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Ozone and potential vorticity at the subtropical tropopause break

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Abstract. Ozone measurements near 200 mbar from two flights between California and Tahiti are interpreted using maps of potential vorticity (PV) on isentropic surfaces. We focus on extremely abrupt changes in ozone mixing ratio observed at latitudes of 13°N and 23.5°N. Their proximity to strong PV gradients on the 350 K isentropic surface shows that they are associated with crossings of the subtropical tropopause. Small-scale anticorrelations between ozone and carbon dioxide near one of the two ozone transitions indicate that some stratosphere-troposphere exchange does occur in this region. Ozone mixing ratios on the stratospheric side of the subtropical tropopause varied from 50 to 100 parts per billion by volume, a range that is more commonly associated with the midlatitude troposphere and is much less than seen on the stratospheric side of the midlatitude tropopause.

Introduction

Differences in the chemical composition of the stratosphere and troposphere are determined in part by the mass fluxes associated with stratosphere-troposphere exchange. Recent progress in understanding the driving forces behind this exchange and the mechanisms through which it occurs is summarized by *Holton et al.* [1995]. In midlatitudes, stratosphere-troposphere exchange is typically associated with irreversible eddy phenomena, such as tropopause folds [*Danielsen,* 1968], cutoff systems [*Bamber et al.,* 1984], or stratospheric streamers [*Appenzeller and Davies,* 1992].

In the subtropics, the tropopause cuts steeply across isentropic surfaces in going from near 380 K in the tropics to 300-330 K in midlatitudes. Stratosphere-troposphere exchange across the subtropical tropopause break will ordinarily be inhibited by strong potential vorticity (PV) gradients. However, *Dessler et al.* [1995] have recently used water vapor profiles to argue that some transport of air from the upper tropical troposphere across the subtropical tropopause break into the lowermost stratosphere [see *Holton et al.*, 1995] is likely to occur. Such transport will moisten the lowermost stratosphere because air entering the stratosphere in this way is not freeze-dried by the extremely cold temperatures of the tropical tropopause. However, neither the amount of tropospheric air entering the stratosphere via this mechanism nor the dynamical mechanisms through which such transport occurs have as yet been well characterized. The subtropical tropopause is also poorly characterized from a chemical point of view. There have been few if any reports of the changes in concentrations of such chemical tracers as water vapor and ozone which accompany the strong PV gradients of the subtropical tropopause.

Chen [1995] has conducted tracer studies on the 350 K isentropic surface using a transport model. He found that exchange along this surface between the upper tropical troposphere and lowermost stratosphere was strongly inhibited in the winter hemisphere but that significant exchange occurred in the summer hemisphere. Furthermore, strong tracer gradients developed along the subtropical tropopause in the winter hemisphere if a "convective-like" tracer was injected onto the 350 K isentropic surface between 15°S and 15°N.

This paper revisits ozone measurements taken during two flights in January 1992 between California and Tahiti as part of the second Airborne Arctic Stratospheric Expedition (AASE 2) [*Folkins et al.*, 1995]. The DC-8 crossed the subtropical tropopause on both of these flights.

Data and Analyses

The National Space and Aeronautics Administration (NASA) DC-8 flew from Moffett Field, California, to Tahiti on January 28, 1992. The return flight started on January 29 but took place mostly on January 30. The two flight tracks are superimposed on contour plots of PV on the 350 K isentropic surface in Figures 1a and 1b. PV was calculated using analysis data from

