Cosmogenic isotope ^{7}Be as a tracer for air mass dynamics

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***Abstract*. Short-living cosmogenic radioisotope ^{7}Be, which is attached to atmospheric aerosols soon after production, is widely recognized as a promising tracer for air mass transport in the atmosphere. Atmospheric changes in the radionuclides concentration are driven by processes that relate to production, air transports and removal. We here apply a combined ModelE of the Goddard Institute for Space Studies and the OuluCRAC:7Be production model to simulate the atmospheric variations in the ^{7}Be concentration for the period of January through February 2005. Significant synoptic variability has occurred at multiple monitoring stations around the globe during the period, and an extreme solar energetic particle (SEP) event was recorded on January 20. The model reproduces the overall level of the measured ^{7}Be concentration near ground and also its synoptic variability at timescales longer than about four days. This outcome confirms the advantage of the combined model of production and transport of the ^{7}Be radionuclide in the atmosphere. A significant impact of the extreme SEP event of January 2005 is clearly demonstrated in polar stratospheric ^{7}Be concentration , while only small (about 2%) and indistinguishable response is observed in the near Earth's surface monitoring stations.**

***Keywords*: cosmic rays, cosmogenic isotope, atmosphere**

I. Introduction

We present a new quantitative method to probe the atmospheric dynamics using the short-lived cosmogenic isotope ^{7}Be as a tracer of air mass. Since it is produced mainly at mid- and high latitudes and mostly in the stratosphere, this tracer appears useful for looking at stratosphere-troposphere exchange and also for horizontal transport, and it can also be used as a tracer for aerosol removal processes. The potential usefulness of this cosmogenic tracer was mentioned since long (e.g., [1], [2], [3]) but now its potential can be explored to much greater extent.

Cosmic rays produce quite a number of different radioactive isotopes in the atmosphere as a byproduct of nucleonic-electromagnetic cascades. One of them is the short-lived radionuclide ^{7}Be ($T_{1/2}$ ≈53.22 days), produced by spallation of atmospheric O and N nuclei caused by the nucleonic component of the cascade. Concentration of ^{7}Be in the ambient air is easy to measure, as done around the globe in the framework of radiation safety monitoring and emergency preparedness. Atoms of ^{7}Be become quickly attached to atmospheric aerosols, picked up by air masses and thus can trace them on the time scale of days to months (e.g., [4], [5], [6], [7], [8]). However, the lack of knowledge of the details about the isotope's production and transport had limited earlier works to correlative studies and use of the isotopic ratio ^{7}Be/^{10}Be. An appropriate model with special emphasis on the production of ^{7}Be by cosmic rays in the atmosphere has recently been developed: the OuluCRAC:7Be (Cosmic Ray induced Atmospheric Cascade) model [9]. The output of this model can be used as an input for an atmospheric general circulation model (GCM), which can predict the expected concentration of ^{7}Be in air at any location and time. These predicted concentrations can be directly compared with the isotope measurements performed regularly in different sites around the world. For the detailed analysis we have chosen the period of January-February 2005, which includes a severe SEP event of 20-01-2005.

II. Data and Models

The studied period corresponds to the middle of boreal winter / austral summer. We used data from nine ^{7}Be monitoring stations (5 in Northern and 4 in Southern hemisphere – Table I), ranging from the tropics to the polar region. The data have been collected by sampling stations of the International Monitoring System (IMS) of the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO), via the Finnish national data centre (FiNDC) at the Finnish Radiation and Nuclear Safety Authority (STUK). Concentration of ^{7}Be is measured, using a standard procedure, in aerosol samples routinely

TABLE I: ^{7}Be measuring sites used in this study.

Code	Location	Coordinates
Northern hemisphere		
SEP63	Stockholm (Sweden)	59.38°N 17.95°E
HEL	Helsinki (Finland)	60.21°N 25.05°E
CAP15	Resolute (Canada)	74.71°N 95.0°W
DEP33	Freiburg (Germany)	47.9°N 7.9°E
USP72	Melbourne (Florida, U.S.A.)	28.1°N 80.6°W
Southern hemisphere		
AUP04	Melbourne (Australia)	37.7°S 145.1°E
AUP10	Perth (Australia)	31.9°S 116.0°E
NZP46	Chatham Island (New Zealand)	43.82°S 176.5°W
NZP47	Kaitaia (New Zealand)	35.07°S 173.3°E

collected at each station. The total uncertainty for the measured ^{7}Be concentration is 7-8% [10].

