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Air Mass Origins and Troposphere-to-Stratosphere Exchange Associated With Mid-Latitude Cyclogenesis and Tropopause Folding Inferred From ^{7}Be Measurements

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The 1984 extratropical mission of NASA's Stratosphere-Troposphere Exchange Project (STEP) studied cross-jet transports in regions of cyclogenesis and tropopause folding. Correlations of ^{7}Be, ozone, water vapor, and potential vorticity measured on a NASA U-2 research aircraft flying in high shear regions above the jet core are indicative of mixing between the cyclonic and the anticyclonic sides of the jet and are consistent with the hypothesis that small-scale entrainments of upper tropospheric air into the lower stratosphere during cyclogenesis are important in maintaining the vertical gradients of ^{7}Be, ozone, water vapor and other trace constituents in the lower few kilometers of the mid-latitude stratosphere. Correlations between ^{7}Be and ozone suggest a lower tropical stratospheric origin for the ozone-poor lamina observed above the jet core.

INTRODUCTION

The spring 1984 flight series of NASA's Stratosphere-Troposphere Exchange Project (STEP) studied transports and exchanges associated with cyclogenesis in the vicinity of mid-latitude upper tropospheric jets. In situ observations made aboard a NASA U-2 high altitude research aircraft included meteorological state variables (pressure, temperature, and horizontal winds) and trace constituent concentrations (ozone, water vapor, and condensation nuclei). An outline of the experimental approach, description of the large-scale synoptic situation during the flight series, and complete listing of the aircraft instrument payload and associated investigators are given in the overview paper [*Russell et al.*, this issue]. Detailed information on the instrumentation is given in the individual accompanying papers; further information on the experimental approach may be found in the papers by *Danielsen et al.* [1987] and *Danielsen et al.* [this issue].

In this paper the ^{7}Be measurements made during this flight series are used to address two topics relevant to the STEP project: identification of air mass origins in the lower mid-latitude stratosphere and entrainments of upper tropospheric air into the lowest few kilometers (the transition zone) of the mid-latitude stratosphere.

As discussed by *Danielsen et al.* [this issue], the stratosphere differs from the troposphere in offering greater resistance to air parcel displacements in both the horizontal and vertical directions and in lacking the negative vertical gradient of diabatic heating caused by the phase change of water vapor in cumulonimbus updrafts. This internal heating, combined with surface heating, is primarily responsible for the deep vertical mixing characteristic of the troposphere. In effect, the troposphere is close to being well mixed vertically, as is evident from the small vertical gradients of many long-lived trace gases.

In marked contrast the stratosphere is never well mixed vertically, except in shallow layers generally less than 1 km in depth. These well-mixed layers are produced by propagating internal waves of short vertical wavelength. This intermittent small-scale stirring, combined with lower level sources and upper level sinks (or vice versa) maintains the vertical gradients of trace constituents characteristic of the stratosphere.

FORMATION AND TRANSPORT OF STRATOSPHERIC ^{7}BE

Beryllium 7 belongs to a large family of natural cosmogenic radionuclides produced in the atmosphere by cosmic rays. Production rates of ^{7}Be are a function of the local concentration of the parent species (nitrogen and oxygen), the local cosmic ray flux and energy spectrum, and the cross sections for the various possible interactions. These have been determined as a function of geomagnetic latitude and altitude by *Lal et al.* [1958], *Lal and Peters* [1962 and 1967], *O'Brien* [1979], and others.

Shortly after their formation, ^{7}Be atoms collide with and become irreversibly attached to submicron-sized particles of the ambient atmospheric aerosol and thus are subject to removal and transport by the same processes affecting the aerosols.

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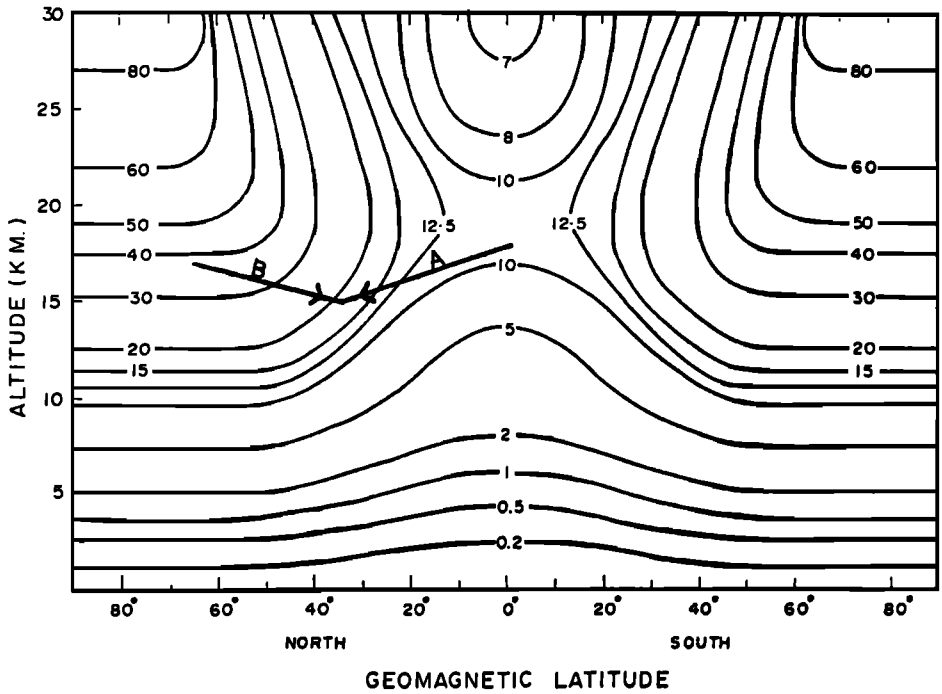

Fig. 1. Beryllium 7 production rate as a function of altitude and geomagnetic latitude (after *Bhandari et al.* [1966]). (See text for a discussion of lines A and B.)

The activity, A, of a given quantity of a radioactive substance is defined as the number of disintegrations occurring per unit time:

$$A = N\lambda. \tag{1}$$

Here N is the number of atoms of radionuclide present per unit volume and λ is the radionuclide's radioactive decay constant. ($\lambda = 0.69/t_{1/2}$, where $t_{1/2}$ is the half-life of the substance.) Thus for ^{7}Be, which has a radioactive half-life of 53 days, a concentration of 10^6 atoms per standard cubic meter may also be expressed as an activity of 9.0 disintegrations per minute per standard cubic meter (9.0 dpm/SCM).

