NOTES AND CORRESPONDENCE

A Physical Examination of Tropopause Height and Stratospheric Air Intrusion—A Case Study

By Kyung-Eak Kim

Dept. of Astronomy and Atmospheric Sciences, Kyungpook National University, Taegu, Korea

Eun-Sil Jung

Remote Sensing Division, Korea Meteorological Administration, Seoul, Korea

Bernard Campistron

Laboratoire d'Aérodynamique (CNRS), Observatoire Midi-Pyrénées, Université Paul Sabatier, Toulouse, France

and

Bok-Haeng Heo

Aviation Weather Office, Korea Meteorological Administration, Seoul Korea

(Manuscript received 3 July 2000, in revised form 11 June 2001)

Abstract

Temperature lapse rate, potential vorticity, Brunt-Väisälä frequency, along with VHF wind profiler observations were employed to examine the temporal variation of the tropopause height and stratospheric air intrusion during an event of tropopause folding. The present study suggests that the tropopause defined by 1.6 PVU is more adapted to analyzing stratospheric air intrusion, compared with the tropopause defined by temperature lapse rate or Brunt-Väisälä frequency. However, the latter two tropopause definitions are more relevant to localizing stratospheric air intrusions into the troposphere than the potential vorticity when the air is intruded in a slantwise direction over the observation site. The intruded air in a slantwise direction is observed as the temperature lapse rate and Brunt-Väisälä frequency anomalies, corresponding to the temperature anomaly, which is predicted as the low level tube by Bithell et al. (1999). The present study suggests that the slantwise intrusion is a type of low level tube developed during tropopause folding.

1. Introduction

The tropopause is generally recognized as the boundary between the troposphere and the stratosphere, based on its classical picture of vertical

temperature profile. The undulation and folding of the tropopause often play a significant role in mid-latitude cyclogenesis and the development of severe weather in the lower troposphere. Tropopause undulation typically exists prior to and during lower tropospheric cyclone development (Hirschberg and Fritsch 1991a, 1991b). Tropopause folding occurs when the undulation becomes unstable and then collapses, allowing the formation of an upper-tropospheric front, cyclogenesis, and making an intrusion channel of stratospheric air into the tropo-

Corresponding author and present affiliation:
Kyung-Eak Kim, Dept. of Astronomy and Atmospheric Sciences, College of Natural Sciences,
Kyungpook National University, Taegu 702-701,
Korea.

E-mail: kimke@knu.ac.kr

©2001, Meteorological Society of Japan

sphere (Carlson 1991).

As known from earlier studies (e.g., Bjerkness and Palmen 1937), the tropopause is not a physical surface made of the same air parcel all the time. It is regarded as a material surface moving with the air (Sawyer 1954). The surface freely deforms in response to vertical air motion and thermal advection. The location of the tropopause height is dependent on the criteria used to define it. Thus, it can be quite variable. Presently two definitions of the tropopause are used: thermal and dynamical tropopauses. According to the WMO criterion (1986), the thermal tropopause is defined as the lower boundary layer in which the temperature lapse rate is less than 2 K km^{-1} for a depth of at least 2 km. The dynamical tropopause is determined by using potential vorticity. The WMO (1986) defines the dynamical tropopause by the value of 1.6 PVU, where the PVU stands for isentropic "Potential Vorticity Units" ($1\text{ PVU}: 1.0 \times 10^{-6}\text{ km}^2\text{ kg}^{-1}\text{ s}^{-1}$). However, other studies suggest values between 1 PVU and 3.5 PVU outside the tropics (Shapiro 1980; Danielsen et al. 1987; Hoerling et al. 1991; Bithell et al. 1999). There have been a few studies comparing the tropopause heights determined by the two different definitions. Hoerling et al. (1991) showed that the value of 1.6 PVU (WMO 1986) considerably underestimates the tropopause height relative to that obtained by the thermal definition, while a value of 3.5 PVU represents an optimal value for tropopause height outside tropics. However, Hoinka et al. (1993) suggested that there is a good agreement between estimations of thermal and dynamical tropopauses using a threshold of 1.6 PVU.

