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Synoptic-scale mass exchange from the troposphere to the stratosphere

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Abstract. The transport of material between the troposphere and the stratosphere is studied with an off-line chemical transport model which uses winds from a global assimilated meteorological data set. The focus is on the role of rapidly growing synoptic waves in the maintenance of lower stratospheric tracer distributions in the extratropics. Satellite observations are used to establish that the modeled transport represents the observed tracer variability with sufficient accuracy to justify more quantitative analysis. Diabatic trajectory calculations are then used to understand the transport mechanisms in the model. Two rapidly developing surface cyclones are specifically studied and found to have qualitatively different impact on the tracer distribution. A strong storm in the Pacific Ocean perturbs the tropopause region, and because it remains relatively stationary, ultimately has transport characteristics similar to a cutoff low. The explosively developing synoptic wave responsible for the March 1993 blizzard in the eastern United States causes large-scale transport between the troposphere and stratosphere. There are two notable characteristics of the transport associated with the U.S. blizzard: (1) The U.S. blizzard moves across many degrees of latitude. This storm develops in the subtropics, with a high tropopause, and later decays in a subpolar environment where the tropopause is naturally much lower. (2) Diabatic processes are crucial to the long-range transport and ultimate transfer of mass to the stratosphere. The transport studied in connection with the United States requires consideration of the entire life cycle of the storm from subtropical cyclogenesis to subpolar decay. The fact that storms that are similar to the U.S. blizzard are quite common and that the transport is consistent with available tracer observations suggest that the large-scale transport of air from the troposphere to the stratosphere is plausible. Further investigation with more sophisticated models and tracer observations is needed to verify the importance of the modeled transport.

1. Introduction

The evaluation of chemical and climatic effects of changing trace gas concentrations requires quantification of transport processes in the vicinity of the tropopause. Specific problems motivating the study of the tropopause region include both assessing changes in the radiative balance of the atmosphere as water vapor and ozone concentrations change and evaluating the impact of current and proposed aircraft on atmospheric chemistry [*Intergovernmental Panel on Climate Change* (*IPCC*), 1995; *Stolarski et al.*, 1995]. An important transport issue is the transport between the stratosphere and the troposphere, but the issues are broader than the ideas traditionally associated with stratosphere-troposphere exchange (STE). In particular, it is also necessary to quantify better the transport between the tropical, middle-latitude, and polar regions which can contain air with different constituent characteristics.

There is a long history of the study of synoptic-scale waves and their role in stratosphere-troposphere exchange. One of the paradigms of STE is based on the work of *Danielsen* [1968] who studied upper tropospheric fronts and associated tropopause folds. Quantification of irreversible exchange during tropopause folding events is a difficult task. Much of the air that intrudes into normally tropospheric altitudes returns to the stratosphere. It is difficult both to design measurement campaigns and to use models to constrain the problem well enough to draw quantitative conclusions. In addition, because different synoptic events vary widely in the details of the processes that might be associated with irreversible transport, for example, wave transience, convective transport, turbulence, etc., it is difficult to isolate statistical attributes that provide useful quantitative estimates of transport.

It is also possible to approach the problem of STE from a general circulation perspective that does not require specific attention to synoptic-scale disturbances [*Holton et al.*, 1995, and references therein]. This approach considers the mean

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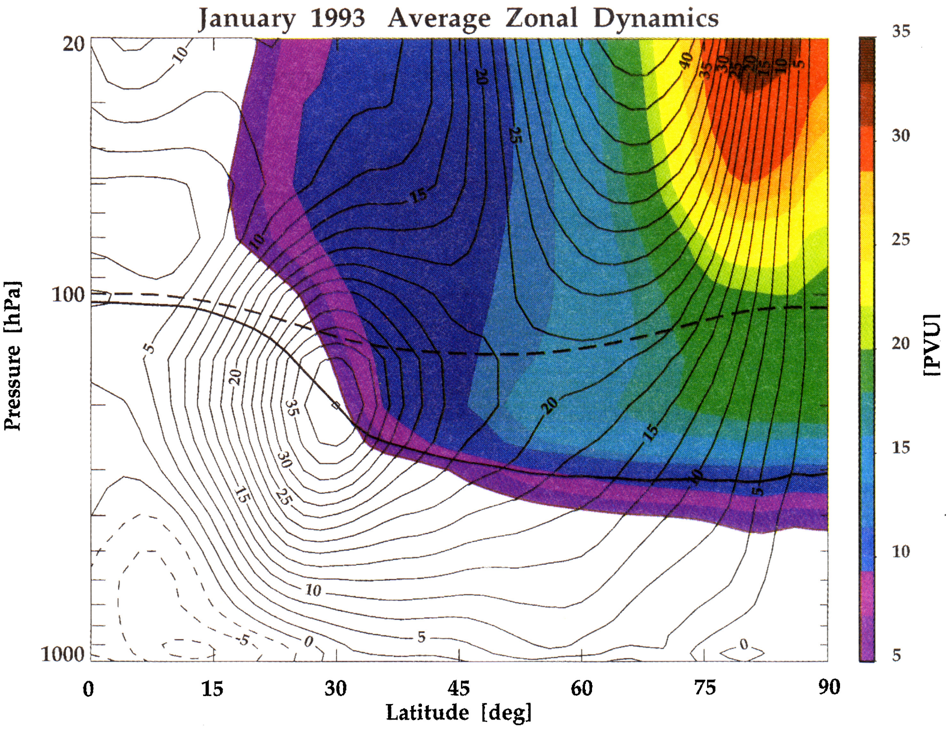


Plate 1. Latitude-height zonal cross section of the mean dynamical fields for January 1993 taken from the GEOS-1 analysis. Thin solid contours represent wind speed at intervals of 2.5 m s^{-1}. Dashed line is the 380 K potential temperature contour, and the thick solid line is the 2.5 PVU Ertel's potential vorticity tropopause. The color image is modified potential vorticity.

circulation induced by the dissipation of gravity and Rossby waves as they propagate from the troposphere into the stratosphere and mesosphere. The general circulation approach is often more productive than the consideration of the details and accumulation of the impact of individual synoptic waves. In fact, *Holton et al.* [1995] argue that studies of seasonal temperature variations and tracer transport indicate that STE is driven by wintertime northern hemisphere Rossby wave activity rather than the intensity and frequency of tropopause fold events. Ultimately, the two approaches to STE, attention to the details of specific events versus an integrated general circulation interpretation, must be reconciled. They provide powerful consistency constraints for each other.

Plate 1 provides the context of the current study. The zonal average of zonal wind, modified potential vorticity [*Lait*, 1994], the 380 K potential temperature contour, and tropopause height for the month of January 1993 are given. Throughout the paper, the tropopause is defined by the 2.5 Ertel's potential vorticity unit (PVU) level (1 PVU = 10^{-6} m^2 Kg^{-1} s^{-1}). Where the 2.5 PVU tropopause pressure was found to be less than 100 hPa, a temperature lapse rate calculation was substituted. Of note are the middle-latitude tropopause, the subtropical jet stream, and the edge of the stratospheric polar vortex, marked by the wind maximum which is the lowermost part of the stratospheric polar night jet. All of these features are associated with persistent potential vorticity (PV) gradients and thus are regions of wave activity [see *Hoskins et al.*, 1985]. Depending on their specific characteristics, the waves might be effective mechanisms of transport between different regions.

Numerous previous papers have contributed to understanding transport by synoptic waves between the different PV regions described in Plate 1. *McKenna et al.* [1989], *Rood et al.* [1992a], *Cariolle et al.* [1990], and *Cerniglia et al.* [1995] study synoptic-scale transport of material between stratospheric middle latitudes and the polar vortex. *Waugh et al.* [1994] and *Plumb et al.* [1994] discuss similar transport, but from a planetary-scale perspective. *Rood et al.* [1992b] discuss synoptic-scale events in the lower stratosphere that transport material from the subtropics to middle latitudes. Also, whether or not there is irreversible transport, synoptic variability is an important component of tracer variability in the lower stratosphere and the upper troposphere. The relation of ozone variability to weather systems has been known for many years [e.g., *Craig*, 1950, and references therein], and total ozone observations are strongly correlated with tropopause variability.

This paper focuses on transport during two specific events in a global model which uses analyzed wind fields from the Goddard Earth Observing System-version 1, data assimilation system (GEOS-1, DAS [*Schubert et al.*, 1993, 1995]). Attention is focused primarily on a storm that caused a major blizzard in the eastern United States, with secondary focus on a large disturbance in the western Pacific. Both storms show rapid development of extratropical surface lows. The U.S. blizzard has its genesis in the subtropics along the jet stream and dissipates at high latitudes. Therefore the blizzard potentially connects all of the regions delineated by PV gradients in Plate 1. In contrast, the Pacific storm is relatively stationary and dissipates in the same area that it formed. One purpose of the study is to evaluate the ability of a global model to represent transport processes without explicit resolution of small spatial scales evident in aircraft observations [see also *Cox et al.*, 1995]. A second purpose is to further define descriptive characteristics of the synoptic-scale waves associated with irreversible transport. In contrast to earlier studies, the paper ultimately focuses on large-scale transport associated with the entire life cycle of the cyclone.

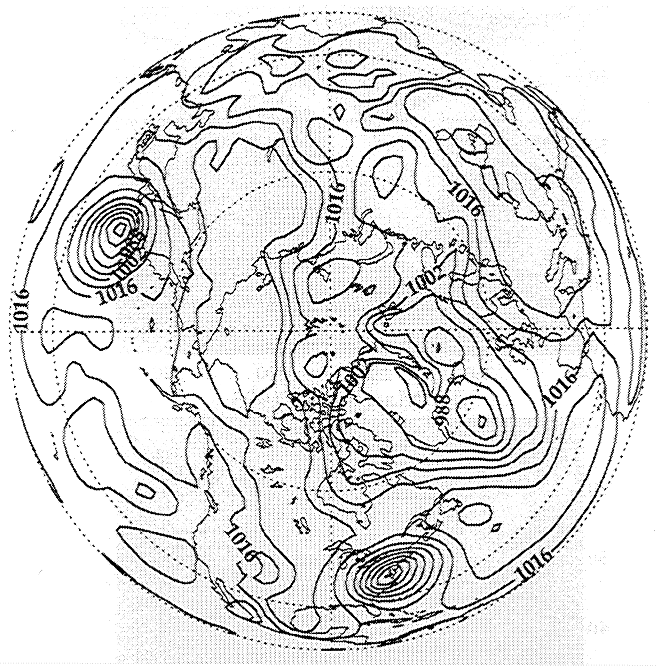


Figure 1. GEOS-1 northern hemisphere sea level pressure map for March 14, 1993. Contour interval is 7.0 hPa. The longitude interval is 90°, and the latitude interval is 30°.

The next section includes a description of the meteorological situation. The model and transport experiments are then described. That is followed by evaluation of the model performance with satellite observations of tracer fields, followed by more detailed analysis of idealized experiments. Integration and summary of the results are given in the final section.

2. Meteorological Situation

In March of 1993 one of several "Storms of the Century" occurred on the East Coast of the United States. Blizzard conditions with heavy snow and hurricane force winds were observed from the southern Appalachian Mountains northward. The storm and its impact are described in detail by *Kocin et al.* [1995]; relevant details are described here. Figure 1 shows a global map of sea level pressure on March 14, 1993, from the GEOS-1, DAS. The resolution of the analysis is 2° × 2.5° (latitude times longitude) with 20 vertical sigma levels from the surface to 10 hPa. Two features are striking in the figure. The first is the blizzard in the United States, and the second is a large cyclone in the western Pacific off the coast of Japan and Kamchatka. Both disturbances have sea level pressures less than 974 hPa.