Were the circulation of the atmosphere purely zonal, the number of ^{7}Be atoms per standard cubic meter of air at any location would reflect the equilibrium between the local rates of production and decay:

$$dN/dT = \text{Production} - \text{Decay} = Q - N\lambda = 0; \tag{2}$$

and the ^{7}Be activity at any given location would simply be that of its local rate of production, plotted as a function of altitude and geomagnetic latitude in Figure 1 [*Bhandari et al.*, 1966].

In the real atmosphere, three processes occur which prevent equilibrium from being attained: precipitation scavenging, sedimentation, and meridional and vertical transports. The first and second of these can be neglected in the stratosphere since there is no precipitation, and the sedimentation velocities (in the lower stratosphere) of the submicron particles to which the ^{7}Be is attached are of the order of 100 m/month [*Junge*, 1963; see also *Martell*, 1968]. Thus the ^{7}Be concentration at any point in the stratosphere is governed by three factors: the local rate of production and the rate of radioactive decay, which are known quantities, and transport, which we are trying to evaluate.

Measured ^{7}Be activities in the upper tropical and mid-latitude troposphere are typically of the order of 1 dpm/SCM [*Feely et al.*, 1963; *Bhandari et al.*, 1966], as production rates in this region of the atmosphere are quite low (see Figure 1), and the ^{7}Be which is produced is rapidly removed by precipitation scavenging. Once in the stratosphere, however, precipitation removal ceases, and the ^{7}Be concentration can start to build up and approach its local equilibrium value, N_{eq}:

$$N = N_{eq}\,(1 - e^{-\lambda t}). \tag{3a}$$

In terms of activity this may be written

$$A = A_{eq}\,(1 - e^{-\lambda t}). \tag{3b}$$

In the lower tropical stratosphere (16–21 km), ^{7}Be production rates are approximately 10 atoms min^{-1}SCM^{-1} (Figure 1), so that in the absence of transport, after 100 days (approximately two ^{7}Be half-lives), ^{7}Be activities in this region would be approximately 75% of the local production rate, i.e., about 8.2 dpm/SCM. This value is, in fact, close to those measured in this region [*Feely et al.*, 1963; *Bhandari et al.*, 1966; M. A. Kritz, unpublished data, 1987], suggesting that residence times in the lower tropical stratosphere are of the order of a few months.

A poleward, quasi-horizontal transport of ^{7}Be from this equatorial reservoir toward mid-latitudes, in a manner similar to that observed for ^{185}W following the injection of this [artificial] radionuclide in the lower tropical stratosphere [cf., *Martell*, 1968; *List and Telegadas*, 1969] would bring this material into regions of increasing ^{7}Be productivity. As seen in Figure 1, local ^{7}Be production rates increase monotonically between the lower tropical stratosphere, where production rates are about 10 atoms SCM^{-1} min^{-1}, and mid-latitudes, where production rates are of the order of 20

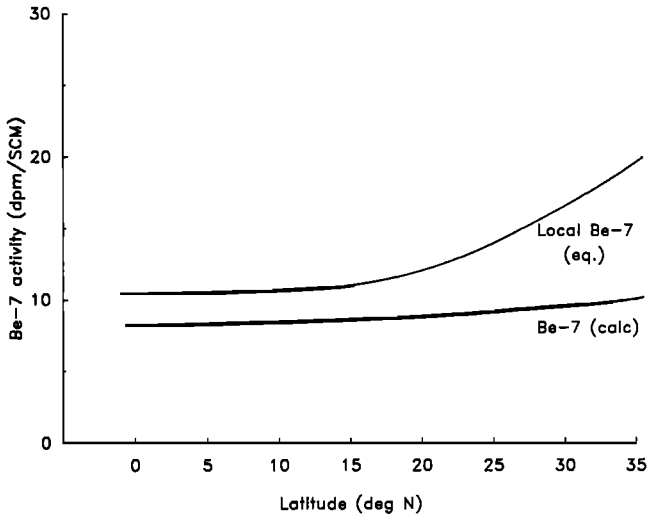

Fig. 2. Change of ^{7}Be activity calculated for transport from the tropical stratosphere (0°N, 18 km) to mid-latitude (35°N, 15 km) over a 30-day period. (See text.)

atoms SCM^{-1} min^{-1} (cf., path "A" in the figure, from 17 km, 0°N to 15 km, 35°N).

The change in ^{7}Be activity that would occur in a hypothetical poleward transport along such a path over a 30-day period is plotted in Figure 2. The calculated ^{7}Be activity rises from an initial value of 8.2 dpm/SCM in the lower tropical stratosphere (typical of the region at an altitude of 17 km, as mentioned earlier), to about 10 dpm/SCM at 15 km, 35°N, i.e., to about half of the 19 dpm/SCM equilibrium ^{7}Be activity at this location. Similarly, a 60-day transport along this path would result in a calculated ^{7}Be activity of 11.4 dpm/SCM at 35°N.

As illustrated above, transports with time scales of 2 months or less would not allow enough time for ^{7}Be activity to respond to the higher production rates of the new surroundings. The activity would thus remain relatively close to its original value and would be easily distinguishable from the higher activities (~16 dpm/SCM) typical of the lower mid-latitude stratosphere [*Bhandari et al.*, 1966], as well as from the ~19 dpm/SCM equilibrium activity of this region. Transport times of the order of 4 months or more would be necessary for ^{7}Be activities to respond to the higher mid-latitude ^{7}Be production rates of the new, higher latitude surroundings.

Similarly, a hypothetical transport from 65°N, 17 km altitude to 35°N, 15 km altitude over a 2-month period (path B in Figure 1) would result in a decrease in ^{7}Be activity from an initial value of 30 dpm/SCM at 65°N (a value typical of those observed at this latitude and altitude, cf., *Feely et al.* [1963] and *Bhandari et al.* [1966]) to 28 dpm/SCM at 35°N. The occurrence of such a value would be easily distinguishable from both the ~19 dpm/SCM equilibrium activity of this region as well as being significantly higher than typical measured values in this region [*Feely et al.*, 1963; *Bhandari et al.*, 1966].

Sampling and Measurement Technique

Atmospheric concentrations of ^{7}Be were determined by passing a known quantity of air through a filter and then measuring the gamma emissions of the collected sample. Sampling aboard the U-2 aircraft was done using a wing tank sampler, in which filters were sequentially exposed to the airstream under pilot control [*Gandrud and Lazrus*, 1981]. Aerosol particles were collected on 11.4-cm-diameter IPC 1478 filters, whose collection efficiency for the submicron particles carrying ^{7}Be is greater than 95% [*Feely et al.*, 1963]. A turbine flowmeter was used to measure the sampling flowrate, which was corrected to STP using temperatures and pressures measured in the flowpath downstream of the filter. The mean sampling volume of the samples reported here was 57 SCM; values of individual filters ranged between 15 and 115 SCM. Between 8 and 12 samples, including procedural blanks, were obtained on each flight.