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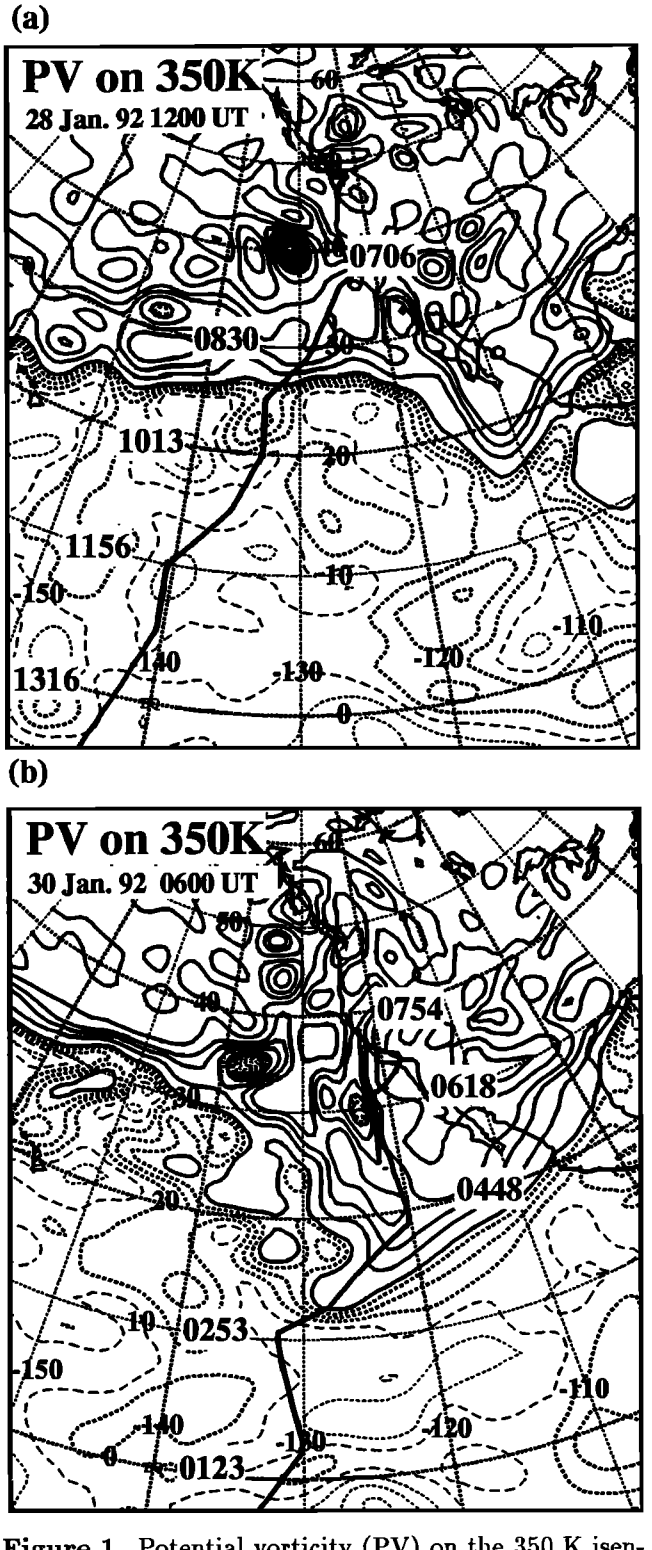

Figure 1. Potential vorticity (PV) on the 350 K isentropic surface from ECMWF T213 initialized analysis data for (a) January 28, 1200 UT and (b) January 30, 0600 UT. The long-dashed line is at 0 PVU, the short-dashed thick lines are at 0.25, 0.5, and 0.75 PVU, and the solid lines are at 1, 2, 3, etc., PVU. Negative values are indicated by thin contour lines (1 PVU = $10^{-6}\,m^2\,s^{-1}\,K\,kg^{-1}$). The flight track is drawn in as a thick solid line. Times along the flight are given as (hours:minutes) UT.

the European Center for Medium Range Weather Forecasts (ECMWF) T213 operational weather prediction model. The initialized analysis data represent a blend of observations with the model's own 6-hour forecast. In subtropical latitudes, the analysis data have a horizontal and vertical resolution of ~ 90 km x 90 km x 2 km and are available in 6-hour intervals [*Simmons et. al.*, 1989]. Their resolution is substantially finer scaled than the three-dimensional meteorological observations over the subtropical western Pacific, so that many of the PV structures are model-evolved features. However, the analysis cycle ensures that they are consistent with all available observations.

Ozone (O_3) was measured every 2 s during the two flights by a chemiluminescent detector [*Ridley et al.*, 1994] and is shown in blue in Plates 1a and 1b. Ozone has a range of 10-25 parts per billion by volume (ppbv) during the tropical sections of the flights. These low values arise from the convective pumping of ozone-depleted equatorial Pacific marine boundary layer air into the upper troposphere. Very sharp transitions to higher ozone mixing ratios are seen on both flights. These transitions occur at 23.5°N on January 28, and at 13°N on January 30.