Figures 2 and 3 show 4 day sequences of the sea level pressure for the two storms. The U.S. blizzard (Figure 2) is evident on March 13, 1993, between 275° and 280°E longitude and 30° and 35°N latitude. Explosive development is observed between the 13th and 14th, with the sea level pressure falling

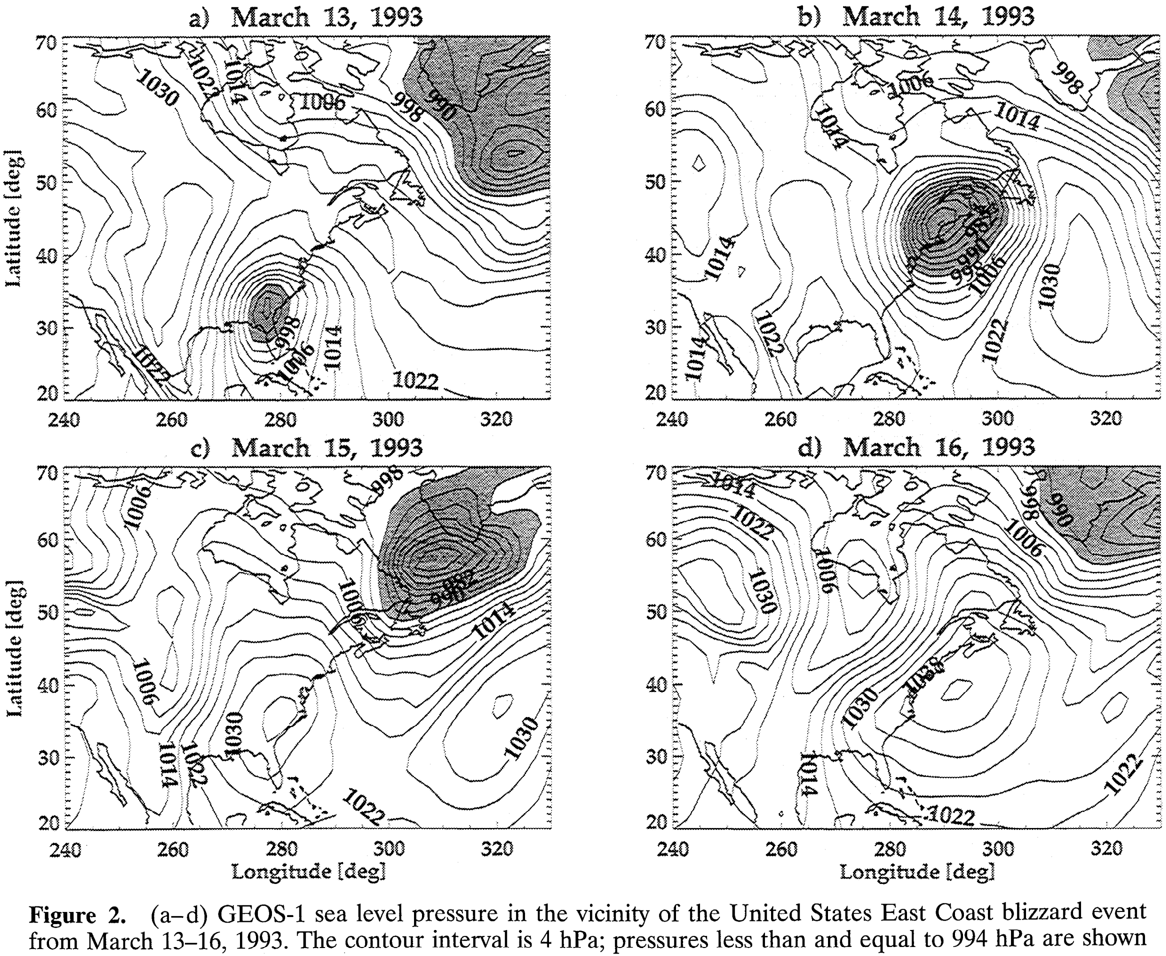


Figure 2. (a–d) GEOS-1 sea level pressure in the vicinity of the United States East Coast blizzard event from March 13–16, 1993. The contour interval is 4 hPa; pressures less than and equal to 994 hPa are shown with gray scale. Latitudes run from 20° to 70°N, and longitudes are from 240° to 330°E.

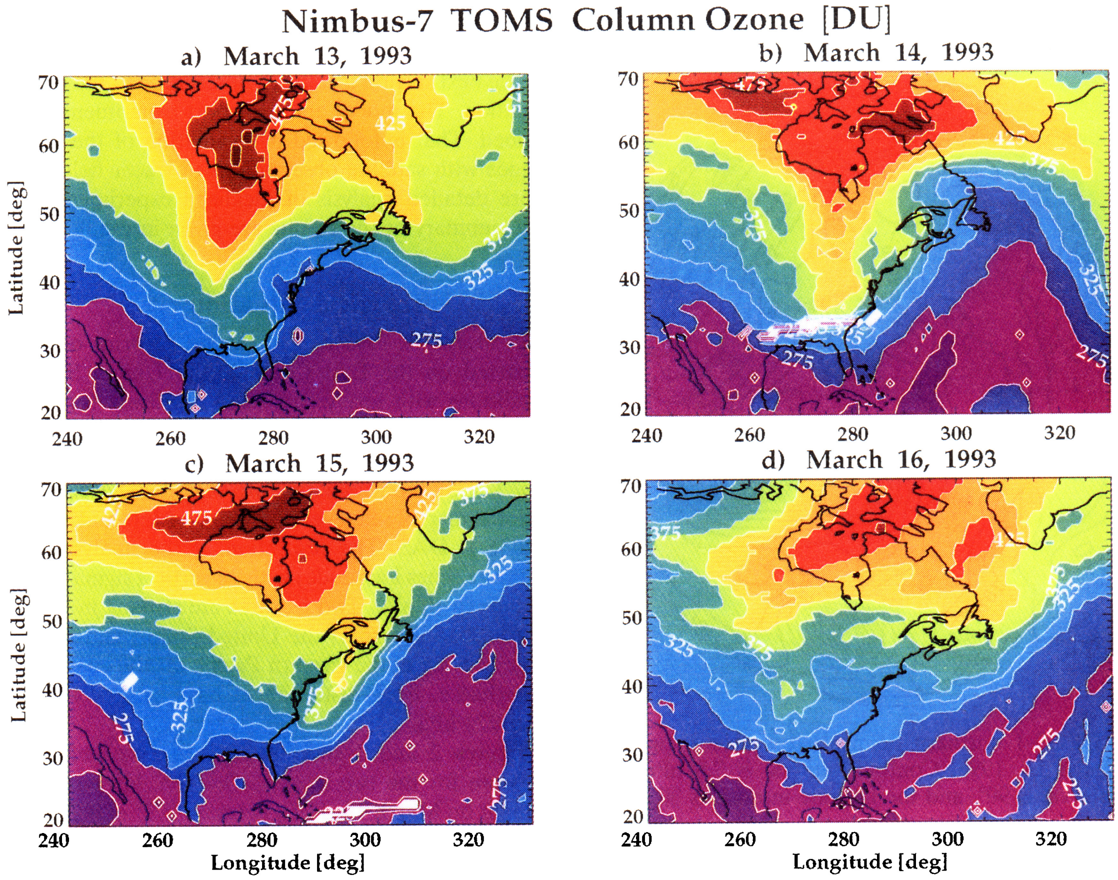


Plate 2. (a–d) Nimbus-7 TOMS high resolution column ozone in the vicinity of the blizzard event from March 13–16, 1993. Contour interval is 25 Dobson units (DU).

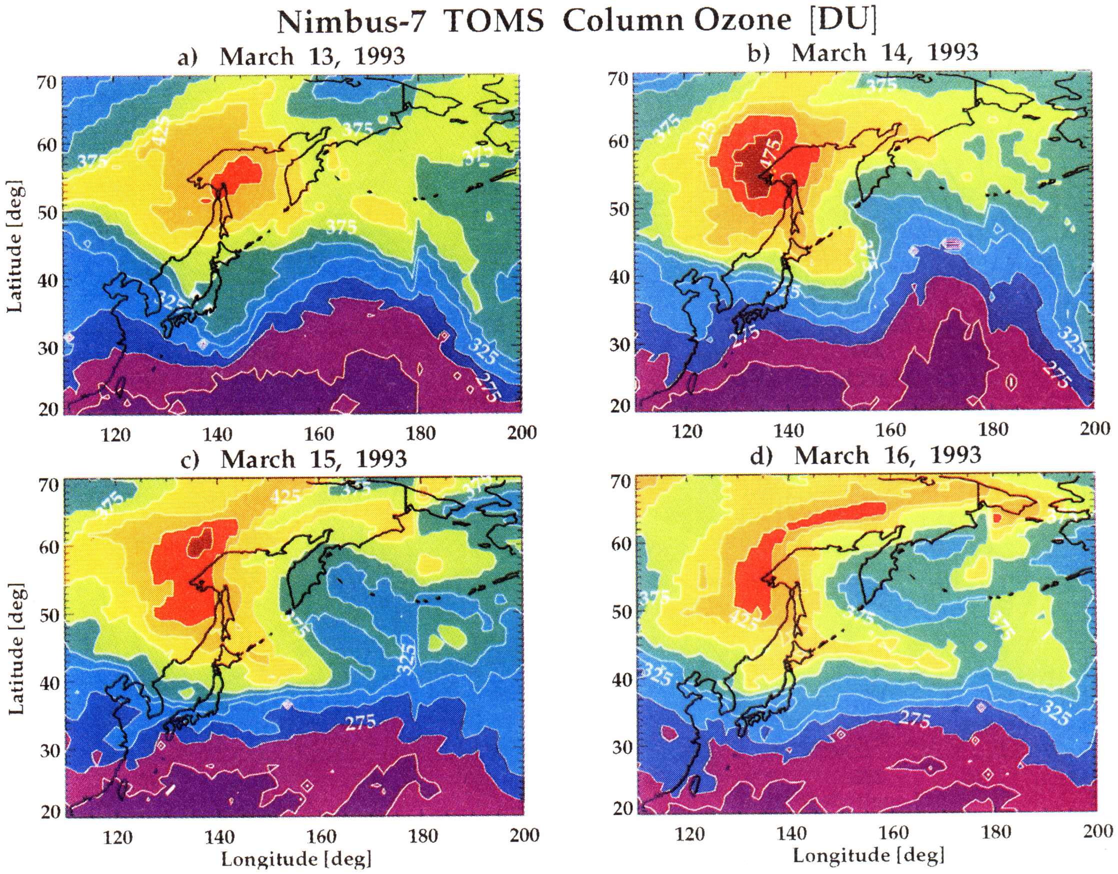


Plate 3. Same as Plate 2 except for the Pacific event.

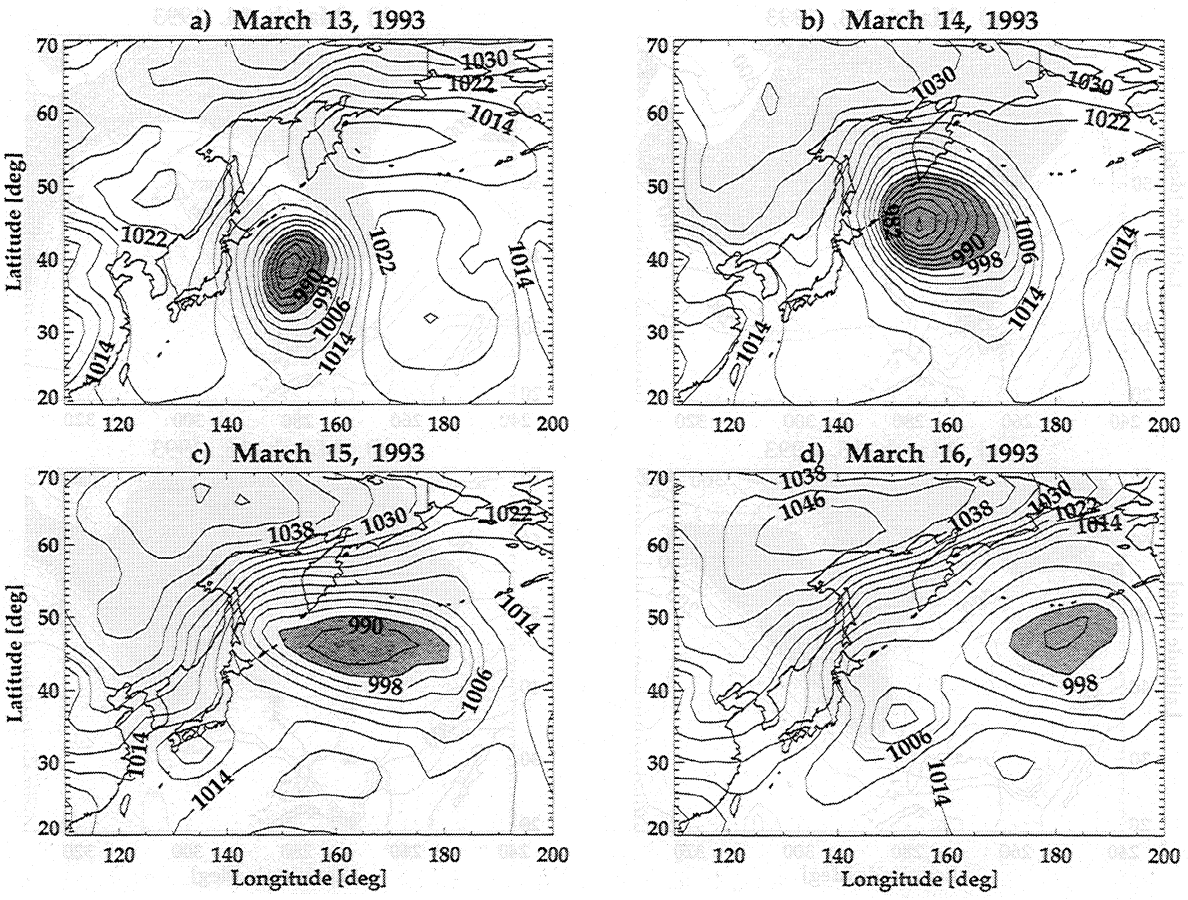


Figure 3. Same as Figure 2 except for the cyclone in the Pacific Ocean (Pacific event). Longitudes are from 110° to 200°E.

from 984 to 964 hPa and the storm moving north and east. The storm continues to move rapidly through the 15th and leaves the domain of the figure and decreases in amplitude on the 16th. By the 16th the eastern United States is covered by the high pressure system following the blizzard, East Coast residents are observed worldwide on the evening news digging out of the snow, and the swans are flying north from Cape Anne.

