Atmos. Chem. Phys. Discuss., 5, 101–129, 2005
www.atmos-chem-phys.org/acpd/5/101/
SRef-ID: 1680-7375/acpd/2005-5-101
European Geosciences Union

Atmospheric Chemistry and Physics Discussions

Deep stratosphere-to-troposphere transport (STT) over SE Europe: a complex case study captured by enhanced ^{7}Be concentrations at the surface of a low topography region

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Received: 15 September 2004 – Accepted: 7 December 2004 – Published: 10 January 2005

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Abstract

In this study we present a complex case study of a Stratosphere-to-Troposphere Transport (STT) event down to the surface of a low topography region in Northern Greece, during the second fortnight of March 2000. During this event our surface station at Livadi (23°15 E/40°32 N, 850 m a.s.l.), was influenced by very different synoptic systems developing over Eastern Europe, N. America and the N. Atlantic, the last one evolving to a cut-off low over France/Spain. This is the first study, to our knowledge, that presents a down to the surface STT event in the eastern Mediterranean. The intrusion is primarily captured with the use of the cosmogenic radionuclide ^{7}Be, which increased to 9.07 mBq m^{-3} and 9.37 mBq m^{-3} on 30 and 31 March 2000, respectively. A ^{7}Be concentration of around 8 mBq m^{-3} recorded during parallel measurements at Thessaloniki (20 m a.s.l.) gives strong evidence that air of stratospheric origins has even gone down to sea level. A rapid increase of 10–15 ppb is also observed in the surface ozone concentration on 31 March 2000. The relative increase of both tracers is consistent with a volume fraction of stratospheric air at the surface of about 5%, but the substantial increase in ^{7}Be flags more clearly the event. Trajectory analyses, in conjunction with the evolution of the synoptic situation described by potential vorticity maps, are used for the exact identification of the different intrusions and the attribution of each intruding parcel of stratospheric air to a certain filament of high PV. Finally, the persistency of the stratospheric layers in the troposphere is another interesting point of this case study. The vast majority of the trajectories spent 7–10 days in the troposphere before reaching the surface at Livadi station.

1. Introduction

Stratosphere to Troposphere Transport (STT) events have been widely studied over the last four decades using both observational case studies and numerical models, as reviewed by WMO (1986), Davies and Schuepbach (1994), Holton et al. (1995), and

Stohl et al. (2003). These STT events, associated with mid-latitude tropopause folds in the extratropics, are characterized by tongues of anomalously high potential vorticity (PV), high ozone, and low water vapour mixing ratio, which may be stretched out into elongated filaments, or roll up to form isolated coherent structures containing high PV air (cut-off lows) (Holton et al., 1995).

Although, in principle, the air remaining in the fold in the upper troposphere re-enters the lower stratosphere towards the jet exit region (Danielsen, 1968), stretching of stratospheric intrusions to even finer scales and deeper into the troposphere leads to irreversible transport as the stratospheric air is getting mixed with the surrounding air. Mixing has been attributed to turbulence, which can destroy the filaments physically (Shapiro, 1980) and radiation, which can dissolve the PV anomalies and have an implication on the occurrence and strength of turbulence (Forster and Wirth, 2000). Furthermore, fragmentation of the intruded filaments into a train of stalactite features is an irreversible process that isolates each feature on an isentropic surface and thereby provides the time and the surface area of the interface between the two air masses for effective subsequent mixing (Appenzeller et al., 1996). Hence, deep and intense intrusions of stratospheric air penetrating down to lower tropospheric levels, or even to the surface, are the potential seat for large stratosphere-to-troposphere transport and they are more relevant than the shallow ones for atmospheric chemistry as they lead to composition changes.

The number of case studies capturing a deep intrusion event on its way down to the earth's surface, based on both measurements and modeling, is limited. Eisele et al. (1999), using lidar sounding data during a large number of STT events, found that all but a few deep intrusions reach a level of 3000 m. At high mountain peaks there is a higher possibility of an observable stratospheric influence (Stohl et al., 2000). Elbern et al. (1997), based on ten years records of ^{7}Be, ozone, and relative humidity, found that deep stratospheric intrusions affect Zugspitze, Germany (2962 m a.s.l.) during 5% of the time while they affect Wank, Germany (1776 m a.s.l.) less than 2.5% although the absolute frequency of deep stratospheric intrusions depends critically on the specification of threshold values for ^{7}Be, ozone, and relative humidity (Stohl et al., 2000).

Beyond the depth of a STT event and the rareness of deep stratospheric intrusion events down to the earth's surface, another important aspect is the lifetime of the filamentary structures of stratospheric origin in the troposphere, which is limited by radiation and turbulence as mentioned above. Bithell et al. (2000) reported the presence of ozone layers originating from the stratosphere that can persist for 10 days in the troposphere and these structures cascade down to smaller scales until they are mixed with the surrounding air.

The generation of filaments during deep STT events has been modeled with relative success as evidenced by modeling studies with mesoscale models (Schuepbach et al., 1999a, b), with Langrangian transport models (Stohl et al., 2000; Cristofanelli et al., 2003; Zanis et al., 2003a; Roelofs et al., 2003), with chemistry-climate models (Kentarchos et al., 1999, 2000; Cristofanelli et al., 2003; Roelofs et al, 2003), with chemistry-transport models (Cristofanelli et al., 2003; Roelofs et al., 2003), and recently with the ECMWF (European Centre for Medium-Range Weather Forecasts) atmospheric model which uses operationally a chemical tracer in a weather forecast model (Zanis et al., 2003a). Nevertheless, the decay of the filamentary structures is completely non-physical in the models and a correct quantification of mixing of stratospheric air with tropospheric air during an intrusion is still an unsolved problem (Stohl et al., 2003).

In this study, an intrusion event that brought stratospheric air down to the surface at Livadi, Greece (850 m a.s.l.) during the second fortnight of March 2000, is presented. The specific period raised our interest because of the enhanced surface concentrations of the cosmogenic radionuclide ^{7}Be measured at Livadi (23°15 E/40°32 N), Greece. ^{7}Be concentrations at surface levels fluctuate normally around 3.5 mBq m^{-3} (e.g. Dutkiewicz and Husain, 1985; Brost et al, 1991) and thus the presence of even a small fraction of stratospheric air at the surface can cause an important increase (values >8 mBq m^{-3}) in the measured ^{7}Be, since its maximum production is found in the stratosphere. Information concerning the production, transport and typical values of ^{7}Be are given in Gerasopoulos et al. (2001) and references therein. As it will be shown, the presence of stratospheric air at the surface is attributed to the advection of persistent layers (9–10 days) of stratospheric origin, intruded into the troposphere more than a week prior to the observation. Furthermore, there is a rather limited number of STT events captured and described in the eastern Mediterranean, which is a region of great interest. On the one hand it is located at a "photochemical crossroads" with enhanced levels of tropospheric ozone exceeding the ozone phytotoxicity EU limit (32 ppbv) throughout the year and the human health protection limit (55 ppbv) most of the time during summer (Zerefos et al., 2002), and on the other hand it lies southwards of the typical position of the polar front jet at the ending point of a path way characteristic of stratospheric intrusions (Stohl et al., 2000; Gerasopoulos et al., 2001; Galani et al., 2003).

