Derivation of Tropospheric Column Ozone from the EPTOMS/GOES Co-located Data Sets Using the Cloud Slicing Technique

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Popular Summary

A recently developed technique called cloud slicing used for deriving upper tropospheric ozone from the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) instrument combined together with temperature-humidity and infrared radiometer (THIR) is no longer applicable to the Earth Probe TOMS (EPTOMS) because EPTOMS does not have an instrument to measure cloud top temperatures. For continuing monitoring of tropospheric ozone between 200-500hPa and testing the feasibility of this technique across spacecrafts, EPTOMS data are co-located in time and space with the Geostationary Operational Environmental Satellite (GOES)-8 infrared data for 2001 and early 2002, covering most of North and South America (45S-45N and 120W-30W). The maximum column amounts for the mid-latitudinal sites of the northern hemisphere are found in the March-May season. For the mid-latitudinal sites of the southern hemisphere, the highest column amounts are found in the September-November season, although overall seasonal variability is smaller than those of the northern hemisphere. The tropical sites show the weakest seasonal variability compared to higher latitudes. The derived results for selected sites are cross validated qualitatively with the seasonality of ozonesonde observations and the results from THIR analyses over the 1979-1984 time period due to the lack of available ozonesonde measurements to study sites for 2001. These comparisons show a reasonably good agreement among THIR, ozonesonde observations, and cloud slicing-derived column ozone. With very limited co-located EPTOMS/GOES data sets, the cloud slicing technique is still viable to derive the upper tropospheric column ozone. Two new variant approaches, High-Low (HL) cloud slicing and ozone profile derivation from cloud slicing are introduced to estimate column ozone amounts using the entire cloud information in the troposphere. A future satellite such as EOS Aura with the ozone monitoring instrument (OMI) can provide better statistics of derived ozone by the increased spatial resolution and concurrent measurements of cloud top pressure and above-cloud column ozone.

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Abstract. A recently developed technique called cloud slicing used for deriving upper tropospheric ozone from the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) instrument combined together with temperature-humidity and infrared radiometer (THIR) is no longer applicable to the Earth Probe TOMS (EPTOMS) because EPTOMS does not have an instrument to measure cloud top temperatures. For continuing monitoring of tropospheric ozone between 200-500hPa and testing the feasibility of this technique across spacecrafts, EPTOMS data are co-located in time and space with the Geostationary Operational Environmental Satellite (GOES)-8 infrared data for 2001 and early 2002, covering most of North and South America (45S-45N and 120W-30W). The maximum column amounts for the mid-latitudinal sites of the northern hemisphere are found in the March-May season. For the mid-latitudinal sites of the southern hemisphere, the highest column amounts are found in the September-November season, although overall seasonal variability is smaller than those of the northern hemisphere. The tropical sites show the weakest seasonal variability compared to higher latitudes. The derived results for selected sites are cross validated qualitatively with the seasonality of ozonesonde observations and the results from THIR analyses over the 1979-1984 time period due to the lack of available ozonesonde measurements to study sites for 2001. These comparisons show a reasonably good agreement among THIR, ozonesonde observations, and cloud slicing-derived column ozone. With very limited co-located EPTOMS/GOES data sets, the cloud slicing technique is still viable to derive the upper tropospheric column ozone. Two new variant approaches, High-Low (HL) cloud slicing and ozone profile derivation from cloud slicing are introduced to estimate column ozone amounts using the entire cloud information in the troposphere. A future satellite such as EOS Aura with the ozone monitoring instrument (OMI) can provide better statistics of derived ozone by the increased spatial resolution and concurrent measurements of cloud top pressure and above-cloud column ozone.

1. Introduction

Satellite remote sensing techniques have been used for studying the global distributions, sources and sinks, transport, and seasonal cycle climatology of tropospheric ozone because of the sparse distribution of ground-based ozone observations and large spatial and temporal variability of tropospheric ozone. The first study by *Fishman and Larsen* [1987] and subsequent study by *Fishman et al.* [1990] were to derive tropospheric column ozone (TCO) by subtracting stratospheric column ozone (SCO) of the Stratospheric Aerosol and Gas Experiment (SAGE) from total column ozone of the Total Ozone Mapping Spectrometer (TOMS). However, the poor sampling of SAGE data restricting daily coverage only to two (sunrise and sunset) narrow 5°-10° latitude bands seriously limits the interpretation of tropospheric column ozone maps from daily to monthly time scale. Although *Fishman et al.* [1996] and *Vukovich et al.* [1996] used vertical ozone profiles from the Solar Backscatter Ultraviolet 2 (SBUV 2) instrument for mitigating this problem, significant discrepancies to ground-based measurements were noted because of the nature of the SBUV retrieval algorithm. *Fishman and Balok* [1999] proposed an improved method by adjusting SBUV data with ozonesonde data for deriving SCO and TCO. A similar approach by *Ziemke et al.* [1998] was to use assimilated Microwave Limb Sounder (MLS) and Halogen Occultation Experiment (HALOE) SCO measurements for deriving TCO with respect to TOMS measurements of total column ozone. That method enables the determination of daily maps of high spatial coverage. However, these types of residual methods have some limitations such as a mismatch in orbital and sampling characteristics between TOMS and the other instruments and inherent sizable inter-instrument calibration errors in calculated TCO.

For overcoming these limitations, *Hudson and Thompson* [1998] proposed a modified residual method to derive TCO from TOMS measurements and ozonesonde climatology in the tropics without other satellite measurements. This technique assumes a zonally invariant stratospheric component and a tropospheric component consisting of a constant background and a zonally varying wave number 1 structure. Although the results may be suited for the Atlantic region, as *Chandra et al.* [1998] pointed out the modified residual method may not fully account for the interannual variability of tropospheric ozone, which is driven largely by El Nino and La Nina.

Ziemke et al. [1998] introduced the convective-cloud-differential (CCD) method to derive TCO using only TOMS measurements. In the CCD method, SCO from nearby column ozone amounts taken above the tops of very high tropopause-level clouds under conditions of high reflectivity ($R > 0.9$) TOMS measurements is subtracted from total column ozone from low reflectivity ($R < 0.2$) TOMS measurements to derive TCO. This technique is also based on the assumption of a zonal invariance of SCO in the tropics as determined from independent SAGE, MLS, and HALOE measurements.

Jiang and Yung [1996] and *Newchurch et al.* [2001a] used the Topographic Contrast Method (TCM) for deriving lower tropospheric ozone by subtracting total column ozone over the mountain regions from nearby sea level total column ozone of TOMS measurements. That method was used to examine long-term time series assuming invariant SCO over the geographically close two regions.

