A multidecadal study of cirrus in the tropical tropopause layer

S. T. Massie, R. Khosravi, and J. C. Gille

Received 18 December 2012; revised 20 June 2013; accepted 24 June 2013; published 29 July 2013.

Changes in the distributions of cirrus in the upper troposphere centered at 100 hPa in the tropical tropopause layer (TTL) during the last 27 years (1985–2012) are quantified based upon an analysis of five independent data sets. Stratospheric Aerosol and Gas Experiment II, Halogen Occultation Experiment, Cryogenic Limb Array Etalon Spectrometer, High Resolution Dynamics Limb Sounder, and Cloud-Aerosol Lidar with Orthogonal Polarization data are used to determine cirrus frequency-of-occurrence geospatial distributions in the TTL in multiple year segments during 1985–2012. Full width at half maximum (FWHM) tropical widths of cirrus zonal averages of occurrence frequency centered at 100 hPa are calculated for each experiment. The FWHMs have a 2σ trend of $0.28 \pm 1.5^\circ$ decade$^{-1}$. This statistically insignificant trend is similar to those calculated by Davis and Rosenlof (2012) based upon analyses of reanalysis tropopause height and tropopause latitudinal gradients near 100 hPa.


1. Introduction

Davis and Rosenlof [2012] review previous studies that quantify the poleward expansion of the latitudinal edge of the tropics, and introduce and apply new edge definitions. Statistically significant Hadley cell expansion trends between $1.0^\circ$ and $1.5^\circ$ decade$^{-1}$ for 1979–2009 have been calculated based upon changes in the mean meridional stream function. Davis and Rosenlof [2012] discuss other diagnostics that yield trends of $-0.5^\circ$ to $0.8^\circ$ decade$^{-1}$ that are statistically insignificant.

Davis and Rosenlof [2012, Figure 1] presents the pressures and approximate heights for which the various tropical width trends have been calculated. Tropopause heights are used to calculate the latitudinal expansion near the tropopause [Seidel and Randel, 2007]. This “$\Delta z_{Tp}$” technique determines when the tropopause height decreases to a threshold, e.g., 1.5 km, below the height at the equator. Davis and Rosenlof [2012] introduce a tropical edge metric ($\Delta z_{Tp}$) based upon the latitudinal gradient of $z_{Tp}$. Hu and Fu [2007] determined the locations where outgoing longwave radiation transitions to a value of 250 W m$^{-2}$ and also located the equatorward latitude of the zero crossing of the mean meridional stream function in separate calculations. The latitudes of the peak wind in the 400–100 hPa range [Archer and Caldeira, 2008] and at 850 hPa [Lorenz and Deweaver, 2007] have been determined in order to quantify changes in the strength and position of the subtropical and polar jet streams. Of the various types of tropical width trends that are tabulated in Davis and Rosenlof [2012, Table 3], only 26% of the trends are statistically significant at the 2σ level. Additional research is warranted to better determine how the tropics are widening.

In this paper we examine the frequency of occurrence of cirrus of five independent experiments. Frequency of occurrence is defined by us to be the percentage of the total number of observations, for a given specified range of altitude centered at 100 hPa, for which cirrus is observed. We calculate cloud frequency of occurrence during the last 27 years and calculate changes in the latitudinal expansion of the tropics based upon an analysis of the cloud frequencies. One hundred hectopascals is located in the tropical tropopause layer (TTL), which extends from 150 to 70 hPa [Fueglistaler et al., 2009]. The TTL is a region of interest since it regulates the amount of water vapor that is transported into the stratosphere from the troposphere.

Cirrus, especially subvisible cirrus, is known to occur throughout the TTL. We hypothesize that changes in the latitudinal distribution of temperature and relative humidity in the TTL during the last 27 years have yielded changes in the latitudinal distribution of cirrus. Solar occultation measurements in the tropics by the Stratospheric Aerosol and Gas Experiment (SAGE) II and the Halogen Occultation Experiment (HALOE), atmospheric emission measurements by the Cryogenic Limb Array Etalon Spectrometer (CLAES) and the High Resolution Dynamics Limb Sounder (HIRDLS), and Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) lidar observations are analyzed in this paper to quantify these changes.

Our paper is organized in the following manner. Section 2 discusses the data we analyze. The analysis methodology is discussed in section 3. Results are presented in section 4. Finally, we discuss the results and present our conclusions in section 5.
2. Data

[7] Observational characteristics of the satellite experiments and data used in our analyses are described below. Summary information is specified in Table 1 and in Figure 1, which summarizes the years for which each experiment observed clouds in the TTL.

