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Evaluation of the SKYHI general circulation model using aircraft N_2O measurements
1. Polar winter stratospheric meteorology and tracer morphology

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Abstract. Winter polar stratospheric nitric oxide (N_2O) measurements made during two NASA polar aircraft field campaigns are used to evaluate the dynamics of the Geophysical Fluid Dynamics Laboratory's "SKYHI" general circulation model. SKYHI has 1° latitude by 1.2° longitude grid spacing and 40 vertical levels (up to 80 km) and prescribed N_2O dissociation coefficients. The model has been integrated a total of 20 months, producing one Antarctic and two Arctic winters. The climatologies of these winters are compared with the known northern and southern hemisphere climatologies and to the meteorological conditions during the time of the field campaigns. The two Arctic SKYHI winters show considerable interannual variability. In the lower stratosphere, SKYHI realistically simulates the magnitude and variability of winds and temperatures both inside and outside the polar vortex and can produce a credible sudden warming. In the Antarctic the magnitude and variability of winds and temperatures around the polar vortex are quite realistic, but inside the vortex, temperatures are too low. Flight data from each mission have been averaged together to produce a contour map showing N_2O morphology in and around the vortex. Because the N_2O distribution in the lower stratosphere is under dynamical control, the mean N_2O field can be used to interpret the dynamics of the polar stratosphere. At the Arctic vortex edge, AASE data show large gradients of N_2O on isentropic surfaces. SKYHI vortex edge gradients are nearly as large, and model mixing ratios between 400 and 500 K (potential temperature) are similar to the observations. In the Antarctic, model mixing ratios are too high everywhere and the edge gradients are flatter than the observed gradients. The comparison of mean N_2O fields suggests realistic wave activity in the SKYHI Arctic winter but inadequate wave activity in the SKYHI Antarctic winter.

1. Introduction

Nitrous oxide is a good tracer of air motions in the lower stratosphere because of its long lifetime there. It is produced at the surface and is destroyed primarily in the tropical middle stratosphere by photolysis and reaction with O^1D to form odd nitrogen. The N_2O measurements made as part of the 1987 Airborne Antarctic Ozone Experiment (AAOE) and the 1989 Airborne Arctic Stratospheric Experiment (AASE) represent the largest data sets of a conservative tracer ever collected at high latitudes in the lower stratosphere. These lower stratospheric N_2O measurements, obtained both inside and outside of both winter polar vortices, produce a picture of N_2O structure clearly illustrating descent and isolation of air inside both the Arctic and the Antarctic vortex [*Podolske et al.*, 1989; *Loewenstein et al.*, 1990]. These observations were crucial to understanding polar vortex dynamics and the role that dynamics plays in the development of ozone "holes" [*Hartmann et al.*, 1989; *Schoeberl et al.*, 1989, 1990]. The AAOE measurements demonstrated that radiatively driven upwelling of ozone-poor lower stratospheric air in the early austral spring, a purely dynamical cause that had been proposed to explain the Antarctic ozone hole [*Mahlman and Fels*, 1986], was not nearly large enough to explain the observations [*Hartmann et al.*, 1989].

The high spatial resolution of these measurements has revealed atmospheric structure never before seen: a vortex edge that occasionally has N_2O gradients as high as 60 ppb in just a few kilometers, "double" vortex edges, and parcels of (low N_2O) vortex air that have been spun off the vortex. This tracer shows just how rich in structure the atmosphere is and how some features having small horizontal scales (such as the vortex edge) are robust and can be observed daily. Not only is N_2O a very useful tracer of air motions in and around the vortex but also these measurements clearly indicate that a good deal of information on atmospheric structure and variability is available. The wealth of information on atmospheric variability that exists in the AAOE and AASE data sets provides a unique opportunity for evaluating the dynamics of the stratosphere of GFDL's SKYHI general circulation model (GCM). The SKYHI model data set is also

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unique because it is the only comprehensive, self-consistent GCM with significant stratospheric resolution that has been run at the high horizontal resolution of 1° latitude grid spacing.

SKYHI is a three-dimensional general circulation model with 1° latitude by 1.2° longitude grid spacing and 40 vertical levels extending to 80 km. There are six pressure levels within the altitude range surveyed by AASE and AAOE (47 to 167 mbar). SKYHI was initialized with output from a 5° x 6° version of SKYHI in the month of October. In the time since the initial study of model climatology by *Mahlman and Umscheid* [1987] (hereafter referred to as MU87), the 1° version of SKYHI has been integrated a total of 20 months, resulting in one Antarctic and two Arctic winters. SKYHI does not parameterize drag forces due to gravity waves, but the Eliassen-Palm flux divergence (EPFD) generated from the explicitly resolved gravity wave field plays an important role in the general circulation [*Hayashi et al.*, 1989]. The N_2O continuity equation is solved by standard second-order differencing in the horizontal and fourth order in the vertical [*Mahlman and Moxim*, 1978]. Ozone, sea surface temperatures, and clouds are prescribed in accordance with climatic values. SKYHI includes a Richardson-number-dependent vertical diffusion parameterization [*Levy et al.*, 1982]. For further model details, see *Fels et al.* [1980]; *Mahlman and Umscheid* [1984]; and *Andrews et al.* [1983].

In this version of SKYHI, N_2O dissociation coefficients in the stratosphere are precomputed and prescribed as a function of height and latitude. Because the distribution of N_2O sources is not well understood, the model has no N_2O source. Since the initialization, model mixing ratios have decreased slowly (due to the N_2O sink). For the analyses presented here and in the companion paper, SKYHI N_2O mixing ratios are scaled by a constant so that mixing ratios at the surface match the observed surface mixing ratios at the time of the AASE and AAOE: 307 ppb in the northern hemisphere (1989) and 305 ppb in the southern hemisphere (1987).

Historically, one of the more difficult dynamics problems in stratospheric modeling has been the issue of excessively low winter polar temperatures and the associated intense westerlies at the edge of the polar vortex [*Manabe and Hunt*, 1968]. The most probable cause of this is inadequate forcing from the troposphere. MU87 have discussed the effects of horizontal resolution in the SKYHI model on winter polar temperatures and found that the higher the resolution, the farther from radiative equilibrium stratospheric temperatures are driven. Figure 1 in that paper compares the December mean temperature at 62°N for four resolutions of SKYHI from 9° to 1° latitude grid spacing. As model resolution increases, the agreement with observations over the range 0.3 to 10 mbar goes from extremely poor at 9° resolution (15-40 K too low) to excellent at 1° resolution. They note, however, that even 1° SKYHI minimum temperatures within the polar vortex between 10 and 100 mbar are still 10 K too low. Large improvements in monthly mean zonal winds from the troposphere to 2 mbar are also reported and attributed to the increased magnitude of the EPFD. *Hayashi et al.* [1989] showed that the weaker, more realistic zonal winds in 1° SKYHI were due to increased EPFD, which is a result not only of increasing the number of resolvable wavenumbers but also of the additional wave-wave interactions that were possible at this resolution. The broader frequency distribution of gravity waves in the 1° version leads to increased gravity wave EPFD. Another success reported by MU87 is the simulation of a realistic sudden warming and its accompanying spectacular effects on the N_2O field.

Before performing a diagnostic study on tracer transport and variability [*Strahan and Mahlman*, this issue], it is worthwhile to examine the 1° SKYHI climatology. Relevant issues include whether the improvements reported by MU87 are also seen in the second Arctic winter, and how well both model hemispheres compare with known climatologies. Because the aircraft observations used in this diagnostic study do not represent zonal or monthly means but rather have very specific spatial and temporal characteristics, it is also worthwhile to examine SKYHI results in the context of meteorological conditions during the time of the observations. Diagnosing dynamics and variability in the model will be more meaningful if the model has meteorological conditions similar to the observations.

2. SKYHI Winters and the Observed Climatology

SKYHI Winter I (AWI) and Winter II (AWII) in the Context of the 26-Year Mean

Northern hemisphere lower stratospheric maps from 1964 to 1989, compiled by the National Meteorological Center, have been analyzed by *Nagatani et al.* [1990]. They compared 26-year means derived from the NMC data with monthly zonal mean 50-mbar temperatures for January and February 1989. Their results are compared with the first and second SKYHI northern winter means in Figure 1. (Hereafter, the first Arctic winter in SKYHI will be referred to as AWI, and the second as AWII.) In January (Figure 1a), 50-mbar temperatures for both SKYHI winters fall within 2σ of the 26-year mean from 20° to 85°N; AWI is within 1σ of the mean above 35°N, while AWII is within 1σ of the mean below 70°N. Because of the lower than normal temperatures in January 1989, both SKYHI winters had 50-mbar temperatures between 60° and 75°N that compared extremely well with the observations.

In February (Figure 1b), AWI is still somewhat cold in the tropics but within 2σ of the mean from 20° to 85°N. AWII is within 1σ of the mean at all latitudes shown. Notice the difference in the two SKYHI winters poleward of 60°N: this is due to a major sudden warming event penetrating to 100 mbar in the first winter (see MU87). The February 1989 temperatures at high latitudes are similar to AWI because of a sudden warming that began in early February. In February of AWII, warming was observed at 30 mbar, but not at 50 mbar; a gradual increase in 50-mbar temperatures began in late March. Although a climatological mean is not yet possible for 1° SKYHI, Figure 1 shows that SKYHI 50-mbar temperatures for the two available northern hemisphere winters are generally within two standard deviations of the 26-year mean and that SKYHI exhibits considerable interannual variability. However, a 10-year climatology is available for the 3° version of SKYHI. For the northern winter (December/January/February), 3° SKYHI has zonal mean 50-mbar temperatures that are within 5 K of the observed means from equator to pole (the largest deviation, -5 K, is above 80°N) and has a realistic interannual variability [*Hamilton et al.*, 1994].

SKYHI Winters in the Context of the 1989 Arctic Winter

Figures 2 and 3 compare SKYHI temperatures and vortex characteristics in the region of the AASE measurements.

