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Signature of a sudden stratospheric warming in the near-ground ^{7}Be flux

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HIGHLIGHTS

- We present a new improved model of ^{7}Be vertical transport in the lower atmosphere.
- The model reproduces the data from Brazil since 1986 except a spike in 2002–2003.
- The spike is explained as a signature of the southern hemisphere SSW of 2002.
- The result suggests that stratospheric aerosols can reach the ground in such events.
- It is discussed that near-ground air ^{7}Be can trace large-scale air mass dynamics.

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ABSTRACT

We present here an evidence that cosmogenic ^{7}Be isotopes produced in the lower stratosphere were measured in near-ground air at Rio de Janeiro, Brazil, after the southern hemispheric Sudden Stratospheric Warming (SSW) of 2002. The analysis presented here is based on a comparison of ^{7}Be data measured around Angra Nuclear Power Station (23°S 44°W) during the last three decades and a model estimate of the near-ground air ^{7}Be concentration using the CRAC:^{7}Be model of cosmogenic production together with a simplified model for atmospheric ^{7}Be deposition that assimilates the regional precipitation data. Our results indicate that an anomalous stratosphere–troposphere coupling associated to the unique SSW of 2002 allowed stratospheric aerosols carrying ^{7}Be to reach the ground level very quickly. This methodology points to an important use of ^{7}Be as a quantitative tracer for stratospheric influence on near-ground air patterns.

1. Introduction

Sudden Stratospheric Warming (SSW) events play an important role in the troposphere-stratosphere-mesosphere coupling process. During these events, transient changes of the temperature, zonal wind patterns and polar vortex shape and dynamics take place from the lower stratosphere (LS) layer up to the upper part of this atmospheric region, propagating such dramatic changes vertically to other layers (O'Neill, 2003).

In late September 2002, an unprecedented Sudden Stratospheric Warming (SSW) event occurred in the southern hemisphere (SH), causing changes in the tropospheric circulation, ozone depletion and weakening of the polar jet in the mesosphere (Thompson et al., 2005; Varotsos, 2002; Liu and Roble, 2005 and references therein). This SSW event was particularly interesting, since it was located in the SH (instead of in the northern hemisphere – NH, where SSW events are normally observed), happened in the end of the austral winter and had a long duration and a huge intensity.

Using re-analysis data from NASA project called MERRA (Modern-Era Retrospective analysis for Research and Applications, available at: http://acdb-ext.gsfc.nasa.gov/Data_services/met/ann_data_help.html), one can see (Fig. 1) that the stratospheric changes due to this SSW happened in different layers of the lower stratosphere (for example at 10 hPa and 30 hPa, as shown in Fig. 1)