[8] SAGE II version 6.1 extinction profile data are archived at wavelengths of 0.385, 0.453, 0.525, and 1.02 μm [Chu et al., 1989]. We analyze complete years of available data from 1985 to 1999. SAGE II experienced a failure of its azimuth gimbal system in July 2000 and resumed operation at a 50% duty cycle after November 2000. Wang et al. [1996] discuss a climatology of clouds for 1985–1990 sensed by SAGE II, with emphasis placed upon the 1.02 μm data, since molecular scattering decreases as wavelength increases. The SAGE II solar occultation retrievals are characterized by a volume with a vertical height of 1 km and a width of 2.5 km, averaged over a 200 km path length centered at the tangent point of the limb view. The upper limit of the SAGE II extinction coefficient at 1.02 μm is 0.02 km⁻¹, and extinction profiles are specified on an altitude grid and reported at every 0.5 km in altitude. Average extinction precision at 1.02 μm centered at 100 hPa is 2%, while HALOE and SAGE II extinction time series comparisons at 25 km over Laramie, Wyoming agree to within 25% [Hervig and Deshler, 2002]. We use extinction data at 1.02 and 0.525 μm.

[8] HALOE extinction coefficient data at 2.45, 3.40, 3.46, and 5.26 μm [Russell et al., 1993] are archived from the fall of 1991 through a portion of 2005, with reduced sampling in the latter years of operation. The HALOE solar occultation experiment on the Upper Atmosphere Research Satellite (UARS) employed broadband and gas filter radiometry. Approximately 900 sunrise and sunset profiles per month between 80°S and 80°N specify extinctions at every 0.5 km step in altitude, at a vertical resolution of 1.6 km. Extinction uncertainties are on the order of 10%–15% [Hervig et al., 1996]. We use the 3.46 μm extinction data in our analysis, averaging on yearly and multiyear scales for which data are available for full years.

[10] The CLAES also flew on UARS and observed atmospheric emission from September 1991 to May 1993. CLAES completed an observation sequence every 65 s and measured gas, aerosol, and cloud profiles with a vertical resolution of 2.5 km [Roche et al., 1993]. This sampling yielded up to 1300 observations per day. Extinctions are reported at 68, 100, and 146 hPa in the TTL. The lifetime of CLAES was set by the amount of cryogen contained in its dewar. CLAES used Fabry-Perot and blocker filters to observe at 0.25 cm⁻¹ resolution in nine filter bands, each of ~10 cm⁻¹ spectral width, between 3.5 and 13 μm. While extinction was measured in each of the bands, the 12 μm channel is of primary interest for aerosol and cloud detection [Mergenthaler et al., 1999] since atmospheric gas absorption is weakest at 12 μm. Extinction accuracies at 12 μm are on the order of 35% [Massie et al., 1996]. Mergenthaler et al. [1999] determined that an extinction threshold of 9 × 10⁻⁴ km⁻¹ could be used to screen for the presence of cirrus in the TTL. Using this threshold, Mergenthaler et al. [1999] averaged CLAES 12 μm extinction at several pressure levels and obtained frequency-of-occurrence geospatial distributions similar to those of Wang et al. [1996].

[11] The HIRDLS experiment [Gille et al., 2008] observed atmospheric emission in 21 spectral bands from February 2005 to March 2008. Profiles of gas species, aerosols, and clouds were measured every 10 s and retrieved [Khosravi et al., 2009] at 1 km vertical resolution. HIRDLS observed approximately 5500 profiles per day. The 12 μm channel is utilized to measure aerosol and cloud extinction [Massie et al., 2007]. Approximately

Table 1. Satellite Experiment Characteristics

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Resolution (km)</th>
<th>Wavelength (μm)</th>
<th>Trend Analysis</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAGE II, O</td>
<td>1</td>
<td>1.02, 0.525</td>
<td>1985–1990, 1995–1999</td>
<td>2 × 10⁻⁵&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>HALOE, O</td>
<td>1.6</td>
<td>3.46</td>
<td>1994–1998, 1999–2003</td>
<td>5 × 10⁻⁶&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>CLAES, E</td>
<td>2.5</td>
<td>12</td>
<td>May 1992 to May 1993</td>
<td>3 × 10⁻⁶&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>HIRDLS, E</td>
<td>1</td>
<td>12</td>
<td>2005 to January 2008</td>
<td>2 × 10⁻⁶&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>CALIOP, L</td>
<td>1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.532</td>
<td>July 2006–2012&lt;sup&gt;d&lt;/sup&gt;</td>
<td>4 × 10⁻⁴&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

O, solar occultation; E, limb view emission; L, nadir lidar.
<sup>a</sup>Extinction sensitivity units are in km⁻¹ for SAGE II, HALOE, CLAES, and HIRDLS.
<sup>b</sup>The vertical binning used in this analysis.
<sup>c</sup>Seasonal analysis uses data starting in July 2006.
<sup>d</sup>Multiyear and annual year trends use full year’s data 2007–2012.
<sup>e</sup>Sensitivity of 80 km averaging (units km⁻¹sr⁻¹).
two thirds of the radiance signal due to the presence of a cirrus layer originates from a 150 km path length centered at the tangent ray point. Postlaunch instrument issues, due to the presence of plastic material in the optical path adjacent to the detector array, complicated the postlaunch calibration of the HIRDLS experiment [Gille et al., 2008]. An extinction threshold of $9 \times 10^{-4}\text{km}^{-1}$ for the 12 $\mu$m channel is used in this paper to discriminate version 7 HIRDLS clouds from aerosols. We also analyze version 6 data to illustrate the sensitivity of our HIRDLS calculations to data version number.