The Pacific storm occurs primarily over the ocean. On March 13, 1993, the sea level pressure is 976 hPa between 150° and 155°E longitude and centered at 40°N latitude. Between the 13th and 14th the storm intensifies with the surface pressure falling to 968 hPa; there is little longitudinal movement, and the center is located about 5° farther north. By the 15th the Pacific storm is less well defined and centered at 165°E longitude. The surface pressure has increased nearly 20 hPa. In the next day the storm moves eastward, and there is continued weakening of the surface low. Both the Pacific storm and U.S. blizzard show substantial growth and decay. A major difference between the storms is that the U.S. storm moves from low to high latitudes, thus dissipating in a subpolar environment. The Pacific storm dissipates in fundamentally the same region in which it forms.

The pressure of the tropopause for the two storms is given in Figures 4 and 5. The tropopause is defined by the 2.5 Ertel's potential vorticity unit (PVU) level (1 PVU = 10^{-6} m^2 K kg^{-1} s^{-1}). Where the 2.5 PVU tropopause pressure was found to be less then 100 hPa, a temperature lapse rate calculation was substituted. For the U.S. blizzard on March 13, 1993, tropopause pressures typical of subtropical latitudes (pressures less than 150 hPa) are moving northward between 280° and 290°E longitude, east of the surface low. An area with tropopause pressures greater than 400 hPa twists southward at 270°E longitude, west of the surface low. In the next 24 hours this area of high-pressure tropopause deepens, and tropopause pressures greater than 500 hPa are visible. The area of high-pressure tropopause follows the movement of the surface low to the north and east. The signal on March 14, 1993, is typical of a tropopause fold, with stratospheric air from high latitudes pushing deep into pressures typical of the undisturbed troposphere. A long narrow tongue of high tropopause pressures follows the blizzard northward and eastward the next 2 days. On March 15, 1993, there is a line from (290°E, 35°N) to (320°E, 55°N) where tropopause pressures typical of the subtropics are in close proximity with tropopause pressures typical of subpolar latitudes. Small-scale processes in this region would cause mixing between the troposphere and the stratosphere.

The behavior of the tropopause pressure with the Pacific storm is significantly different. There is a high-pressure tropopause, with characteristics of folding (March 13, 1996). There is northward distortion of the subtropical tropopause on following days, but there is not the obvious northward movement of subtropical air to middle latitudes as observed with the U.S. blizzard. The graphs of the tropopause pressure for the Pacific storm show a twisted pattern with broken off areas of strato-

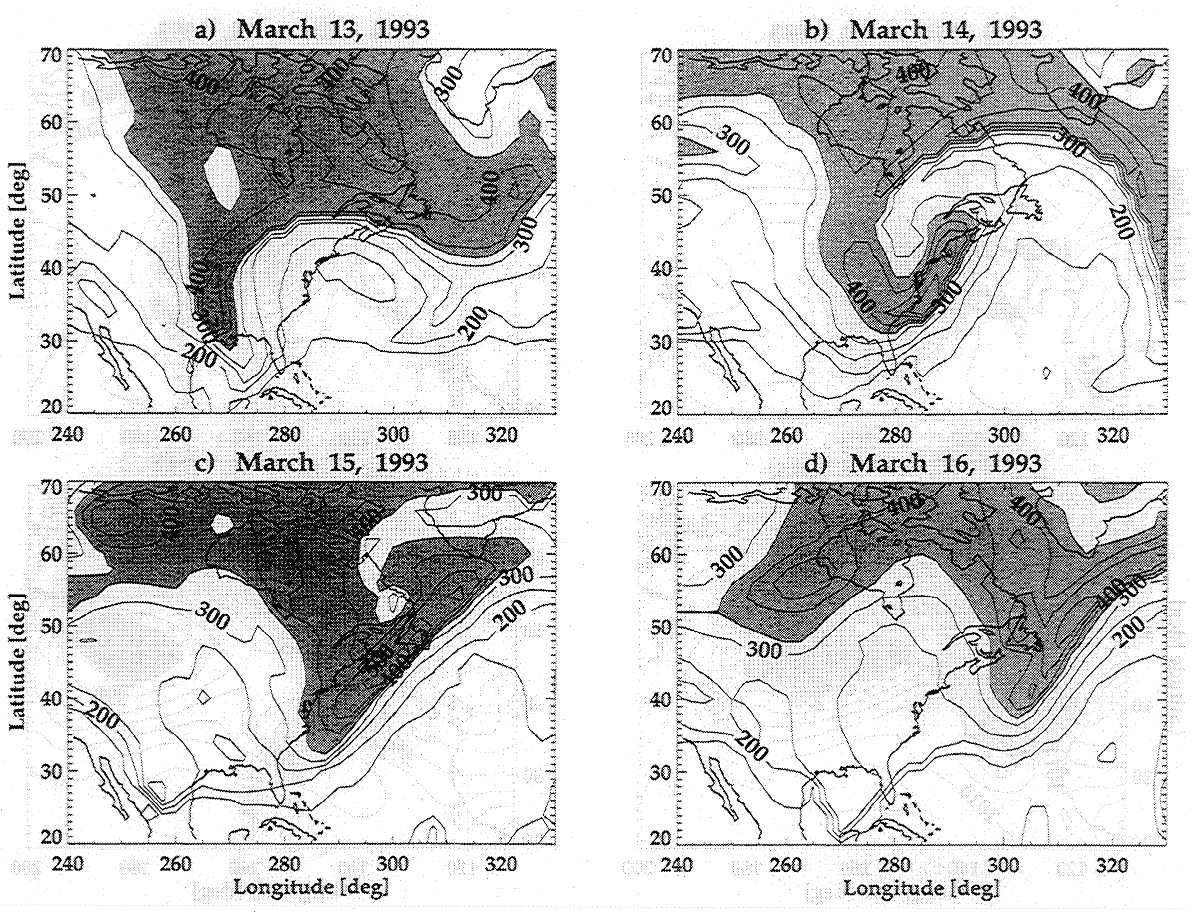


Figure 4. (a–d) GEOS-1 tropopause pressure in the vicinity of the blizzard event from March 13–16, 1993. The contour interval is 50 hPa; pressures greater than and equal to 350 hPa are shown with gray scale. Latitudes run from 20° to 70°N, and longitudes are from 240° to 330°E.

spheric air residing in an environment more typical of the middle-latitude troposphere.

Figure 6 shows cross sections to describe the vertical structure of the two storms on March 14, 1993, along 285° and 155°E. The meteorological information is from the GEOS-1 analysis [*Schubert et al.*, 1993]. Figure 6a shows the zonal mean wind (solid lines) and potential temperature surfaces (dashed lines) for the U.S. blizzard. The characteristic two jet structure [e.g., *Danielsen*, 1968] is present. Just north of 30° is the main part of the subtropical jet with winds greater than 80 m s^{-1}. Compared with the Pacific storm (Figure 6b), the U.S. blizzard has similar surface winds but larger upper tropospheric winds and hence greater vertical shear. The greater vertical shear suggests that the U.S. blizzard is more likely to intensify through baroclinic instability than in the Pacific storm [see *Holton*, 1992].

Figures 6c and 6d show the potential vorticity (solid lines) and vertical motion cross sections from the two disturbances. Both are similar with upward motion on the poleward side of the storms and downward motion on the equatorward side. The upward and downward cells of the vertical motion are closer together in the U.S. blizzard. The potential vorticity in the U.S. blizzard is more distorted than in the Pacific storm with a protrusion deep into the troposphere. Also on the poleward side of the primary cell of upward velocity are large horizontal gradients in the potential vorticity field. Figure 6 is similar to the canonical figures used to describe tropopause folds by *Danielsen* [1968]. The stretching of the potential vorticity contours into the troposphere in the U.S. blizzard suggests a higher likelihood of irreversible transport from the stratosphere to the troposphere than in the Pacific storm.

3. Model and Experiment Design

Off-line transport experiments are performed using winds and surface pressure from the Goddard Earth Observing System-version 1, data assimilation system (GEOS-1, DAS [*Schubert et al.*, 1993, 1995]). In addition, several other fields are used in the interpretation of the results. These include temperature, geopotential, potential vorticity, latent heat release, turbulent kinetic energy, and radiative forcing.

The winds are used in the transport algorithm developed by *Lin and Rood* [1996]. The transport algorithm uses the piecewise parabolic implementation of the Lin and Rood scheme with monotonicity constraints. The chemistry-transport model (CTM) is run at 2° × 2.5° (latitude times longitude) with 20 vertical sigma levels from the surface to 10 hPa. A 600 s time step is used. Vertical transport due to convective cloud mass flux and planetary boundary layer mixing has been incorporated according to the algorithm described by *Allen et al.* [1996]. The CTM is initialized on March 6, 1993, 0000 UT and runs through March 17, 1993, 1800 UT.

Three CTM experiments will be used in the paper: ozone, water vapor, and a contrived tropospheric tracer. These exper-

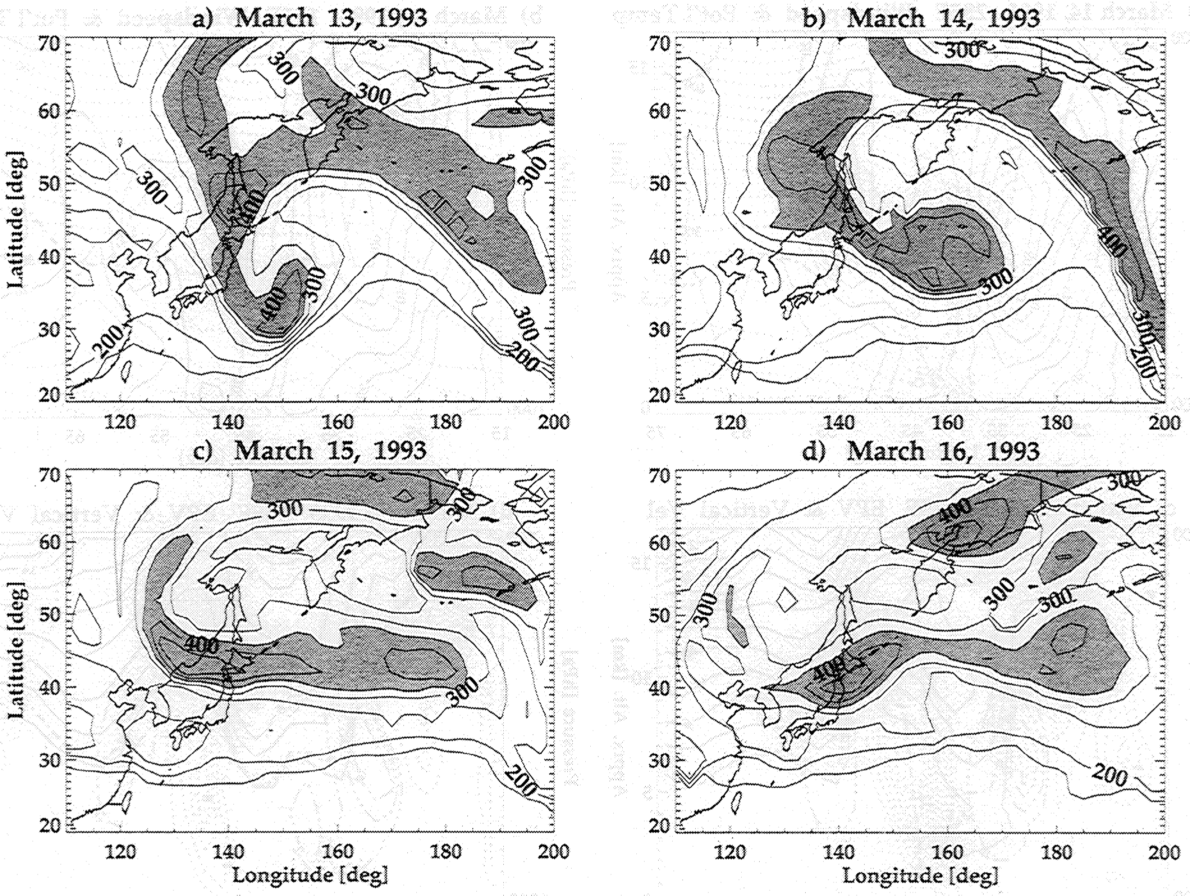


Figure 5. Same as Figure 4 except for the Pacific event.

iments were designed to validate model performance as well as to help diagnose transport mechanisms.