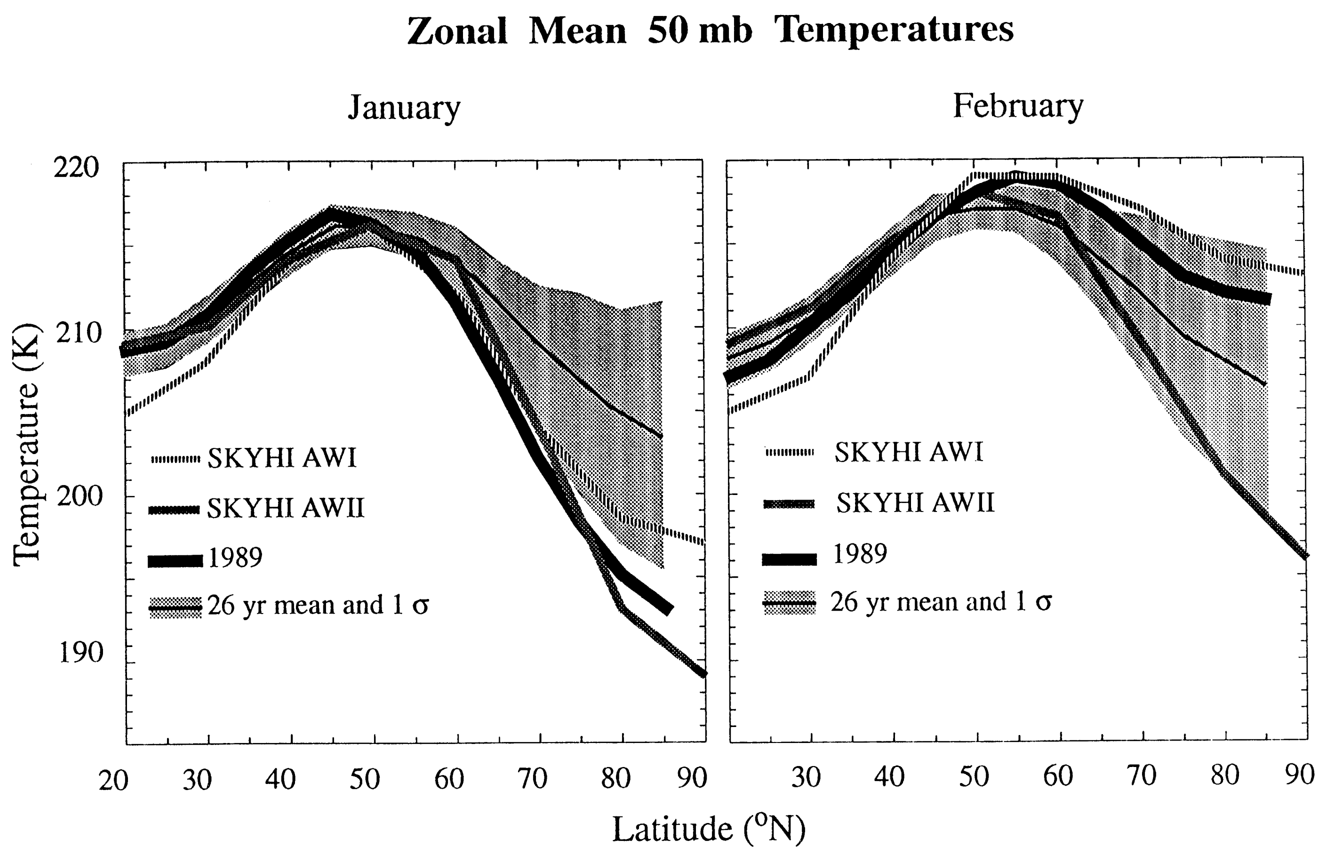

Fig. 1a Fig. 1b

Figure 1. Comparison of the 26-year mean of northern hemisphere zonal mean 50-mbar temperatures with the first and second SKYHI winters and 1989. (a) January: SKYHI and 1989 have a cold January at high latitudes. (b) February: high temperatures at high latitudes for 1989 and SKYHI AWI reflect warming events.

Figure 2a shows a time series of 1989 50-mbar temperatures at 60°N, 6°E (Stavanger) and 80°N, 20°E (Spitzbergen) from late December to mid-February [*Newman et al.*, 1989]. These locations represent points that are almost always outside (60°N) and always inside (80°N) the vortex. Before the warming, both model winters have temperature and variability at 60°N that look remarkably like the 1989 conditions (Figures 2b and 2c). The first SKYHI winter has a sudden warming similar to the one observed in 1989, with warming at 60° leading that at 80° by a few days; even the rate and magnitude of warming are comparable. Throughout both model Januaries there is excellent agreement at 60°N with the observed 50- and 100-mbar temperatures (100-mbar temperatures not shown). At 80°N 20°E the model 50-mbar temperatures in the month preceding the warming average about 4 K lower than the 1989 temperatures, although the 100-mbar temperatures (not shown) are in good agreement.

In Figure 3 the second SKYHI Arctic winter vortex and the 1989 vortex are compared by looking at the latitude and wind speed at the vortex edge at 10°E [*Newman et al.*, 1989]. The vortex edge is defined by the location of the maximum gradient of potential vorticity; this is generally collocated with the wind speed maximum. For simplicity, AWI results are omitted from this figure; they are very similar to the AWII and the following description applies to AWI results as well. The 550 K surface was chosen because it is just above the range of the AASE measurements and because the edge is always well defined at this level. The 425 K surface was also examined (not shown) because it represents a level near the "bottom" of the real and the model vortex. (The bottom of the vortex implies a level below which there is little barrier to mixing between polar and lower latitude air and no large potential vorticity gradients.) At 550 K the model wind speed maximum has realistic daily variability, and the mean wind maximum in January and February is very similar to the 1989 mean maximum. The average location of the model edge is slightly south of the mean 1989 vortex edge, but variability of the edge latitude compares well. Model winds at the 425 K vortex edge tend to be a little weaker than 425 K AASE winds, and the edge was often difficult to define. The frequent lack of a model wind speed maximum at 425 K, or the presence of a very diffuse one, indicates that the 425 K surface is sometimes below the "bottom" of the model vortex. That is, the 425 K polar air may not be so isolated from lower latitude air as it appeared to be in AASE.

In summary, although model 50 mbar (~460 K) temperatures are a little low inside the vortex and the vortex loses some of its isolation below 425 K, SKYHI is otherwise able to credibly simulate the magnitude and variability of winds and temperatures in the Arctic lower stratosphere during winter, including a realistic sudden warming. These two model winters cannot represent a complete climatology, but the interannual variability shown is encouraging; the coincidental agreement with the AASE winter is fortuitous for this study.

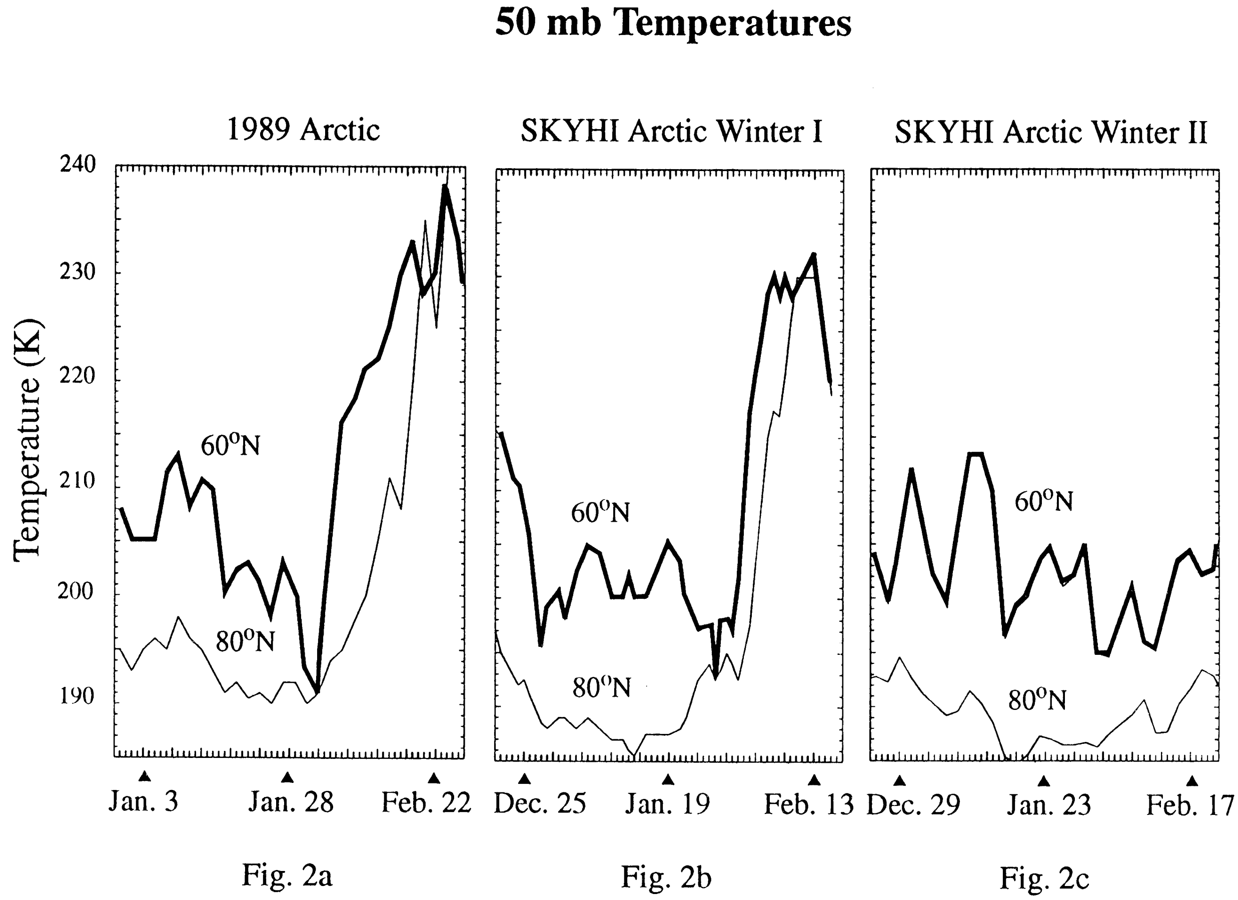

Figure 2. The 50-mbar temperature time series, beginning in early winter, at two locations that represent points typically outside (Stavanger, Norway 60°N, 6°E) and inside (Spitzbergen, Norway 80°N, 20°E) the polar vortex. (a) 1989 observations. (b) SKYHI Arctic winter I (AWI). (c) SKYHI Arctic winter II (AWII). AWI shows a sudden warming very similar to the one observed in 1989. Before the warming, model temperatures and variability at 60°N for both winters are quite similar to the observations.