[12] The CALIOP nadir view lidar on the CALIPSO satellite began making measurements in June of 2006 and continues to make observations. The CALIOP lidar observes at 532 and 1064 nm [Winker et al., 2010]. The design 532 nm signal-to-noise ratio (SNR) of 50, at an altitude of 30 km, has been exceeded by on-orbit SNRs near 80 [Hunt et al., 2009]. The cloud feature and layer property algorithms are discussed in Vaughan et al. [2009]. The magnitude and variation of lidar backscatter at 532 and 1064 nm are used in an adaptive threshold technique to discriminate between clouds and aerosols [Liu et al., 2009].

[13] CALIOP 5 km cloud layer (CLay) files are used in our study to calculate cloud frequency of occurrence. These files specify the cloud tops and bases in kilometers of clouds along the orbit track at 5 km horizontal resolution with 60 m vertical resolution for altitudes between 8.2 and 20.2 km. We determine frequency of occurrence near 100 hPa by selecting data when clouds are present in the altitude range of 16.2 to 17.2 km. A cloud is counted to be present in the 16.2 to 17.2 km altitude range if the CLay file cloud top or cloud bottom altitude is between 16.2 and 17.2 km. The frequency of occurrence is then determined by dividing these counts by the total number of processed CLay profiles. Analysis of Global Modeling and Assimilation Office GOES 5.1 temperature-pressure profiles and the cloud top layer and cloud bottom layer temperature-pressure-altitude data associated with the CLay files indicate that 100 hPa is near the 16.7 km altitude. The 16.2–17.2 km altitude range brackets the 100 hPa height of 16.7 km altitude, giving an effective vertical resolution of 1 km, which then matches the 1 km vertical resolution of the HIRDLS experiment.

[14] Since we use a nadir view and limb view experiments in tandem, the question arises of whether or not the two types of experiments can report similar cirrus geospatial patterns. If the horizontal scales of cirrus in the TTL were predominantly small (e.g., 20 km), then situations would arise when CALIOP would not count a cloud, while the limb view HIRDLS experiment, which integrates over a ~150 km path length centered at the tangent ray point, would count a cloud along the ray path. As discussed in Massie et al. [2010], over half the horizontal scales of cirrus observed by CALIOP in the 16–17 km range (pressures near 100 hPa) are greater than 100 km in horizontal length. This leads to the situation that the nadir and limb view experiments will produce similar cloud frequencies. As illustrated in Massie et al. [2010, Figures 2, 3, 6, and 7], latitude-longitude maps of monthly and seasonal averages of CALIOP and HIRDLS data are similar throughout the 90–177 hPa range. This indicates that the two experiments are mutually consistent.

[15] The last column of Table 1 specifies the detection sensitivities of each experiment. For the SAGE, HALOE, CLAES, and HIRDLS experiments, the sensitivities (in km$^{-1}$ units) were derived by calculating the probability distribution functions (pdfs) of the number of observations of extinction between 10$^{-4}$ and 0.1 km$^{-1}$, with positive precisions less than 100%, in a pdf containing 100 log extinction bins. The detection sensitivity is the extinction of the first bin for which the number of counts is (arbitrarily) greater than 10. Table 1 indicates that the experiments became more sensitive with time. Since cirrus extinction is on the order of 10$^{-3}$ km$^{-1}$, the four limb view experiments measure both aerosol and cloud extinction with ample sensitivity—thus, there is the need to apply a cloud extinction threshold (i.e., the Mergenthaler value of $9 \times 10^{-4}\text{km}^{-1}$). The detection sensitivity of CALIOP is the 5 km sensitivity determined for daytime observations [McGill et al., 2007], divided by a random-noise scaling factor of $\sqrt{80/5}$ to represent the sensitivity of 80 km horizontal averaging. As verified observationally by Rogers et al. [2011] and Yorks et al. [2011], the SYBIL cloud detection methodology of Vaughan et al. [2009] applies 5, 20, and (up to) 80 km horizontal averaging to discriminant cloud layers from background Rayleigh scattering. This methodology detects cloud presence and cloud top heights to comparable accuracy of airborne lidars, e.g., Cloud Physics Lidar (CPL) and the NASA Langley Research Center High Spectral Resolution Lidar, which have inherent sensitivities many times better than the 5 km CALIOP backscatter signal. Yorks et al. [2011] determined that the CALIOP

---

**Figure 2.** The wavelength dependence of subvisible cirrus extinction based upon the cirrus size distribution of Lawson et al. [2008]. The extinction is normalized to unity at 12 $\mu$m. Small case letters indicate the observation wavelengths of the SAGE (S), CALIOP (C), HALOE (H), CLAES (CL), and HIRDLS (HIR) experiments. Vertical labels indicate the specific wavelengths of the cirrus extinction data utilized in our analysis.
Cloud fractions are 3.5% less than CPL cloud fractions for transparent cloud layers.

