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National Center for Atmospheric Research, Boulder, U.S.A.,
Department of Atmospheric Science, Colorado State University, Fort Collins, U.S.A.,
Los Alamos Research Laboratory, Los Alamos, U.S.A.

Vertical Mass- and Trace Constituent Transports in the Vicinity of Jet Streams*

M. A. Shapiro, E. R. Reiter, R. D. Cadle, and **W. A. Sedlacek**

With 12 Figures

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Summary

Detailed analyses of radiosonde and aircraft data were used to identify regions of stratospheric air incursions into the troposphere and of tropospheric air inflow into the stratosphere. The latter flow phenomenon was associated with a distinct separation between potential vorticity tropopause and stability tropopause. It occurred in the region of confluence between jet branches of different origin and was connected with strong anticyclonic shears which are associated with the presence of a wind maximum above the stability tropopause.

Zusammenfassung

Der Vertikaltransport von Luftmassen und Spurenstoffen im Bereich von Strahlströmen

Detaillierte Analysen von Radiosonden- und Flugzeugdaten wurden benützt, um das Eindringen von Stratosphärenluft in die Troposphäre und das Einströmen von troposphärischen Luftmassen in die Stratosphäre zu identifizieren. Der letztere dieser beiden Austauschvorgänge war mit einer signifikanten Differenzierung zwischen potentieller Vorticity-Tropopause und Stabilitätstropopause assoziiert. Er trat in der Konfluenzregion zwischen zwei Strahlstromästen verschiedenen Ursprungs auf und war mit starker, antizyklonaler Scherung verbunden, die im Zusammenhang mit einem Windmaximum oberhalb der Stabilitätstropopause stand.

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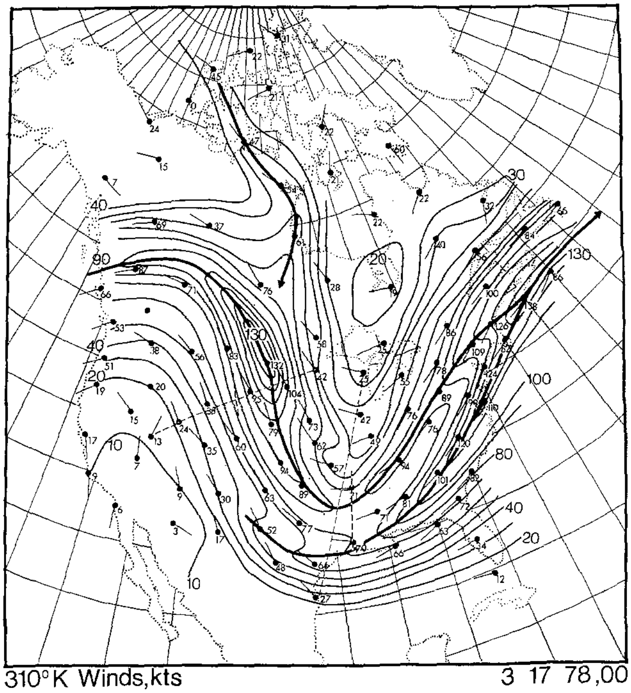

Fig. 1. Isotachs (knots) on the 310 K isentropic surface, 17 March 1978, 00 GMT. Dashes plotted at individual stations indicate wind direction, numerical values give wind speeds in knots. Heavy solid lines are jet axes. Heavy dashed line gives the position of aircraft tracks and thin dashed lines mark the locations of the cross-sections shown in Figs. 3 to 6

1. Introduction

Stratospheric-tropospheric mass exchange in the vicinity of jet streams not only affects the seasonal distribution of radioactive fallout at the earth's surface (see e. g. Steinhauser [12, 13]) but can contribute to the injection of man-made pollutants into the stratosphere [1, 11]. Unfortunately, estimates of the flow of tropospheric air into the stratosphere are not plentiful, nor have the flow mechanisms leading to such upward transport of tropospheric air been studied in detail [4, 7].