Previous methods are only useful for deriving TCO under some assumptions and in limited regions such as the tropics and mountain regions. Recently, *Ziemke et al.* [2001] introduced a new technique, called "Cloud Slicing" to derive upper tropospheric ozone amount given coincident Nimbus-7 measurements of both temperature humidity and infrared radiometer (THIR) cloud-top pressure and TOMS above-cloud column ozone over a broad region (5° x 5° bin). Because the TOMS instrument measures backscattered ultraviolet wavelength radiation, it cannot detect ozone lying below dense water vapor clouds. This opaque property of clouds can be used directly in conjunction with co-located cloud-top pressure data to derive ozone profile information in the troposphere. That pilot study showed promising results to distinguish upper and lower tropospheric column ozone from CCD-derived TCO for the 1979-1984 Nimbus-7 time frame in the tropics. Unfortunately, the current Earth Probe TOMS (EPTOMS) does not have an instrument to provide in situ cloud-top pressure information like Nimbus 7 THIR.

This study tests the feasibility of the cloud slicing method beyond the Nimbus-7 era and tropics by deriving upper tropospheric column ozone from the EPTOMS/ Geostationary Operational Environmental Satellite (GOES) co-located data sets for 2001 and early 2002. In the next section, we will explain how GOES data is archived and co-located in time and space with EPTOMS. In section 3, the derived results for selected sites will be cross validated with the statistics of ozonesonde measurements and results from THIR for 1979-1984, and two new variant approaches will be proposed to extend the capability of cloud slicing over entire tropospheric column ozone. For studying the implications of the ozone monitoring instrument (OMI) providing much greater spatial and spectral information to do cloud slicing, the effects of the improved spatial resolution on the increase of the number of co-located data will be examined by increasing the sizes of bins over a few selected locations with the Nimbus 7 THIR data. In the final section, we will summarize the results from cloud slicing and briefly discuss future works with respect to the ozone monitoring instrument (OMI).

2. Data and Methodology

The GOES-8 spacecraft launched on April 13, 1994 is operational as GOES-EAST at 75W, and is still providing clear imagery for monitoring weather conditions such as tornadoes, flash floods, hail storms, and hurricanes. It circles the Earth in a geosynchronous orbit, which means it orbits the equatorial plane of the Earth at a speed matching the Earth's rotation. This allows it to hover continuously over one position on the surface. The geosynchronous plane is about 35,800 km (22,300 miles) above the Earth, high enough to allow a full-disc view of the Earth (http://www.oso.noaa.gov/goes/index.htm). GOES-8 data from infrared channel 4 (11μm) were selected to be co-located with EPTOMS for the consistency of data analyses of Nimbus-7 THIR. GOES has the nearly same channel as a spectral channel of 10.5-12.5um (11.5μm mean) of THIR to provide cloud top temperatures. GOES provides high frequency of data at every 15 minute increment that enables us to collocate time and space with EPTOMS without matching orbits of other sun-synchronous satellites such as the EOS-Terra Moderate Resolution Imaging Spectroradiometer (MODIS) and Tropical Rain Measuring Mission (TRMM).

Brightness temperature from GOES infrared channel is converted to 1-byte grayscale in 256 steps with 0.5K wide, downward from 320K to 192K and stored as Tag Image File Format (TIFF) on the web site (http://rsd.gsfc.nasa.gov/). These GOES-8 TIFF files were automatically downloaded from this site with a large time window of 22 Universal Time Coordinate (UTC) through 9 UTC over 5 sectors covering most of North/South America and adjacent oceans for a year period from March of 2001 through the end of February of 2002. Each sector is centered on and named after a geographical region, such as 'Conus', 'Brazil', 'Galapagos', 'Easter', and 'Argentina'. A more detailed information of GOES data can be obtained from the web site above.

Figure 1 shows 30 co-located study sites including two ozonesonde stations, in San Cristobal and Natal. These sites were selected as evenly spaced over each limited geographic sector as possible when 5° x 5° bins are used to make the ensemble statistics of above-cloud ozone and cloud top pressure.

A precise collocation task is the most crucial step to do cloud slicing with combined EPTOMS/GOES data sets. Prior to spatial collocation, a median UTC (hour: minute: second) of EPTOMS was computed from the EPTOMS Greenwich Mean Time (in second of day at start of scan) record using a 3° x 3° bin over a center of each site and a GOES TIFF file with corresponding time stamp within 15-30 minute was found from the GOES archive directory. Figure 2 shows time collocations of 3 longitudes (105W, 90W, and 75W) at 40N for February 2002. The EPTOMS coverage for one cross track corresponds to about 20 degree longitude at the equator with 4 degree missing orbit, and thus it takes about 15 orbits per day to cover the entire globe. The nadir track shifts about 10 degree eastward each day. Therefore, the orbits at 40N are slightly overlapped. These orbital characteristics of EPTOMS are well represented in Figure 2 by aligning the UTC times of EPTOMS and GOES-8 to one-to-one line with about 1 hour interval that is approximately equal to 15 degree longitude. The numbers in parentheses indicate available co-located data sets (days per month) for each site. Less than 28 co-located data sets implies either missing orbits of EPTOMS or missing GOES files to be co-located. This time–matched GOES file was used for detecting much smaller high resolutions of GOES pixels (4 km x 4 km) analytically at the given EPTOMS instantaneous field of view (IFOV) coordinates. The footprint size of EPTOMS IFOV is dependent on scan angles from 38 km (at nadir) to 200 km (at off-nadir), about 100 km on average. Figure 3 compares small and large EPTOMS footprints with co-located GOES data points within 5 degree by 5 degree bin frames. The number of co-located GOES data within each EPTOMS IFOV is a range of approximately 60~230 which is proportional to the sizes of nadir and off-nadir EPTOMS IFOV. These results indicate a precise collocation of time and space and adequate estimate of cloud top pressure with enough GOES data for each EPTOMS IFOV.

The daily 5° longitude x 2° latitude gridded National Centers for Environmental Prediction (NCEP) meteorological analyses of brightness temperatures to 18 pressure levels (1000-0.4hPa) were used for deriving the cloud top pressures of GOES. The tropopause pressure heights were determined by finding a pressure level coincident with the minimum temperature from a temperature profile for each NCEP grid. The mean and standard deviation of GOES brightness temperatures within EPTOMS IFOV coordinates were computed, and that mean value was converted into a cloud top pressure from a corresponding NCEP temperature profile.