3. Methodology

Frequency of occurrence of clouds, mapped at a resolution of 5° latitude × 10° longitude, for the SAGE II, CLAES, HALOE, and HIRDLS experiments centered at 100 hPa and CALIOP occurrence distributions for the 16.2–17.2 km altitude range are calculated for the years specified in Table 1. Both yearly and multiyear geographical distributions are calculated for years in which data are available throughout each year. The maps are prepared at 1 and 3 km vertical resolution since there is a range of vertical resolutions of the different experiments.

Latitude-longitude maps of cirrus observed by the solar occultation experiments are well defined when multiyear averages are calculated. Solar occultation experiments observe ~30 profiles per day. HIRDLS and CALIOP monthly averages yield well-defined distributions because these experiments observe substantially more data than the solar occultation experiments. HIRDLS observed ~5500 profiles per day, while the CALIOP 5 km CLay data files contain ~122,000 profiles per day. Though clouds near 100 hPa of course are not present in every profile, there is a large difference in the sampling statistics of the previous solar occultation experiments and that of the HIRDLS and CALIOP experiments.

Most of the extinction retrieved by the limb-viewing experiments is due to small subvisual cirrus particles. The limb view path geometry enhances optical depths along the ray path. This is especially true when particles are present. Larger cirrus particles are not retrieved when the optical depths along the line of sight become too large. Wang et al. [1996, Figures 2–4] discuss that opaque clouds, with unretrievable extinction greater than 0.1 km\(^{-1}\), occur less frequently than the subvisual cirrus in the TTL. Deep convection, the source of the larger particles, only occupies 6% of the tropics [Roca and Ramanathan, 2000]. Subvisual cirrus particles that are produced by the uplift of humid layers are more ubiquitous in geospatial extent.

Since the five experiments do not observe at the same wavelengths, it is useful to examine the expected wavelength dependence of the subvisual cirrus extinction. The Lawson et al. [2008] subvisible cirrus particle size distribution and Warren and Brandt [2008] ice refractive indices are used in Mie calculations [Bohren and Huffman, 1983] to generate the wavelength-dependent extinction presented in Figure 2. The particle size distribution, measured during the Costa Rica Aura Validation Experiment, is a composite of
Figure 2, the extinction spectrum is normalized to unity at wavelengths of the cirrus extinction used in our analysis. In data of the experiments, while the vertical labels indicate the Figure 2 indicates observation wavelengths of the extinction 0.532 HALOE, and CALIOP wavelengths of 1.02, 3.46, and cirrus has values within 10% of unity at the SAGE II, normalized spectrum in Figure 2.

The vertical resolutions are near 1 km.

WB-57F aircraft 2D-S and CAPS measurements along 1800 km of flight distance. The small case symbols in Figure 2 indicate observation wavelengths of the extinction data of the experiments, while the vertical labels indicate the wavelengths of the cirrus extinction used in our analysis. In Figure 2, the extinction spectrum is normalized to unity at 12 μm. The normalized extinction spectrum of the subvisual cirrus has values within 10% of unity at the SAGE II, HALOE, and CALIOP wavelengths of 1.02, 3.46, and 0.532 μm, respectively, which are listed in Table 1.

If larger particles are in the retrieved extinctions, then the cirrus wavelength dependence is very flat since the Q_{ext} extinction efficiency factor asymptotes to a value of 2, independent of wavelength, as the size parameter 2πμm/λr >> 1. Thus, the wavelength-dependent factors in Figure 2 are lower limits to what occurs in the atmosphere.

Frequency-of-occurrence maps for CLAES and HIRDLS are prepared by averaging extinction for the range 9.0 × 10^{-4} to 1.0 × 10^{-2} km^{-1}. For the HALOE experiment, the range is reduced by a factor of 0.98 based upon the normalized spectrum in Figure 2.

For the SAGE II experiment, we determine frequency-of-occurrence maps by applying an extinction ratio technique. As discussed by Kent et al. [1993] and Massie et al. [2003], the ratio of extinction β at 1.02 and 0.525 μm can be used to distinguish between cirrus and aerosol, since the ratio is low for sulfate aerosol in the stratosphere, while the ratio asymptotes to unity as cirrus particles increase in size. We prepare frequency-of-occurrence maps of SAGE II by selecting data when the extinction ratio (β(1.02 μm)/β(0.525 μm)) is between 0.8 and 1.2. In comparing the 1.02 μm extinction and ratio technique maps, the map using the ratio technique had less clutter, and these maps are used in our study.

