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Meteorological analysis of tropospheric ozone profiles at Bermuda

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Abstract. As part of the North Atlantic Regional Experiment (NARE) a number of ozonesonde profiles were obtained from Bermuda during the spring and summer of 1993. We present meteorological case studies of two instances of elevated O_3 mixing ratio in the middle and upper troposphere which took place during the summer. The ozonesonde profile of July 9, 1993, indicated ozone mixing ratios exceeding 100 parts per billion by volume (ppbv) from ~5 km to above 15 km above sea level. A series of profiles for August 2–4 indicated elevated ozone in a layer which initially extended from 8 to 9 km and thickened to cover the 8- to 14-km range. Isentropic trajectories lead back to potential source areas over North America 2 to 5 days prior to the events. Objective analyses based on radiosonde data demonstrate that the air masses, as indicated by the trajectories, pass through areas of elevated isentropic potential vorticity located in troughs in the tropopause-level geopotential height field. The conformation and temporal development suggest that active planetary wave breaking was responsible for stratosphere-troposphere exchange in these systems. These results suggest an important role for O_3 of stratospheric origin in the western North Atlantic Ocean area, transported into the troposphere upstream over or near North America. It is notable that these events took place in the summer months of July and August, when such events had been considered unlikely.

Introduction

Tropospheric O_3 is an important photochemical oxidant and a damaging secondary pollutant. There are both natural and anthropogenic sources for O_3 in the troposphere, with downward transport of stratospheric O_3 being the primary natural source. Recent work by *Parrish et al.* [1993] has indicated that in the summer months, high O_3 mixing ratios at the surface over the northwestern North Atlantic are dominated by transport of anthropogenic pollution, as indicated by data from the months of July–September, 1991. These authors did note one moderate episode of O_3 presumably associated with stratospheric injection (high in O_3 and low in CO, the tracer for anthropogenic pollution). Similar results are being reported from the 1993 North Atlantic Regional Experiment (NARE) surface and aircraft intensive, indicating that O_3 from impacted areas is important in the lower troposphere in the area downwind of North America. For example, *Kleinmann et al.* [this issue] present data showing that a variety of air mass types reach the area. Prominent among these is moist continental boundary layer air with high concentrations of O_3 and other anthropogenic pollutants. Analysis of the meteorological situation shows that flow from the southwest in the warm sector of weak cyclonic storm systems is responsible for the largest fraction of the flux of lower level air from the continental boundary layer in this area [*Merrill and Moody*, this issue]. In earlier work as part of the Atmosphere/Ocean Chemistry Experiment (AEROCE), *Dickerson et al.* [1995] report on an event in June, 1992, with elevated O_3 arriving at Bermuda together with enhanced CO, NO_x, and NO_y. One scenario they present for this event is of polluted air from the continental boundary layer lifted convectively to the free troposphere and subsequently transported out over the ocean, where it subsides and returns to the surface; further, they estimate that photochemical production during transit of 10–20 parts per billion by volume (ppbv) of O_3 would be consistent with the NO_x mixing ratio observed at Bermuda. On a somewhat larger spatial scale, numerical model studies [*Jacob et al.*, 1993] indicate that >50% of the O_3 produced in the boundary layer over the United States is transported to the global troposphere.

Calculations based on observed winds indicate a northern hemisphere winter maximum in the extratropical downward flux of air into the lower stratosphere [e.g., *Rosenlof*, 1995]. These estimates are made using the "downward control principle" [*Haynes et al.*, 1991], and this variation appears to be consistent with seasonally increased planetary-scale wave forcing of stratospheric momentum. *McIntyre and Palmer* [1984] discuss middle-stratosphere transport and dynamics more generally, emphasizing the importance of wave breaking. The forgoing discussion concerns exchange into the lower stratosphere and the upper troposphere. In contrast, meteorologists estimated that the midlatitude flux of O_3 from the stratosphere to the troposphere would peak in the spring months in correspondence with the prominent spring maximum in the mixing ratio of O_3 above the tropopause, together with the seasonally varying flux of air into the troposphere [*Austin and Follows*, 1991]. The downward flux across the tropopause is assumed proportional to midlatitude tropospheric eddy activity by J. F. Austin and M. J. Follows. Recent work using a mass-conserving nu-

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merical model based on analyzed winds to simulate the cross-tropopause transport along isentropic surfaces [*Chen*, 1995] indicates that the extratropical downward flux at potential temperature levels which reach the middle and lower troposphere does not exhibit the winter maximum in the northern hemisphere noted above. Rather there is vigorous stratosphere-troposphere exchange of air during all seasons at and below $\theta = 330$ K.

Continuous observations at the surface at Bermuda do show a maximum in the mixing ratio of O_3 during the spring months, with average values in excess of 45 ppbv, and with significantly lower values, approximately 20 ppbv, in the summer [*Oltmans and Levy*, 1992]. In our research in AEROCE, we have found a strong correlation of dry air and elevated surface O_3 concentration (12-hour average mixing ratios of 60 ppbv or greater) in the spring months occurring with large-scale subsidence and northwesterly flow after the passage of cold fronts on Bermuda [*Moody et al.*, 1995]. We have concluded that under these conditions the site is ventilated with middle-tropospheric air, in support of the transport relationship determined subjectively by *Oltmans and Levy* [1992]. Also, satellite remote sensing results indicate that tropospheric column burdens of O_3 exceed 40 Dobson units (DU) over large areas of the North Atlantic in both the spring and the summer [*Fishman et al.*, 1990].

During the August, 1993 NARE intensive field campaign a number of events of transport from the northeast United States to the Canadian Maritimes were examined using both surface-based and airborne platforms. *Kleinmann et al.* [this issue] report aircraft observations in the lower troposphere showing evidence of dry air masses with high O_3 concentrations, some of which may originate in the upper troposphere upwind of Nova Scotia. *Moody et al.* [this issue] present an analysis of the late August, 1993 event with the most significant flux of O_3 to the surface sites in Nova Scotia. They illustrate that O_3-rich air in the lower levels of the troposphere there occurs in the southwesterly flow near the surface in advance of eastward moving upper level troughs. They also present evidence that the upper tropospheric disturbances which generate these surface systems have the potential to inject stratospheric O_3 into the troposphere, where it is advected by the disturbed westerly winds to upper and middle-tropospheric levels over the subtropical western North Atlantic Ocean.

Analysis of the entire set of ozonesonde data from Bermuda for 1993 confirms the indication from satellite-derived estimates that summertime tropospheric column amounts are comparable to the spring maximum values [*Oltmans et al.*, this issue]. Further, these data show that the highest O_3 mixing ratios and temporal variations are in the upper half of the troposphere. In the work presented here we discuss supporting meteorological analyses for O_3 profiles at Bermuda and focus on two events during the summer of 1993.

Observations and Analysis Techniques

Ozonesondes. A series of 60 ozonesonde profiles was obtained at Bermuda during 1993–1994 in an intensive sampling campaign. Approximately 25 sondes were launched each season during the spring and summer months. Balloonborne electrochemical cell ozonesondes were used. Here we identify periods of significant O_3 transport in the free troposphere based on some of these data. Our initial analysis combined the thermodynamic and wind data from the routine radiosonde profile at Bermuda and trajectory analysis with the O_3 data. The O_3 results from Bermuda are put in the context of other recent ozonesonde profile data by *Oltmans et al.* [this issue].