In 1978 a cooperative program, involving scientists from the National Center of Atmospheric Research (NCAR), from Colorado State University (CSU), and from the Los Alamos Scientific Laboratories (LASL), was launched to trace the vertical exchange processes between stratosphere and troposphere

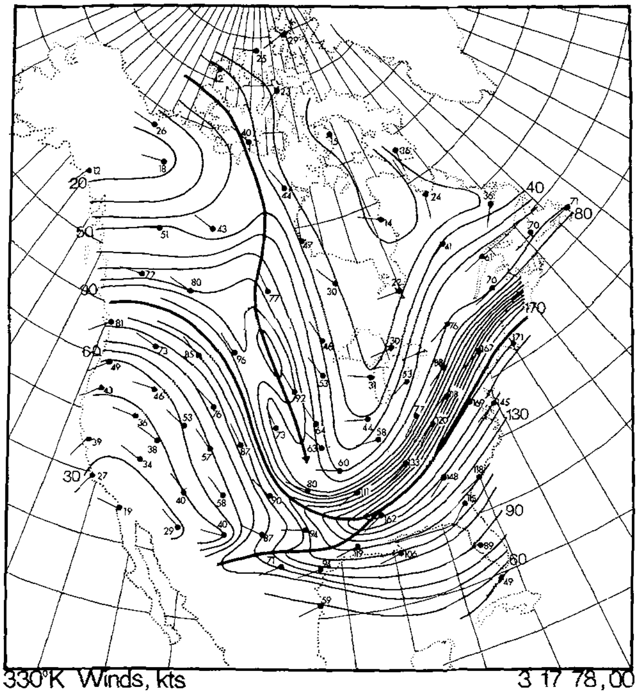

Fig. 2. Similar to Fig. 1, except 330 K isentropic surface

in the vicinity of cyclogenetically active jet-stream maxima. Several research flights were conducted by the NCAR Sabreliner and the NASA RB-57. The aircraft data yielded cross-sections of potential temperature, wind, ozone and condensation nuclei (CN) concentrations. Ozone can be regarded as a tracer of stratospheric air, whereas high concentrations of condensation nuclei are characteristic of tropospheric air.

A detailed investigation of the atmospheric conditions surrounding the research flights on 16 March 1978 was made. As was the case in a previous study [1, 8], painstaking analyses of synoptic information proved to be of high enough quality and reliability to provide an excellent fit between aircraft and radiosonde data. The flight observations were taken close to the 00 GMT synoptic period on 17 March 1978.

2. The Atmospheric Flow Pattern

Fig. 1 shows an analysis of isotachs on the 310 K isentropic surface close to the time at which aircraft measurements were conducted along a flight path indicated in this diagram by a heavy, dashed line. The two thin dashed

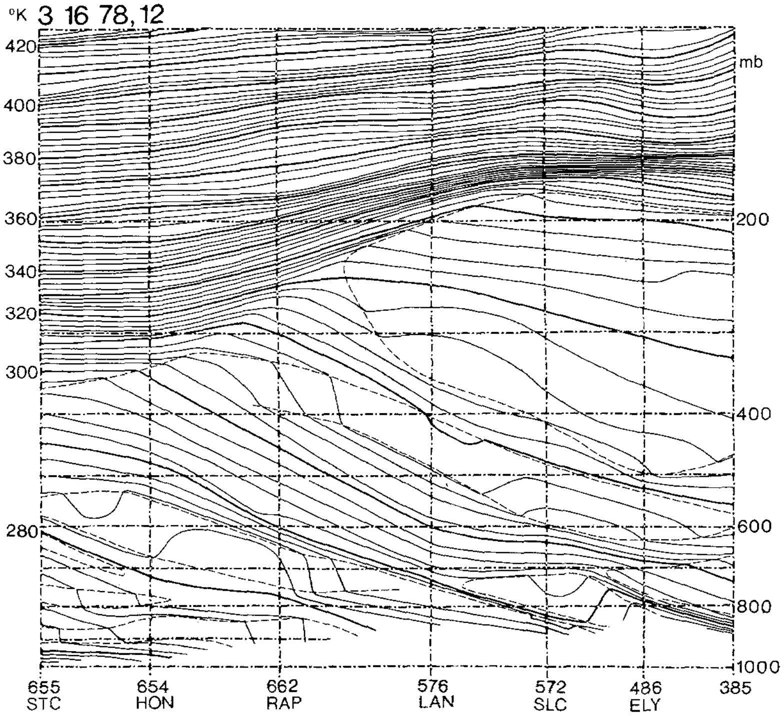

Fig. 3. Cross-section of potential temperature (K) between St. Cloud, Minnesota (655, STC) and station 385 in Nevada, 16 March 1978, 12 GMT. (For the location of this cross section see Fig. 1.) Thin dashed lines mark the boundaries of stable layers and of the stability tropopause. Temperatures were analyzed at 2 K intervals. 10 K intervals are marked by heavier lines

lines refer to the orientation of vertical cross-sections which will be discussed later. Fig. 2 gives a similar analysis for the 330 K surface. Especially on the 310 K surface, which lies inside the stable layer of extruding stratospheric air masses, the jet-stream patterns reveal a significant "fingery" structure. This structure tends to become more uniform and smooth on higher-lying isentropic surfaces. There is a good reason for these differences in the jet-stream structure on different isentropic surfaces, which becomes obvious upon inspection of the cross-sections shown in Figs. 3 to 6.