2. Site description and instrumentation

Measurements of ^{7}Be and surface ozone concentrations have been conducted at Livadi (LVD) (23°15 E/40°32 N) during the STACCATO EU project. Livadi is a semi-elevated, rural village located on the eastern peak of Mt. Hortiatis, at an elevation of 850 m a.s.l. It is situated at a distance of 50 km from Thessaloniki. It is placed over a flat region surrounded by short hills from all sides. To the north the slope drops down gradually and views Lagada and Volvi lakes whereas to the west it views Thermaikos gulf. Apart from a limited number of cars there are no other significant local sources of pollution at Livadi. Surface ozone was monitored for a period of two years (March 2000–March 2002) while daily ^{7}Be measurements were performed during alarms of forecasted intrusion events (Zanis et al., 2003a) or scheduled campaigns. For the presented intrusion event simultaneous measurements of ^{7}Be were also performed at Thessaloniki (THE) (40.63° N–22.97° E, 20 m), the major city of the area.

The sampling of ^{7}Be is carried out with the use of high volume air samplers on glassfiber filters and the ^{7}Be activity is obtained via high-resolution gamma spectrometry (Gerasopoulos et al., 2003). Surface ozone is monitored using a Dasibi 1008 RS ozone analyzer (Kouvarakis et al., 2002).

3. Observations

24-h ^{7}Be sampling was performed daily during two campaigns (6 March–23 April 1999 and 22 March–19 April 2000) at LVD. A mean value of 6±2 mBq m^{-3} was calculated from the daily concentrations during these campaigns, which is a value slightly higher than the monthly mean of March (4.2±1.4 mBq m^{-3}) and April (5.2±2.8 mBq m^{-3}) derived from a time series of ^{7}Be obtained at THE, during a full 11-year solar activity cycle (1988–2002) (Gerasopoulos et al., 2003). During the campaigns an interesting case of high ^{7}Be concentrations was isolated and thoroughly studied, in order to investigate its relation with a stratosphere-to-troposphere exchange event. After a period of heavy snow, intense atmospheric washout led to low ^{7}Be content at the altitude of LVD (<2 mBq m^{-3}) (Fig. 1), while during the following sunny days a gradual increase of the concentrations was observed. Already on 30 and 31 of March 2000 the concentrations went up to 9.07 mBq m^{-3} and 9.37 mBq m^{-3}, respectively, values well above the usual threshold of 8 mBq m^{-3} used for the identification of intrusion events (Sladkovich and Munzert, 1990; Scheel et al., 1999; Stohl et al., 2000). Simultaneous measurements at THE (20 m a.s.l.) also revealed a gradual increase of the values with a maximum of 8.2±0.7 mBq m^{-3} on 30 March, indicating that the event that influenced the concentrations at the LVD altitude has posed an effect down to sea level as well.

Daily averages of surface ozone concentrations at LVD showed no significant scatter over this period. Nevertheless, surface ozone during 31 March deviated from the March-April diurnal mean as shown in Fig. 2. A rapid increase of 10–15 ppb was observed at 05:30 (UTC) and also a second peak at 20:00 UTC is seen. Such deviations are common within the two years period of measurements and are mostly related to transport of polluted air masses from neighbor areas. The time of occurrence of the first deviation assures that no local photochemical production may have taken place and that the source of the increase has to be questioned.

Finally, using vertical profiles of relative humidity from radiosondes (Hellenic Meteorological Service) the descent of rather dry air was captured (Fig. 3). On 29 March a wide layer of air with RH<20% was observed between 5 and 8 km. During the next days, the descent of dry air reached altitudes of 3 km (on 30 March) with RH between 20–30%, and 800 m (on 31 March) covering the altitude of the LVD station. At this point, RH was on the order of 30–40% still indicating dry air masses.

4. Synoptic development

The event was well related to different stratospheric intrusions that developed over a large area between the North Pacific and East Europe, during 15–31 March 2000. In order to visualize, both spatially and in time, the evolution of the synoptic situation in combination with the intrusion events, PV charts on 290, 295, 300, 305 and 310 K were investigated. PV on the 300 K isentropic surface between 16 and 27 March 2000 is presented in Fig. 4. Dark areas (red-yellow) on the charts correspond to stratospheric values of PV (>2 PVU).

Already from 15 March 2000 a PV streamer is formed over Scandinavia and Poland (not shown here), which on 16 March is well established over the whole Eastern Europe, to the North of Greece (Fig. 4a). On 17 March it breaks up to form an isolated coherent structure containing high PV, covering an extensive area over Eastern Europe, from Scandinavia down to Greece (Fig. 4b). Henceforth, this will be called the "Eastern Europe PV streamer". At the same time, another filamentary structure is formed over the eastern frontiers between the U.S. and Canada (Fig. 4b), which will be called the "American east coast PV streamer". The "Eastern Europe PV streamer" continues to rotate until 22 March, propagating very slowly eastwards over the Black Sea (Fig. 4c–g) and then starts dissipating in the westerly flow (Fig. 4h). On 18 March the "American east coast PV streamer" has already passed to the Atlantic (Fig. 4c) before vanishing on 19 March (Fig. 4d). Moreover, on 18 March, a "hook" shaped high PV structure is situated over the eastern N. Pacific, henceforth called the "N. Pacific PV streamer" (Fig. 4c). By 20 March the "N. Pacific PV streamer" has moved eastwards forming a thin filamentary structure over the western U.S. (Fig. 4e) and then it attenuates on 21 March (Fig. 4f). On 22 March a new PV streamer is located over the central N. Atlantic which will be referred to as the "N. Atlantic PV streamer" (Fig. 4g). On 23 March a "hook" shaped pattern has formed south of Iceland (Fig. 4h), which then moves slowly eastwards where it almost stays for four days, from 24 to 27 March, over the UK and Western Europe (Fig. 4i–l). On 28 March it breaks up to form an isolated pool of high PV over western France and northern Spain and then it gradually dissipates in the westerly flow the following days (not shown here). There is also a second filamentary structure of high PV following the "N. Atlantic PV streamer" which is located over North America on 23 March (Fig. 4h) and then slowly propagates eastwards with the easterly flow over the Atlantic Ocean till 27 March, before dissipating (Fig. 4i–l). A final structure of high PV is situated over the Baltic countries on 24 March (Fig. 4i) moving southeasterly during the next days and gradually dissipating on 26 March (Fig. 4k). As it will be shown in Sect. 5 via the 10-days back trajectory analysis, the four filamentary structures of high PV, namely "Eastern Europe PV streamer", "American east coast PV streamer", "N. Pacific PV streamer" and "N. Atlantic PV streamer" are all responsible and can be considered as the source regions for the diagnosed STT event down to the surface at our observation site.