Following each flight, the individual filters were compressed into a standard counting geometry and analyzed for ^{7}Be on an anticoincidence shielded Ge (Li) gamma-ray spectrometer. For the standard counting period of 1000 min a ^{7}Be activity of approximately 140 dpm resulted in a 2σ counting uncertainty of +/−10%; however, ^{7}Be activities of the samples at the time of counting (see Table 1) were 2 to 10 times greater than this figure. Blank corrections were typically less than 3%. These analyses were performed under subcontract by the Battelle Pacific Northwest Laboratories.

Taking into account the uncertainty in the sampling flowrate measurement and possible variations in counting geometry, the nominal overall uncertainty of the stratospheric ^{7}Be activities reported here is no greater than +/−15%.

Results and Discussion

The flight series was conducted from Moffett Field, California, in April and May 1984. There were four data flights: April 20, April 24, May 5, and May 6. The April 20, 24, and May 6 flights ("fold" flights) were conducted just above the jet core, in regions of active tropopause folding. The May 5 flight (the "Baja" flight) was flown off the coast of Mexico to make observations in and above the high level outflow from a tropical vortex. The individual ^{7}Be measurements made during the flight series are summarized in Table 1.

The overall synoptic situation on April 20 is shown in the 310 K Montgomery stream function analysis in the accompanying overview paper (Figure 2 of *Russell et al.* [this issue]; see also *Danielsen et al.* [1987]). A cross section showing the track of the U-2 aircraft relative to the jet core and the tropopause fold structure is shown in Figure 3 of the overview paper. Figure 3*a* of this present paper shows the location of the eight ^{7}Be samples and the ^{7}Be activities measured on the four constant altitude legs flown above the jet core on this date. (A sample identification number is also shown.) Figure 3*b* shows the aircraft flight path relative to the potential vorticity isopleths derived by *Danielsen et al.* [this issue] for this flight. Similar plots of potential temperature, wind perpendicular to the cross section, ozone, water vapor, and condensation nuclei appear in the paper by *Danielsen et al.* [this issue].

Figures 3*c* and 3*d* are similar to 3*a*, showing the flight track on the measured ^{7}Be activities for the samples collected on the April 24 and May 6 flights. An analysis of the geopotential height field at 150 mbar for the May 6 case, with the U-2 flight track superimposed, is given in Figure 4 of the overview paper. Potential vorticity analyses similar to the one shown in Figure 3*b* are not available for these flights.

TABLE 1. Beryllium 7 Activities and Ozone Concentrations for Samples Collected on Flights of April 20, April 24, May 5, and May 6, 1984

Sample Number	Time of Exposure, UT	Altitude, kft/km	Airflow, SCM	Filter ^{7}Be Activity, dpm	Mean ^{7}Be Concentration, dpm/SCM	Mean Ozone Concentration, ppbv
			April 20, 1984			
12	1722–1743	60/18.3	28	839	30	...
13	1808–1835	40/12.2	84	1009	12	332
14	1835–1903	40/12.2	84	1777	21	593
15	1910–1934	50/15.2	58	1559	27	1194
16	1934–1958	50/15.2	57	1083	19	710
17	2003–2024	60/18.3	28	680	24	1812
18	2024–2046	60/18.3	27	656	24	1824
19	2054–2113	68/20.7	14	406	29	3790
20	2114–2138	68/20.7	17	411	24	3352
			April 24, 1984			
13	1911–1943	41/12.5	110	808	7	193
14	1943–2014	41/12.5	107	1541	14	452
15	2023–2054	50/15.2	73	885	12	434
16	2054–2124	50/15.2	72	546	8	216
17	2134–2202	60/18.3	39	1095	28	1928
18	2202–2230	60/18.3	35	732	21	1779
19	2245–2314	68/20.7	20	370	18	2999
			May 5, 1984			
12	1723–1757	60/18.3	47	875	19	1005
13	1757–1831	60/18.3	46	1048	23	1115
14	1832–1906	60/18.3	47	816	17	990
15	1907–1941	60/18.3	46	821	18	984
16	2011–2039	50/15.2	76	301	4	140
17	2059–2141	68/20.7	30	575	19	2885
			May 6, 1984			
11	1743–1812	41/12.5	97	252	3	100
12	1813–1847	41/12.5	116	866	7	203
13	1847–1918	41/12.5	97	1550	16	446
14	1922–1944	50/15.2	57	1144	20	860
15	1944–2008	50/15.2	63	1084	17	537
16	2008–2028	50/15.2	55	712	13	390
17	2033–2107	60/18.3	43	1010	23	1568
18	2107–2143	60/18.3	47	1197	25	1883

Filter activities are corrected to the time of sampling.

Movement of stratospheric air to the mid-latitude sampling location. If the ^{7}Be and ozone concentrations are compared for each constant altitude leg of the three fold flights, and for the May 5 Baja flight (these are plotted in Figures 4–7 using ozone concentration data appearing in *Danielsen et al.* [this issue] and provided by Starr (W. Starr, personal communication, 1988)), there is a consistent positive linear correlation between the concentrations of these two constituents. This is shown in Figure 8, which plots the measured ^{7}Be concentration of each mid-latitude filter sample (these are mean values, averaged over the filter sampling period) against the corresponding mean ozone concentration observed during each filter sampling period. (The mean ozone values for each sample are given in Table 1.) The four lines in the figure correspond to samples collected at 41-kft (12.5 km), 50-kft (15.2 km), 60-kft (18.3 km), and 68-kft (20.7 km) altitudes. (The ^{7}Be-ozone correlations shown in Figure 8 are based on samples collected in a narrow latitude band over a short time period. As correlations in other regions or at other times may be significantly different, the particular values reported here should not be taken as representative of any sort of stratospheric mean.)

As seen in the figure, there is a good linear relationship between the mean ozone and mean ^{7}Be concentrations for each altitude of sampling, even though, as shown in Figures 4–7, large fluctuations in ozone concentration sometimes occurred while a ^{7}Be sample was being collected. Using ozone as an index of sample homogeneity, these fluctuations suggest that air from two or more different sources contributed to such ^{7}Be samples.