SKYHI Antarctic Winter in the Context of the 12-Year Mean

In Figure 4, 12 years of southern hemisphere 50-mbar zonal mean temperatures for August and September are shown [*Randel*, 1992], in order to place the SKYHI and 1987 data into the context of a climatological mean. The model does a good job simulating the midlatitude warm belt. At the high latitudes, August 1987 appears to be an average August, while September 1987 is 1σ below the mean. Compared to monthly mean temperatures in the northern winter (Figure 1), the southern temperatures show much less interannual variability. This is due to more intense and variable wave activity in the northern winter. Equatorward of 65°S, SKYHI is within 1σ of the 12-year mean, but poleward of 65° SKYHI temperatures are more than 2σ below the mean. For August and September between 55° and 80°S, where most model/data comparisons will be made, SKYHI goes from being very similar to 1987 conditions to being roughly 7 K too cold.

A 10-year climatology of the 3° version of SKYHI gives roughly the same comparison with observations as 1° SKYHI. There is little difference between lower stratospheric temperatures poleward of 50°S in 1° and 3° SKYHI; both are in the range of 0-10 K below the climatological mean for the June/July/August period. The higher model resolution improves Antarctic winter temperatures and winds only above 10 mbar.

SKYHI Antarctic Winter in the Context of the 1987 Antarctic Winter

Figures 5 and 6 compare SKYHI temperatures and vortex characteristics in the region of the AAOE measurements. Figure 5 shows a time series of 50-mbar temperatures at 55°S, 290°E (near Punta Arenas, Chile) and 80°S, 290°E (near the Palmer peninsula) from mid-August to early October [*Newman et al.*, 1988]. These locations represent points that are almost always outside (55°S) and always inside (80°S) the vortex. The model 50-mbar temperatures and variability at 55°S are quite similar to the 1987 conditions, and this good agreement also exists at 100 mbar (not shown). Inside the vortex, at 80°S, the figure shows the cold polar vortex problem, with 100-mbar temperatures averaging 3 K too low and 50-mbar temperatures about 7 K too low. No warmings were observed in the model or in August or September 1987.

Figure 6 shows the latitude and wind speed at the 550 K vortex edge for SKYHI and the 1987 vortex [*Newman et al.*, 1988]. Both the 425 K and 550 K surfaces were examined for

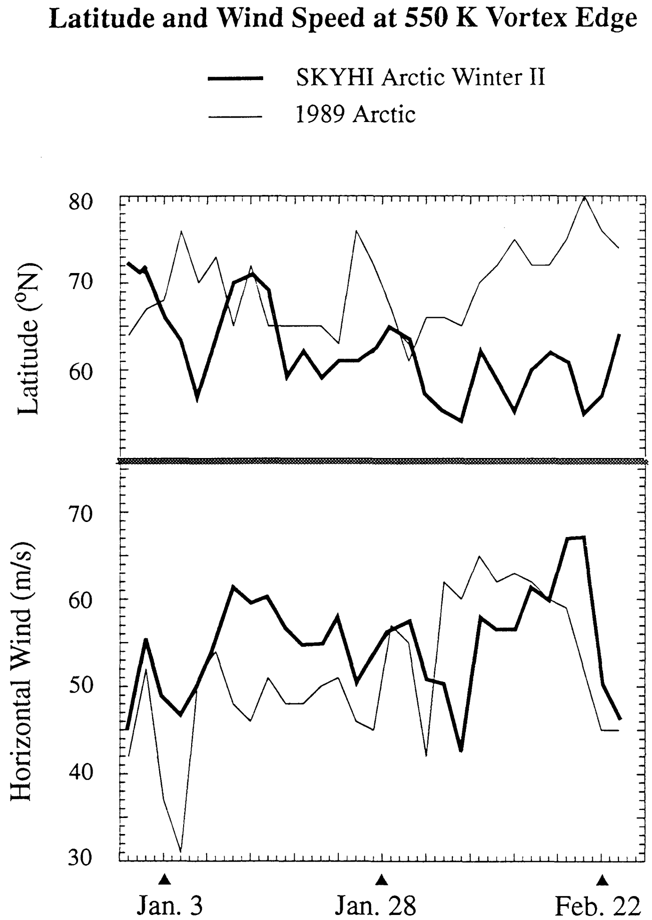

Figure 3. Time series of the vortex edge latitude and wind speed maximum at 10°E on the 550 K surface for SKYHI AWII and the 1989 Arctic vortex. On the average, the SKYHI vortex edge (thick curve) is located a few degrees south of the 1989 edge; model horizontal winds are comparable to the observations. The model vortex edge and wind speed maximum show variability matching the observations. This suggests that the model vortex is disturbed by wave activity outside the vortex to a similar extent as the real atmosphere.

the same reasons previously mentioned. At 550 K the wind speed maximum and edge latitude for SKYHI are in excellent agreement with the magnitude and variability of the 1987 vortex. Although model winds at the 425 K vortex edge tend to be a little weaker than AAOE winds, the edge was easier to identify than in the Arctic at 425 K, and its average location is the same as the 1987 425 K edge. The higher 425 K wind speed maximum suggests that Antarctic vortex air is more isolated than Arctic air at this altitude. The SKYHI Antarctic mean vortex edge occurs at the same latitude as the mean 1987 edge and wobbles around in a realistic way (similar edge latitude variability). It has realistic wind speed maxima both above and below the levels of the AAOE observations. The overall appearance of the SKYHI vortex is much like the 1987 Antarctic vortex, with the exception that lower stratospheric temperatures inside the model vortex are too low.

The conclusions reached in MU87 concerning improved zonal winds in the 1° version of SKYHI are supported by this study. In fact, the wind speed maxima for both the northern and the southern vortex at 425 and 550 K are slightly weaker than the observations. SKYHI 50-mbar temperatures are in good agreement with AASE and AAOE observations and with the climatological means everywhere except inside the Antarctic vortex. The cold pole problem is still apparent in the Antarctic lower stratosphere in spite of increases in E-P flux convergence in the 1° latitude model that have brought the lower stratospheric vortex wind maximum into agreement with climatological winds [MU87]. This result suggests that the polar jet should be too strong higher up; other model analysis shows this to be the case.

3. N_2O Morphology in the Polar Vortices

The availability of high-latitude stratospheric N_2O observations has made a detailed diagnostic study of SKYHI winter hemisphere polar dynamics possible. The AAOE and AASE data sets each span about 5 weeks of winter and cover a roughly 20° latitude by 140 K potential temperature cross section of the lower stratosphere. Averaging together all flight data from each mission produces a contour map that illustrates N_2O morphology in and around the vortex. Because N_2O is a conservative tracer in this region, examining N_2O morphology provides a means to interpret the dynamics of the polar stratosphere. For example, tracer gradients on isentropic surfaces across the vortex edge reveal the balance between quasi-horizontal mixing in midlatitudes and diabatic descent at high latitudes. The mean N_2O fields derived from these unique data sets provide an opportunity to evaluate the results of 1° latitude SKYHI dynamics and transport.

Aircraft Observations

The observations used in this analysis were made by the Airborne Tunable Laser Absorption Spectrometer (ATLAS), flying on board the NASA high-altitude ER-2 aircraft [*Podolske et al.*, 1989; *Loewenstein et al.*, 1990]. ATLAS data are reported at 1 Hz, equivalent to a spatial resolution of 200 m. Power spectra of the flight data show white (instrument) noise below scales of 500 m on most flights; the results here are averaged over five data points, resulting in 1-km resolution. N_2O data were collected during two major field campaigns: the Airborne Arctic Stratospheric Expedition (January-February 1989) and the Airborne Antarctic Ozone Experiment (August-September 1987). For a description of the AASE mission and the logistics of the ER-2 flights, see *Turco et al.* [1990]; for the AAOE, see *Tuck et al.* [1989].

Observations of Arctic N_2O were made during 14 ER-2 flights from January 3 to February 10, 1989 (AASE). All flights originated in Stavanger, Norway (59°N, 5°E), and went as far north as 82°, covering longitudes from 5°E to 20°E, with one flight to Greenland (37°W). Most flight tracks were on isentropic surfaces between 400 K and 510 K (~15 to 21-km pressure altitude). Nearly all flight tracks had a vertical profile that sampled isentropic surfaces from 370 to 470 K (approximately), usually at the northern end of the flight track. Flight duration was typically 6 to 7 hours. Meteorological data including pressure, temperature, and wind speeds (u, v, and w) were measured by the meteorological measurement system (MMS) [*Chan et al.*, 1990].