The described evolution of the synoptic situation via the ipv charts is well related to the presence of characteristic patterns of geopotential height. Thus, with the use of NCEP 500 hPa geopotential height charts (source: http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html) (not shown here), the "Eastern Europe PV streamer", for instance, is clearly connected with an upper level trough that developed over Eastern Europe on 15 March. It detached from the main flow on 17 March, forming a cut-off low over the area until 21 March, and finally reconnected slowly to the main flow after 22 March. Similar patterns of steep pressure gradients induced by the presence of either a dipole of high and low pressure (upper level ridge and trough, respectively) or cut-off lows, accompany also the other PV streamers over the N. Pacific/America and N. Atlantic mentioned above.

5. Trajectory analysis

A number of tracers such as ^{7}Be, O_3 and RH have given the first strong evidence for the presence of stratospheric air almost down to the surface. Description of the synoptic situation during the previous days has also led to patterns that are frequently related to STT events. A final verification of the stratospheric origin of the event is given via trajectory analyses. Trajectories were calculated from 6-hourly ECMWF analysis fields with the trajectory tool LAGRANTO (Wernli and Davies, 1997). For the needs of the specific event the following methodology has been adopted: 10-day back-trajectories that originate in the stratosphere (PV>2 pvu), descend into the troposphere and end within a box around Thessaloniki have been calculated. The box was defined between 20–26° E and 38–43° N with a height of 800–1000 hPa. Trajectories were calculated for the period 25–31 March 2000, each day at 00:00, 06:00, 12:00 and 18:00 UTC, a period during which the ascending branch of the ^{7}Be values is seen (Fig. 1) and the descending layers of dry air (Fig. 3) have been observed.

With this criterion, a significant number of trajectories have been identified that show a deep STT down to the surface influencing the area during the period 25–31 March 2000.

Before presenting the detailed analysis of the trajectories, definitions for terms used henceforth will be given. The term “intrusion” will refer to the crossing of the 2 pvu surface by each trajectory, “intrusion time” and “intrusion surface” are defined as the time and the isentropic surface, respectively, where each STT trajectory crosses the tropopause. As “intrusion duration” we shall refer to the time between the “intrusion time” and the trajectory starting time (t=0), expressing the time needed for each trajectory to reach the Livadi area after crossing the 2 pvu surface. Finally, the term “stratospheric source" of the trajectories defines the area in the stratosphere from where trajectories originate and it is calculated as the coordinates of the minimum pressure along each trajectory.

During the period 15–27 March 2000 about 200 trajectories of stratospheric origin that intruded into the troposphere, reaching our station between 25 and 31 March 2000, were calculated, according to the criterion mentioned in the first paragraph of this section. More than 60% of them intruded on 19 and 20 March whereas an equal percentage of around 20% intruded the days before and after these two "hot spot" days.

With the evolution of the filamentary structures of high PV already presented in Sect. 4 and the main PV streamers pointed out, it is possible to identify the locations of the tropopause crossings. These locations are illustrated on ipv maps produced on isentropes that are characteristic for a certain group of STT trajectories (mean potential temperature (PT) of a group of trajectories). In Fig. 5 a selection of ipv maps on different isentropes are shown and two surfaces are overlayed: the "intrusion surface" (dashed black line) and the "stratospheric source" (solid green line). At this point, it has to be noted that the area of each of the above mentioned surfaces is not proportional to the number of trajectories related to this area and it just represents the spatial limits of the intrusions.

During 15–18 March 2000 the vast majority (80%) of the intrusions takes place over Eastern Europe. The mean potential temperature (PT) of the trajectories is 293±4.7 K and the mean relative humidity (RH) is 34±12% (the number after ± is the standard deviation of the mean). The rest of the intrusions take place to the east of Canada over the N. Atlantic mainly during 15–17 March. The mean PT of these trajectories is 298±3.5 K and the mean RH is 25±2%. Both intrusion surfaces are illustrated on the 295 K ipv map of 18 March 2000 at 12:00 UTC and are denoted by letters A and B (Fig. 5a). It is evident that the intrusion surface A is linked to the "Eastern Europe PV streamer", while intrusion surface B is related with the "American east coast PV streamer", both described in Sect. 4.

On 19 March, one of the days with increased number of intruding trajectories, the

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intrusions are confined to Eastern Europe and the intrusion surface C is linked to the "Eastern Europe PV streamer" (Fig. 5b). The mean PT of these trajectories is 291±2.5 K and the mean *RH* is 36±13%. Instead of the 290 K which is closer to the mean PT of the trajectories, the 295 K isentrope is used for the ipv map of 19 March 2000 at 12:00 UTC, since it could better reveal the connection with the "Eastern Europe PV streamer".

On 20 March, the second day with increased number of intruding trajectories, the strong influence of the "Eastern Europe PV streamer" is still evident (Fig. 5c) since the 84% of the STT trajectories during this day originate over this area. The trajectories which intrude exactly near the PV streamer have a mean PT of 291±2.1 K and a mean *RH* of 41±11%, while a second fragment of the intrusion surface E mostly extending over N. Italy, has a mean PT of 302±1.7 K and a mean *RH* of 18±3%. The rest of the intrusions take place over N. Canada (intrusion surface D) (Fig. 5c), the mean PT of these trajectories is 301±4.9 K and the mean *RH* is 29±8%. This intrusion is related to the evolution of the "N. Pacific PV streamer" even though the location of the intrusion surface D does not provide clear proof. Nevertheless, things become clearer on 21 March when the intrusion takes place only over the western parts of the U.S. and Canada as denoted by intrusion surface F, in conjunction with the "N. Pacific PV streamer" (Fig. 5d). The mean PT of these trajectories is 303±2.6 K and the mean *RH* is 26±5%.