Trajectories. Isentropic air mass trajectory analysis back in time (based on gridded meteorological fields produced routinely every 12 hours, the National Meteorological Center (NMC) global analysis) has been used to study the transport paths of hypothetical air parcels in the vertical distribution indicated in the ozonesonde profiles. The trajectories lead back to possible source regions above or offshore of North America. The isentropic conversion and trajectory analysis technique is that which has been used in the AEROCE program [*Merrill*, 1994]. Briefly, the three-dimensional gridded fields of geopotential and horizontal velocity are transformed to fields of pressure and velocity on surfaces of constant potential temperature at intervals of 5 K, and saved. In a subsequent calculation, trajectories are constructed using the velocities alone; no explicit vertical velocity estimates are used, as the vertical displacement is implicit in the motion along the sloping isentropic surfaces [*Merrill et al.*, 1986]. Gridded model fields are available with higher spatial resolution than that of the NMC global analysis, but do not extend as far offshore as Bermuda. This is unfortunate because there are trajectory models available which do not require the isentropic approximation [*Draxler*, 1992]. Here swarms of four trajectories starting back from points surrounding the site are used. This allows us to assess the diffluence in the flow at the end point near Bermuda.

Isentropic potential vorticity (IPV). IPV is a quasi-conservative dynamical variable in the atmosphere. Its usefulness as a tracer was recognized soon after *Rossby* [1940] developed simplified models of the distribution of potential vorticity and explored its role in atmospheric motion. Recently, there has been a resurgence of interest in IPV by dynamicists and meteorological analysts because it plays a central role in modern models of cyclogenesis and has wide utility as a tracer. The isentropic potential vorticity, defined as

$$\mathrm{IPV} = -g(f + (\partial v/\partial x)_\theta - (\partial u/\partial y)_\theta) \cdot \frac{\partial \theta}{\partial p}$$

is determined by the distribution of absolute vorticity (approximated isentropically), $f + \zeta_\theta$, and the static stability, $\partial\theta/\partial p$. The conservation of IPV means that there is the potential for changing the relative vorticity, ζ_θ, in a parcel of air by changing its latitude or by adiabatically altering the separation, ∂p, between surrounding isentropic levels. IPV is commonly discussed in "potential vorticity (PV) units," $= 10^{-6}$ m^2 s^{-1} K kg^{-1} [*Hoskins et al.*, 1985]. For an atmosphere with no relative vorticity and at $f = 10^{-4}$ s^{-1}, this unit corresponds to a stratification of 10 K of potential temperature in 100 hPa. Tropospheric values are thus generally less than 1 PV unit in the absence of significant cyclonic relative vorticity, and in most cases, less than 1.5 units overall. IPV jumps to stratospheric values of 4 or higher at the tropopause and rises steeply with height, because of the very strong stratification above this level. The conservation of IPV is exact only in the absence of friction and diabatic effects (radiational divergence, latent heating, or vertical mixing by convection, for example). However, *Danielsen* [1968], using ozone and radioactive tracer data, demonstrated that IPV remains a good indicator of the stratospheric origin of air, even when the IPV distribution is changed by convection and subsynoptic-scale mixing. Further remarks on the relationship between IPV and chemical tracers are in the discussion section, below.

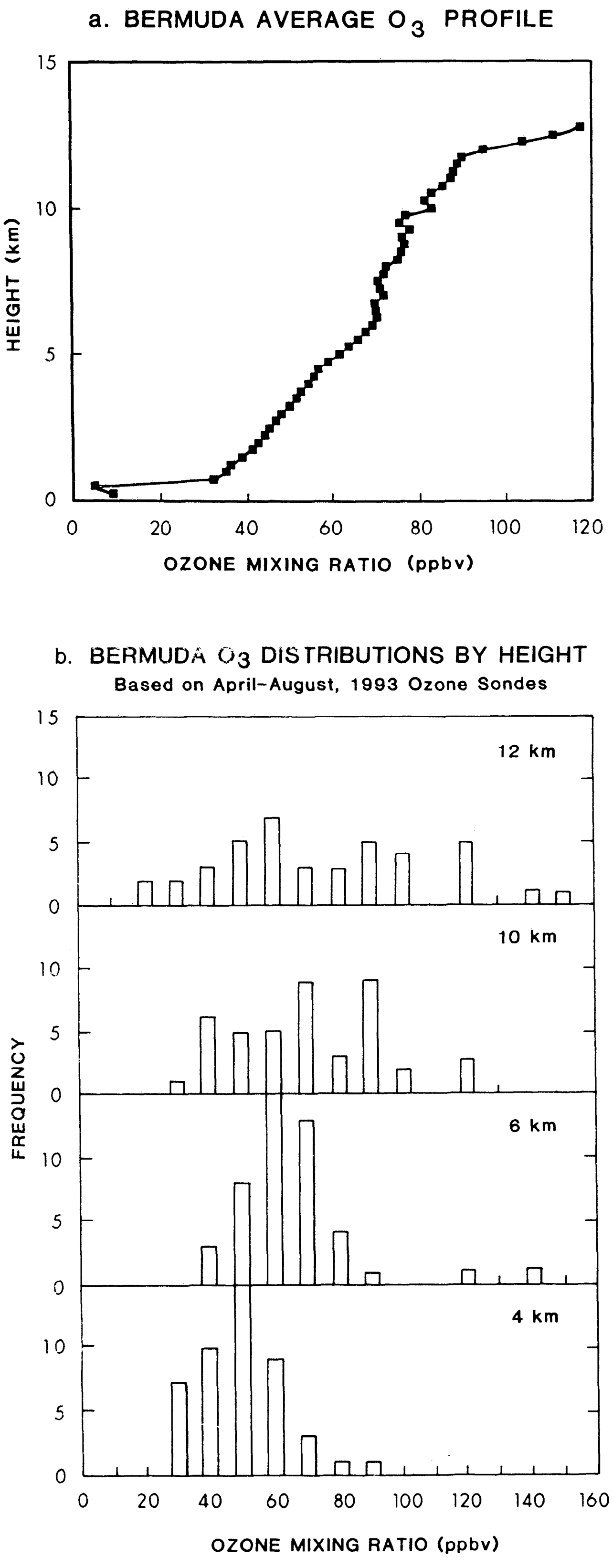


Figure 1. (a) Vertical profile of O_3 mixing ratio estimates in the troposphere averaged from ozonesondes during the April–August, 1993 period. (b) Distribution of O_3 mixing ratio estimates from ozonesondes during the April–August period at levels of 4, 6, 10, and 12 km. The frequency of O_3 mixing ratio estimates are shown as the number of cases at these four heights. Note that the abscissa scales differ in Figure 1a and 1b.

