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Abstract

The representation of the Tropical Tropopause Layer in 13 different Chemistry Climate Models designed to represent the stratosphere is analyzed. Simulations for 1960–present and 1980–2100 are analyzed and compared to reanalysis model output. Results indicate that the models are able to reproduce the basic structure of the TTL. There is a large spread in cold point tropopause temperatures that may be linked to variation in TTL ozone values. The models are generally able to reproduce historical trends in tropopause pressure obtained from reanalysis products. Simulated historical trends in cold point tropopause temperatures and in the meridional extent of the TTL are not consistent across models. The pressure of both the tropical tropopause and the level of main convective outflow appear to be decreasing (increasing altitude) in historical runs. Similar trends are seen in the future. Models consistently predict decreasing tropopause and convective outflow pressure, by several hPa/decade. Tropical cold point temperatures increase by 0.2 K/decade. This indicates that tropospheric warming dominates stratospheric cooling at the tropical tropopause. Stratospheric water vapor at 100 hPa increases by up to 0.5–1 ppmv by 2100. This is less than implied directly by the temperature and methane increases, highlighting the correlation of tropopause temperatures with stratospheric water vapor, but also the complex nature of TTL transport.

1 Introduction

The Tropical Tropopause Layer (TTL), the region in the tropics within which air has characteristics of both the troposphere and the stratosphere, is a critical region of the atmosphere. The TTL is the region in the tropics between the level of main convective outflow and the cold point, about 10–18 km (Gettelman and Forster, 2002). The TTL is maintained by the interaction of convective transport, convectively generated waves, radiation, cloud microphysics and the large scale stratospheric circulation. The TTL is the source region for most air entering the stratosphere, and therefore the chemical boundary conditions of the stratosphere are set in the TTL. Clouds in the TTL, both thin cirrus clouds and convective anvils, have a significant impact on the radiation balance and hence tropospheric climate (Stephens, 2005).

Changes to the tropopause and TTL may occur over long periods of time in response to anthropogenic forcing of the climate system. These trends are in addition to natural variability, which includes interannual variations such as the Quasi Biennial Oscillation (QBO, ~2 years), the El Niño Southern Oscillation (ENSO, 3–5 years) or the solar cycle (11 years). Changes in the thermal structure of the TTL may alter TTL clouds, affecting global climate through water vapor and cloud feedbacks (Bony et al., 2006) in the TTL. Changes to TTL structure may alter TTL transport and TTL water vapor. TTL water vapor in turn may affect stratospheric chemistry, ozone (Gettelman and Kinnison, 2007) and water vapor, as well as surface climate (Forster and Shine, 2002). Changes in the Hadley circulation and the stratospheric Brewer-Dobson circulation (Butchart et al., 2006) may affect the meridional extent of the TTL. The changes may be manifest as changes to the mid-latitude storm tracks (Yin, 2005).

Several studies have attempted to look at changes to the tropopause and TTL over time. Seidel et al. (2001) found decreases in tropopause pressure (increasing height) trends in tropical radiosonde records. Gettelman and Forster (2002) described a climatology of the TTL, and looked at changes over the observed record from radiosondes, finding similar decreases in tropopause pressure (increasing height) with little significant change in the bottom of the TTL (see below). Santer et al. (2003) examined simulated changes in thermal tropopause height and found that they could only explain observations if anthropogenic forcings were included. Dameris et al. (2005) looked at simulations from 1960–1996 in a global model and found no consistent trend in thermal tropopause pressure or water vapor. Son et al. (2008)[1] looked at changes to the global

[1]Son, S. W., Polvani, L. M., Waugh, D. W., Birner, T., Garcia, R. R., Gettelman, A., and Plummer, D. A.: The tropopause in the 21st century as simulated by stratosphere-resolving Chemistry-Climate Models, J. Climate, submitted, 2008.

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thermal tropopause pressure in global models and found a decrease (height increase) through the 21st century, less in models with ozone recovery. Fu et al. (2006) and Hu and Fu (2007) found that the Hadley circulation was expanding poleward resulting in widening of tropical dynamics.

Recently, Gettelman and Birner (2007), hereafter GB2007, have shown that two Coupled Chemistry Climate Models (CCMs), which are General Circulation Models (GCMs) with a chemistry package coupled to the radiation (so chemical changes affect radiation and climate), can reproduce key structural features of the TTL and their variability in space and time. GB2007 found that 2 models, the Canadian Middle Atmosphere Model (CMAM) and the Whole Atmosphere Community Climate Model (WACCM), were able to reproduce the structure of TTL temperatures, ozone and clouds. Variability from the annual cycle down to planetary wave time and space scales (days and 100 s km) was well reproduced. There were significant differences in the treatment of TTL clouds and convection between the two models, but this did not seem to alter the structure of the TTL. GB2007 conclude that CMAM and WACCM are able to reproduce important features of the TTL, and that these features must be largely regulated by the large scale structure, since changes to sub-grid scale processes (like convection) did not alter TTL structure or variability.

In this work, we will look at changes to the TTL over the recent past (1960–2005) and potential changes over the 21st century. We apply a similar set of diagnostics as GB2007 to WACCM, CMAM and 11 other CCMs that are part of a multi-model ensemble run with forcings for the historical record from 1960–2005, and using scenarios for the future from 1980–2100. We will compare the models to observations over the observed record, and then examine model predictions for the evolution of the TTL in the 21st Century. These simulations have been used to assess future trends in stratospheric ozone in Eyring et al. (2007) and World Meteorological Organization (2007), chapter 6.

The methodology, models, data and diagnostics are described in Sect. 2. The model climatologies are discussed in Sect. 3. Past and future trends from models and analysis

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systems are in Sect. 4. Discussion of some key issues is in Sect. 5 and Conclusions are in Sect. 6.

2 Methodology

In this section we first describe the definition and diagnostics for the TTL (Sect. 2.1). We then briefly describe the models used and where further details, information and output can be obtained (Sect. 2.2). Finally we verify that using zonal monthly mean data provides a correct picture of the climatology and trends (Sect. 2.3).

2.1 Diagnostics

To define the TTL we focus on the vertical temperature structure, and we adopt the TTL definition of Gettelman and Forster (2002) as the layer between the level of maximum convective outflow and the cold point tropopause. The maximum convective outflow level is diagnosed from the minimum potential temperature lapse rate ($d\theta/dz$). This definition is not the only possible one, but conceptually marks the boundary between which air is generally tropospheric (below) and stratospheric (above). The definition is convenient because the TTL can be diagnosed locally from a temperature sounding, and facilitates comparisons with observations.

We use diagnostics previously defined by GB2007. The top of the TTL is the Cold Point Tropopause (CPT). We also calculate the Lapse Rate Tropopause (LRT) for comparison and for analysis of the subtropics. The LRT is defined using the standard definition of the lowest point where the lapse rate is less than 2 K km^{-1} for 2 km ($-dT/dz<2$ K km^{-1}). The bottom of the TTL is defined as the level of maximum convective outflow. Practically, as shown by Gettelman and Forster (2002) this is where the potential temperature Lapse Rate Minimum (LRM) is located (the minimum in $d\theta/dz$), and it is near the Minimum Ozone level (minO3).

We also introduce 2 new diagnostics. First, a meridional boundary of tropics, or

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"TTL edge". One of the key features of the TTL is the level of zero radiative heating (LZH). Below the LZH air in clear-sky descends due to radiative cooling, and above the LZH air rises due to radiative heating. If we require that the TTL has the level of zero radiative heating (LZH) below the tropopause altitude, then the TTL edge is where the tropopause intersects the LZH. The LZH lies at about 135–150 hPa, or about 35 hPa below the tropical tropopause. We thus define the edge of the tropics as where the LRT pressure is less than the mean tropical LRTP+ΔP, where ΔP=35 hPa, since we do not have heating rates archived from most models. The edge defines the region where the thermal tropopause drops off rapidly in pressure coordinates, and it is focused on the upper boundary of the TTL. The goal is not so much to determine an exact latitude as a trend over time. The estimated trends are not sensitive to the exact value of ΔP over the range 25–60 hPa.

Second, we examine the Zero Lapse Rate level (ZLR). This is similar to the lapse rate tropopause, except stating that instead of the threshold of $-2°\text{K km}^{-1}$, it is $0°\text{K km}^{-1}$. For the zonal monthly mean data available for this study the ZLR can capture changes to the thermal structure not seen in CPT or LRT levels. The CPT is defined to be a model level, while the ZLR can be interpolated like the LRT. It also serves as a check on the CPT. Table 1 provides a list of these abbreviations.

2.2 Models

This work uses model simulations developed for the Chemistry Climate Model Validation (CCMVal) activity for the Stratospheric Processes and Their Role in Climate (SPARC) project of the World Meteorological Organization (WMO) and the World Climate Research Program (WCRP). The work draws upon simulations defined by CCMVal in support of the Scientific Assessment of Ozone Depletion: 2006 (World Meteorological Organization, 2007). There are two sets of simulations used. The historical simulation REF1 is a transient run from 1960 or 1980 to the present and was designed to reproduce the well-observed period of the last 25 years. An assessment of temperature, trace species and ozone in the simulations of the thirteen CCMs participating here was presented in Eyring et al. (2006). Scenarios for the future are denoted “REF2” and are analyzed from 1960 or 1980 into the future. These simulations are described in more detail by Eyring et al. (2006), who projected the future evolution of stratospheric ozone in the 21st century from the same CCMs used here. Table 2 lists the model names, horizontal resolution and references, while details on the CCMs can be found in Eyring et al. (2006, 2007) and references therein. For the MRI and ULAQ CCMs the simulations used in Eyring et al. (2006, 2007) have been replaced with simulations from updated model configurations as the previous runs included weaknesses in the TTL.

