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Lower stratospheric temperature differences between meteorological analyses in two cold Arctic winters and their impact on polar processing studies

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Abstract. A quantitative comparison of six meteorological analyses is presented for the cold 1999-2000 and 1995-1996 Arctic winters. Using different analyzed data sets to obtain temperatures and temperature histories can have significant consequences. The area with temperatures below a polar stratospheric cloud (PSC) formation threshold commonly varies by $\sim$25% between the analyses, with some differences over 50%. Biases between analyses vary from year to year; in January 2000, Met Office analyses were coldest and National Centers for Environmental Prediction (NCEP) analyses warmest, while NCEP analyses were usually coldest in 1995-1996 and NCEP/National Center for Atmospheric Research Reanalysis (REAN) usually warmest. Freie Universität Berlin analyses are often colder than others at T$\lesssim$205 K. European Centre for Medium-Range Weather Forecasts (ECMWF) temperatures agreed better with other analyses in 1999-2000, after improvements in the assimilation system, than in 1995-1996. Temperature history case studies show substantial differences using Met Office, NCEP, REAN, ECMWF, and NASA Data Assimilation Office (DAO) analyses. In January 2000 (when a large cold region was centered in the polar vortex), all analyses gave qualitatively similar results. However, in February 2000 (a much warmer period) and in January and February 1996 (comparably cold to January 2000 but with the cold region near the polar vortex edge), distributions of "potential PSC lifetimes" and total time spent below a PSC formation threshold varied significantly between the analyses. Largest peaks in "PSC lifetime" distributions in January 2000 were at 4-6 and 11-14 days while in 1996, they were at 1-3 days. Different meteorological conditions in comparably cold winters have a large impact on expectations for PSC formation and on the effects of discrepancies between different meteorological analyses. Met Office, NCEP, REAN, ECMWF, and DAO analyses are commonly used in modeling polar processes; the choice of analysis can strongly influence the results of such studies.

1. Introduction

The joint SAGE III Ozone Loss and Validation Experiment and Third European Stratospheric Experiment on Ozone 2000 (SOLVE/THESEO 2000) were conducted dur-

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ing the 1999-2000 Arctic winter to investigate processes involved in Arctic ozone loss. The 1999-2000 winter was one of the coldest on record, comparable in recent years only to 1995-1996 [e.g., *Manney and Sabutis*, 2000; *Davies et al.*, 2001]. There is evidence for substantial ozone loss in both winters [e.g., *Manney et al.*, 1996a; *Santee et al.*, 2000], and for widespread denitrification in 1999-2000 [e.g., *Santee et al.*, 2000]. Numerous studies of polar processes, including polar stratospheric cloud (PSC) formation, denitrification and ozone loss, have been and are being conducted for the 1995-1996 and, especially, the 1999-2000 Arctic winters [e.g., *Newman et al.*, 2001]. PSC formation, composition, and the potential for denitrification all depend critically on temperature; chlorine activation and subsequent ozone loss are in turn strongly dependent on those processes [e.g., *World Meteorological Organization*, 1999, and references therein].

While many instruments made local temperature measurements during SOLVE/THESEO 2000, polar processing studies frequently require large-scale meteorological analyses. The most commonly used products for polar process studies have been those from the US National Centers for Environmental Prediction/Climate Prediction Center (NCEP), the U.K. Met Office, the NCEP/National Center for Atmospheric Research (NCAR) Reanalysis Project (REAN), the NASA Data Assimilation Office (DAO), and the European Centre for Medium-Range Weather Forecasts (ECMWF); also, temperatures and geopotential heights on a few levels in the lower stratosphere are produced daily by the Freie Universität Berlin (FUB). Winds from the Met Office, REAN, DAO, and ECMWF data, and winds calculated from the NCEP data, are commonly used to drive transport models and trajectory calculations for polar process studies.

Several studies have compared subsets of the analyses listed above or compared one or more of them with other local temperature data sets. *Manney et al.* [1996b] found that NCEP temperatures were consistently closer to radiosonde temperatures and lower than those from the Met Office during the 1991-1992 and 1994-1995 Arctic winters. *Knudsen* [1996], *Knudsen et al.* [1996], and *Pullen and Jones* [1997] found similar warm biases in ECMWF and Met Office temperatures with respect to sondes and other balloon observations in several Arctic winters. *Pawson et al.* [1999] compared temperatures from the FUB data with those derived from geopotential heights from the TIROS Operational Vertical Sounding (TOVS) system, and showed that the FUB temperatures were generally lower, but with large dispersion around the mean difference. *Manney and Sabutis* [2000] showed that Met Office minimum temperatures were lower than those from NCEP in January 2000. *Davies et al.* [2001] found that in cold regions Met Office temperatures were lower than ECMWF temperatures in January 2000 but higher in February 2000. They also showed that chemical transport model (CTM) runs driven with ECMWF and Met Office fields produced significantly different patterns of denitrification, chlorine activation, and ozone loss.

During SOLVE/THESEO 2000, some analysed temperatures have been compared with in situ, balloon, and sonde measurements. B. M. Knudsen et al. ("Accuracy of analyzed stratospheric temperatures in the winter Arctic vortex from infrared Montgolfier long duration balloon flights. Part II: Results", submitted to *Journal of Geophysical Research - Atmospheres*, hereinafter Knudsen et al., submitted manuscript) compared temperatures from ECMWF, Met Office, NCEP, REAN and DAO analyses with those from long-duration balloon flights during SOLVE/THESEO 2000; they found that the NCEP, REAN, and Met Office data had larger scatter around the balloon values than the ECMWF data, and that Met Office, REAN, and NCEP data had a cold bias with respect to balloon measurements at high temperatures, and a warm bias at low temperatures. *Bevilacqua et al.* [2001] compared Met Office data with high-latitude radiosondes from November 1999 through January 2001 and found larger individual differences later in the season, but no clear systematic or time-varying bias. *Davies et al.* [2001] noted that Met Office January temperatures were lower than those from radiosondes at some stations in the high Arctic. S. Pawson et al. ("Stratospheric analysis and forecasting in the Northern winter of 1999/2000: The NASA DAO's GEOS-3 system", submitted to *Journal of Geophysical Research - Atmospheres*, hereinafter Pawson et al., submitted manuscript) compared DAO analyses with radiosondes and with data from the Meteorological Measurement System (MMS) on NASA's ER-2 aircraft. They found the DAO analyses to be generally slightly colder than radiosondes in the lower stratosphere (but with geographical variations in the sign of the bias), and to have a small ($\lesssim$1 K) warm bias with respect to MMS temperatures. S. Buss et al. ("Arctic stratospheric temperature in the winters 1999/2000 and 2000/2001: A quantitative assessment and microphysical implications", submitted to *Journal of Geophysical Research - Atmospheres*) compared ECMWF and Met Office temperatures with radiosondes and MMS observations, and found that while ECMWF had overall smaller biases, Met Office analyses captured the lowest temperatures better. J. Burris et al. ("Validation of temperature measurements from the Airborne Raman Ozone Temperature and Aerosol Lidar during SOLVE", submitted to *Journal of Geophysical Research - Atmospheres*) compared Airborne Raman Ozone Temperature and Aerosol Lidar temperatures with Met Office, DAO, and REAN analyses in December 1999 and found differences $\lesssim$1 K below 25 km. These and future studies comparing temperature analyses

with measurements will be helpful in assessing the accuracy of an analysis for specific periods and locations. However, because most polar processing studies require large-scale analyses, because many processes in such studies depend so critically on temperature (especially "threshold" phenomena such as PSC formation), and because it is inherently difficult to quantify the uncertainties in the meteorological analyses, it is also very important to assess the impact on modeling studies of the different meteorological analyses used for model input.

In the following, we compare temperatures from all of the commonly-used meteorological analyses for the cold and much-studied 1999-2000 and 1995-1996 Arctic winters. We focus on comparisons of low temperatures that are relevant to PSC formation and chemical ozone loss. We also examine temperature histories along trajectories to explore in more detail how differences between the analyses may affect polar processing studies. In comparing analyses and temperature history differences between 1995-1996 and 1999-2000, we show how different overall meteorological conditions in comparably cold winters may impact both polar processing and the agreement between meteorological data sets.

2. Data and Analysis

2.1. Data

A brief description of the analysis systems compared here, including key references, is given below.

2.1.1. Met Office Data. The Met Office data are from the troposphere-stratosphere data assimilation system developed for the Upper Atmosphere Research Satellite (UARS) project [*Swinbank and O'Neill*, 1994], and have been produced since October 1991. The assimilation uses an analysis-correction scheme as described by *Lorenc et al.* [1991]. The model upon which the Met Office assimilations are based uses a hybrid vertical coordinate, changing from a terrain-following coordinate in the troposphere to a pressure coordinate in the stratosphere, with vertical resolution of $\sim$1.6 km in the stratosphere. Satellite data used in the Met Office assimilations are National Environmental Satellite Data and Information Service (NESDIS) layer-mean temperatures from the TOVS sounders on the National Oceanic and Atmospheric Administration (NOAA)'s *TIROS-N* series of satellites. The Met Office data (three-dimensional winds, temperature, and geopotential height) are supplied once-daily at 12UT on a 2.5° latitude by 3.75° longitude grid, and at UARS pressure levels (6 levels per decade in pressure) between 1000 and 0.3 hPa ($\sim$2.5 km vertical spacing). There were no major changes in the Met Office assimilation system between 1995-1996 and 1999-2000. However, erroneous top level ozone data were in use in 1999-2000, resulting in large decreases in upper stratospheric temperatures; comparisons with analyses from the new three-dimensional variational (3D-Var) assimilation system [*Lorenc et al.*, 2000] that became operational in late 2000, and with Met Office analyses before the error was introduced suggest that the erroneous top level ozone could also account for a systematic decrease of $\sim$1 K in lower stratospheric temperatures.

2.1.2. NCEP Data. The NCEP/CPC objective analysis system is a modified Cressman analysis for pressure levels 70, 50, 30, 10, 5, 2, 1, and 0.4 hPa [*Finger et al.*, 1965, 1993; *Gelman et al.*, 1986, 1994]; these analyses have been available since June 1979. The analyses in the upper stratosphere are based on TOVS and Revised TOVS (RTOVS) data; at and below 10 hPa, radiosonde data are also used. Analyses at and below 100 hPa are from the tropospheric analysis and forecast cycle [*Derber et al.*, 1991], which directly assimilates radiances from the TOVS instruments [*Derber and Wu*, 1998; *McNally et al.*, 2000]. The NCEP data are provided once a day at 12UT on a 65×65 polar stereographic grid for each hemisphere; for the analyses shown here, these have been interpolated to a 2.5°×5° latitude/longitude grid. Horizontal winds are calculated from the NCEP geopotential heights using a form of the primitive equations that neglects the vertical advection and time tendency terms [*Randel*, 1987; *Newman et al.*, 1989]. Several changes were made in the satellite data inputs to the NCEP objective analysis system between 1995-1996 and 1999-2000; differences introduced by these changes are typically smaller than 1 K below 10 hPa.

2.1.3. NCEP/NCAR Reanalysis Data. The NCEP/NCAR 50-year reanalysis project is described by *Kalnay et al.* [1996] and *Kistler et al.* [2001], and is based on a version of the 3D-Var scheme used in NCEP's operational forecast system. This includes a spectral model at T62, with 28 sigma levels in the vertical, and coarse vertical resolution in the lower stratosphere. The assimilation system has been constant (although the inputs have changed) during the entire period of the reanalysis. After 1978, the NESDIS retrievals of TOVS/RTOVS data were included. The REAN data, including winds, temperature and geopotential height, are available at 17 pressure levels between 1000 and 10 hPa (including 100, 70, 50, 30, 20, and 10 hPa), on a 2.5°×2.5° latitude/longitude grid. They are available as both 4 times daily and daily average files. *Trenberth and Stepaniak* [2001] noted a pathological problem in REAN data in the stratosphere that affects primarily the wind fields over steep topography; although strongest effects are over the Andes, the topography of Greenland is large enough that such effects might be present in Arctic winter (K. Trenberth, private communication). In March 1997, a problem with filtering of the TOVS data was introduced, which resulted in global mean

temperature increases near 100 hPa; this problem may have had some impact on the lower stratospheric winds and temperatures used here for 1999-2000. The REAN data after March 1997 are being rerun; preliminary results indicate that 30 hPa Arctic temperatures averaged over January through March 2000 are up to $\sim$1 K lower in the corrected data than in the REAN data used here.