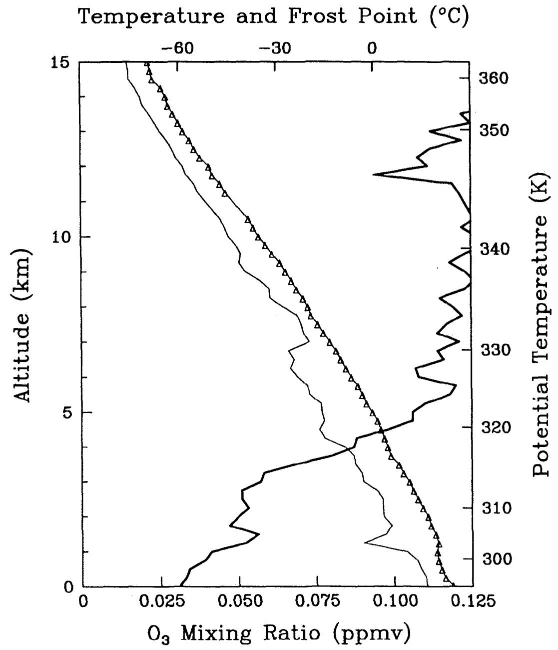


Figure 2. (bottom) Vertical profile of O_3 (thick line), (top) temperature and frost point (thin line with and without symbols) at Bermuda on July 9, 1993. The data are presented as averages over 250-m intervals in the vertical, and the corresponding potential temperature levels are indicated on the right-hand scale.

Aerological data. Our upper air analysis is based on radiosonde data over the North American area acquired from the archives of the National Center for Atmospheric Research. The data were screened carefully for errors, and each sounding

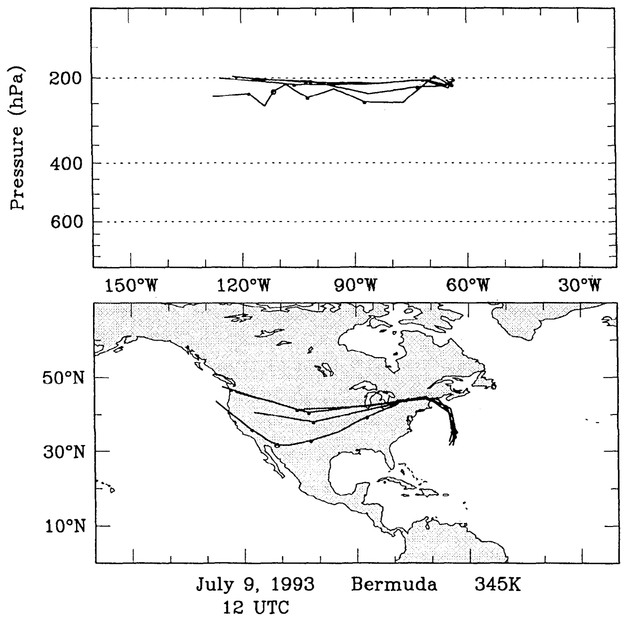


Figure 3. Isentropic trajectories at the 345 K potential temperature level of four parcels back from 1200 UTC, July 9, 1993, near Bermuda. (bottom) Trajectory points at intervals of 12 hours are connected, and the point at 0000 UTC each day is indicated with an open circle. (top) the trajectory is plotted in a vertical section in which the ordinate is proportional to height (i.e., to $p^{-\kappa}$, where $\kappa = R/c_p$).

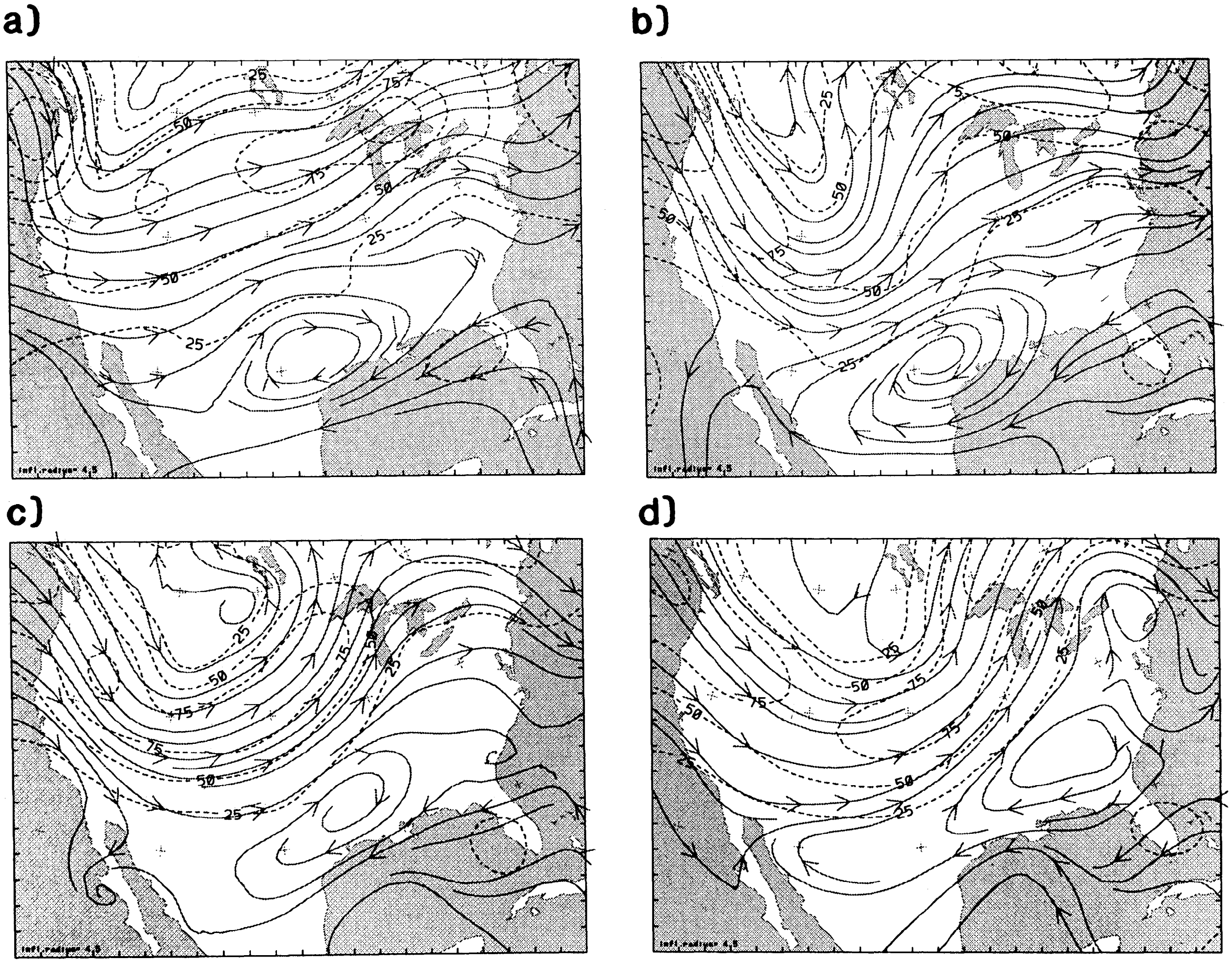


Figure 4. Streamline isotach depiction of objectively analyzed radiosonde winds at 345 K for 0000 UTC on 4 days in July, 1993. (a) July 3; (b) July 4; (c) July 5; (d) July 6. Streamlines are solid lines with arrows, and the dashed lines are isotachs at intervals of 25 kt. The pressure level of the 345 K isentropic surface varies from ~200 to 250 hPa and is plotted for three of these times in Figure 5.