Our purpose is not so much to evaluate individual models, but to look for consistent climatology and trends across the models. Details of individual model performance are contained in Eyring et al. (2006). We first will analyze model representation of the recent past to see if the models reproduce TTL diagnostics from observations. This provides some insight into the confidence we might place in future projections. We will have more confidence of future projections for those diagnostics that (1) have consistent trends between models and (2) trends which match observations for the past.

Model output was archived at the British Atmospheric Data Center (BADC), and is used under the CCMVal data protocol. For more information obtaining the data, consult the CCMVal project (http://www.pa.op.dlr.de/CCMVal). The analysis from 11 models is conducted on monthly zonal mean output. In Sect. 2.3 below we describe the implications of using monthly zonal means for calculating diagnostics rather than full 3-D fields.

For comparison with model output for the historical “REF1” runs, we use model output from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis Project (Kalnay et al., 1996), and the European Center for Medium rage Weather Forecasting (ECMWF) 40 year reanalysis “ERA40” (Uppala et al., 2005). Because of significant uncertainties in trend calculations due to changes in input data records, we restrict our use of the NCEP/NCAR and

ERA40 reanalysis data to the period from 1979–2005, when satellite temperature data is available for the reanalysis.

Trends are calculated from annual diagnostic values using a bootstrap fit (Efron and Tibshirani, 1993). The bootstrap fitting procedure yields a standard deviation (σ) of the linear trend slope, which can be used to estimate the uncertainty. For calculations here we report the 2σ (95%) confidence interval. For multimodel ensembles we use a mean of the trend slopes and mean of the 2σ uncertainty to estimate a 95% confidence interval for significance of the multi-model mean. We have chosen simple linear regression for trend analysis. Multiple regression, including other climate forcings could be included in the REF1 (historical) calculation, but different models include different forcings (e.g. some models do not have volcanic eruptions), and this might complicate multi-model analysis.

2.3 Analysis

Zonal monthly mean output on a standard set of levels is available from most models. In this section we show that use of zonal monthly mean temperatures and ozone on these standard levels to calculate TTL diagnostics has only minor affects on the results of the analysis to be presented in Sects. 3 and 4 below.

In general a diagnostic calculated from an average of individual profiles is not equal to the average of the diagnostic calculated for each profile. In the case of LRT interpolation to standard levels and monthly and zonal averaging of a model temperature field is involved. However, the LRT definition is mainly based on the (linear) vertical temperature gradient. Therefore averaging is not expected to greatly affect the results in this case. The same holds for ZLR, however for the CPT the situation is not as clear.

However, we do have 3-D instantaneous model output available from WACCM and CMAM for comparison to verify that the averaging does not affect the results. This has also been discussed by Son et al. (2008)[1] for global tropopause height trends using a subset of model runs in this study.

Figure 1 shows WACCM January zonal mean Cold Point Tropopause Temperature

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(CPTT-top), Lapse Rate Tropopause Pressure (LRTP- middle) and Lapse Rate Minimum pressure (LRMP) from 3-D instantaneous profiles (black) and from monthly zonal mean output (gray) for 60 S–60 N latitude. The monthly zonal mean cold point and lapse rate minimum are well reproduced, within 1 K and 10 hPa respectively in the tropics. The LRMP is also reproduced in the tropics, but since it is a level and not interpolated, a single monthly mean has a coarse distribution depending on model pressure levels. A plot of LRMP like Fig. 1 for CMAM also shows agreement between zonally averaged and 3-D output. Results for other months are similar for WACCM and CMAM.

We have also performed an analysis like that in Fig. 1 using the tropopause edge definition, which produces a consistent value and trend regardless of whether 3-D or zonal monthly mean temperatures are used for input. This is not surprising as the definition is based on Lapse Rate Tropopause pressure.

Note that the level of the ozone minimum is often not well defined in zonal mean data because the mid-tropospheric gradients are small. Thus we refrain from showing these diagnostics for zonal mean output.

Trends calculated using WACCM and CMAM 3-D monthly mean fields on model pressure levels are used to estimate the diagnostics at each point, and compared this to trends estimated using zonal mean temperature and ozone interpolated to a standard set of levels to estimate the diagnostics for each models. Zonal monthly means are available for all models from the BADC archive. For the diagnostics in Sect. 4, the individual annual tropical means in WACCM have a linear correlation of ~0.96 between 2-D and 3-D output. The trends in WACCM and CMAM differ by only a few percent, and are not statistically different. We expect this result to be valid for models which performed interpolation only once when data was put into the archive, as discussed by Son et al. (2008)[1] for a subset of these models. The GEOSCCM model has undergone a double interpolation for tracer fields, which may effect trends. GEOSGCM is not reported in the multi-model ensemble trend numbers, but is shown on the plots.

3 Multi-model climatology

First we show a few examples of the climatology from the multi-model ensemble from the historical scenarios to verify that models beyond WACCM and CMAM analyzed by GB2007 do reproduce the basic structure of the TTL.

Figure 2 illustrates the annual cycle of tropical (±15deg latitude) cold point tropopause temperature (CPTT) for 1980–2000. The full field is shown in Fig. 2a and anomalies about the annual mean (highlighting the annual cycle) are shown in Fig. 2b. Models are shown with solid (S) or dashed (D) lines as indicated in the legend for Fig. 2a.

Results are similar (but not identical) to the 100 hPa Temperatures shown in Fig. 7 of Eyring et al. (2006). The amplitude of the annual cycle is larger (6 K CPTT v. 4 K 100 hPa amplitude for ERA40), but the seasonality is similar.

All models have a similar annual cycle of CPTT (Fig. 2b). This is also true for the Lapse Rate Tropopause Temperature (not shown). Tropical mean CPTT is lowest in January–March, and highest in August–September. There are some models in which the annual cycle is shifted by 1–2 months relative to the reanalysis (red lines in Fig. 2). The amplitude of annual cycle is similar in most models (4–5 K) (Fig. 2b), but the absolute value varies by 10 K (Fig. 2a). The reasons for the differences in CPTT are complex, having to do both with model formulation and possibly with 2-D output. Note that this CPTT analyzed from monthly mean output on standard levels and may not be relevant for water vapor, since 3-D transport plays a role (see Sect. 5). The difference in CPTT is partially due to slight differences in the pressure of the minimum temperature, which varies similarly to the LRTP (see Fig. 5 below). Variations are due to model vertical resolution and vertical interpolation to standard pressure levels.

Differences between 3-D WACCM or 3-D CMAM (calculated on model levels using 3-D monthly means) and 2-D WACCM or CMAM indicate about 1–2 K temperature differences, and make it somewhat difficult to relate this variation to differences in water vapor noted by Eyring et al. (2006). It also makes it difficult to know how much the

CPTT is affected by output and analysis, though for CMAM and WACCM the effect is small. The reanalysis systems have warmer CPTT than most models, which may be a bias in the analysis (Pawson and Fiorino, 1999), or due to coarse vertical resolution (Birner et al., 2006). The inter-annual variability, shown as a 2 standard deviation (σ) confidence interval for the reanalysis in Fig. 2a, is about 2 K.

Figure 3a illustrates the annual zonal mean Lapse Rate Tropopause Pressure (LRTP). The lapse rate tropopause pressure is a better metric than the cold point tropopause pressure for trends, because in many cases the cold point is ALWAYS the same level. This occurs when variability is less than the model vertical grid spacing. The seasonal cycle is not shown, but the LRTP is lowest (highest altitude) in February–April (flat in winter), and maximum, (lowest altitude) in July–October. There is more variation seasonally between models, but models are generally clustered with an annual tropical mean of between 92–102 hPa and an annual cycle amplitude of about 10hPa. There is more variation between models poleward of 30deg latitude.

The Lapse Rate Minimum (LRM) pressure is illustrated in Fig. 3b. The LRM is generally around 250 hPa in the deep tropics (15 S–15 N latitude), with 2 models near 200 hPa, and scatter below this. There is little annual cycle in most models (not shown). The LRM is well defined in convective regions (see GB2007 for more details) within ~20 degrees of the equator. It is not well defined outside of the tropics and is not a useful diagnostic there.

Tropical edge latitudes (Fig. 3-dashed vertical lines) defined by looking at the meridional gradient of LRTP (see Sect. 2.1) are similar for all models, with a spread of less than 10 degrees latitude. The annual cycle is basically identical for all models, and is also about 10 degrees latitude (not shown), with the tropics extending more into summer hemisphere. Models are in good agreement with observations of the tropical edge from NCEP/NCAR and ERA40 analyses.

4 Long term trends

As noted in Sect. 2.3 we have analyzed trends from WACCM and CMAM with both 3-D and zonal monthly mean data, and found no significant differences in LRTP, CPTT or LRMP. For WACCM the correlation correlation between 3-D and 2-D annual means is ~0.96. So for estimating trends, we use the zonal monthly mean data available from all the models. We start with historical trends (REF1: 1960–2005) in Sect. 4.1 and then discuss scenarios for the future in Sect. 4.2. Table 3 summarizes multi-model and observed trends for various quantities, with statistical significance based on the 2σ (95%) confidence intervals from a bootstrap fit. For the last two columns, not all models provide output over the entire time period (see for example, Fig. 4). 13 models are included in statistics for REF1 and 10 for REF2. E39C and UMETRAC REF2 runs were not available, and the GEOSCCM values were not included due to double interpolation.

4.1 Historical trends

Little change is evidenced from 1960–2005 in simulated CPTT (Fig. 4). It is hard to find any trends which are significantly different from zero in the simulations (Table 3). Some models appear to cool, some to warm, but these do not appear to be significant trends. However, many models and the reanalysis systems do indicate cooling from 1991–2004. This analysis is consistent with Fig. 2 of Eyring et al. (2007) that shows the vertical structure of tropical temperature trends. There is little positive trend in CPTT estimated from ERA40. However, NCEP has a large cooling trend not seen in ERA40. This may be due to inconsistencies in the NCEP analysis system (Randel et al., 2006) resulting from changes in input data over time. Thus there is also significant uncertainty in CPTT trends in the reanalysis data.

