Analysis of Stratosphere-troposphere exchange processes associated to the Northern Subtropical Jet Stream

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Abstract

An intensive campaign of 41 ozonesoundings was conducted from February 1st to April 23rd 1999 at Tenerife (28ºN, 16ºW). The Subtropical Jet Stream (STJ) is located close to the Canary Islands in this period. A case analysis (March 25th and 26th) is presented to describe in detail the STE processes associated to the STJ, using both, meteorological analysis and information provided by the ozone soundings. Ozone sonde statistical analysis assess the significant role played by the STJ in the intrusions of subtropical upper tropospheric air masses into the mid-latitude lower stratosphere.

1. Introduction.

Stratosphere and troposphere exchange (STE) processes have been broadly studied. A detailed summary of this subject can be found in the review work by Holton (1995). However most of the STE works are focused on mid-latitudes and related to cut-off lows (COL) and upper troughs developments.

Studies that relate STE processes with high ozone concentrations in the North Atlantic subtropical mid and lower troposphere have been also performed. High ozone episodes (O_3> 70 ppbv) are frequently observed at Izaña Observatory (28ºN, 16ºW, 2360m a.s.l.) in late spring and early summer. High Be^7 records at Izaña suggest that these episodes are associated to transport of air masses from the higher troposphere, and probably from the lower stratosphere, to Izaña Observatory [Cuevas, 1995; Prospero et al., 1995]. The isentropic back-trajectories confirm this result. On the other hand ozone sonde intensive campaigns performed in different mid-latitude and subtropical stations show that the lower and middle subtropical troposphere is characterized by an ozone and dew point layered structure [Cuevas, 1995; Oltmans et al., 1996] observed mainly in spring and summer. The events above described are connected to mid-latitude upper-level troughs or COL developments which are quite frequent to occur in this season at the west of the Iberian Peninsula [Cuevas, 1995]. Some times upper-level troughs and COL developments over or in the surroundings of the Canaries can also be the origin of high surface ozone concentrations measured at Izaña Observatory [Kentarchos et al., 2000].

Folkins and Appenzeller (1996), using aircraft observations, have reported evidences of transport from the subtropical troposphere to the lower mid-latitude stratosphere. Baray et al. (2000) present the results of an intensive campaign of daily ozone soundings performed in the Southern Hemisphere (La Reunion Island), showing that the potential vorticity and ozone layering found between 6 and 10 km is associated to the subtropical jet. Kowol-Santel et al. (2000) analyze and model a case analysis of STE associated to the Subtropical Jet Stream (STJ) above the Canaries using aircraft and ozone sounding measurements. An estimation of the net upward flux of tropospheric air into the stratosphere caused by upper level frontogenesis associated to the STJ is performed in that work.

Incursions of subtropical air into the mid-latitude lower stratosphere have been inferred from observational data [e.g., Dessler et al., 1995]. However these works are based on single case analysis. In this work special attention is paid to the troposphere-to-stratosphere intrusions in the framework of an ozone sounding intensive campaign of almost three months.

The first goal of this work is to describe the STE processes associated to the STJ with one representative case study, based on ozonosonde observations and meteorological analysis. The second goal is to present the results of an intensive campaign of near-daily ozone soundings performed in spring 1999 in Tenerife, showing the disturbance that the STJ causes in the upper troposphere and lower troposphere above Tenerife.

2. Experimental. Campaign description.

An intensive campaign of 41 ozonesoundings was conducted from February 1st to April 23rd 1999 at Tenerife (28ºN, 16ºW). The location of this station is favorable to perform studies of chemical and transport processes in the subtropical stratosphere and evaluate their importance for mid-latitudinal ozone levels.

ECC-6A-type ozonesondes, Scientific Pump Co. and RS-80 radiosondes (Väisäla) were flown with helium-filled latex balloons (1200 g). Ozonesondes were checked before launching with a Ground Test with Ozonizer/Test Unit TSC-1. A constant mixing ratio above burst level is assumed for the determination of the residual ozone if an altitude equivalent to 17 hPa has been reached. The integrated ozone column (starting at 2400 m a.s.l.), for those ozone sondes that reach a burst level of at least 17 hPa, is ratioed with the same column amount measured with the Brewer#157 located at Izaña Observatory (WMO ozone station #300). Most of the Brewer/ECC coefficients fall in the 0.95-1.05 range. This coefficient is only used as a quality control parameter but it is not applied to the tropospheric ozone, as it is suggested by Smit et al. (1998). Pump efficiency correction is applied and the box temperature is measured with the thermistor in the pump hole, as recommended by the quality control team of THESEO, in both stations. The NDSC quality control and quality assurance requirements are fulfilled, and data is routinely archived into the NILU database.