During 22–24 March, the intrusion surface G is linked to the "N. Atlantic PV streamer" as shown in Fig. 5e, whereas the stratospheric source is located over Greenland. These trajectories have a mean PT of 292±2.2 K and a mean *RH* of 36±4%. Finally, during 25–27 March the intrusion surface H is situated over the Scandinavian Peninsula and the UK, related again to the "N. Atlantic PV streamer" which has started to detach from the main flow (Fig. 5f). The mean PT of these trajectories is 296±1.5 K and the mean *RH* is 30±5%. Once more, the stratospheric source is located over Greenland.

Linking each STT trajectory to one of the intrusions defined above and taking into account the PV streamer which each intrusion surface is related to, reveals that almost 70% of the trajectories that reached the Livadi station were linked to the "Eastern Europe PV streamer" that was maintained over the area during the period 15–20 March. The next most important PV streamer that influenced our measurements was the "N. Atlantic PV streamer" during 22–27 March (14% of the trajectories), then the "N. Pacific PV streamer" during 20–21 March (11% of the trajectories) and finally the "American east coast PV streamer" during 15–17 March (5% of the trajectories).

Concerning the "intrusion duration" the analysis has revealed that for most of the intrusions the air masses needed between 6 and 10 days after crossing the 2 pvu surface to reach the Livadi station. More specifically, the intrusion duration related to the "Eastern Europe PV streamer" ranged between 6 and 10 days (7.8 days mean value), with the exception of those trajectories intruding over N. Italy on 20 March that were much faster. The respective intrusion duration ranged between 4.5 and 7.5 days (6.2 days mean value) and the fact that these air masses are drier (18% RH instead of 41% RH) may be also related to their different intrusion duration.

Intruding air masses linked to the "N. Atlantic PV streamer" spent 7 to 9 days (7.8 days mean value) into the troposphere before descending down to the surface, whereas those trajectories that crossed the tropopause over the Scandinavian Peninsula and UK at a later stage of the streamer's evolution, had intrusion durations between 3.5 to 5.5 days (4.4 days mean value). The fact that the specific PV structure changed its slow eastwards motion to the south creating an isolated pattern over western France and northern Spain may have accelerated the descent. Common intrusion durations are found for the air masses linked to both the "N. Pacific PV streamer" and the "American east coast PV streamer" ranging between 8 and 10 days (9 days mean value).

The influence of the trajectories reaching our site was almost balanced during the period 25–31 March with a maximum of 22% of the trajectories reaching the site on 26 March and a minimum of 4% on 30 March, as shown in Fig. 6. The maximum number of trajectories on 26 March coincides with the maximum ^{7}Be increase of 2.24 mBq m^{-3}

between the same day and the day after (Fig. 1). It is clearly evident that during 25–29 March the "Eastern Europe PV streamer" has mainly influenced the STT event at our station, with only a small fraction of trajectories intruding over the east coast of the U.S. After 28 March the "N. Pacific PV streamer" also induces a certain number of trajectories, whereas the intrusions related to the "N. Atlantic PV streamer" becomes dominant on 31 March when also the maximum ^{7}Be concentration is measured.

The resulting trajectories are shown in the 3-D diagrams of Fig. 7, after separating them according to the PV streamer they were related to. Thus, in Fig. 7a those STT trajectories induced by the "Eastern Europe PV streamer" are illustrated and in Figs. 7b and c the respective trajectories for the "N. Pacific" plus "American east coast" and the "N. Atlantic" PV streamers. These diagrams provide information for both the geographical position and the altitude of the air parcels on their way down to our station. In general, the trajectories from the "Eastern Europe PV streamer" originated from altitudes with minimum pressure 378±39 hPa and went down to 947±52 hPa, the ones from the "N. Pacific" and the "American east coast" PV streamers descended from 325±28 hPa and 303±29 hPa down to 882±39 and 871±38 hPa, respectively, and finally the trajectories related to the "N. Atlantic PV streamer" begun their downward motion from 327±42 hPa and reached a level of 890±44 hPa.

6. Summary and discussion

A complex STT event that took place during March 2000 and influenced Northern Greece has been studied in detail in this paper. A number of key points concerning different characteristics of the event make it particularly interesting.

First of all, it is the first study, to our knowledge, that presents a down to the surface STT event in the eastern Mediterranean, at a region with low topography. This feature is revealed both by surface measurement and trajectory analyses. Surface measurements of ^{7}Be at Livadi (850 m a.s.l.) well exceeded the threshold of 8 mBq m^{-3} on 30 and 31 March 2000. A maximum value of around 8 mBq m^{-3} measured at Thessaloniki (20 m a.s.l.) on 30 March, indicates that the tongues of stratospheric air have even gone down to sea level. A more attenuated stratospheric signal has been added to the surface ozone, illustrated as a 3–5 h increase of 10–15 ppb during times when no local photochemical production may have occurred, So, in this case study, it was mainly ^{7}Be with its substantial increase from tropospheric background values that flagged the intrusion of stratospheric layers down to the earth's surface whereas observed ozone values indicated an ozone increase which can be considered typical for our site when transport patterns change and comparable with the diurnal ozone variability.

An attempt was made to evaluate the observed values of both tracers (O_3 and ^{7}Be) at our site by means of the mixing that takes places between stratospheric and tropospheric air, assuming a typical volume fraction of stratospheric air at the surface R=5% (Follows and Austin, 1992; Zanis et al., 2003b). Thus, if for a tracer X a stratospheric and a tropospheric value X_{str} and X_{trop}, respectively, are considered, then the measured value X_{meas} down to surface should be given by the following simplified equation, $X_{meas}=X_{str}\cdot R+X_{trop}\cdot(1-R)$. Let us assume a stratospheric value for ^{7}Be equal to 100 mBq m^{-3} which is within the range of lower-stratospheric ^{7}Be levels (Dibb et al., 1994). Taking into account the mean of Marches (4.2±1.4 mBq m^{-3}) and Aprils (5.2±2.8 mBq m^{-3}) at Thessaloniki during 1988–2002 (one 24-h sampling per month), and the average daily concentration from 23 March to 26 March (Fig. 1), then a tropospheric value of 4.5 mBq m^{-3} can be applied. For R=5% then a value of 9.3 mBq m^{-3} is expected down to surface which coincides with the values measured at LVD on 30 and 31 March 2000. For ozone, a mean value of 43.5 ppb is measured during 00:00–05:40, just before the increase possibly related with the intrusion, which is used as the tropospheric value. Assuming, a lower-stratospheric value of 250 ppb based on the ozone annual mean between 200 hPa and 250 hPa from Logan climatology (Logan, 1999), for the grid 52° N–60° N/17.5° W–12.5° W which is a typical source region for stratospheric intrusions reaching SE Europe (Galani et al., 2003) and the same volume fraction of stratospheric air at the surface, an increase of 10 ppb is expected. Indeed, a mean value of 53.8 ppb is measured during 05:50–11:00 with values ranging between 50–