The Lapse Rate Tropopause Pressure (LRTP) does appear to decrease in the simulations and analyses (Fig. 5), indicating a lower pressure (higher altitude) to the tropical tropopause of −1 to −1.5 hPa/decade (Table 3). Quantitatively the reanalysis trends

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are 50% larger than model trends. The LRTP decrease in the tropics is consistent with other work with models (Santer et al., 2003; Son et al., 2008[1]) and observations (Seidel et al., 2001; Gettelman and Forster, 2002). LRTP trends are smaller than ZLRP trends. The trend in LRTP can also be seen in CPTP. In general the trend from the models is consistent across models in Fig. 5. Variability in models is generally less than in the analyses. As noted, CPTT is correlated with CPT pressure. This can be seen in the LRTP as well in Fig. 5: models with lower pressure LRTP have colder CPTT (Fig. 4).

These changes represent the "top" of the TTL. The "bottom" of the TTL is represented by the Lapse Rate Minimum pressure (LRMP), which is related to the main convective outflow, and thus a measure of where convection impacts the thermodynamic profile in the TTL. Trends in LRM pressure are shown in Fig. 6. There are few significant trends in simulated LRM pressure in most models. Large variability in ULAQ is likely due to coarse (2500 m) vertical and horizontal resolution ($10^{\circ}\times22.5^{\circ}$).

The multi-model trend is larger for the shorter (1979–2001) period, with a significant LRMP decrease of $\sim$–2 hPa/decade. ERA40 shows a large (–3.5 hPa/decade) decrease in LRMP, mostly from 1990–2001. However, NCEP shows virtually no change in LRM Pressure. The reason for this discrepancy in the analysis systems is not known. It might be due to missing the vertical correlation structure in NCEP seen by Son et al. (2008)[1]. The LRM diagnostic is not tightly constrained and can vary with model formulation. However, the LRTP in Fig. 5 is much more tightly constrained, with both analysis systems highly correlated, and many of the models also having correlated interannual variability, most likely forced by Sea Surface Temperature patterns (ENSO).

To better understand the above trends, we have analyzed CPTT (Fig. 7a), LRTP (Fig. 7b) and LRMP (Fig. 7c) trends at each point in the REF1 WACCM simulations using 3-D monthly mean output. The trends are indicated in Fig. 7, along with trends in cloud top pressure by location (Fig. 7d). Shaded trends more than one contour interval from zero in Fig. 7 are almost always significant at the 95% (2σ) level. The figure represents an average of trends from all 3 WACCM REF1 realizations, which all have similar patterns. WACCM has moderate correlations with reanalysis LRTP (Fig. 5), but with less interannual variability.

In Fig. 7a CPTT decreases slightly throughout the tropics in WACCM and increases in the subtropics. WACCM CPTT changes are largest centered over the Western Pacific, but CPTT actually increases over Tropical Africa. Thus the zonal mean trend is not significant. These changes are somewhat coherent with the pattern of changes in cloud top pressure (Fig. 7d), with decreasing pressure (higher clouds) in the W. Pacific. This appears to be a shift in clouds towards the equator from the South Pacific Convergence Zone (SPCZ), which would cool the tropopause by enhancing tropical wave modes (Kelvin and equatorial Rossby waves), noted by Kerr-Munslow and Norton (2006). Note that increases in the subtropical stratocumulus regions west of Africa and S. America in Fig. 7d should be discounted since clouds are at high pressure and the change represents a small height change.

Figure 7b shows that the LRTP decreases almost everywhere in the tropics and subtropics. The largest values are in the East Pacific where the LRTP is slightly higher pressure. The LRM pressure (Fig. 7c) does not have a coherent trend in WACCM, consistent with Fig. 6.

There are very large differences in mean 300 hPa ozone in the tropical troposphere in the models (Fig. 8b). 300 hPa is a level near the ozone minimum. This result is not unexpected since tropospheric ozone boundary conditions were not specified, and the models have different representations of tropospheric chemistry. The spread of ozone at 300 hPa is 10–80 ppbv with most models clustered around the observed value of 30 ppbv (from SHADOZ Ozonezondes). The model which is significantly lower (CMAM) is lower due to a lack of tropospheric ozone sources or chemistry which may impact CPTT.

Even at 100hPa near the tropopause there are variations in ozone between 75–300 ppbv (Fig. 8a). These differences are much larger at the high end than the ~120 ppbv observed from SHADOZ. Most models have a low bias relative to SHADOZ. Several models are not clustered with the others in Fig. 8a, including LMDZ, MAECHAM, MRI, SOCOL and ULAQ. For MAECHAM this is related to ascent rates in the lower stratosphere (Steil et al., 2003). There is also a correlation (linear correlation coefficient ∼0.6) between Cold Point Temperature and ozone around the tropopause (150–70 hPa). Models with higher ozone have higher tropopause temperatures in Fig. 2, consistent with an important role for ozone in the radiative heating of the TTL. Thus the ozone climatology in models varies and is a source of spread in tropopause temperatures. We discuss this further in Sect. 5.

Figure 9 takes the tropical edge latitudes to define a "width" of the tropics. This width is generally about 65 degrees latitude. The spread of model mean values is about 6 degrees, consistent with Fig. 3. Models do not seem to capture the increase in tropical width clearly evident in the reanalyses. The reanalyses indicate that the tropics has been getting wider, significantly in the NCEP/NCAR analyses (Table 3). This is consistent with recent work (Seidel and Randel, 2007). While some models show slight trends in Fig. 9, these trends for most models and the multi-model mean are not significantly different than zero due to large inter-annual variability.

4.2 Future scenarios

We now examine the evolution of the TTL for the future scenario (REF2). As discussed in Eyring et al. (2007), the future scenario uses near common forcing for all models. Models were run from 1960 or 1980 to 2050 or 2100. Surface concentrations of greenhouse gases (CO_2, CH_4, N_2O) are specified from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) GHG scenario A1B (medium) (IPCC, 2000). Surface halogens (chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and halons) are prescribed according to the Ab scenario of World Meteorological Organization (2003). Sea surface temperatures (SSTs) and sea ice distributions are derived from IPCC 4th Assessment Report simulations with the coupled ocean-atmosphere models upon which the CCMs are based. Otherwise, SSTs and sea ice distributions are from a simulation with the UK Met Office Hadley Centre coupled ocean-atmosphere model HadGEM1 (Johns et al., 2006). See Eyring et al. (2007) for details. Trends in Table 3 are calculated from available data for each model from 1980 to the end of the run (mostly 2050 or 2100). Since trends are broadly linear, mixing periods does not quantitatively change the multi-model ensemble trend.

Figure 10 illustrates changes in CPTT, similar to Fig. 4 but for the future (REF2) scenario. Models generally project cold point or lapse rate tropopause temperatures to increase. The rate of temperature increase is only 0.1–0.2 deg/decade (Table 3), but is significant. For AMTRAC, the increase is almost 0.3 deg/decade, which may be coupled to the low ozone at the tropopause (Son et al., 2008[1]). The analysis is consistent with Fig. 2 of Eyring et al. (2007) that shows the vertical structure of tropical temperature trends.

In addition to the small temperature increase, the pressure (height) of either lapse rate or cold point tropopause decreases as well (altitude increase), seen in Fig. 11. The rate of decrease is ~−0.5 hPa/decade, which is less than observed during the historical record in REF1 scenarios or observed in the reanalyses. (Table 3). However, there is very good consistency among the model trends (though with some spread in magnitude), which is clear in Fig. 11. The ~15hPa spread in pressure is likely due to different model formulations and vertical resolution.

Figure 12 indicates that the Lapse Rate Minimum pressure (LRMP) decreases significantly in some simulations (CMAM, WACCM, AMTRAC, MAECHAM), and does not change in others (SOCOL). In some simulations (MRI), the LRMP is not well defined, and it's pressure is indeterminate. In other simulations (CMAM) there are apparent differences in trend before and after 2000. Since the LRMP represents the impact of convection on thermodynamics, differences are likely due to different convective parameterizations in the simulations. For the multi-model ensemble, the change is nearly −2 hPa/decade, and is significant. The LRMP is linked to convection, and thus changes in the LRMP indicate changes in the outflow of convection in the upper troposphere.

Figure 13 illustrates the map of trends for WACCM from the REF2 runs from 1975–2050. As with Fig. 7, this is one of 3 runs with similar patterns. WACCM trends in CPTT are smaller than some models (Fig. 10). WACCM LRTP trends are very similar to other models (Fig. 11). Figure 13a indicates that CPTT increases in most regions of the tropics. CPTT trends are largest (0.2 K/decade) over 0–120 E (Africa–Indonesia). There are slight Temperature decreases in the subtropical Pacific. These decreases are consistent with an upper level wave response to enhanced convection (or decreased cloud top pressure) over the Central Pacific in WACCM (Fig. 13d). Clouds go up to higher altitudes, trends up to −12 hPa/decade, over the C. Pacific, extending into the W. Pacific. This might be interpreted as an extension of the convective region eastward.

The Lapse Rate Tropopause Pressure appears to decrease everywhere in the tropics (Fig. 13b). There is not much structure to the decrease, though it is larger over the Central Pacific where clouds are going higher in WACCM (Fig. 13d). The LRMP (Fig. 13c) also goes up in most regions of the tropics. The pattern does not have much structure, and appears moderately correlated with cloud changes in (Fig. 13d). There are larger changes near the coast of S. America, but this appears to be associated with an increase in cloud pressure (lower cloud). It may be that another variable would be better suited to looking at coupling between cloud detrainment and the LRMP, but only limited diagnostics are available. These diagnostics do not indicate as direct a connection between clouds and LRMP changes as seen in REF1 runs (Fig. 7).