Intrusion of stratospheric air into the troposphere proceeds in a stable layer with high values of potential vorticity, as will be shown later. This means that within the stable layer underneath the jet core, where this intrusion process occurs, the horizontal wind shears will be nearly constant and positive. Isotach surfaces tend to orient themselves along isentropic surfaces

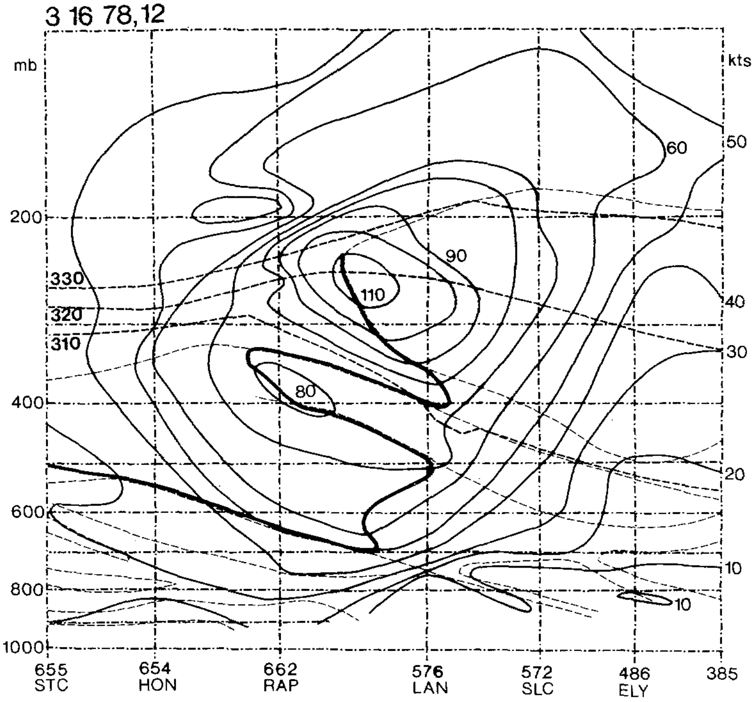

Fig. 4. Same section as in Fig. 3, but analyzed for wind speeds in knots. Thin dashed lines indicate the boundaries of stable layers and the stability tropopause. The heavy dashed lines mark the position of the 310 K, 320 K and 330 K isentropic surfaces. The heavy solid line marks the edge of the stratospheric air intrusion into the troposphere as obtained from stability and horizontal wind-shear conditions. There is no evidence in this cross-section of significant return flow of tropospheric air into the stratosphere

as evident from the cross-section diagrams. Such an almost-constancy of wind speed on an isentropic surface, portrayed in the cross sections, manifests itself by a "splitting" of the jet stream, with very weak horizontal wind shears between the two resultant jet axes on the 310 K isentropic surface, which characterizes the flow within the stable jet-stream front. Thus the space between the two major jet branches shown in Fig. 1 encompasses the air involved in the major intrusion process of stratospheric air. On 16 March 1978, 12 GMT such an intrusion event was under full development over the Rocky Mountains as can be seen from Figs. 3 and 4. During the subsequent synoptic observation period (17 March, 00 GMT) the flight paths pursued by the two research aircrafts intercepted the "tail end" of this intrusion. By this time the stratospheric air had subsided to relatively low tropospheric elevations (ca. 500 mbar), as can be seen from