The procedure of cloud slicing is to make a linear fit between co-located measurements of GOES cloud top pressure over a pre-selected pressure band (200-500 hPa in this study) and footprints measurements of above-cloud column ozone from EPTOMS. The mean slope of this linear equation then yields directly mean volume mixing ratio for ozone within that pressure band. Specifically, mean volume mixing ratio ($\overline{X}$, in ppmv) is determined from $\overline{X} = 1.27\Delta\Omega/\Delta P$, where Ω is above column ozone (in DU) and P is cloud-top pressure (in hPa). In principle, cloud slicing in this study is the same as the original cloud slicing technique described in *Ziemke et al.* [2001] except for relaxing some thresholds to increase available number of ensemble co-measurements over 5 degree x 5 degree binned regions per day because of the limited co-located data sets for one year period. EPTOMS footprints scenes with reflectivity greater than 0.4 are used as 100% cloud-filled (i.e., 100% cloud fraction scenes) scenes as *Eck et al.* [1987] showed for Nimbus 7 TOMS, instead of 0.6 value of reflectivity by *Ziemke et al.* [2001]. The daily minimum number of co-measurements within a 5 degree x 5 degree bin is also decreased to 3 from 20. Another threshold applied to daily computed upper tropospheric column ozone (UTO) is to filter out extreme values (greater than 190 ppbv or less than 13 ppbv, which is nearly same as 2-sigma filtering rule of *Ziemke et al.* [2001]), which could be generated by strong dynamics associated with wind jet and mesoscale convective complex (MCC) regions that causes an inverse relationship between above-cloud ozone and cloud top pressure near tropopause, particularly in the mid latitudes of the northern hemisphere [*Poulida et al.* 1996]. Over clean tropical oceans, this convection effect will distribute low ozone air throughout the troposphere regardless of cloud height. These regions may not support the assumption of well-mixed ozone and hydrostatic atmosphere in the troposphere. Finally, a monthly mean was computed using at least 3 days per month under these requirements.

Ozonesonde climatology from World Ozone and Ultraviolet Radiation Data Center (WOUDC, http://www.msc-smc.ec.gc.ca/woudc/) and cloud slicing-derived UTO from the Nimbus 7 THIR study is compared with the results from this study for validation purposes.

3. Results and Discussions.

In order to demonstrate a typical linear relationship between cloud top pressure and above-cloud column ozone, scatter plots for six selected sites in Figure 4 are constructed with available co-measurements for a month period of March 2001. The first numbers in parenthesis indicate 2-sigma uncertainties, and second numbers are the number of available days per month for each frame in Figure 4. The magnitudes of scattering of data implies not only potential conversion errors from cloud top temperature to pressure and ozone retrieval algorithm of EPTOMS, but also true photochemical changes or perturbations of column ozone, as noted by *Ziemke et al.* [2001], because the data points for each frame in Figure 4 are accumulated over an entire month. The mean volume mixing ratios on a daily basis for these sites are similar to those on a monthly basis because of relatively less dynamic meteorological conditions compared to sites in the mid latitudes beyond +/- 20 degree latitudes. However, it is not available for most all of mid latitudinal sites to derive a meaningful mean volume mixing ratio by fitting monthly co-measurements. Therefore, daily mean volume mixing ratios are used for all sites to make monthly means for further seasonal cycle comparisons hereafter.

3.1. Upper Tropospheric Ozone from Cloud Slicing.

In order to augment the validation of the results from cloud slicing in this study, we refer to the results in Figure 4 (not shown here) from *Ziemke et al.* [2002] where WOUDC ozonesondes climatology were compared with the results from cloud slicing for the Nimbus 7 time frame of 1979-1984. The locations of several ozonesonde stations were from mid/high latitudes in the northern hemisphere (i.e., U.S., Europe, Japan) except for Natal (6S, 35W) and Aspendale-Laverton (38S, 145E) sites. The seasonal cycles and mean amounts in UTO from Cloud Slicing compared well with ozonesondes with largest UTO in spring months in both hemispheres.

Figure 5 summarizes the results of derived UTO from cloud slicing as a function of month for four representative sites plotted with associated uncertainty bars of 1 standard deviations that show relatively large errors due to the minimum samples of 3 used for computing the mean ozone volume mixing ratio per day. Each frame in Figure 5 is arranged from the northern hemisphere (40N, 90W) to the southern hemisphere (35S, 60W), and monthly averages for January and February 2002 are also plotted together with those of 2001 for a better understanding of seasonal cycles and latitudinal variability of UTO for the one year period. The results from Nimbus 7 THIR are superimposed on corresponding locations for making comparisons of seasonal variability with the ones from EPTOMS/GOES co-located data sets.

The largest ozone variability of the midlatitudinal sites of the northern hemisphere is found around winter-spring months, peaking in March-May season while smallest ozone amounts occur in the fall season (September-November). For the southern hemisphere, these seasonal cycles are reversed with less variability than those of the northern hemisphere. The tropical sites within +/- 10 degree latitudes show a weak seasonal cycle variability and smallest UTO compared to higher latitudinal sites. Some of the sites do not have sufficient clouds to derive UTO mainly due to dry seasons in the tropics or low marine stratocumulus clouds, usually below 700 hPa for all 25S sites over oceans. These seasonal characteristics and morphology are well coincident with the climatological results from Nimbus 7 THIR, though being discrepancy among them. Figure 6 shows available number of days used for computing monthly mean UTO from cloud slicing for corresponding sites in Figure 5. Most of the large uncertainty bars and inconsistent variability in UTO are associated with small samples (less than 4 days per month).

3.2. Mean Tropospheric Column Ozone from High-Low (HL) Cloud Slicing.

It might not be enough to filter out partial cloud effects of EPTOMS data only with the threshold above 0.4 of EPTOMS reflectivity because of its coarse resolution, which may result in a biased estimation (over- or underestimation) of above-cloud column ozone. Standard deviations computed from the GOES temperature to cloud top pressure conversion process within each EPTOMS IFOV are used as a threshold to filter out broken clouds in terms of spatial statistics. Figure 7 shows scatter plots of standard deviations of GOES brightness temperature versus cloud top pressures for 6 sites using 5 months composite data from March through July 2001. Low standard deviation values indicate relatively very homogeneous EPTOMS IFOV representing optically thick dense clouds. These results show that optically thick dense clouds are usually found from low pressure around 150-250 hPa and high pressure around 700-800hPa rather than intermediate pressure levels 400-600 hPa where most of multi-layer broken clouds exist. The variant approach, called Hi-Low (HL) cloud slicing might be proposed based upon these findings to extend derived TCO below 500 hPa by using available low cloud heights information. Figure 8 shows the results of derived TCO in the pressure band of 200 (center of high clouds, 150-250 hPa) through 750 hPa (center of low clouds, 700-800 hPa) from HL cloud slicing for the corresponding 6 sites using the monthly data for April 2001. Before fitting the clusters around 200 hPa and 750 hPa, the data above standard deviation of 5 K were removed to use only spatially homogeneous data assuming optically thick clouds. Latitudinal gradients of derived TCO amounts (in ppbv) from HL cloud slicing are well represented in Figure 8 from high to low latitudes except for a site at 30N and 105W. HL cloud slicing might be a promising approach to derive TCO for the pressure band between 200-750 hPa, particularly in mid/high latitudes having both enough high and low clouds available.