Recently, the Brunt-Väisälä frequency has been used to locate the tropopause using ST (Stratosphere and Troposphere) radar data, because the sharp increase of this frequency near the tropopause is closely related with the enhancement of clear air echo intensity (Revathy et al. 1996; Hermawan et al. 1998). Further, employing the aspect sensitivity of the echoes, static stability (Brunt-Väisälä frequency), vertical shear of horizontal wind, and turbulence intensity (deduced from the C_n^2 , the air refractive index structure parameter), Caccia and Cammas (1998) were able to investigate the tropopause break, slope, and turbulence associated with an upper-level frontal zone. There are few studies that carefully compare the variations of tropopause height and stratospheric air intrusion during a tropopause folding event by using VHF radar ob-

servations and NCEP/NOAA reanalysis data. The NCEP/NOAA stands for the National Centers for Environmental Prediction/National Oceanic and Atmospheric Administration.

The purpose of the present study is to investigate the variation of the tropopause height and stratospheric air intrusion during tropopause folding. Both the conventional lapse rate and potential vorticity, including Brunt-Väisälä frequency, were employed to examine the variation and the lowest level of the tropopause height, and the intrusion of stratospheric air into the troposphere during tropopause folding. The originality of this paper, compared with other papers on the same topic, is a more complete and detailed description of the temporal tropopause variation, intrusion of the stratospheric air, and the horizontal dimension of tropopause folding, based on analyses of radar aspect sensitivity, vertical air velocity, the temperature lapse rate, potential vorticity, and Brunt-Väisälä frequency including three-dimensional tropopause surfaces.

2. Data and analysis

The present study was of a baroclinic wave of the westerly jet that developed over Western Europe and the nearby Atlantic Ocean on March 3, 1995. During this event there was a cold air break in a strong northerly flow crossing the British Isles, the west of France, and the north of Spain. A more detailed synoptic overview is found in Campistron et al. (1999).

The change of the tropopause height and its folding were analyzed from two data sources: VHF radar observations and NCEP/NOAA reanalysis data. The VHF radar observation of the tropopause folding was performed at the Atmospheric Research Center at Lannemezan (0.367E, 43.133N), France during the period from 1500 UTC 3, March to 1000 UTC 5, March 1995. The observation was a part of ESTIME (in French, Stratosphere-Troposphere Exchanges, Mesoscale Experiment). The main characteristics of the VHF radar used are as follows: a 45 MHz transmitted frequency with a 6 kW peak power, a 6,400 Hz pulse repetition frequency, and, a 25 microsecond coded pulse. The radar makes use of five beams (one vertical and four oblique with an off zenith angle of 15°) of a 5.6° aperture. Vertical profiles of the three components of the wind were obtained every 15 min. with a vertical resolution of 375 m. A more detailed explanation of the VHF radar can be found in Campistron

et al. (1999).

The tropopause height and folding event were analyzed through the aspect sensitivity and vertical velocity of the echoes provided by the VHF radar data, and through potential vorticity, temperature lapse rate, and Brunt-Väisälä frequency derived from NCEP/NOAA reanalysis data. The Brunt-Väisälä frequency is used to characterize a gravity wave (or buoyancy wave) frequency, and is introduced to set the boundary between the troposphere and stratosphere, and to locate the stable air originating in the stratosphere. The NCEP/NOAA data were used for the analysis of temperature lapse rate, potential vorticity and Brunt-Väisälä frequency during the same period of the VHF radar observation. The NCEP/NOAA reanalysis data set consisted of air temperature and specific humidity, including wind at twelve different pressure levels: 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, and 100 hPa. The temporal and spatial resolutions of the NCEP data are 6 hours, and 2.5 degrees (about 250 km) in both latitude and longitude, respectively. Although the data resolution is not adequate to analyze meso-beta or meso-gamma scale weather phenomena, the NCEP data can be used to analyze the dynamical and thermodynamic characteristics of weather phenomena of synoptic or meso-alpha scale such as tropopause folding.