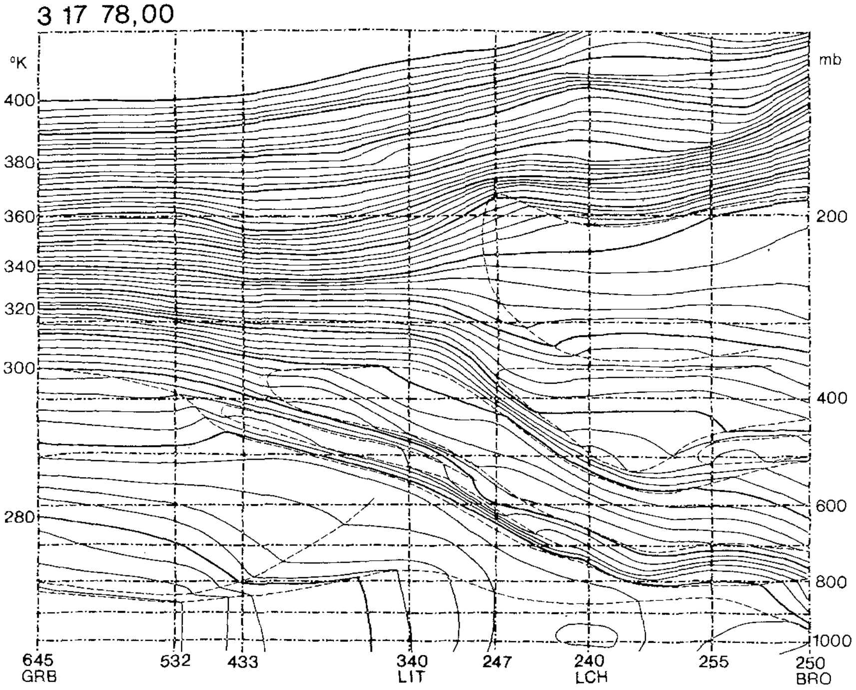

Fig. 5. Cross-section of potential temperature (K) between Green Bay, Wisconsin (645, GRB) and Brownsville, Texas (250, BRO), 17 March 1978, 00 GMT. This section lies close to the aircraft tracks (see Fig. 1). For further details see legend to Fig. 3

the encounter of high ozone and low condensation nuclei concentration values shown in Figs. 7 and 8. The southernmost extension of the extruded air is found slightly south of Lake Charles, Louisiana. The extrusion boundary coincides with the jet axis of the southern jet branch in Fig. 1. In the cross-sectional diagrams this extrusion boundary is marked by a sudden upward slope of isotachs out of the stable layer of intruding stratospheric air, and therefore by the northern edge of a zone of anticyclonic wind shear.

On higher-lying isentropic surfaces (such as the 330 K surface, for which a wind analysis is presented in Fig. 2) the isotach patterns tend to form a single jet axis which is positioned close to where the northern jet branch was found at the 310 K surface. Again, by virtue of the discontinuity of potential vorticity, the jet axis appears to delineate the boundary of tropospheric air intrusion into the stratosphere (see Figs. 7 and 8). The strong cyclonic and anticyclonic shears evident on the 330 K isentropic surface provide a sharp potential vorticity discontinuity at the jet axis which restricts transitions of air masses between stratosphere and troposphere.

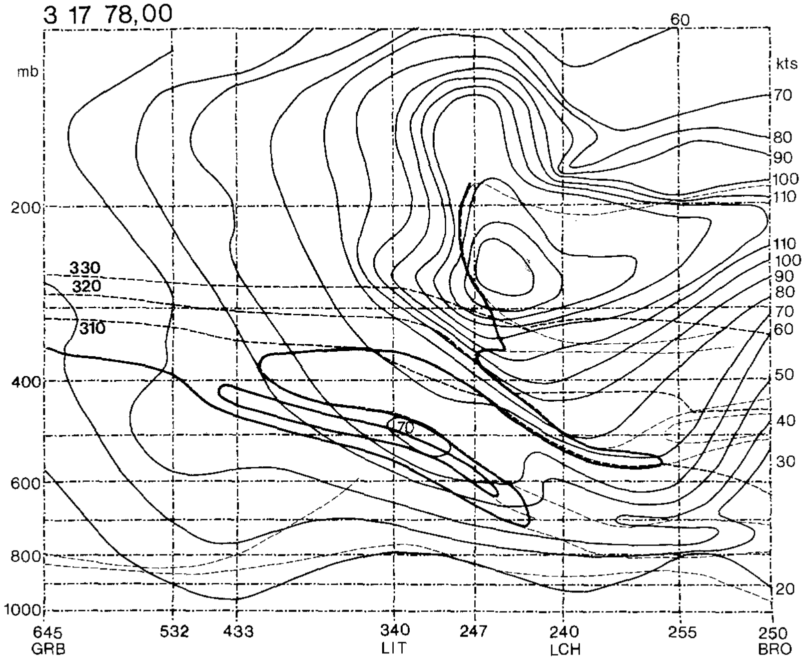

Fig. 6. Same section as Fig. 5, but analyzed for wind speeds in knots. (For details see legend to Fig. 4.) The return flow of tropospheric air into the stratosphere takes place on the anticyclonic side of the extension of the wind maximum above the stability tropopause

3. Details of the Intrusion Process

The isotach analysis shown in Fig. 9 was obtained from aircraft measurements and was used to compute potential vorticities. This cross-section fits well with the one obtained from radiosonde data (Fig. 6), except for winds in excess of 170 kts above the 180 mbar level reported at station 247, which could not be substantiated by aircraft observations.