The Zero Lapse Rate (ZLR) pressure (ZLRP) and temperature (ZRLT) are another way to examine the thermal structure around the tropopause. The ZLR is defined identically to the Lapse Rate Tropopause, but for a lapse rate of 0 K/km not −2 K/km. It is similar to the cold point, but can be interpolated from coarse temperature profiles. The ZLRT and ZLRP trends are indicated in Table 3, and are basically identical to CPTT and LRTP trends. Figures look very similar to trends from the REF1 scenarios and reanalyses (Fig. 4 and Fig. 5) as well as similar to the REF2 scenarios (Fig. 10 and Fig. 11). This serves as a consistency check on the derived tropopause trends.

Changes in the projected width of the tropics are shown in Fig. 14, as for Fig. 9. 3 simulations (ULAQ, MRI, GEOSCCM) show significant positive trends (a broadening of the tropics) one simulation (CCSRNIES) has a significant negative trend and the rest are not significant. The multi-model ensemble indicates no significant trend. No significant trends are seen in either the Northern or Southern edge. The lack of consistent trend in tropical edges may be due to the relatively coarse horizontal resolution of many of the models. An investigation of trends with a higher horizontal resolution version of WACCM (2×2.5 degrees instead of 4×5 degrees) indicates trends in edge latitude which are slightly larger and significant at higher resolution, but only 0.1 deg/decade. Across models there is no correlation between edge trends and horizontal resolution. Thus the model simulations do not show significant changes at 200–400 km horizontal resolution.

5 Discussion

Finally we address three derived questions that result from these simulations. First, we try to use the spread of model ozone values to ask if ozone matters for the TTL structure. Second, we look at why Cold Point Temperatures increase but the tropopause rises (decreases in pressure). Third, we look at the implications of tropopause temperature changes on stratospheric water vapor.

5.1 Ozone impacts on Tropopause

Given the wide variation and differences in ozone (Fig. 8), this is a natural experiment to see if ozone matters for the structure of the TTL, as discussed by Thuburn and Craig (2002). It does appear that tropopause level ozone is correlated with temperature: those models with colder CPTT (Fig. 4) do appear to have less ozone at tropopause levels (Fig. 8), but the correlation is not perfect (0.6). It is not clear whether ozone differences are due to transport or chemistry. For some models (i.e. CMAM) low ozone is due to missing chemical processes (i.e. lightning NOx production for CMAM). For other models, transport may bring high ozone from the stratosphere (MAECHAM). In addition, models with a colder tropopause have a higher tropopause, but higher (altitudes) should have more ozone and more heating, indicating this may not be the dominant contributor to observed variability.

We have also looked at the trends in LRT and CPT pressure and temperature as a function of mean 100 hPa O_3. There does not seem to be a correlation in the trends, though as noted there is a correlation in the absolute temperature. This is not surprising given the small TTL ozone trends in these simulations but highlights that ozone may matter for TTL structure.

5.2 Tropopause changes

It is useful to consider the geometric picture of tropopause trends for an analysis of changes in tropopause temperature given changes in tropopause height (or pressure) and changes in tropospheric and stratospheric temperature, respectively. Assume that the temperature profile is piecewise linear and continuous in height with distinct tropospheric and stratospheric temperature gradients Γ_t and Γ_s, respectively: $T=\Gamma_t z+T_{\mathrm{sfc}}$ for $z \leq z_{\mathrm{TP}}$ and $T=\Gamma_s z+T_{0\mathrm{s}}$ for $z \geq z_{\mathrm{TP}}$. Here, z_{TP} refers to tropopause height, T_{sfc} refers to surface temperature and its changes represent tropospheric temperature trends, and $T_{0\mathrm{s}}$ is the temperature at which the stratospheric profile would intersect the ground and its changes represent stratospheric temperature trends. It is straight forward to combine both tropospheric and stratospheric temperature profiles to yield tropopause temperature:

$$T_{\mathrm{TP}} = \frac{\Gamma_t + \Gamma_s}{2} z_{\mathrm{TP}} + \frac{T_{\mathrm{sfc}} + T_{0\mathrm{s}}}{2} .$$

In the tropics a first order approximation is $\Gamma_t \approx -\Gamma_s$, i.e. tropopause temperature is approximately independent of tropopause height. Trends in tropopause height in the tropics therefore do not necessarily imply trends in tropopause temperature. Potential trends in tropical tropopause temperature rather result directly from the combined trends in tropospheric and stratospheric temperature.

A back of the envelope analysis of changes to the TTL given greenhouse gas forcing indicates that the tropical tropopause pressure should decrease, but it is not clear what should happen to tropopause temperature. If the troposphere warms, the upper troposphere may warm by a larger amount than the surface (Santer et al., 2005). Assuming no change to stratospheric temperatures, this would push the tropopause to higher altitudes (lower pressures) and warmer temperatures. If the stratosphere cools and the troposphere stays constant, this would push the tropopause to higher altitudes (lower pressures) and colder temperatures.

In reality, radiative forcing by anthropogenic greenhouse gases both warms the troposphere (increasing T_{sfc}) and cools the stratosphere (which will change T_{0s}, depending on the structure and magnitude of the temperature change). This is illustrated in the vertical profile of temperature trends from these simulations, Fig. 2 of Eyring et al. (2007). The change from warming to cooling is right around the tropopause.

Thus we expect tropopause rises, but what will happen to its temperature? Figure 15 illustrates 1980 (solid) and 2050 (dashed) profiles from WACCM (orange-red) and CMAM (purple) realizations. Here it is clear that the troposphere is warming, and the stratosphere is cooling, but the result is a slight warming of the tropopause temperature. This response seems consistent across all model simulations (Fig. 10). As noted by Son et al. (2008)[1] this is dependent upon ozone recovery, and may be different for those models without interactive ozone chemistry.

5.3 Stratospheric water vapor

Tropical tropopause temperatures control stratospheric water vapor (Holton and Gettelman, 2001; Randel et al., 2006). Analysis indicates that the variation in CPTT among the models does strongly affect stratospheric water vapor. Figure 16 shows a scatterplot of the mean annual saturation vapor mixing ratio (Q_{sat}) at the CPTT for all the models, plotted as a function of mean annual 90hPa water vapor. Also included are points representing analysis CPTT from NCEP or ERA40 and Halogen Occultation Experiment (HALOE) annual mean 100 hPa water vapor (HALOE data was not available at 90 hPa). HALOE/NCEP is an outlier because of the warm bias of NCEP temperatures at the cold point tropopause. The plot indicates that all models and the analy-

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sis systems over the historical record fall below a 1:1 line (100% relative humidity at 90 hPa if limited by the CPTT), close to a 1:0.6 (60% at 90 hPa), and that there is a correlation between CPTT and tropical 90 hPa water vapor, indicating that CPTT limits stratospheric water vapor. This is a tropical mean, so reflects transport processes as well. Two models (MRI, CCSRNIES) lie above this line, which may indicate differences in transport, such that airs has bypassed the tropical tropopause.

The projected increase in tropopause temperature would be expected to increase stratospheric water vapor. The magnitude of the warming to 2100 is only ~1.8 K. For a tropopause at 191 K and 90 hPa, this warming would change the Saturation Vapor Mixing Ratio (SVMR) of water vapor by 1.5 ppmv (4.4 to 5.9 ppmv), a 35% increase Eyring et al. (2007) show that the mean 50 hPa tropical (25 S–25 N) water vapor increase in the models is 0.5–1 ppmv by 2100, slightly less than this (but still a ~25% increase). The increase also includes some effect from increasing methane (though this should not be large at 50 hPa in the tropics).

It is not surprising that the increase in water vapor is less than the SVMR increase, as the latter is a mean annual value based on average CPTT temperatures, and may not be exactly relevant for water vapor as the tropical tropopause temperatures vary in space and time, and water vapor is transported three dimensionally in the TTL.

6 Conclusions

We have analyzed the representation of the Tropical Tropopause Layer in 13 different Coupled Climate Models designed to represent the stratosphere. Results indicate that the models are able to reproduce the basic structure of the TTL. The models are generally able to reproduce past trends observed by reanalyses.

There are not consistent historical trends in Cold Point Tropopause Temperatures. NCEP/NCAR reanalyses show decreases in cold point temperatures, but ERA40 has a slight increase. Some of these differences are related to the fundamental climatologies: while model tropopause pressures are in close agreement, there are large

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(10K) variations in tropopause temperatures. Some of this appears to be related to the wide spread of ozone at tropopause levels in the simulations and to different altitudes of the tropopause. Differences in CPTT are correlated with differences in simulated stratospheric water vapor.

Models and reanalyses indicate decreases in tropopause pressure in the observed record of similar magnitude, a result also found in other studies of radiosonde temperatures. Differences are correlated and consistent, indicating higher confidence in these trends.

Over the observed record there are significant changes in the minimum lapse rate level. The changes seen in WACCM are coherent with changes in convection.

The reanalyses indicate that the TTL is getting "wider", as the TTL edges move poleward by 0.5–1 deg/decade. The change is only significant in NCEP/NCAR reanalyses. The tropics does not seem to get any wider in the historical simulations, due to large variability.

What does this mean for the future trends, and what do we have confidence in?

1. Models consistently show continued decreases in tropopause pressure into the future. Trends are of lower magnitude than historical trends. This result is consistent with the global results of Son et al. (2008)[1] from a subset of these models (AMTRAC, CMAM, GEOSCCM, WACCM). They also show modest increases in cold point temperature. This "raising and warming" is broadly consistent with theory, but also illustrates that projected tropospheric warming may dominate stratospheric cooling at the tropopause in the 21st century.