3.3. Ozone Profiles Derived from Cloud Slicing.

Ozone profile information can be constructed from cloud slicing if the concurrent measurements of clear sky total column ozone are available. Natal site (6S, 35W) is selected to show a potential use of cloud slicing for deriving ozone profile information. This site has sufficient clouds representing a good linear relationship of cloud top pressure and above-cloud ozone for cloud heights from 200 hPa through 800 hPa for April and June 2001. Figure 9 shows the comparisons of ozone profiles from cloud slicing and WOUDC climatology for April and June. Cloud top pressures are converted to logarithm-scale standard altitude (in km, using a scale height of 7 km). Therefore, cloud top pressure of 200 hPa is nearly equal to 11 km, and 800 hPa about 1.6 km. Virtual clear-sky total column ozone amounts are computed from a linear fit equation at 900 hPa assuming zero below-cloud ozone amount below this pressure. Accumulated column ozone is computed by subtracting above-cloud ozone at a given pressure level from the virtual clear-sky total column ozone.

In general, the TOMS retrieved ozone amounts above clouds tend to be overestimated due to the increased multiple scattering inside clouds and between multi-layer clouds, particularly in the lower troposphere by increasing photon absorption path lengths [*Hudson et al.* 1995; *Kurosu et al.,* 1997; *Mayer et al.,* 1998; *Newchurch et al.,* 2001b; *Thompson et al.* 1993]. Therefore, the back-scattered radiation from cloudy scenes is a complicated process of the reduced probability of photons reaching TOMS detectors due to strong Rayleigh scattering at UV wavelengths (i.e., a poor retrieval efficiency) and enhanced absorption path length, particularly when high ozone amounts exist inside clouds. Unfortunately, the current opaque Lambertian reflecting model of EPTOMS algorithm does not fully explain the enhanced ozone above clouds. Therefore, the more error in the estimated ozone amounts above the mid/lower clouds may cause the steeper slope of linear equation that could result in a larger error in the derived ozone profile in the lower troposphere below 5 km, as compared to those from WOUDC climatology. Summer (June) season is consistently higher, about ~15 DU in the upper troposphere than spring season (April) in both results from cloud slicing and WOUDC climatology. The derived ozone profiles from cloud slicing are comparable with the results within the uncertainty ranges of WOUDC climatology.

3.4 Implications for future EOS Aura

The OMI on the EOS-Aura scheduled for the launch of 2004 will provide much greater spectral and spatial resolution (around 13 km x 24 km) compared to six wavelengths and relatively coarse resolution of EPTOMS. Cloud top pressure can be measured directly using the molecular oxygen dimmer (O2-O2) method [*Acarreta and de Haan*, 2001] and the rotational Raman scattering "Ring Effect" [*Joiner and Bhartia*, 1995] without converting cloud top temperature to cloud top pressure from NCEP meteorological analyses. Under the assumption of fractal geometry of clouds (i.e., similar clouds are randomly scattered and found without respect to the size of IFOV at least in a limited range of scales), the effects of increased spatial resolution of OMI on the number of co-measurements can be simply simulated by increasing bin sizes over six selected locations with the Nimbus 7 THIR data for August 1980 in Figure 10. The OMI spatial resolution is at least 5 times better than the EPTOMS at nadir position (i.e., about 5 = (38 km x 38 km)/(13 km x 24 km)). The number of co-measurements is exponentially increased from (2 degree x 2 degree) through (10 degree x 10 degree) bins for most all of locations. As a result, the remarkably increased samples of co-measurements and a slightly reduced bin size to avoid wind-driven perturbation within the current 5 degree x 5 degree bins will provide a much improved statistics of derived UTO from cloud slicing.

4. Summary

The collocation of EPTOMS and GOES-8 in space and time presented in this study is the first approach for studying UTO in the pressure band of 200-500hPa from cloud slicing beyond the tropics from independent satellite platforms. By doing a precise collocation, we can conclude the same results as those of the Nimbus 7 THIR analyses from cloud slicing in a consistent fashion. The cloud slicing technique, even with the minimum threshold strategy (3 co-measurements, [13 ppbv $\leq$UTO $\leq$190 ppbv] per day, 3 measurements per month) is still effective to derive UTO from the EPTOMS/GOES co-located data sets. This study enables us to extend the cloud slicing technique not only to extra-tropical regions, but also to the EPTOMS spacecraft despite the paucity of co-measurements in terms of ensemble statistics. Furthermore, HL cloud slicing and ozone profiling introduced in this study are innovative applications of cloud slicing with entire cloud information in the troposphere used for inferring ozone amounts. We speculate that the major error sources in these approaches are both multiple scattering effects which cause unusually high ozone amounts over clouds and heavy convective storms which perturb ozone amounts in the upper troposphere. The hyperspectral capacity of OMI and new cloud top pressure algorithms such as the molecular oxygen dimmer (O2-O2) method will reduce these errors by providing better estimates of cloud top pressure and above-cloud ozone. The improved spatial resolution of OMI will be benefit to obtain more robust monthly basis statistics of derived UTO from cloud slicing by increasing the number of co-measurements within a bin at a given site.

The proposed new techniques, including HL cloud slicing and ozone profile derivation, will also take advantage of the improved estimation of cloud top pressure and above-cloud ozone from OMI. Nevertheless, a further study to refine and optimize thresholds of cloud slicing approaches still remains for a better understanding of the relationship of cloud top pressure and above-cloud ozone amounts with respect to temporal and spatial variability of tropospheric column ozone.

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Figure Captions

Figure 1. EPTOMS/GOES-8 co-located sites of 30 over 5 GOES sectors, including 'Conus', 'Galapagos', 'Brazil', Easter', and 'Argentina'. Two ozonesonde stations are represented as square marks on the San Cristobal (SAN) and Natal (NAT) sites, respectively. Others are represented as circles located over each sector as evenly as possible with approximately 15 degree longitudinal interval.