The flow on the 370 K isentropic surface (Fig. 10) indicates that this erroneously reported, high wind velocity at station GGG/247 should have been approximately 130 kts. This value has been used for the analysis of Fig. 6. In spite of this downward correction of wind speed on the 370 K isentropic surface we should give credence to the indication of an extension of the wind maximum to yet higher potential temperatures in the vicinity of this station. Fig. 10 indicates that such a secondary wind maximum had considerable geographic extent, stretching between the confluence region of the two major jet branches, and the position of the jet maximum on the 370 K surface.

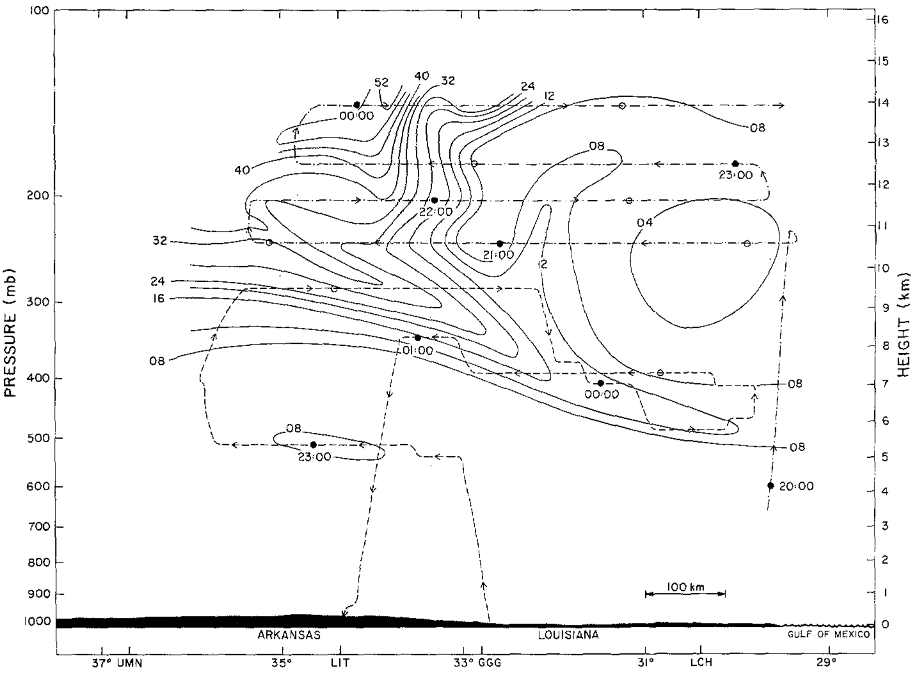

Fig. 7. Ozone concentrations, in parts per hundred million by volume, measured by research aircraft on 16 and 17 March, 1978. Flight paths are indicated by dashed lines with arrows. Observation times in GMT have been entered along flight paths

From a potential vorticity cross-section (Fig. 11) it appears that on the anticyclonic side of the jet maximum found over Longview, Texas (GGG/247) a distinct and highly significant separation occurs between the tropopause defined by a discontinuity in thermal stability (the "stability tropopause" in Fig. 12 and indicated in Figs. 3 and 5 by thin dashed lines), and the 100 ($\cdot 10^{-7}$K mbar^{-1}s^{-1}) potential vorticity value that elsewhere in this cross-section can be regarded as the demarcation value between stratospheric and tropospheric air. The use of potential vorticity as an indicator of stratospheric air, and its discontinuities as demarcations of the dynamically defined tropopause have been advocated by Reed [2]. We find that the area with potential vorticity < 100 bulges strongly upward by more than 5 km between Longview (247) and Lake Charles (240) into the stable region of the thermally defined "stratosphere". Conveniently enough, we find that this bulge of low potential vorticity air coincides with an intrusion of relatively high CN concentrations and with an even better-marked deficit in O_3 – indicative of tropospheric air above the stability tropopause. From