Figure 9 shows the ozone concentration isopleths derived by *Danielsen et al.* [this issue] for the April 20 flight with aircraft flight path superimposed. Comparing this figure with Figure 4*b*, which shows the ^{7}Be sampling locations superimposed on the ozone concentrations measured on the 50-kft (15.2 km) leg of this flight, it is seen that the sharp fluctuations in ozone concentration observed during this leg are associated with the upper ozone-poor lamina in Figure 9. The initial low ozone concentration and subsequent sharp ozone increase occurring near the start of the leg (1910 in Figure 4*b*) occurred as the plane briefly entered the bottom of this ozone-poor layer before flying through an ozone-rich region, while the marked ozone decrease observed during the middle portion of the leg (1931–1948) occurred as the plane again skimmed the bottom of this same ozone-poor layer.

Thus both of the two 24-min ^{7}Be filter samples collected during this leg (samples 15 and 16) appear to have straddled

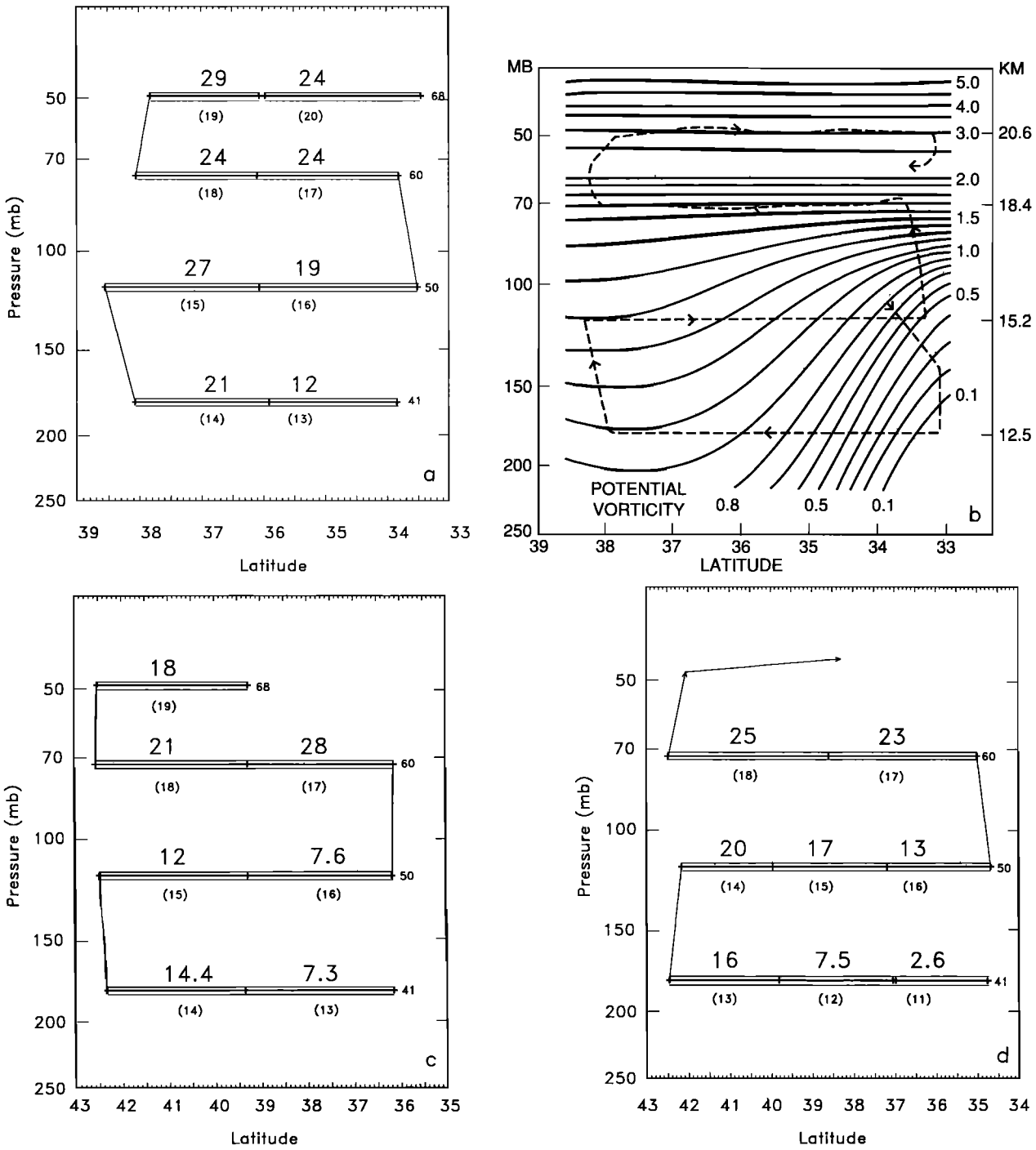

Fig. 3. Aircraft flight paths for the April 20, April 24, and May 6 flights, showing the location of the filter samples, and the measured ^{7}Be activities (dpm/SCM). The numbers in parentheses correspond to the sample numbers in Table 1. (*a*) April 20, 1984, (*b*) same as 4*a*, showing the April 20 flight path superposed on the potential vorticity isopleths constructed by *Danielsen et al.* [this issue], (*c*) April 24, 1984, and (*d*) May 6, 1984.

two distinct air masses. Sample 15 comprised air filtered while flying through a small portion of an ozone-poor layer (1910 to 1911), a region containing a local ozone maximum (1912 to 1926), and the ozone-poor layer again (1931 to 1934). The second filter (sample 16) sampled air in the ozone-poor layer during the first part of the sampling period (time 1934 to 1948), and air from an ozone-rich layer during the latter portion of the sampling period (time 1948 to 1958).

Using the ozone concentrations observed during these subintervals as a diagnostic, we can use Figures 4*b* and 8 to estimate the ^{7}Be contribution to the filter from the ozone-rich and ozone-poor sampling subregions of this flight leg. We illustrate the idea using sample 16, collected over the period 1934 to 1958 which had a ^{7}Be activity of approximately 19 dpm/SCM. The mean ozone concentration during the first portion of this sample (1934 to 1948), while the plane was in the ozone-poor layer, was approximately 586 ppb. Referring to the 50,000-foot curve in Figure 8, this corre-