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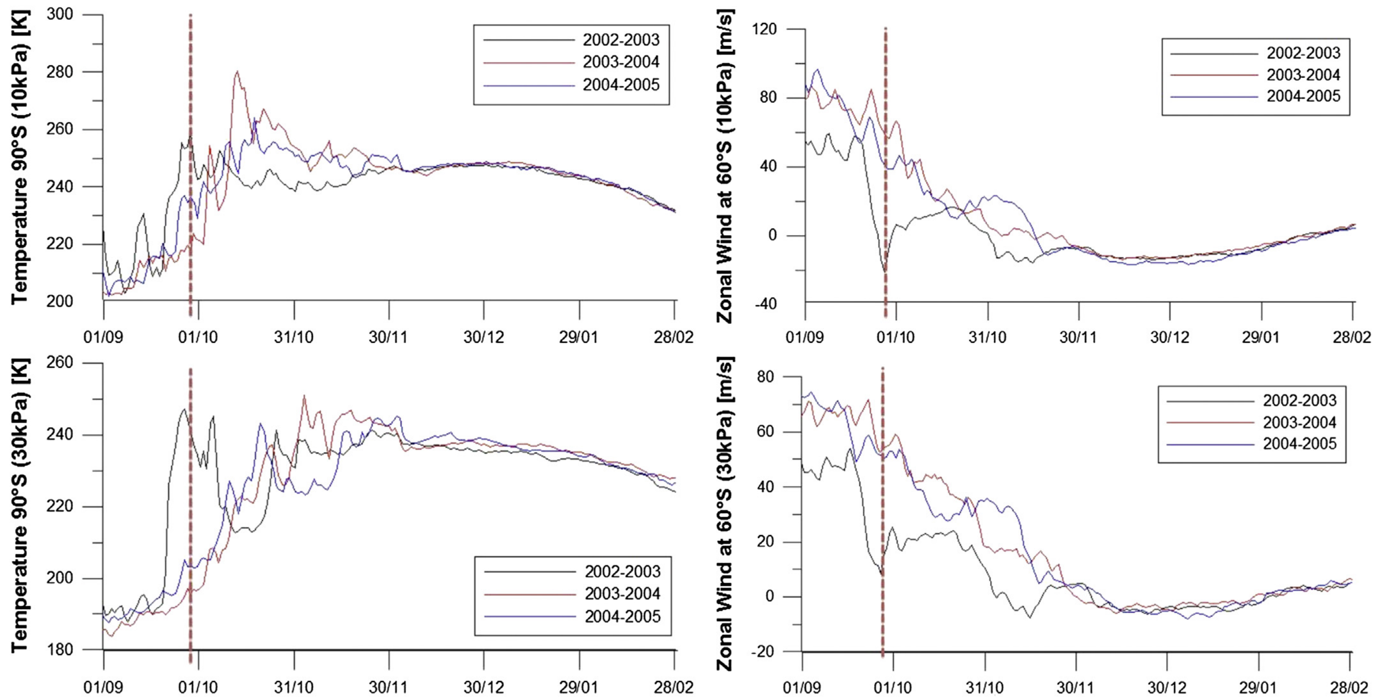

Fig. 1. Stratospheric temperature at 90°S (left panels) and Mid-latitude zonal wind (right panels), for the levels of 10 hPa and 30 hPa, for the period between 1st Sep and 28th Feb (black: 2002–2003; red: 2003–2004; blue: 2004–2005). The vertical red lines indicate the date of the peak of the SSW (27th Sep 2002). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

not restricted only to the polar latitudes, but also affecting the mid-latitude (60°) zonal wind (due to the enlargement of the polar vortex), and these anomalies were persistent until mid-November.

In addition, the SAM index (Southern Hemisphere Annular Mode) at 10 hPa dropped from −2 to −9 in a period of 7 days, reaching a peak value of −9.8 on 27 September 2002. Negative values of the SAM index are defined as strengthening of the westerly zonal flow along 60°S and anomalously high geopotential heights over the polar cap, and can be used as a good proxy of the coupled variations in the zonal flow of the SH stratosphere and troposphere (e.g. Thompson et al., 2005).

There is an observational evidence suggesting that anomalies in the stratosphere play an important role in driving tropospheric weather (Baldwin and Dunkerton, 2001; Baldwin et al., 2003; Polvani and Waugh, 2004; Thompson and Solomon, 2002; Gillett and Thompson, 2003; Tomassini et al., 2012). Accordingly, stratospheric anomalies can produce tropospheric changes that persist for up to 60 days in NH and up to about 90 days in the SH, as observed after the 2002 SSW (Thompson et al., 2005). However, it is still not clear how such influence takes place.

Radioactive environmental techniques for tracing large-scale air-mass transport have been applied in studies of atmospheric dynamics for decades (see, for example, Bhandari et al., 1966), and they are becoming more and more precise due to the improvement of the instrumental sensitivity and associated modeling. Measurements of cosmogenic isotopes in the near-ground air can provide information on physical processes involved in their production and transport.