Antarctic N_2O observations were made from August 17 to September 22, 1987, during the 12 ER-2 flights of the AAOE. N_2O measurements from the first two flights (August 17

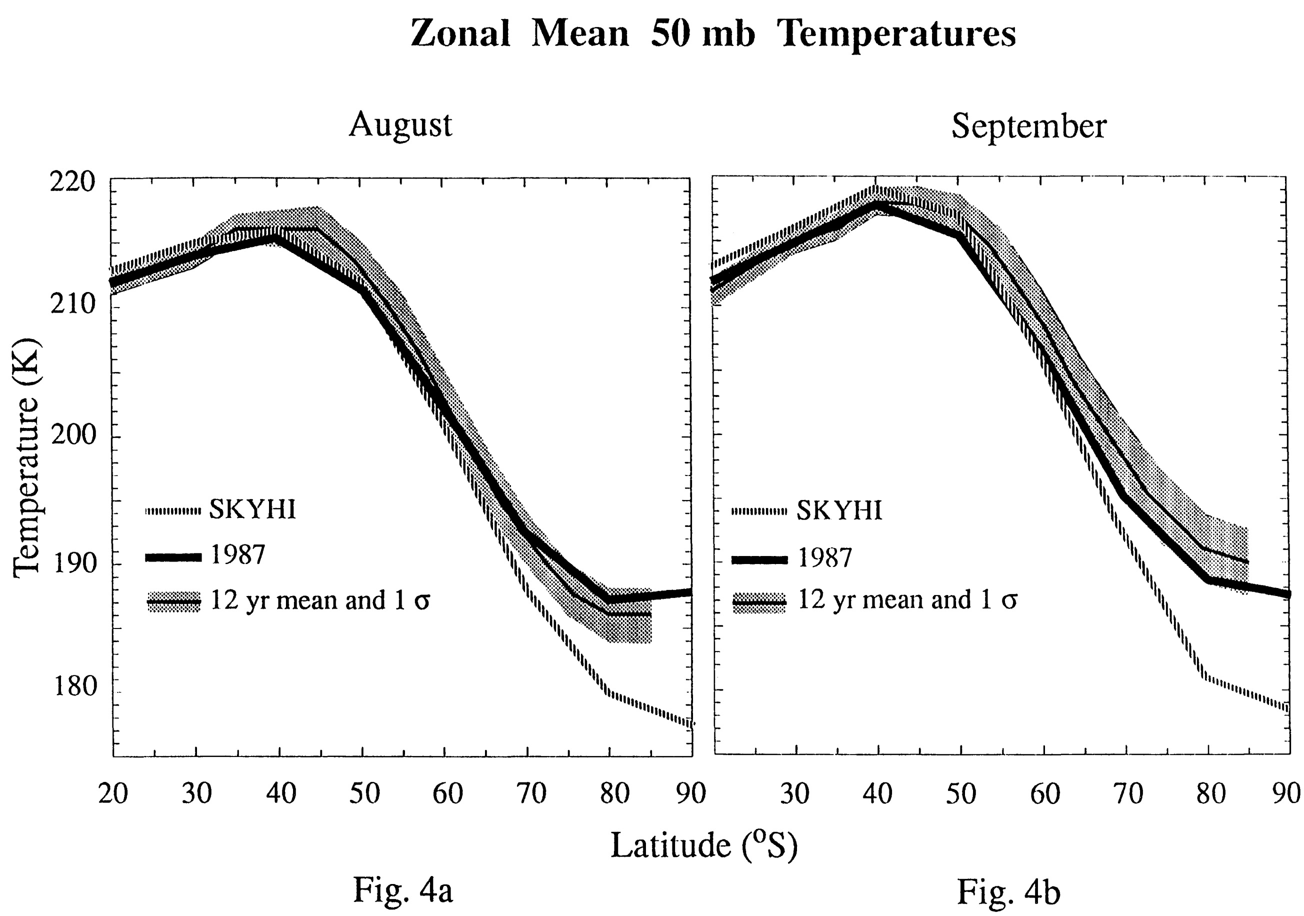

Figure 4. Comparison of a 12-year mean of southern hemisphere zonal mean 50-mbar temperatures [*Randel*, 1992] with the SKYHI southern winter and 1987 temperatures. (a) August and (b) September. The model cold pole bias is apparent poleward of 70°S.

and 18) had excessive instrument noise and are not used in this analysis. All flights originated in Punta Arenas, Chile (53°S, 289°E), and went as far south as 72°, with longitudes ranging from 280°E to 300°E (near the Antarctic peninsula). Most flight tracks were on isentropic surfaces between 400 K and 500 K (~15 to 19-km pressure altitude) and lasted roughly 6 hours. Most flights included a vertical profile at 72°S that sampled isentropic surfaces from 350 to 450 K (approximately). Meteorological data for AAOE are reported by *Chan et al.* [1989].

Calculation of Mean N_2O Fields for SKYHI, AASE, and AAOE

Calculation of mean N_2O fields from the observations involves binning all flight data by latitude relative to the vortex edge and potential temperature. For each mission all flight data were sorted into bins of 0.5° relative latitude and 5 K potential temperature and then averaged. Although the range of bins sampled was -16° to +15° relative latitude (< 0 implies outside the vortex) and 360 K to 510 K for AASE, not every latitude/potential temperature bin was sampled. To fill in gaps, an N_2O value was interpolated from surrounding isentropic bins. If the adjacent vertical (potential temperature) bins had values but the horizontal ones (relative latitude) did not, the N_2O value was obtained by interpolation of the vertical profile at that latitude. To produce the results shown, smoothing by third-order polynomial curve fitting was done iteratively on individual isentropic surfaces and then on the vertical profile at each latitude. The final results of this interpolation and curve-fitting process for AASE and AAOE are seen in Plates 1a and 2a, respectively. Statistical information on the contour map bins containing aircraft measurements (rather than interpolated values) and their interflight variance is presented in Table 1.

On many flight days the ER-2 passed outbound through the edge at one latitude and isentrope but returned inbound across the edge at a different latitude and different isentrope, revealing that the vortex edge is tilted in the vertical. However, because the mean N_2O field is calculated by binning all data with respect to distance from the vortex edge, the best results are obtained by choosing a vortex edge latitude for each isentropic flight segment, rather than using one latitude for the vortex edge for the entire flight. This method produces the best estimate of the mean on each isentropic surface, but information on the vertical structure of the vortex edge is lost. Consequently, vertical gradients shown in Plates 1 and 2 have some uncertainty (e.g., the vortex edge at 460 K may not lie directly under the 480 K edge on a given day). The SKYHI vortex edge also has vertical tilt, but for consistency with AASE the SKYHI mean fields are calculated in exactly the same way; thus the resulting mean fields do not contain precise vortex vertical structure information either. For the model and the observations, the more accurate representation of tracer gradients at the vortex edge is seen in the horizontal, not the vertical. Details of the flight data and model output used in the mean field calculations are found in Table 2.

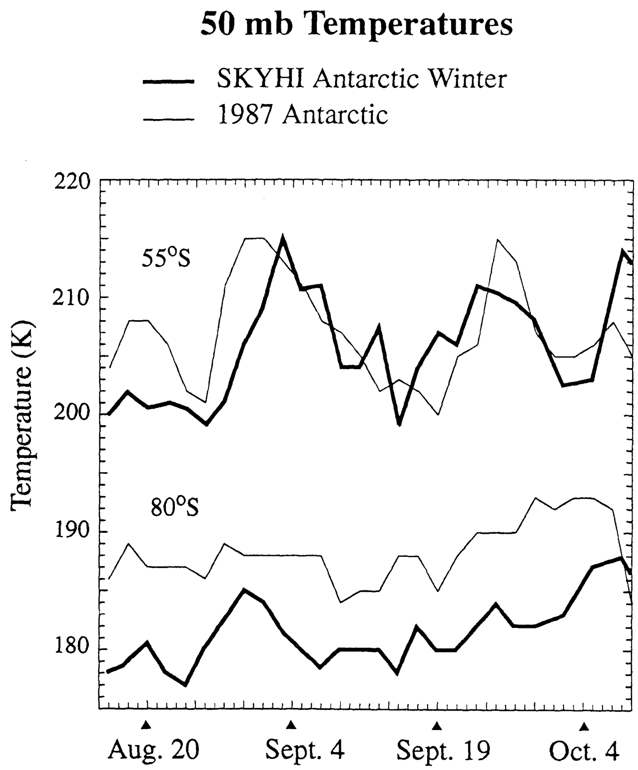

Figure 5. The 50-mbar temperature time series, beginning in late winter, at two locations that represent points typically outside (near Punta Arenas, Chile 55°S, 290°E) and inside (near the Palmer peninsula, Antarctica 80°S, 290°E) the polar vortex for the 1987 observations and SKYHI (thick curve). While the model temperatures and variability outside the vortex are very similar to the observations, model temperatures inside the vortex average about 7 K too low during the late winter/early spring time period.

Mean model N_2O fields were calculated from existing model output. For the SKYHI Arctic mean, 24 days were selected that spanned model days December 31 to February 15 (about every other day); for the Antarctic mean, 23 days between August 16 and October 1 were used. These particular time periods were chosen to cover the dates of the observation periods and include about a week before and after those dates. To calculate mean fields up to 15° outside and 20° inside the vortex, latitudes from 50° to 89° were used. For each hemisphere, four longitudes were used that spanned the longitudes of the observations: 3.6°-18.0°E for the Arctic and 280°-300°E for the Antarctic. Eight isentropic surfaces from 360 K to 500 K were used in both hemispheres. Averages were calculated by binning the model data by latitude relative to the vortex edge and potential temperature; bin sizes were 1° relative latitude and 20 K. Mean SKYHI AWII Arctic and AWI Antarctic N_2O fields are shown in Plates 1b and 2b, respectively. A mean field for SKYHI AWI was also calculated but is not shown here. Compared to Plate 1b, the SKYHI Antarctic of Plate 2b shows flatter N_2O gradients at the vortex edge and higher mixing ratios both inside and outside the vortex. This is partly caused by the initialization of 1° SKYHI three months earlier from a 5° latitude version of SKYHI. The 5° version has much flatter meridional N_2O slopes than 1° SKYHI, and a year or more is required for the N_2O structure to achieve "slope equilibrium" [*Mahlman et al.*, 1986]. In AWI the tracer slopes are still adjusting from their relatively flat initial state.