was processed with potential temperature as the vertical coordinate. Subsequently, the data were converted to grid point estimates, on isentropic surfaces at intervals of 5 K, using a technique of objective analysis [*Bleck and Mattocks*, 1984]. As in many objective analysis schemes, grid point estimates of each meteorological variable (e.g., u) are formulated as a weighted average of nearby observations. Differentiating these weights with respect to the grid point location produces sets of weights which express $\partial u/\partial x$ and $\partial u/\partial y$ at the given point in terms of nearby observations of u. By this approach one proceeds directly to analysis of the needed values of the components of the relative vorticity, avoiding finite differencing of analyzed u and v fields. The polar stereographic grid used has a grid interval of 1.92 degrees, and the influence radius used in the calculations is 4.5 grid units. The accuracy of the static stability variable, $\partial\theta/\partial p$, is dependent upon adequate vertical resolution. We met this need in the data by using only soundings with both mandatory and significant level information available. The accuracy of the relative vorticity estimates is more dependent upon the characteristics of the horizontal objective analysis. We varied the potential temperature resolution and the influence radius and find that the IPV results are quite robust.

Results

The profile of the O_3 mixing ratio, averaged over the 46 soundings taken in the months April–August is shown in Figure 1a. The increase from values less than 20 ppbv near the surface to over 75 ppbv in the middle to upper troposphere is notable. The rapid increase with height of the O_3 mixing ratio above ~13 km indicates the presence of stratospheric air there. The variability about the average distribution shown in Figure 1a at four heights in the troposphere is shown in Figure 1b. The increasing occurrence of higher O_3 mixing ratio estimates as the height increases is obvious in the figure. Also, the variability increases with height, such that at 6 km, and especially at 10 and 12 km the distribution is far from Gaussian.

The variations indicated by these distributions can occur over short timescales, and soundings on successive days often indicate strong contrasts in the O_3 profile. A particularly remarkable transition was evident in the profiles obtained on April 20–21, 1993 (not shown). On April 20 the O_3 mixing ratio was uniform at about 45 ppbv from the surface to ~11.5 km. On April 21 the middle and upper tropospheric values began to increase, exceeding 60 ppbv at all levels above ~5 km and exceeding 80 ppbv at and above 10 km. The initially uniform profile is easily explained by strong convective mixing carrying surface level air depleted of O_3 through the entire troposphere. The sounding indicates that the air is saturated through the entire depth of the troposphere, and the satellite image shows cold cloud tops, indicating deep convection. The subsequent transition to higher O_3 values is related to horizontal transport caused by a developing synoptic-scale system northeast of Bermuda. We examine here two cases which occurred during the summer months of 1993, at a time when high O_3 mixing ratios are not generally expected in the remote troposphere, and when it has been believed that the importance of O_3 transport associated with stratosphere-troposphere exchange would be relatively small.

Case one. Figure 2 shows the ozonesonde profile on July 9, 1993, and indicates O_3 mixing ratios above 100 ppbv in a layer extending from ~5 km to >15 km above sea level. In the context of the O_3 profile statistics developed during this campaign these are significantly elevated mixing ratios. It is especially notable to see high mixing ratios of O_3 extending through such a deep layer. The O_3 mixing ratio in the near-surface layers is much lower, at a value which is typical of this season [*Oltmans and Levy*, 1992], consistent with the surface-level air having spent long periods of time over the open ocean [*Merrill*, 1994], where there are no pollution sources and where destruction of O_3 can occur.

Trajectory analysis back in time from the site indicates that air parcels in the upper half of the column had passed over a variety of areas over the North American continent 2 to 4 days before arriving near Bermuda. Figure 3 shows the path of a swarm of four parcels, and indicates that they reached Bermuda at a pressure level of ~220 hPa after passing through a deep trough over the midwestern United States and subsequently rising through a ridge over the northeastern United States and moving slowly toward the south. These trajectories are at the 345 K potential temperature level and extend over the 3 to 5 days back from the ozonesonde profile date of July 9, 1993. Near Bermuda this isentropic surface lies near an elevation of 11.5 km above sea level (note the potential temperature scale on Figure 2). A similar pattern of motion is indicated by trajectory analysis at levels below this (not shown).

The development of the trough over the midwestern United States from July 3 to 6, 1993, is indicated by the streamline isotach analyses shown in Figures 4a–4d and the potential vorticity values shown in Figure 5a–5c. These estimates were determined by objective analysis. The winds as observed at the radiosonde stations are shown in Figure 5; not shown are the isentropic thicknesses which also enter into the IPV estimates. On July 3 (Figure 4a), the wind speed exceeds 100 kt upstream of the sharp trough in the northwestern United States. By 0000 UTC on July 4 (Figure 4b) the trough has deepened and its axis has rotated so that the flow from the northwest extends eastward to 110°W. Meanwhile, the wind speeds exceeding 75 kt have spread and extend both upwind and downwind of the trough axis. At this time a pool of stratospheric air, with IPV > 4 PV units, is situated north of 40°N and west of ~105°W (Figure 5a). The trough broadens somewhat by July 5 (Figure 4c) and then broadens further by July 6 to cover the entire western United States (Figure 4d). During this period the area in which IPV exceeds 4 PV units expands and deforms rapidly. The 8 PV units contour, which extends from the northwest into the region north of 40°N along 110°W on July 5 (Figure 5b) opens up to the northeast by July 6 (Figure 5c) as winds both upstream and downstream of the trough axis exceed 100 kt.