Cosmogenic radionuclide ^{7}Be (half-life time $T_{1/2} = 53.22 \pm 0.06$ days - Tilley et al., 2002) is produced as a result of nuclear spallation of atmospheric constituents (mainly oxygen and nitrogen) by cosmic-ray particles (Usoskin and Kovaltsov, 2008). Considering the vertical profile of the target-constituent concentration and the development of the cosmic-ray induced cascade in the atmosphere, the optimal condition for the isotopes production occurs at the height of 15–20 km above the sea-level (Yoshimori, 2005; Usoskin and Kovaltsov, 2008). Thus, the production of this cosmogenic radionuclide is largest in the low stratosphere and decreases with the altitude both up and downwards. After their production in the atmosphere, ^{7}Be nuclei are attached predominantly to small aerosols (diameter ~3 μm) and follow their transport and deposition process (Ioannidou and Paatero, 2014). Thus, the temporal variations of the cosmogenic beryllium concentration in the near-surface atmosphere can provide information on the air mass dynamics, precipitation patterns, stratosphere–troposphere coupling and cosmic ray variations (McHargue and Damon, 1991).

We present here a study of the impact of the 2002 SSW upon the atmospheric vertical dynamics based on ^{7}Be measurements in near ground air, using both numerical and conceptual models and direct data of ^{7}Be measurements.

2. ^{7}Be data and the two-layer vertical deposition model

The present study is based on an analysis of ^{7}Be concentration measured in near-ground air in the city of Angra dos Reis, Rio de Janeiro state, Brazil (23°00′S 44°19′W, geomagnetic cutoff rigidity Pc = 11.6 GV) between 1987 and 2009. The activity concentration of ^{7}Be was routinely measured (with 3-month time resolution) by several air filter stations located around Angra Nuclear Power Stations in the framework of a radiation safety monitoring. In each station, the ambient air was continuously pumped through a fine fiber-glass filter and the atmospheric aerosols were collected weekly. At the end of the sampling period, the filter were replaced. The weekly changed filters were collected together during a three-month period and then together placed directly into an HPGe gamma-detector mounted inside a lead castle for the reduction of background radiation. The intensity of the 477.59 keV gamma-line, corresponding to the decay of ^{7}Be, is determined from the measured spectrum, and the activity concentration (in Bq m^{-3}) is calculated afterwards.

The 20-year long dataset used in this study was kindly made available by the environmental monitoring program of Angra Nuclear Power Station. The mean ^{7}Be activity concentration during the entire period was 0.84 ± 0.44 mBq.m^{-3} and there was a clear outlier (~3.5 mBq·m^{-3}) in 2002–2003. A spectral analysis shows an absence of a significant solar cycle modulation imprints over this Angra's ^{7}Be data. These results were present in a previous work (Leppänen et al., 2010) and can be justified by the high local geomagnetic cutoff rigidity (~12 GV) and the complex regional synoptic-scale climatic systems, suggesting that an important part of the total ^{7}Be atoms available in Rio de Janeiro latitudes is not produced locally, but brought by air-masses from other sites, turning the atmospheric dynamics to a dominant driver of the cosmogenic modulation measured in near-ground air.

Pacini et al. (2011) presented an analysis of a weekly ^{7}Be data obtained in Rio de Janeiro city during the years 2008–2009 and also found that the depositional flux and the air-mass transport are the dominant sources of ^{7}Be variability in the low atmosphere, overwhelming changes on the *in situ* cosmogenic production. Moreover, the results obtained by Pacini et al. (2011) indicate that anomalous events of tropospheric dynamics, such as the occurrence of strong downward air flux, leave an imprint of the 3D motion of air masses to the near-ground air ^{7}Be data, making ^{7}Be a useful tracer of its peculiar dynamics at local and synoptic scales in the troposphere (cf. Jasiulionis and Wershofen, 2005; Usoskin et al., 2009; Tositti et al., 2014). Those results were obtained by using a simplified tropospheric ^{7}Be model deposition based on a two-layer transport model. This model considers the equilibrium condition between ^{7}Be production and loss in the troposphere divided in two layers: from 0 km to 4 km height (or from 1033 to 620 g/cm^2 in the atmospheric depth), corresponding to the Convective Layer (CL); and 4 km up to ~10 km (or from 620 to 240 g/cm^2), corresponding to the upper troposphere (UT). The model includes two sources of ^{7}Be production in CL (the *in situ* cosmogenic production and sedimentation of ^{7}Be atoms from the UT), and two removal mechanisms (radioactive decay and wet depositional flux). The wet deposition process in CL for removal due to collisions between the aerosol and the raindrops is effectively represented by the washout coefficient (Λ in h^{-1}), described by Apsimon et al. (1985) as: $\Lambda = 0.18 \cdot R^{0.8}$, where R is the mean rain precipitation rate (in mm/h) for the period under consideration. In the UT, we assumed the equilibrium between the cosmogenic production and losses due to radioactivity decay and the depositional gravitational downward flux.