2. There are also significant decreases in the Lapse Rate Minimum Pressure, amounting to a change of −17 hPa over the 21st century, which indicates a significant increase in the mean convective outflow level on the order of 250 m. This change is dependent on a sub-grid scale process (convection) but is likely driven by surface changes (warmer temperatures). As a result there is spread to the model trends. Historical trends in the LRMP are hard to ascertain.

3. There does not appear to be a significant change in the models in the width of the

tropics over the observed record or in the future. This disagrees with the analyses and with previous work, and may be related to the coarse horizontal resolution of the models, as observed changes are less than a model grid box. Changes are not correlated with model horizontal resolution.

Thus models are able to represent the TTL structure, and reproduce observed tropopause height trends. If tropopause height and particularly temperature trends are to be believed, it may have significant impacts on stratospheric water vapor due to warmer temperatures.

Furthermore, it is desirable that future modeling efforts pay closer attention to TTL ozone, which seems to be correlated with the absolute value of tropopause temperature, and may be important for affecting trends, though no explicit correlation was found.

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Table 1. Diagnostic Abbreviations used in the text.

Abbreviation	Name
CPT[T/P]	Cold Point Tropopause [Temperature/Pressure]
ZLR[T/P]	Zero Lapse Rate [Temperature/Pressure]
LRT[T/P]	Lapse Rate Tropopause [Temperature/Pressure]
LRMP	Lapse Rate Minimum Pressure
LZH	Level of Zero Heating

Table 2. CCMs Used in this study. Abbreviations for Institutions: Geophysical Fluid Dynamics Laboratory (GFDL), National Institute for Environmental Studies (NIES), Deutsches Zentrum für Luft- und Raumfhart (DLR), National Aeronautics and Space Administration – Goddard Space Flight Center (NASA-GSFC), L'Institut Pierre-Simon Laplace (IPSL), Max Planck Institute (MPI), Meteorological Research Institute (MRI), Physikalisch-Meteorologisches Observatorium Davos (PMOD), Eidgenössische Technische Hochschule Zürich (ETHZ), National Center for Atmospheric Research (NCAR).

Model	Resolution	Institution	Reference
AMTRAC	$2^\circ \times 2.5^\circ$	GFDL, USA	Austin and Wilson (2006); Austin et al. (2007)
CCSRNIES	$2.8^\circ \times 2.8^\circ$	NIES, Japan	Akiyoshi et al. (2004); Kurokawa et al. (2005)
CMAM	$3.75^\circ \times 3.75^\circ$	Univ. Toronto, York Univ., Canada	Beagley et al. (1997); de Grandpré et al. (2000)
E39C	$3.75^\circ \times 3.75^\circ$	DLR, Germany	Dameris et al. (2005, 2006)
GEOSCCM	$2^\circ \times 2.5^\circ$	NASA/GSFC, USA	Bloom et al. (2005); Stolarski et al. (2006)
LMDZrepro	$2^\circ \times 2.5^\circ$	IPSL, France	Lott et al. (2005); Jourdain et al. (2008)[2]
MAECHAM4	$3.75^\circ \times 3.75^\circ$	MPI Met & MPI Chem, Germany	Manzini et al. (2003); Steil et al. (2003)
MRI	$2.8^\circ \times 2.8^\circ$	MRI, Japan	Shibata and Deushi (2005); Shibata et al. (2005)
SOCOL	$3.75^\circ \times \times 3.75^\circ$	PMOD & ETHZ, Switzerland	Egorova et al. (2005); Rozanov et al. (2005)
ULAQ	$10^\circ \times 22.5^\circ$	Univ. L'Aquila, Italy	Pitari et al. (2002)
UMETRAC	$2.5^\circ \times 3.75^\circ$	Met Office, UK	Austin (2002); Austin and Butchart (2003) Struthers et al. (2004)
UMSLIMCAT	$2.5^\circ \times 3.75^\circ$	Univ. Leeds, UK	Tian and Chipperfield (2005)
WACCM	$4^\circ \times 5^\circ$	NCAR, USA	Garcia et al. (2007)

[2]Jourdain, L., Bekki, S., Lott, F., and Lefèvre, F.: The coupled chemistry model LMDz Reprobus: description of a transient simulation of the period 1980–1999, Ann. Geophys., submitted, 2008.

Table 3. Trends (per decade "d") in Key TTL quantities from analysis systems (NCEP/NCAR and ERA40) and model simulations. Trends significantly different from zero (based on 2σ confidence intervals, or 95% level) indicated with an asterix. 13 models are included in statistics for REF1 and 10 for REF2.

Diagnostic	Units	NCEP/NCAR 1979-2005	ERA40 1979-2001	Sim REF1 1979-2001	Sim REF1 1960-2004	Sim REF2 1960-2100
CPTT	K/d	−1.1*	0.54*	−0.04	−0.07	0.18*
ZLRT	K/d	−1.1*	0.53*	−0.04	−0.06	0.18*
ZLRP	hPa/d	−0.28	−0.86*	−0.70*	−0.74*	−0.49*
LRTP	hPa/d	−1.4*	−1.3*	−0.83*	−0.91*	−0.54*
LRMP	hPa/d	−3.5*	−1.5*	−2.0*	−1.1	−1.7*
Edge	deg/d	0.89*	0.63	0.35	0.19	−0.0

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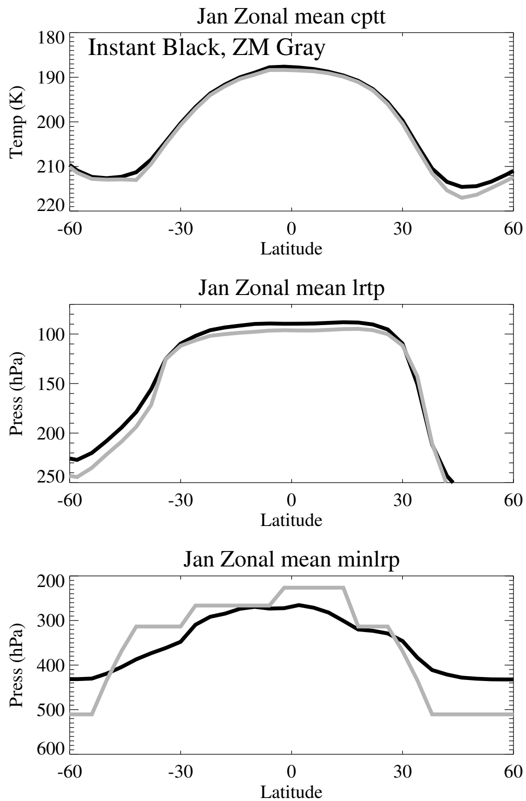

Fig. 1. Comparison between TTL diagnostics calculated using instantaneous 3-D output (Black) and zonal mean monthly output (Gray) for Cold Point tropopause temperature (top), lapse rate tropopause pressure (middle) and lapse rate minimum pressure (bottom).

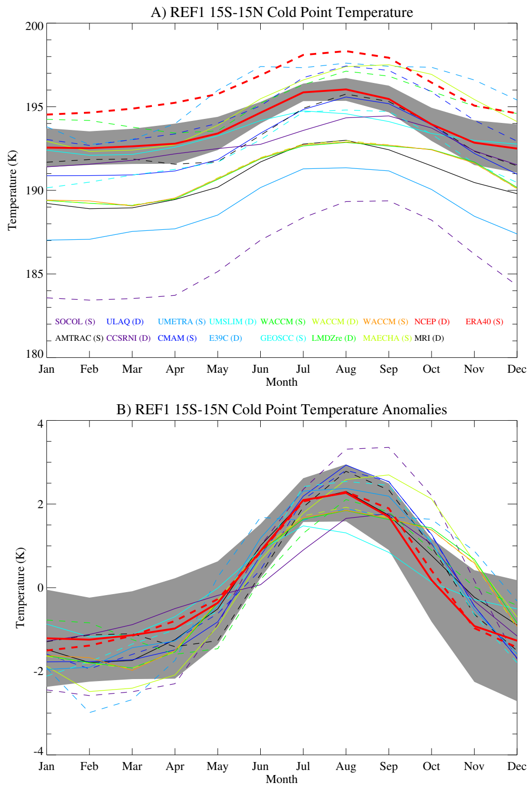

Fig. 2. Annual Cycle of Tropical (15 S–15 N) Zonal mean Cold point Temperature from REF1 (1980–2005) scenarios of CCMVal Models. **(A)** Temperature. **(B)** Temperature anomalies (annual mean removed). Thick Red lines are NCEP/NCAR (dotted) and ERA40 (solid) Reanalysis. Gray shading is ±2 standard deviations from ERA40. Models are either solid (S) or dashed (D) lines as indicated in the legend.

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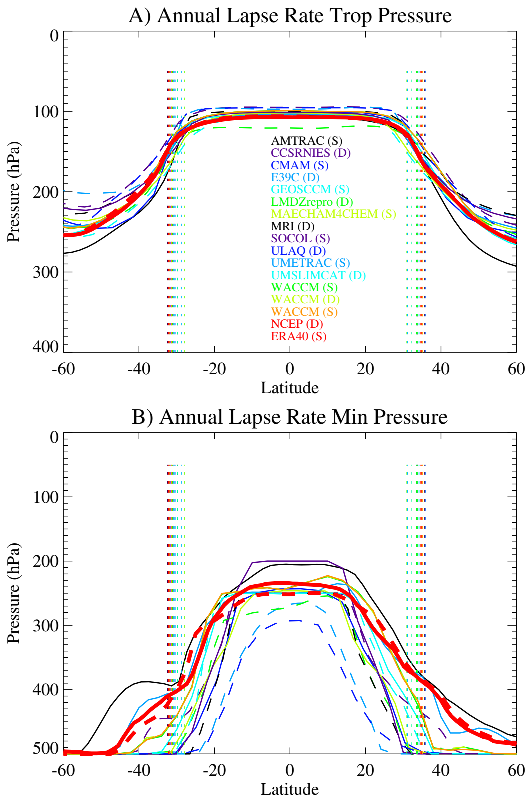

Fig. 3. Zonal mean **(A)** Lapse Rate Tropopause Pressure and **(B)** Lapse Rate Minimum Pressure from CCMVal models (REF1 scenarios, 1980–2005). Vertical Dotted lines are meridional tropopause edges. Thick Red lines are NCEP/NCAR (dashed) and ERA40 (solid) Reanalyses. Models are either solid (S) or dashed (D) lines as indicated in the legend in (A).