2.1.4. Freie Universität Berlin Data. The Freie Universität Berlin data are from a subjective analysis based on radiosonde data and have been produced since July 1964; thicknesses from satellites are utilized over data-sparse areas [*Pawson and Naujokat*, 1999]. FUB temperatures and geopotential heights are available once daily at 00UT on a $5^\circ \times 5^\circ$ latitude/longitude grid for the northern hemisphere, at 50, 30, and 10 hPa. Since these data are available only on three levels, they are used only in comparisons of temperatures on those individual levels. The FUB analysis system did not change between 1995-1996 and 1999-2000.

2.1.5. ECMWF Data. ECMWF assimilation systems have produced analyses including the lower stratosphere operationally since August 1979. The ECMWF analysis system was considerably changed between 1995-1996 and 1999-2000. The model uses a hybrid vertical coordinate, changing from a terrain-following coordinate in the troposphere to a pressure coordinate in the stratosphere. A 31-level version was operational in 1995-1996 with coarse vertical resolution in the lower stratosphere (top levels at 70, 50, 30, and 10 hPa). On 30 January 1996, ECMWF switched from optimal interpolation to 3D-Var, using preprocessed NESDIS radiances and radiosonde data [*Ritchie et al.*, 1995; *Courtier et al.*, 1998]. In 1999, a 60-level version was introduced, extending to 0.1 hPa with a vertical spacing of 1.5 km between 60 and 5 hPa [*Untch and Simmons*, 1999], providing substantially better stratospheric analyses and forecasts. Additionally, the 4D-Var assimilation system (in use since 1997, *Klinker et al.* [2000]) now uses raw TOVS/Advanced TOVS (ATOVS) radiances [*McNally et al.*, 1999], leading to additional improvement, especially in the lower stratosphere. In 1995-1996, the spectral model used a T213 truncation; by 1999-2000 the spectral resolution was increased to T319, but a reduced Gaussian grid the same as that for a T213 model was used. Spectral data for both winters have been transformed to a $2.5^\circ \times 2.5^\circ$ latitude/longitude grid. Data are used here at 100, 70, 50, 30, and 10 hPa for 1995-1996 and 100, 70, 50, 30, 20, 10, 7, 5, and 3 hPa for 1999-2000.

2.1.6. NASA Data Assimilation Office Data. The DAO analyses are performed with the Goddard Earth Observation System, version 3 (GEOS-3) data set. The data set is obtained by the assimilation of ground- and space-based observations in a system based on the GEOS model, the Physical-space Statistical Analysis Scheme (PSAS, *Cohn et al.* [1998]) and the Incremental Analysis Update (IAU, *Bloom et al.* [1996]) technique of combining model forecast and analysis. Aspects of the GEOS-3 data relevant to the middle atmosphere are described in more detail by Pawson et al. (submitted manuscript). The analyses in the lower stratosphere are impacted most strongly by the inclusion of radiosonde observations of wind and temperature and by geopotential thicknesses from NESDIS retrievals. Analyses are produced four times a day on a $1^\circ \times 1.25^\circ$ latitude/longitude grid on 48 terrain-following levels, with a vertical resolution of about 1.2 km in the lower stratosphere. For the purposes of this study the 12UT data were interpolated to a $2^\circ \times 2.5^\circ$ latitude/longitude grid on standard meteorological levels, including 100, 70, 50, 40, 30, 20, 10, 7, 5, and 3 hPa. In 1995-1996, DAO data were produced, using GEOS-1; these data are not widely used in polar process studies, so are not included in this comparison.

2.2. Diagnostics

While some of the data sets used here are available up to four times daily, the diagnostics shown here are done once daily at 12UT (except for the FUB, which is available only at 00UT), for comparability; *Knudsen et al.* [2001] and *Keil et al.* [2001] noted that differences in time resolution have a larger effect than spatial resolution on calculated trajectories. The REAN calculations have been made using both the 12UT and daily average data sets, and differences are much less than between different analysis systems. Analyses of minimum temperatures and areas of low temperature are done on the grids noted above, where the high-resolution data sets (DAO, ECMWF) were interpolated to grids comparable to other data sets. To plot vertical sections, the analyses are linearly interpolated in log-p to UARS pressure levels. For gridpoint-by-gridpoint temperature comparisons, all other analyses are bilinearly interpolated to the coarsest grid, $5^\circ \times 5^\circ$, of the FUB data. Potential Vorticity (PV) is calculated from each data set using a version of the algorithm described by *Manney et al.* [1996b], adapted from *Newman et al.* [1989].

The area with temperature less than the formation threshold for nitric acid trihydrate (NAT) PSCs (T_{NAT}), as calculated by *Hanson and Mauersberger* [1988], is shown here. To obtain "standard" profiles for the calculation, we have averaged UARS Cryogenic Limb Array Etalon Spectrometer nitric acid and Microwave Limb Sounder water vapor data during December and January 1991-1992 and 1992-1993. Using these profiles, the NAT threshold at 50 hPa is 195.5 K (HNO_3 = 9.1 ppbv, H_2O = 5.0 ppmv) and at 30 hPa is 193.5 K (HNO_3 = 12.0 ppbv, H_2O = 5.5 ppmv). For calculations on the 465-K isentropic surface, 195 K is used as

an approximate value for the NAT threshold.

Isentropic trajectory calculations at 465 K are used to obtain temperature histories from Met Office, NCEP, REAN, ECMWF, and DAO analyses. The trajectory code is an isentropic version of that described by *Manney et al.* [1994a]. It uses once-daily (12UT) horizontal winds from each analysis on the latitude/longitude grids described above. While isentropic trajectories are not realistic for 20-30-day periods (the length of calculations done here), these calculations provide quantitative comparisons of very large numbers of trajectories in order to characterize differences between analyses and the impact of different meteorological conditions; they are neither intended nor appropriate for detailed polar processing studies.

3. Synoptic Temperature Comparisons

Examination of monthly average and minimum temperatures, the number of days with $T \leq T_{NAT}$ [e.g., *Manney and Sabutis*, 2000], and other diagnostics in the lower stratosphere indicate that there are notable differences between the analyses even in monthly means. In both Januaries, temperatures remained below 195 K for the entire month in substantial regions [e.g., *Naujokat and Pawson*, 1996; *Manney and Sabutis*, 2000]; the size of these regions varies between analyses. The fact that substantial differences are visible in monthly means suggests the presence of persistent, systematic differences between analysis temperatures.

Plate 1 shows time series of 50 hPa minimum temperatures from November through March in the two winters. The evolution of minimum temperatures, as shown here, is frequently used in polar processing studies to provide an overview of the times favoring PSC formation [e.g., *Manney et al.*, 1994b; *Bevilacqua et al.*, 2001]. While the lines for various analyses frequently cannot be easily distinguished, the envelope indicates differences between analyses of up to $\sim$5 K, with many of the largest differences occurring at low temperatures. Some systematic differences are apparent: In December 1999 and January 2000, the Met Office analyses are usually coldest, while the NCEP analyses are often warmest. In contrast, in 1995-1996, the REAN analyses are usually, and the Met Office occasionally, warmest, while the FUB and NCEP are coldest during January. Larger differences, with similar apparent biases, are seen at 30 hPa (not shown), with the REAN data in 1995-1996 standing out as almost always 1-2 K warmer than the Met Office, which is in turn usually warmer than the ECMWF, NCEP, and REAN. Since the analyses differ by up to 5 K, and since these estimates would be expected to vary further depending on the grid that is used when finding the minimum values, conclusions regarding minimum temperatures drawn solely from one of these meteorological analyses may be uncertain by well over 5 K.

Comparing the curves for 1999-2000 with those for 1995-1996 emphasizes how similar these two winters were when judged solely by the minimum temperature evolution: Both show very low temperatures in January, an increase in late January, lower temperatures again in February, and a final warming beginning in mid-March. While January 2000 was slightly colder than January 1996, February 1996 was colder than February 2000.

Similar patterns of differences between analyses can be seen in Plate 2, the area with $T \leq T_{NAT}$ (referred to hereinafter as A_{NAT}). Overall variations in A_{NAT} were commonly $\sim$25%, and occasionally over 50% (e.g., at 30 hPa in January 1996), during the cold periods, with from 7 to 17 days difference between analyses in time spent at $T \leq T_{NAT}$. Consistent with the higher minimum temperatures, the REAN stands out at 30 hPa with smallest A_{NAT} and fewest days with $T \leq T_{NAT}$. While ECMWF showed relatively large A_{NAT} at 30 hPa in late December 1995 and January 1996, it showed substantially smaller A_{NAT} at 50 hPa than the other analyses; this difference between levels was absent in the 1999-2000 ECMWF data and was reduced in February and March 1996, probably as a result of improvements in the assimilation system (section 2.1.5). The Met Office analyses had among the largest A_{NAT} in 1999-2000, and the NCEP among the smallest, while the opposite was true in 1995-1996. A_{NAT} in January was comparable between the two years, but a bit larger in 2000; A_{NAT} in February was larger (in both area and vertical extent) in 1996 than in 2000.

Plate 3 shows a comprehensive pressure-time view of A_{NAT} (calculated as a function of pressure, nitric acid, and water vapor, as described in section 2.2). The Met Office analysis in 1999-2000 shows strikingly larger A_{NAT} than any other analysis in November through January. The very large area of low temperatures extending into the middle stratosphere in the 1999-2000 Met Office data likely results from the erroneous top-level ozone data in use at this time (section 2.1.1). The NCEP analyses show much smaller A_{NAT} than the other analyses from December 1999 through February 2000. In contrast, in 1996 the NCEP analyses show overall larger A_{NAT}, and the REAN smaller, although differences between all analyses are larger in 1995-1996 than in 1999-2000. From the areas shown here, the Met Office, REAN, and ECMWF (as well as FUB at 30 and 50 hPa, Plate 2) analyses suggest that conditions were more favorable for PSC formation in the lower stratosphere in January-February 2000 than in January-February 1996, but the NCEP analyses suggest the opposite.

Turning to a more general comparison of high-latitude temperatures, Figure 1 shows, at 50 hPa for January and Fe-

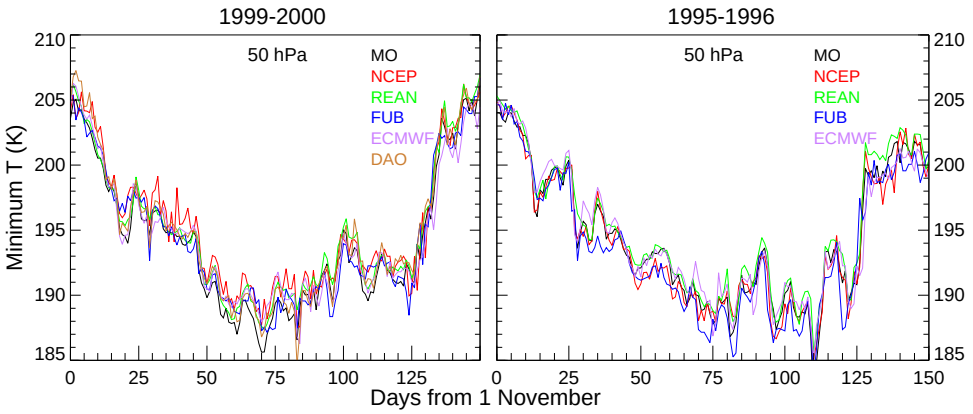

Plate 1. Time series of minimum temperature (K) at 50 hPa for November through March (left) 1999-2000 and (right) 1995-1996, for six analyses (five in 1995-1996). Minima are searched for north of 40°N.