The ozone soundings where performed under daily alert messages e-mailed by the Service d'Aéronomie (CNRS). Measurements were normally decided when the STJ or high PV layers were close to Tenerife station, based on forecasts provided by the KNMI.

Meteorological analysis are performed with the 0.5ºx0.5º INM's High Resolution Limited Area Model (HIRLAM). The analysis of surface pressure, atmospheric temperature, wind, and humidity is based on an optimum interpolation scheme, which has been derived from the one developed at the European Centre for Medium-range Weather Forecasts (ECMWF). The HIRLAM model is run on INM's Cray C-94 and the analysis is performed at the Izaña Observatory with a McIDAS (Man computer Interactive Data Access System) station real time connected to the Cray.

Quasi-isentropic mixing across the STJ are studied between 300 K and 400 K using ozone and water vapor as tracers of the exchanges. The Brunt-Väisäla frequency (BVF) is defined by the potential temperature gradient

$$N^2 = \frac{g}{q}\frac{dq}{dz}.$$

This is the natural frequency of baroclinic gravity waves in a continuously stratified fluid. Negative values indicate instability. This parameter is also used to identify layers result of STE processes. The thermal tropopause [WMO, 1957] is used in this work.

Daily STJ's geographical positions were determined detecting the maximum wind speed on HIRLAM analysis at 330 K, 340 K and 350 K in the study region bounded by (65ºN, 66.5ºW) and (15ºN, 30ºE). Only wind speeds greater than 35 ms^{-1} were considered. Averaged positions for each longitude-degree of the STJ was obtained for February, March and April 1999, respectively.

In February the STJ was located far away to the south of the Canary islands (Figure 1), between 340 K and 350 K (10,500 m - 12,400 m altitude), with a mean wind speed of 45 ms^{-1} at 16ºW. In March a very active STJ of 50 ms^{-1} mean wind speed is found at 350 K, very close but still to the south of the Canary islands. In this month is when the STJ is strongest and when it might significantly contribute to irreversible mixing between the stratosphere and troposphere. For this reason the intensive ozone campaign is centered in this month. In April the mean position of the STJ is almost above to the Canaries, showing a significant scattering. The STJ is located some days to the north of the Canaries. In this month the STJ weakens (40 ms^{-1} mean wind speed at 16ºW) significantly.

3. Case Analysis: March 25th and March 26th

The case analysis March 25th-26th is chosen because it is quite representative of the STE processes associated to the STJ. On March 25th the STJ is located just above the Canaries, as it can be seen in Figure 2. The core of the jet is located between 9.6 km and 12.2 km with wind speeds greater than 60 ms^{-1} from W-SW direction. The water vapor METEOSAT image shows a dark band indicating a general subsidence in this region while high water vapor (white band) coincides with a cirrus band. A potential vorticity (PV) barrier separating the lower mid-latitude stratosphere from the subtropical upper troposphere is found at the position of the STJ. The first tropopause (middle latitude tropopause) is not detected on March 25th (12 GMT) neither on March 26th (00 GMT).

A threshold value of 160 ppbv has been determined averaging all the ozone soundings performed in this campaign, as it is indicated hereafter. This value corresponds to the ozone found at the averaged first-tropopause level, indicating a lower-limit of stratospheric ozone concentrations. As it can be seen on Figure 3 a high ozone (O_3>160 ppbv) layer is present between 330 K and 335 K. In this layer high BVF values, and a ratio of 99 ppbv/PVU are found, what suggests a downward transport of ozone rich air masses.

In Figure 4 Latitude-longitude/pressure cross sections of potential vorticity (PVU), potential temperature (K), wind velocity (ms^{-1}) and RH (%), along a direction perpendicular to the STJ axis determined by the coordinates (35ºN, 23ºW) and (20ºN, 8ºW), are depicted. The jet core is located in the tropopause jump that separates the lower mid-latitude stratosphere from the upper subtropical troposphere. Beneath the jet core a strong tropopause fold is observed with the isentropes plunging within the subtropical troposphere. A tongue-like of dry air indicates a stratospheric intrusion between 315 K and 335 K. The ozone peak observed in the ozone vertical profile (Figure 3) corresponds to the upper limit of this intrusion (around 300 hPa).