Figure 2. Time collocation of EPTOMS and GOES-8 for February 2002 at 3 locations, (40N,105W), (40N,90W), (40N, 75W). Numbers in parentheses for each location denote available co-located data sets (days) per month.

Figure 3. Comparisons of spatial collocation of EPTOMS and GOES-8 for small and large EPTOMS IFOV coordinates cases within 5 degree x 5 degree bins centered at (40N, 72W) and (40N,80W), respectively for February 28, 2002. Red polygons are EPTOMS IFOVs, and black dots denote relatively fine GOES pixels falling into each EPTOMS IFOV. Land coastal lines are shown as a green color.

Figure 4. Scatter plots of cloud top pressures versus above-cloud column ozone for 6 study sites from a monthly data of March, 2001. Each frame shows the mean volume mixing ratio (VMR, in ppbv) with 2-sigma uncertainty and available days per month in parenthesis.

Figure 5. Derived UTO in the pressure band of 200~500 hPa from cloud slicing using the minimum threshold strategy (3 co-measurements, [13 ppbv $\leq$ UTO $\leq$ 190 ppbv] per day, 3 measurements per month) with +/- 1 standard deviation bar. Available N-7 THIR climatology for 1979-1984 time period is added to the corresponding site for visual comparisons.

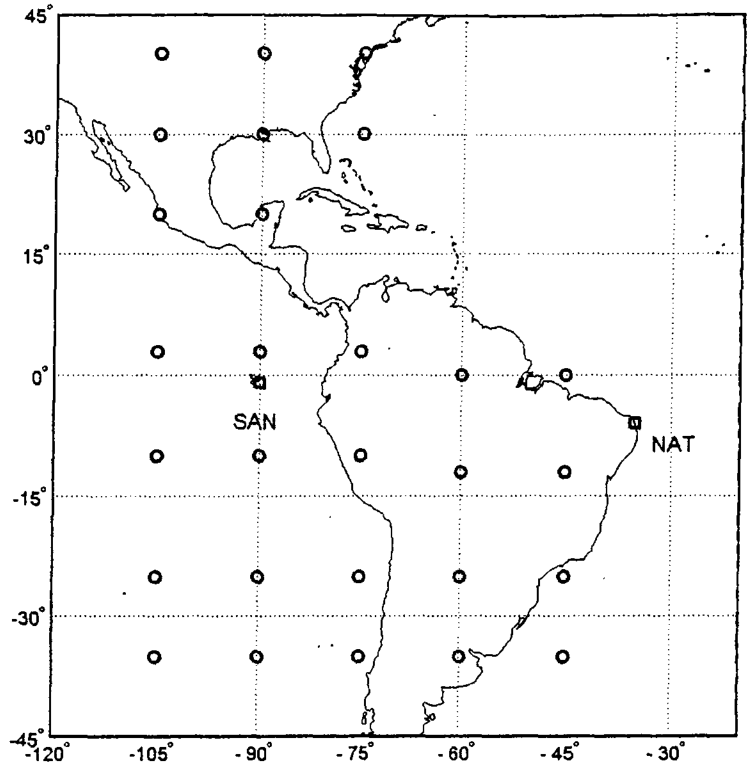
Figure 6. Number of computed UTO per month for making a monthly mean using the minimum threshold strategy (3 co-measurements, [13 ppbv $\leq$ UTO $\leq$ 190 ppbv] per day, 3 days per month).

Figure 7. Scatter plots of standard deviations of GOES brightness temperatures within each EPTOMS IFOV as a function of cloud top pressure from the co-measurement data of 5 months for March through July, 2001.

Figure 8. Hi-Low cloud slicing by fitting the data clusters around 200 hPa and 750 hPa for six selected sites using the monthly data of April, 2001.

Figure 9. Comparisons of ozone profiles from cloud slicing for 2001 and the 1960-1999 time period climatology of WOUDC for April and June with +/- 1 standard deviations (dotted line) at Natal site (6S, 35W).

Figure 10. Number of cumulative co-measurements for a month period of August ,1980 by changing the size of bin from (2 degree x 2 degree) through (10 degree x 10 degree) with Nimbus 7 THIR at the selected 6 sites for studying the effects of the improved spatial resolution on the increase of sample size.



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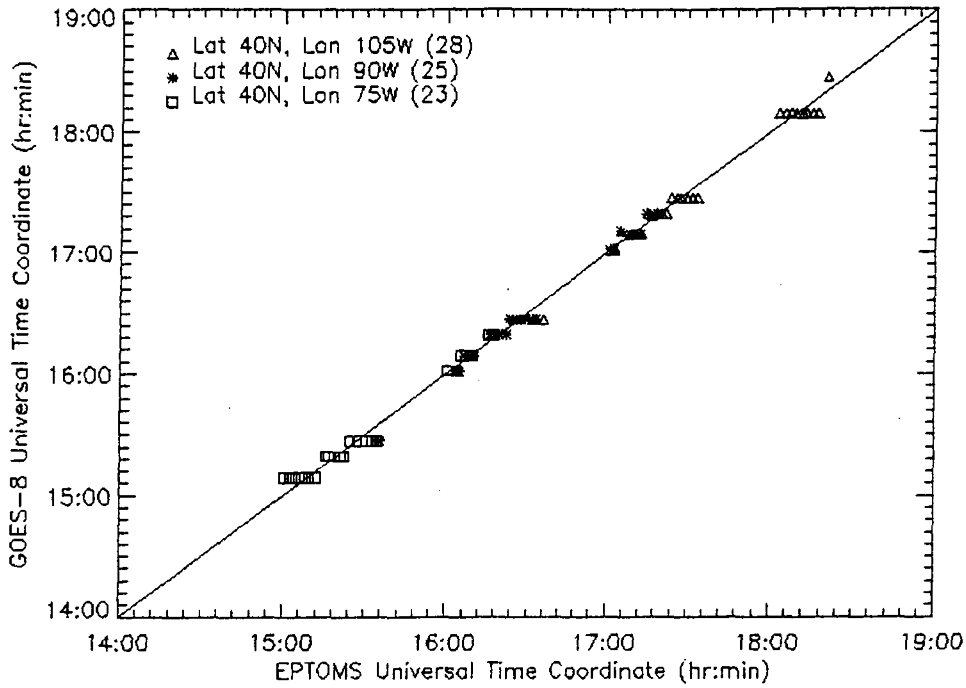