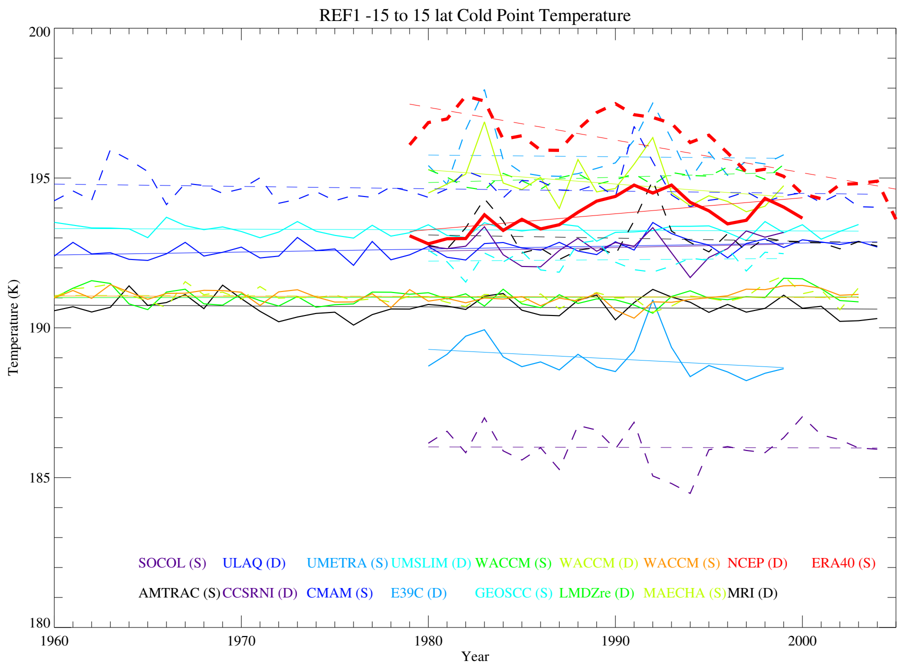

Fig. 4. Tropical mean Cold Point Tropopause Temperature from various models for Historical (REF1) runs. Thin lines are linear trends. Models are either solid (S) or dashed (D) lines as indicated in the legend. Thick Red lines are NCEP/NCAR (dashed) and ERA40 (solid) Reanalyses.

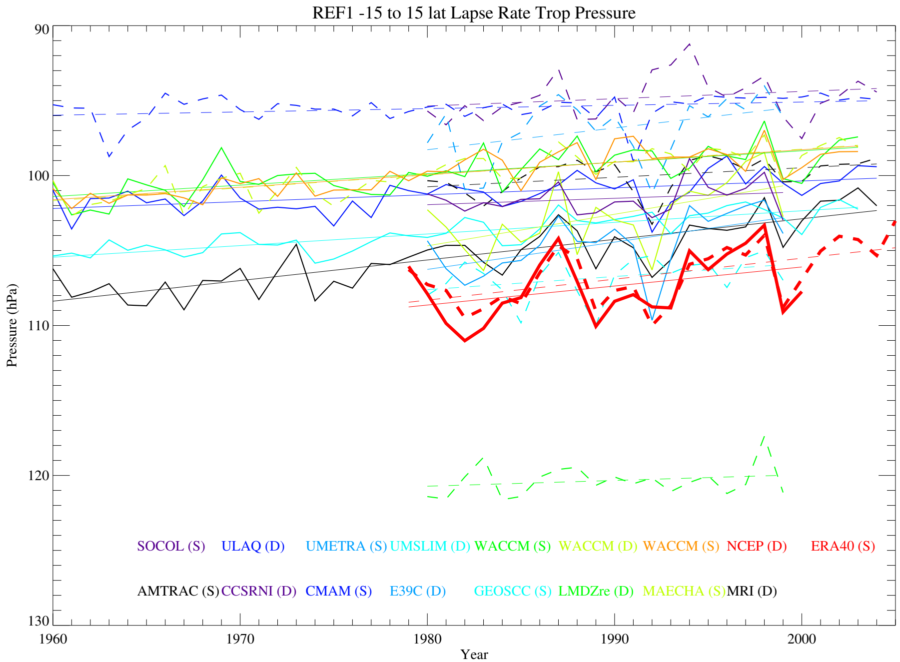

Fig. 5. Tropical mean Lapse Rate Tropopause Pressure from various models for Historical (REF1) runs. Thin lines are linear trends. Models are either solid (S) or dashed (D) lines as indicated in the legend. Thick Red lines are NCEP/NCAR (dashed) and ERA40 (solid) Reanalyses.

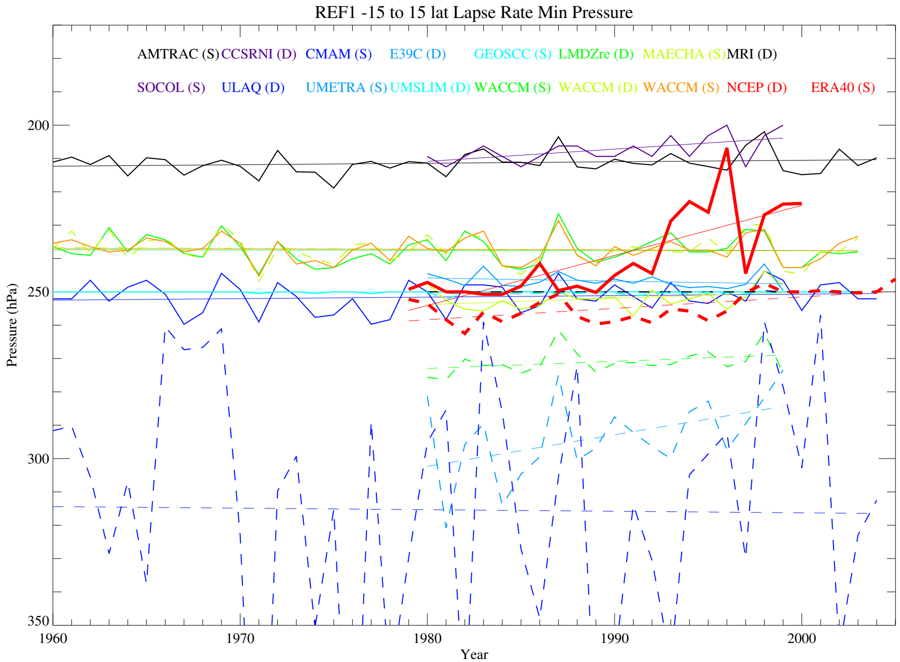

Fig. 6. Tropical mean Lapse Rate Minimum Pressure from various models for Historical (REF1) runs. Thin lines are linear trends. Models are either solid (S) or dashed (D) lines as indicated in the legend. Thick Red lines are NCEP/NCAR (dashed) and ERA40 (solid) Reanalyses.

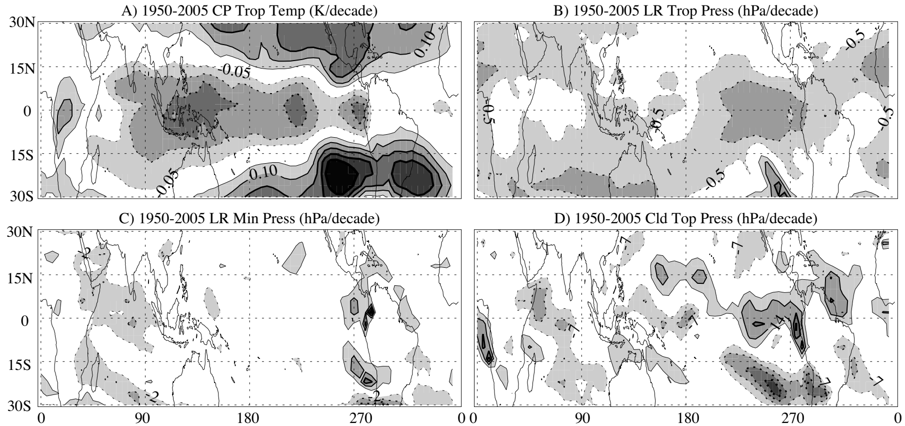

Fig. 7. Map of trends from historical (REF1) WACCM simulations. **(A)** Cold Point Tropopause Temperature trends, contour interval 0.05 K/decade. **(B)** Lapse Rate Tropopause pressure trends, contour interval 0.5 hPa/decade **(C)** Lapse Rate Minimum Pressure trends, contour interval 2 hPa/decade. **(D)** Cloud Top Pressure trends, contour interval 7hPa/decade. Dashed lines are negative trends, no zero line.

