UAH than RSS. The slight difference in TLT-TMT is unlikely to be significant. The correlation of the monthly means between JRA25 and the observations is 0.96 and between ERA-Interim and JRA25 is 0.98.

4. Model results

Three simulations of the coupled MPI, ECHAM5/OM model at T63 resolution for the period 1979-2008 are investigated. As described in section 2, observed greenhouse gases and aerosols were used prior to year 2000 thereafter the corresponding data from the IPCC scenario A1B integrations are used. We restrict the evaluation to the tropical belt. The result for TLT (Figure 5) shows large inter-annual variations reflecting marked ENSO events. It also shows large differences between the three integrations, mainly because the strong inter-annual events are uncorrelated resulting in significantly different 30-year trends (Table 4). The normalized monthly variance is larger than for the observations in the 1979-2008 period. As suggested from the 500 year control integration this is likely to be a model defect. In Table 4 we compare the model trends for TLT and TMT using the weights for both UAH and RSS respectively, with the observed trends from RSS and UAH. As might be expected using the weights given for RSS and UAH only implies minor differences and will not be discussed further. As can be seen from Table 4 the difference in TMT-TLT is positive for the observations but negative for the model suggesting a warm bias in the upper troposphere for the model, the difference amounts to 0.04-0.06 K/decade. We have investigated whether this might be an effect of reduced stratospheric cooling in the model runs. This is not the case as the difference is unchanged if we artificially remove the stratospheric weights above 100 hPa. The reason is that the model also simulates a stratospheric cooling similar to the observations.

To obtain further support for the upper tropospheric bias we analysed a 20 year run with the ECHAM5 model using the atmospheric component only and forced with observed SST’s for the period 1979-1999. The TLT and TMT are found to follow very closely the observed evolution with some 80%

correlation but show a similar negative value in the TLT-TMT difference as in the coupled model runs confirming the temperature bias in the upper troposphere. Furthermore, there was no indication of the high monthly variance that was found for the coupled model suggesting the cause of this might be due to the interaction with the oceans.

5. Significance assessment

To test the significance of the trends computed so far we proceed in analogy to the calculations above by calculating the consecutive TLT and TMT 30 year trends for the tropical oceans, from monthly mean data of the 500 year pre-industrial integration of the coupled ECHAM5/OM model. This is done by stepping the 30 year periods forward by one month, giving 470 samples of 30 year periods. It is found that these trends undergo significant variations. This is indicated in Figure 6 showing the time evolution of the 30 year TLT in the form of a frequency distribution. The observed and modelled linear trends of 1979-2008 are within the natural distribution but in the case of RSS close to its upper positive limit. We have similarly calculated the TLT-TMT 30 year trends for the tropical ocean region and note that these variations are smaller by about an order of magnitude with a range of ±0.03K/decade. As can be seen from Figure 6c the GFDL model has a slightly smaller range. This means that both the observed and the re-analysis trends in the lapse rate are outside this distribution. The result is unaffected by the small contribution in TMT from the stratosphere as the stratosphere cooling trend also exists in the model result. We conclude from this that the larger warming trend in the upper troposphere (or less cooling in the lower stratosphere in TMT) is likely to be due to a systematic model error occurring in both the ECHAM5 and the GFDL model. We have examined the typical conditions for the extremes in the lapse rate trend. When the tropical oceans are relatively colder than normal then TLT-TMT is positive indicating a smaller warming trend aloft and the reverse when the tropical oceans are warmer than normal. Consequently, the model lapse rate trend depends on the state of the climate system.

There are several possible causes for this, including a preference in present models to generate deep convective warming instead of shallow convection. This can in turn be related to aliasing effects due to insufficient resolution. We intend to explore this in a further study.

6. Discussion and conclusions

We have compared TLT and TMT using data provided by RSS and UAH, respectively with RSS providing slightly larger positive trends. The results for the two re-analyses, JRA25 and ERA-Interim are closer to UAH but TLT-TMT are more similar and positive for the two periods 1979-2008 and 1989-2008 respectively. The re-analyses show a larger warming trend in the lower atmosphere, between 1000 and 700hPa, than in the upper troposphere between 500 and 200hPa supporting the assumption that TLT-TMT can be seen as an approximate measure of the lapse rate trend.

To evaluate a coupled climate model integration using observed data can only be done in a statistical sense. In order to determine the significance of the 30 year trends we have calculated all such trends from a 500-year control integration with natural forcing only and a similar atmospheric composition (greenhouse gases and aerosols). The naturally generated 30 year TLT and TMT trends fall between ±0.2 °K/decade (Figure 6a and b). Present observed trends from RSS for the tropical oceans are within this range of natural variability but the probability of being a natural trend is less than 2.5%. Figure 7 shows an extreme 30 year trend of the control integration that is 50% larger than the observed TLT trend for 1979-2008 from RSS. The observed trends from UAH and from the JRA25 reanalyses are much smaller and consequently the probability for TLT to be a natural trend are significantly higher (based on UAH data it is 27%).