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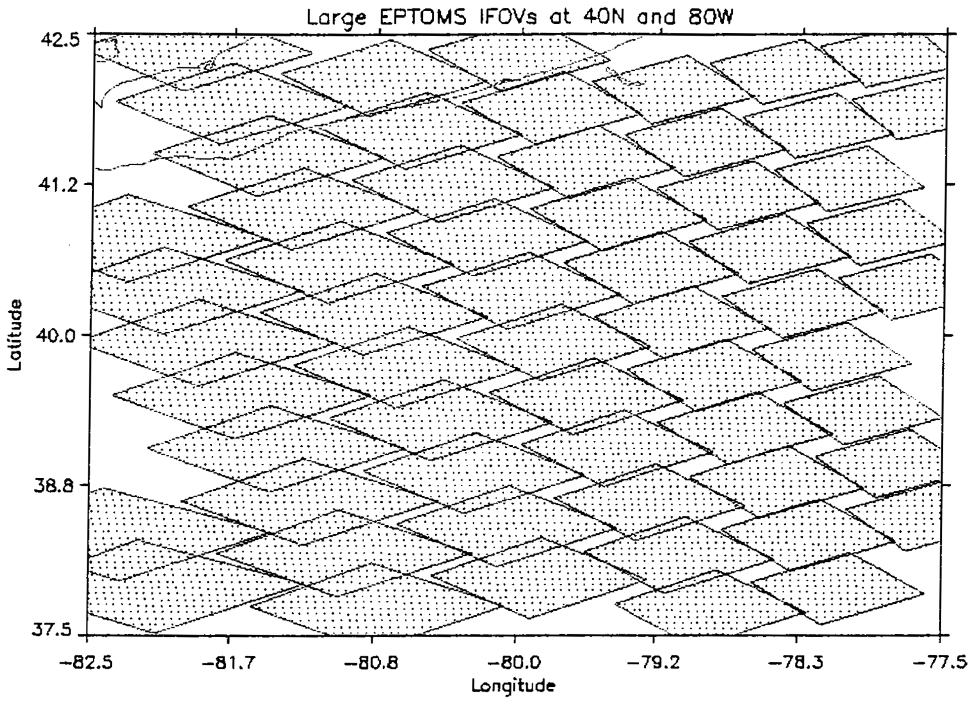

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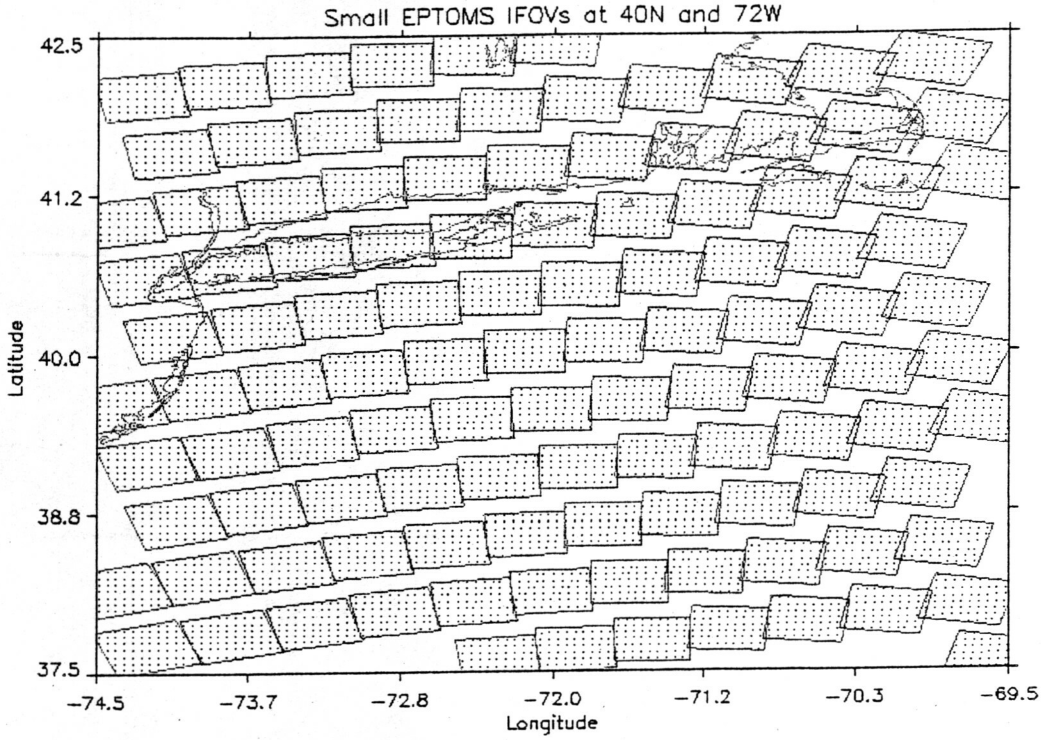
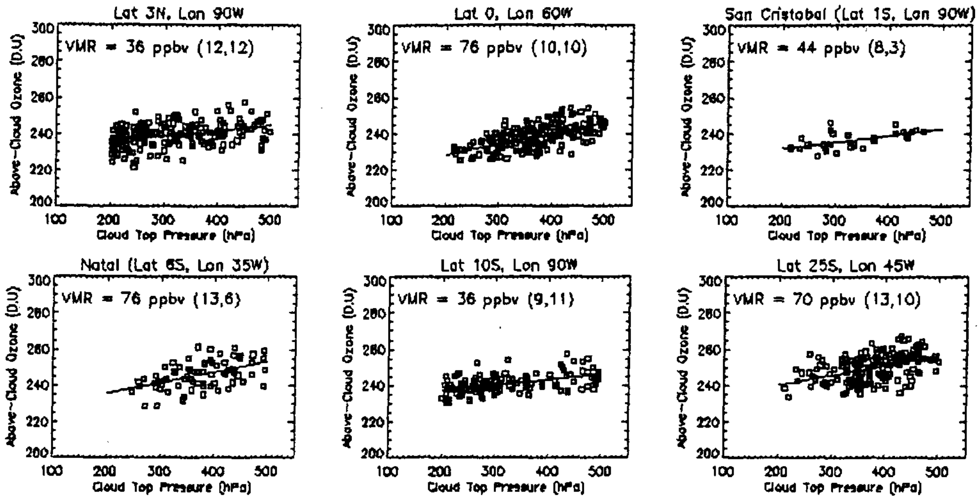

Small EPTOMS IFOVs at 40N and 72W
42.5
41.2
40.0
38.8
37.5
Latitude
-74.5
-73.7
-72.8
-72.0
-71.2
-70.3
-69.5
Longitude

Figure 3b.