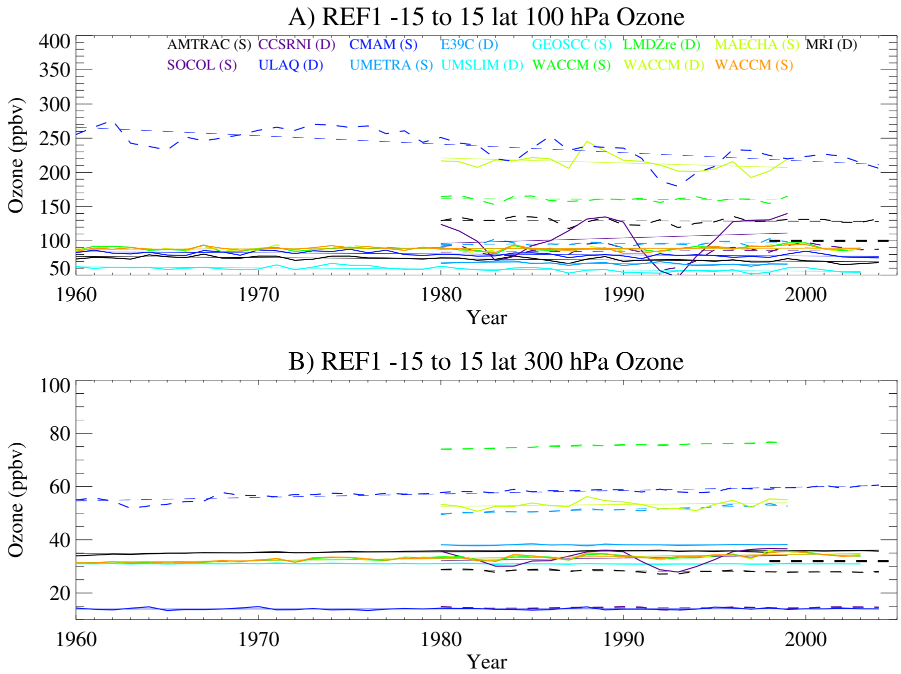

Fig. 8. Tropical mean Ozone from various models at **(A)** 100 hPa and **(B)** 300 hPa. Thin lines are linear trends. Thick black dashed lines are the SHADOZ observed mean from 1998–2005 at these levels. Models are either solid (S) or dashed (D) lines as indicated in the legend.

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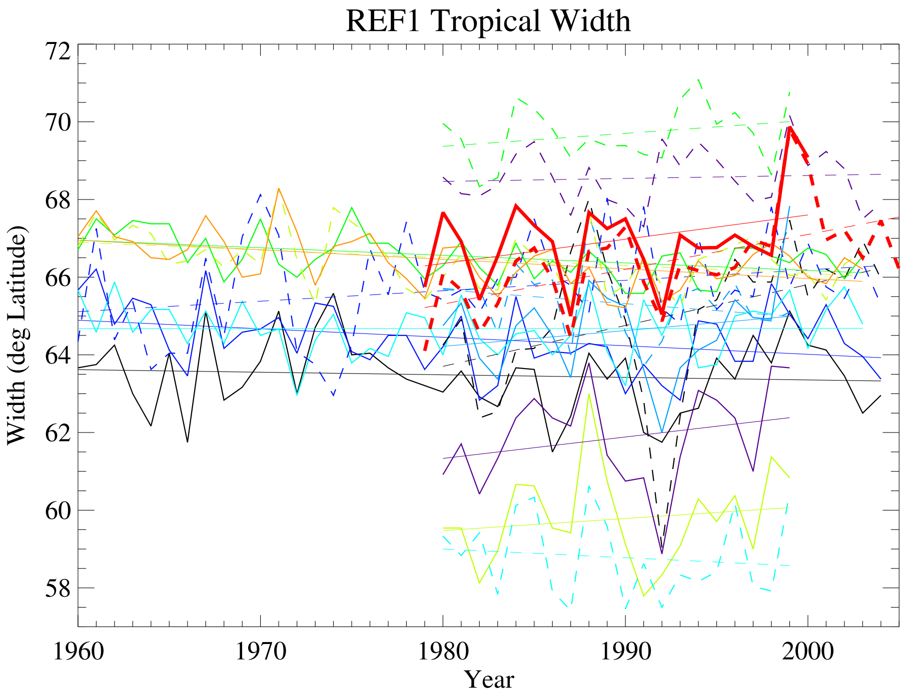

Fig. 9. Tropical mean TTL width (in latitude) models for historical (REF1) scenarios. Thin lines are linear trends. Models are either solid (S) or dashed (D) lines as indicated in the legend for Fig. 8. Thick Red lines are NCEP/NCAR (dashed) and ERA40 (solid) Reanalyses.

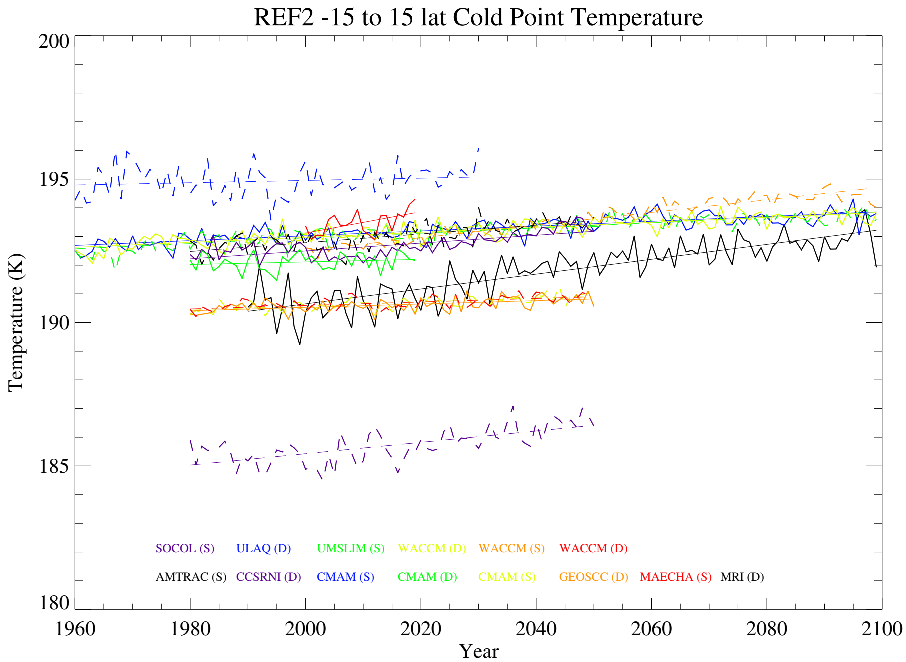

Fig. 10. Tropical mean Cold Point Tropopause Temperature from various models showing expected future scenarios (REF2). Thin lines are linear trends. Models are either solid (S) or dashed (D) lines as indicated in the legend.

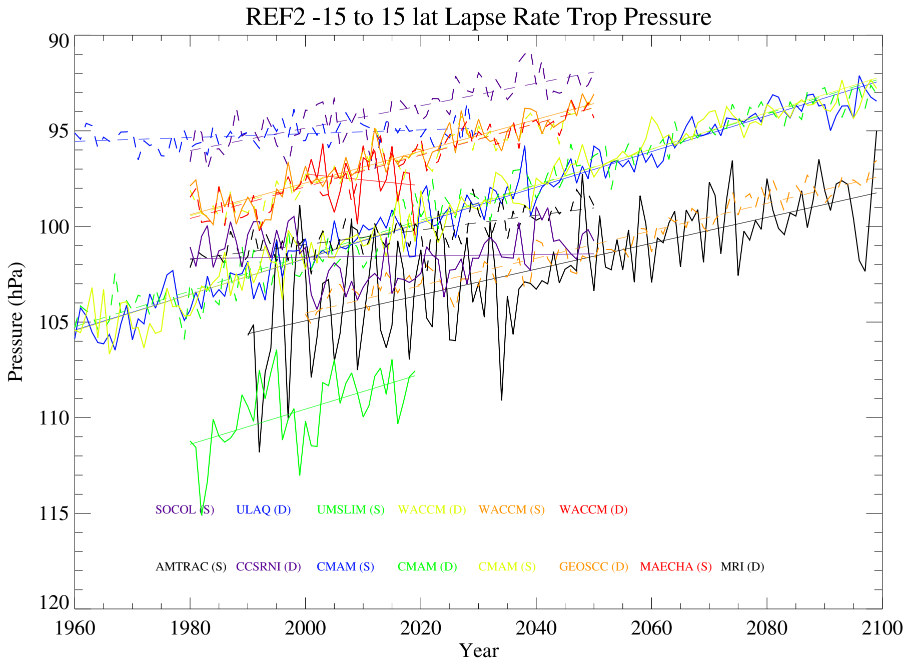

Fig. 11. Tropical mean Lapse Rate Tropopause Pressure from various models showing expected future scenarios (REF2). Thin lines are linear trends. Models are either solid (S) or dashed (D) lines as indicated in the legend.