The aspect sensitivity of the VHF radar signals is used to detect tropopause folding because strong aspect sensitivity is usually associated with stable atmospheric layers. Three types of aspect sensitivity, which is linked to the thermal stability and reduced to null turbulence, can be used to analyze tropopause folding (e.g., Gage and Green 1978; Hocking et al. 1986; Tsuda et al. 1986; Campistron et al. 1999). These are vertical echo power (P_v), the ratio of vertical to oblique echo powers (P_v/P_o), and normalized vertical spectral width (σ_v/σ_b). However, this study utilizes only one aspect sensitivity parameter, the ratio of P_v/P_o , in detecting tropopause folding since the ratio of echo powers (P_v/P_o) usually provides a better insight into the location and the track of the tropopause folding than the other two aspect sensitivity parameters.

The temperature lapse rate was calculated from the NCEP/NOAA data using the method defined by the WMO. The potential vorticity is computed on the isentropic surface according to the equation given by Reed (1955):

$$PV = -g(\zeta_\theta + f)\frac{\partial\theta}{\partial p}, \quad (1)$$

where ζ_θ is the relative vorticity on isentropic surface, and g is the earth's gravitational acceleration. f is the Coriolis parameter, and θ is the potential temperature. The dynamical tropopause is estimated by applying the WMO criterion (1.6 PVU) of the potential vorticity. The Brunt-Väisälä frequency, N (rad s^{-1}), was computed using the following equation that makes sense only for a stable atmosphere:

$$N = \sqrt{\frac{g}{\theta} \frac{\partial\theta}{\partial z}}, \quad (2)$$

where z is the altitude. The effect of water vapor mixing ratio on N was neglected in our calculation because the mixing ratio is usually very low at the level of tropopause.

3. Analysis of aspect sensitivity and vertical air velocity

The aspect sensitivity of VHF radar signals was analyzed to examine tropopause folding and then the intrusion level of stable stratospheric air. Among the three different sensitivity analyses made by Campistron et al. (1999), the time-height section of the aspect sensitivity (P_v/P_o), which is presented in Fig. 2(b) in their paper, was employed to illustrate tropopause folding.

Figure 1 shows the aspect sensitivity measured between the altitudes of 4 and 15 km during the passage of a tropopause folding event linked to a cut-off low developed in the upper troposphere. In the figure, a tongue of strong aspect sensitivity sloping downward with time is regarded as the stable air region of tropopause folding. However, the starting time of the folding over the radar site is not apparent because there is no clear boundary between the isolines of aspect sensitivity which can be used to define it. In spite of some uncertainty, the folding seems to have started at about 0000 UTC 4 March in the figure. This is because at about 9.5 km, there is a core of high aspect sensitivity of 20 dB. This idea can be supported by the time-height cross sections of vertical air velocity, Brunt-Väisälä frequency, temperature gradient, and potential vorticity. Figure 2 displays the profile of the vertical air velocity observed by the VHF radar, which shows two regions (unshaded) with negative velocities ranging from -0.2 to 0 m s^{-1} before 0000 UTC 4 March. One is located between 8 and

Fig. 1. Time-height cross sections of the aspect sensitivity observed by the VHF radar: P_v/P_0 from 1500 UTC 3 to 1000 UTC 5 March 1995 (Campistron et al. 1999).

Fig. 2. Time-height cross sections of the vertical velocity of air obtained by the VHF radar.

10 km, and the other above 13 km. The latter appears directly linked to the folding over the observation site since the contour of 0 to 0.2 m s^{-1} encircling the region of the negative vertical velocity above 13 km, which almost extended to 0000 UTC 4 March, shows a connection with the region of 0 to 0.2 m s^{-1} at the level of 12 km. Further, our determination of the starting time of the folding is supported from Figs. 3, 4 and 5, where the shape of a sloping channel, which is a direct evidence of the tropopause folding, can be traced easily, by comparing these figures with Fig. 1. We interpreted the descending of the tropopause before 0000 UTC 4 March as a tropopause undulation, a step prior to the folding. A downward air motion is generally expected where tropopause folding occurs. However, there was no region of downward motion after 0000 UTC 4 March in Fig. 2. This may be attributed to orographic effects since the VHF radar is located close to the Pyrenees Mountains.