The frequency for the trend of the lapse rate expressed as the trend of TLT-TMT (Figure 6c) shows a significantly reduced variability. Observed and re-analyzed lapse rate trends are all positive and for the period 1979-2008 well outside the range of natural variability while the different model runs both when forced with observed SST or in the form of transient runs are within the range of the long control integration. The frequency distribution is slightly skewed towards the negative side indicating that high negative values of the trend are more common than high positive values. We further note that the TLT-TMT from the GFDL model has a frequency distribution that is very similar but with a slightly smaller variance. We consequently believe that both the ECHAM5 and the GFDL model have a tendency to warm the upper troposphere more than indicated from MSU observations and the recent re-analyses investigated here. A comparison with the coupled climate runs for the 20th century (until 2008) confirms this finding.

In summary the following could be concluded from this study:

1 Present re-analysis data sets such as JRA25 and ERA-Interim studied here appear to be approaching a state where they can be used to explore tropospheric climate trends for the last 30 years and we would argue that they are in several respects superior to traditional studies based on individual sets of observations. More interaction between the modelling community and the re-analyses groups are likely to accelerate further improvements of both models and re-analyses.

2. The 30-year trends in TLT and TMT differ considerably between RSS and UAH while the reanalyses are in broad agreement with UAH. It is suggested that the higher values in TLT and TMT in RSS after 1992 are unlikely to be correct as for the period 1993-2008 they are inconsistent with SST. This is not the case for the UAH and the reanalyses neither for RSS for the earlier period 1979-1992.

3. The present 30-years of tropospheric temperature observations are still insufficient to identify robust trends as the internal variability of realistic climate models is larger than the observed trends. This is the reason we believe that many validation studies in the past have been inconclusive as periods are much too short. Instead efforts should rather be concentrated on evaluating climate models using actual observations in order to identify any particular systematic differences between the state of the model and the observed state of the atmosphere. Such experiments could concentrate on shorter periods of specific interest such as ENSO-events with their large tropospheric temperature variation and will

have the distinct advantage of being possible to evaluate the models. Forcing the model with observed SST is a first step in this direction.

4. An evaluation of the tropospheric lapse rate trend taken as the difference between TLT and TMT suggests that models warm the upper troposphere more than the lower troposphere suggesting a systematic bias. However, these lapse rate errors are modest but point nevertheless to a scientific issue that needs further attention.

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Captions

Tables

Table 1 Difference in TLT and SST (TLT-SST) averaged over the tropical oceans between 20^0S and 20^0N and over the period 1979-2008.

Table 2 Summary of the tropical ocean temperature trends between 1979 and 2008 using observations and JRA25. Values are in K per decade.

Table 3 Summary of tropical ocean temperature trends between 1989 and 2007 using observations, JRA25 and ERA-Interim. Values are in K per decade.

Table 4 Summary of tropical ocean TLT and TMT trends between 1979 and 2008 from observations and from three members of a transient integration with the ECHAM5/OM coupled model using the MSU weights from RSS and UAH respectively. Values are in K per decade.

Figures

Figure 1 (a) Observed MSU TLT and linear trend for RSS and UAH for the period 1979-2008 for tropical oceans between 200S and 200N. Unit is K for TLT and K/decade for the trend, (b) TLT-SST averaged over the tropical oceans between 200S and 200N

Figure 2 Maps of decadal trends in MSU, TLT(left) and TMT(right) for the 1979–2008 period. (a) and (b) from RSS, (c) and (d) from UAH, (e) and (f) JRA25 using weights from RSS, (g) and (h) the same but using weights from UAH. Land areas are masked. Unit K/decade.

Figure 3 Maps of decadal trends in MSU TLT(left) and TMT(right) for the period 1989-2007. (a) and (b) from RSS, (c) and (d) from UAH, (e) and (f) JRA25 using weights from RSS, (g) and (h) ERA-Interim using weights from RSS. Land areas are masked. Unit K/decade,

Figure 4 Time series of (a) TLT and (b) TMT anomalies computed from monthly mean temperatures over the tropical oceans between 20^0S and 20^0N, from observations (UAH) and from the JRA25 reanalysis computed using the UAH eights.

Figure 5 TLT anomalies computed from monthly mean temperatures over the tropical oceans between 20^0S and 20^0N from the three ECHAM5 coupled model integrations covering the period 1979-2008, computed from UAH weights.

Figure 6 Frequency distributions of all 30-year TLT and TMT trends in 500-year integrations for the tropical oceans for (a) ECHAM5 and (b) GFDL, vertical lines indicate the observed values for RSS (red) and UAH (blue) respectively for the TLT (solid) and TMT (dashed) respectively. (c) The distributions of TLT-TMT for ECHAM5 and GFDL. Unit K/decade.