Schoeberl et al. [1992] have estimated mean AASE and AAOE N_2O fields using a reconstruction technique whereby aircraft N_2O data are mapped onto a potential vorticity/potential temperature coordinate system. By using this coordinate system and by taking advantage of the partial conservation of potential vorticity (PV) and complete conservation of N_2O over the duration of each aircraft campaign, NMC analyses of PV and potential temperature can be used as a rough estimate of N_2O outside the aircraft flight region [*Schoeberl et al.*, 1989; *Lait et al.*, 1990]. The mean N_2O fields reconstructed by *Schoeberl et al.* [1992] are very similar to the fields presented here but with two important differences. First, their reconstructed fields are shown on pressure surfaces, giving them the appearance of a downward bulge near the vortex edge; this is simply a function of the differences between pressure and isentropic surfaces at high latitudes in winter. Second, their reconstruction technique allows them to calculate the tilt of the vortex edge with respect to height. As mentioned before, this is not possible for mean fields calculated from ER-2 measurements alone.

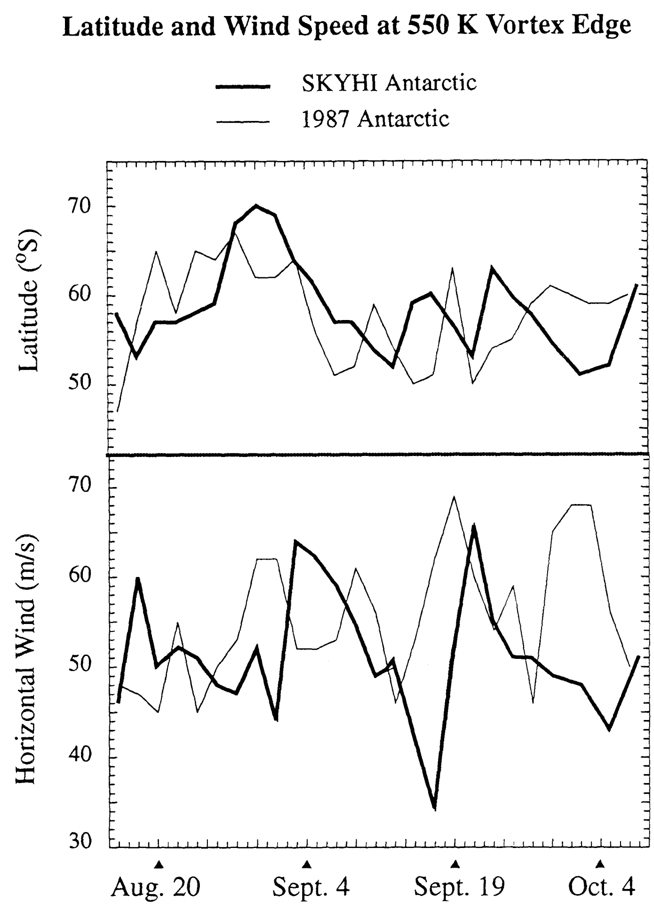

Figure 6. Time series of the vortex edge latitude and wind speed maximum at 200°E on the 550 K surface for SKYHI and the 1987 Antarctic vortex. On the average, the SKYHI vortex edge (thick curve) is located at the same latitude as the 1987 edge, and the horizontal winds are comparable to the observations. The model vortex edge and wind speed maximum show variability matching the observations. Similar agreement is seen on the 425 K surface, near the bottom of the model vortex.

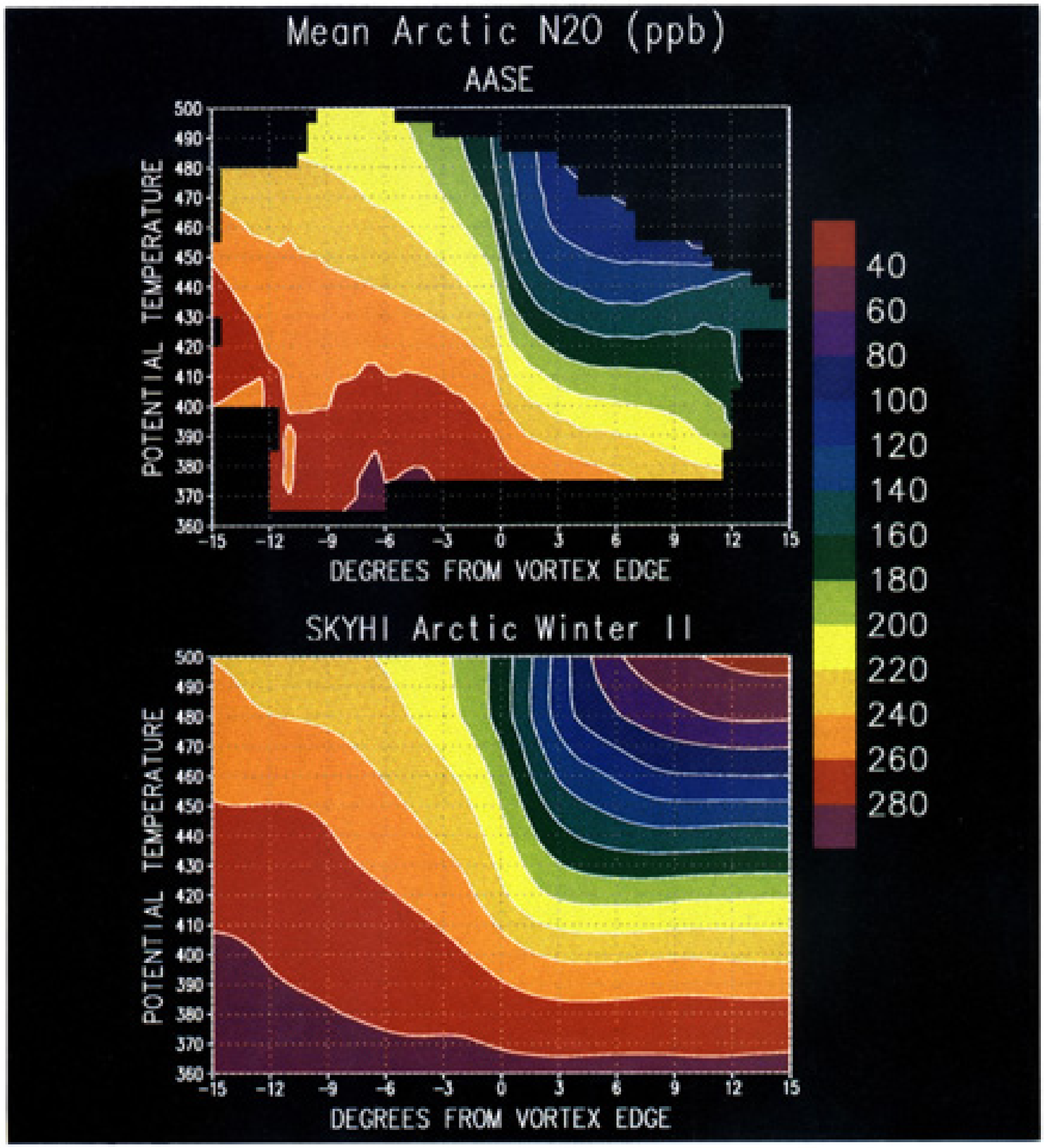

Plate 1. (a) Mean N_2O mixing ratios on potential temperature surfaces calculated from 14 Airborne Arctic Stratospheric Experiment (AASE) flights. The latitude coordinate is "degrees latitude relative to the vortex edge" (see text). Contour intervals are 20 ppb. Black areas indicate no data. (b) Same, except using SKYHI model results from 24 days covering the same spatial and temporal region.

Comparison of Mean N_2O Fields

The mean AASE N_2O field in Plate 1a is characterized by very steep N_2O gradients on isentropic surfaces at the vortex edge and a difference of about 100 K between N_2O isopleths inside and outside the vortex (above 460 K outside). Above 400 K the AWII mean field in Plate 1b shows roughly the same steepness at the edge; this is a good indication that the model has sufficient planetary wave breaking in the region outside the vortex (the "surf zone"). The primary differences between Plates 1a and 1b are the flatter model vortex edge below 400 K and mixing ratios that are somewhat high below 450 K, especially inside the vortex. The AASE mean shows lower N_2O inside the vortex even at 370 K. Below 400 K the flat model gradients imply a relatively weak barrier to mixing between the two regions, whereas the observations indicate greater isolation of the polar air. Between 400 and 500 K both inside and outside the vortex, AWII N_2O mixing ratios are within 10-20 ppb of the observed mixing ratios.

Plate 2 shows that the agreement between observed and SKYHI mean tracer fields in the Antarctic is not so good as the Arctic. Model mixing ratios are too high everywhere, by 20-60 ppb outside and 30-90 ppb inside the vortex, and the edge gradients are a little flat. In the AAOE mean field, although the gradients are much flatter than in AASE, the tracer gradients are concentrated over a narrower region (12^o-15^o latitude)