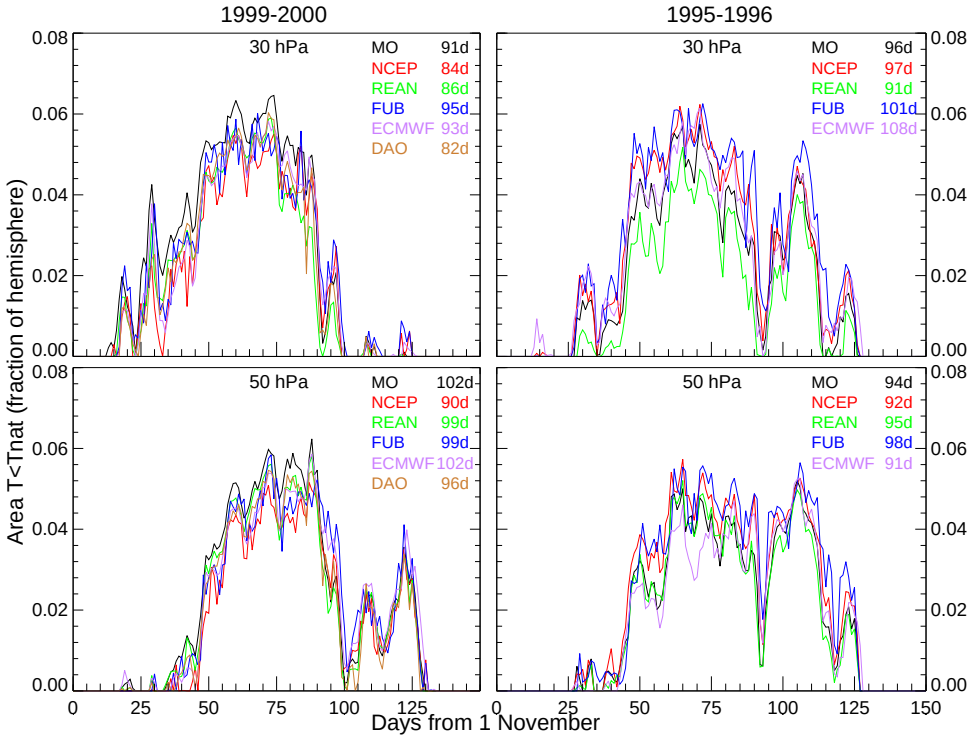

Plate 2. Time series of the area (north of 30°N) with $T \leq T_{NAT}$ (fraction of a hemisphere) at (top) 30 and (bottom) 50 hPa for November through March (left) 1999-2000 and (right) 1995-1996 for six analyses (five in 1995-1996). Numbers for each analysis indicate the total number of days spent at $T \leq T_{NAT}$.

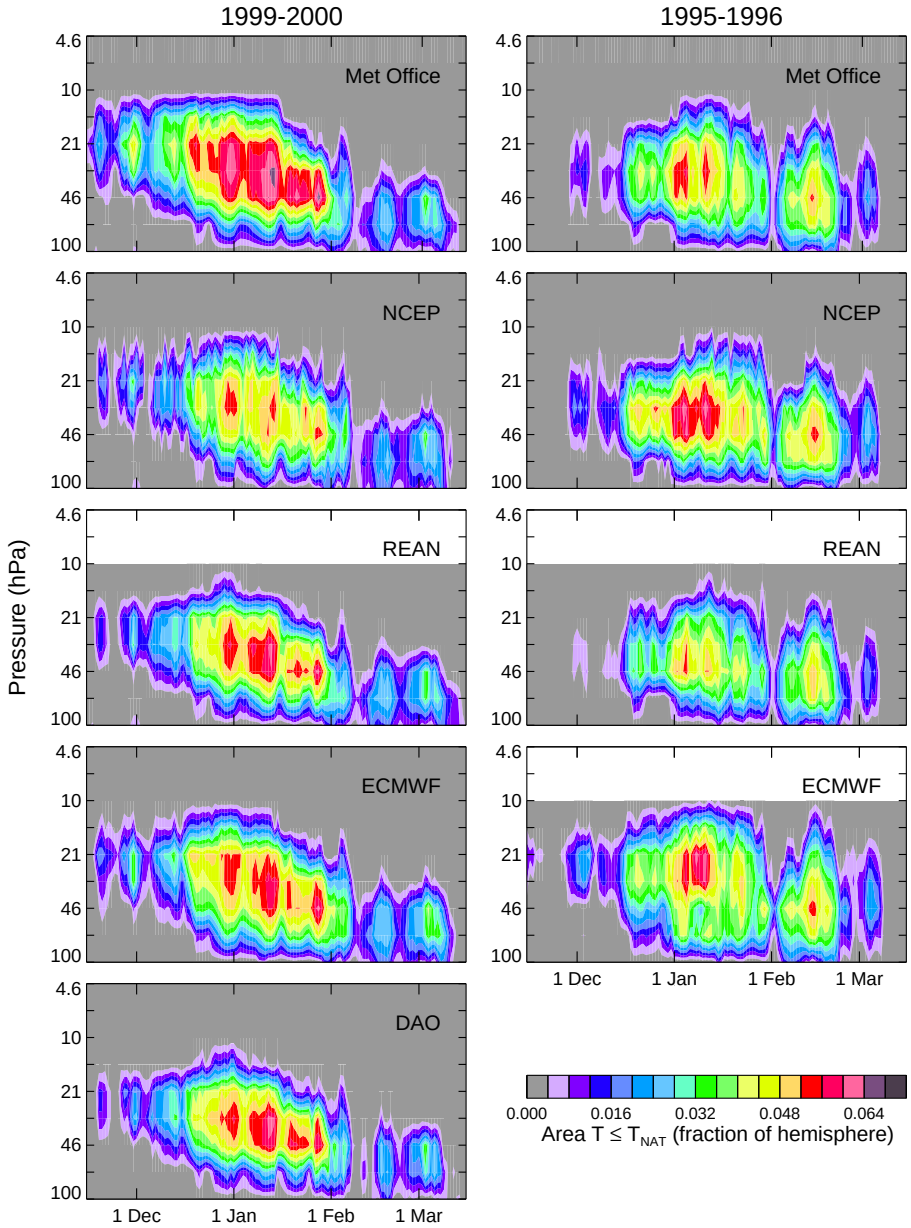

Plate 3. Pressure/time cross-sections of the area with $T \leq T_{NAT}$ (fraction of a hemisphere) for 15 November through 15 March, in 2000 and 1996, from (top to bottom) Met Office, NCEP, REAN, ECMWF, and DAO (1999-2000 only) temperatures.

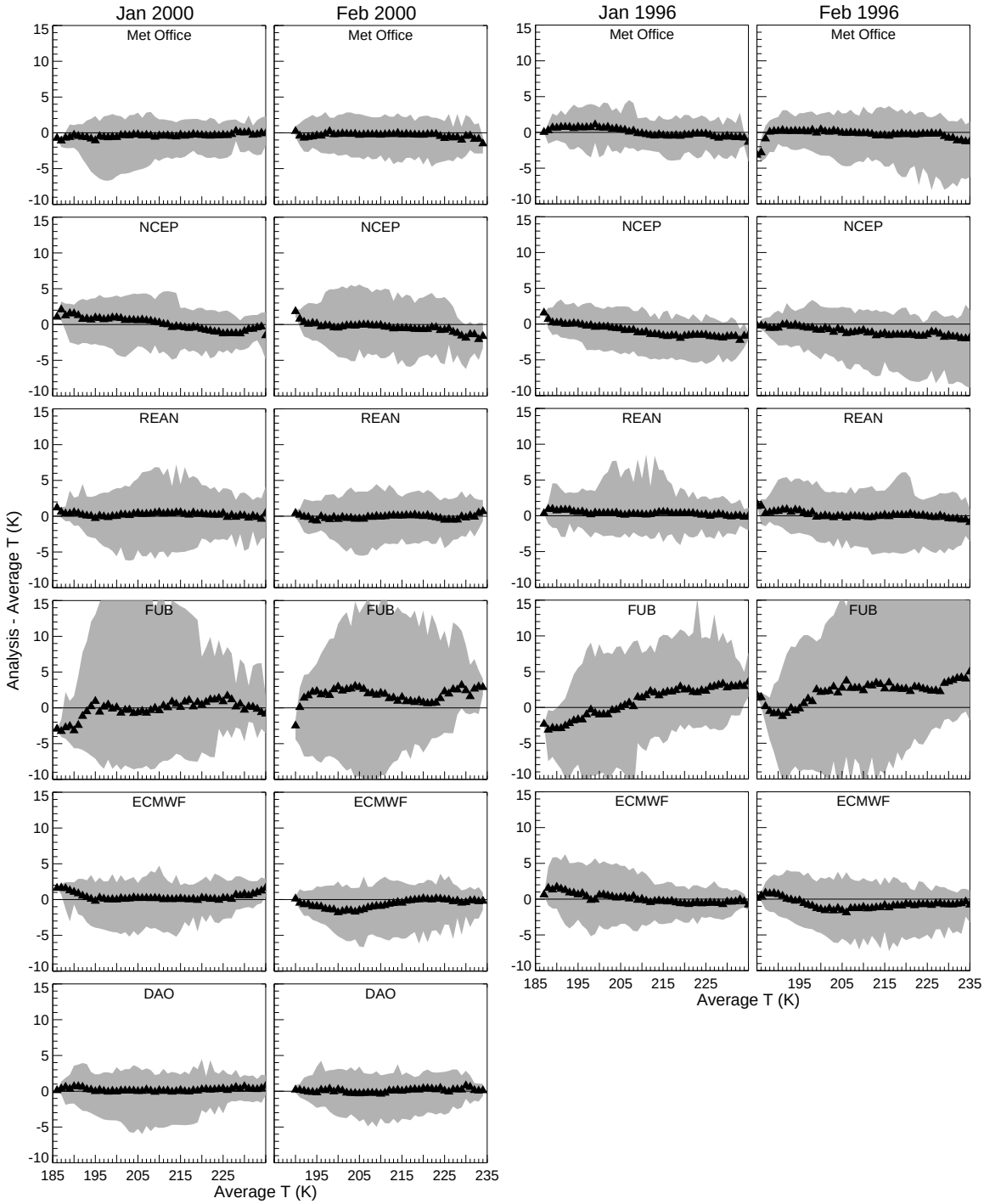

Figure 1. Scatter plots of the difference between temperatures from each analysis and the ensemble mean temperature (average over all analyses at each grid point) as a function of the ensemble mean, for all gridpoints on a $5^\circ \times 5^\circ$ grid from 60° to 90°N, at 50 hPa, for January and February 2000 and 1996. The shaded region shows the area filled by the individual scattered points. The solid triangles show the average difference (analysis temperature - ensemble mean temperature) in each 1-K average temperature bin. The thin line is at zero difference.

bruary, the difference between each of the analysis temperatures and the ensemble mean (the average temperature over all analyses at each gridpoint) in the region north of 60°N, versus the ensemble mean. As described in section 2.2, these comparisons were made on a 5°×5° grid. Table 1 shows the average differences between the ensemble mean and each of the analyses for November through March in the two winters. As seen dramatically in Figure 1, by far the largest scatter around the average difference is in the FUB analyses. The FUB analyses are closely matched to radiosonde observations and consequently may capture local variations in the vicinity of the radiosonde stations that are smoothed over in the other systems that also give weight to low vertical resolution satellite data [e.g., *Pawson et al.*, 1999]; however, away from the radiosonde locations they are more poorly constrained than the other analyses, and may miss or severely smooth temperature variations that occur between observation locations. At temperatures above ∼210-215 K the FUB temperatures have a large warm bias compared to all the other analyses. The opposite is generally true at lower temperatures; that is, the FUB data tend to be colder than average and the NCEP, REAN, and ECMWF warmer. The Met Office data are usually near the ensemble mean but also show a slight warm bias at low temperatures in January 1996 and a comparable cold bias in January 2000. The cold bias in the Met Office data at lowest temperatures in February 1996 comes from two or three very cold days (including 20 February) when a strong upper tropospheric ridge resulted in a large cold region near the vortex edge in the lower stratosphere [e.g., *Manney et al.*, 1996a]; on these days, the Met Office analyses produced lower temperatures than any of the others.