Figure 7 Simulated maximum TLT trend from the 500-year control run. Tropical oceans between 200S and 200N. Unit K/decade.

Tables

	1979-1992	1993-2008
UAH-SST	0.01	0.01
RSS-SST	-0.01	0.13
JRA25(UAH)-SST	0.00	0.00
JRA25(RSS)-SST	0.00	0.00

Table 1 Difference in TLT and SST (TLT-SST) averaged over the tropical oceans between 20^0S and 20^0N and over the period 1979-2008.

1979-2008			
	TLT	TMT	TLT-TMT
Obs. (RSS)	0.15	0.11	0.035
Obs. (UAH)	0.05	0.02	0.036
JRA25 (RSS)	0.07	0.03	0.043
JRA25 (UAH)	0.07	0.02	0.056

Table 2 Summary of the tropical ocean temperature trends between 1979 and 2008 using observations and JRA25. Values are in K per decade.

1989-2008			
	TLT	TMT	TLT-TMT
Obs. (RSS)	0.22	0.16	0.059
Obs. (UAH)	0.10	0.06	0.037
JRA25 (RSS)	0.12	0.09	0.034
JRA25 (UAH)	0.12	0.09	0.035
ERA (RSS)	0.12	0.09	0.028

Table 3 Summary of tropical ocean temperature trends between 1989 and 2008 using observations, JRA25 and ERA-Interim. Values are in K per decade.

1979-2008			
	TLT	TMT	TLT-TMT
Obs. (RSS)	0.15	0.11	0.035
Obs (UAH)	0.05	0.02	0.036
20C_1(RSS)	0.20	0.22	-0.024
20C_1(UAH)	0.23	0.23	-0.002
20C_2(RSS)	0.14	0.17	-0.030
20C_2(UAH)	0.16	0.18	-0.018
20C_3(RSS)	0.09	0.11	-0.019
20C_3(UAH)	0.11	0.11	-0.007

Table 4 Summary of tropical ocean TLT and TMT trends between 1979 and 2008 from observations and from three members of a transient integration with the ECHAM5/OM coupled model using the MSU weights from RSS and UAH respectively. Values are in K per decade.