The core of high sensitivity in Fig. 1 may be explained by the Fresnel reflection from the above stable layer initiated by the intrusion of the stratospheric air. Following the intrusion, the stable air split into two branches. The upper branch reached about 12 km at 1200 UTC 4 March, and then maintained almost the same altitude. The lower branch, as shown in Fig. 1, formed a tongue of intrusion of stratospheric air into the troposphere. The tongue of strong aspect sensitivity sloped downward from an altitude of 11 km on 3 March, to 5 km at the beginning of 5 March. From 0000 UTC 4 to 1200 UTC 4 March, the two branches of radar reflectivity greater than 12 dB show the tropopause folding. The tropopause folding and the downward transport of stratospheric air is also found from the analysis of the temperature gradient and potential vorticity analyses, and will be discussed in the following section.

4. Tropopause change and stratospheric air intrusion

Figure 3 shows the temporal variation of thermal tropopause at the VHF radar site. The bold line in Fig. 3(a) indicates the contour of the lapse rate with 2 K km^{-1} . According to the figure, the tropopause height was about 10 km until 1200 UTC 3 March and then descended to 7.6 km at 0000 UTC 4 March. Thereafter the tropopause height increased, and reached approximately 10 km at 1200 UTC 4 March. The height increase continued until 1800 UTC 4 March, and then maintained its height

at about 11 km. As depicted in Fig. 3, there was an isolated, absolutely stable layer at about 3 km bound by the contour of temperature lapse rate, 4 K km^{-1} , smaller than the moist adiabatic lapse rate. The layer may be regarded as an absolutely stable layer because the moist adiabatic lapse rate was 5.8 K km^{-1} at 700 hPa and 273.15 K (Curry and Webster 1999). The air in this stable layer seems to have been originated in the stratosphere, since the lapse rate was too low to be expected under normal atmospheric conditions such as cloud layer, or entrainment zone, above the convective boundary layer. That layer may indicate a frontal surface. It is also apparent that the stable air did not directly come from the stratosphere just over the radar observation site because there is no continuous descending track of air with temperature lapse rate, 4 K km^{-1} in the figure. The same feature is found in Fig. 4, based on the contour line of $14 (\times 10^{-3} \text{ rad s}^{-1})$.

To explain this feature, we must look at other slantwise channels through which the air could be transported. The channels seem to correspond to the low-level tube for stratospheric air intrusion suggested by Bithell et al. (1999). This argument can be also supported from three different aspects: stable air source; radar aspect sensitivity; and, horizontal dimension of the stable layer. As can be seen in Fig. 3(a), the air with the lapse rate of 4 K km^{-1} existed just below the tropopause, except for the stable layer at about 3 km. The aspect sensitivity analysis in Fig. 1 indicates that the stable stratospheric air ($> 12 \text{ dB}$) was transported downward to the height of 4.5 km during the observation period. The height of the stable layer top was 3.5 km in Fig. 3(a). Furthermore, the extent of the stable layer was more than 500 km in horizontal dimension when applying "the principle of time-space conversion", based on the assumption that the stable air moves with the speed identical to the wind speed at the height of 3 km (about 15 m s^{-1}) during the time length of the layer (about 10 hr). All these observations strongly suggest that the source of the stable layer at 3 km was near the tropopause or the lower stratosphere.

The change of temperature gradient for the five different levels is are given in Fig. 3(b). It shows that the lowest level of the tropopause was 7.6 km at 0000 UTC, corresponding to the onset of the tropopause folding in the analysis of aspect sensitivity. Over the whole analysis period, the lapse rate at the level of 12 km never exceeded 2 K km^{-1} .

Fig. 3. Time series of (a) temperature gradient ($^{\circ}\text{C km}^{-1}$) with height, and tropopause height (thick solid line) and (b) temperature gradient at the given levels above the radar site from 0000 UTC 3 to 1800 UTC 5 March 1995. Shaded region in (b) indicates the stratosphere.

Fig. 4. Time-height cross section of the Brunt-Väisälä frequency ($10^{-3} \text{ rad s}^{-1}$) over the VHF radar site from 0000 UTC 3 to 1800 UTC 5 March 1995.