Table 1 shows that there is considerable variation in the overall high-latitude temperature biases during the two winters. Of particular note is the overall cold bias in Met Office analyses throughout 1999-2000, contrasted with a warm bias in November 1995 through January 1996. This may be related to the incorrect top-level ozone data used in 1999-2000. In both years the FUB shows large cold biases in November and December, smaller cold biases in January, and warm biases in February and March. NCEP, REAN, ECMWF, and DAO all show modest warm biases in November through January. Root-mean-square differences between analyses and the average (not shown) indicate that FUB analyses show larger scatter than the other analyses throughout the winter. Met Office, NCEP, REAN, and ECMWF analyses typically show larger scatter in February and March than in earlier months.

4. Trajectory Histories

Temperature histories along trajectories are used to examine more closely how the meteorological data set used may affect calculations common to polar processing studies.

To examine temperature histories at high latitudes and in the vortex, 30-day back trajectories on the 465-K isentropic surface were run for parcels initialized from 40° to 90°N on an equal area grid with 0.5°×0.5° equatorial spacing (∼50 km spacing, ∼30,000 parcels); parcel positions were saved every 3 hours. These runs were initialized on 30 January and 10 March 1996 and 2000. From these, we constructed maps of the total number of days air was at T≤195 K (Plate 4). This diagnostic is relevant to chlorine activation, in that the total time air parcels spend in PSCs strongly influences the amount of chlorine activation. In January 2000, each of the analyses shows parcels remaining at T≤195 K for the entire 30-day period; however, the number and spatial distribution of the parcels that do so vary considerably between the analyses. The maximum total time spent at T≤195 K is 14-16, 17-20, and 10-12 days for the February/March 2000, January 1996, and February/March 1996 cases, respectively. As will be seen below, temperatures in 1999-2000 were usually nearly concentric with the vortex [e.g., *Manney and Sabutis*, 2000], while in 1995-1996 the cold region was frequently near the vortex edge [e.g., *Manney et al.*, 1996a]. Temperatures were comparable in January 2000, January 1996, and February/March 1996. In January 2000, however, the parcels spent a longer time being advected within the cold region, rather than moving in and out of it as they did in 1996. Less variability in the vortex and low temperature region, and a stronger correlation between those regions, in January 2000 than in the other periods can also be seen in the position of the overlaid temperature contours, which are averaged over the duration of the trajectory runs.

Compared to the other analyses, the NCEP plot in January 2000 shows higher average temperatures and the vortex less completely filled with parcels that remained cold for a long time. The Met Office and, to a somewhat lesser extent, the ECMWF analyses show more of the vortex filled with air that spent the entire month at low temperature. In each of the other three periods, the REAN calculations show the shortest times at low temperature and highest average temperatures. In 1996, the NCEP results show the longest time and largest area of parcels at low temperature (although ECMWF values are nearly as large, and ECMWF shows the lowest average temperatures). Many of the analyses show materiel drawn off the vortex that has spent significant time at low temperature. In March 2000, ECMWF trajectories show considerably more processed air in the large fragment

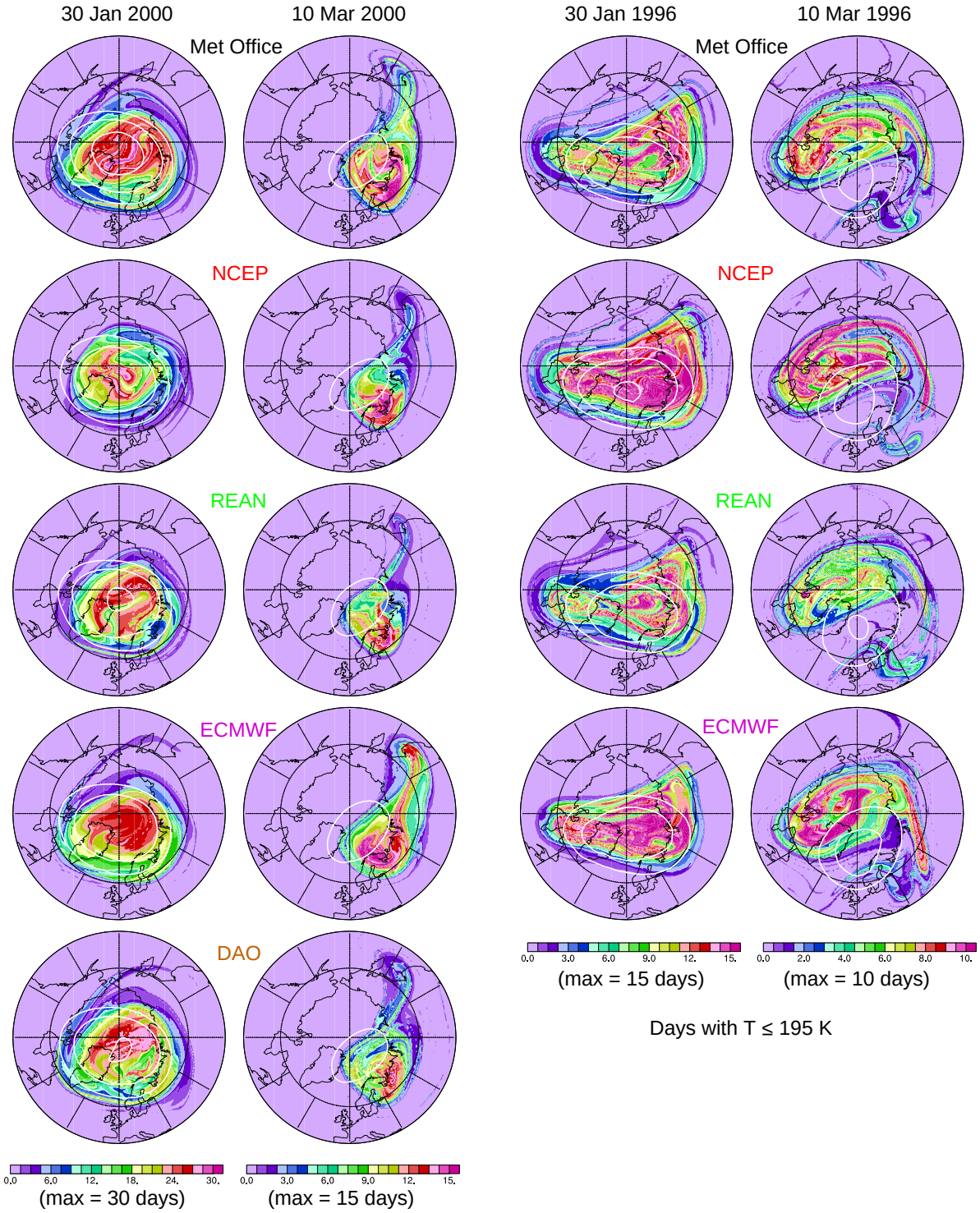

Plate 4. Maps of total time spent at temperatures below 195 K in the 30 days prior to (left) 30 January and (right) 10 March 2000 and 1996, from 465-K back trajectory calculations from 40°N to the pole (see text) for (top to bottom) Met Office, NCEP, REAN, ECMWF, and DAO (2000 only) trajectories. Note that the color scale extends to 30 days for 30 January 2000, 15 days for 10 March 2000 and 30 January 1996, and 10 days for 10 March 1996. Overlaid white contours show average temperatures over the 30 days of the runs; contour values are 200, 195, and 190 K (outermost to innermost). The map projection is orthographic, with 0°longitude at the bottom and 90°E to the right. The domain is from 40°N to the pole, with a thin dashed line at 60°N.

Table 1. Average 60°–90°N 50 hPa temperature differences

Analysis	Month				
	Nov	Dec	Jan	Feb	Mar
1999-2000					
Met Office	-0.08	-0.06	-0.59	-0.32	-0.50
NCEP	0.94	1.07	0.71	-0.29	-0.15
REAN	0.26	0.34	0.15	-0.29	-0.42
FUB	-3.10	-2.76	-0.72	1.94	1.65
ECMWF	0.67	0.70	0.37	-1.01	-1.07
DAO	1.34	0.70	0.22	-0.03	0.16
1995-1996					
Met Office	0.43	0.72	0.41	-0.04	-0.50
NCEP	0.15	0.24	-0.44	-0.82	-1.08
REAN	0.66	0.74	0.46	0.18	-0.41
FUB	-2.17	-3.09	-0.93	1.23	3.13
ECMWF	0.94	1.39	0.49	-0.76	-1.42

being pulled off the vortex south of Alaska; both NCEP and ECMWF show more processed air than the other analyses in the tongue being pulled off the vortex in March 1996. This behavior may have implications for the mixing of chemically processed air into midlatitudes [e.g., *Norton and Chipperfield*, 1995].

To examine in more detail the history of parcels at low temperature, trajectory runs at 465 K were initialized with parcels on an equal area grid with $0.25^\circ \times 0.25^\circ$ equatorial spacing within the area with T$\leq$195 K on the initialization day; these runs used $\sim$1800-18,000 parcels, depending on the initialization day and the analysis. These runs were initialized on 10 January and 20 February 1996 and 2000; 20-day trajectories were run both backward and forward, and the parcel positions were saved every hour. Plate 5 shows temperatures, along with an indication of the extent and strength of the polar vortex, on two of the initialization days, 10 January 2000 and 20 February 1996. Besides substantial differences in the size of the cold region between analyses (to be quantified by the number of parcels in each run), the difference in the relative locations of the cold regions with respect to the vortex in 2000 versus 1996 is seen clearly here; as mentioned previously, during most of the 1999-2000 winter the cold region was centered in the vortex, while in 1995-1996, it was commonly near the vortex edge. The NCEP data show a much smaller area of low temperatures on both initialization days in 2000 than the other analyses; the REAN data show a substantially smaller cold area in February 1996 than the other analyses. The ECMWF analyses on 10 January 1996 (not shown) have a much smaller area of low temperatures than the other analyses for this date.