The ozone experiment included parameterized production and loss [see *Douglass et al.*, 1996]. The initial ozone field was created by mapping a zonal-mean field representative of mid-March taken from the Goddard Space Flight Center (GSFC) two-dimensional model output. This initialization employed a potential-vorticity equivalent latitude/potential temperature vortex-centered coordinate system [*Lary et al.*, 1995]. The ozone lifetime at these altitudes is long compared with the length of the experiments; therefore ozone is essentially a tracer of stratospheric air.

The second CTM experiment was the passive transport of water vapor. The starting field was taken from the GEOS-1 output. Negative mixing ratios in the GEOS-1 analysis were replaced with a value of 1×10^{-15}.

Water vapor should provide a good contrast between stratospheric and tropospheric air, as well as between tropics and middle latitudes. However, as discussed by *Read et al.* [1995], the quality of the GEOS-1 water vapor product is strongly dependent on the availability of radiosonde observations of moisture. To circumvent this weakness, a tropical tropospheric tracer, trop1, was constructed for the final experiment. This field was initialized by defining a region inside the tropics, vertically bounded by the tropopause (as defined earlier). All model grid points of the tracer within this volume were assigned a value of 10; elsewhere the tracer was set to zero. The meridional location of the tropical edge was defined at all longitudes and at pressures above and including 775 hPa by utilizing winds from GEOS-1 to determine latitudes of maximum wind speed along the subtropical jet stream in both hemispheres. Below the 775 hPa level the latitude positions of the maximum winds at the 775 hPa level were used.

4. Validation of Tracer Experiments

Tracer observations from satellite instruments will be used to establish that the use of the chemistry-transport model (CTM) for further analysis is appropriate. Total ozone, which is a measure of upper troposphere and lower stratosphere dynamics, will be used along with lower stratospheric ozone and 215 hPa water from the Microwave Limb Sounder (MLS) [*Barath et al.*, 1993] aboard the Upper Atmosphere Research Satellite [*Reber et al.*, 1993].

Plates 2 and 3 show high resolution total ozone column data from the total ozone mapping spectrophotometer (TOMS) [see *Herman et al.*, 1991] for the same 4 days as shown in Figures 2–5. For the U.S. blizzard on March 13, 1993, the TOMS data show a piece of material breaking off at (270°E, 35°N) coincident with the high pressure in the tropopause pressure field in Figure 4a. On March 14, 1993, a prominent feature is the subtropical and tropical air pushing northward between 300° and 320°E. On March 15, 1993, the tropical air is aligned along the same axis as the tropopause fold shown in Figure 4c. Finally, on March 16, 1993, the most notable difference from the initial field is that the transition region between the 300 and 400 Dobson units (DU) contours are more spatially spread out.

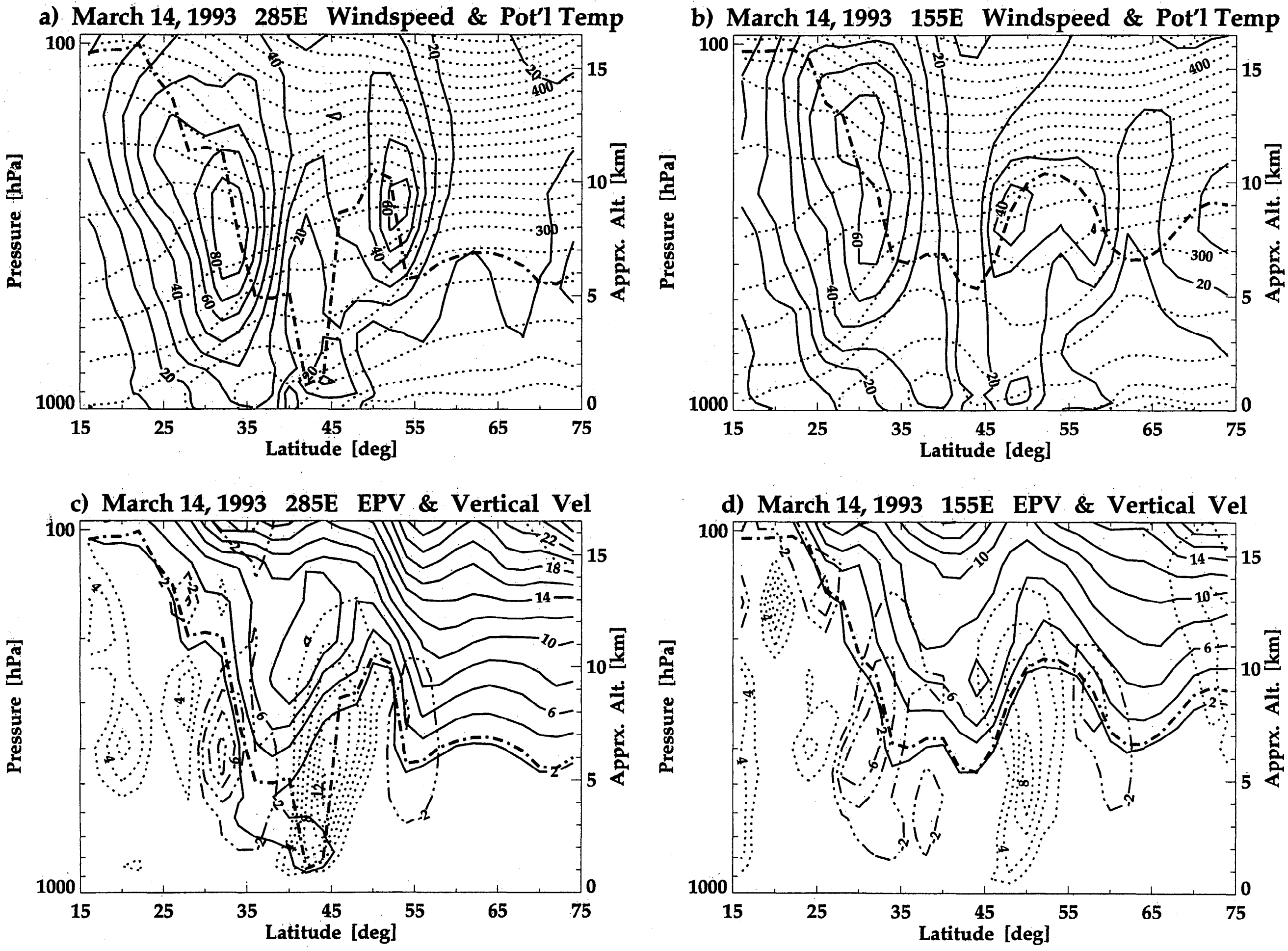


Figure 6. (a) Latitude-height cross section of wind speed (solid lines) and potential temperature (dotted lines) on March 14, 1993, at 285°E longitude. Contour intervals are 10 m s^{-1} and 10 K, respectively. (b) Same as in Figure 6a except at 155°E longitude. (c) Latitude-height cross section of potential vorticity (solid lines) with upward vertical velocities (dotted lines) and downward vertical velocities (dash-dotted lines) on March 14, 1993, at 285°E longitude. The contour interval is 2 PVU and 2 cm s^{-1} respectively. (d) Same as in Figure 6c except at 155°E longitude. The 2.5 PVU tropopause (dash-dotted) is shown in each panel. Latitudes run from 15° to 75°N, and pressures extend from 1000 to 94.6 hPa.

The Pacific storm has a notably different structure. On March 13, 1993, there is a high area of total ozone at (145°E, 55°N) which is largely isolated, being surrounded by air with lower ozone concentrations. In the next 24 hours, as the surface low intensifies (Figure 3b), the total ozone maximum increases. As in the U.S. blizzard, there is a perturbation of subtropical ozone northward, and the total ozone and the tropopause pressure field move together. By March 16, 1993, the total ozone field has a narrow feature stretched along 40°N similar to the tropopause pressure field in Figure 5d. However, the high in total ozone greater than 425 DU, north of 50°N, does not have a corresponding feature in the tropopause field (as was the case with this high on March 13, 1993). There is a minimum in the total ozone field linked to the minimum in the tropopause pressure at (150°E, 55°N).

As expected, the total ozone field is related to the height of the tropopause, with low total ozone correlated with the low pressure subtropical tropopause and vice versa. The behavior is especially evident in the U.S. blizzard; however, it is difficult to draw any conclusions about transport from the total column observed during the progression of the storm. The total ozone in the Pacific storm is not as well correlated with the tropopause height. Further analysis reveals that the total ozone over the Pacific storm is strongly influenced by ozone that has broken off from the stratospheric vortex due to planetary wave activity at higher altitudes. Since the planetary wave activity is not directly related to tropopause dynamics, the correlative link between tropopause pressure and total ozone weakens.

Model column ozone is shown in Plates 4 and 5. The capability of the model to represent total ozone has been established in many experiments [e.g., *Douglass et al.*, 1996, and references therein]. The CTM integration has a low bias because the highest model level is at 10 hPa and no attempt was made to normalize initial column amounts to be consistent with TOMS observations. In the U.S. blizzard there is the material breaking off as the high-pressure tropopause moves southward at (270°E, 35°N) on March 13, 1993. Subsequent days show similar features as the TOMS observations, and by March 16, 1993, the CTM shows a reduction of the gradients between the subtropics and middle latitudes. The simulation of the Pacific storm is also consistent with the TOMS observations. The weaker correlation between tropopause height and

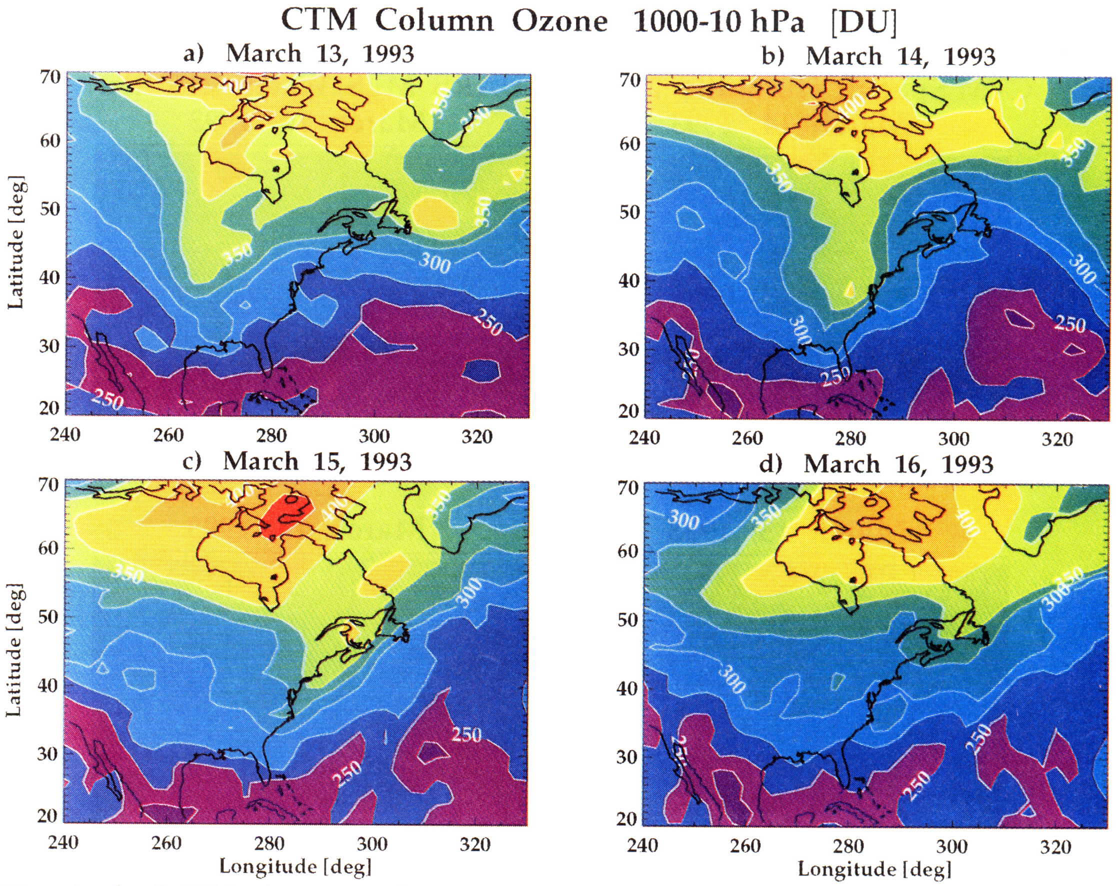


Plate 4. (a–d) CTM column ozone from 1000 to 10 hPa in the vicinity of the blizzard event from March 13–16, 1993. Contour interval is 25 Dobson units (DU).