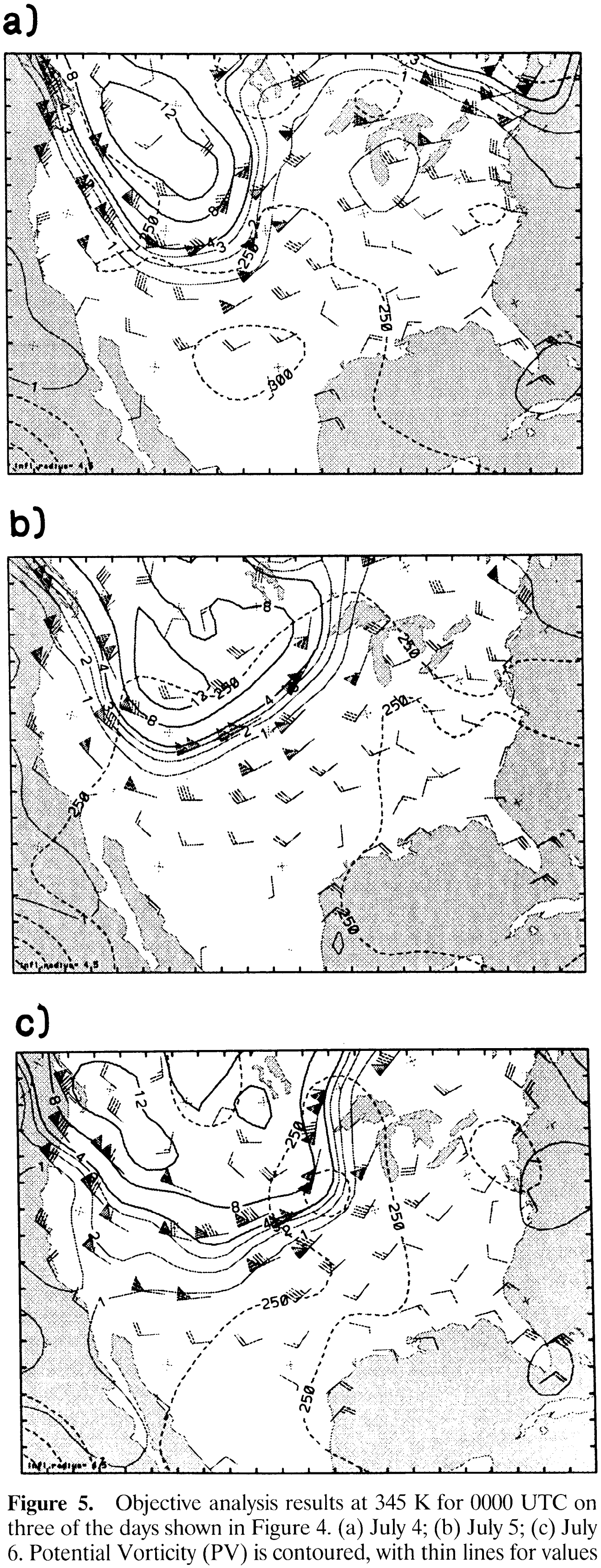


Figure 5. Objective analysis results at 345 K for 0000 UTC on three of the days shown in Figure 4. (a) July 4; (b) July 5; (c) July 6. Potential Vorticity (PV) is contoured, with thin lines for values of 1, 2, 3 PV units and thick lines for values ≥4 PV units (where the contour interval is 4 PV units). Also shown are the winds at the radiosonde stations (for those lying within the grid area) in conventional meteorological notation (short barbs: 5 kt, long barbs: 10 kt, triangles: 50 kt). The dashed contours show the pressure level of the isentropic surface, labeled in hectopascal.

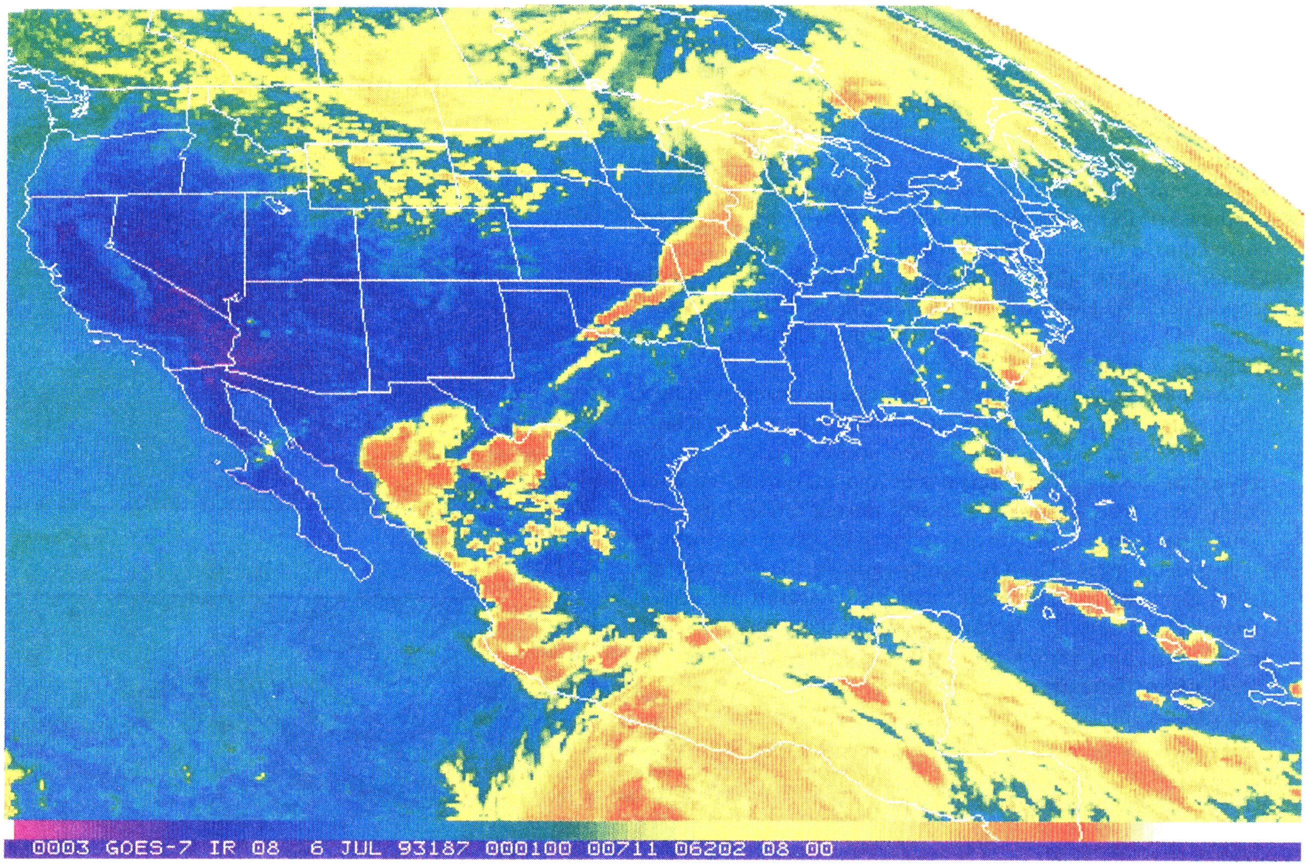


Plate 1. Enhanced GOES infrared satellite image from 0100 UTC on July 6, 1993, showing the band of deep convection over the midwestern states of Oklahoma, Nebraska, Missouri, Iowa, Illinois, and Wisconsin.