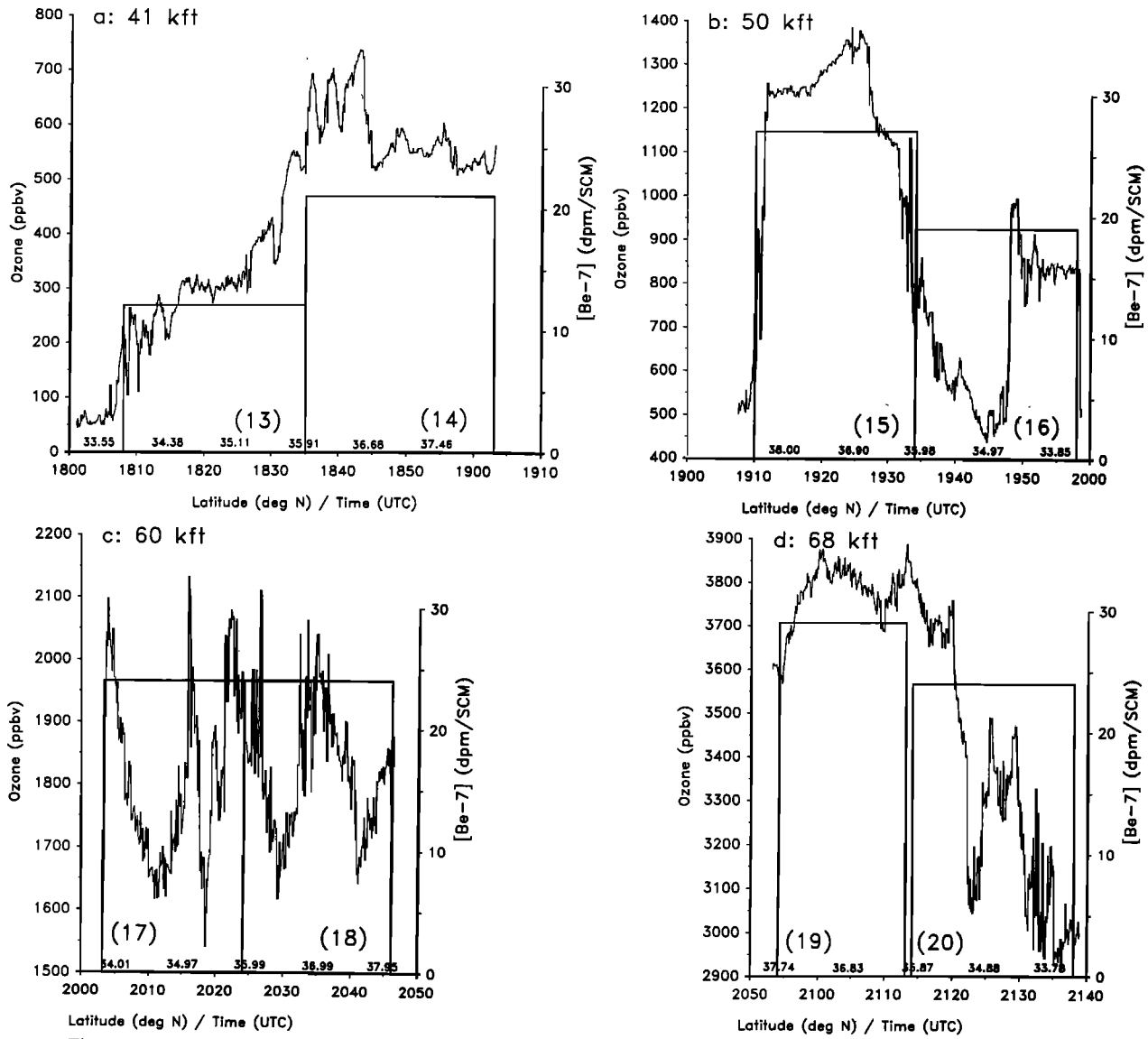

Fig. 4. Beryllium 7 activities and ozone concentrations for the four constant altitude legs of the April 20, 1984, flight.

sponds to a mean ^{7}Be concentration of 15.6 dpm/SCM. Similarly, the mean ozone concentration during the second portion of the sample (1948 to 1958) was approximately 851 ppb, corresponding to a mean ^{7}Be concentration of approximately 21.2 dpm/SCM. Taking the weighted average of these two subregions (0.58 × 15.6 and 0.42 × 21.2) yields a total ^{7}Be concentration of 17.9 dpm/SCM, in close agreement with the measured value (19 dpm/SCM) for this sample.

Using this same procedure and regression line to determine inferred ^{7}Be concentrations for the peak ozone value of 1350 ppb (1925 in sample 15) and the ozone minimum of 450 ppb (1945 in sample 16) yields inferred ^{7}Be concentrations of 31.9 dpm/SCM for the ozone maximum and 12.6 dpm/SCM for the ozone minimum.

Referring to Figure 1, which plots the ^{7}Be production rate as a function of latitude and altitude, and the earlier discussion of that figure, it is clear that the high ^{7}Be value associated with the ozone maximum could have had only a poleward, higher altitude origin, while the lower ^{7}Be value associated with the ozone minimum and the ozone-poor lamina in Figure 9 could only have originated in the lower tropical stratosphere. However, even though the ^{7}Be values inferred for the lamina provide good evidence for the poleward movement of this ozone-poor lamina, the ensemble of ^{7}Be results, together with the correlations with water vapor, potential vorticity, and ozone observed during the flight series [*Danielsen et al.*, this issue] are consistent with a general equatorward movement of ozone-rich air from higher latitudes to the mid-latitude, lower stratospheric locations where our observations were made. Previous evidence for such transports, based on correlations between potential vorticity and ozone, was presented by *Danielsen* [1968], and discussed in World Meteorological Organization (WMO) [1985].

Entrainment of upper tropospheric air into the lower-mid-latitude stratosphere. The ^{7}Be activities of the samples collected just above the jet core (a region of strong vertical and horizontal wind shear) are similar to those which would result from the mixing of stratospheric air from the cyclonic (polar) side of the jet with tropospheric air from the anticyclonic side of the jet.