PV is a conservative tracer under adiabatic conditions and is typically much higher in the stratosphere than in the troposphere. On an isentropic surface, the tropopause is therefore coincident with a strong PV gradient, and in midlatitudes, the 2 PVU (1 PVU = $10^{-6}\,m^2\,s^{-1}\,K\,kg^{-1}$) surface has been used to identify the tropopause [*Hoskins et al.*, 1985]. Ozone also increases in going from the troposphere to the stratosphere, and this helps give rise to the well-known positive correlations between ozone and PV in the vicinity of the midlatitude tropopause [e.g. *Danielsen*, 1968]

A comparison of Figure 1 and Plate 1 indicates that both the 23.5°N ozone transition on January 28, and the 13°N ozone transition on January 30, occur near the strong PV gradients associated with the subtropical tropopause. The 23.5°N ozone transition occurs as the DC-8 passes over an interval of enhanced PV gradients and and enters the region of low PV values characteristic of the upper tropical troposphere. On the return flight, the 13°N ozone transition occurs as the DC-8 crosses a strongly localized PV gradient (from 0.25 to 1 PVU) at the tip of a tongue of high PV extending southwest away from the lowermost stratosphere.

Plates 1a and 1b also show ECMWF PV linearly interpolated in space and time to the DC-8 flight tracks. On January 28, the PV decrease to tropospheric values occurs slightly to the south of the 23.5°N ozone transition, while on January 30, the PV increase and the ozone transition coincide to within a degree of each other.

It is difficult to use the data shown in Plate 1 to associate the subtropical tropopause with a particular interpolated PV value, in part because the tropopause PV gradients are rapidly advected by the strong ambient wind of the subtropical jet, and the linear interpolation

is based only on the two adjacent (± 3 hours) analyses. It is clear, however, that such a PV value would be < 2 PVU. The interpolated PV never exceeds 2 PVU during the January 28 flight, while on January 30, the tropopause occurred between values of 0 and 1 PVU.

Water vapor is frequently used as a chemical tracer in the vicinity of the tropopause because the stratosphere is much drier than the troposphere. Frost point temperatures were measured during the flights by a frost point hygrometer [*Gaines et al.*, 1992], and these were converted into water vapor mixing ratios using expressions from *Marti and Mauersberger* [1993]. These mixing ratios are somewhat uncertain because the accuracy and response time of the hygrometer are poor at the cold temperatures of the upper troposphere. They do however provide additional evidence that the two ozone transitions discussed above are indeed tropopause crossings. Water vapor mixing ratios were 30-40 parts per million by volume (ppmv) on the stratospheric side of the 23.5°N ozone transition on January 28, and 10-25 ppmv on the stratospheric side of the 13°N ozone transition on January 30.

The linearly interpolated water vapor mixing ratios based on ECMWF analyses, also shown in Plate 1, roughly follow the observed humidity structure. Although both sets of mixing ratios are higher than the 4-6 ppmv of the stratospheric overworld, they are within the range of values measured in the lowermost stratosphere [*Dessler et al.*, 1995].

There were several other tropopause crossings during the two flights in addition to the two discussed above. During the outbound flight, the DC-8 likely first entered the troposphere just south of the radar altitude increase to 11 km at 30°N. Strong isobaric potential temperature increases starting 1°south of this height change were accompanied by an increase in ozone and a decrease in water vapor. During the return flight, the ozone and water vapor data indicate an entry into the troposphere near 29°N, followed by a brief reentry into the stratosphere between 32°N and 35°N.

Because the isobaric flight path of the DC-8 cuts sharply across isentropic surfaces during the midlatitude portions of the flights, Figure 1b cannot be used to help interpret the latter stages of the return flight. PV on the 330 K isentropic surface for this section of the flight track is given in Figure 2. The entry of the DC-8 into the troposphere near 29°N occurs during a transverse descent across PV contours south of 30°N. The reentry into the stratosphere at 32°N occurs during an ascent across PV contours after the change in direction at 30°N. The DC-8 finally leaves the stratosphere as it begins its final descent into Moffett Field at 35°N.

There are a variety of PV features in Figures 1 and 2 in which air having PV values characteristic of the upper tropical troposphere is entirely or partially engulfed by higher-PV stratospheric air. At the ECMWF resolution, it is not possible to tell if these PV features are simply momentary and reversible undulations of the subtropical tropopause or are associated with small-scale processes such as vortex rollup which rapidly accelerate irreversible mixing [*Appenzeller et al.*, 1996] and therefore induce stratosphere-troposphere exchange. For the most part, however, the good agreement between the highly resolved chemical tracers and the coarse-grained PV maps supports the notion that most PV features do correspond to realistic mesoscale atmospheric structures and are not artificially generated by the model.