This indicates that the stratospheric air occupied this level at all times. Conversely, the lapse rate at 9 km was below 2 K km^{-1} from 0000 UTC to 1600 UTC 3 March. However, the lapse rate at 9 km was between 0 and 2 K km^{-1} from 1600 UTC 3 to 0730 UTC 4 March. This suggests that the stratospheric air existed at a level of 9 km through this period.

To define the tropopause using the Brunt-Väisälä frequency, its threshold is chosen to be compatible with the threshold used for the lapse rate. A Brunt-Väisälä frequency is selected as the threshold, $20 \times 10^{-3} \text{ rad s}^{-1}$, showing the highest correlation (0.96) between the tropopause heights defined by the lapse rate and the Brunt-Väisälä frequency, respectively. The Brunt-Väisälä frequency is chosen as the threshold in the present analysis. Figure 4 is a time-height cross section of the Brunt-Väisälä frequency, in which the contour of $20 \times 10^{-3} \text{ (rad s}^{-1}\text{)}$ clearly exhibits the tropopause folding even though the feature is not as prominent as in Figs. 1 and 3. As in Fig. 3(a), a closed region of $14 \times 10^{-3} \text{ (rad s}^{-1}\text{)}$ below 4-km height seems to originate from the tropospheric region just below the stratosphere. This is because the typical magnitude of the Brunt-Väisälä frequency is $10 - 12 \times 10^{-3} \text{ rad s}^{-1}$ (Holton 1992; Revathy et al.

1996). The present analysis suggests that the Brunt-Väisälä frequency can be used not only to examine a variation of the tropopause height, but also to detect the tropopause folding and the stratospheric air intrusion into the troposphere. This suggestion is also supported by Fig. 16 in Caccia and Cammas's study (1998). In their figure, the regions of N^2 greater than $2.0 \times 10^{-4} \text{ (rad}^2 \text{ s}^{-2}\text{)}$ below about 5-km height correspond to the region of the stratospheric air intrusion shown in Fig. 4.

Figure 5 represents the time series plots of the potential vorticity with height. The 1.6 PVU potential vorticity contour, as shown in Fig. 5(a), clearly displays the temporal variation of tropopause height during the tropopause folding. However, the figure does not show a clear-cut section of the tropopause folding and the stratospheric air intrusion as observed in Fig. 1. In addition, it is obvious that in Fig. 5(a) there is no region of stratospheric air intrusion below 4 km detected in Figs. 2 and 3. There is no region below the tropopause where the potential vorticity is greater than 1.6 PVU in Fig. 5(a). Compared to the analysis of temperature gradient and the Brunt-Väisälä frequency, the local potential vorticity analysis is found to have a limitation in the examination of stratospheric air intrusion.

Fig. 5. Time series of (a) potential vorticity (PVU) with height and (b) potential vorticity variations at the given levels above the radar site from 0000 UTC 3 to 1800 UTC 5 March 1995. The solid line with 1.6 PVU in (b) indicates the dynamical tropopause in middle latitudes. Shaded region in (b) indicates the stratosphere.

Fig. 6. The spatial distributions of the tropopause height determined from value of 1.6 PVU for (a) 0000 UTC 4 March and (b) 1200 UTC 5 March 1995 in the region of $30^{\circ} \sim 65^{\circ}\text{N}$, $30^{\circ}\text{W} \sim 30^{\circ}\text{E}$. The arrows indicate the beam pointing direction of VHF radar at the site.

The potential vorticity variations at the given levels are shown in Fig. 5(b), in which the shaded region belongs to the stratosphere with the potential vorticity greater than 1.6 PVU. According to the figure, the lowest level of the tropopause was 6.5 km during the tropopause folding. This level is 1.5 km higher than the lowest level estimated by the aspect sensitivity analysis in Fig. 1. The spatial distributions of tropopause during the folding are given in Fig. 6. As illustrated in the figure, the folding occurred over the longitudinal range of about 10 degrees, approximately 1,000 km in horizontal dimension, or about one fourth of the wavelength of a typical tropopause undulation (Hirschberg and Fritsch 1991a).