Figures

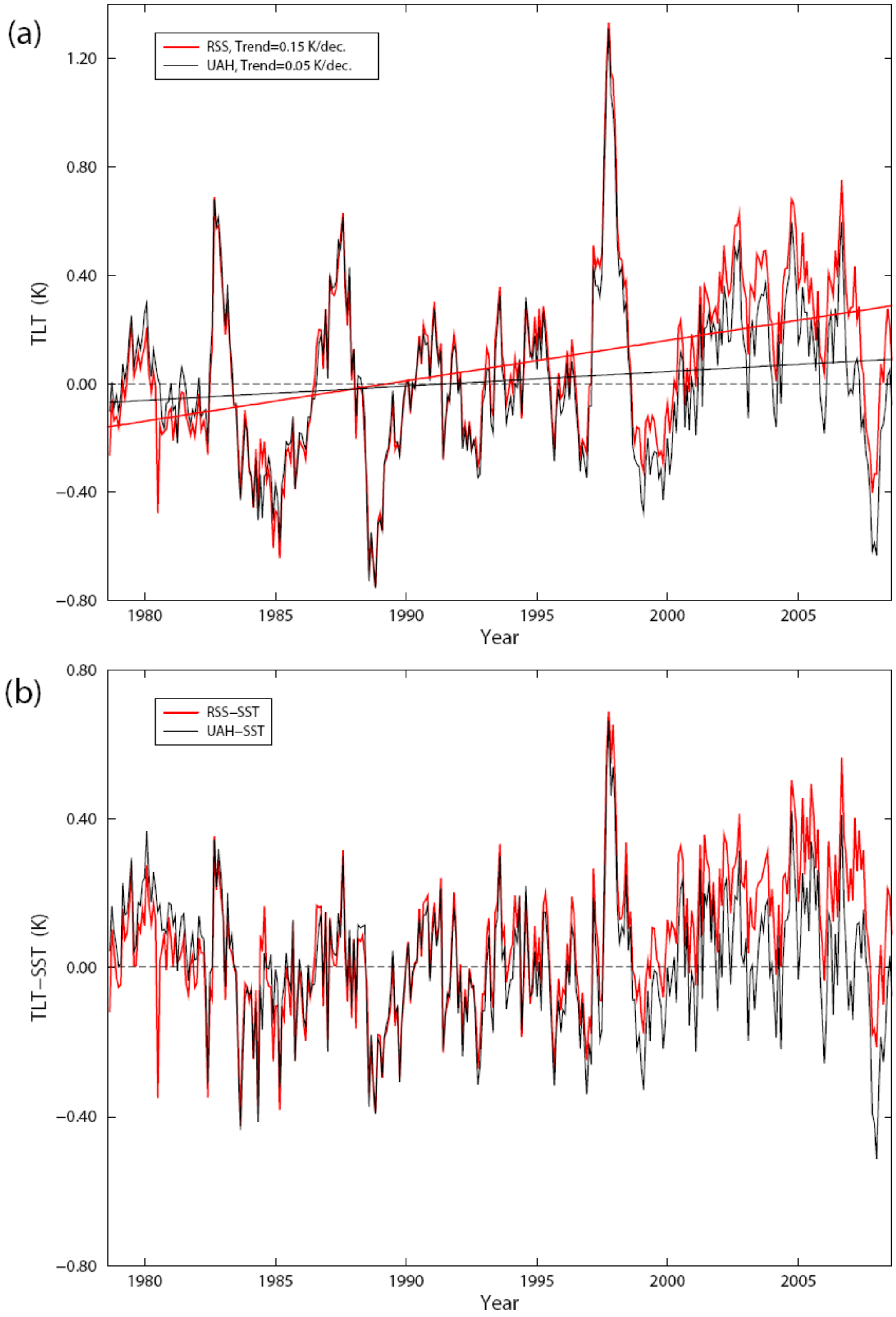
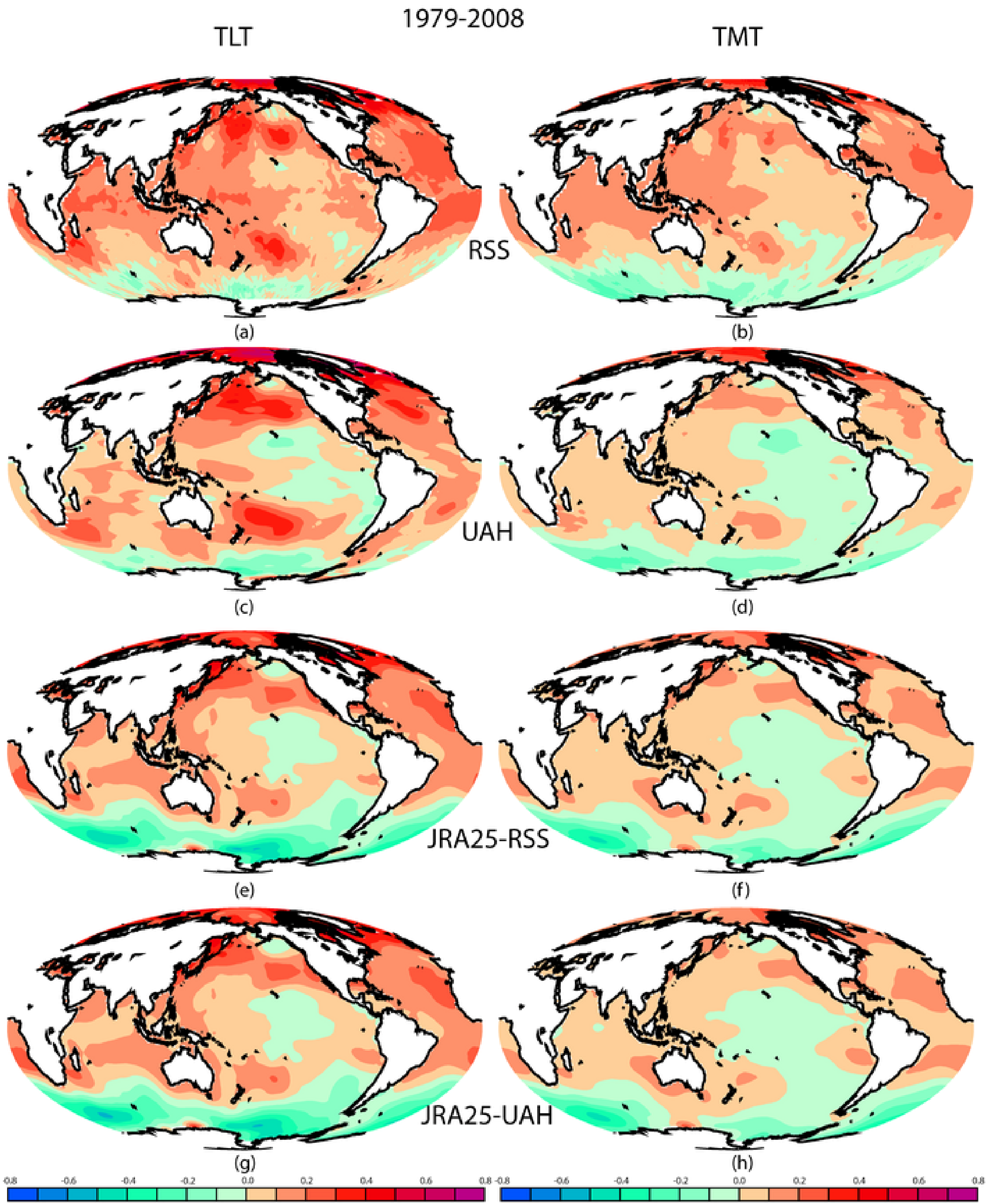


Figure 1 (a) Observed MSU TLT and linear trend for RSS and UAH for the period 1979-2008 for tropical oceans between 20^0S and 20^0N. Unit is K for TLT and K/decade for the trend, (b) TLT-SST averaged over the tropical oceans between 20^0S and 20^0N.