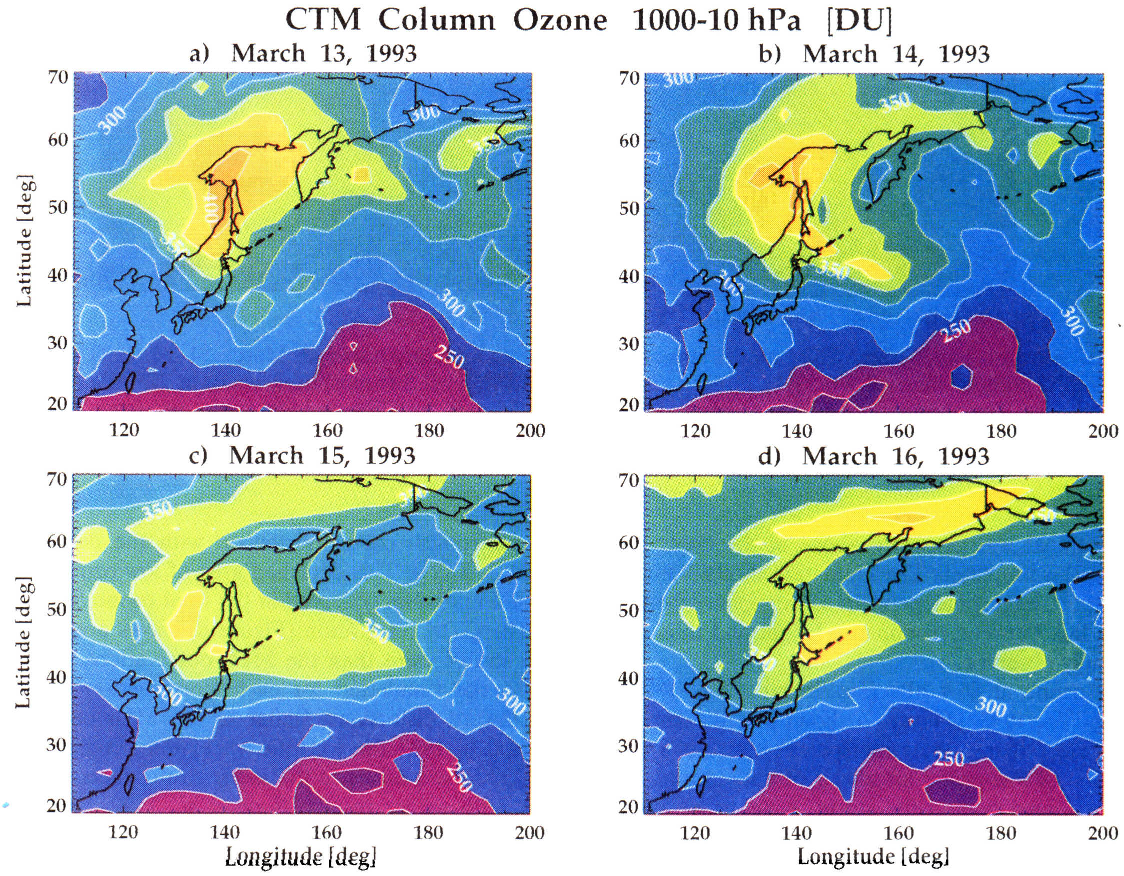


Plate 5. Same as Plate 4 except for the Pacific event.

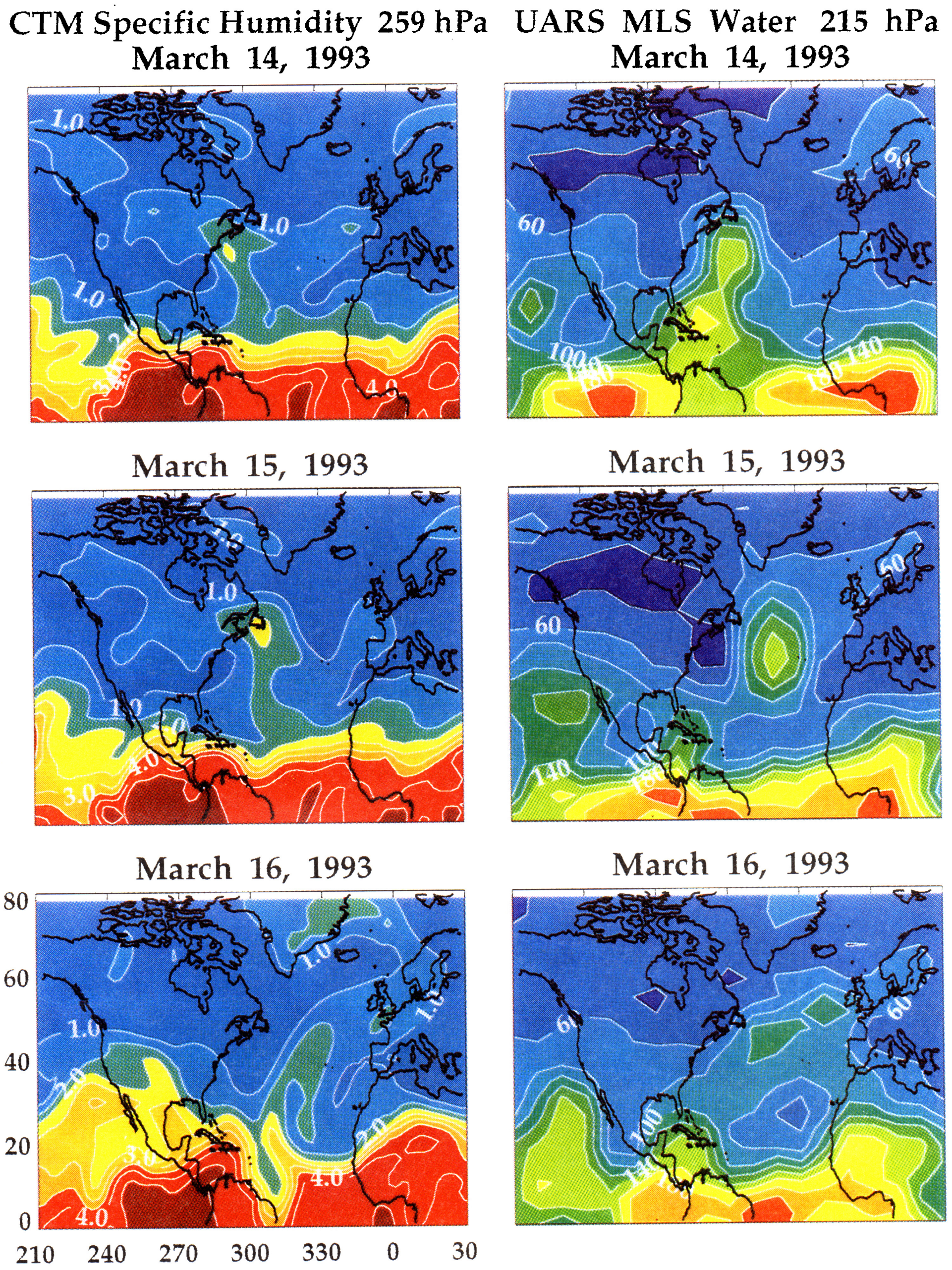


Plate 6. Left panels show CTM model output of the specific humidity tracer on March 14–16, 1993, at 259 hPa. The contour interval is 0.5 g kg^{-1}. Right panels show UARS MLS tropospheric water at 215 hPa for the same days. The contour interval is 20 ppmv. Latitudes run from 0° to 80°N, and longitudes are from 210° to 30°E. Continental outline is also shown.

column ozone that was discussed above in the observations (Plates 2 and 3) is simulated. The simulation shows that stratospheric transport, largely independent of tropopause dynamics, weakens the link between tropopause height and total ozone that is normally observed.

The MLS ozone at 46.4 hPa [*Froidevaux et al.*, 1996] on March 14 and 16, 1993, (Figure 7) shows that the impact of both storms extends into the stratosphere. There is a northward excursion of low-ozone air ahead of both storms and a southward excursion behind the storm. A sequence of plots (not shown) reveals that the signal of the Pacific storm in the stratosphere is often stronger than the U.S. blizzard. On March 16, 1993, only the Pacific storm suggests any obvious transport of subtropical ozone northward with the detached blob at (150°E, 52°N). This detached area of low ozone is collocated with a minimum observed in the total ozone field (Plate 3d).

The CTM integration (Figure 8) shows a weaker signal in the stratosphere than the MLS observations. On March 14, 1993, the simulation for each storm shows northward and southward distortions similar to the MLS observations. On March 16, 1993, there is little correlation between the modeled and observed ozone in the lower stratosphere. This is consistent with earlier results [*Rood et al.*, 1992a, Figure 4] which shows that the modeled influence of synoptic variations does not reach as far into the stratosphere as that observed by ozonesondes.

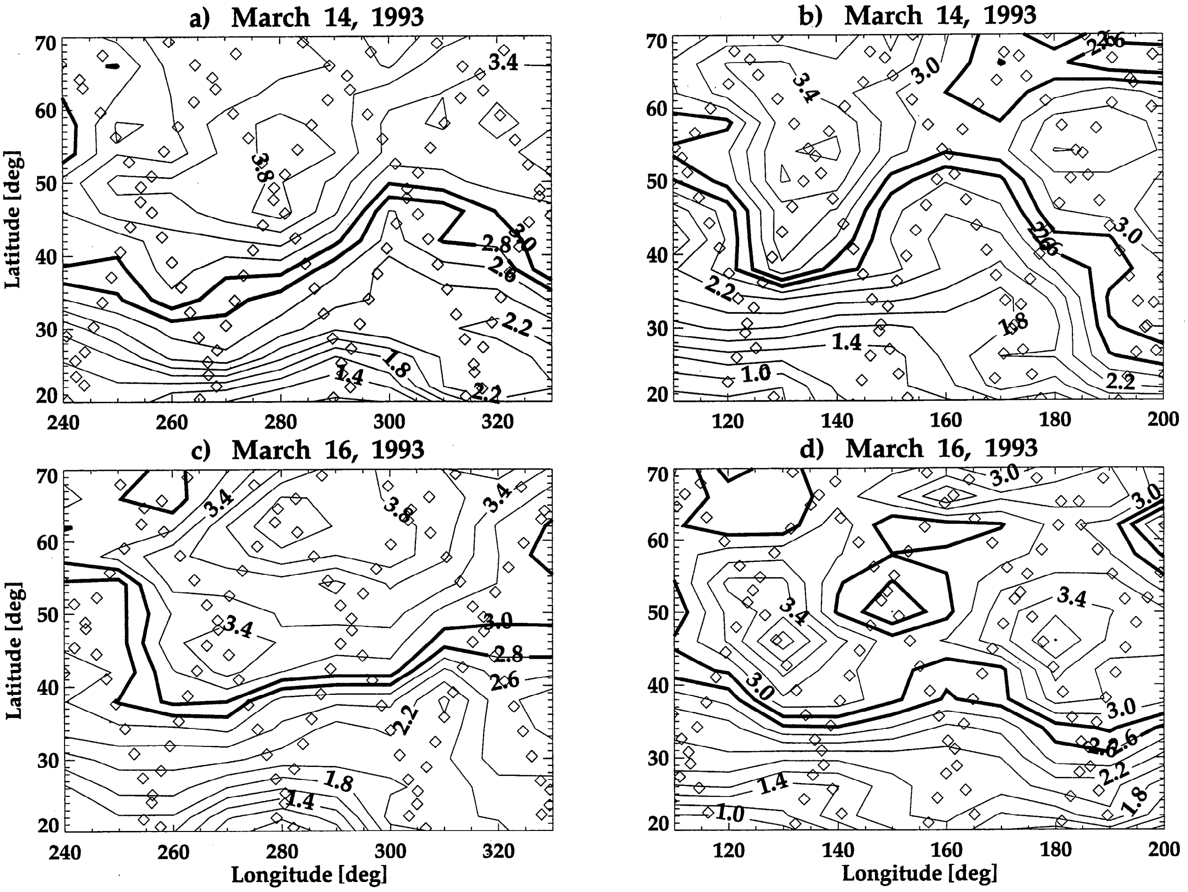


Figure 7. UARS MLS ozone at 46.4 hPa in the vicinity of (a and c) the blizzard event and (b and d) the Pacific event on March 14 and 16, 1993. The contour interval is 0.2 ppmv. The 2.8 and 3 (2.6 and 2.8) ppmv contours are highlighted for the blizzard (Pacific) event. Satellite tracks are plotted as diamonds.