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57 ppb. Hence, we get a rather consistent relative increase of both tracers at our site assuming the same volume fraction of stratospheric air at the surface. However, the use of ^{7}Be as an index of stratospheric air should be particularly noted as it flags more clearly the intrusion of stratospheric air down to the surface even if it is aged and persistent. The most important limitation of ^{7}Be serving as a stratospheric index is the wet scavenging of the carrying aerosols (Feely et al., 1989; Zanis et al., 1999).

The second interesting feature of this case is the fact that our station was influenced by very different synoptic systems within a time period of a few days and that during some days the influence was simultaneous. Four main patterns of high PV that induced the intruding air parcels of stratospheric origins have been identified, as described in full detail in Sects. 4 and 5. The most persistent system that was responsible for the gradual enhancement of ^{7}Be concentrations during 25–29 March was the "Eastern Europe PV streamer". However, the maximum ^{7}Be concentrations are found when trajectories indicate the influence of the "N. Atlantic PV streamer", pointing to the role of the low pressure systems formed over Iceland, known as "Icelandic lows", and in agreement with the pathway of high ^{7}Be concentrations to Greece found in previous studies (Gerasopoulos, 2001).

Each pattern of high PV values had more or less its own special characteristics. Thus, in the case of the "Eastern Europe PV streamer", both the intrusion surface and the stratospheric source are well coinciding with the isolated PV streamer, indicating that an almost vertical initial movement took place. As shown in Fig. 7a, three or four downward paths were mainly followed by stratospheric air parcels. One of them has initially been redirected over N. Italy before descending further down over N. Greece while the rest form a vertical current that brought stratospheric air down to the surface. More gradual descent of stratospheric layers is observed in Fig. 7b, for trajectories originating over the N. Pacific/N. America, whereas the majority of the trajectories from the "N. Atlantic PV streamer" (Fig. 7c) followed a downward motion from Greenland to England down to 800 hPa, then an ascending loop is formed up to 500 hPa before they start going down again.

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Trajectories related to the “N. Pacific” and the “American east coast” PV streamers were the driest, with RH 28±7% and 27±3%, respectively, while the trajectories from the “Eastern Europe PV streamer” had a mean RH of 36±13% and those from the “N. Atlantic PV streamer” 33±5%. Within the latter two systems there were trajectories with special characteristics mainly related to their particularly low intrusion duration. Thus, the trajectories that circled over N. Italy were faster in average than the rest of the trajectories related to the “Eastern Europe PV streamer” during the same day (6.2 days instead of 7.8 days) and moreover they were considerably drier (18±3% instead of 41±1%). The trajectories that intruded over Scandinavia were drier than the rest of the trajectories from the “N. Atlantic PV streamer” (30±5 vs. 36±4 %), and descended to the surface at Livadi faster than most of the other examples in this case study (4.4 days on average).

The correlation of the time that the trajectories have spent in the troposphere with their mean RH reflects the mixing that the air masses of stratospheric origin experience with the ambient tropospheric air. Thus, excluding the trajectories from the “N. Pacific” and the “American east coast” PV streamers, which were in the total much drier, and also excluding 10% of the RH values and 20% of the PT values that were detached from the rest, a scatter plot of the mean relative humidity and potential temperature of each trajectory versus intrusion duration was created (Fig. 8). It is obvious that the longer the air mass has spent in the troposphere the less dry it remains and at the same time a decline in its mean potential temperature takes place. From the slope of the regression lines it comes out that for each additional day in the troposphere a trajectory experiences an increase of 7.8% in its mean RH and a drop of around 1 K in its mean PT.

Finally, the persistency of the stratospheric layers in the troposphere is worth noting. Apart from the trajectories from Scandinavia and those that traveled over N. Italy which were relatively faster, the rest of the trajectories spent 7–10 days in the troposphere before reaching the surface.

Acknowledgements. One of the authors, E. Gerasopoulos, was kindly supported by the Greek

State Scholarship Foundation under contract No. 2955 (32nd program, 1998–1999).

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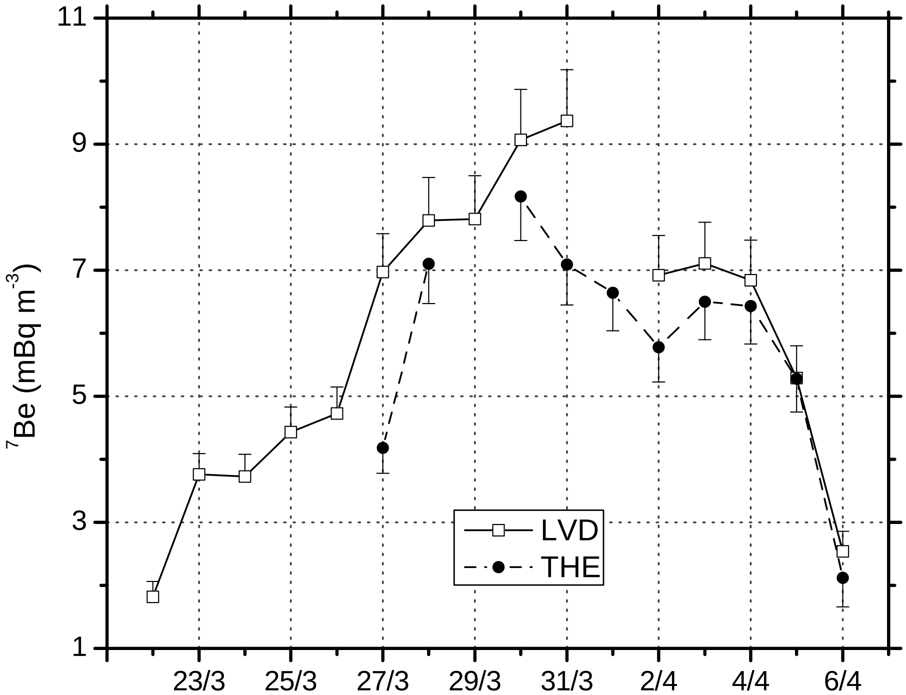

Fig. 1. ^{7}Be daily concentrations for the period 22 March 2000–6 April 2000 at two sites of 50 km distance, **(a)** Livadi (LVD) 850 m a.s.l. (squares) and **(b)** Thessaloniki (THE) 20 m a.s.l. (black spots).