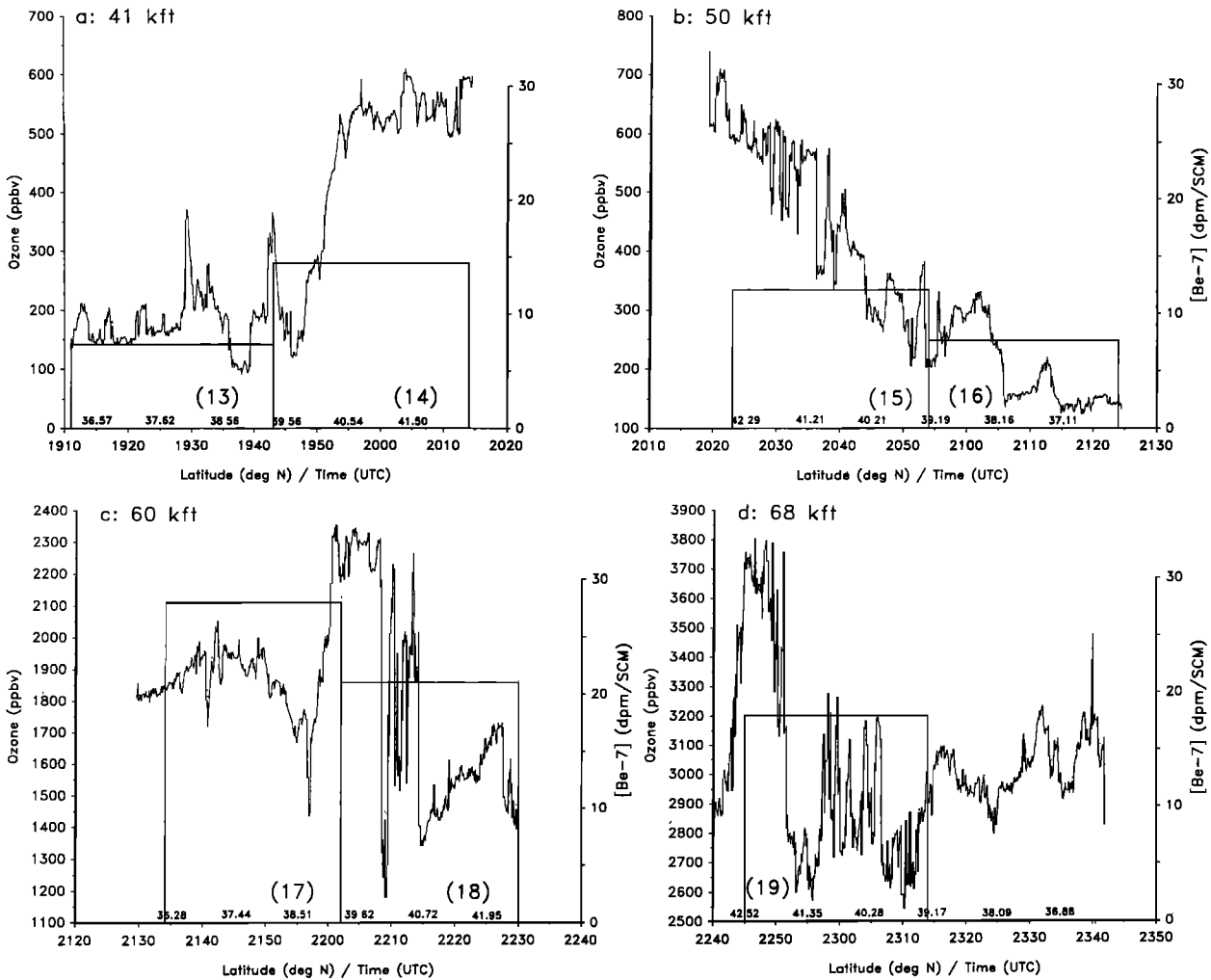

Fig. 5. Beryllium 7 activities and ozone concentrations for the four constant altitude legs of the April 24, 1984, flight.

A good example of this can been seen in the 41-kft (12.5 km) leg of the April 20 flight (Figure 4*a*). The position of this leg with respect to the overall fold structure is shown in Figure 3 of the overview paper [*Russell et al.*, this issue]. The ^{7}Be activities measured on this leg are plotted in Figures 3*a* and 4*a*. Using those values and taking 1 dpm/SCM as representative of ^{7}Be in the upper mid-latitude troposphere [*Feely et al.*, 1963], the relative contributions of tropospheric and stratospheric air to the intermediate region (where ^{7}Be sample 13 was collected) may be estimated using a simple mixing equation

$$1X + 21(1 - X) = 12 \qquad X = 0.45$$

Here the ^{7}Be activities are in dpm/SCM, X is the relative contribution from the troposphere, and $(1 - X)$ is the relative contribution from the stratosphere (^{7}Be, sample 14).

Similar computations may be made for ozone, water vapor, and potential vorticity. As seen in Figure 4*a*, ozone concentrations in the stratospheric portion of the leg were approximately 575 parts per billion by volume (ppbv), while those in the adjacent troposphere (the extreme left-hand portion of the ozone trace in this figure) were approximately 50 ppbv. Assuming simple mixing, as before, the relative proportions of tropospheric and stratospheric air in the intermediate region (where ozone concentrations were approximately 300 ppbv) may be estimated by the same equation used earlier

$$50X + 575(1 - X) = 300 \qquad X = 0.52$$

The calculation for water vapor (concentrations are in parts per million by volume (ppmv)), made using the results of Kley (plotted in Figure 6.2 of *Danielsen et al.* [this issue]) yields

$$28X + 4(1 - X) = 14 \qquad X = 0.42$$

Finally, the calculation for potential vorticity (units are 10^{-5} cm^2 K g^{-1} sec^{-1}) made using the analysis of *Danielsen et al.* [this issue] (Figure 4 of that paper; Figure 3*b* of this work) yields

$$0.05X + 0.93(1 - X) = 0.56 \qquad X = 0.42$$

Another instance of apparent mixing was observed in the 41-kft (12.5 km) leg of the May 6 flight, whose position relative to the jet was similar to that of the 41-kft (12.5 km) leg on the April 20 flight. As seen in Figure 6*a*, three ^{7}Be samples were taken on that leg. As before, we write for ^{7}Be

$$2.6X + 16(1 - X) = 7.5 \qquad X = 0.63$$

for ozone

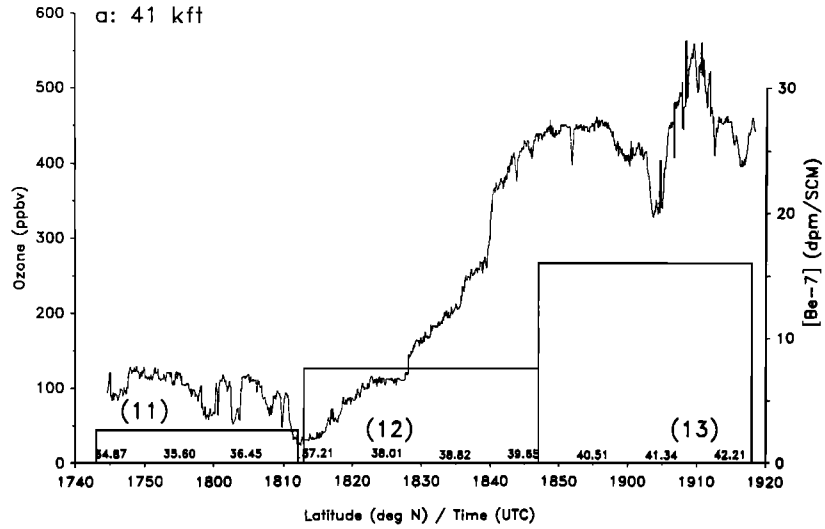

Fig. 6. Beryllium 7 activities and ozone concentrations for the three constant altitude legs of the May 6, 1984, flight.

$$90X + 450(1 - X) = 250 \qquad X = 0.65$$

and for water vapor

$$20X + 5(1 - X) = 14 \qquad X = 0.60$$

Thus in the first example the agreement between the relative proportions of tropospheric and stratospheric air calculated for the intermediate region from four independent tracer measurements (^{7}Be, ozone, water vapor, and potential vorticity) is better than +/−11%; in the second example, for three independent measurements (a potential vorticity analysis is not available for this flight) the agreement is better than +/−4%.