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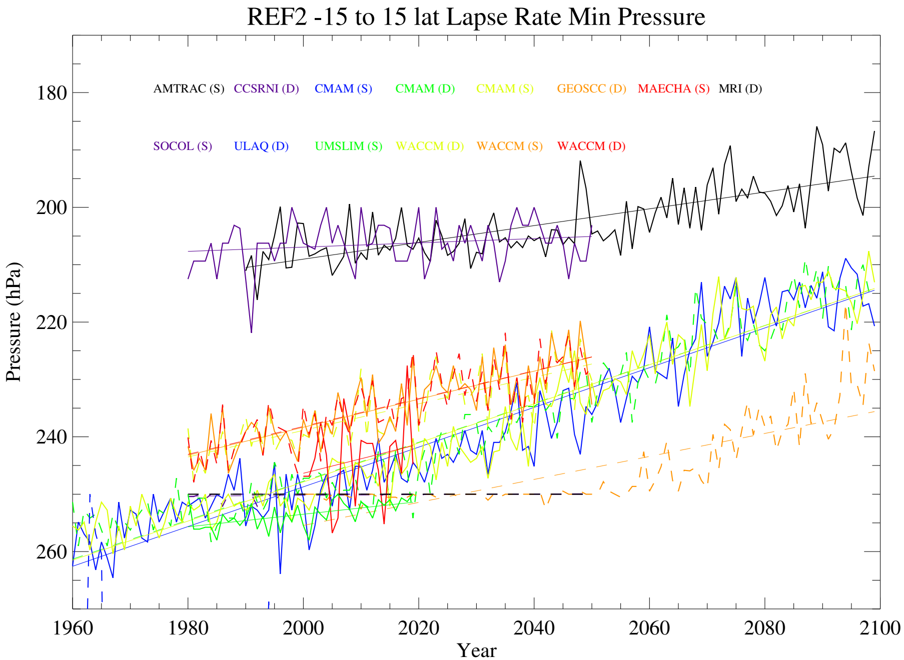

Fig. 12. Tropical mean Lapse Rate Minimum Pressure from various models showing expected future scenarios (REF2). Thin lines are linear trends. Models are either solid (S) or dashed (D) lines as indicated in the legend. Note that ULAQ is off scale.

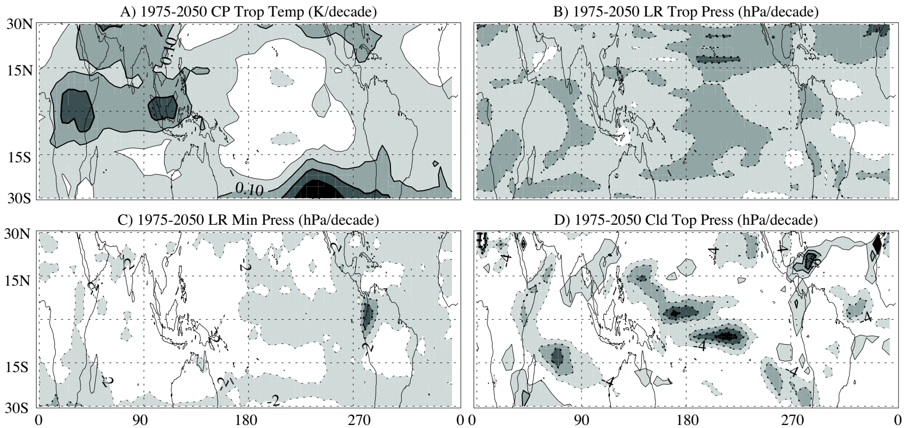

Fig. 13. Map of trends from future (REF2) WACCM simulations. **(A)** Cold Point Tropopause Temperature trends, contour interval 0.05 K/decade. **(B)** Lapse Rate Tropopause pressure trends, contour interval 0.5 hPa/decade **(C)** Lapse Rate Minimum Pressure trends, contour interval 2 hPa/decade. **(D)** Cloud Top Pressure trends, contour interval 2 hPa/decade. Dashed lines are negative trends, no zero line.

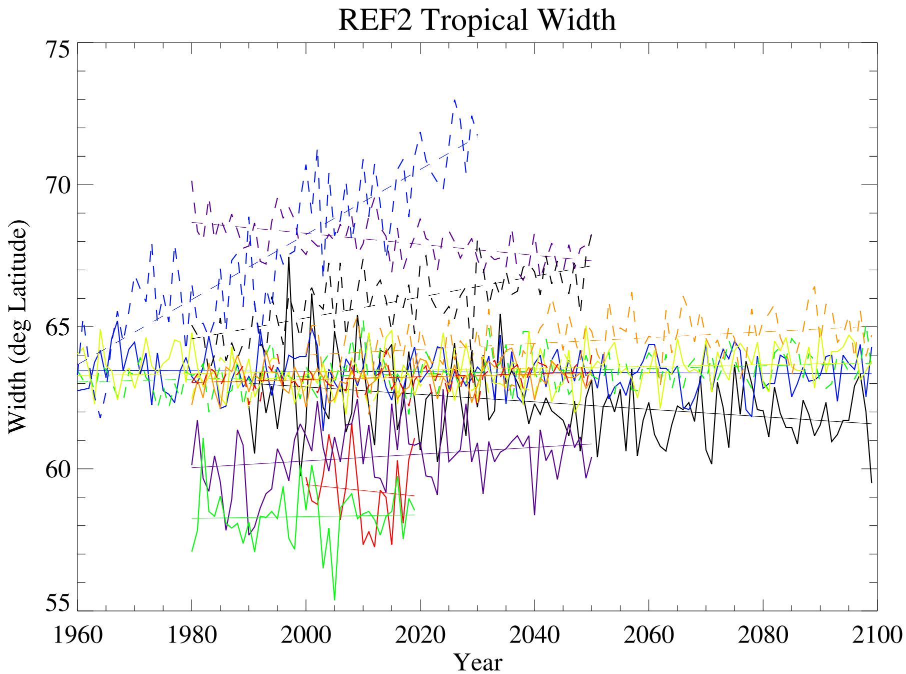

Fig. 14. Tropical mean TTL width (in latitude) models for future (REF2) scenarios. Thin lines are linear trends. Models are either solid (S) or dashed (D) lines as indicated in the legend for Fig. 12.

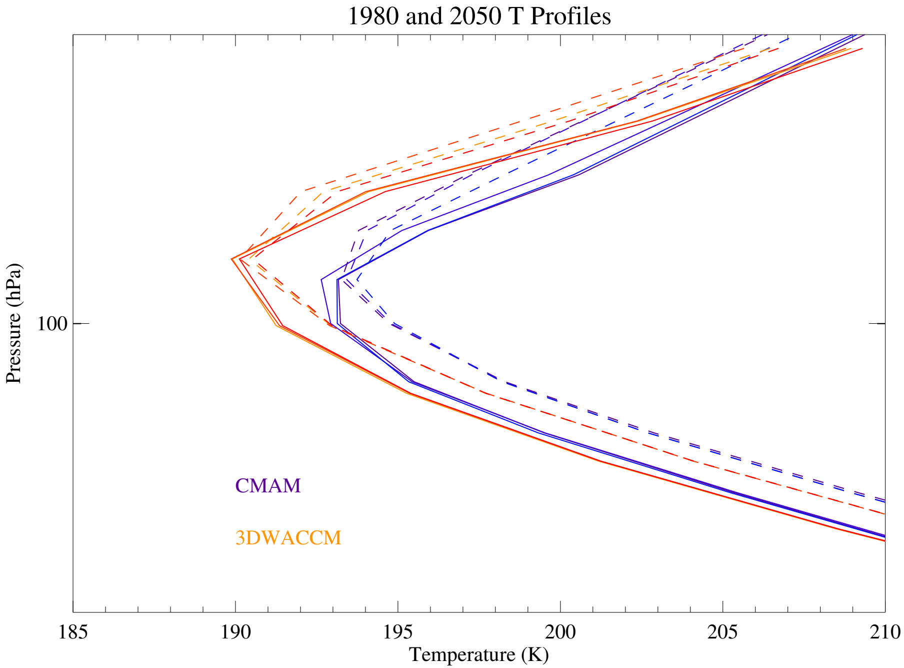

Fig. 15. Tropical temperature profiles from WACCM and CMAM models for future (REF2) scenarios. Solid lines: 1980 average. Dashed lines: 2050 average for each of 3 realizations.

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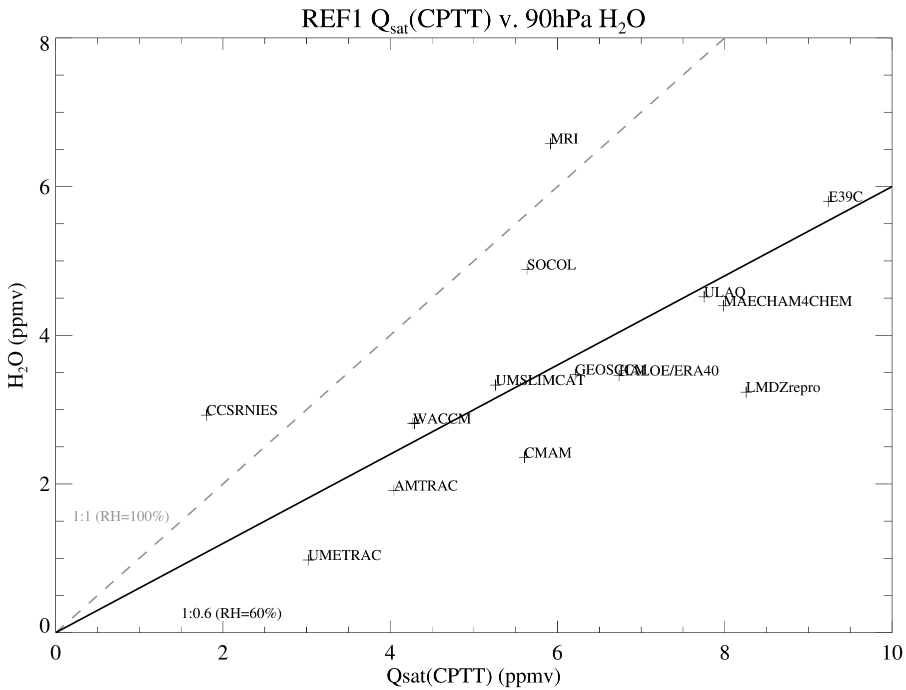

Fig. 16. Scatterplot of Saturation Vapor Mixing Ratio of the Cold Point Tropopause Temperature, Q_{sat}(CPTT) and the 90 hPa tropical water vapor mixing ratio fore each historical (REF1) run, as well as using ERA40 temperatures and HALOE 100hPa water vapor (ERA40/HALOE). Gray dashed line is 1:1 line (100% RH), Black solid line is 1:0.6 (60% RH).

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