5. Discussions and conclusions

The tropopause height variation and stratospheric air intrusion were examined using radar aspect sensitivity, vertical air velocity, Brunt-Väisälä frequency, and the definitions of thermal and dynamical tropopause. The major results are summarized as follows.

The present study indicates that the three aforementioned parameters (the radar aspect sensitivity, Brunt-Väisälä frequency and thermal definition) can identify the temporal variations of the tropopause height, and that the tropopause defined by the value of 1.6 PVU was lower than the tropopause height obtained by the thermal definition, as given by Hoinka et al. (1993). The dynamical tropopause of 3.5 PVU (Hoerling et al. 1991) significantly underestimated the intrusion level of stratospheric air, compared to the tropopause of 1.6 PVU. The tropopause heights deduced from the Brunt-Väisälä frequency ($20 \times 10^{-3} \text{ rad s}^{-1}$) were higher than that based on either the temperature lapse rate or the potential vorticity. Concerning the tropopause folding, all three parameters failed to show its detailed feature detected by the VHF aspect sensitivity analysis. The data used may not be sufficient to resolve the detailed feature of the tropopause folding. As for the detection of stratospheric air descended directly over the observation site, the potential vorticity analysis was better than the other two parameters. However, the temperature lapse rate and Brunt-Väisälä frequency were found to be more useful for the analysis of stratospheric air intruded in a slantwise direction at the observation site than the potential vorticity. The air intruded in a slantwise direction was observed in terms of the temperature lapse rate and Brunt-

Väisälä frequency anomalies. They are regarded as strong evidence for the existence of a low-level tube, as described by Bithell et al. (1999). Potential vorticity analysis failed to reveal the stratospheric air intruded in a slantwise direction at the site.

Therefore, the present analysis suggests that the temperature lapse rate and the Brunt-Väisälä frequency can be used to investigate a synoptic scale or larger scale intrusion of stratospheric air. Similar to Caccia and Cammas (1998), our study also shows that the Brunt-Väisälä frequency is a useful parameter to examine the variation of the tropopause height, and to detect tropopause folding and stratospheric air intrusion into the troposphere. However, as in the case of temperature lapse rate and potential vorticity, a representative threshold value of this parameter, which can be used to define the tropopause height, is needed. In view of our present analysis, a threshold at the frequency of $20 \times 10^{-3} \text{ rad s}^{-1}$ is recommended. Our analysis shows that both thermal and dynamical definitions including Brunt-Väisälä frequency are complementary in the analysis of tropopause variation and stratospheric air intrusion during tropopause folding. The thermal definition and Brunt-Väisälä frequency have an operational advantage in the estimation of the tropopause from a single temperature profile. In contrast, the dynamical definition is more conducive to the analysis of mid-latitude cyclones and severe weather occurrences than the thermal definition and Brunt-Väisälä frequency.

There were several studies as to which definition of the tropopause is more appropriate in characterizing tropopause height. However, it seems irrelevant to compare the thermal and dynamical tropopause directly, and to expect a good agreement between the two tropopause heights obtained by the two different definitions. This is because the temperature gradient is not a conserved parameter like the potential vorticity which is conserved following the flow in the absence of diabatic heating and turbulence. The physical process which is responsible for the modification of these two parameters and the consequent tropopause are quite different; the dynamical tropopause changes through diabatic heating such as radiative heating due to ozone, while the thermal tropopause is modified by vertical air motion and horizontal thermal advection. In addition, a more fundamental problem occurs in the case of tropopause folding when comparing the two tropopauses physically. In ac-

tual atmospheric soundings, two (or three) thermal tropopauses are observed at two (or three) different altitudes from a single vertical temperature sounding or from the temporal variation of aspect sensitivity of VHF radar data when the tropopause folding occurs. The situations with two or three tropopauses cannot be obtained from the potential vorticity analysis at a given point because the potential vorticity and then dynamical tropopause can be obtained only from the observations of atmospheric motion and thermodynamic variables at two or three points. Therefore, no direct comparison of tropopauses is appropriate, when the two different definitions of the tropopause are employed.

Acknowledgments

This study was supported by the Korea Science and Engineering Foundation (KOSEF 985-400-004-2). The ESTIME experiment was supported by the French CNRS/INSU organization.