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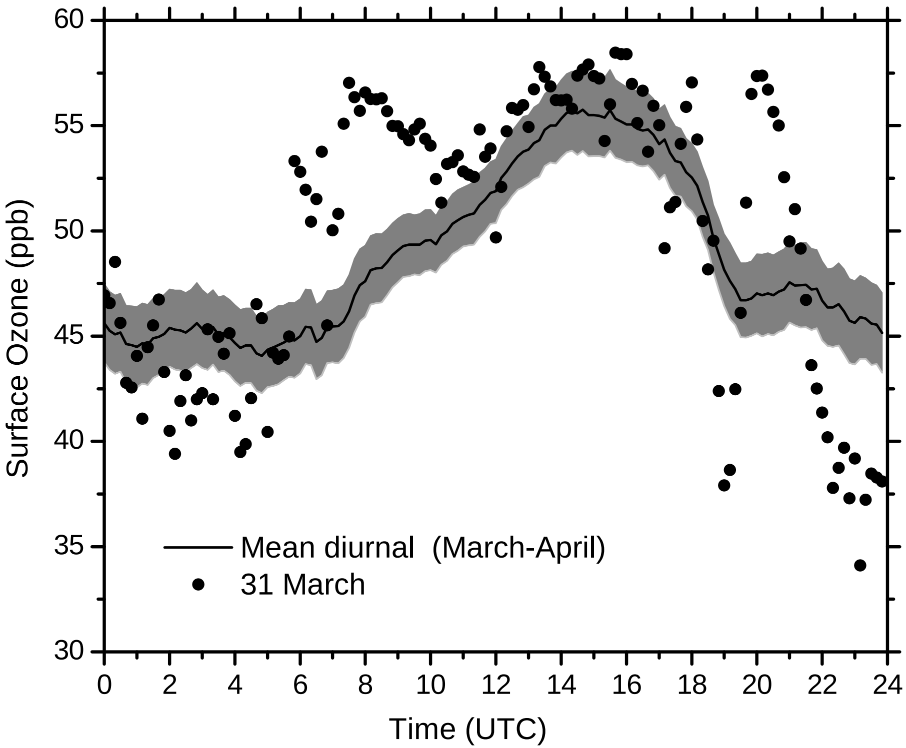

Fig. 2. Surface ozone diurnal cycle (hourly means) on 31 March 2000 at Livadi (black spots). The solid line represents the mean diurnal cycle of surface ozone concentrations for March and April 2000, whereas the dark area corresponds to the 95% confidence level.

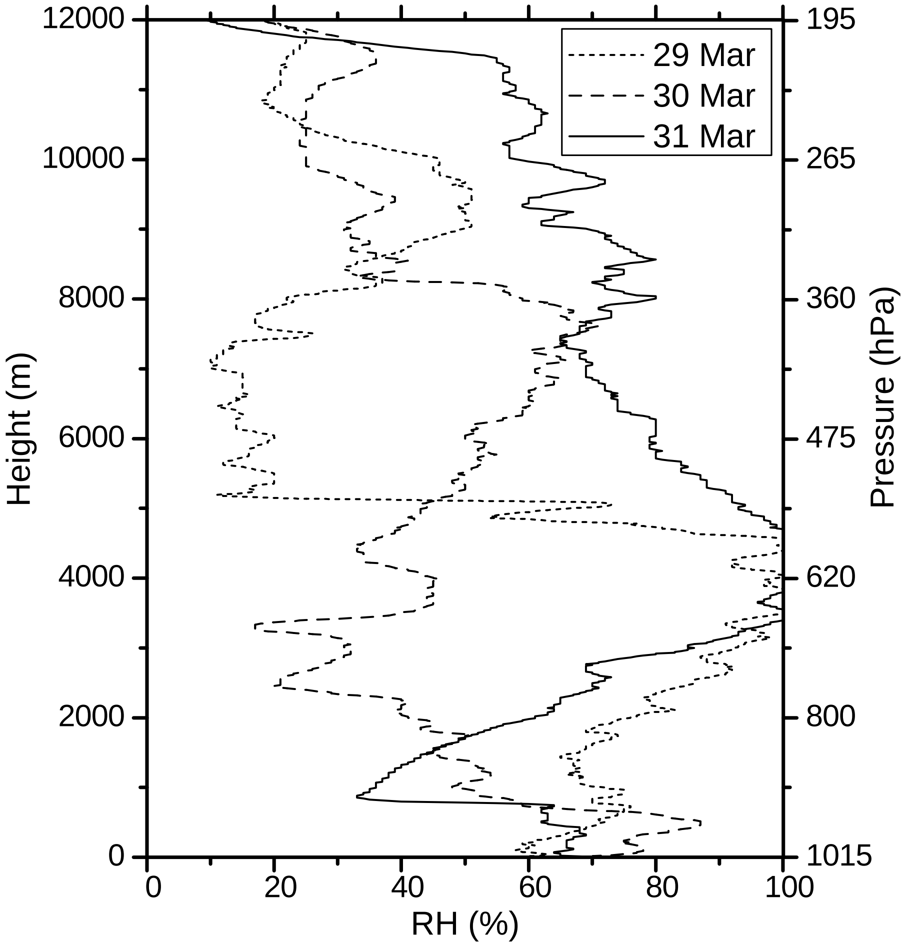

Fig. 3. Vertical profiles of relative humidity derived from radiosondes for 29, 30 and 31 March 2000.