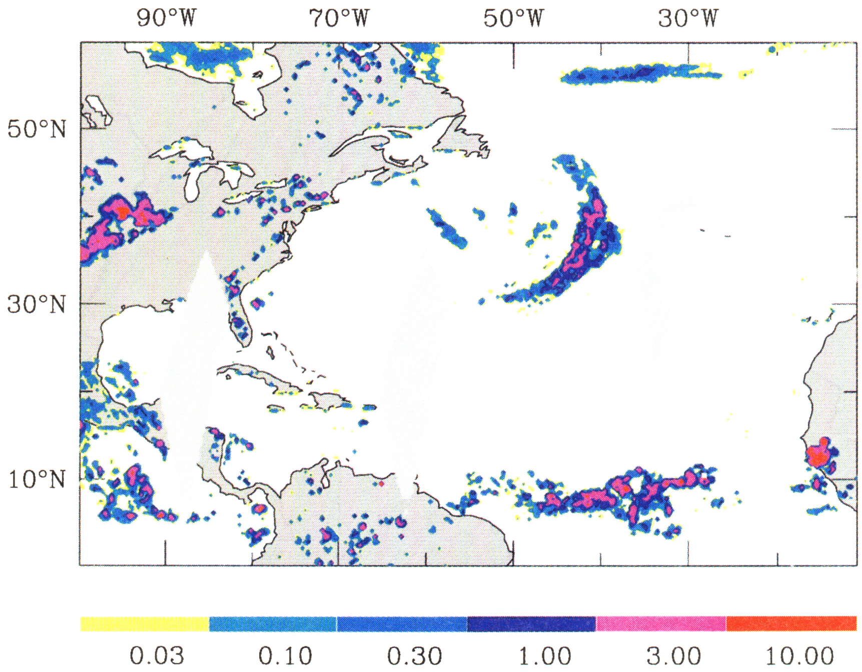
At the time of the IPV analysis shown in Figure 5c, July 6 at 0000 UTC, the end points of the trajectories west of 100°W plotted in Figure 3 are on the periphery of the high-IPV area. Two of the trajectory end points lie in the 4 to 8 PVU area, and a third lies between 1 and 2 PVU. The rapid and irreversible deformation of the IPV contours shown in Figure 5a–5c indicate that large-scale wave breaking occurred at and near the 345 K level during this period. Wave breaking is an important mechanism for midlatitude cross-tropopause exchange from the stratosphere to the troposphere. These results suggest that natural stratospheric ozone, exchanged into the troposphere and transported to the area near Bermuda, is responsible for the elevated O_3 mixing ratios observed there on July 9, 1993.

The satellite image (Plate 1) shows the region of intense convection in the upper Mississippi valley at the time of the last IPV analysis, July 6, 1993. The devastating midwestern flood was caused by the persistence of this convection. Such convective systems could transport surface level elevated O_3 or O_3 precursors, or inject nitrogen oxides generated by lightning, into the upper troposphere, providing an alternate explanation for the elevated mixing ratios observed at Bermuda. We ascribe the O_3 event at Bermuda to stratosphere-troposphere exchange upstream of the convective system, not to photochemical production downwind of it nor to upward vertical transport of air from the surface which is rich in O_3.

This deep convection spoils the assumption of overall static stability required by the isentropic analysis, calling in to question the accuracy of the trajectory calculations as the air passes through the convective region. However, the primary effect of such convection will be to distribute the properties of any air mass entering the clouds at a given potential temperature level over a range of potential temperatures, not to cause abrupt changes in that potential temperature value itself. In particular, it is possible that convective vertical transport mixed O_3-rich air downward over a significant depth in the upper troposphere, accounting for the very thick layer of elevated O_3 observed (Figure 2). Downstream of the convective complex, the trajectories pass through areas where there was only sporadic convection, as indicated by the scattered precipitation areas in the eastern United States shown in Plate 2a–2b. Estimates of the rainfall rate obtained from the special sensor microwave imager (SSM/I) on the DMSP F10 and F11 platforms are included in these plots [*Ferraro et al.*, 1994a, b].

Case two. The ozonesonde profile on August 2, 1993 (Figure 6a), includes a maximum in the mixing ratio extending from 8 to 9 km above the surface and exceeding 100 ppbv there. On the following days this maximum deepened to cover the layer from 6 to 9 km (Figure 6b) and subsequently extended from 8 to 14 km (Figure 6c). The streamline isotach analyses at the 340 K isentropic level show a deep trough east of the Great Lakes at 0000 UTC on July 31 (Figure 7a), which becomes narrower as it moves toward the southeast and offshore over the next 24 hours (Figure 7c, 0000 UTC on August 1). The IPV analysis (Figure 7b) shows that on July 31 at 0000 UTC there was an area of elevated IPV covering the northeastern United States, with values exceeding 12 PVU in an area extending to the north. By 0000 UTC on August 1 (Figure 7d) the area of elevated IPV has moved offshore of the United

a. Rain Rate mm/hour for 930707



b. Rain Rate mm/hour for 930708

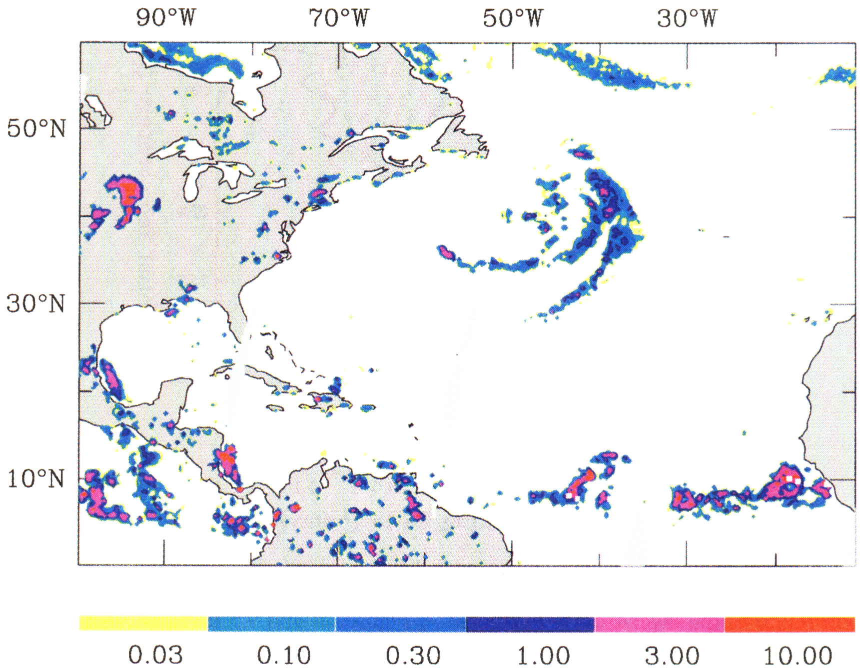


Plate 2. Rainfall area maps for (a) July 7, 1993, and (b) July 8, 1993. Because these are composites based on snapshot estimates of the rainfall rate (up to four estimates each, from ascending and descending orbits of the two satellites) they do not relate directly to accumulated total precipitation or to the rain rate at a specific time. Data voids are indicated by the grey trapezoidal areas, for example, near 85°W and 62°W in Plate 2a.