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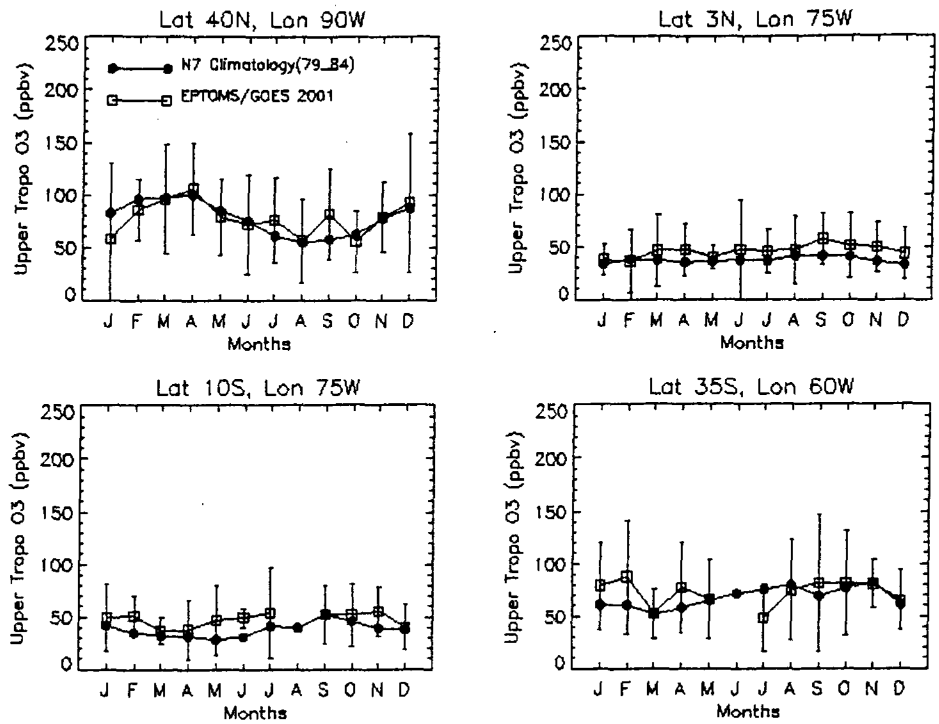

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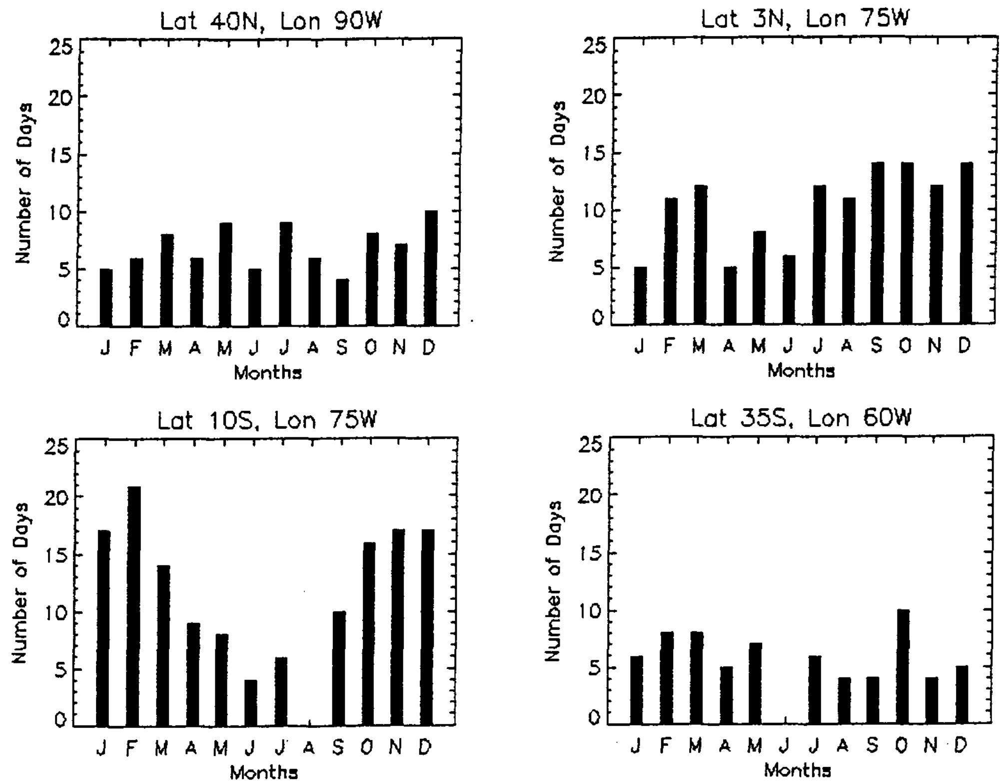

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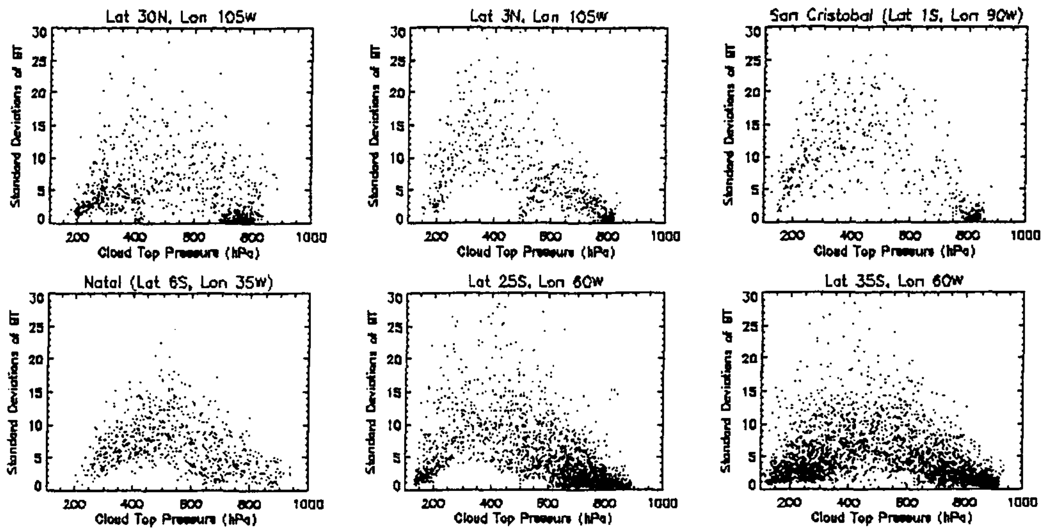