The mean cosmogenic production rates were computed for each layer between the latitudes 0 and 60°S using the numerical model CRAC:7Be (Cosmic Ray induced Atmospheric Cascade applied to ^{7}Be), which computes a 3D production rate of ^{7}Be in realistic conditions (Usoskin and Kovaltsov, 2008; Kovaltsov and Usoskin, 2010) and using values of the heliospheric modulation potential as calculated from the neutron monitor network (Usoskin et al., 2005, Usoskin et al., 2011). This latitudinal range was chosen because Rio de Janeiro is located at the convergence area of two atmospheric circulation cells (Hadley and Ferrel), receiving influence from a wide range of latitudes. The mean residence time in the troposphere, τ_{tropo} (28.8 days, see Papastefanou, 2009), was considered when computing the depositional flux of ^{7}Be atoms from UT to the CL. That allows one to quantitatively reproduce the observed ^{7}Be seasonal variability in Rio de Janeiro. A more detailed description of the two-layer conceptual model can be found in Pacini et al. (2011).

3. The three-layer vertical ^{7}Be deposition model: equilibrium and SSW scenario

In this work, we have further developed the two-layer model described above by adding one more atmospheric layer: the lower stratosphere (LS) from the tropopause up to 24.5 km of height (or 240–30 g/cm^2 in atmospheric depth). In normal conditions, the contribution of the low-stratospheric ^{7}Be to the near-ground isotopic variability would be very small, since the mean residence time of the ^{7}Be in the stratosphere is very long (about two years, as found by Rehfeld and Heimann, 1995; using a 3D Global Circulation Model). That was a reason to neglect the stratospheric source by Pacini et al. (2011). Thus, in the equilibrium scenario, the ^{7}Be estimate based in the three-layer model was not expected to be much different from the two-layer results. On the other hand, stratospheric source can be crucial for the SSW event.

Using the limited monthly precipitation rate data available for Angra in Soares (2006) and following the methodology described above, we could determine the washout coefficient values, Λ, only for the period of 1986–2005. The estimated values of Λ indicated a mean ^{7}Be washout removal time about 0.8 days for the studied period, agreeing with Pacini et al. (2011) empirical estimatives for the typical ^{7}Be-aerosols residence time in the lower troposphere in Rio de Janeiro (~1 day). Running both the two-layer and the three-layer deposition models for the 1986–2005 period, it was possible to compare the obtained results. The boxplot of the absolute errors (differences between modeled and measured ^{7}Be concentrations) associated to both models (Fig. 2) shows that the inclusion of the LS layer slightly improves the reproduction of the ^{7}Be concentration patterns measured in near-ground air, but the difference is minor, supporting the idea that the stratospheric source does not play a notable role in the near-ground ^{7}Be concentrations in (quasi) steady conditions. It is important to notice that the three-layer model explain the ^{7}Be activity concentration in 2001 that was an outlier in the 2-layer model, thus showing the improvement of the description. On the other hand, neither two-, nor three-layer model could explain the 2002–2003 outlier, when assuming equilibrium conditions. In fact, considering all the changes in the tropopause region associated to stratospheric anomalies, we propose a new ^{7}Be depositional scenario for the SSW period, in which the LS layer becomes essential.