States and is confined to a narrow band with somewhat lower maximum values. This rapid deformation of IPV contours is consistent with stratosphere-troposphere exchange. The trajectory plot (Figure 8) shows the paths of parcels reaching Bermuda at 340 K at 1200 UTC on August 3. This isentropic layer lies above the peak in the O_3 mixing ratio at this time. The transport pattern toward Bermuda is not very coherent in this case (i.e., only one trajectory from the swarm of four extends back over the high IPV area for the time shown in Figure 9d, 0000 UTC on August 1). However, at other times and at the 335 K isentropic level there is additional evidence of transport from the area of elevated IPV toward Bermuda, arriving be-

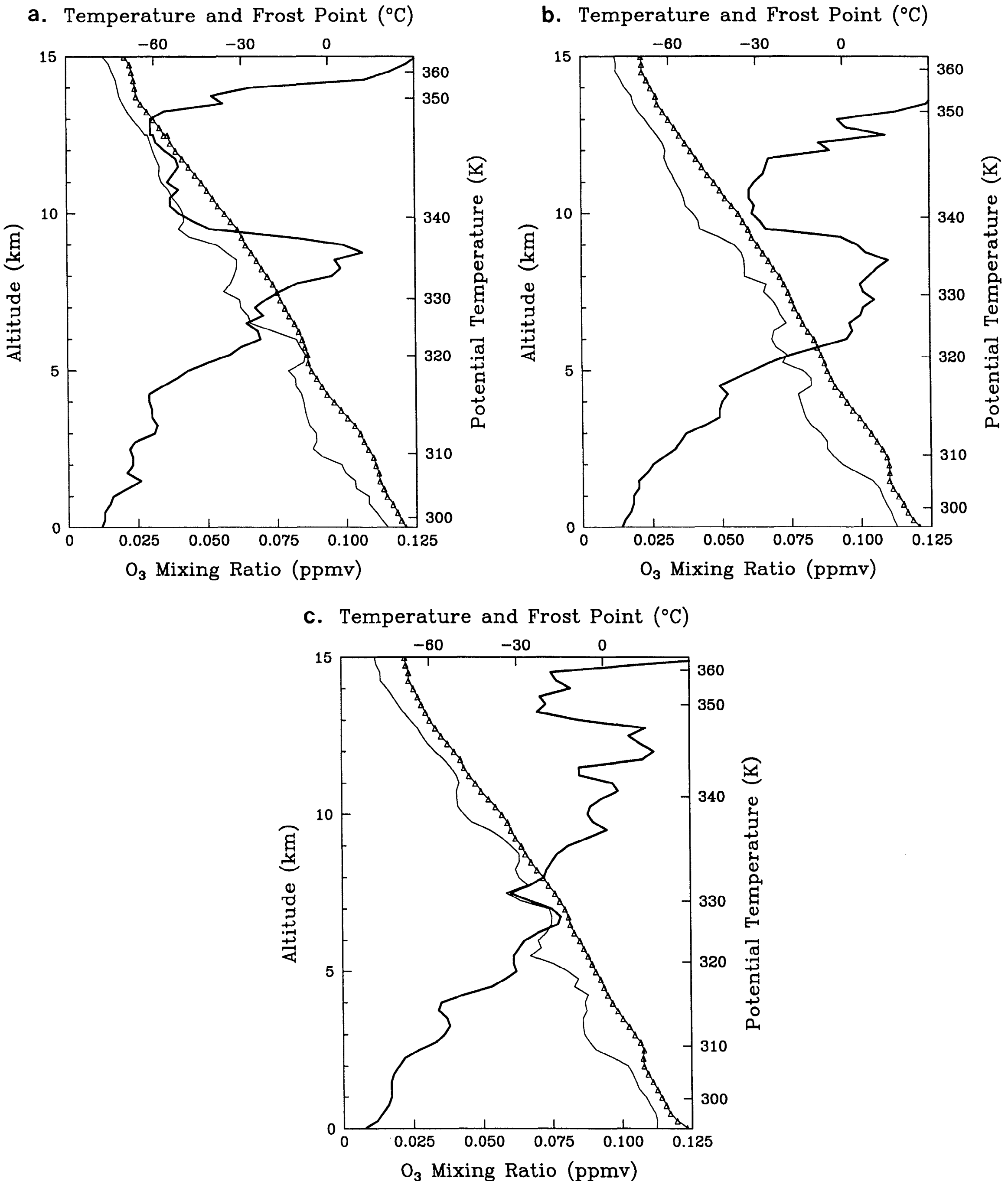


Figure 6. (a) Vertical profile of O_3, temperature, and frost point at Bermuda on August 2, 1993. The data are presented as in Figure 2: (b) August 3, 1993; (c) August 4, 1993. The values exceeding 100 ppbv in Figure 6a at 8 to 9 km relate to the layer from 6 to 9.5 km in Figure 6b and 9.5 to 13 km in Figure 6c.

tween August 2 and August 4, 1993. The trajectories are plotted as straight line segments between end points at 12-hour intervals. The trajectory off Cape Cod in Figure 8 is shown as moving from northwest to southeast, while the winds indicated in Figure 7d downstream of the trough are toward the north. A more detailed plot of the trajectory would show it skirting the trough off the East Coast, passing through the high IPV air before turning south toward Bermuda. Also, the conformation of the O_3 maximum region in the profile in Figure 6a–6c is suggestive: the wedge shape could be the leading edge of a tropopause fold, which would thicken and appear to rise as it is advected over the Bermuda area. We attribute the O_3 maximum observed on August 2–4, 1993, to natural stratospheric ozone exchanged into the troposphere.

Discussion

Adequacy of IPV as a tracer. It could be argued that IPV is destroyed by diabatic phenomena in the troposphere and is not conserved over extended times. The same processes which destroy or reduce IPV spoil the approximations used in isentropic analysis, reducing the accuracy of isentropic trajectories,