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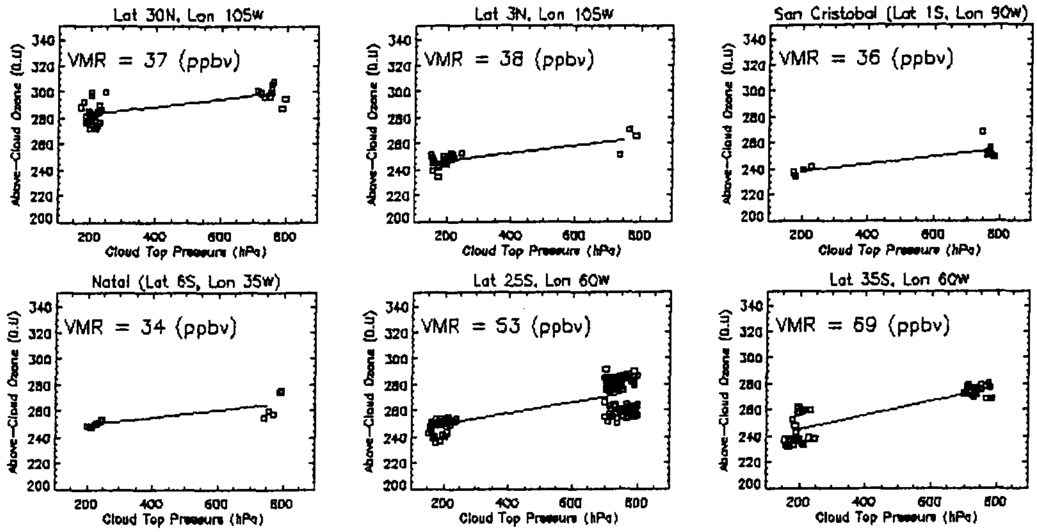

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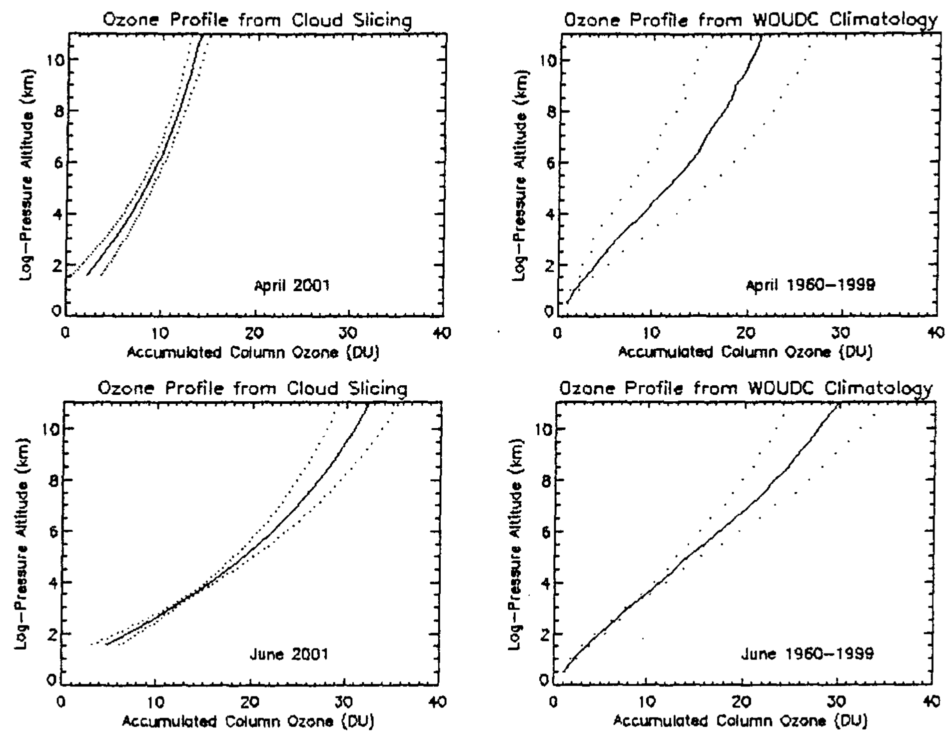

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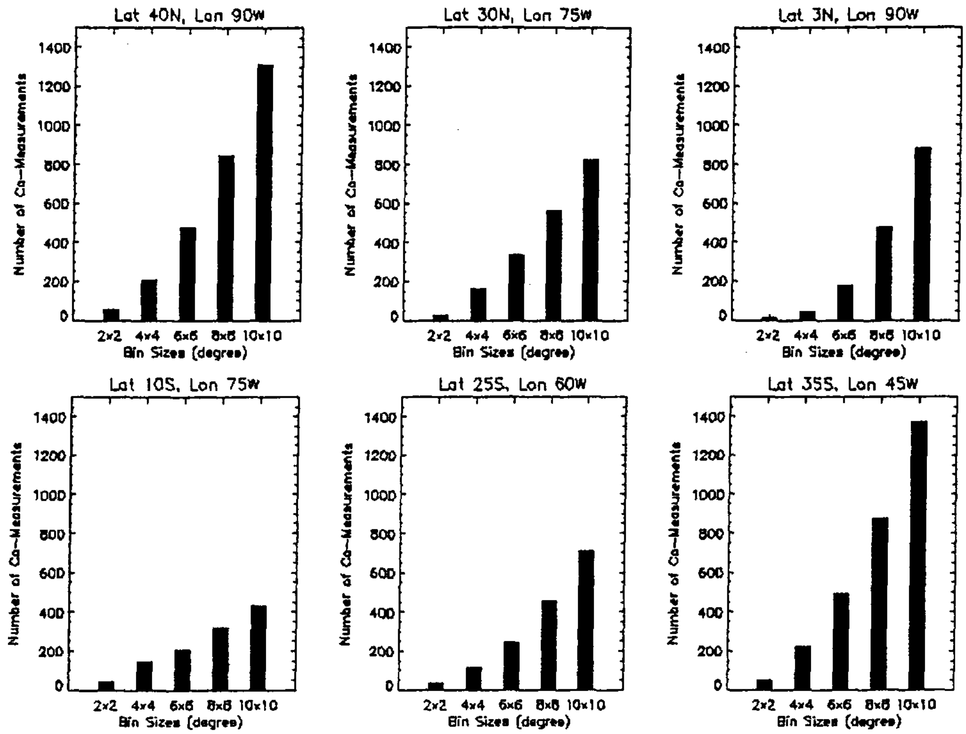

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Gerald Ziemke, Oct. 22, 2002

Signature Date

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1/8/1999