References

- Bithell, M., L.J. Gray and B.D. Cox, 1999: A three-dimensional view of the evolution of midlatitude stratospheric intrusions. *J. Atmos. Sci.*, **56**, 673–688.
- Bjerkness, J. and E. Palmén, 1937: Investigation of selected European cyclones by means of serial ascent, Geofis. Publ. 12, *Amer. Meteor. Soc.*, 62pp.
- Caccia, J.L. and J.-P. Cammas, 1998: VHF-ST radar observations of an upper-level front using vertical and oblique-beam C_2^n measurements. *Mon. Wea. Rev.*, **126**, 483–501.
- Campistron, B., Y. Pointin, F. Lohou and J.-P. Pagés, 1999: Aspect sensitivity of VHF radar echoes observed in the middle and upper troposphere during the passage of a cut-off low. *Radio Sci.*, **34**, 667–779.
- Carlson, T.N., 1991: *Mid-latitude weather systems*, Harper Collins, 507 pp.
- Curry, J.A. and P.J. Webster: *Thermodynamics of atmosphere and oceans*, Academic Press, 471 pp.
- Danielsen, E.F., R.S. Hipskind, S.E. Gaines, G.W. Sachse, G.L. Gregory and G.F. Hill, 1987: Three-dimensional analysis of potential vorticity associated with tropopause folds and observed variation of ozone and carbon monoxide, *J. Geophys. Res.*, **92**, 2103–2111.
- Gage, K.S. and J.L. Green, 1978: Evidence for specular reflection from monostatic VHF radar observations of the stratosphere, *Radio Sci.*, **13**, 991–1001.
- Hermawan, E., T. Tsuda and T. Adachi, 1998: MU radar observations of tropopause variations by using clear air echo characteristics. *Earth Planets Space, Japan*, **50**, 361–370.
- Hirschberg, P.A. and J. Michael Fritsch, 1991a: Tropopause undulation and the development of extracyclones. Part I: Overview and Observations from a cyclone event. *Mon. Wea. Rev.*, **119**, 496–517.
- and ———, 1991b: Tropopause undulations and the development of extracyclones. Part II: Diagnostic Analysis and conceptual model. *Mon. Wea. Rev.*, **119**, 518–550.
- Hocking, W.K., R. Ruster and P. Czechowsky, 1986: Absolute reflectivities and aspect sensitivities of VHF radio wave scatterers with the Soudy radar, *J. Atmos. Terr. Phys.*, **48**, 131–144, 1986.
- Hoerling, M.P., T.K. Schaak and A.J. Lenzen, 1991: Global objective tropopause analysis. *Mon. Wea. Rev.*, **119**, 1816–1831.
- Hoinka, K.P., M.E. Reinhardt and W. Metz, 1993: North Atlantic air traffic within the lower stratosphere: cruising times and corresponding emissions. *J. Geophys. Res.*, **98**, 23113–23131.
- Holton, J.R., 1992: *An Introduction to Dynamic Meteorology*, 3rd ed. Academic Press Inc., 511pp.
- Reed, R.J., 1955: A study of characteristic type of upper level frontogenesis, *J. Meteor.*, **12**, 226–237.
- Revathy, K., S.R. Prabhakaran Nair and B.V. Krishna Murthy, 1996: Deduction of temperature profile from MST radar observations of vertical wind. *Geophys. Res. Lett.*, **23**, 285–288.
- Sawyer, J.S., 1954: Day-to-day variations in the tropopause. *Geophys. Mem.*, **92**, Meteor. Office, London, 40 pp.
- Shapiro, M.A., 1980: Turbulent mixing within tropopause folds as a mechanism for the exchange of chemical constituents between the stratosphere and the troposphere. *J. Atmos. Sci.*, **37**, 994–1004.
- Tsuda, T., T. Sato, K. Hirose, S. Fukao and S. Kato, 1986: MU radar observations of the aspect sensitivity of backscattered VHF echo power in the troposphere and lower stratosphere. *Radio Sci.*, **21**, 971–980.
- World Meteorological Organization, 1986: *Atmospheric Ozone 1985*, Vol. 1, No. 16, Geneva, 392pp.