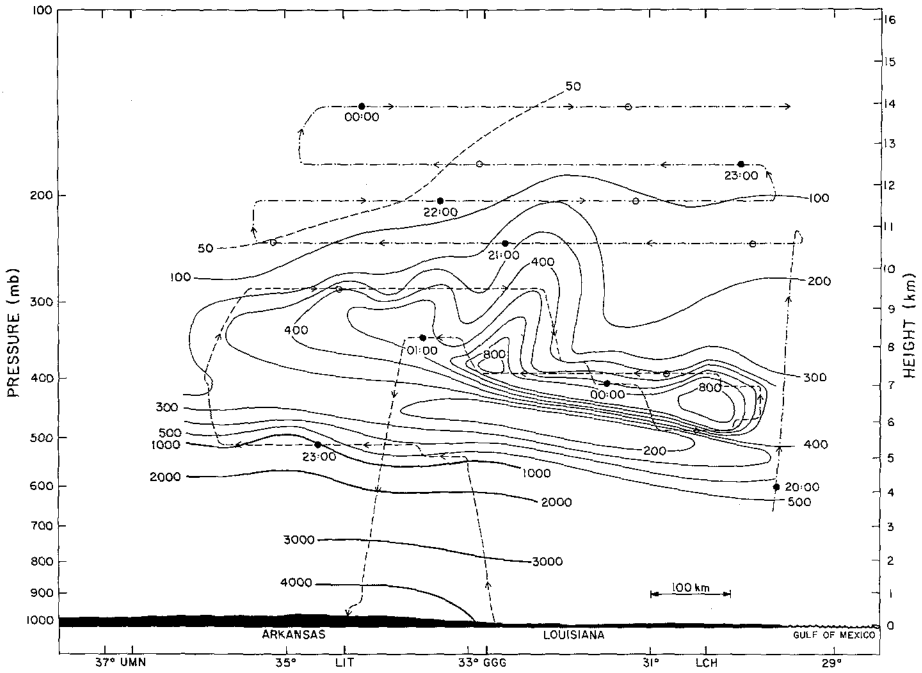

Fig. 8. Similar to Fig. 7, except Aitken particle concentrations in terms of particles per m^3 reduced to 1000 mbar and 293 K

Figs. 6 and 10 it appears, that this tropospheric air intrusion coincides with the anticyclonic side of the extension of the wind maximum above the stability tropopause mentioned earlier. Such upward extensions of wind maxima, and even secondary maxima above the stability tropopause have been found quite frequently during earlier jet stream studies [3] but had not been considered as a significant feature. It now appears that enhanced values of horizontal anticyclonic shears in the altitude range of this extended wind maximum provide in a significant way the low potential vorticity values characteristic for tropospheric air with its concomitant chemical composition. We should, furthermore, note that this intrusion under strong anticyclonic shear conditions, according to Fig. 10, is associated with a southwesterly jet branch that overrides the northwesterly flow of stratospheric air subsiding into the jet stream front (Fig. 12). This flow configuration agrees well with earlier presentations by Reiter and Nania [5] and Reiter and Whitney [6].

Sorting out the evidence presented in the preceding diagrams we arrive at the following picture of stratospheric-tropospheric air-mass exchange in the vicinity of active jet streams:

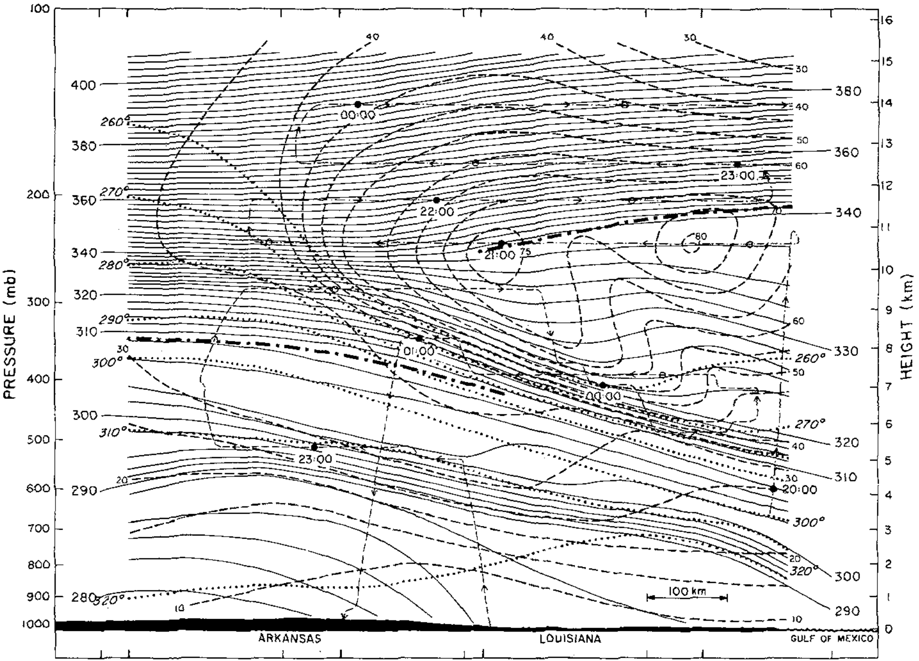

Fig. 9. Similar to Fig. 7, except potential temperatures (K, thin lines), and isotachs (m/s, dashed lines). Positions of the stability tropopauses are indicated by heavy dashed-dotted lines

On the cyclonic side of the jet maximum, where high values of potential vorticity prevail, the 100 ($\cdot 10^{-7}$K mbar^{-1}s^{-1}) isoline of potential vorticity coincides well with the discontinuity of stability (Fig. 11), which is the usual manifestation of the tropopause. The coincidence of these two lines extends into the "jet-stream front" underneath the jet core, i. e. the stable layer in which stratospheric air of high O_3 and low CN concentrations extrudes into tropospheric layers. The importance of turbulent mixing in carrying air and chemical constituents across the potential vorticity discontinuity has been described by Shapiro [9, 10, 11].