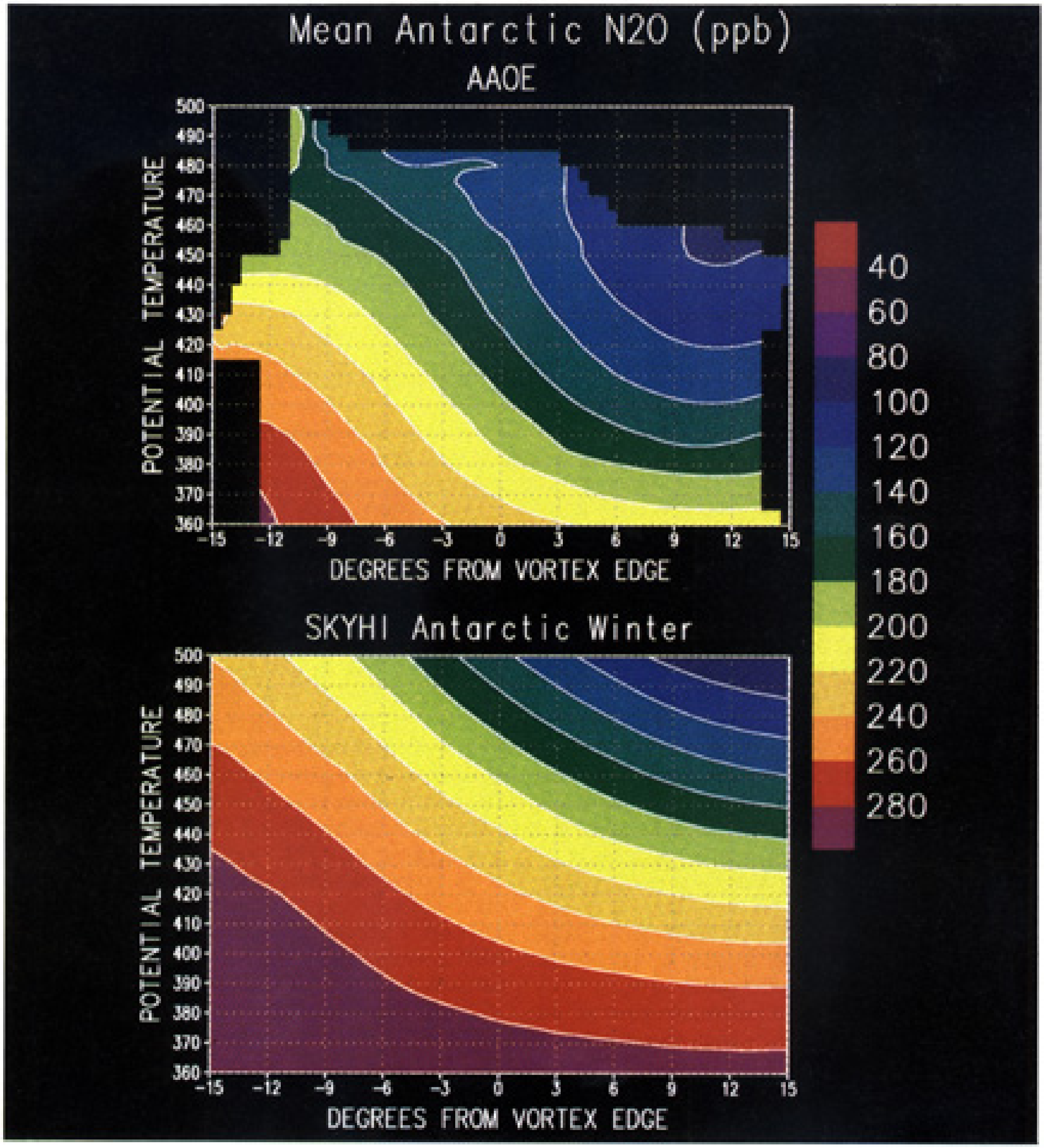

Plate 2. (a) Mean N_2O mixing ratios on potential temperature surfaces calculated from 10 Airborne Antarctic Ozone Experiment (AAOE) flights. The latitude coordinate is "degrees relative to the vortex edge." Contouring is identical to Plate 1. (b) Same, except using SKYHI model results from 23 days covering the same spatial and temporal region.

than in the model. The model requires ~25° of latitude to produce approximately as much N_2O decrease as seen in AAOE. The lack of a well-defined edge in the model southern hemisphere suggests there is insufficient wave activity necessary to (1) generate enough of an edge-sharpening surf zone [*McIntyre and Palmer*, 1983] and (2) induce a strong enough diabatic descent within the vortex [*Mahlman et al.*, 1986].

The high mixing ratios in the Antarctic are an indication of the time needed to establish tracer equilibrium, as has been suggested by the difference between AWI and AWII mean fields. Because the southern hemisphere winter stratosphere is less dynamically forced than the northern hemisphere, the equilibration time will be longer. A comparison of mean June fields of N_2O in the SKYHI southern hemisphere year 1 and year 2 (8 and 20 months, respectively, since initialization) shows rather different N_2O structure for the Antarctic vortex. Using the differences between the June isopleths of year 1 and year 2 and the motion of the isopleths between June and September in year 1, it is estimated that in September of year 2, mixing ratios at 470 K will decrease by ~15 ppb outside and by ~50 ppb inside the vortex. Although the estimated changes at 420 K are smaller and mixing ratios will still remain substantially too high everywhere at low altitudes, the effect of additional equilibration time will help considerably to steepen the model's edge gradients.

Table 1. Statistics on Flight Data Used to Calculate Mean Fields

	AASE	AAOE
Number of bins shown in contour maps*	1241	1378
Percentage of bins containing observations	70	46
Percentage of bins containing observations having only a single observation†	34	34
Percentage of bins having more than one observation that have an interflight standard deviation of < 10%	70	70
Percentage of bins having more than one observation that have an interflight standard deviation of < 15%	87	88

AASE, Airborne Arctic Stratospheric Experiment; AAOE, Airborne Antarctic Ozone Experiment.

*Bins are 0.5° latitude and 5 K potential temperature.

†A bin containing a "single observation" means that the relative latitude and potential were sampled on only one flight leg. The "single observation" is actually the mean of ~ 275 measurements made within that bin on that flight leg. The Airborne Tunable Laser Absorption Spectrometer N_2O instrument has 200-m spatial resolution, resulting in up to ~ 275 measurements over 0.5° latitude (~ 55-km) distance.

Comparison of Nonaveraged Features

An important feature of the observations is extremely sharp gradients of N_2O on isentropic surfaces at the edge of the Arctic vortex. On one flight, a 60 ppb change in N_2O was observed during ~5 km of isentropic travel, and every flight had an edge gradient at least as steep as 75 ppb per 100 km. One degree (110 km) SKYHI is able to produce gradients as high as 56 ppb/110 km and 99 ppb/220 km on the 460 K surface. Figure 7 illustrates the similarities between AASE and AWII isentropic data. Given the horizontal resolution of 1° latitude (~110 km), SKYHI cannot match observed gradients having a scale of a few kilometers, but over a distance of only two grid points (220 km) the average AWII 460 K edge gradient is 54 ppb/220 km, nearly as steep as the average AASE edge gradient (400-500 K) of 67 ppb/220 km.

In both the model and the observations, gradients at the Antarctic vortex edge are much less steep than the Arctic gradients. N_2O "cliffs" such as the 60 ppb/5 km drop observed in AASE, were not observed in AAOE. Figure 8 shows the steepest AAOE edge gradient (61 ppb/140 km); average AAOE gradients are 35 ppb/110 km and 45 ppb/220 km. The sharpest gradient found in this SKYHI data set is 29 ppb/220 km, while SKYHI average gradients are 11 ppb/110 km and 19 ppb/220 km, less than half the AAOE averages.

Sometimes a double edge was observed on AASE flights. Synoptically, this would appear as a filament of vortex air being sheared away from the vortex (e.g., from a wave breaking event), with an intrusion of lower-latitude (higher N_2O) air between the vortex and the filament. In Plate 3 the filament of low N_2O air (green) stretches from 0° to 60°E. This sort of double edge is observed frequently in the SKYHI northern hemisphere (Plate 3). Plate 3 also illustrates how the edge gradients vary with longitude (in relation to the strength of the horizontal wind). Therefore as the vortex rotates, data collected from a fixed longitude will show variations in edge gradients. Although no high-resolution hemispheric map of lower stratospheric N_2O observations exists, the variance of the mean AASE edge gradient can be used as a rough estimate of longitudinal variability. The standard deviation of the AASE 110- and 220-km edge gradients are 25-30% of the mean, while for AWI and AWII they are about 33%. This suggests that the real longitudinal variations in N_2O edge gradients may look something like what is seen in SKYHI in Plate 3.

Table 2. Flight Data and Model Results Used to Calculate Mean Fields

	Number of Flight Legs or Model Days	Dates	Potential Temperature, K	Latitude	Degrees Relative to Vortex Edge	Longitude
AASE	28	January 3 - February 10	365-500	60°-82°N	-15.5 to +15	5°-22°E*
SKYHI AWII	24	December 31 - February 15	360-500	50°-89°N	-18 to +28	4°-18°E
AAOE	20	August 23 - September 22	345-500	54°-72°S	-16 to +15.5	63°-80°W
SKYHI Antarctic	23	August 16 - September 29	360-500	50°-89°S	-15 to +31	64°-78°W

AWII, second Arctic winter. For each hemisphere, SKYHI output from eight isentropic surfaces (360 to 500 K, inclusive) and four longitudes are used to calculate mean N_2O fields. Thus there are actually 32 "flight legs" for each SKYHI model day used.

*The flight of February 10, 1989 went to Greenland (37°W). The vast majority of the flight data was collected between 6° and < 20°E.

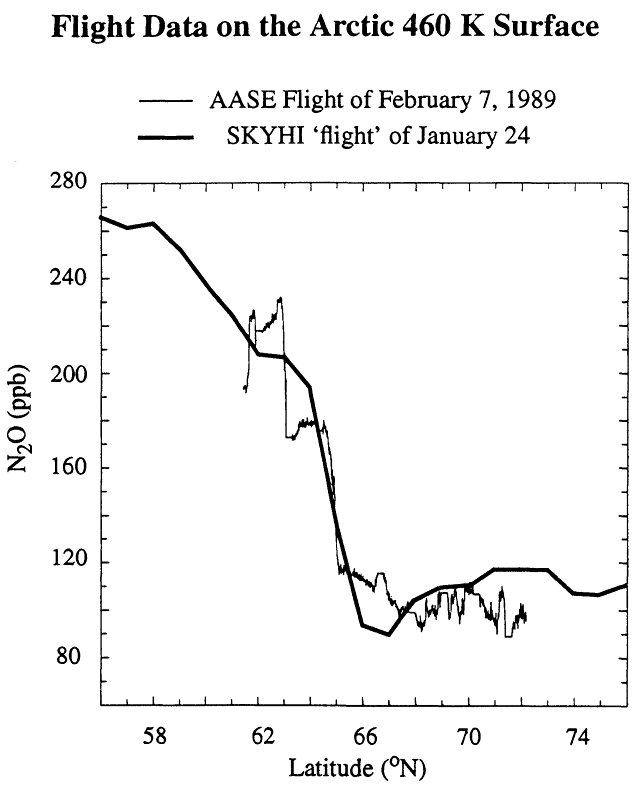

Figure 7. Comparison of AASE flight data with SKYHI output on the 460 K surface. AASE data have a 1-km spatial resolution, model results have 110-km resolution. However, over 2° of latitude the model is able to produce an N_2O gradient matching the observed gradient. Model mixing ratios on the 460 K surface inside the vortex agree well with the observations.