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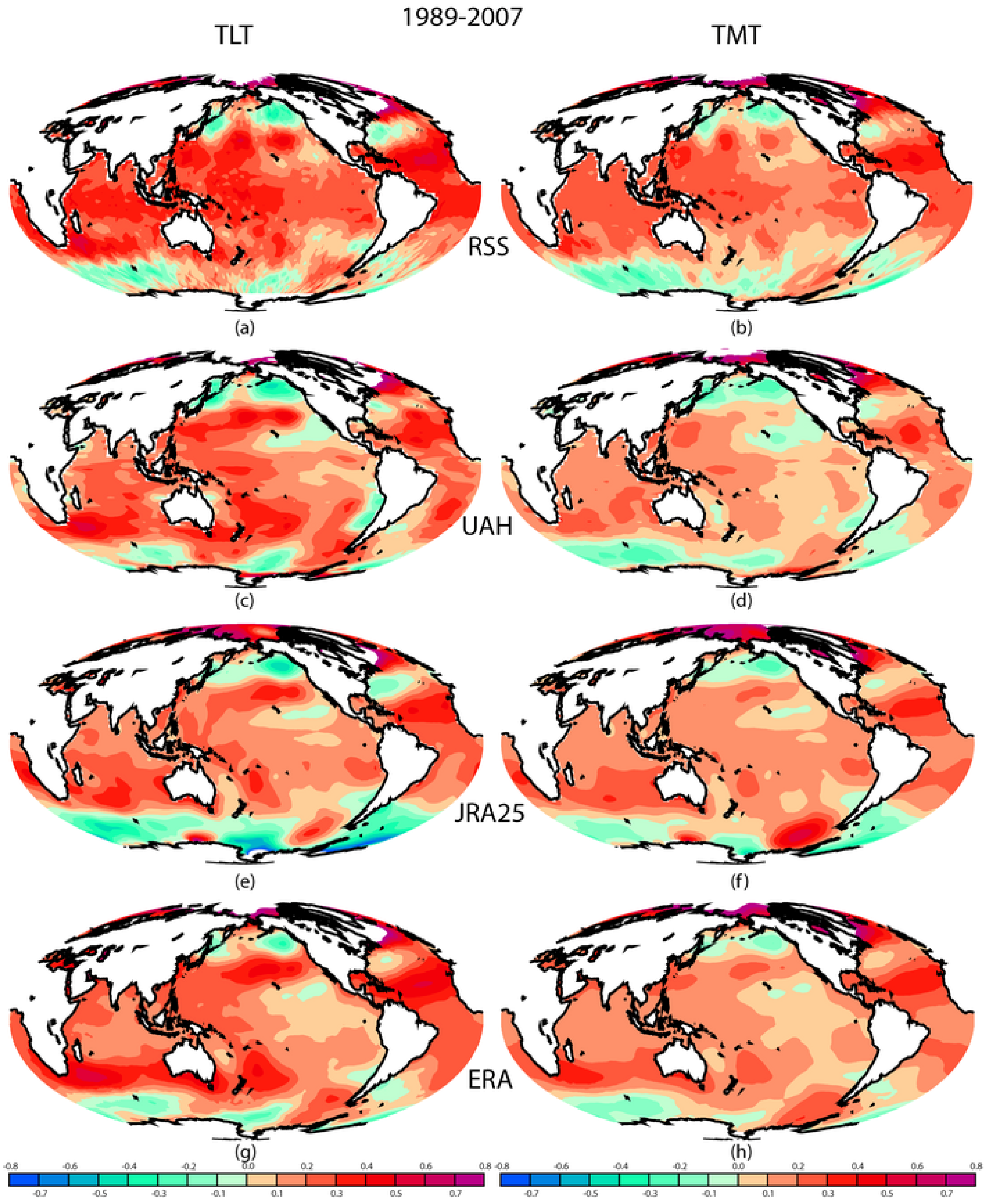