In a previous discussion of these flights [*Folkins et al.*, 1995], it was assumed that the two rapid ozone changes at 23.5°N and 13°N occurred in the troposphere. This inference was based largely on the behavior of ozone and nitrous oxide (N_2O) at the two transitions. Ozone mixing ratios in the stratosphere are usually > 100 ppbv. In fact, the observed range of 40-100 ppbv north of the two subtropical tropopause crossings is more characteristic of the midlatitude troposphere than the stratosphere. Nitrous oxide is a tropospheric source gas with chemical sinks in the stratosphere. However, N_2O was confined to a typical tropospheric range of 309-311 ppbv during the outbound flight, with no discernible change at the 23.5°N tropopause crossing [*Gaines et al.*, 1992]. During the return flight, N_2O remained > 309.5 ppbv well north of the 13°N tropopause crossing. The behavior of the two chemical tracers from 32°N to 35°N, in which ozone went above 200 ppbv and nitrous oxide went below 305 ppbv, is much more representative of most midlatitude tropopause crossings.

Plates 1a and 1b also show the zonal wind u during the two flights. As can be anticipated, the tropopause crossings occur near the maxima in zonal wind associated with the subtropical jet. The red curve in Plate 1 is a reference zonal wind profile obtained from assuming that air parcels are injected into the upper tropical troposphere at the equator with zero zonal wind and that absolute angular momentum is conservative tracer. The latter is true in the absence of zonal frictional or pressure torques [e.g., *Holton*, 1992]. Conservation of zonal mean angular momentum has been invoked in some descriptions of the Hadley cell [*Held and Hou*, 1980].

Strong tracer gradients are sometimes associated with barriers to mixing. However, small-scale tracer variability near the subtropical tropopause during the outbound flight appeared to imply that some transport from the lowermost stratosphere into the upper tropical troposphere does occur. Figure 3 is a more highly resolved plot of ozone, total reactive nitrogen (NO_y), and carbon dioxide (CO_2) in the vicinity of the January 28 23.5°N tropopause crossing. There was a small increase in CO_2 as the DC-8 passed through the subtropical tropopause into the troposphere due, presumably, to the upward trend of CO_2 in the troposphere. South of the tropopause at 23.5°N, there were a number of small-scale decreases in CO_2, each of which was associated with O_3 increases. These occurred at 22.6°N, 22.7°N, 22.8°N, 22.9°N, and 23.1°N. NO_y is a tracer with large stratospheric sources, and many of the small-scale ozone

increases were associated with NO_y increases as well. For the most part, the magnitudes of these tracer fluctuations are larger than the precision errors of the instruments [*Ridley et al.*, 1994; *Anderson et al.*, 1993].

Mixing between the stratosphere and the troposphere is the most likely explanation for the small-scale correlations between O_3, CO_2, and NO_y shown in Figure 3. They were not observed elsewhere in the upper tropical troposphere during the two flights (though O_3 and NO_y are usually positively correlated in the troposphere [see e.g., *Ridley et al.*, 1994]). This mixing may be associated with the small-scale PV feature along the flight track shown in Figure 1a, which extends southwest away from the subtropical tropopause.

It is more common to argue for a stratospheric component to tropospheric air parcels on the basis of an anticorrelation between ozone and water vapor. It was, however, unfortunately impossible to do that in this case because of the poor response time of the frost point hygrometer.

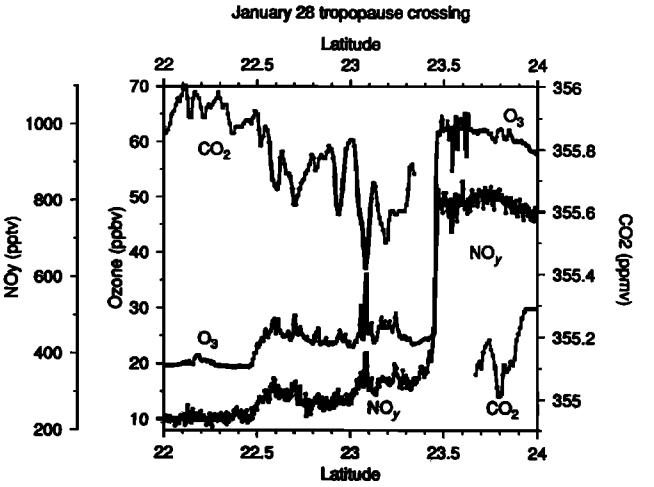

Figure 3. A more highly resolved plot of O_3, NO_y, and CO_2 near the January 28 23.5°N tropopause crossing.