Plate 4 shows the SKYHI Antarctic vortex for September 23; a filament of air being sheared off from the vortex by a wave breaking event can be seen. Compared to the Arctic, the edge gradients are much flatter at all longitudes and the vortex is less perturbed. From model dates August 16 to October 1, no warming events were observed in the lower stratosphere. The Antarctic vortex is relatively quiescent compared to the Arctic, and this is reflected in the smaller model mean edge gradient, about one third that of the Arctic. It is also much less active than the observed 1987 vortex, judging by the differences in both mean and standard deviation of AAOE and model tracer gradients (45 ± 16 ppb/220 km for AAOE and 19 ± 3 ppb/220 km for SKYHI).

Plate 4 also shows much greater zonal symmetry than Plate 3, illustrating the differences in dynamical forcing between the hemispheres. The effects of the dynamical forcing asymmetry are also manifested in greater descent in the northern midlatitudes, where N_2O mixing ratios are considerably lower than in the southern midlatitudes.

4. Summary

With only 20 months of integration no climatological mean can be established for the 1° version of SKYHI. However, SKYHI January and February temperatures in the two northern hemisphere winters were found to be within 2σ of a 26-year mean and the high latitudes exhibit considerable interannual variability. In the comparison with meteorological conditions during the time of the AASE measurements, both model winters showed great similarity to the observed 50-mbar and 100-mbar temperatures at 60°N. At 80°N, near Scandinavia, the model January 50-mbar temperatures averaged about 4 K too low, although the 100-mbar temperatures were in good agreement. The wind speed maximum for both SKYHI winters has realistic daily variability; the mean wind maximum for AWI is about 8 ms^{-1} lower than the observations, while AWII wind maximum is very similar to the 1989 winds. Winds at 425 K are too weak in both winters, suggesting that the vortex loses some of its isolation below 425 K, whereas isolation of AASE vortex air appears to extend to ~370 K. The average location of the model edge in both winters is a few degrees south of the mean 1989 vortex edge, but variability of the edge latitude compares well with the 1989 vortex. Overall, SKYHI is able to simulate the magnitude and variability of winds and temperatures in the Arctic lower stratosphere during winter with credibility, including a realistic sudden warming (in AWI).

In the southern hemisphere in late winter, SKYHI zonal mean temperatures are within 1σ of the observed climatology equatorward of 65°S but are more than 2σ colder poleward of 65°S. For August and September between 55° and 80°S, SKYHI goes from being very similar to 1987 conditions to being roughly 7 K too cold. The SKYHI Antarctic vortex edge is found at the right latitude and wobbles around in a realistic

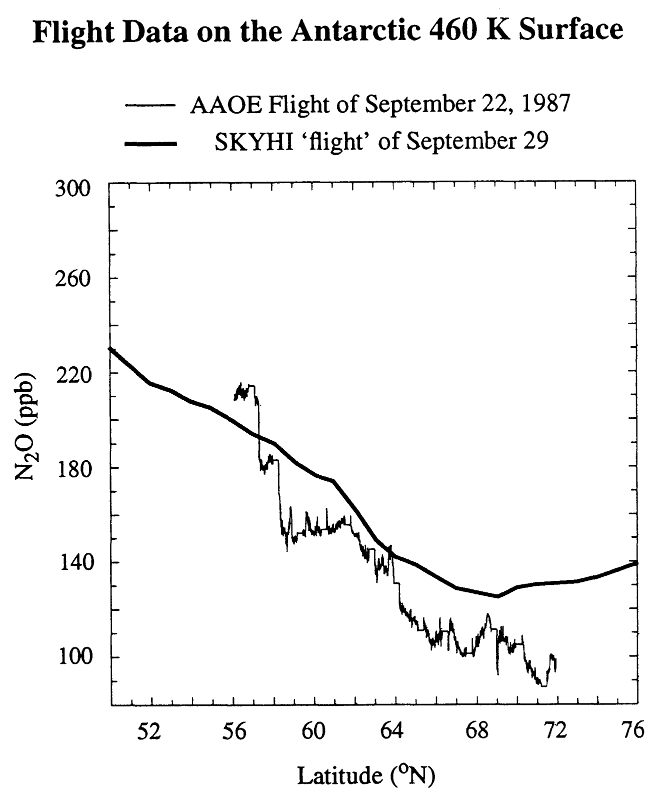

Figure 8. Comparison of AAOE flight data with SKYHI output on the 460 K surface. The gradient observed between 57° and 72°S is slightly greater than that produced in the model. Model mixing ratios are consistently too high at all latitudes shown.

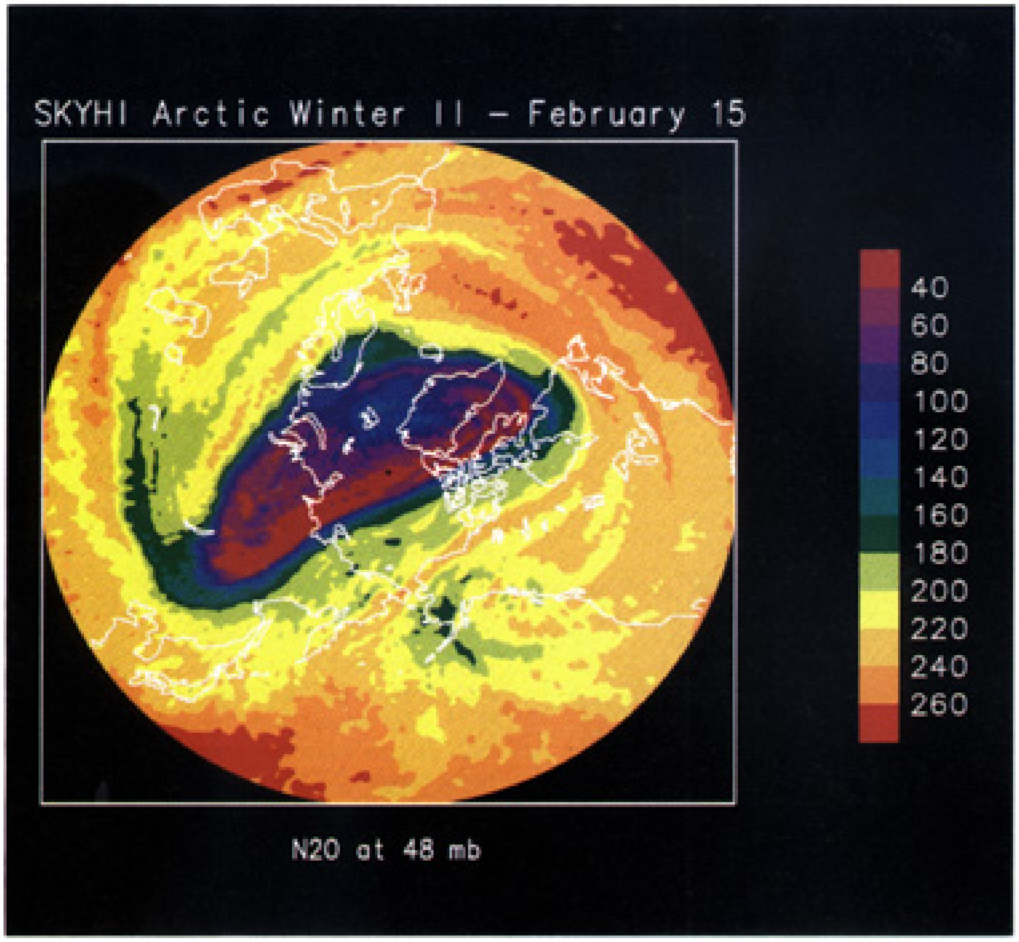

Plate 3. North polar satellite view of SKYHI N_2O at 48 mbar on model date February 15. A filament of vortex edge air (dark green) is being sheared away from the vortex over Europe and Asia, and higher mixing ratios (yellow) are intruding poleward of the filament. Note the high density of contours at the vortex edge.

way. It has wind speed maxima comparable to the AAOE wind maxima both above and below the levels of the observations, and the overall appearance is that of a realistic vortex. The conclusions reached by MU87 concerning improved polar night winds and temperatures in the northern hemisphere of the 1^o version of SKYHI are supported by this study, however, the cold pole problem is still quite apparent in the Antarctic lower stratosphere.

The AWII mean N_2O field shows roughly the same steepness at the edge as the AASE mean field, but there is slightly less descent of the isopleths inside the vortex. Below 400 K, nearly flat edge gradients in the model imply a weak barrier to mixing between the two regions, whereas the observations indicate a more isolated air mass. Between 400 and 500 K, both inside and outside the vortex, AWII N_2O mixing ratios are close to the observed mixing ratios. In the Antarctic, model mixing ratios are too high everywhere and the edge gradients are a little flat, but because the gradients are spread over more degrees of latitude, almost as much descent is seen overall as in AAOE. This results in the edge being less well defined. It is estimated that in the second SKYHI Antarctic winter mixing ratios both outside and inside the vortex will decrease (improve), with greater descent inside than outside the vortex leading to steepening of the edge gradients above 420 K. This picture of the polar vortices, with sharp meridional gradients at the edge and an isolated interior, is in close agreement with the analysis of *Schoeberl et al.* [1992].

Extremely sharp gradients of N_2O on isentropic surfaces at the Arctic vortex edge are a regular feature of the observations. The observed gradients often occur over a distance too small to be matched by SKYHI (e.g., 10 km), but over a distance of only two grid points (220 km) the average AWII edge gradient is comparable to the average AASE edge gradient. In the southern hemisphere the average gradients in the SKYHI data set are less than half the AAOE average gradients. The SKYHI Antarctic edge gradients have much less variability than the observed edge gradients, further indicating that the vortex is too undisturbed. Antarctic vortex gradients in both the model and the observations are much less steep than the Arctic gradients. On a hemispheric scale, the SKYHI Antarctic gradients are much flatter at all longitudes than AWII, and the vortex is less perturbed (more zonally symmetric).