Thus, only the wavelength dependence in Figure 2 that applies to the HALOE experiment needs to be considered. As discussed later in this paper, consideration of the HALOE extinction scaling factor of 0.98 displayed in Figure 2 turns out to be inconsequential.

Due to differences in the vertical resolution of the experiments, we perform analyses at two vertical resolutions. The first analysis is done at a vertical resolution near 1 km, the vertical resolution of the HIRDLS experiment, and includes data from the SAGE, HALOE, HIRDLS, and CALIOP experiments. The second analysis is done at a vertical resolution near 3 km and includes data from the CLAES experiment (2.5 km vertical resolution) and data averaged over 3 km for the other experiments (i.e., the three HIRDLS pressure levels centered at 100 hPa since the HIRDLS vertical profile is in 1 km vertical steps, the 15.2–18.2 altitude range for the CALIOP experiment, and two adjacent 1.6 km vertical-resolution HALOE observations).

Zonal average curves of frequency of occurrence are calculated in 5° latitude bins in addition to the latitude-longitude maps. The zonal curves are normalized to unity by finding the maximum value of each individual curve, followed by division by the peak value.

The metric adopted to measure the width of the tropics is based upon finding the full width at half maximum (FWHM) of each normalized curve. The FWHM metric is used in many other applications (such as optics and spectroscopy) as a well-defined metric of the width of a distribution and is appropriate in this paper since the term “width of the tropics” implies knowing how the edge of the distribution has expanded to more poleward latitudes. The normalized curve has frequency of occurrence between unity and zero, with well-defined values greater than 0.25 on both sides of the maximum. We find the three values that are near 0.50 on each side of the curve and perform a linear least squares fit of these values to determine the interpolated latitudes which define the 0.50 values on each side of the curve. The FWHM is then the sum of the absolute values of the two interpolated latitudes.

A least squares linear fit to the FWHM of each experiment, spanning a 27 year time period, then yields a linear trend in the FWHMs as a metric of measured change. This procedure is carried out for multyear and yearly averages, at the two vertical resolutions, and on seasonal time scales for the HIRDLS and CALIOP data.

We note that the geospatial distributions of cirrus are also influenced by physical influences other than climate change. The monsoon season is known to shift northward the frequency of occurrence of cirrus in the TTL as convection is generated in summer over the Indian subcontinent and central America to a lesser extent. This is readily apparent in maps of cirrus in June-July-August (e.g., Wang et al. [1996, Figure 4] at 17.5 km near 8 hPa, Mergenthaler et al. [1999, Figure 3] centered at 100 hPa, and Massie et al. [2010, Figure 1] at 121 hPa). The cloud frequency near 100 hPa varies from month to month. Massie et al. [2009, Figure 9] indicates that 20° S–20°N averages of CALIOP and HIRDLS cirrus occurrence frequencies are larger in winter than in summer. Wang and Dessler [2012, Figure 3] presents latitude-longitude graphs of the seasonal variation of cirrus at

Figure 4. HIRDLS and CALIOP cloud frequency of occurrence centered at 100 hPa and for the 16.2–17.2 km altitude range, respectively, in April 2007. The vertical resolutions are 1 km.
380 K (~16 km altitude). Cirrus frequency of occurrence is again more prevalent in winter than in other seasons. El Niño conditions in 1997 shifted eastward the longitudinal distributions of surface temperature, convection, and upper tropospheric cirrus [Massie et al., 2000]. The longitudinal centroid of the cirrus centered at 100 hPa shifts eastward by ~30° during 1997, from a normal position centered over the maritime continent to a position near the dateline.

Observations of cirrus frequency after the major volcanic eruptions of El Chichon (in April 1982) and Mount Pinatubo (in June 1991) showed decreases in the tropics [Wang et al., 1996; Mergenthaler et al., 1999; Massie et al., 2003] in SAGE II, CLAES, and HALOE data. SPARC Report No. 4 [2006, Figure 4.4] indicates substantial data gaps for the SAGE experiments during 1982–1984 (after El Chichon) and 1992–1993 (after Mount Pinatubo). We therefore exclude SAGE II and HALOE data for several years after the El Chichon and Mount Pinatubo eruptions. CLAES data for 1991–1992 are also excluded. Since there are a large number of CLAES observations to work with, we purposely include CLAES data for the last year of its operations to illustrate how natural variability (i.e., the effects of the Mount Pinatubo volcanic eruption) impacts calculations of the widening of the tropics.

Multiyear averages (see Table 1) are calculated by averaging on the order of 5 years for periods that exclude several years after the Mount Pinatubo and El Chichon eruptions, since they impact the sampling characteristics of the experiments. We include the El Niño year of 1997 since the El Niño event shifted the geospatial pattern of cirrus but did not reduce the number of observations in 1997.