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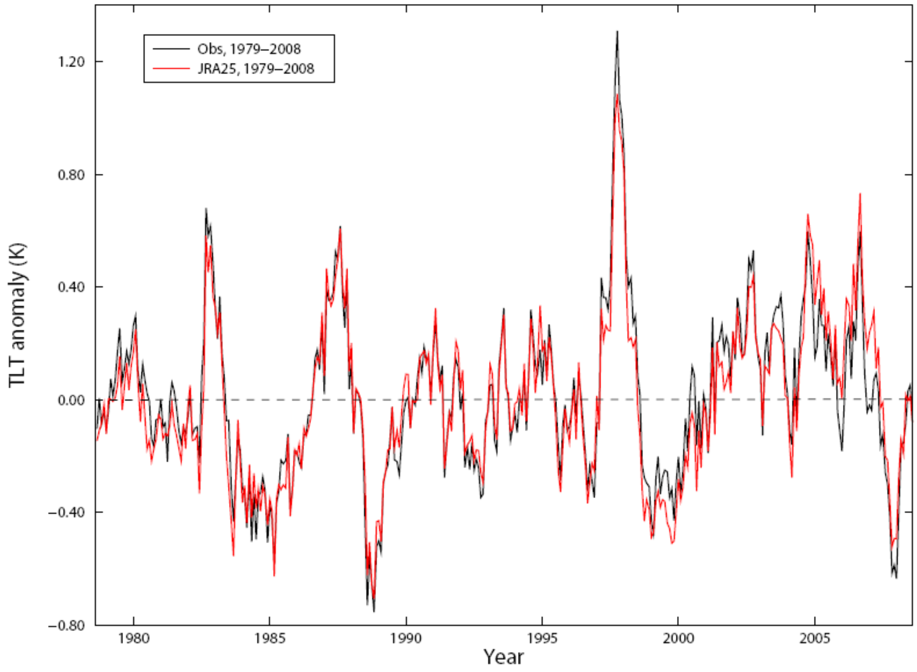
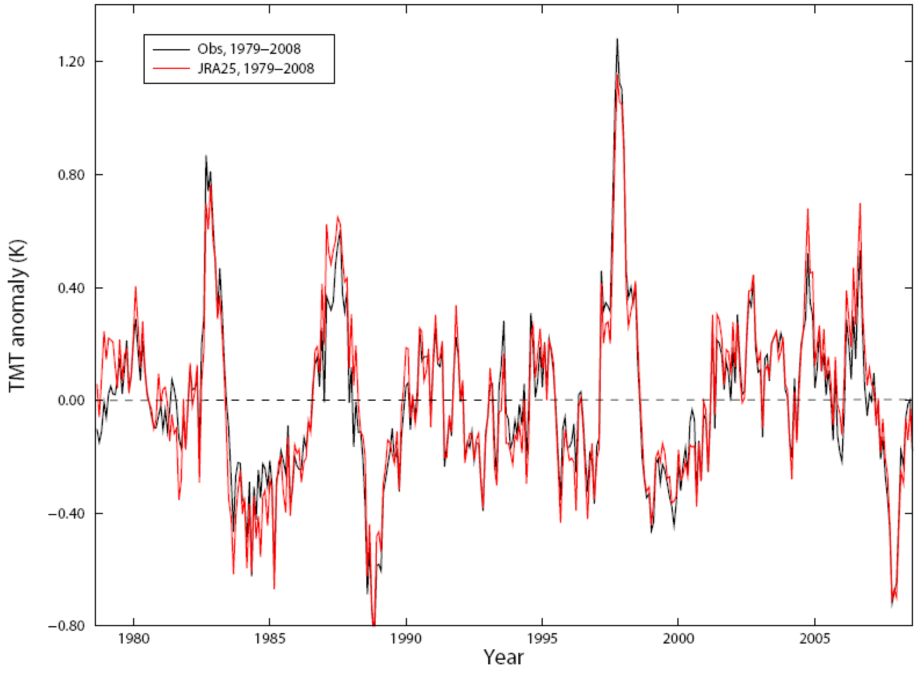
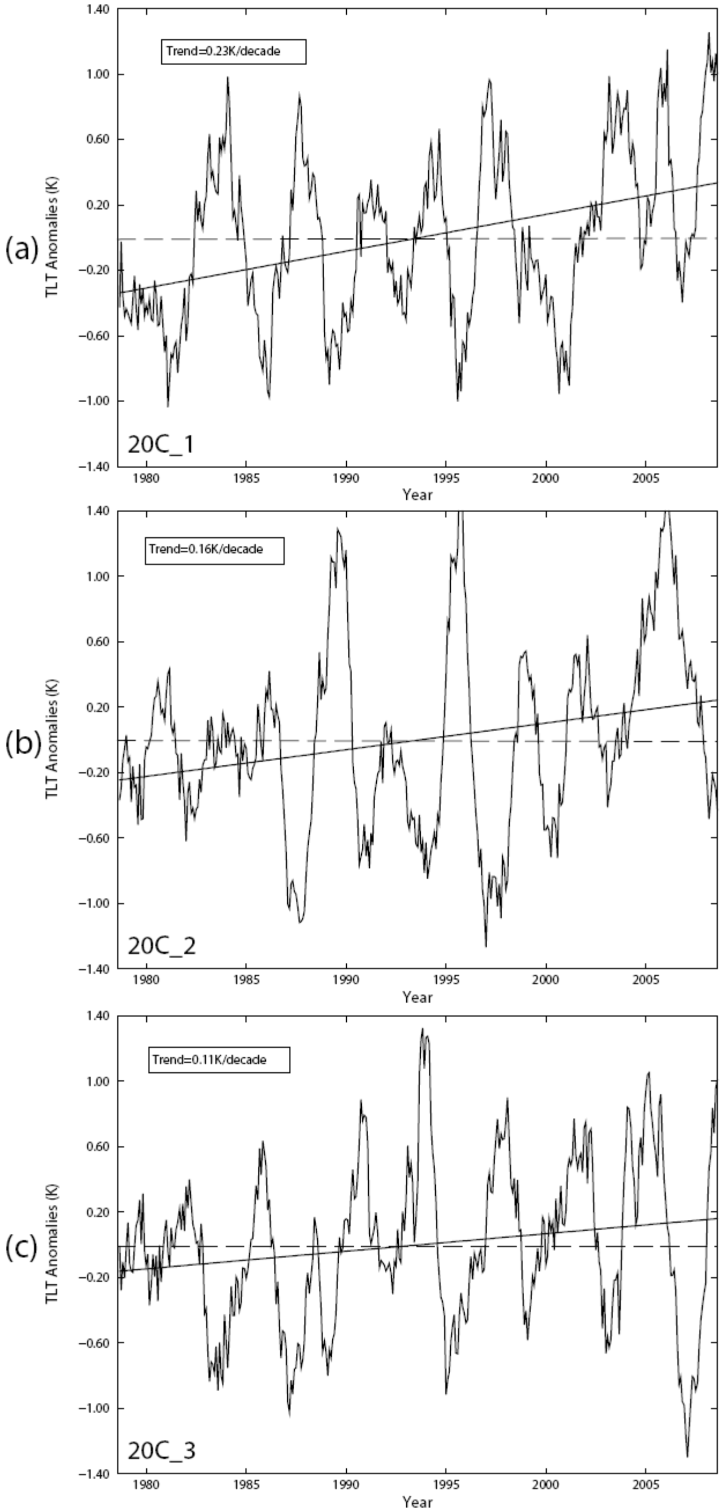