The fact that the variability of ozone in these two intermediate regions (sample 13 on April 20 and sample 12 on May 6; see Figures 4*a* and 6*a*) was small relative to the ozone values characteristic of the adjacent regions (sample 14 on April 20 and samples 11 and 13 on May 6) is in marked contrast to the large ozone fluctuations observed during the 60-(18.3 km) and 68-kft (20.7 km) legs of the April 24 flight (between 2205 and 2215 and between 2255 and 2310; see Figures 5*c* and 5*d*).

As discussed by *Danielsen et al.* [this issue], these large fluctuations and the accompanying steep concentration gradients are due to waves of short vertical wavelength, which deform the tracer distribution surfaces by folding them and greatly increasing their area, while confluence normal to these surfaces increases the mixing ratio gradients. The effect of these deformations, as discussed by *Danielsen et al.* [this issue] is to increase the probability and effectiveness of small-scale, irreversible mixing.

The low ozone concentration variability and low concentration gradients observed in sample 13 on April 20 and sample 12 on May 6 (see Figures 4*a* and 6*a*) indicate that mixing down to the resolution scale of the ozone measurement had already ocurred. It follows that this situation was preceded by one in which higher variability and sharp spatial gradients obtained (e.g., as described in the preceding paragraph), at which time rapid small-scale mixing took place.

Vertical gradients of trace constituent concentrations in

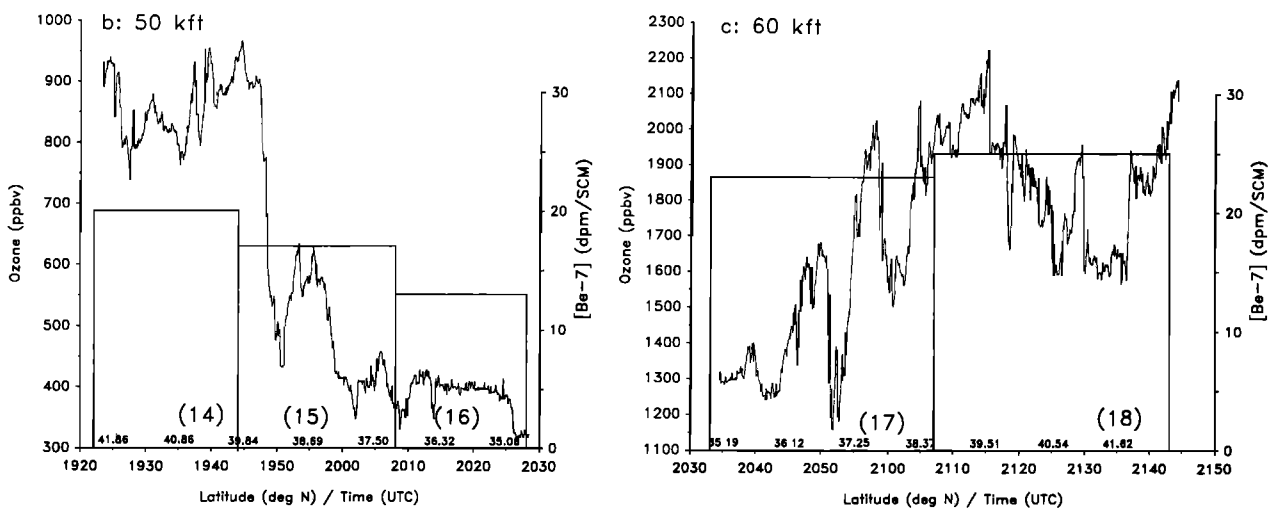

Fig. 6. (continued)

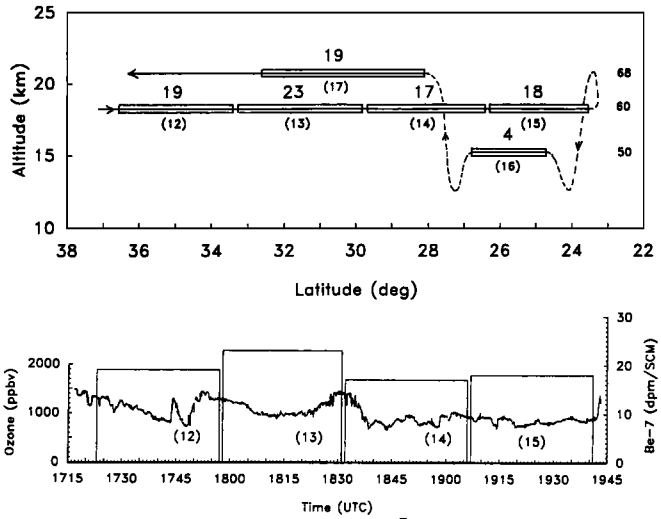

Fig. 7. (Top) Aircraft flight path and ^{7}Be sampling locations for the May 5, 1984 (Baja) flight. The ^{7}Be activity (dpm/SCM) appears above each sample and the sample number below. (Bottom) ^{7}Be activities and ozone concentrations for the southbound (60 kft (18.3 km)) leg of this flight.

the lower mid-latitude stratosphere. The entrainment of upper tropospheric air into the lower stratosphere described above may be important in maintaining the observed vertical gradients of many trace constituents in the lower few kilometers of the mid-latitude stratosphere. For example, the vertical profiles of water vapor observed by *Kley et al.* [1979] at mid-latitudes did not show a discontinuous change in slope or value at the tropopause but rather continued to decrease with altitude, reaching a minimum value (the "hygropause") several kilometers above the tropopause. In this region between the hygropause and the tropopause (the transition zone), stratospheric properties of the air appear to be diluted by increasing proportions of tropospheric air as the tropopause is approached.