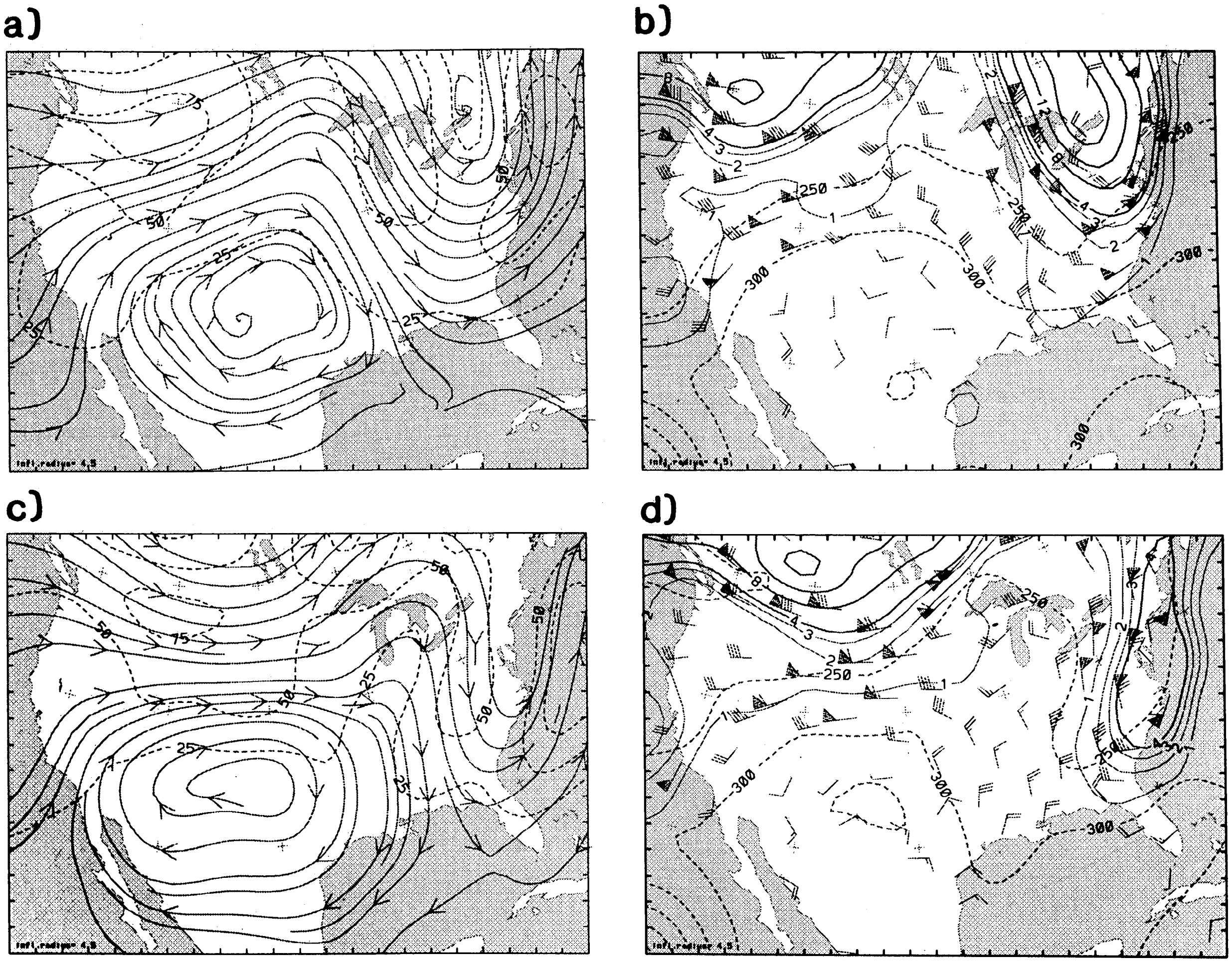


Figure 7. (a, b) Objective analysis results at 340 K for 0000 UTC on July 31, 1993 and (c, d) August 1, 1993. Streamline isotach analysis using the same plotting conventions as in Figure 4 are shown in Figure 7a and Figure 7c. Isentropic potential vorticity (IPV), winds, and pressure levels (as plotted in Figure 5) are shown in Figure 7b and Figure 7d.

perhaps drastically and abruptly. The present analysis is dependent upon the quasi-conservation of IPV and the adequacy of isentropic trajectory analysis over periods of a few days. However, numerous studies have shown the utility of isentropic trajectories and of IPV used as a tracer in such circumstances. More generally, it has been shown that addressing the macroscopic budget of IPV as a tracer, IPV can neither exhibit a net transport across isentropic levels nor be simply created or destroyed in an isentropic layer [*Haynes and McIntyre*, 1987]. There is a level of subtlety in the interpretation of this impermeability principle [*Danielsen*, 1990; *Haynes and McIntyre*, 1990], relating in part to the possible presence of diabatic cross-isentropic transport of mass and of chemical tracers, but the basic result can be stated succinctly (see section 4.6.3 of *Holton* [1992]). The implication that stratosphere-troposphere exchange can be analyzed isentropically has been supported by recent modeling work [*Hoerling et al.*, 1993] which shows that the overall exchange in middle and subpolar latitudes is dominated locally by adiabatic transports along isentropes crossing the tropopause, and that the estimated fluxes can be interpreted in the framework of trajectories around areas of cyclogenesis.

Representativeness of data from 1993 and of the cases presented here. Of course there were unusual weather events over the continental United States during the summer of 1993, most notably the copious rainfall and resultant flooding. It could be argued that the conditions leading to the persistent rainfall are anomalous, and that the elevated O_3 values observed at Bermuda might not be representative. However, the profile data, integrated to column burdens of O_3, apparently corroborate the satellite-based estimates of the tropospheric residual O_3 burden for the area. Satellite data were collected years ago [*Fishman et al.*, 1990]. Additional profiles obtained in another ozonesonde campaign in the summer of 1995 provide in situ verification of this analysis.

The cases presented above were selected for analysis because high O_3 mixing ratios were present in the middle and upper troposphere. However, they were also the first two cases we examined for the summer season. That is, they were not chosen for analysis because of distinctive meteorological features. As noted above, another summertime case which fits into the same general picture is discussed by *Moody et al.* [this issue].

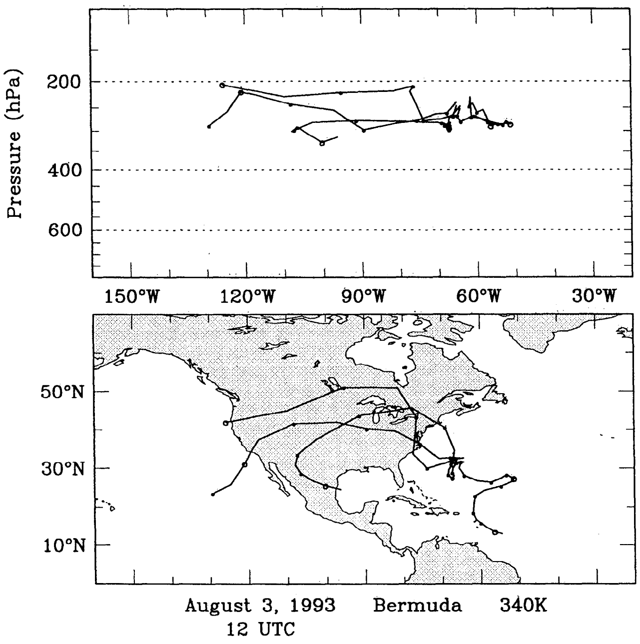


Figure 8. Isentropic trajectories of four parcels back from 1200 UTC near Bermuda at 340 K on August 3, 1993. Trajectory points are plotted as in Figure 3.

Summary and Conclusions

The vertical profile of O_3 mixing ratio estimates based on ozonesonde observations made at Bermuda in the spring and summer of 1993 includes higher values below 3 km in the spring months than in the summer, consistent with the seasonal variation determined from continuous surface-based measurements at Bermuda. The mean O_3 mixing ratio for this campaign exceeds 60 ppbv above ~5 km, and numerous values in the troposphere exceed 100 ppbv. Case studies of two events with elevated mixing ratios in the middle and upper troposphere, using isentropic trajectory analysis and isentropically estimated potential vorticity charts based on routine radiosonde profiles, show that irreversible breaking of Rossby waves takes place 2 to 4 days upwind of the observation of enhanced O_3.

These case studies support the assertion that stratosphere-troposphere exchange of air is a significant source of ozone to the middle and upper troposphere at Bermuda, even in the summer months of July and August. Together with the information on the time mean profile of O_3 (and the corresponding tropospheric column burdens of O_3), these results suggest the need for careful examination of the conventional view that exchange of O_3-rich air into the troposphere at northern midlatitudes occurs most importantly in the spring months of April and May.

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