Plate 6 summarizes the average temperature history of the air parcels in each of the four periods. Often, differences of a few K between average temperature histories from different analyses could affect the amount, type and/or extent of PSC formation, e.g., on 29 December 1999, 5 February 2000, 2 January 1996, and 14 February 1996. The large scatter about the average (the one standard deviation envelope of $\sim$10-20 K) indicates large variations in the temperature histories of different parcels all initialized within the cold region on a given day. This scatter is smaller during January and early February 2000, when the cold region was nearly concentric with the vortex. The impact of different meteorological conditions during comparably cold periods is immediately apparent in comparing January 2000 with both January and February 1996; while most of the air remained cold for long periods (tens of days in some cases) in January 2000, the initially cold air in both January and February 1996 moved rapidly in and out of the cold region. Lower Met Office temperatures in January 2000 combined with a

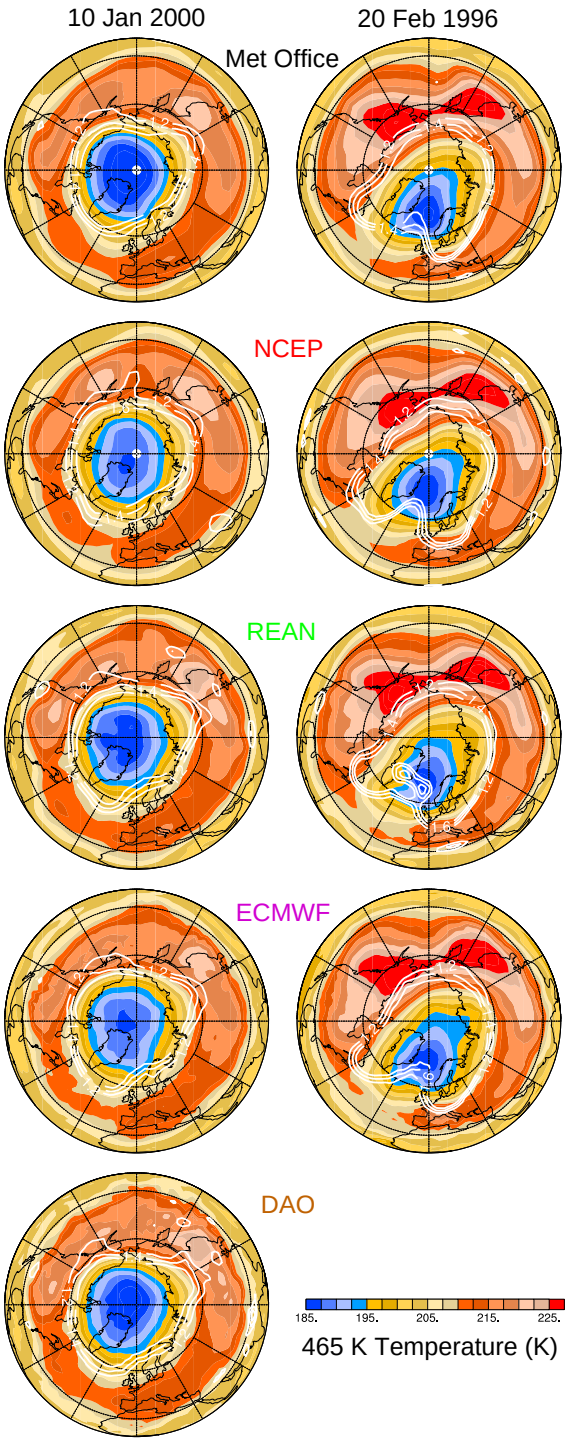

Plate 5. 465 K temperature maps on 10 January 2000 and 20 February 1996, from analyses used for trajectory calculations (Met Office, NCEP, REAN, ECMWF, and DAO for 2000). Overlaid white contours are PV on the same days in the vicinity of the vortex edge. The map projection is orthographic, with 0°longitude at the bottom and 90°E to the right. The domain is from equator to pole, with thin dashed lines at 30° and 60°N. The blue region shows the area below 195 K in which trajectory runs were initialized (see text).

cold region that was concentric with the vortex resulted in a Met Office average that was continuously below the NAT PSC threshold for much longer than the other analyses.

The discrepancies between analyses seen in Plates 4 and 6 result from differences in both winds and temperatures. Plate 6 shows that the minima and maxima are often concurrent in all analyses but of different amplitudes. This suggests parcel trajectories that are similar, but pass through different temperature extrema. Some qualitative differences (e.g., early March 1996, late December 1995) suggest differences in the morphology of wind and/or temperature fields. In a further attempt to diagnose whether differences in winds or temperatures may be dominant, temperature histories like those in Plate 4 were calculated using temperatures from each of the analyses with the Met Office trajectories and, conversely, trajectories from each analysis with the Met Office temperatures (not shown). While both had significant effects, in most cases, using Met Office temperatures with individual trajectories produced temperature histories with closer agreement (suggesting that temperature differences between the analyses had a greater impact). Exceptions are for the REAN and DAO analyses in January 2000, for which runs with Met Office trajectories produced closer agreement (suggesting differences in the trajectories had a greater impact). Thus there is some variation in which effect is dominant, although differences in temperature most often seem to play a larger role.

To look more quantitatively at the differences in temperature histories, Figures 2–5 show histograms for each of the four cases initialized in the cold regions of the total time the parcels were at T$\leq$195 K (referred to hereinafter as TT195) during the 40-day period covered by the runs, and the time they were continuously at T$\leq$195 K before and after the initialization day (referred to hereinafter as CT195). The former diagnostic (TT195) is related to the total amount of processing on PSCs and hence to chlorine activation. The latter diagnostic (CT195) is more directly relevant to PSC formation and denitrification since the continuous time at low temperature affects the composition and size of PSC particles, and hence the rate at which they sediment. A quantity like CT195 has been used to estimate potential PSC "lifetimes"; for example, *Tabazadeh et al.* [2000, 2001] did similar calculations during cold periods in several Arctic winters, using 40 parcels in each cold region and combining the statistics for many days. The four cases shown here are sufficient to examine the dependence of the results on the analysis and on a variety of meteorological conditions. The number of parcels used to construct the histograms is proportional to the area of the cold region on the initialization day.

In general, the distributions of both TT195 and CT195 are broad and multi-peaked. Substantial differences are seen be-

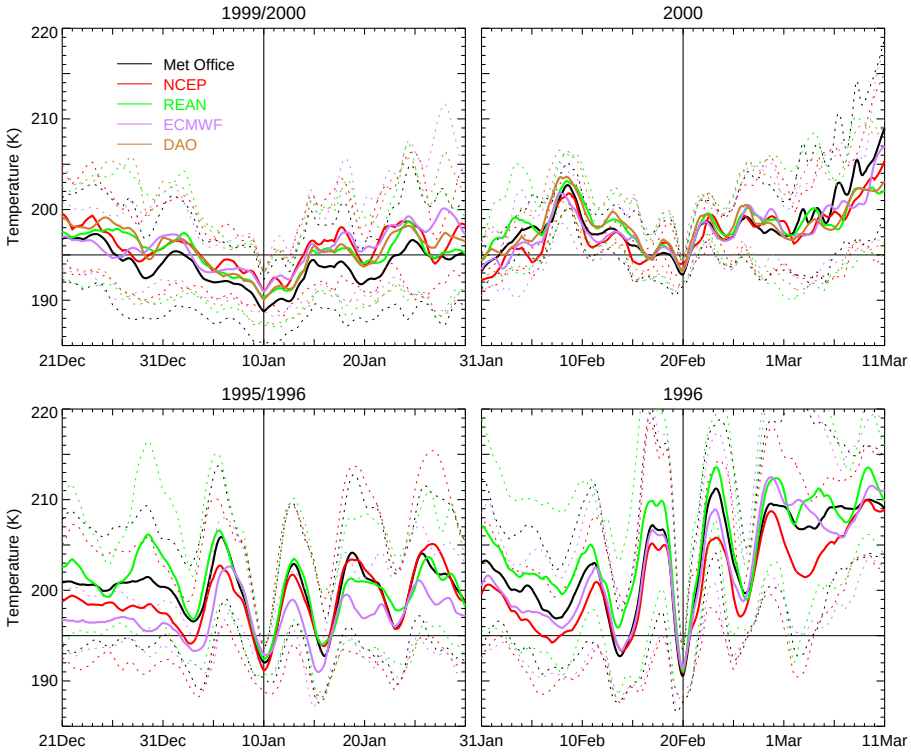

Plate 6. Plots of the average (thick solid lines) and one standard deviation envelope (thin dashed lines) for the trajectory runs initialized within the cold region on (left) 10 January and (right) 20 February (top) 2000 and (bottom) 1996.

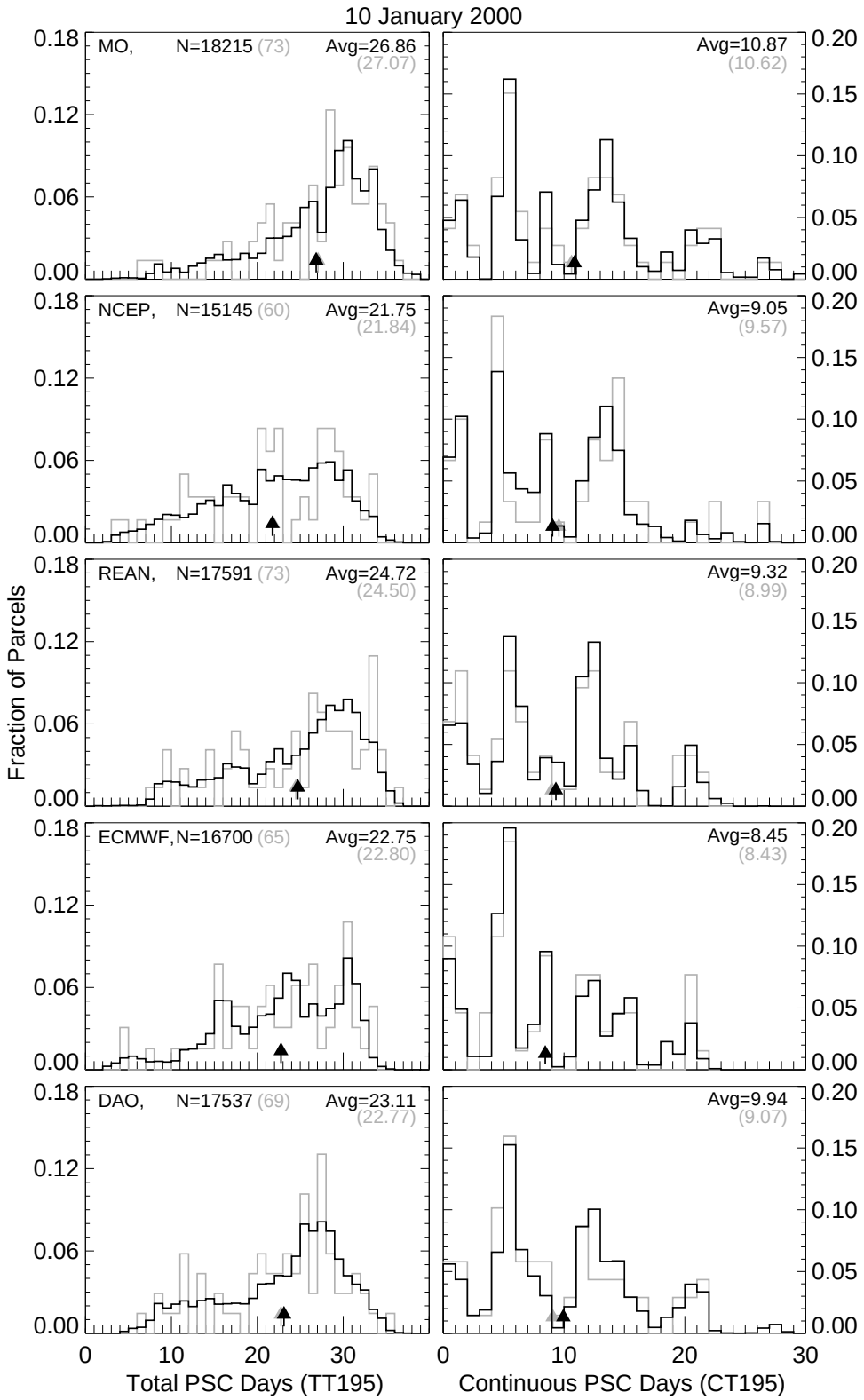

Figure 2. Histograms of (left) the total number of days spent at T≤195 K and (right) the number of days surrounding the initialization time continuously at T≤195 K for trajectory runs initialized in the cold region on 10 January 2000. Thick solid lines, labels, and arrows are for the complete set of initialized parcels; shaded lines, labels, and arrows are for a set of 1/256th of the parcels obtained by retaining every 16th parcel in both latitude and longitude. The arrows show the average number of days; number of parcels used and average number of days are given in the labels.

tween analyses in both the averages and the location of peaks in the distributions. In January 2000 (Figure 2), both TT195 and CT195 distributions from all analyses have broadly similar shapes. The NCEP TT195 distribution is less strongly peaked; the Met Office, REAN, and DAO TT195 distributions show a strong peak near 28-35, 27-33, and 24-30 days, respectively, while the ECMWF distribution shows multiple peaks at 13-17, 22-25 and 30-32 days. The CT195 distributions from each of the analyses have peaks near 1-2 days, 4-6 days, and 11-14 days, with ∼65-70% of the parcels in the 4-9 and 11-16 day bins. About 11-18% of the parcels stay cold continuously for 0-3 days, and all distributions also show a small but significant peak in CT195 (∼4% for NCEP, ∼6% for ECMWF, ∼9-11% for others) near 19-24 days. Although other scenarios may produce the same result, a multi-peaked distribution of expected PSC lifetimes is consistent with the presence of both small (liquid and/or solid) particles that form quickly and very large particles that take longer to grow but would sediment quickly once formed, similar to behavior seen in aircraft observations [*Fahey et al.*, 2001].