4. Results

Figure 3 presents cirrus frequency-of-occurrence maps centered at 100 hPa based upon SAGE II 1.02 μm, HALOE 3.46 μm, and HIRDLS 12 μm extinction data and CALIOP cloud layer data. Similar to previous studies, the largest concentration of cirrus is over the maritime continent, with smaller concentrations over South America and Africa. There are regions with low frequency of occurrence on the equator over the mid-Atlantic and at longitudes near 60°E and 140°W. As presented in Massie et al. [2010, Figure 6], these regions have low values of AURA Microwave Limb Sounder relative humidity. The FWHM width of the tropics, based upon the normalized zonal averages of the frequency of occurrence of the observed cirrus, is not calculated from a geospatial distribution which has equal weighting at each longitude since the frequency of occurrence near 120°W longitude is low near the equator and high near 120°E longitude for the 20°S to 20°N latitude range. The same numerical procedure (i.e., the calculation of the FWHM of the normalized curve) is used consistently, however, for each experiment.

Figure 5. Normalized cloud frequency-of-occurrence curves centered at 100 hPa at vertical resolutions near 1 and 3 km for all longitudes for the five experiments. The dates indicate the average year of the multiyear averages. A zonal curve is normalized to unity by finding the maximum value of the frequency-of-occurrence curve, followed by division by the maximum value.

Figure 6. Average cloud frequency of occurrence centered at 100 hPa of the CLAES experiment between May 1992 and May 1933. Note the asymmetry in occurrence frequency between the northern and southern latitudes over the maritime continent. Mount Pinatubo erupted at 15°N, 120°E in the Philippines on 15 June 1991.
and changes in the FWHM values are then used to calculate a linear trend in the width of the tropics.

Figure 4 displays monthly averages of cirrus frequency of occurrence centered at 100 hPa and for the 16.2–17.2 km altitude range as observed in April 2007 by HIRDLS and CALIOP, respectively. The figure emphasizes that the two experiments give very similar geospatial distributions for the same month and that monthly averages are well defined by the two experiments. The figure, as well as examination of monthly maps from various years, indicates that there are geospatial details in each month’s cirrus distribution due to short-term variations in the cloud fields. Determinations of changes in TTL width, due to trends in cirrus geospatial distributions, are subject to cirrus geospatial monthly variability.

Curves of normalized zonal averages of the frequency of occurrence of cirrus for the five experiments at vertical resolutions near 1 and 3 km are presented in the bottom and top panels of Figure 5, respectively. The peaks of the curves of frequency of occurrence (before normalization) varied from 19% to 30%. Several years’ data from each of the experiments are averaged in order to produce maps (see Figure 3) and the normalized curves in Figure 5 that are well defined.

It is likely that there is an inherent relative offset in the FWHMs of the limb view experiments and the CALIOP experiment due to the differences in the limb viewing technique and the lidar backscatter technique. We note, however, that the frequency of occurrence curves of the V7 HIRDLS and CALIPSO experiments, before normalization, both have peak frequencies near 21%, differing by less than 1% (the difference is 4% if the V6 HIRDLS data is used in the comparison). The 1% difference is small and indicates that the two experiments measure cloud frequencies that are mutually consistent.

It is apparent in the bottom panel of Figure 5 that the CLAES curve is anomalous, differing from the other curves. This is due to the fact that the CLAES longitude-latitude map of frequency of occurrence displayed in Figure 6 has maximum frequencies southward of the equator. This asymmetry is not apparent in the multiyear averages of the CALIOP and HIRDLS data presented in Figure 3. As remarked above, the CLAES curve is consistent with other experiments displaying lesser cloud frequency of occurrence after the Mount Pinatubo eruption (at 15°N, 120°E in the Philippines on 15 June 1991). We hypothesize that the CLAES curve in 1993 would have displayed larger cirrus frequencies at the equator if Mount Pinatubo had not erupted in 1991 and that the CLAES curve in Figure 5 would then be closer to the other curves.

Figure 7 presents FWHMs calculated from the normalized curves for the SAGE, HALOE, HIRDLS, and CALIOP experiments. Error bars are derived from information inherent in the Figure 5 curves and other considerations. For example, the SAGE II 1985–1990 frequency-of-occurrence map presented in Figure 3 has a spotty appearance (due to a limited number of observations), which gives rise to variations near

Figure 7. FWHM tropical widths of the normalized cloud frequency-of-occurrence curves displayed in the top panel of Figure 5, for data with a vertical resolution near 1 km. The linear least squares fit to the data has a (2σ) trend of 0.28 ± 1.5° per decade.