Conclusions

This paper has examined the relationship between ozone and PV in a section of the tropopause which until recently has received very little attention. The juxtaposition of extremely sharp isobaric ozone changes and strong PV gradients confirms the prediction by *Chen* [1995] of sharp tracer gradients in winter at the subtropical tropopause. The subtropical tropopause occurs at an interpolated PV value which is < 2 PVU, the value typically used in midlatitudes.

The measurements also show that the chemical criteria often used to distinguish stratospheric from tropospheric air, based largely on midlatitude tropopause crossings, are inapplicable in the subtropics. On both flights, air which was unambiguously stratospheric from dynamical considerations had ozone mixing ratios consistently < 100 ppbv and had nitrous oxide mixing ratios > 309 ppbv. On both counts, such air would ordinarily be considered tropospheric.

The near-tropospheric mixing ratios of ozone and nitrous oxide in stratospheric air parcels near the subtropical tropopause indicate that their degree of exposure to the ultraviolet wavelengths at which molecular oxygen and nitrous oxide are photolyzed must be exceedingly small. There are two possible explanations for this. First, it is likely that air parcels near the subtropical tropopause are very "new." On average, the amount of time spent in the stratosphere by these air parcels since upward injection across tropical tropopause is probably much less than for air parcels near the midlatitude tropopause. A second explanation is isentropic advection of air from the upper tropical troposphere into the lowermost stratosphere. The fact that water vapor mixing ratios in the stratosphere near the subtropical tropopause were 10-30 ppmv, as opposed to the 4-5 ppmv of the stratospheric overworld, is consistent with the argument of *Dessler et al.* [1995] that such transport does occur.

There were also indications of small-scale reverse transport of air from the lowermost stratosphere into the upper tropical troposphere. Such transport could have a significant effect on the chemical composition of the upper tropical troposphere, especially for such species as ozone and NO_y, and deserves to be further investigated.

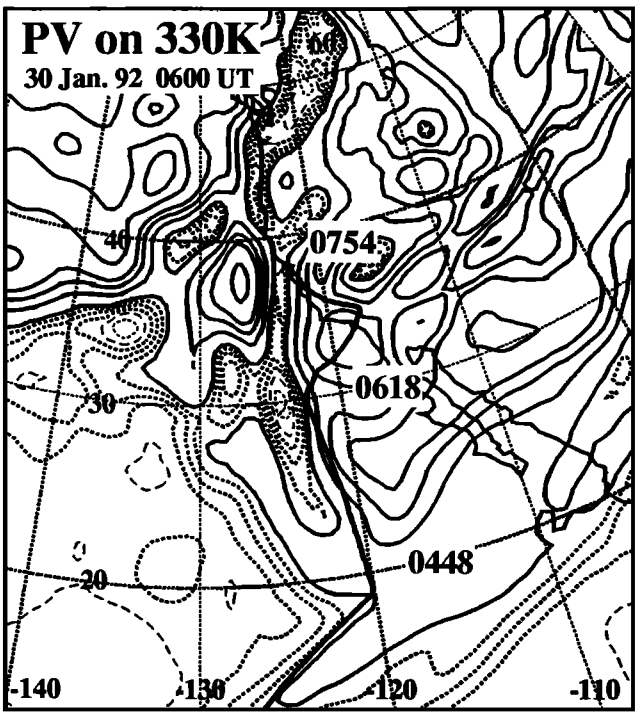

Figure 2. ECMWF PV on the 330 K isentropic surface for 0600 UT on January 30. Contours as in Figure 1.