The water vapor profiles observed during the 1984 flight

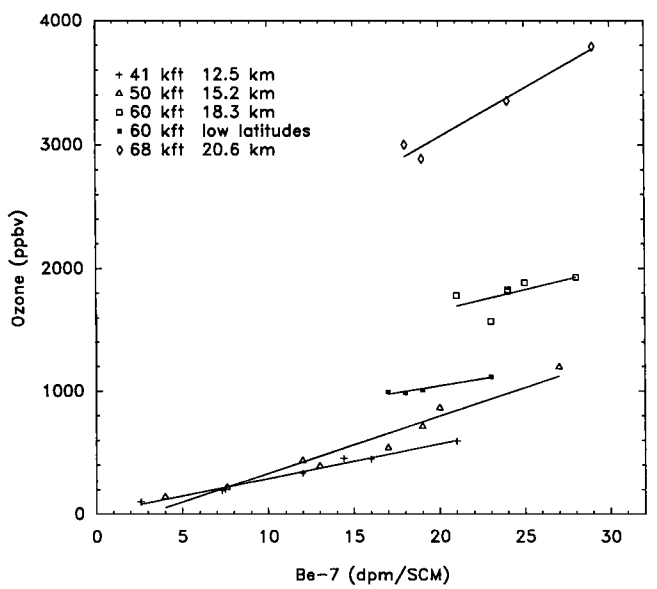

Fig. 8. Linear fit of ^{7}Be activity versus mean ozone concentration for the complete 1984 data set, grouped by altitude. (See text.)

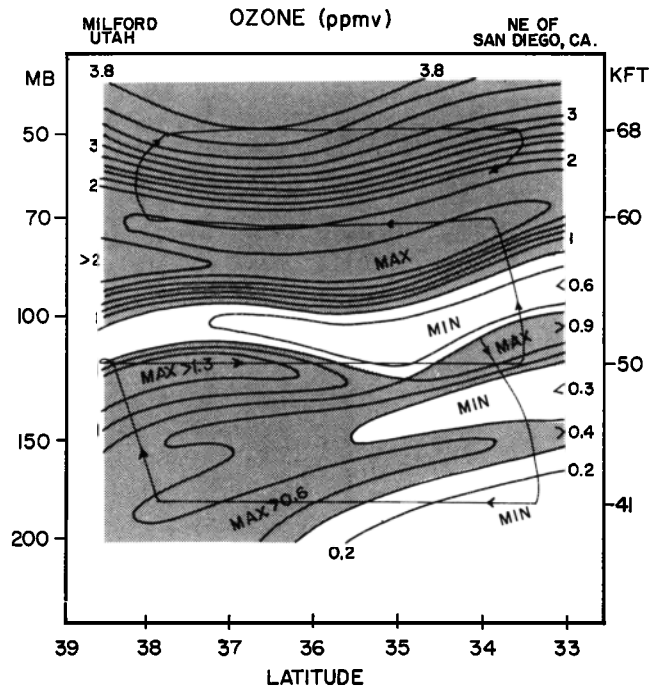

Fig. 9. Ozone isopleths constructed by *Danielsen et al.* [this issue] for the April 20 flight, with the flight path superimposed.

series (D. Kley, personal communication, 1990) also show this gradual transition between tropopause and hygropause. Similar transitions in the vertical distributions of ^{7}Be and ozone were observed in the lower stratosphere during the May 5 Baja flight, which unlike the other three flights of the 1984 series was not made in a region of active cyclogenesis. The aircraft flight path and measured ^{7}Be and ozone concentrations for the flight are plotted in Figure 7.

On this flight the U-2 flew southward at a constant altitude of 18.3 km (60 kft). As the plane approached the southern end of its flight path (22.5°N), it ascended to 20.5 km, reversed course back toward the north, and then descended to 12.0 km (entering the troposphere). It then immediately climbed back to 15.2 km and flew at this altitude for approximately 30 min before again descending briefly to 12.0 km (again entering the troposphere), after which it climbed to 20.7 km and returned to base.

If the 4.0 dpm/SCM ^{7}Be activity measured in sample 16 collected during the short 15.2-km leg of the flight is interpreted as a mixture between upper tropospheric air and higher level stratospheric air, then a similar correlation would be expected for ozone, since both substances are conserved in this region of the atmosphere. Using the higher level ^{7}Be activity of 17.8 dpm/SCM (sample 15, which as seen in Figure 7 was collected almost immediately above sample 16) and a value of 1 dpm/SCM, as before, as representative of the upper tropospheric ^{7}Be activity [*Feely et al.*, 1963], the tropospheric ^{7}Be contribution to the 15.2 km sample may be estimated using the mixing equation

$$1X + 17.8(1 - X) = 4 \qquad X = 0.82$$

where X is the fraction of air in sample 15 of recent tropospheric origin and $(1 - X)$ the fraction of recent stratospheric origin.

A similar computation can be made for ozone. (Water

vapor data were not available for the relevant portions of this flight.) The average ozone concentration in the 15.2-km leg was 200 ppbv, while that measured immediately above (during the collection of ^{7}Be, sample 15) was 900 ppbv. The ozone concentration measured in the upper troposphere during the two brief descents to 12 km at either end of this leg was approximately 50 ppbv (W. L. Starr, unpublished data, 1984). Using the mixing equation as before we have

$$50X + 900(1 - X) = 200 \qquad X = 0.82$$

While the close agreement of some of the above calculations is undoubtedly fortuitous, taken together, the results are consistent with the hypothesis that the entrainment of upper tropospheric air during cyclogenesis contributes significantly to the maintenance of the vertical gradients of ^{7}Be, ozone, and other trace constituents in the mid-latitude lower stratosphere.

It is important that this process be viewed in context. In particular, as residence times in the lower stratosphere are much shorter than those of the stratosphere as a whole [*List and Telegadas*, 1969; *Hunten*, 1975], and ascent from the lower mid-latitude stratosphere to higher altitudes would seem to be precluded by the low heating rates characteristic of the lower mid-latitude stratosphere, the subsequent transport of air entrained in this manner to higher, more chemically active altitudes of the stratosphere (for example to levels where chlorofluorocarbon photolysis occurs) appears unlikely.

CONCLUSIONS

The spatial gradient of the ^{7}Be equilibrium isopleths slopes upward and to the north in the northern hemisphere, similar to the concentration gradient of ozone. This similarity in gradient should lead to a positive correlation in the concentrations of these two trace constituents. This was in fact consistently observed during the experiment, as shown in Figure 8. Using these correlations we have shown that the air in the ozone-poor lamina at 100 mbar in Figure 9 could only have originated in the lower tropical stratosphere.

Linear mixing computations based on simultaneous measurements of ^{7}Be, ozone, and other trace constituents above the jet core on the April 20 and May 6 flights are consistent with the entrainment and irreversible mixing of upper level tropospheric air into the lower stratosphere and suggest that this process may be important in maintaining the vertical trace constituent gradients observed in the lower few kilometers of the mid-latitude stratosphere.

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