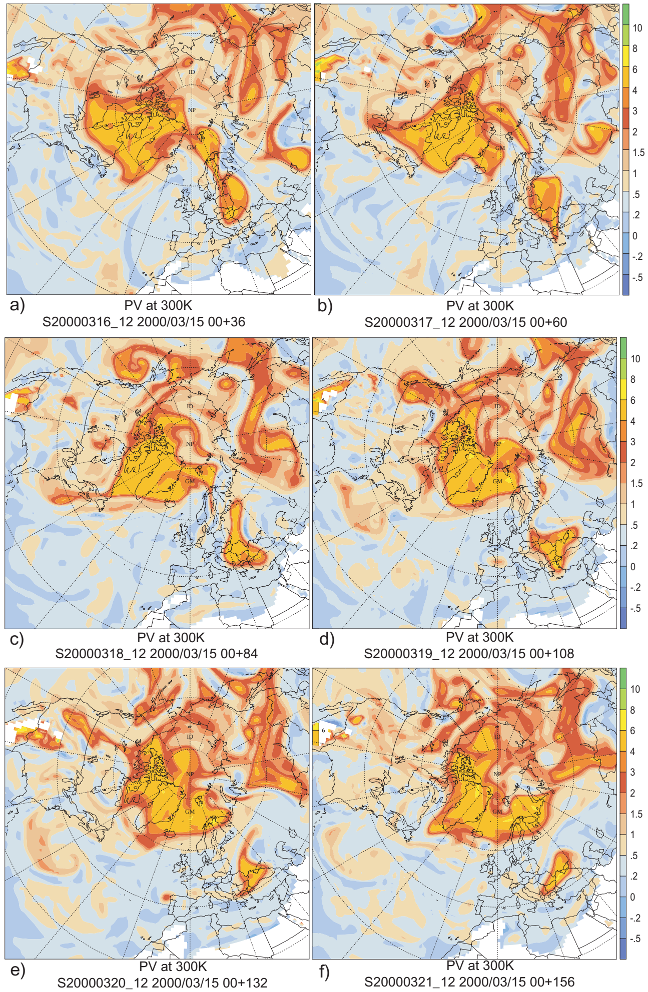

Fig. 4. Potential vorticity maps along the 300˚K isentropic surface for the period 16 March 2000–27 March 2000.

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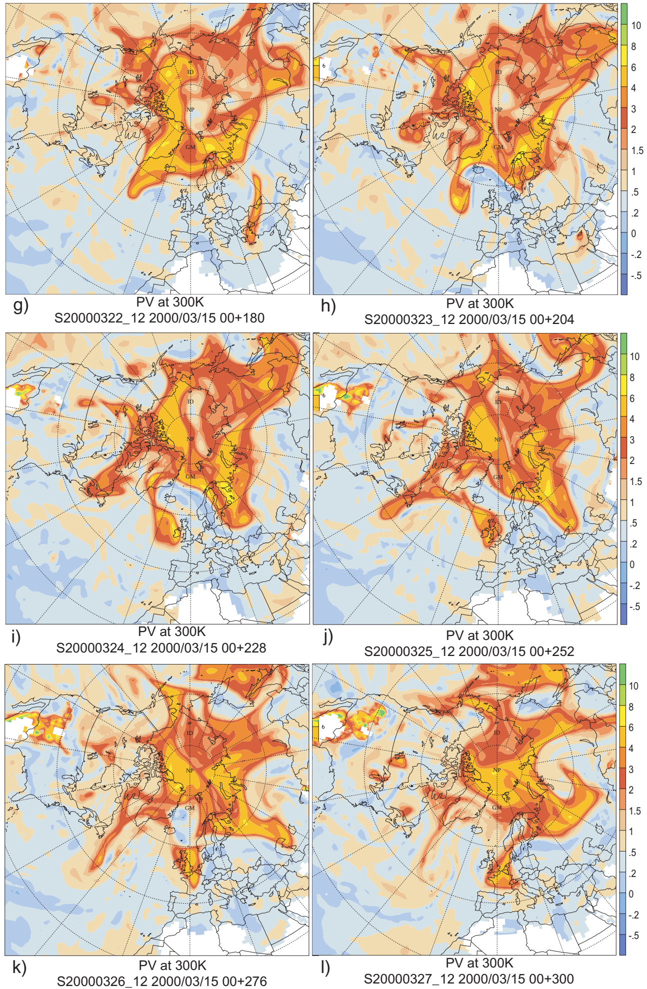

Fig. 4. Continued.

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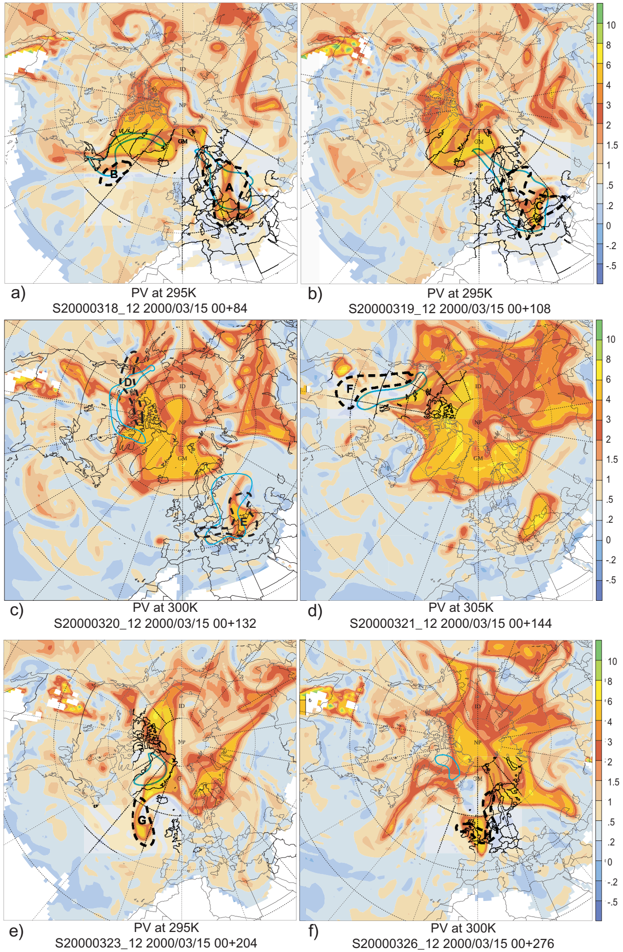

Fig. 5. Potential vorticity maps on which the "intrusion surface" (dashed black line) and the "source surface" (solid green line) for each PV streamer pattern is illustrated.