Above this peak very low ozone values are found between 340 K and 370 K (Figure 3), with O_3/PV ratios of about 30 ppbv/PVU. In this range negative values of BVF are recorded indicating unstability. The vertical cross section of RH (Figure 4), shows an entrance of humid subtropical upper-tropospheric air into the lower stratosphere that explains the observed low ozone values in the stratosphere (86 ppbv at 355 K). Even just above 380K a low ozone and negative BVF layer is also observed.

On March 25th the STJ accelerates over Tenerife. Therefore, a thermally direct vertical circulation results in the entrance region. In this transverse circulation there must be ascent under regions of upper-level divergence, within the right entrance of the jet. Likewise, where the convergence overlies divergence, we find descent within the left entrance of the jet. This direct transverse ageostrophic circulation can be deduced from the different panels of Figure 4.

On March 26th, 1999, the STJ moves southward, being located its core at 25ºN, as it can be seen in Figure 5.The first tropopause is found at 11.1 km (229 hPa, 342 K) with 5.1 PVU and 357 ppbv (Figure 6) Just below the tropopause, a layer of high ozone (near 360 ppbv at 340 K) and high O_3/PV ratio (70 ppbv/PVU). This layer is caused by an intrusion of stratospheric air into the subtropical troposphere. The ozone vertical profile is quite similar to that of March 25th, but the ozone values between 340 K and 370 K are slightly higher. Furthermore, the layer of low ozone and negative BVF values at 380K has disappeared, indicating that the subtropical troposphere injection into the mid-latitude stratosphere is weaker when the STJ moves southward.

Latitude-longitude/pressure cross sections of different meteorological parameters performed at different longitudes (from 30ºW to 0º), for March 25th and 26th show quite similar results (not shown here). A tropopause fold associated to the STJ and the corresponding intrusions are observed: subtropical tropospheric air into the lower mid-latitude stratosphere and mid-latitude stratospheric air into the upper subtropical troposphere. This fact indicates that the STE processes associated to the STJ take place along a region of thousands of kilometers long.

Most of the STJ analysis performed during this intensive campaign show a tropopause enfolding similar to that observed on March 25th and 26th case study.

4. STE processes related to the geographical position of the subtropical jet stream

Baray et al. (2000) show high ozone layers in the middle and upper subtropical troposphere above La Reunion Island (21ºS) in July, result of stratospheric intrusions associated to the STJ. In wintertime the Southern Hemisphere STJ is located at its most southward position. The results presented in this work correspond to the opposite situation (the jet is located to the south of Tenerife). In this intensive campaign all the ozone soundings were performed when the STJ was located to the south or above the Canaries, so mainly tropospheric intrusions into the lower mid-latitude stratosphere are expected to be observed.

In Figure 7 the evolution of ozone mixing ratio between 7 km and 16 km over Tenerife during the intensive ozone sounding campaign is depicted. In the same figure the differences between the latitude of the STJ's core at 16ºW and the latitude of Tenerife (28ºN), herefater refered as “latitude differences” for each day, are indicated (green line), as well as the tropopause height (white line). Negative latitude differences indicate that STJ is located at the south of Tenerife. The tropopause is located during the whole campaign between 12 km and 13 km. A good agreement is found between the ozone and the position of the STJ. As the STJ moves northward and it is located near Tenerife, lower ozone values are recorded in the lower stratosphere (above 13 km.). Conversely, layers of relatively high ozone (> 160 ppbv) are observed in the upper troposphere, between 9 km and 12 km. This fact confirms the persistent role played by the STJ in the transport of subtropical tropospheric air into the lower mid-latitude stratosphere. These results agree Timmis et al. (1999) who found a potential vorticity layering between 360K and 380K, which lies above and to the north of the STJ wind maxima (350K), in the latitude band of 30N - 40N.

When the jet is located almost above Tenerife, relatively high ozone layers appear in the upper troposphere just below the tropopause (between 11 and 12 km), indicating stratospheric intrusions in the subtropical upper troposphere.