(a) TLT



(b) TMT

Figure 4 Time series of (a) TLT and (b) TMT anomalies computed from monthly mean temperatures over the tropical oceans between 20^0S and 20^0N, from observations (UAH) and from the JRA25 reanalysis computed using the UAH eights.



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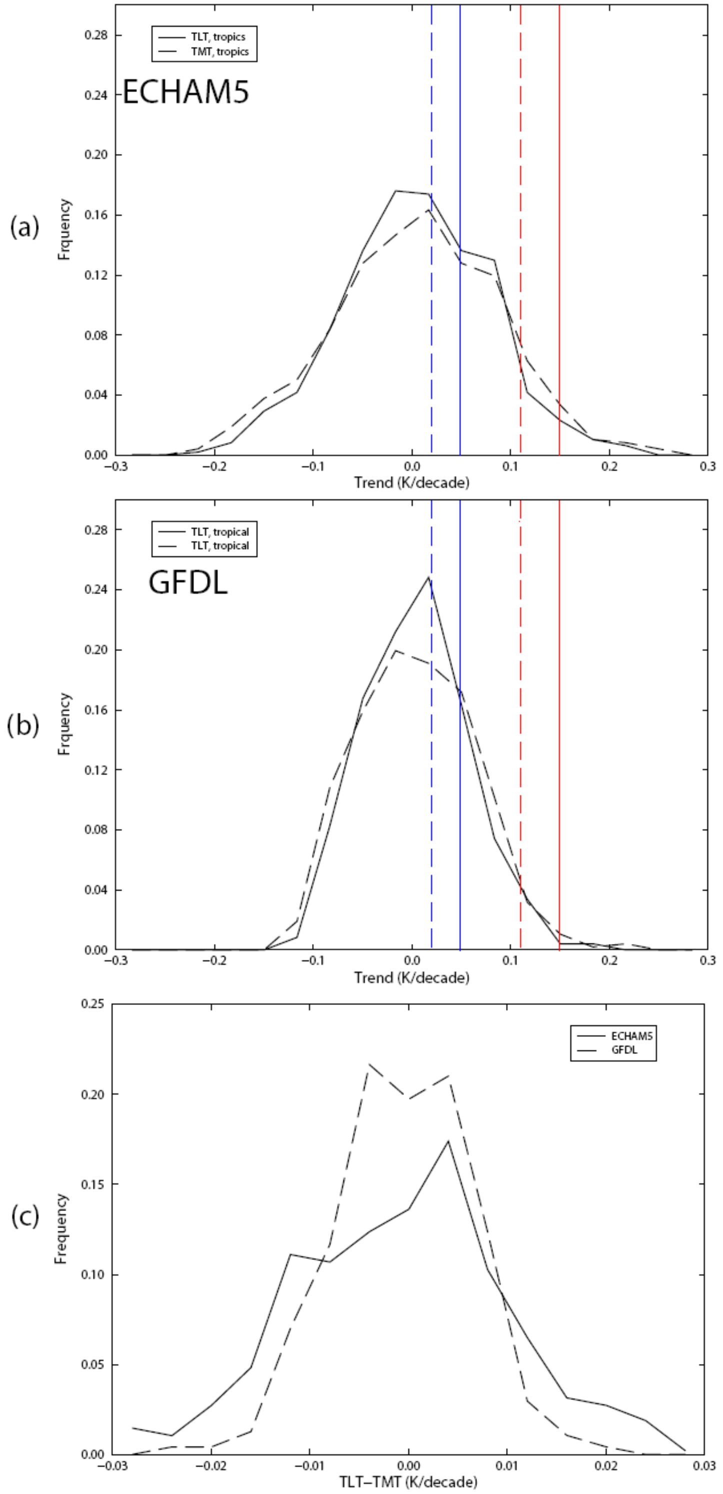