For computations of the ^{7}Be production rate we used the OuluCRAC:7BE model [9] based on detailed Monte-Carlo simulations of the nucleonic-muon-electromagnetic cascade initiated by cosmic rays in the Earth's atmosphere. Details of the ^{7}Be computations for the studied period are given elsewhere [10]. An example of altitude profile of ^{7}Be production is shown in Fig. 1 for GCR (galactic cosmic rays) and SEP. One can see that the maximum production of ^{7}Be due to GCR corresponds to the altitude of 12–15 km. Contribution from SEP becomes important at higher altitudes because of their greater flux but softer energy spectrum.

Simulations of the air mass transport were performed using the GISS ModelE, which is capable of simulating a variety of climatological features (e.g., [11], [12], [13]). The decay of ^{7}Be is straightforwardly accounted in the model and the 53-day half-life is considerably longer than the weekly and monthly time-series against which we compare our model output, therefore it does not affect our results. We assume that ^{7}Be attaches to sulfate aerosols immediately after production and that the sulfate aerosols are 100% soluble. The simulated ^{7}Be is subject to all the advection, mixing and convection processes consistent with the model air mass fluxes. In different clouds, aerosol species are transported and handled appropriately. Aerosol gravitational settling is also included [3]. The same turbulent exchange coefficients as those used for the model humidity are applied to ^{7}Be near the surface. The resistance-in-series scheme [14], [11] is the basis for the model's dry deposition scheme.

We ran the simulations from Jan-1 through Feb-27, 2005, using a present-day atmospheric composition, and forced the model with observed sea surface temperatures and sea ice values. We used NCEP/NCAR reanalysis data to "nudge" the model winds so that they more closely resemble the observed values [15]. The spin-up to Jan-1, 2005, was over a 10-year period with 2004 wind conditions so that the ^{7}Be was in full equilibrium.

III. Results

The model results were compared with the measurements for each site (Fig. 2). The agreement is very good for the Stockholm station (Panel SEP63). The

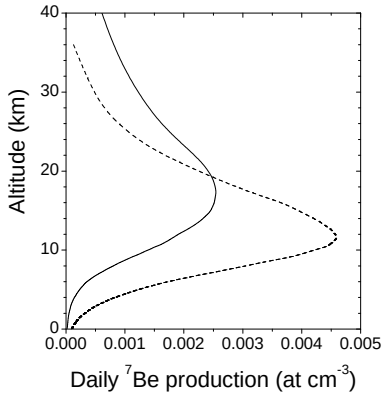

Fig. 1: Daily production of ^{7}Be in a high-latitude region (P_c=2 GV) as a function of altitude: solid curve – the effect of the SEP event of January 20, 2005; dotted curve – GCR for a quiet day of January 12, 2005 (see [9]).

absolute value of the modelled concentration matches well with the measured one, including a low level of 2–4×10^{-16} ppmv in January and an enhancement towards late February. The main temporal features are also well reproduced, except for a small observed peak ca. day 14. Measurements at the HEL station are also well reproduced by the model, except for a peak at day 26 which is predicted by the model but absent in the data. The large perfectly modelled ^{7}Be enhancement in the Fennoscandic region (SEP63 and HEL) ca. day 38–39 was related to a large-scale intrusion and lowering of a continental air mass rich in ^{7}Be. The data from the Canadian site (CAP15) was relatively stable during the studied period, without distinct peaks and is well reproduced by the model. Data is reasonably well modelled for the DEP33 site until day 42, but the observed peak ca. day 17 does not appear in the model results. The data at the USP72 site are well reproduced, including the baseline and a peak ca. day 24. Some spurious peaks appear in the model results in the late part of the analyzed interval. The above Northern sites were under winter conditions, while Southern hemisphere corresponds to mid-summer. The agreement between model and measurements is excellent for the AUP04 site. Data for the AUP10 site is generally well reproduced but some fine details are missing in the model results. Variations of ^{7}Be are precisely modelled for site NZP46 before the day 25, but underestimates the isotope's concentration after that. The main pattern at the station NZP47 is captured in general by the model, but the details and the exact timing are only poorly reproduced.