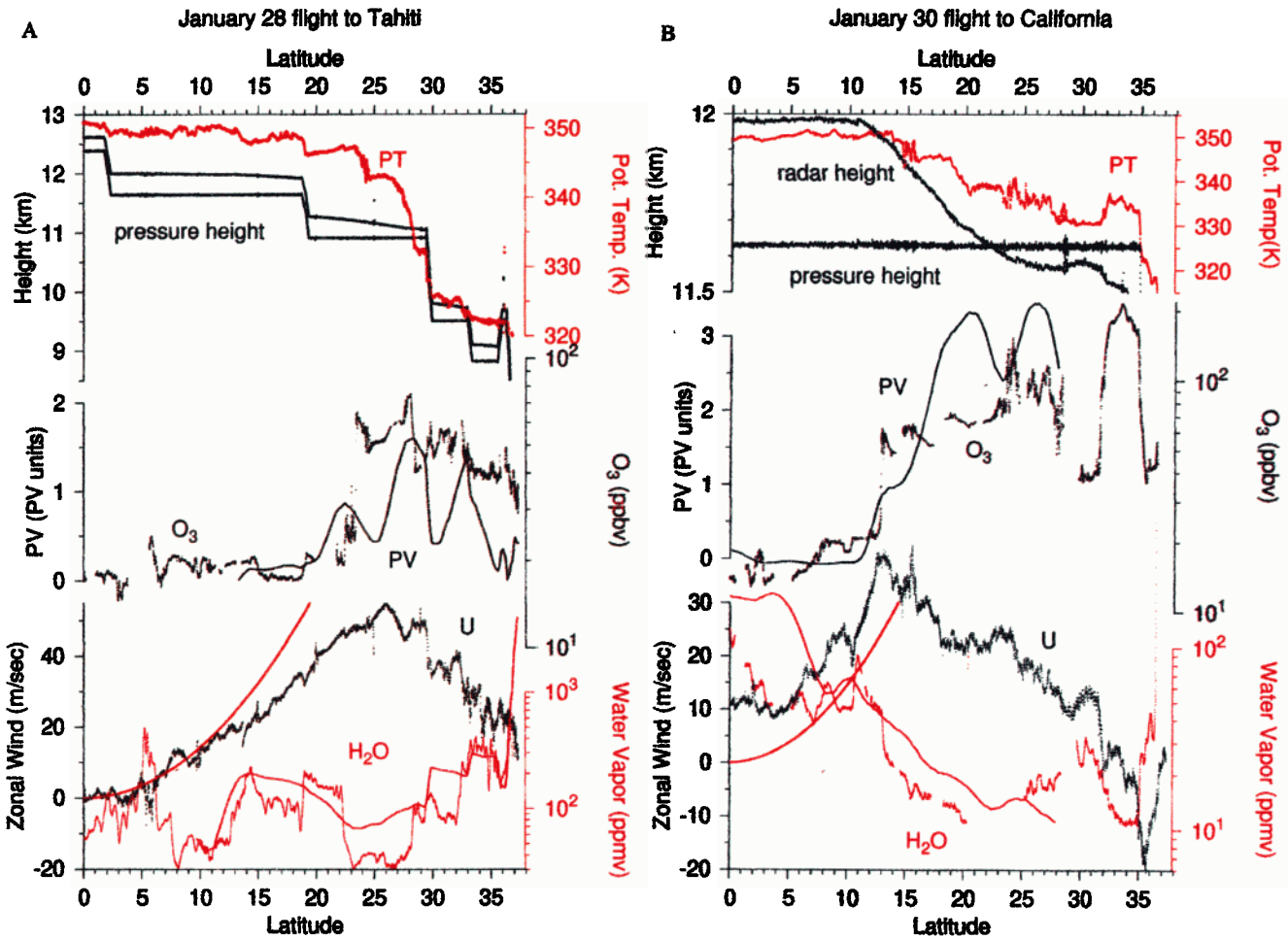

Plate 1. Data from the (a) January 28 flight from NASA Ames Research Center to Tahiti and (b) January 30 return flight to Ames. In situ and ECMWF water vapor are shown together at the bottom. The zonal wind is given in black, together with a constant angular momentum profile in red. Ozone is plotted together with interpolated ECMWF PV. Pressure height was inferred from pressure using a scale height of 7.5 km. Radar height corresponds to geometric distance from sea level over the ocean. ECMWF data in Plate 1a were linearly interpolated to the flight track from January 28 gridded model output at 0600 and 1200 UT, while the data in Plate 1b were interpolated from January 30 model data at 0000 and 0600 UT.

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