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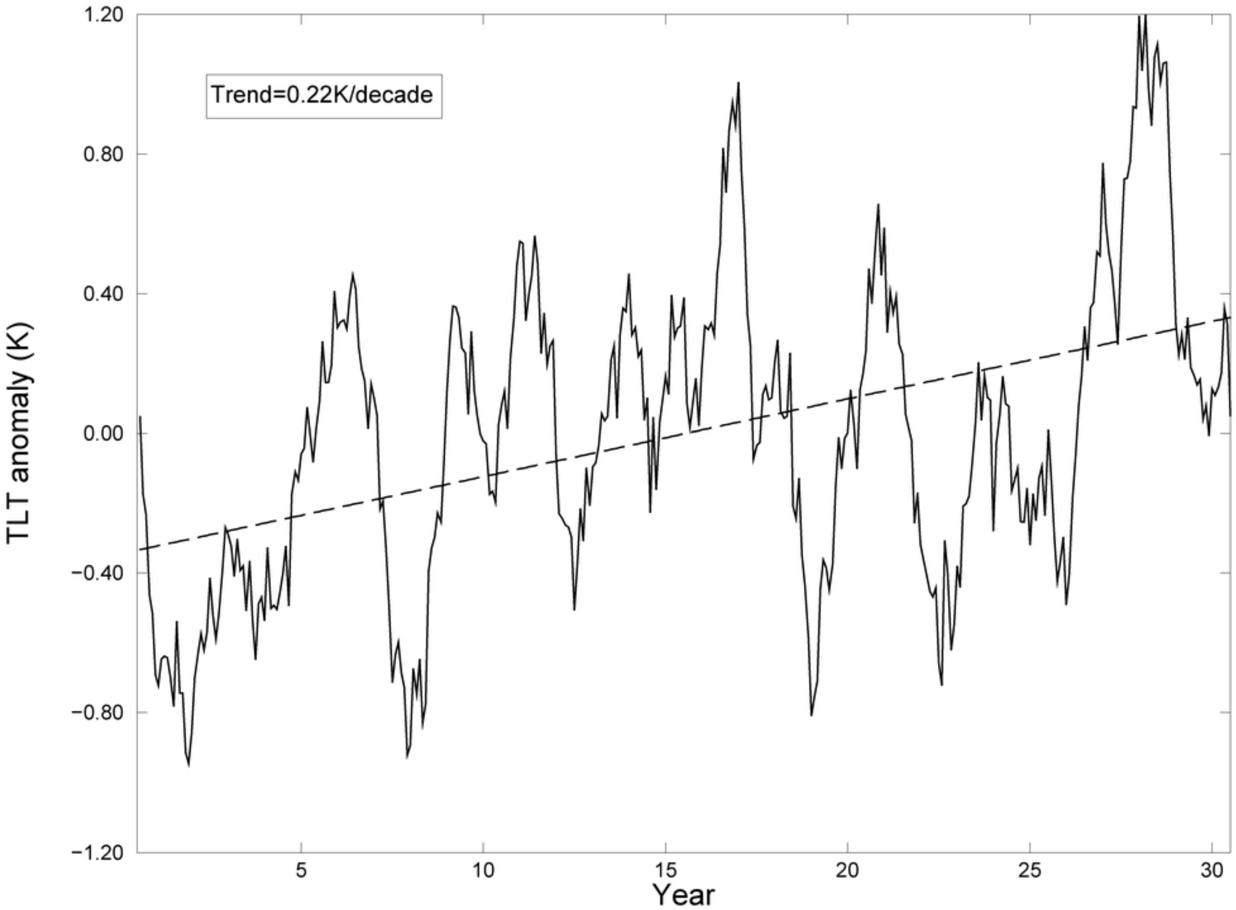

Figure 7 Simulated maximum TLT trend from the 500-year control run. Tropical oceans between 20^0S and 20^0N. Unit K/decade.