A schematic view of the three-layer model is presented in Fig. 3, considering both the equilibrium scenario and a disturbed scenario

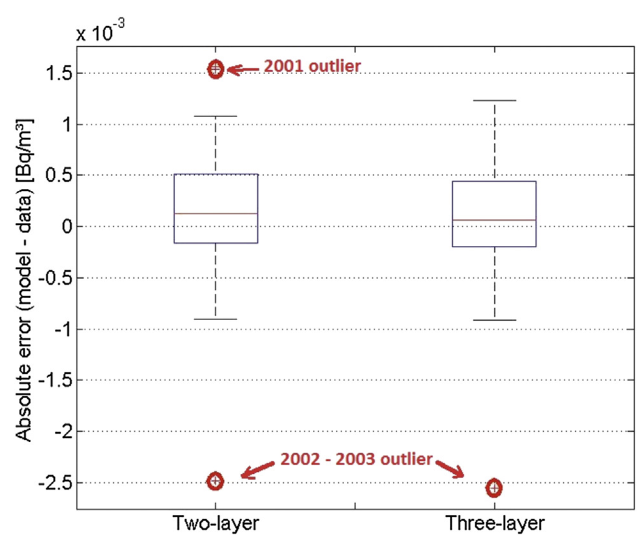

Fig. 2. Boxplot of the absolute errors associated with the two-layer model and three-layer model estimates. The red horizontal lines represents the medians error values, the box limits show the 25th and 75th percentiles and the whiskers are indicating the extreme not-outliers values. The outliers are plotted individually as red circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

associated to the SSW occurrence. In both scenarios, the *in situ* ^{7}Be productions rate at LS, UT and CL are indicated as q_0, q_I and q_{II}, respectively. The ^{7}Be losses due to its radioactive decay are represented by the ^{7}Be life time, τ. The depositional downward fluxes from the upper layers (q_{D1} and q_{D2}) are represented by the ^{7}Be residence times in the stratosphere and troposphere, τ_{strato} and τ_{tropo}, respectively, and are considered losses for the upper layers and gains for the bottom ones.

Based on the stratospheric data from MERRA, we considered the SSW scenario with a ^{7}Be intrusion from the LS into the UT due to the SSW event that lasted ~90 days after the SSW peak (period that took part of the last 3-month of 2002 and part of the first 3-month of 2003). Instead of the normal gravitational sedimentation of stratospheric ^{7}Be to the upper troposphere, it was considered that all the amount of ^{7}Be existed in the LS was transferred to the upper troposphere in last three months of 2002 and first three months of 2003.

The ^{7}Be concentrations for the near-ground air computed by the three-layer model for both scenarios are plotted in Fig. 4, along with the ^{7}Be data measured in Angra between Jun 2000 and Jun 2004 (period that includes the studied outlier). One can see that the high level of near-ground air ^{7}Be activity concentration during the period just after the SSW can be well reproduced by this simplified depositional scenario of the three-layer model considering the stratospheric intrusion. On the other hand, the equilibrium scenario is unable to reproduce the observed spike. This result suggests that stratospheric aerosols have reached the ground level during several months after the SSW event, showing that its tropospheric consequences can be much larger than it is usually considered.

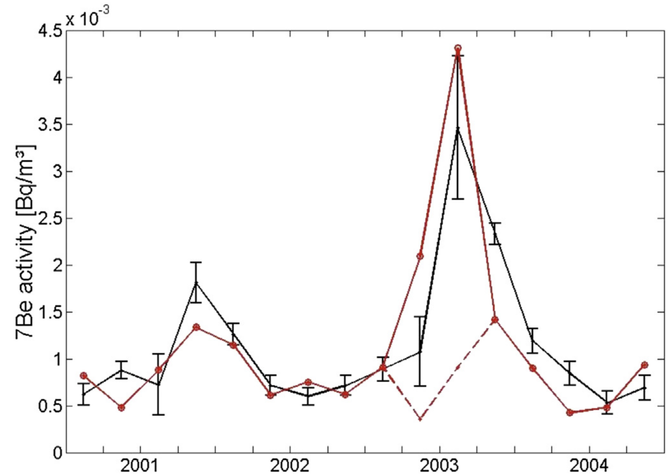

Fig. 4. Measured ^{7}Be activity concentration data for Rio de Janeiro - Angra (black) along with the results obtained with the three-layer model (red) in the equilibrium conditions (dotted) and considering the stratospheric intrusion in 2002.75 (continuous line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Summary and conclusions

This work reports a clear signature of the SSW of 2002 in the near-ground air ^{7}Be data obtained at Angra dos Reis (Rio de Janeiro), Brazil, reinforcing the potentiality of the use of the cosmogenic isotopes measurements in studies of the vertical