Some "seepage" of tropospheric air into the stratosphere is observed sometimes in the region of the jet core, in which the isentropic surfaces are almost horizontal and in which a stability tropopause is ill defined (Fig. 5). This seepage is illustrated by a tongue of relatively low O_3 values extending northward between the 200- and 300 mbar levels over Little Rock (340) (Fig. 7) (see also Cadle et al., [1]; Reiter, Glasser and Mahlman, [7].

The major upward extension of tropospheric air above the stability tropopause occurs immediately to the south of the jet core, in a region of marked

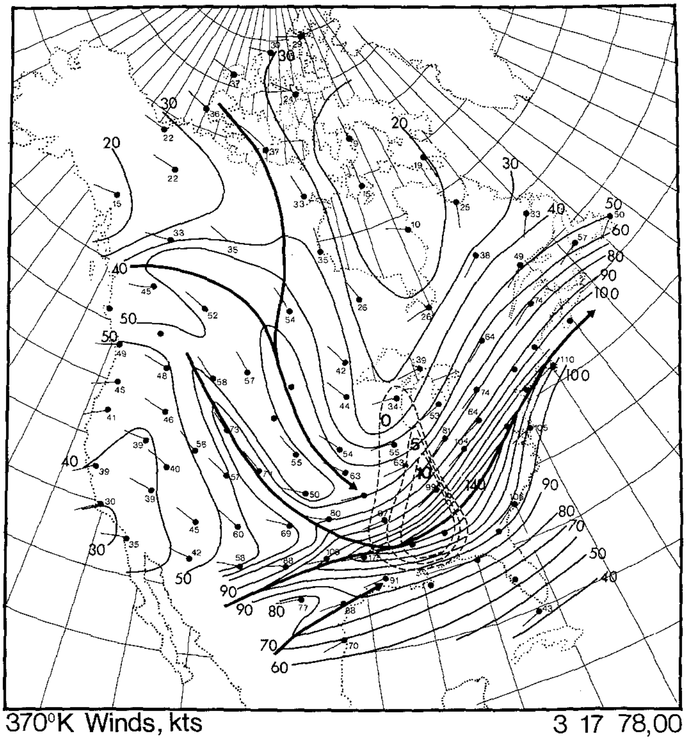

Fig. 10. Similar to Fig. 1, except 370 K isentropic surface. The dashed lines give the difference in wind speeds between the 370 K isentropic surface and a secondary wind maximum located at a somewhat higher elevation

anticyclonic wind shear on isentropic surfaces. This region is characterized by a distinct separation between "potential vorticity tropopause" and "stability tropopause". The potential vorticity tropopause may assume various shapes, depending on the more or less complex nature of the jet-stream structure and of the merger of jet stream "fingers".

In Fig. 12 we show schematically the transport processes described above – the one proceeding from the stratosphere to the troposphere and carrying high O_3 values, and the other proceeding in the reverse direction, carrying high CN and low O_3 concentrations.

The arrow marking the upward transport of tropospheric air should not be construed as vertical flow crossing insentropic surfaces. Most likely, this transport of tropospheric air above the stability tropopause occurs quasi-horizontally, entailing the confluence of air masses from different origins. This difference in origin becomes evident by comparing Figs. 1, 2 and 10 with each other.