In order to evaluate this influence of the STJ on the upper troposphere and lower stratosphere above Tenerife, three different sets of ozone soundings have been selected and averaged. An ozone, relative humidity and BVF mean vertical profile of all the ozonesoundings performed during this campaign will be used as a reference of the different meteorological conditions found in this period. A second averaged vertical profile is obtained with those ozone sondes launched when the STJ was clearly located to the south of the Canaries (16 cases). The third averaged profile corresponds to those ozone sondes performed when the STJ's core was above the Canaries ± 2º latitude (6 cases). Upper-level troughs and cut-off lows frequently disturb the STJ. These events mask the STE processes associated to steady STJ's. For this reason only vertical profiles corresponding to those days when the STJ is not affected by other meteorological systems in a broad region around the Canaries have been considered.

In Figure 8 the above described three averaged profiles are depicted. The mean vertical profile corresponding to all the ozone soundings show a typical shape with increasing ozone as we ascend, with ozone values of 160 ppbv in the first tropopause. The first averaged tropopause is found at 340 K (11.7 km). When the STJ is located to the south of the Canaries the vertical profiles is completely different. Low ozone values (lower than 160 ppbv) are found between 335k and 350 K and at 370 K. These low ozone values correspond to cross-isentropic transport of subtropical tropospheric air into the mid-latitude stratosphere. The averaged vertical profile corresponding to the STJ over Tenerife shows also low ozone between 345 K and 355 K, and relatively low ozone at 380 K. Indeed relatively high RH values can be observed at 345 K. The integrated ozone between the tropopause level and 16 km is 21.4 DU in the averaged profile of all ozonesoundings performed during the campaign. When the STJ is located at its most northern position, near the Canaries, this amount can be lower than 15 DU. Conversely rich-ozone layers are found in the upper troposphere, just beneath the tropopause, indicating stratospheric intrusions associated to the tropopause enfolding.

5. Conclusions

Meteorological analysis focused on the STJ and information provided by ozone sondes reveal that the tropopause enfolding associated to the STJ is significant and persistent, appearing in all the analyzed steady STJ cases.

A detailed description of the STE processes associated to the SJT has been provided with the case analysis performed on March 25th and 26th.

Evidences of subtropical upper tropospheric ozone-poor air intrusions into the mid-latitude lower stratosphere are shown in this work. This STE process is well observed when the STJ is located above or near to the south of the Canaries. Injections of mid-latitude stratospheric air into the subtropical troposphere (just beneath the tropopause) are observed when the STJ is located above the Canaries. The STJ disturbs significantly the upper troposphere and the lower stratosphere between 9 km and 16-km altitude.

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Figure captions:

Figure 1; Monthly averaged position of the STJ at 350 K, with the corresponding standard deviation for February, March and April 1999, respectively.

Figure 2; (a) METEOSAT water vapor image plus wind (wind arrows and isotachs in KTS) at 325 K; (b) the same METEOSAT image plus potential vorticity (PVU) at 335K for March 25th, 1999.

Figure 3; Vertical profile of ozone (ppbv) and Brunt-Väisäla frequency (s^{-2}) between 300 K (3.2 km) and 400 K (16.5 km) for March 25th, 1999.

Figure 4; (a) Latitude-longitude/pressure cross section of potential vorticity (PVU) and potential temperature (K) along the direction indicated in the map for March 25th, 1999 (12 GMT). The chosen direction is perpendicular to the STJ axis over Tenerife. (b) Latitude-longitude/pressure cross section of wind speed (m s^{-1}) and the potential vorticity (PVU). (c) Latitude-longitude/pressure cross section of relative humidity (%) and potential vorticity (PVU).

Figure 5; The same as Figure 4 but for March 26th, 1999 (12 GMT).

Figure 6; The same as Figure 3 but for March 26th, 1999.

Figure 7; Evolution of ozone mixing ratio between 10 km and 18 km over Tenerife during the intensive ozone sounding campaign (from February 1st to April 23rd 1999). The green line represents the relative position of the STJ's core to Tenerife (latitude differences).

Figure 8; (a) Averaged vertical profile of ozone, relative humidity and BVF of all the ozonesoundings performed during the intensive ozone sonde campaign; (b) averaged vertical profile when the STJ is located to the south of the Canaries; (c) mean vertical profile when the STJ is over Tenerife.