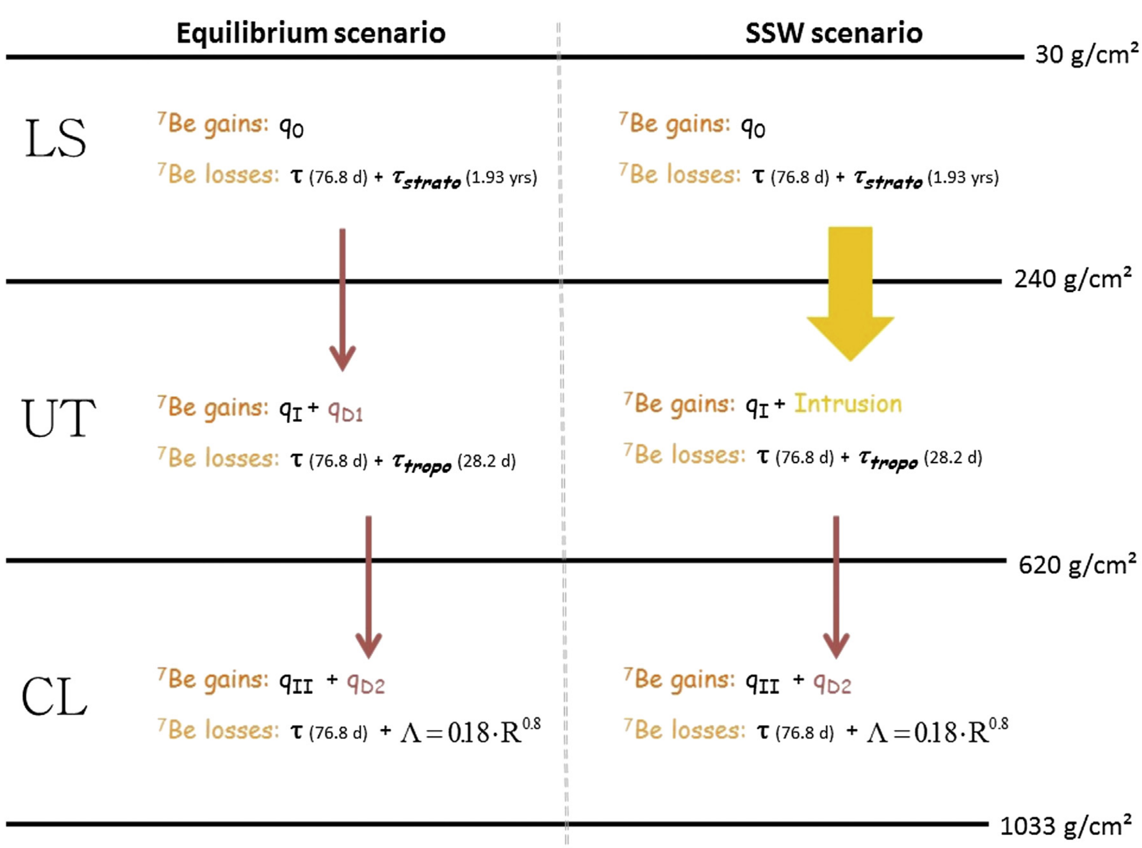

Fig. 3. Three-layer (LS — low stratosphere; UT — upper troposphere; CL — convective layer) numerical model for ^{7}Be atmospheric deposition considering the normal equilibrium scenario (left) and the disturbed scenario for the SSW period (right).

atmospheric dynamic. By refining the ^{7}Be depositional conceptual model presented in our previous work (Pacini et al., 2011), we were able to reproduce the isotope's measured concentrations in an equilibrium scenario, considering also the ^{7}Be dynamics from the LS down to the surface. Our results corroborate the previous ones (showing that anomalous events of stratospheric–tropospheric dynamics do imprint information about air masses 3D movement in the near-ground air ^{7}Be data) and indicate that a strong stratospheric air intrusion happened after the SSW bringing stratospheric aerosols from the LS to the surface.

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