Another MLS product is water at 215 hPa [*Read et al.*, 1995]. Water on the 215 hPa surface would normally be in the troposphere in the tropics and in the stratosphere at high latitudes (see Plate 1). Quantitative calibration of MLS water has not been established, but the morphology and evolution of the water vapor field are qualitatively accurate. Plate 6 shows a sequence of MLS and CTM water from March 14–16. Though blotchy because of the relatively low horizontal resolution of the MLS observations, the signature of the U.S. storm is obvious. On March 14, 1993, air high in water vapor is moving out of the subtropics and is broken off from the subtropics over the middle Atlantic (March 15, 1993). To the west of this moist air, air is very low in water vapor, coincident with the tropopause fold and linked to the descent of dry stratospheric air behind the blizzard. Intuitively, the moist air that is broken off from the tropics appears to be irreversibly transported to the extratropics. The Pacific storm does not have a robust signature in the water vapor field.

The model integration at 259 hPa (also Plate 6) shows the distortion and extrusion of water from the subtropics. In the model on March 16, 1993, there is a continuous region of moist air from the subtropics to Greenland associated with the northeastward movement of the U.S. blizzard. Though not continuous, the MLS water also shows an area of moist air appearing over Greenland on March 16, 1993. While the details vary, both the MLS water and the model suggest transfer of water from low to high latitudes with the spatial scale of synoptic waves. Furthermore, given the normal variation of the height of the tropopause, the tropospheric air from the subtropics should take on the thermodynamic characteristics of stratospheric air with time. This should result in transfer of air from the troposphere to the stratosphere on larger spatial scales than normally associated with, for instance, tropopause folds.

5. Analysis of Transport

The previous section establishes that the CTM experiments capture many of the phenomena of the observed tracer variability. The experiments are rich in possibility, and focus will be given to the quasi-horizontal transport suggested by the MLS water vapor observations of the U.S. storm (Plate 6). Aside from the movement of air across a wide range of latitude, there is another important aspect of the modeled transport. Referring to Plate 1, the height of the tropopause is much higher in the subtropics than in the subpolar latitudes. Therefore air that was originally in the tropical troposphere ends up in the background environment that maintains subpolar stratospheric characteristics. The problem of troposphere to stratosphere exchange as well as identification of irreversible transport will be confronted with the use of the Goddard trajectory model [*Schoeberl and Sparling*, 1995] modified for diabatic calculations.

Several scenarios were run in both the isentropic and diabatic modes. Only the diabatic cases are discussed here. For

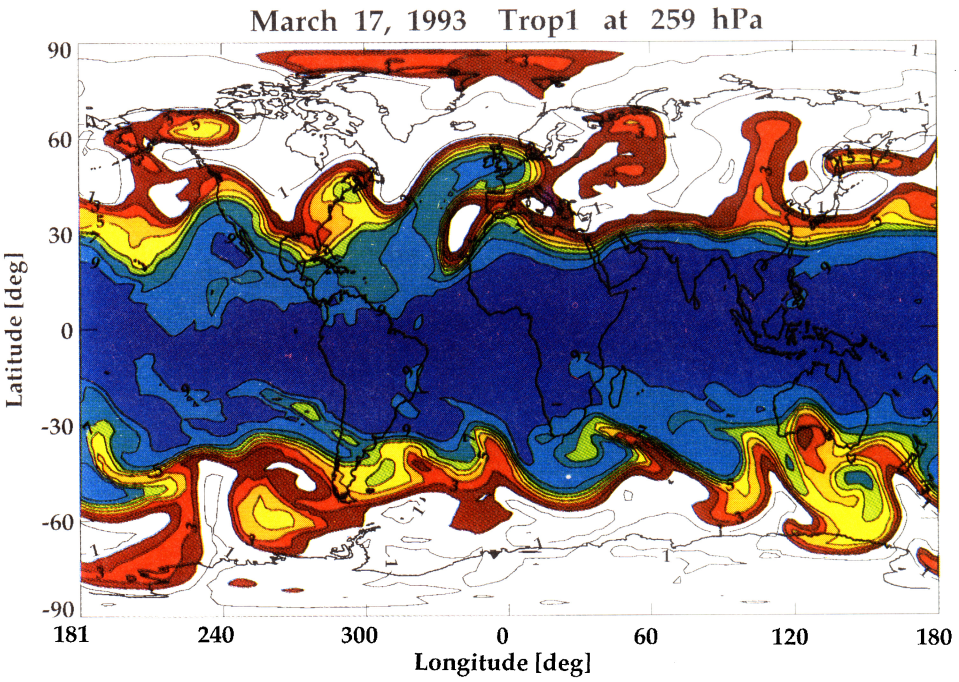


Plate 7. Global projection of the tropical tropospheric tracer, trop1, on March 17, 1993, at 259 hPa. The contour interval is 1 arbitrary volumetric mixing ratio units.

each run a cluster of approximately 120 parcels was uniformly initialized on a latitude-longitude grid at pressures corresponding to a potential temperature of 315 K with a horizontal spacing of approximately 1°. Parcel trajectories are calculated using a fourth-order Runga-Kutta integration scheme which incorporates analyzed winds fields and vertical motions determined by archived heating rates. For each parcel, GEOS-1 meteorological fields are linearly interpolated in time to the parcel's current position. The parcel is then advected backwards in time to a new pressure and horizontal location. The time step is 900 s.

Plate 7 shows a contour plot of the tracer, trop1, on March 17, 1993, at 258 hPa. This artificial tracer was originally contained in the tropical and subtropical troposphere and allows definitive location of formerly low latitude air at higher latitudes. In both the northern and southern hemispheres, much structure has developed between the subtropics and the middle latitudes. Material is distorted poleward from the subtropics, with most of the extensions remaining connected to the subtropical reservoir. The deep tropics remain relatively undisturbed. The northern hemisphere middle latitudes contain large regions where no trop1 is present. Animation shows that

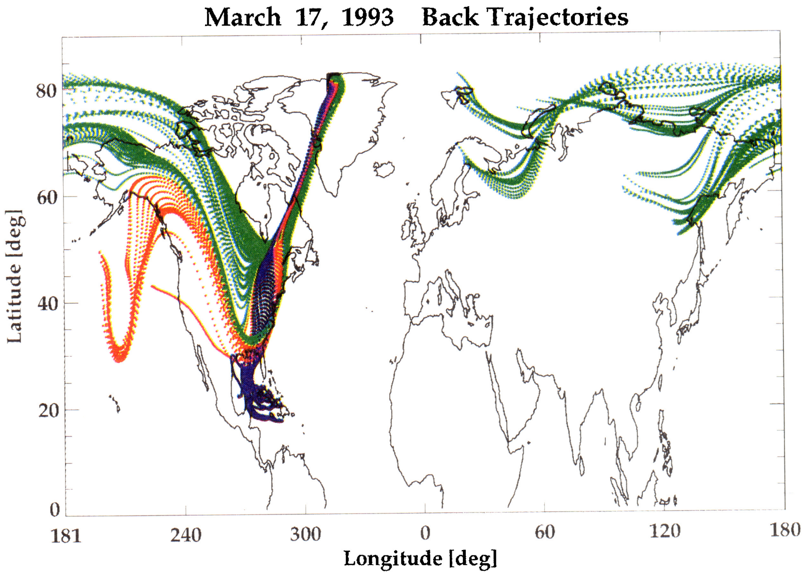
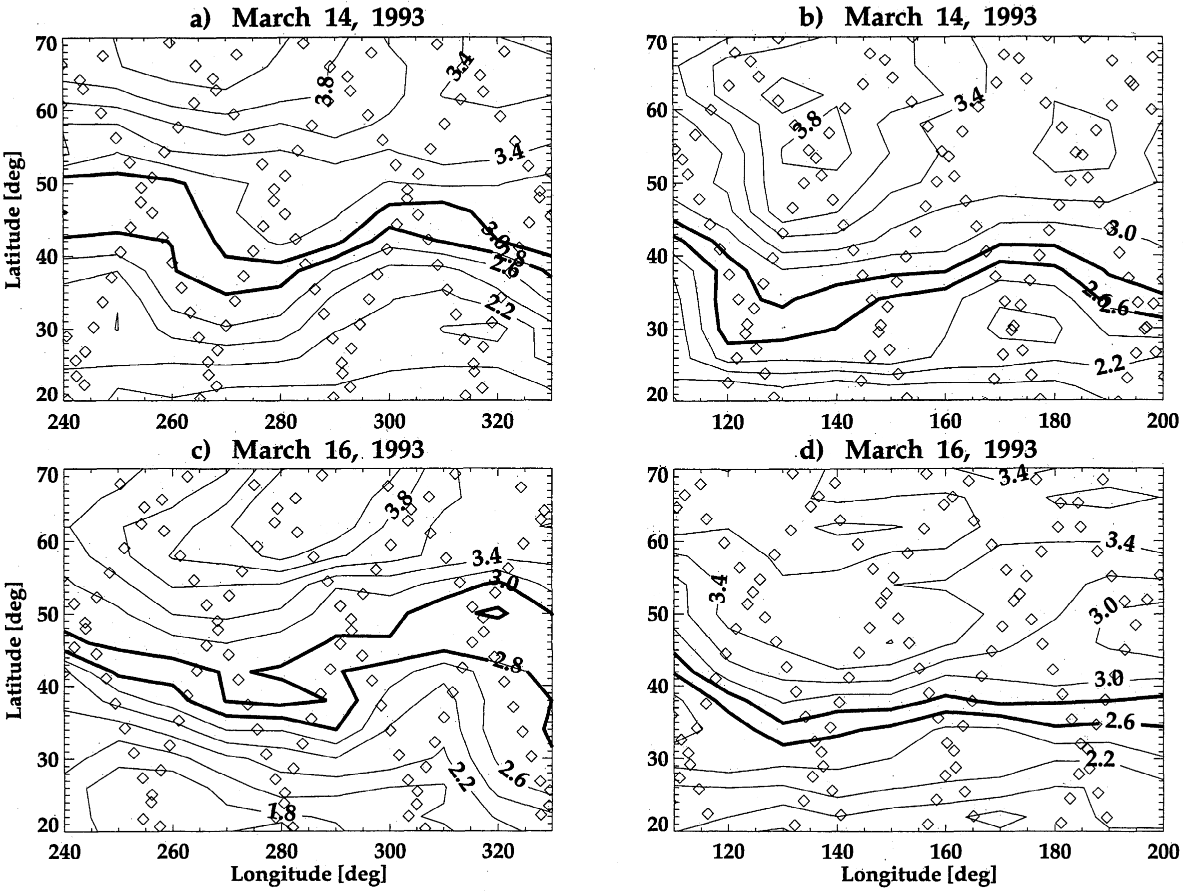


Plate 8. Summary of 7-day diabatic back trajectories that terminate on March 17, 1993, at the 315 K potential temperature surface. Green parcels originated in northern Eurasia, red parcels originated in the Pacific Ocean, and the blue parcels began over the Gulf of Mexico.


a) March 14, 1993

b) March 14, 1993

c) March 16, 1993

d) March 16, 1993

Figure 8. Same as Figure 7 except for CTM ozone at 48.6 hPa. Model ozone was interpolated to the same horizontal grid as the MLS data displayed in Figure 7.

the concentration of trop 1 at very high northern latitudes that extends from Canada to Scandinavia is associated with the U.S. blizzard. Back trajectories will be computed from points in this high latitude maximum. This area of high trop1 is consistent with the signature in the water field (Plate 6).

Plate 8 shows a summary of 7-day back trajectories that originate on the 315 K potential temperature surface on March 17, 1993. Broadly, the parcels arriving at the high latitude maximum in Plate 7 come from three different regions. One family (green) originates over northern Eurasia. Member parcels remain at high latitudes, and parcels are entrained into the blizzard over the eastern United States and Canada. The second family (red) of trajectories begins over the Pacific Ocean. Parcels move northward over the ridge in the western United States, and then they are incorporated into the developing synoptic disturbance that becomes the blizzard. The third family (blue) begins over the Gulf of Mexico. Parcels from this family are drawn into the blizzard at the time of rapid cyclogenesis over the southern United States.

Each of these trajectory families have distinct characteristics. Figure 9 shows four panels which are typical of all of the trajectories beginning over the central Pacific (the red family). Figure 9a shows the latitude of the parcel, with the northward excursion over the western United States, followed by southward motion, then motion to 80°N with the blizzard. Figure 9b shows the pressure altitude of the parcel as a solid line and the pressure altitude of the tropopause as a dashed line. The parcels start in the upper troposphere at altitudes near, but below, the tropopause and end up at altitudes above the tropopause on the 17th. The solid line in Figure 9c shows the potential vorticity of the parcel, and the dashed line is the potential temperature of the parcel. The potential temperature variation is small, of the order of 1–2 K. As the parcel becomes entrained in the synoptic wave of the blizzard on the 13th and 14th of March, its potential vorticity increases from values typical of the troposphere to values typical of the stratosphere. The PV field is consistent with the parcel moving from below to above the tropopause.