In February 2000 (Figure 3), Met Office, NCEP, REAN, and ECMWF TT195 distributions have double peaks at times varying by ∼2-5 days between analyses; the DAO distribution has a very different shape. The CT195 distributions for February 2000 all show substantial qualitative differences. In January 1996 (Figure 4), the TT195 and CT195 distributions from Met Office, NCEP, and REAN analyses are broadly similar: The CT195 distributions have peaks near 2 and 3 days, with ∼25-30% of the parcels in bins at less than 2 days, and ∼15-30% in bins from 2-3 days. The ECMWF distributions for this period (before the change to a 3D-Var assimilation, section 2.1.5) are quite different, with the CT195 peaks more closely clustered around 2.5 days, and ∼30% (∼45%) of the parcels at $<$2 days (2-3 days). Each of the TT195 distributions in February 1996 (Figure 5) has a different character. The NCEP, Met Office, and ECMWF CT195 distributions in February 1996 are broadly similar (∼55% of parcels at 2-3 days), while the REAN distribution shows strongest peaks at shorter lifetimes (∼60% of parcels at 1-2 days).

The conditions in January 2000 represent a situation where the parcels' histories are less dependent on the details of the wind and temperature fields, so a more consistent picture is seen between the different analyses. Situations like the other periods studied (with higher temperatures and/or low temperatures less concentric with the vortex) are more common in Arctic winter [e.g., *Pawson and Naujokat*, 1999], so one may expect trajectory-based temperature histories in general to depend very strongly on which analysis is chosen for the calculations. In the 1996 cases, even the averages for TT195 differ by nearly 6 days between the longest and shortest time. PSC lifetimes of one to a few days (as in CT195 in February 2000 and in 1996) are in the range where such processes as phase changes in PSCs may occur [e.g., *Tabazadeh et al.*, 1996, 2001; *Fahey et al.*, 2001], so even small differences can be very significant.

To test the sample size needed to accurately represent the distributions, sub samples of various sizes were made. Figures 2–5 also show the distributions obtained by reducing the number of parcels by a factor of 256. The impact of retaining too few parcels is clear in February 2000 (Figure 3), when the reductions resulted in fewer than 25 parcels used; some of the strongest peaks during this period are at locations substantially different from those in the full distribution. While retaining 40-80 parcels gives a reasonable distribution, using more than 100 parcels in any of these cases gave a distribution very similar in character to that obtained using the complete set of parcels.

The huge impact of the different meteorological conditions in 1996 and 2000 is reflected in averages and peaks at much shorter times in TT195 and CT195 distributions for 1996 than for January 2000, even though the temperatures were comparable to those in January 2000. Average "potential PSC lifetimes" (CT195) in January 2000 were 9-10 days, whereas in each of the other time periods, they were 1.6-4.0 days, with nearly all parcels having expected lifetimes less than 7.5 days. These averages, however, frequently lie near minima in the distributions, and thus are not representative of common lifetimes. The distributions for February 2000 show more parcels with lifetimes over ∼3 days (∼20-40%) than in February 1996 (∼0-7%), even though February 2000 was much warmer; short lifetimes in 1996 are consistent with the location of low temperatures near the vortex edge, and the behavior shown in Plate 6. The prevalence of very long lifetimes in 1999-2000 may have led to phenomena that are quite uncommon in the Arctic winter: large solid PSC particles [e.g., *Fahey et al.*, 2001], widespread denitrification [e.g., *Santee et al.*, 2000; *Popp et al.*, 2001, and others], and large ozone losses [*Santee et al.*, 2000; *Sinnhuber et al.*, 2000; *Richard et al.*, 2001; *Gao et al.*, 2001, and others]. Neither widespread denitrification nor as much ozone loss at some levels as in 1999-2000 were seen in the comparably cold 1995-1996 winter [e.g., *Santee et al.*, 1996, 2000, 2001; *Manney et al.*, 1996a].

5. Discussion and Conclusions

We have compared temperatures from the Met Office, NCEP, REAN, FUB, ECMWF, and DAO (for 1999-2000) analyses in the 1999-2000 and 1995-1996 Arctic winters. Temperature histories from trajectory calculations were compared for all except the FUB analyses. The two winters cho-

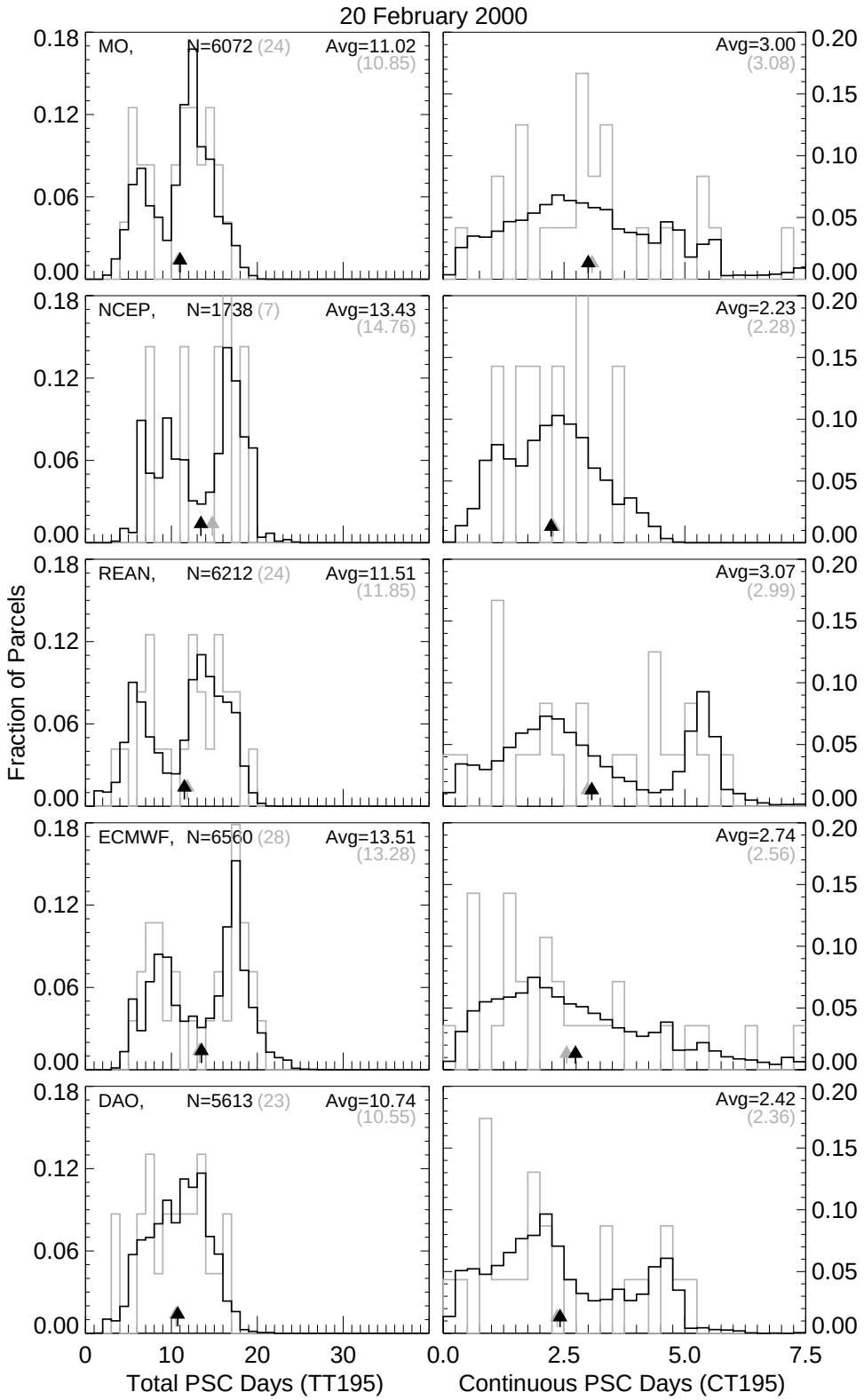

Figure 3. As in Figure 2, but for 20 February 2000. Note that the right-hand (continuous days at T≤195 K) axis goes only to 7.5 days, as opposed to 30 days in Figure 2 for 10 January 2000.

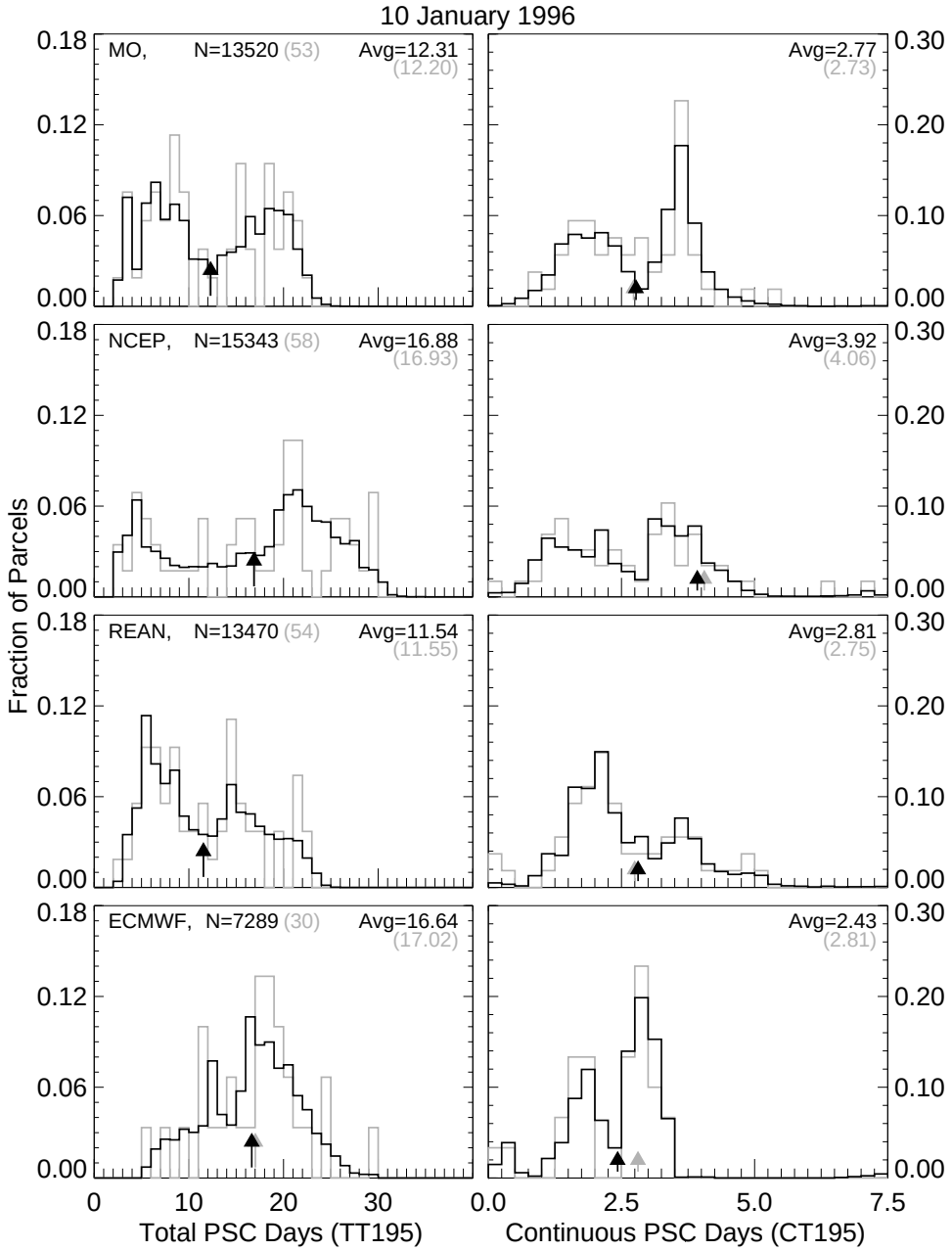

Figure 4. As in Figure 3, but for 10 January 1996.