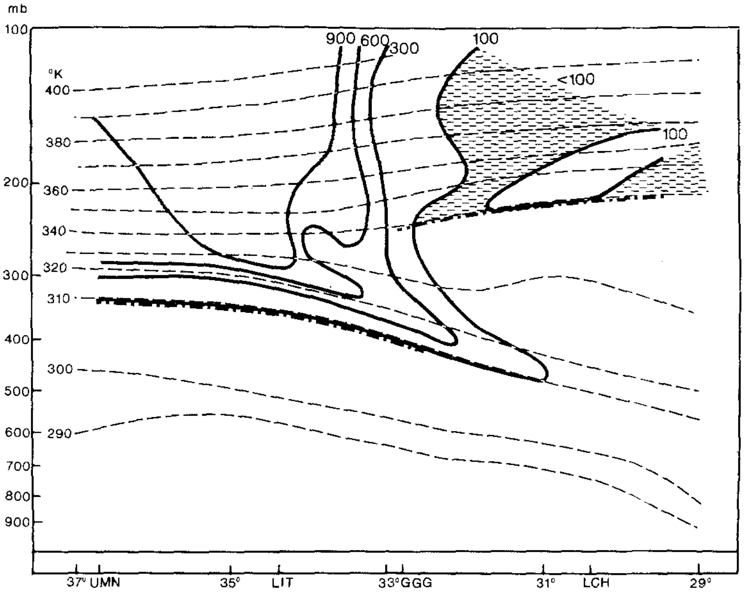

Fig. 11. Similar to Fig. 7, except potential vorticity isolines (10^{-7} K mbar^{-1} s^{-1}). Dashed lines show potential temperatures (K) taken from Fig. 9. Stability tropopauses are indicated by heavy dashed-dotted lines. Shaded areas mark potential vorticity values $< 100 \cdot 10^{-7}$ K mbar^{-1} s^{-1} occurring above the stability tropopause

The question remains, how air of tropospheric origin could become stable enough to assume stratospheric characteristics of thermal stability, thus causing the observed separation between potential-vorticity and stability tropopauses. As evident from Figs. 1, 2 and 10, tropospheric air flowing into the anticyclonic shear region south of the jet axis near and above the jet core, rapidly decreases its absolute vorticity. In doing so, conservation of potential vorticity requires a rapid increase in thermal stability.

4. Conclusions

Evidence has been presented of massive upward transport of tropospheric air by as much as 5 km above the stability tropopause. The transport processes can be identified by differences in O_3 and CN concentrations and are well marked by potential vorticity patterns in vertical cross sections. These patterns reveal a distinct separation of the potential vorticity tropopause from the stability tropopause in the region of tropospheric air transport into layers above the stability tropopause. Regions of such

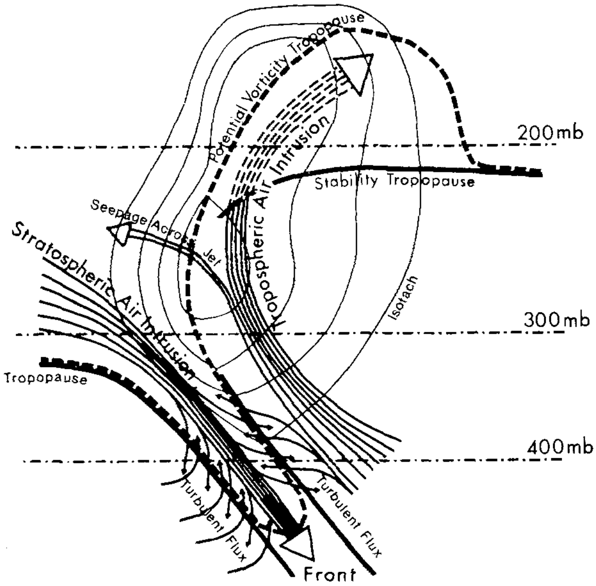

Fig. 12. Schematic diagram of stratospheric-tropospheric air-mass exchange in the vicinity of a cyclogenetically active jet maximum

transports are often marked by an upward extension of the jet core in vertical cross sections and occur in the confluence region of jet branches having different origins.

Reed [2] has investigated a number of studies of stratospheric air intrusions into the troposphere. His work has also caused a redefinition of the boundary surface between tropospheric and stratospheric air by using the concept of potential vorticity. The present work demonstrates that transport processes of tropospheric air into layers previously deemed to be "stratospheric" according to their thermal stability configuration, can be reconciled with Reed's concepts of the distribution of potential vorticity in troposphere and stratosphere. It will require further research to determine if the low potential vorticity air found above the stability tropopause south of strong jet maxima slowly assumes all other characteristics of stratospheric air (e. g. high potential vorticity and ozone values), or whether it descends below the stability tropopause after relatively short distances of travel.

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Authors' addresses: Prof. M. A. Shapiro, NCAR, P.O. Box 3000, Boulder, CO 80307, U. S. A.; Prof. E. R. Reiter, Department of Atmospheric Science, Colorado State University, Foothills Campus, Solar House 3, Ft. Collins, CO 80523, U. S. A.; Prof. R. D. Cadle, NCAR, P. O. Box 3000, Boulder, CO 80307, U. S. A.; Dr. W. Sedlacek, Los Alamos Scientific Laboratory, CNC-11, P. O. Box 1663, Los Alamos, NM 87544, U.S.A.