Figure 9d shows the latent heat release (solid lines) and the longwave heating (dashed lines) at the location of the parcel. All of the parcels show weak longwave cooling initially, followed by a period where the longwave term is close to zero as the air moves southward over the central and western United States. This is followed by an increase of latent heating which is partially compensated by increased cooling. Highly correlated with the latent heat release is an increase of potential vorticity and an increase of the potential temperature. During this time period the parcel moves up, and the tropopause height moves to higher pressure (lower altitudes). In all cases the parcel moves from the troposphere to the stratosphere, and strong diabatic processes are correlated with changes in the potential vorticity of the parcel. The role of latent heat release in the life cycle of the storm will be discussed more fully in the next section.

The members of the family of parcels that begins over the Gulf of Mexico (the blue family) are also very consistent with

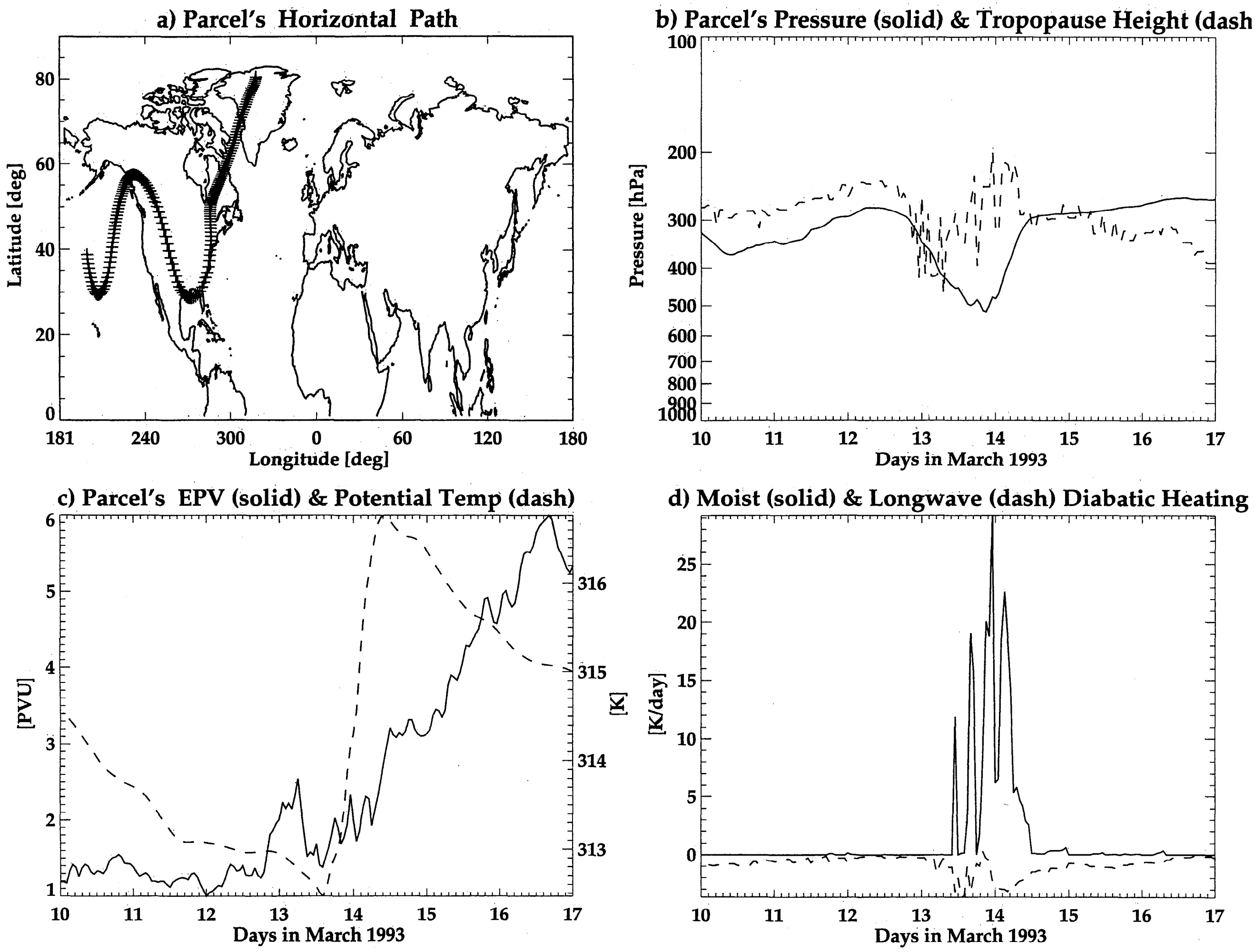


Figure 9. Diagnostics of an individual parcel which is characteristic of trajectories that originated over the Pacific Ocean (red family). (a) Parcel's horizontal path during the trajectory calculation; labeled with plusses. (b) Solid line represents the parcel's pressure as a function of time. Dashed line is the tropopause height at the parcel's position. (c) Solid (dashed) line represents the potential vorticity (potential temperature) of the parcel as a function of time. (d) Solid (dashed) line represents the diabatic heating rate as a function of time due to moist (longwave radiative) processes at the location of the parcel.

each other. The shape of the latitudinal excursion (Figure 10a) shows direct south to north motion. The pressure of the parcels in this family behaves differently from the parcels in the family originating over the Pacific. The parcels begin deep in the troposphere, often in the planetary boundary layer, and move upward to tropopause heights. The potential vorticity starts at very low values typical of the lower troposphere and increases rapidly to stratospheric values during the storm.

The diabatic terms are shown in Figure 10d. (Note that ordinate scale is different from Figure 9.) The latent heat release is larger than in the red family which originated over the Pacific, and there is weak, persistent longwave cooling. The potential temperature of the parcel increases more than 15 K. The latent heat release is once again correlated with the increase in potential vorticity. After the burst of latent heat release, the parcel reaches tropopause height, and the tropopause height is at higher pressure (lower altitude).

The family of parcels noted in Plate 8 with an origin over Eurasia (green) do not cross the tropopause (not shown). Those that start in the stratosphere remain in the stratosphere. Similarly, parcels that start in the troposphere remain there, maintaining their relationship with the tropopause. The diabatic terms are relatively small. This is true for parcels throughout the northern hemisphere that are not associated with the U.S. blizzard. Even in the vicinity of the Pacific storm the parcel trajectories behave quasi-isentropically, with little apparent exchange between the troposphere and the stratosphere.

The characteristics of the trajectories of the families of parcels of Pacific and Gulf of Mexico origin, which end up in the stratosphere, are consistent with each other and model physics. However, diabatic processes associated with synoptic waves and, more generally, moist processes in global models are notoriously difficult to represent accurately. Some confidence is derived from the fact that parcels not associated with the storm behave quasi-isentropically, while those directly linked to the storm exhibit specific characteristics that are repeatable. Whether or not an atmospheric process is being quantitatively represented, the model has identifiable mechanisms that are producing transport between the troposphere and stratosphere. Further identification of the characteristics of this event provides an idea of what observable features might be

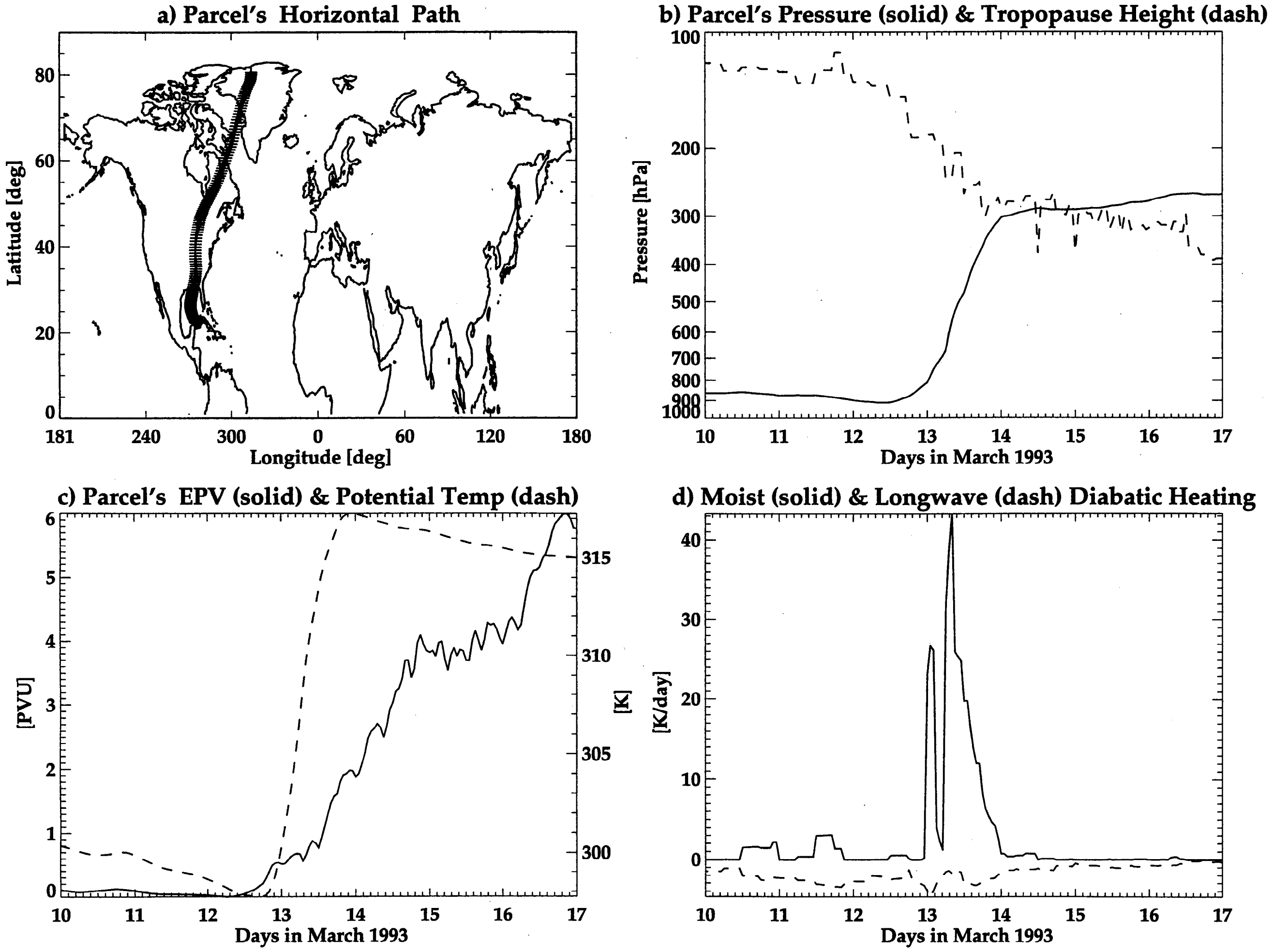


Figure 10. Same as Figure 9 except for a parcel representative of trajectories that originated over the Gulf of Mexico (blue family).

associated with storms that effectively transfer mass between the troposphere and stratosphere.

6. Synthesis and Conclusions

In this paper constituent transport by two specific synoptic events is investigated using model simulations. The model performance is judged to represent satellite tracer observations with adequate quality to justify more quantitative analysis. The two large synoptic-scale storms have similar surface characteristics, but are modeled to have much different impacts on tracer fields. Both storms show the characteristics of a tropopause fold; however, attention is given to the long-range (quasi-horizontal) transport from the subtropics into polar latitudes. The time-latitude plots of the idealized tropospheric tracer, trop1, in Figure 11 summarizes the difference of the cross-latitudinal transport characteristics of the two storms. The U.S. blizzard pulls tracer out of the tropics, and the material is transported directly to high latitudes where it remains. The Pacific storm pulls material out of the subtropics, but most of it returns to the subtropics. This reveals the first characteristic of the transport processes of the U.S. blizzard: the synoptic wave decays in a background environment that is different from the environment in which the wave grew.

The second characteristic is that diabatic processes are crucial to any ultimate exchange of mass between the stratosphere and troposphere. In the model, latent heat release, and concomitant convective transport, is essential for transporting air into the upper troposphere and producing air with potential temperature and potential vorticity typical of stratospheric air. After the storm has decayed, the background environment, which had originally been typical of the subtropical troposphere, is typical of the subpolar stratosphere. Active thermodynamic processes are likely to change the potential vorticity of the transported air, breaking the correlation between potential vorticity and tracers. This will result in exchange between the troposphere and the stratosphere. Compared with localized turbulent processes associated with the tropopause fold, this diabatically induced irreversibility is large scale.