This analysis can be summarized as:

- The model reproduces within about 10% accuracy the overall level of the near-ground ^{7}Be concentration, which varies by an order of magnitude between (sub)polar and tropical sites.
- The slowly changing (time scales of a week and longer) baseline of the ^{7}Be concentration is well reproduced by the model for all the sites in both

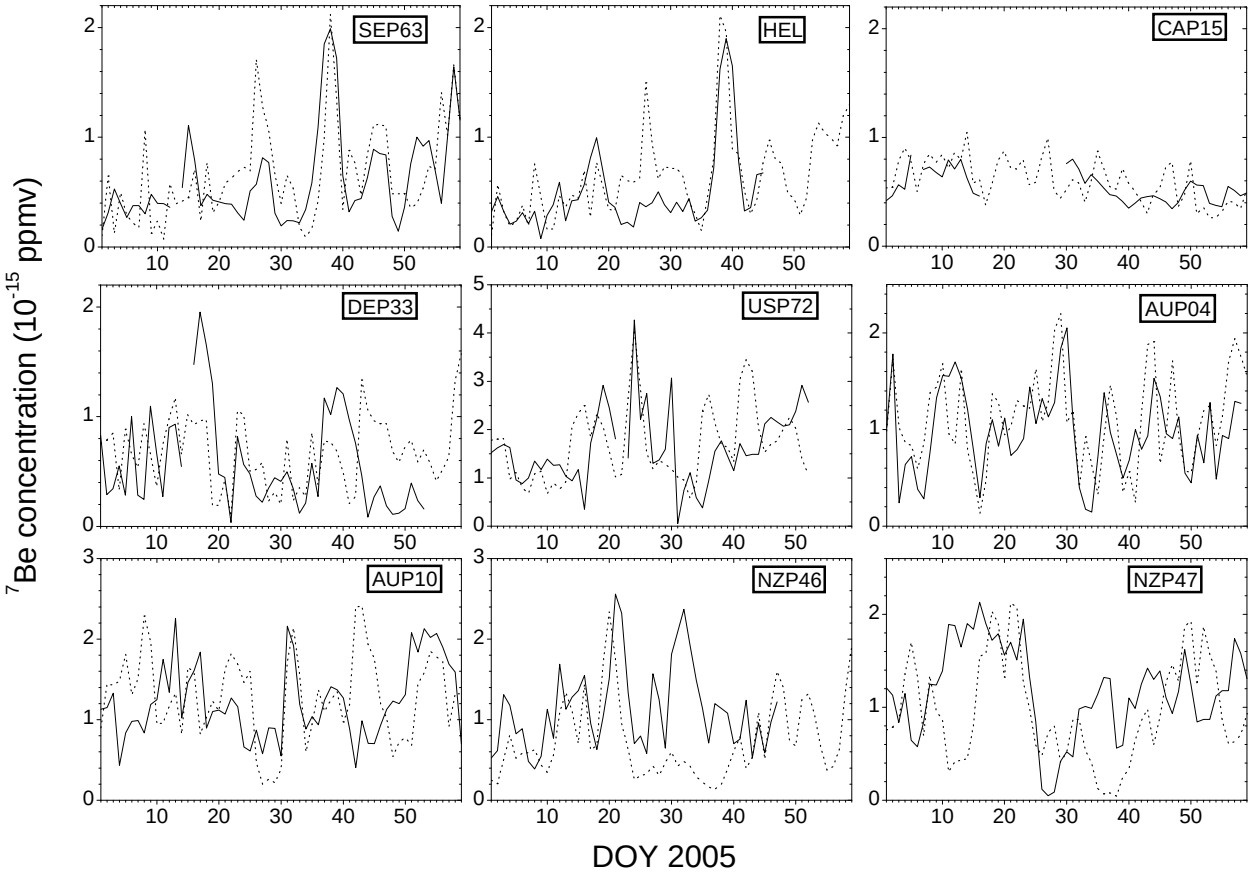

Fig. 2: Measured (solid curves) and modeled (dotted curves) daily concentration of ^{7}Be in the near-ground air for the beginning of the year 2005. Each panel corresponds to a measuring site (see Table I) in the Northern hemisphere. Concentration is presented in 10^{-15} ppmv.

winter and summer conditions.

- Most of the strong peaks in the measured ^{7}Be concentration are well reproduced by the model, in terms of both the timing and amplitude. However, some increases in concentration are not adequately reproduced by the model. The model sometimes yields short spurious peaks, as e.g., ca. day 26 at SEP63 and HEL sites.

Thus, while the model does not resolve all the small scale dynamics in the observed air mass transport, it is pretty good in reproducing the large scale pattern (time scales of a week and longer), both qualitatively and quantitatively. This timescale is associated with the synoptic weather systems at these latitudes and is a consequence of the large-scale coherence of the model to the observed sea level pressure patterns. Discrepancies between the modeled and observed ^{7}Be may also be related to the model's inability to resolve small-scale occurrences of stratosphere-troposphere exchange.