Model temperatures in the polar lower stratosphere and tracer gradients across the vortex edge are a direct result of lower stratospheric dynamics. The comparison of mean tracer fields suggests realistic wave activity in the SKYHI Arctic winter lower stratosphere, but unrealistically weak wave activity in the southern hemisphere. In part 2 the results presented here will be used to supplement further diagnostic studies that assess the tracer variability and diabatic meridional circulation of SKYHI.

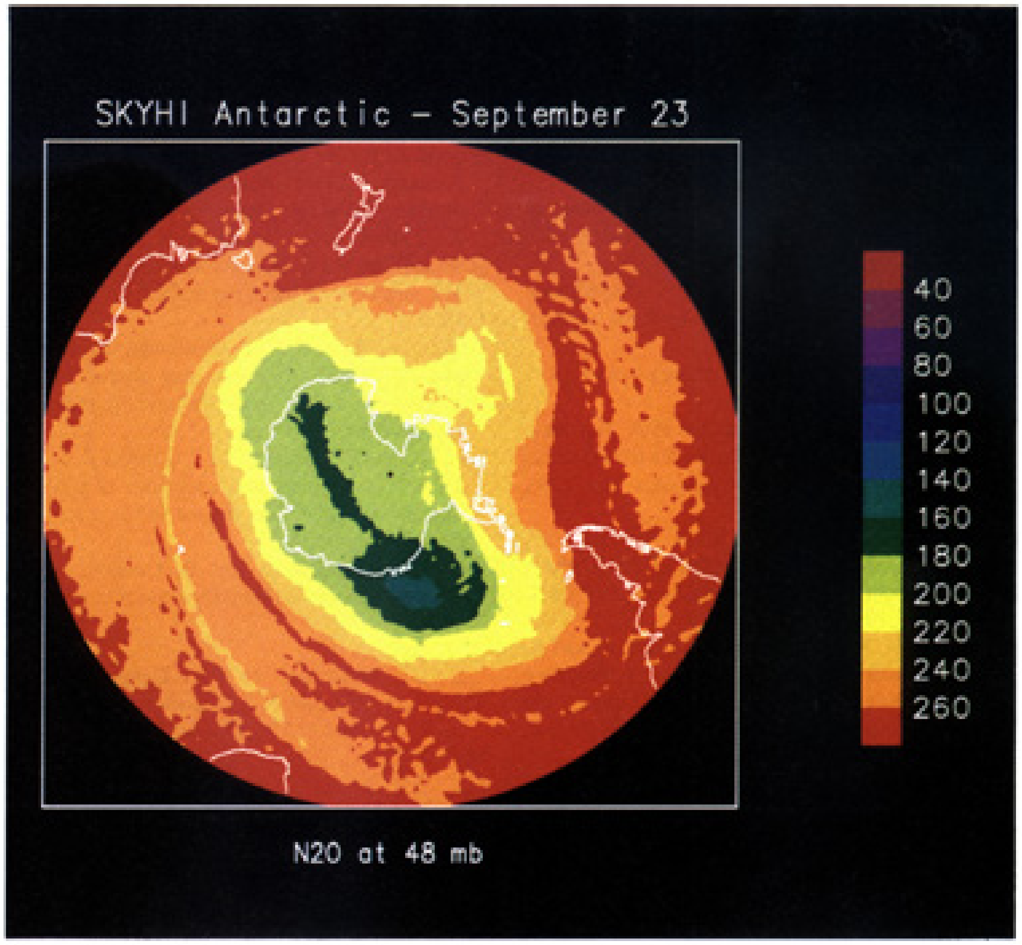

Plate 4. South polar satellite view of SKYHI N_2O at 48 mbar on model date September 23. Although the Antarctic vortex is less perturbed than the Arctic by planetary wave breaking outside the vortex, filamentation can still be seen. Contour density at the edge of the vortex is much less than for the northern vortex shown in Plate 3.

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References

Andrews, D. G., J. D. Mahlman, and R. W. Sinclair, Eliassen-Palm diagnostics of wave, mean-flow interaction in the GFDL 'SKYHI' general circulation model, *J. Atmos. Sci., 40*, 2768, 1983.

Chan, K. R., S. G. Scott, T. P. Bui, S. W. Bowen, and J. Day, Temperature and horizontal wind measurements on the ER-2 aircraft during the 1987 Airborne Antarctic Ozone Experiment, *J. Geophys. Res., 94*, 11,573, 1989.

Chan, K. R., S. W. Bowen, T. P. Bui, S. G. Scott, and J. Dean-Day, Temperature and wind measurements and model atmospheres of the 1989 Airborne Arctic Stratospheric Expedition, *Geophys. Res. Lett., 17*, 341, 1990.

Fels, S. B., J. D. Mahlman, M. D. Schwarzkopf, and R. W. Sinclair, Stratospheric sensitivity to perturbations in ozone and carbon dioxide: Radiative and dynamical response, *J. Atmos. Sci., 37*, 2265, 1980.

Hamilton, K., R. J. Wilson, J. D. Mahlman, and L. J. Umscheid, Climatology of the SKYHI Troposphere-Stratosphere-Mesosphere General Circulation Model, *J. Atmos. Sci.*, in press, 1994.

Hartmann, D. L., L. E. Heidt, M. Loewenstein, J. R. Podolske, J. Vedder, W. L. Starr, and S. E. Strahan, Transport into the South Polar vortex in early spring, *J. Geophys. Res., 94*, 16,779, 1989.

Hayashi Y., D. G. Golder, J. D. Mahlman, and S. Miyahara, The effect of horizontal resolution on gravity waves simulated by the GFDL "SKYHI" general circulation model, *Pure Appl. Geophys., 130*, 421, 1989.

Lait, L. R., et al., Reconstruction of O_3 and N_2O fields from ER-2, DC-8, and balloon observations, *Geophys. Res. Lett., 17*, 521, 1990.

Levy, H., II, J. D. Mahlman, and W. J. Moxim, Tropospheric N_2O variability, *J. Geophys. Res., 87*, 3061, 1982.

Loewenstein, M., J. R. Podolske, K. R. Chan, and S. E. Strahan, N_2O as a dynamical tracer in the Arctic vortex, *Geophys. Res. Lett., 17*, 477, 1990.

Mahlman, J. D., and S. B. Fels, Antarctic ozone decreases: A dynamical cause?, *Geophys. Res. Lett., 13*, 1316, 1986.

Mahlman, J. D., and W. J. Moxim, Tracer simulation using a global general circulation model: Results from a midlatitude instantaneous source experiment, *J. Atmos. Sci., 35*, 1340, 1978.

Mahlman, J. D., and L. J. Umscheid, Dynamics of the middle atmosphere: Successes and problems of the GFDL "SKYHI" general circulation model, in *Dynamics of the Middle Atmosphere*, edited by J.R. Holton and T. Matsuno, Terra Scientific, Tokyo, 1984.

Mahlman, J. D., and L. J. Umscheid, Comprehensive modeling of the middle atmosphere: The influence of horizontal resolution, in *Transport Processes in the Middle Atmosphere*, edited by G. Visconti and R. Garcia, D. Reidel, Norwell, Mass., 1987.

Mahlman, J. D., H. Levy II, and W. J. Moxim, Three-dimensional simulations of stratospheric N_2O: Predictions for other trace constituents, *J. Geophys. Res., 91*, 2687, 1986.

Manabe, S., and B. G. Hunt, Experiments with a stratospheric general circulation model, 1., Radiative and dynamic aspects, *Mon. Weather Rev., 96*, 477, 1968.

McIntyre, M. E., and T. N. Palmer, Breaking planetary waves in the stratosphere, *Nature, 305*, 593, 1983.

Nagatani, R. M., A. J. Miller, M. E. Gelman, and P. A. Newman, A comparison of Arctic lower stratospheric winter temperatures for 1988-89 with temperatures since 1964, *Geophys. Res. Lett., 17*, 333, 1990.

Newman, P. A., D. J. Lamich, M. Gelman, M. R. Schoeberl, W. Baker, and A. J. Krueger, Meteorological atlas of the southern hemisphere lower stratosphere for August and September 1987, *NASA Tech. Memo. 4049*, 1988.

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, *NASA Tech. Memo. 4145*, 1989.

Podolske, J. R., M. Loewenstein, S. E. Strahan, and K. R. Chan, Stratospheric nitrous oxide distribution in the southern hemisphere, *J. Geophys. Res., 94*, 16,767, 1989.

Randel, W. J., Global atmospheric circulation statistics, 1000-1 mb, *NCAR Tech. Note* 366, 1992.

Schoeberl, M. R., et al., Reconstruction of the constituent distribution and trends in the Antarctic polar vortex from ER-2 flight observations, *J. Geophys. Res., 94*, 16,815, 1989.

Schoeberl, M. R., M. H. Proffitt, K. K. Kelly, L. R. Lait, P. A. Newman, J. E. Rosenfield, M. Loewenstein, J. R. Podolske, S. E. Strahan, and K. R. Chan, Stratospheric constituent trends from ER-2 profile data, *Geophys. Res. Lett., 17*, 469, 1990.

Schoeberl, M. R., L. R. Lait, P. A. Newman, and J. E. Rosenfield, The structure of the polar vortex, *J. Geophys. Res., 97*, 7859, 1992.

Strahan, S. E., and J. D. Mahlman, Evaluation of the SKYHI general circulation model using aircraft N_2O measurements, 2, Tracer variability and diabatic meridional circulation, *J. Geophys. Res.*, this issue.

Tuck, A. F., R. T. Watson, E. P. Condon, J. J. Margitan, and O. B. Toon, The planning and execution of ER-2 and DC-8 aircraft flights over Antarctica, August and September 1987, *J. Geophys. Res., 94*, 11,181, 1989.

Turco, R., A. Plumb, and E. Condon, The Airborne Arctic Stratospheric Expedition: Prologue, *Geophys. Res. Lett., 17*, 313, 1990.

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