The U.S. blizzard will be the primary subject of the discussion below. The impact of the Pacific storm will be briefly summarized. Though initially characterized by fast growth, the Pacific storm does not move far from its growth region. Both Plate 7 and Figure 11 show that tracer is pulled out of the subtropics, and ultimately much of it arches back into the subtropics. The ozone field shows that the storm significantly disturbs the lower stratosphere (Plates 3 and 5 and Figures 7 and 8). The tropopause pressure shown in Figure 5 suggests fragments of stratospheric air broken off of high latitudes

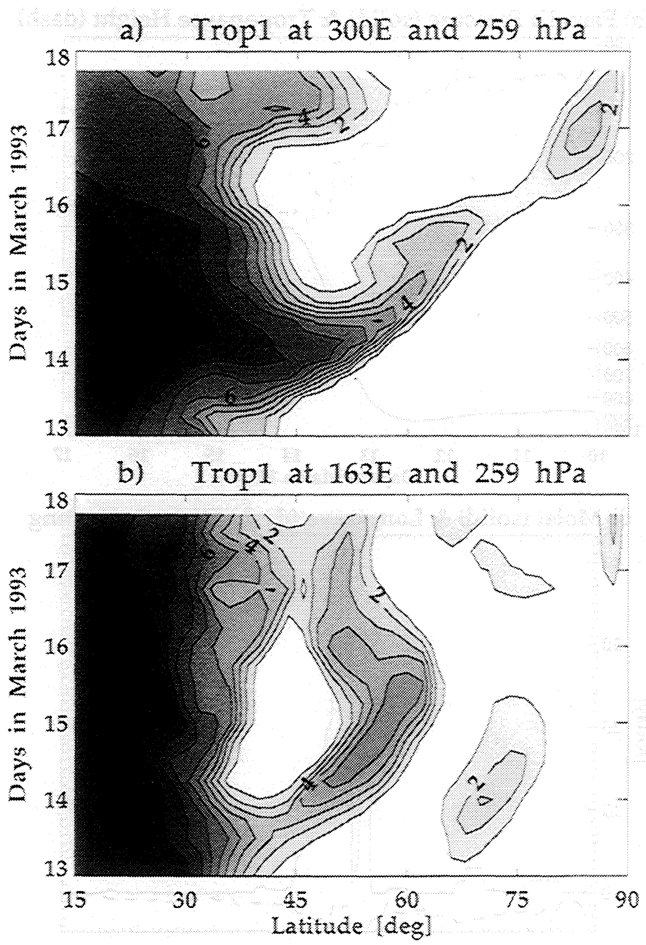


Figure 11. (a) Time-latitude contour of the tropical tropospheric tracer, tropl, at 300°E and 259 hPa. The contour interval is 1 arbitrary volumetric mixing ratio units. Latitudes run from 15° to 90°N. (b) Same as in Figure 11a except at 163°E longitude.

surrounded by tropospheric air. This is similar to the fragmentation discussed by *Appenzeller et al.* [1996] and should result in transport of air from the stratosphere to the troposphere. Because the Pacific storm is relatively stationary, the transport associated with the storm is similar to that of a cut off low [see, e.g., *Price and Vaughan*, 1993].

There are two tasks for establishing if the modeled transport processes of the U.S. blizzard represent real atmospheric processes. The first is the plausibility of the dynamical and thermal processes in the modeled transport; the second is rationalization with available tracer data and previous studies of stratospheric-tropospheric exchange.

While the U.S. blizzard and the Pacific storm are both intense events, storms of this magnitude are common. Storms like the U.S. blizzard, with explosive cyclogenesis and rapid movement across many degrees of latitude, have been described as atmospheric "bombs" [*Sanders and Gyakum*, 1980; *Roebber*, 1984]. The majority of deep cyclones which commonly dissipate in the North Atlantic and Pacific fall into this category. Bombs are also the synoptic waves most capable of irreversibly deforming the potential vorticity gradients that bound the lowermost stratosphere (see Plate 1 and discussion). Therefore, if the transport mechanisms revealed in this paper are representative of reality, the common occurrence of explosively developing storms suggests they could have a primary role in maintaining a mixture of tropospheric and stratospheric air in the lowermost extratropical stratosphere.

The trajectory calculations summarized in Figures 9 and 10 show that latent heat release is correlated with the exchange between the troposphere and stratosphere. The job of understanding and quantifying the role of latent heat release in the U.S. blizzard and transfer of mass between the stratosphere and the troposphere is difficult. The interactions between dynamical and thermal processes in the storm are naturally complex. They occur on a variety of space and timescales that have often been isolated in theoretical studies simply to grasp the important aspects of the component processes. Fully interactive studies have relied on comprehensive models. However, physical processes in these models are highly parameterized and resolution dependent, and often they are the least well known components of the model. Therefore many uncertainties exist in quantitative, and even qualitative, descriptions of the transport linked to explosive extratropical cyclones.

Uccellini [1991] reviews the dynamics and modeling of explosive extratropical cyclones, highlighting long-standing debates between advocates of dynamical (kinematic) theories and advocates of thermal theories. Explosive cyclogenesis requires the alignment of several contributing processes, including a background flow conducive to rapid wave growth, strong low-level sources of latent heat, and transfer of moisture from the ocean surface.

Dynamical processes that do not include moist physics can lead to rapid cyclogenesis [*Thorncroft et al.*, 1993] depending on the background state of the flow. The vertical structure of the two storms presented in Figure 6 shows that the U.S. blizzard is more prone to baroclinic development. However, though baroclinic processes alone can lead to qualitative representations of observed cyclones, forecast and process-oriented models show that quantitative representation of explosive cyclogenesis requires the explicit inclusion of latent heat release [*Chang et al.*, 1982; *Uccellini*, 1991, and references therein]. Latent heat release is responsible for the generation of high potential vorticity air in the lower troposphere. The potential vorticity source is proportional to the gradient of diabatic heating [*Andrews et al.*, 1987; *Lamarque and Hess*, 1994; R. X. Black, The maintenance of intraseasonal transient eddy activity in the GEOS-1 assimilated dataset, submitted to *Journal of Atmospheric Sciences*, 1997, hereinafter referred to as Black, submitted manuscript, 1997], and strong gradients of latent heat release are expected in the storm. Three-dimensional parcel trajectories generated during a simulation of the 1979 Presidents Day Storm, analogous in many ways to the U.S. blizzard in 1993, are very similar to those presented above [see *Uccellini*, 1991, Figures 6.12–6.14]. Parcels in the lower troposphere experience an increase in potential vorticity due to latent heat release, followed by lofting into the upper troposphere. No attempt was made by *Uccellini* [1991] to determine if the ultimate fate of these parcels was tropospheric or stratospheric.

The diabatic processes that generate the high potential vorticity air in the lower troposphere are strong local processes associated with the cloud and rain bands of the cyclone. In models, latent and sensible heat flux from the ocean surface are also important to storm development. When the integrated effects of the explosive cyclones are considered over a season, then the latent heat plays a much different role than in the lower tropospheric cyclogenesis. Black (submitted manuscript,

1997) shows that the wintertime mean contribution to the potential vorticity budget of the latent heat release in the upper troposphere is negative, decreasing potential vorticity. Maximum sinks of potential vorticity are coherently located in Atlantic and Pacific storm tracks. These persistent regional sinks tend to convert air to lower potential vorticity, making the air more tropospheric.

From the above description, the high latitude, wintertime, and springtime tropopause is difficult to pin down. There is rapid, episodic transfer of subtropical tropospheric air to the subpolar stratosphere and slower, systematic return of that air to the troposphere. The tropopause itself, in as much as it is defined as a potential vorticity surface, is difficult to define because diabatic forces which act as potential vorticity sources and sinks are active. It is difficult to assess the net effect of the constant impact of the cyclones on the high latitude tropopause region. *Grewe and Dameris* [1996], extending work of *Hoerling et al.* [1993], calculate that there is mean mass exchange from the troposphere to the stratosphere north of 40° latitude in the wintertime. The *Grewe and Dameris* [1996] conclusions are consistent with the net impact of the transport associated with explosive extratropical cyclones moving material from the troposphere into the lower stratosphere. *Holton et al.* [1995] comment that within the context of the general circulation, if such transport is real, it must be important in a layer only very close to the tropopause. The apparent complexity of this region provides reinforcement of the *Holton et al.* [1995] premise that the tropopause is not a good control surface to study mass exchange from the upper atmosphere into the lower atmosphere.

Tracer observations provide a powerful mechanism to illustrate atmospheric transport. There have been numerous campaigns to collect and interpret meteorological and tracer data to study stratospheric-tropospheric exchange associated with strong synoptic waves. Most attention has been focused on postulated transport mechanisms in the upper troposphere in the vicinity of the tropopause fold [*Danielsen*, 1968; *Shapiro et al.*, 1980; *Shapiro*, 1980; *Ebel et al.*, 1991; *Lamarque and Hess*, 1994; *Cox et al.*, 1995] or within cut off lows [*Bamber et al.* 1984; *Vaughan and Price*, 1989; *Price*, 1990; *Price and Vaughan*, 1993; *Ancellet et al.*, 1994]. The transport associated with the U.S. blizzard takes place over a much larger spatial domain than the studies referenced above, and we know of no data collected to focus specifically on the tracer transport during the entire life cycle of the storm. Furthermore, since modeled storms like the U.S. blizzard require a strong interaction with the ocean surface, many of the continental-based campaigns do not sample similar storms.

The deuterium data discussed by *Smith* [1992] for storms with similar characteristics to the U.S. blizzard suggest that water vapor just below the tropopause in North Atlantic storms has a source over the ocean off of the southeastern United States a few days earlier. Therefore the presence of air originating at the surface at lower latitudes and being deposited in the vicinity of tropopause at higher latitudes, as modeled, can be substantiated by tracer observations.

The modeled transport of the U.S. blizzard is also consistent with some of the recent tracer observations that have come from in situ aircraft measurements. *Folkins and Appenzeller* [1996] and *Dessler et al.* [1995] have studied transport in the lowermost stratosphere in middle latitudes. *Folkins and Appenzeller* [1996] argue that air that is unambiguously of stratospheric meteorological character, but with tropospheric concentrations of trace gases, can be identified from aircraft data. *Dessler et al.* [1995] argue that water vapor observations from aircraft measurements require a mixture of stratospheric and tropospheric air in what has been traditionally considered the lower stratosphere. *Dessler et al.* [1995] then conclude that there must either be direct injection of tropospheric air into the stratosphere across the midlatitude tropopause or quasi-isentropic mixing of tropospheric and stratospheric air across the subtropical jet stream.

Folkins and Appenzeller [1996] and *Dessler* [1995] have cited numerous studies to support their interpretation of the tracer data. The transport studies of *Chen* [1995] and *Yang and Pierrehumbert* [1994] both investigate the feasibility of quasi-isentropic mixing across the subtropical jet stream. In companion papers *Poulida et al.* [1996] and *Stenchikov et al.* [1996] argue that direct injection of tropospheric air into the lower stratosphere by convective processes is possible during midlatitude summertime mesoscale convective complexes. Similarly, the large-scale synoptic transport discussed in this paper would have the same effect of mixing tropospheric and stratospheric air in the lowermost stratosphere. While the horizontal aspects of the transport might have a similar appearance to quasi-isentropic mixing, the transport studied in this paper is strongly linked to diabatic processes and should be distinguished from the mechanisms in the aforementioned studies.

The deuterium and other tracer data establish the plausibility of synoptic-scale transport from the lower troposphere to the vicinity of the tropopause. The modeled transport is qualitatively consistent with the understanding of the dynamics of explosive cyclones, and storms like the U.S. blizzard are a frequent and important part of the winter and spring circulation. However, the modeled transport depends largely on parameterizations of moist processes in the model-assimilated data. These parameterizations are amongst the most difficult and uncertain parameterizations in any model. Furthermore, the behavior of the parameterizations in the assimilation cycle is suspect [see *Molod et al.*, 1996]. The chemistry transport model directly uses cloud mass fluxes, and the trajectory model uses archived diabatic forcing terms. Consistency between the Eulerian model and the Lagrangian diagnostics is difficult to assure with such strong diabatic terms. Uncertainties in the described mechanisms remain large. More detailed modeling and further scrutiny of observations (or new observations) are needed to establish the reality of the modeled transport and the impact of explosively developing synoptic waves on the tracer composition of air in the lowermost stratosphere. High-resolution process models might provide further information with their more robust physical parameterizations. However, such models would have to be extended to have an adequate domain for storm growth and decay, as well as to maintain a quality simulation for several days. It is also of value to determine if the modeled transport is present in general circulation models that do not have the repeated insertion of data used in data assimilation. Ultimately, the proof of the transport mechanism will lie in tracers observations that definitively link the subtropical troposphere with the subpolar stratosphere. Campaigns to make such measurements must consider the special aspects of rapidly developing storms, perhaps exploiting the fact that marine air is involved which might provide a set tracers not usually considered in studies of stratosphere-troposphere exchange.

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