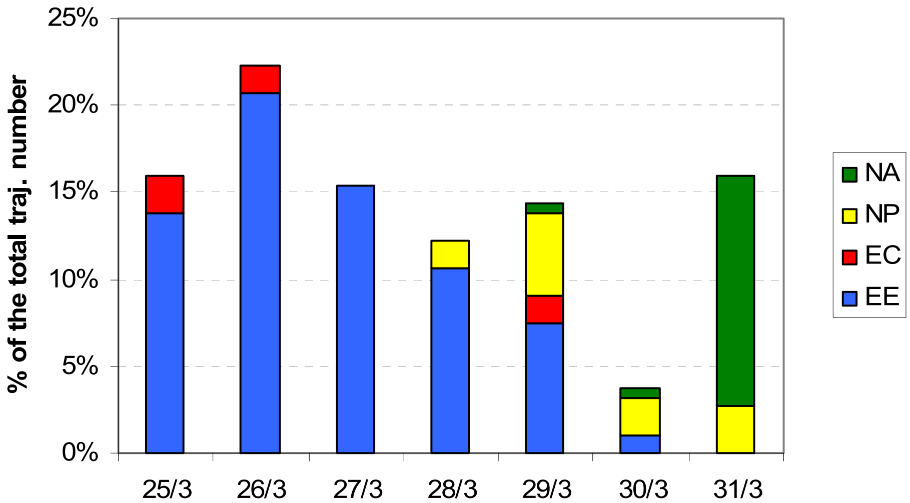

Fig. 6. Percentage contribution of each PV streamer structure to the number of trajectories that reached Livadi during 25 and 31 March 2000. PV streamers are denoted as: NA – "N. Atlantic PV streamer", NP – "N. Pacific PV streamer", EC – "Eastern coast PV streamer", EE – "Eastern Europe PV streamer".

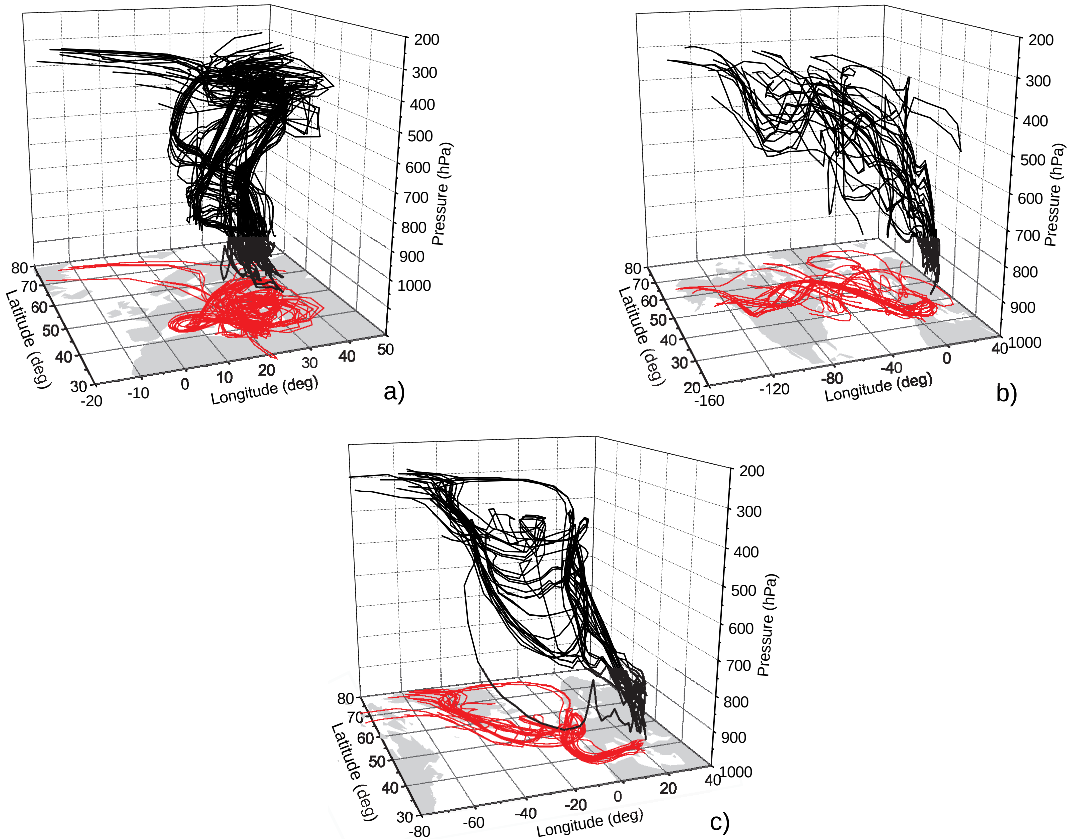

Fig. 7. 10-days back-trajectories (6 h step) that originate in the stratosphere (PV>2 pvu). The calculations were performed at 00, 06, 12 and 18 h each day. On the horizontal plane the trace of each trajectory (red line) is presented for the visualization of the geographical origins of the air-masses. Panels **(a)**, **(b)** and **(c)** present the trajectories related to the “Eastern Europe”, “N. Pacific/Eastern coast” and “N. Atlantic” PV streamers, respectively.

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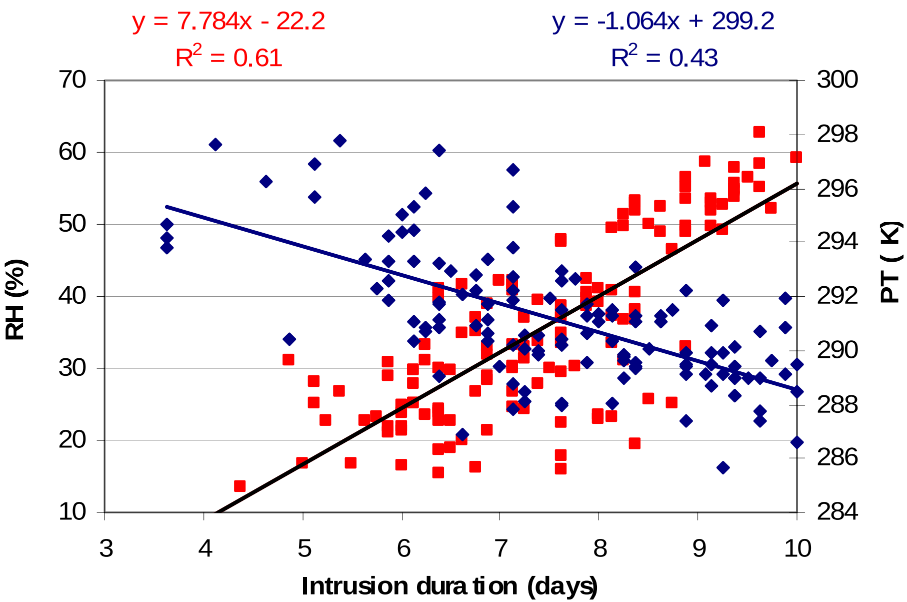

Fig. 8. Scatter plot of the mean relative humidity – *RH* (red squares) and potential temperature – PT (blue diamonds) with the intrusion duration of each trajectory.

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