Figure 8. FWHM tropical widths of the normalized cloud frequency-of-occurrence curves displayed in the bottom panel of Figure 5, for data with a vertical resolution near 3 km. The linear least squares fit to the data has a (2σ) trend of 0.25 ± 2.3° per decade.
the equator in the Figure 5 SAGE II 1987 normalized curve. We divide the SAGE II 1987 normalized curve by the average of the HIRDLS 2006 and CALIOP 2010 normalized curves (the "baseline curve") and calculate the standard deviation of the ratios for the 10°S to 10°N range of latitude, i.e., 5%. A limited range of latitude is used since differences in the two curves are potentially larger as one proceeds further away from the peak of the normalized curves near the equator. Applying random 5% perturbations to the baseline curve for an ensemble of 100 perturbed curves, we obtain the corresponding FWHMs with a standard deviation of 0.49° for the "noisy curve" contribution to the error budget. Standard deviations are calculated for the HALOE, CLAES, HIRDLS, and CALIOP experiments in a similar manner.

As a sensitivity test, we modify the SAGE extinction ratio technique by changing the ratio threshold range from 0.80–1.2 to 0.85–1.15, yielding a difference in SAGE FWHMs of 1°. For HALOE, the FWHMs differ by 0.2° when the factor of 0.98 is applied and not applied to the HALOE extinctions. The use of the HALOE 0.98 scaling factor of Figure 2 is inconsequential. For HIRDLS, the V7 FWMs are 0.8° less than the V6 FWHMs due to the differences in the extinctions of the two data versions. Finally, reanalysis is required to specify the 100 hPa altitude for the CALIOP data. As a sensitivity test, we note that CALIOP FWHMs are 0.4° larger when the 16–17 km altitude range is used to bracket 100 hPa, compared to the 16.2–17.2 km altitude range.

[37] "Other contributions" to the error budget are as follows. As a sensitivity test, we modify the SAGE extinction ratio technique by changing the ratio threshold range from 0.80–1.2 to 0.85–1.15, yielding a difference in SAGE FWHMs of 1°. For HALOE, the FWHMs differ by 0.2° when the factor of 0.98 is applied and not applied to the HALOE extinctions. The use of the HALOE 0.98 scaling factor of Figure 2 is inconsequential. For HIRDLS, the V7 FWMs are 0.8° less than the V6 FWHMs due to the differences in the extinctions of the two data versions. Finally, reanalysis is required to specify the 100 hPa altitude for the CALIOP data. As a sensitivity test, we note that CALIOP FWHMs are 0.4° larger when the 16–17 km altitude range is used to bracket 100 hPa, compared to the 16.2–17.2 km altitude range.

[38] If the temperatures in 1980 at 100 hPa are different from those in 2010 due to changes in tropopause height and cold point temperatures, then there is an evolving offset in the altitude of the 100 hPa level during the last 30 years. Gettelman et al. [2010] note that models indicate a mean trend of −0.6 hPa/decade in the TTL lapse rate tropopause. With a scale height of 5.81 km and temperature near 200 K at 100 hPa, a pressure change of −1.8 hPa over 30 years corresponds to an altitude displacement of 100 m. Wang et al. [2012] argue that models likely overestimate decadal changes since radiosonde data used by the models are subject to instrument drift and bias effects. The use of "adjusted" radiosonde data, which accounts for these effects, yields a cold point temperature change of −0.59 K/decade. This cold point trend corresponds to an altitude displacement of 50 m over 30 years. Based upon the CALIOP offset of 0.4° discussed above, for a 200 m shift in altitude, the 100 and 50 m vertical displacements correspond to small evolving offsets of 0.2° and 0.1°, respectively, in our calculations.

Figure 9. FWHM tropical widths of the normalized cloud frequency-of-occurrence curves for yearly data with a vertical resolution near 1 km. The linear least squares fit to the data has a (2σ) trend of 0.26 ± 1.5° per decade.

Figure 10. (top) Seasonal variations of HIRDLS and CALIOP FWHM tropical widths centered at 100 hPa and for the 16.2–17.2 km altitude range, respectively. The fit to the data has a trend of −0.63 ± 3.6° per decade. (bottom) The data in the top panel minus the average seasonal variation. The fit to the data has a trend of −0.43 ± 3.2° per decade.
Since Wang et al. [2012] argue that tropopause trends are uncertain, the evolving offset is also uncertain.

[39] The error bars in Figure 7 are the root square sums of the noisy curve and other contributions' error budget terms. Figure 8 displays the FWHMs of the 3 km vertical-resolution data, with error bars calculated in a similar manner to those in Figure 7. The CLAES FWHM average for May 1992 to May 1993 is included in Figure 8.

[40] The dashed lines in Figures 7 and 8 are the linear least squares fits to the data and have (2σ) slopes of 0.28 ± 1.5° and 0.25 ± 2.3° decade⁻¹ for the 1 and 3 km vertical-resolution data, respectively. As with many of the 15 km altitude tropopause zTp and ΔzTp trends [see Davis and Rosenlof, 2012, Table 3], these linear trends are not significant.