IV. The effect of solar energetic particles

In order to study in detail the effect of the SEP event, we compared the results of two model runs: a realistic "SEP" and a "no SEP" run, where the effect of the additional ^{7}Be production due to SEP was excluded [10]. The temporal and altitude variability of the SEP effect (defined as $[\frac{C_{\rm SEP}}{C_{\rm no\,SEP}} - 1]$) is shown in Fig. 3 for subpolar zone (60–64° N). While the absolute production of ^{7}Be peaks around 15–20 km, the SEP effect starts dominating over the GCR production above 20 km altitude (Fig. 1). Accordingly, the immediate SEP effect can be directly observed only in the upper stratosphere. The modelled effect of SEP event is very strong (two orders of magnitude greater than the daily GCR-related production) and instantaneous at the altitude above 50 km. The additionally produced ^{7}Be does not stay at this atmospheric level but moves down as shown in the figure, descending to 40–50 km within a week. After a fortnight there is no indication of the enhanced ^{7}Be concentration at these altitude. In the lower stratosphere and troposphere, the effect is two-fold: a peak of ^{7}Be concentration on the first day appears as a result of the direct production effect, followed by enhanced concentration, extending for months, due to the descent of ^{7}Be produced in higher atmospheric layers. The expected effect (2–3%) of an extreme SEP event, as predicted by the model, is too small to be detected at the near-ground data analyzed here. Direct measurements in the stratosphere, where the ^{7}Be concentration is expected to be enhanced by a factor of 2–10 during the weeks following the event, would make

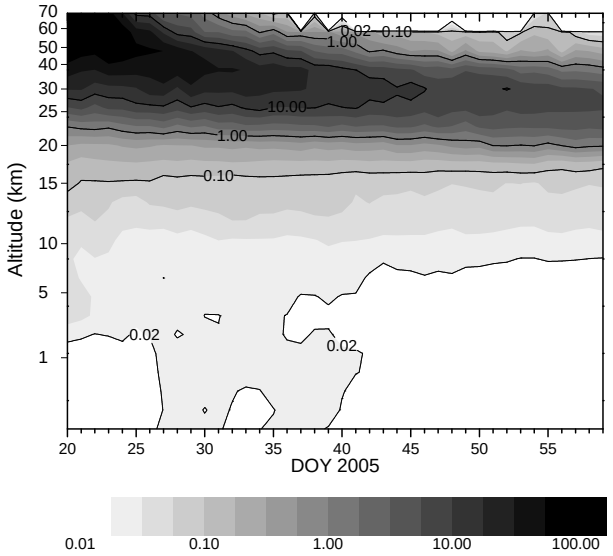

Fig. 3: Effect of SEP from the event of January 20, 2005 on the computed ^{7}Be concentration in the atmosphere in subpolar zonal mean (60–64° N latitude) [10].

it possible to test the model results directly. However, we are not aware of such measurements performed during January or February 2005.

V. Conclusions

We tested here an atmospheric GCM model using the cosmogenic isotope ^{7}Be as a tracer of air mass transport in the Earth's atmosphere. A combination of a numerical OuluCRAC:7Be [9] ^{7}Be production model and GISS ModelE [13] atmospheric circulation model, has been used to trace the air mass transport by means of the ^{7}Be concentration in full 3D on daily timescales. The results were directly compared with routine daily measurements of the ^{7}Be concentration in near-ground air around the world. The model reproduces well both the overall level of ^{7}Be concentration in the near-ground air, which varies by an order of magnitude between different monitoring stations, and the large scale variations at time scale of a week and longer. The overall agreement with measurements obtained here implies that our OuluCRAC:7Be model correctly simulates the production of ^{7}Be, including the overall normalization. The combined model simulates correctly the large-scale atmospheric dynamics but does not possess sufficient precision to distinguish small scale effects. The analysis shows that the effect of a severe SEP event on ^{7}Be concentration is two-fold. The instantaneous effect of the enhanced local production due to solar particles is limited to polar regions but occupies the entire atmospheric column, varying from two to three orders of magnitude in the upper stratosphere to a few percent in the lower troposphere. This immediate effect dominates in the upper atmosphere, from where ^{7}Be produced by the SEP event descends to the stratosphere within several days. On the other hand, the enhanced concentration of ^{7}Be in stratosphere and troposphere is prolonged for month(s), mostly because of the downward transport of ^{7}Be from upper atmospheric layers. The expected effect of the SEP event is too small at the ground level to be securely detected in the measured data.

In conclusion, we have developed and directly verified a novel combined model of production and transport of the cosmogenic tracer ^{7}Be in the atmosphere. We have shown that synoptic variations in ^{7}Be can be captured by a nudged GCM including aerosol tracers. Further analysis of the causes of these variations and more detailed studies of stratosphere/troposphere interactions may allow better tests of the model leading to better understanding of the air mass transport processes.

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