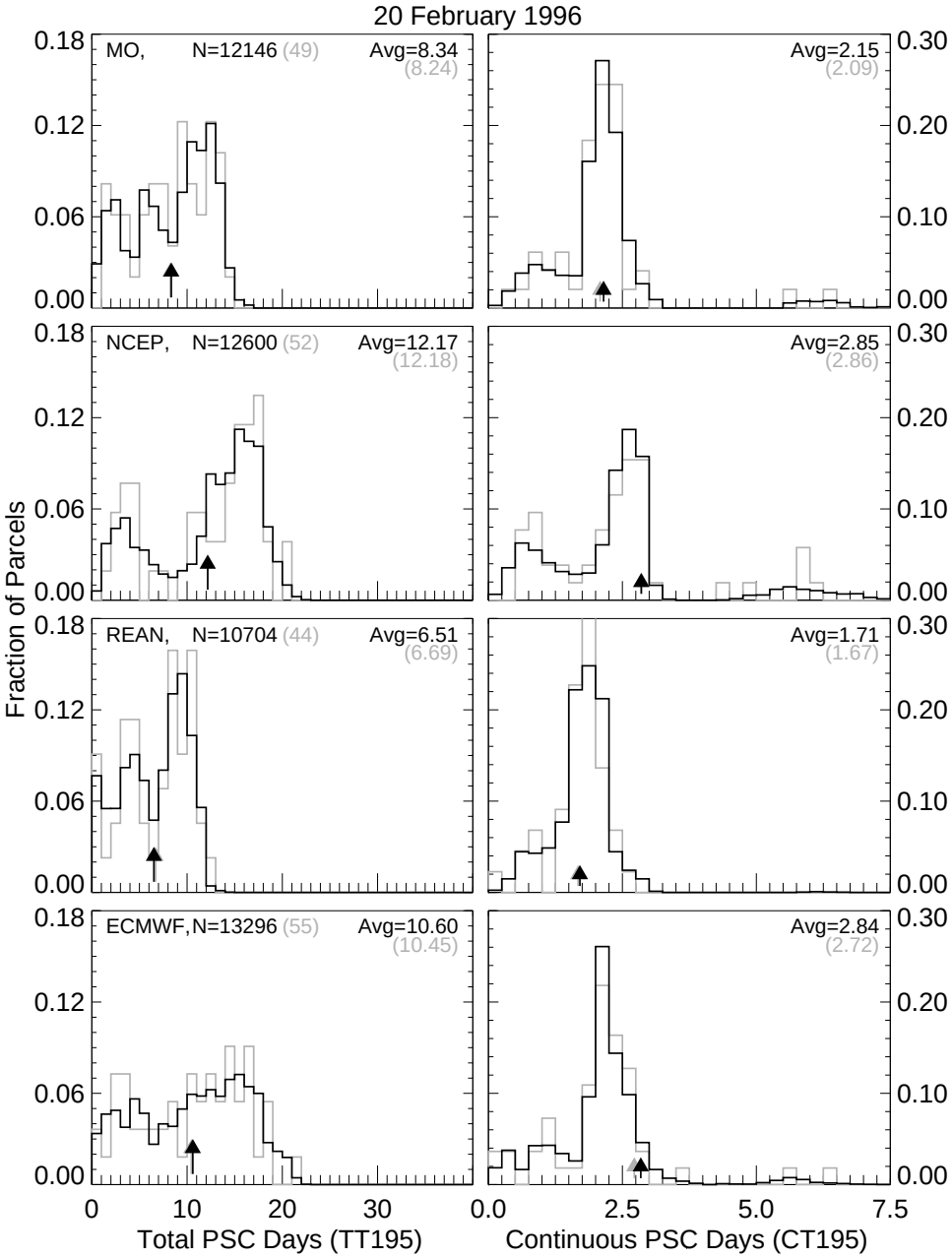

Figure 5. As in Figure 3, but for 20 February 1996.

sen for study were the coldest recent winters, and among the most frequently used in Arctic polar process studies. Although they were comparably cold in January and February, the meteorological situations were otherwise very different, with the cold region typically centered in the vortex during 1999-2000 and near the vortex edge in 1995-1996.

Minimum lower stratospheric temperatures typically vary by up to $\sim$5 K between the analyses. Areas of low temperature usually vary up to $\sim$25% between analyses during cold periods, with occasional variations of over 50%. There are several periods during which one or two analyses stand out as significantly different. In December and January 2000, Met Office temperatures were substantially lower than those of each of the other analyses; during the same period, NCEP temperatures were typically highest. In contrast, in 1995-1996, Met Office temperatures were among the highest, and NCEP temperatures among the lowest. January 2000 would be thought to be warmer than January 1996 if looking at NCEP data, but the opposite conclusion would be drawn by looking at Met Office, REAN, ECMWF, or FUB. In 1995-1996, before substantial improvements in the ECMWF analysis system and lower stratospheric vertical resolution, ECMWF temperatures were among the warmest at 50 hPa but among the coldest at 30 hPa; in 1999-2000, ECMWF temperatures agreed much better with other analyses. Largest discrepancies between ECMWF and other analyses were in late 1995 and in January 1996, before the switch to a 3D-Var assimilation system.

Differences between temperature analyses were generally larger in 1995-1996 than in 1999-2000; since only one of the analyses (ECMWF) underwent very substantial changes between these two years, this is likely to be related in part to the different meteorological conditions in the two years. In the more variable situation in 1995-1996, with very low temperatures often near the vortex edge, whether an analysis captured particular local features may depend more strongly on the horizontal and vertical resolution and on the details of how the data are ingested into the analysis system.

Several of the analyses (REAN, and often NCEP, DAO, and ECMWF) typically have a warm bias at low temperatures with respect to the average for all analyses. A similar bias is seen in the Met Office analyses in January and March 1996, but a cold bias at the lowest temperatures is seen in 1999-2000 and in February 1996. The FUB data usually show the opposite, being generally colder than the other analyses at $T \lesssim 205$ K. At higher temperatures, FUB data are generally warmer, and NCEP, REAN, and frequently Met Office, colder, than the average. The amount of scatter seen between the FUB temperatures and the average is much larger than in any of the other analyses. As subjective analyses based almost entirely on radiosondes, the FUB analyses closely follow extrema in radiosonde data near the observation locations, but are more poorly constrained than the other analyses away from these locations. The close match to radiosonde data at the observation locations may also explain the relative cold bias of the FUB at low temperatures, since some of the other products typically have a warm bias with respect to sondes at low temperatures [e.g., *Knudsen*, 1996; *Manney et al.*, 1996b; *Pullen and Jones*, 1997].

Temperature histories from trajectory calculations using the Met Office, NCEP, REAN, ECMWF, and DAO analyses show how differences between analyses may impact polar processing studies. In these diagnostics, the effect of different meteorological conditions (not merely temperature) on the comparison between analyses becomes even more pronounced. Substantial and persistent differences between the analyzed temperatures in January 2000 were described above, of similar magnitude to those in other periods studied. However, the differences between temperature histories for January 2000 are considerably smaller than for any of the other periods. This period was only slightly colder than the January and February 1996 periods studied; more significant than the large region of low temperatures is the fact that the cold region was approximately centered within the vortex, so that many of the parcels in the initially cold region were simply advected within that region. In January 2000, although temperature differences led to variations between analyses in the details of locations that spent the most time at low temperatures, the distributions of "potential PSC lifetimes" and total time spent at $T \leq T_{NAT}$ were qualitatively similar for each of the meteorological analyses. In the other cases examined here, the analyses showed qualitatively different distributions of both potential PSC lifetimes and total time spent at low temperature; the maximum difference in the average total time at $T \leq 195$ K was almost 6 days.

Estimates of potential PSC lifetimes for January 2000 show peaks near 1-2 days, 4-6 days, 11-14 days, and 19-24 days (with those at 4-6 days and 11-14 days accounting for more than half the parcels). Average lifetimes are 9-10 days and located in a deep minimum in the distributions. Each of the other periods studied (February 2000 and January and February 1996) had average lifetimes from 1.6-4 days, with peaks at different times in different analyses. The February 2000 lifetimes were short because it was not very cold; the 1996 lifetimes were short because parcels passed rapidly into and out of a large cold region. Although the four cases shown here may not represent the most persistently cold periods in each winter, and thus may not compare the longest lifetimes in each year, the general pattern of differences between 1996 and 2000 is persistent throughout the winters. These four cases span a variety of the meteorological conditions encountered in the Arctic winter. For a comprehensive

survey one would want to do calculations for many periods [e.g., *Tabazadeh et al.*, 2000]; this is feasible because only ∼40-80 parcels in the cold region are needed to capture the main features of the distributions. However, it is important to keep in mind that an average lifetime from such calculations provides little information about the typically broad and multi-peaked distributions. In addition, calculations run along a smaller number of trajectories, such as those done by *Tabazadeh et al.* [2001] for 20 parcels, may not capture all the important features of the temperature history.

Potentially long PSC lifetimes in January 2000, compared to those in the comparably cold 1995-1996 winter, are consistent with reports of widespread denitrification in 1999-2000 but not in 1995-1996 [e.g., *Santee et al.*, 2000]. Long continuous cold periods would spur the formation of large particles that quickly sediment, as reported by *Fahey et al.* [2001]. The effect of the contrasting meteorological situations in 1999-2000 and 1995-1996 on chlorine activation and ozone loss is much more complicated, as the location of the cold region on the vortex edge in 1996 would be expected to favor the distribution of activated chlorine throughout the vortex, and the asymmetry of the vortex would also tend to position it so as to receive more sunlight, thus facilitating greater ozone loss [e.g. *Waters et al.*, 1993; *Manney et al.*, 1997; *Santee et al.*, 1997]. On the other hand, some studies indicate that denitrification may enhance ozone loss [e.g., *Rex et al.*, 1997; *Tabazadeh et al.*, 2000; *Gao et al.*, 2001]. Thus it is not immediately obvious which set of conditions might lead to greater ozone loss, although some observational studies indicate greater losses at certain altitudes in 1999-2000 [e.g., *Santee et al.*, 2000]. Many detailed modeling studies are being done [e.g., *Davies et al.*, 2001; *Drdla et al.*, 2001; *Drdla and Schoeberl*, 2001; *Grooß et al.*, 2001] in an attempt to address these issues. In the performance of such studies, all of which depend on one (or more) of the meteorological analyses discussed here, it is important to keep in mind that substantial quantitative and qualitative differences may arise from the choice of meteorological analysis products used.

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References

Bevilacqua, R. M., et al., Observations and analysis of PSCs detected by POAM III during the 1999/2000 Northern Hemisphere winter, *J. Geophys. Res., in press*, 2001.

Bloom, S. C., L. L. Takacs, A. M. da Silva, and D. Ledvina, Data assimilation using incremental analysis updates, *Mon. Weather Rev.*, *124*, 1256–1271, 1996.

Cohn, S. E., A. da Silva, J. Guo, M. Siekenwicz, and D. Lamich, Assesssing the effects of data selection with the DAO physical-space statistical analysis system, *Mon. Weather Rev.*, *126*, 2913–2926, 1998.

Courtier, P., E. Andersson, W. Heckley, J. Pailleux, D. Vasiljevic, M. Hamrud, A. Hollingsworth, F. Rabier, and M. Fisher, The ECMWF implementation of three-dimensional variational assimilation (3D-Var). I: Formulation, *Q. J. R. Meteorol. Soc.*, *124*, 1783–1807, 1998.