[41] Our analysis of yearly averages of the experimental data at a vertical resolution near 1 km is displayed in Figure 9. There is more spread in the FWHM values, compared to Figure 7, and the linear trend is 0.25 ± 1.6° decade⁻¹. Examination of annual SAGE and HALOE latitude-longitude graphs (in the style of Figure 3), however, reveals a patchy latitude-longitude coverage in the tropics on a year-by-year basis (not shown). Yearly data from the HIRDLS and CALIOP experiments display well-defined geospatial patterns similar to those in the bottom two panels of Figure 3, while annual SAGE and HALOE latitude-longitude maps are not as well defined due to a relatively smaller number of data points in a single year.

[42] Since the HIRDLS and CALIOP data define well-determined monthly and seasonal geospatial frequency-of-occurrence maps (see Figure 4) and normalized curves (Figure 5), Figure 10 presents seasonal time series and the linear fit to the time series. In the top panel, the seasonal data are presented, with a trend of −0.63 ± 3.6° decade⁻¹. Average seasonal variations in the FWHMs were then calculated from the CALIOP seasonal data. In the bottom panel, the average seasonal variations in the FWHMs are subtracted from the data in the top panel. The trend in the bottom panel is −0.43 ± 3.2° decade⁻¹. The bottom panel indicates that deviations from the seasonal means are substantial. Any changes in TTL latitudinal width, due to trends in cirrus geospatial distributions, are embedded in substantial seasonal variations.

5. Discussion

[43] The linear trends associated with Figures 7, 8, and 9 are similar, even though the analyses are at vertical resolutions near 1 and 3 km for the multiyear data, and Figure 9 presents annual data. We feel the most informative trend (0.28 ± 1.5° decade⁻¹) is that presented in Figure 7 for the 1 km vertical-resolution data for the following reasons. The multiyear averages of SAGE and HALOE data (see the top panels of Figure 3) yield latitude-longitude graphs that more closely approach the well-defined averages of the HIRDLS and CALIOP data in the bottom panel of Figure 3, when compared to yearly averages, and coarser vertical resolution usually yields lower information content than finer resolution.

[44] As discussed above in section 1, Davis and Rosenlof [2012, Table 3 and Figure 1] present global tropical width trends for eight metrics. Of these metrics, the zTp and ΔzTp metrics at 15 km are closest in altitude to our calculations centered at 100 hPa. The two metrics are applied to six meteorological reanalyses, each of which spans two to three decades. The National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) and Modern Era Retrospective Analysis for Research and Applications (MERRA) reanalyses yield statistically significant zTp trends of 1.4 ± 0.48° and 0.56 ± 0.33° decade⁻¹, respectively, and the NCEP CFSR reanalyses yield a significant ΔzTp trend of 0.65 ± 0.41° decade⁻¹, while nine other trends are statistically insignificant (i.e., 25% of these TTL trends are statistically significant). Our determination of a trend of 0.28 ± 1.5° decade⁻¹ of the cirrus FWHM tropical width is similar to many of the zTp and ΔzTp trends presented in Davis and Rosenlof [2012, Table 3] in that the trend is not statistically significant.

[45] With the advent of the HIRDLS and CALIOP data, it has become possible to examine frequency of occurrence of cirrus in the TTL with enhanced temporal and spatial resolution (see Figure 4), compared to the sampling characteristics of previous solar occultation data (see Figure 3). Though the HIRDLS and CALIOP data have only become available during the last 8 years, the data can be used in a determination of changes in the width of the tropics. The trend of −0.43 ± 3.2° decade⁻¹ in the bottom panel of Figure 10, in which the seasonal variations have been subtracted from the seasonal time series, is not statistically significant. Variations in cloud geospatial distributions due to cloud and transport dynamics during the 8 year time scale of the HIRDLS and CALIOP data mask any underlying trend in the width of the tropics due to the slower changes in the latitudinal distribution of temperature and relative humidity in the TTL.

[46] The availability of monthly cirrus maps, such as those presented in Figure 4, presents the opportunity for modelers to test the realism of their calculations of the monthly variations in cirrus frequency of occurrence, since many small spatial-scale features consistently are present in the independent HIRDLS and CALIOP data. Though the 8 years of CALIOP data currently do not display a statistically significant trend in TTL cirrus, modelers can validate their models for years for which the cirrus data are available. Once validated, they can then have more confidence that their long-range calculations (e.g., for 2000–2050) are realistic, as global warming and other factors alter the temperature fields in the troposphere.

[47] Acknowledgments. This research is supported by NASA grant NNX11AE54G. Helpful comments by Helen Worden and Gene Francis of NCAR and Thomas Bimer of Colorado State University are acknowledged. NCAR is sponsored by the National Science Foundation.

References