Davies, S., et al., Modeling the effect of denitrification on Arctic ozone depletion during winter 1999/2000, *J. Geophys. Res., in press*, 2001.

Derber, J. C., and W. Wu, The use of TOVS cloud-cleared radiances in the NCEP SSI analysis system, *Mon. Weather Rev.*, *126*, 2287–2299, 1998.

Derber, J. C., D. F. Parrish, and S. J. Lord, The new global operational analysis system at the National Meteorological Center, *Weather Forecasting*, *6*, 538–547, 1991.

Drdla, K., and M. Schoeberl, Microphysical modelling of the 1999-2000 Arctic winter: 2. chlorine activation and ozone depletion, *J. Geophys. Res., submitted*, 2001.

Drdla, K., M. Schoeberl, and E. V. Browell, Microphysical modelling of the 1999-2000 Arctic winter: 1. polar stratospheric clouds, denitrification, and dehydration, *J. Geophys. Res., in press*, 2001.

Fahey, D. H., et al., The detection of large HNO_3-containing particles in the winter Arctic stratosphere, *Science*, *291*, 1026–1031, 2001.

Finger, F. G., H. M. Woolf, and C. E. Anderson, A method for objective analysis of stratospheric constant pressure charts, *Mon. Weather Rev.*, *93*, 619–638, 1965.

Finger, F. G., M. E. Gelman, J. D. Wild, M. L. Chanin, A. Hauchecorne, and A. J. Miller, Evaluation of NMC upper-stratospheric temperature analyses using rocketsonde and lidar data, *Bull. Am. Meteorol. Soc.*, *74*, 789–799, 1993.

Gao, R. S., et al., Observational evidence for the role of denitrification in Arctic stratospheric ozone loss, *Geophys. Res. Lett.*, *28*, 2879–2882, 2001.

Gelman, M. E., A. J. Miller, K. W. Johnson, and R. M. Nagatani, Detection of long term trends in global stratospheric temperature from NMC analyses derived from NOAA satellite data, *Adv. Space. Res.*, *6(10)*, 17–26, 1986.

Gelman, M. E., A. J. Miller, R. M. Nagatani, and C. S. Long, Use of UARS data in the NOAA stratospheric monitoring program, *Adv. Space. Res.*, *14(9)*, 21–31, 1994.

Grooß, J.-U., et al., Simulation of ozone depletion in spring 2000 with the Chemical Lagrangian Model of the Stratosphere (CLaMS), *J. Geophys. Res.*, *in press*, 2001.

Hanson, D., and K. Mauersberger, Laboratory studies of the nitric acid trihydrate: Implications for the south polar stratosphere, *Geophys. Res. Lett.*, *15*, 855–858, 1988.

Kalnay, E., et al., The NCAR/NCEP 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471, 1996.

Keil, M., M. Heun, J. Austin, W. Lahoz, G. P. Lou, and A. O'Neill, The use of long-duration balloon data to determine the accuracy of stratospheric analyses and forecasts, *J. Geophys. Res.*, *106*, 10,299–10,312, 2001.

Kistler, R., et al., The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation, *Bull. Am. Meteorol. Soc.*, *82*, 247–267, 2001.

Klinker, E., F. Rabier, G. Kelly, and J.-F. Mahfouf, The ECMWF operational implementation of four-dimensional variational assimilation. I: Experimental results and diagnostics with operational configuration, *Q. J. R. Meteorol. Soc.*, *126*, 1191–1215, 2000.

Knudsen, B. M., Accuracy of Arctic stratospheric temperature analyses and the implications for the prediction of polar stratospheric clouds, *Geophys. Res. Lett.*, *23*, 3747–3750, 1996.

Knudsen, B. M., J. M. Rosen, N. T. Kjome, and A. T. Whitten, Comparison of analyzed stratospheric temperatures and calculated trajectories with long-duration balloon data, *J. Geophys. Res.*, *101*, 19,137–19,145, 1996.

Knudsen, B. M., J.-P. Pommereau, A. Garnier, M. Nunez-Pinharanda, L. Denis, G. Letrenne, M. Durand, and J. M. Rosen, Comparison of stratospheric air parcel trajectories based on different meteorological analyses, *J. Geophys. Res.*, *106*, 3415–3424, 2001.

Lorenc, A. C., R. S. Bell, and B. Macpherson, The Meteorological Office analysis correction data assimilation scheme, *Q. J. R. Meteorol. Soc.*, *117*, 59–89, 1991.

Lorenc, A. C., et al., The Met. Office global three-dimensional variational data assimilation scheme, *Q. J. R. Meteorol. Soc.*, *126*, 2991–3012, 2000.

Manney, G. L., and J. L. Sabutis, Development of the polar vortex in the 1999-2000 Arctic winter stratosphere, *Geophys. Res. Lett.*, *27*, 2589–2592, 2000.

Manney, G. L., R. W. Zurek, A. O'Neill, and R. Swinbank, On the motion of air through the stratospheric polar vortex, *J. Atmos. Sci.*, *51*, 2973–2994, 1994a.

Manney, G. L., M. L. Santee, L. Froidevaux, J. W. Waters, and R. W. Zurek, Polar vortex conditions during the 1995–96 Arctic winter: Meteorology and MLS ozone, *Geophys. Res. Lett.*, *23*, 3203–3206, 1996a.

Manney, G. L., R. Swinbank, S. T. Massie, M. E. Gelman, A. J. Miller, R. Nagatani, A. O'Neill, and R. W. Zurek, Comparison of U. K. Meteorological Office and U. S. National Meteorological Center stratospheric analyses during northern and southern winter, *J. Geophys. Res.*, *101*, 10,311–10,334, 1996b.

Manney, G. L., L. Froidevaux, M. L. Santee, R. W. Zurek, and J. W. Waters, MLS observations of Arctic ozone loss in 1996–97, *Geophys. Res. Lett.*, *24*, 2697–2700, 1997.

Manney, G. L., et al., Chemical depletion of ozone in the Arctic lower stratosphere during winter 1992-93, *Nature*, *370*, 429–434, 1994b.

McNally, A. P., E. Andersson, G. Kelly, and R. W. Saunders, The use of raw TOVS/ATOVS radiances in the ECMWF 4D-Var assimilation system, *ECMWF Newsletter*, *83*, 2–7, 1999.

McNally, A. P., J. C. Derber, W. Wu, and B. B. Katz, The use of TOVS level-1b radiances in the NCEP SSI analysis system, *Q. J. R. Meteorol. Soc.*, *126*, 689–724, 2000.

Naujokat, B., and S. Pawson, The cold stratospheric winters 1994/1995 and 1995/1996, *Geophys. Res. Lett.*, *23*, 3703–3706, 1996.

Newman, P. A., L. R. Lait, M. R. Schoeberl, R. M. Nagatani, and A. J. Krueger, Meteorological atlas of the Northern Hemisphere lower stratosphere for January and February 1989 during the Airborne Arctic Stratospheric Expedition, *Tech. Rep. 4145*, NASA, 1989.

Newman, P. A., et al., An overview of the SOLVE-THESEO 2000 campaign, *J. Geophys. Res.*, *accepted*, 2001.

Norton, W. A., and M. P. Chipperfield, Quantification of the transport of chemically activated air from the northern hemisphere polar vortex, *J. Geophys. Res.*, *100*, 25,817–25,840, 1995.

Pawson, S., and B. Naujokat, The cold winters of the middle 1990s in the northern lower stratosphere, *J. Geophys. Res.*, *104*, 14,209–14,222, 1999.

Pawson, S., K. Krüger, R. Swinbank, M. Bailey, and A. O'Neill, Intercomparison of two stratospheric analyses: Temperatures relevant to polar stratospheric cloud formation, *J. Geophys. Res.*, *104*, 2041–2050, 1999.

Popp, P. J., et al., Severe and extensive denitrification in the 1999-2000 Arctic winter stratosphere, *Geophys. Res. Lett.*, *28*, 2875–2878, 2001.

Pullen, S., and R. L. Jones, Accuracy of temperatures from UKMO analyses of 1994/95 in the Arctic winter stratosphere, *Geophys. Res. Lett.*, *24*, 845–848, 1997.

Randel, W. J., The evaluation of winds from geopotential height data in the stratosphere, *J. Atmos. Sci.*, *44*, 3097–3120, 1987.

Rex, M., et al., Prolonged stratospheric ozone loss in the 1995–96 Arctic winter, *Nature*, *389*, 835–838, 1997.

Richard, E. C., et al., Severe chemical ozone loss inside the Arctic polar vortex during winter 1999-2000 inferred from *in situ* airborne measurements, *Geophys. Res. Lett.*, *28*, 2197–2200, 2001.

Ritchie, H. C., A. Temperton, A. S. aand M Hortal, T. Davies, D. Dent, and M. Hamrud, Implementation of the semi-Langrangian method in a high resolution version the ECMWF forecast model, *Mon. Weather Rev.*, *123*, 489–514, 1995.

Santee, M. L., G. L. Manney, W. G. Read, L. Froidevaux, and J. W. Waters, Polar vortex conditions during the 1995–96 Arctic winter: MLS ClO and HNO_3, *Geophys. Res. Lett.*, *23*, 3207–3210, 1996.

Santee, M. L., G. L. Manney, L. Froidevaux, R. W. Zurek, and J. W. Waters, MLS observations of ClO and HNO_3 in the 1996–97 Arctic polar vortex, *Geophys. Res. Lett.*, *24*, 2713–2716, 1997.

Santee, M. L., G. L. Manney, N. J. Livesey, and J. W. Waters, UARS Microwave Limb Sounder observations of denitrification and ozone loss in the 2000 Arctic late winter, *Geophys. Res. Lett.*, *27*, 3213–3216, 2000.

Santee, M. L., A. Tabazadeh, G. L. Manney, M. D. Fromm, E. J. Jensen, R. M. Bevilacqua, and J. W. Waters, A Lagrangian approach to studying Arctic polar stratospheric clouds using UARS MLS HNO_3 and POAM II aerosol extinction measurements, *J. Geophys. Res.*, *in press*, 2001.

Sinnhuber, B.-M., et al., Large loss of total ozone during the Arctic winter of 1999/2000, *Geophys. Res. Lett.*, *27*, 3473–3476, 2000.

Swinbank, R., and A. O'Neill, A stratosphere-troposphere data assimilation system, *Mon. Weather Rev.*, *122*, 686–702, 1994.

Tabazadeh, A., O. B. Toon, B. L. Gary, J. T. Bacmeister, and M. R. Schoeberl, Observational constraints on the formation of type Ia polar stratospheric clouds, *Geophys. Res. Lett.*, *23*, 2109–2112, 1996.

Tabazadeh, A., M. L. Santee, M. Y. Danilin, H. C. Pumphrey, P. A. Newman, P. J. Hamill, and J. L. Mergenthaler, Quantifying denitrification and its effect on ozone recovery, *Science*, *288*, 1407–1411, 2000.

Tabazadeh, A., E. J. Jensen, O. B. Toon, K. Drdla, and M. R. Schoeberl, Role of the stratospheric polar freezing belt in denitrification, *Science*, *291*, 2591–2594, 2001.

Trenberth, K. E., and D. P. Stepaniak, A pathological problem with NCEP reanalyses in the stratosphere, *J. Climate*, *in press*, 2001.

Untch, A., and A. Simmons, Increased stratospheric resolution in the ECMWF forecasting system, *ECMWF Newsletter*, *82*, 2–8, 1999.

Waters, J. W., L. Froidevaux, W. G. Read, G. L. Manney, L. S. Elson, D. A. Flower, R. F. Jarnot, and R. S. Harwood, Stratospheric ClO and ozone from the Microwave Limb Sounder on the Upper Atmosphere Research Satellite, *Nature*, *362*, 597–602, 1993.

World Meteorological Organization, Scientific assessment of stratospheric ozone, 1998, U. N. Environ. Program, Geneva, Switzerland, 1999.

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