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Winter extremes of beryllium-7 surface concentrations in northern Europe

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Abstract

Specific activity of cosmogenic ^{7}Be in surface air generally shows a spring-summer maximum. However, extremely high ^{7}Be concentrations in surface air also occur during winter. The aim of our analysis is to characterise temporal and spatial prevalence of winter extreme events, and to investigate the associated synoptic meteorological conditions in northern Europe. Four measurement sites, with an approximate weekly sampling rate over the 2001–2010 period, are selected from the online Radioactivity Environmental Monitoring (REM) Database. The extremes in the ^{7}Be surface concentration are defined as measurements above the 90th percentile in each location.The results indicate that at each measurement site, 10–20 % of the extremes occur during winter (November, December, January and February). Two types of ^{7}Be extremes are distinguished: 1) approximately half of these occurrences are isolated events detected in one or two stations, and 2) the other half are events grouped within four months, when at least three ^{7}Be extremes per month are observed. The monthly Scandinavia (SCAND) teleconnection index for isolated extreme events (type-1) is positive and, with only one exception, larger than 0.4, while in the case of type-2 events, the monthly SCAND is very high (larger than 1).This finding implies that in northern Europe during winter, the atmospheric conditions associated with a high SCAND index facilitate an occurrence of extreme ^{7}Be surface concentration.

Introduction

Cosmogenic beryllium-7 reaches the Earth's surface via vertical transport. This radioisotope is produced in spallation reactions that occur in the upper troposphere and lower stratosphere (UTLS region) (Lal & Peters, 1967), and is further transported through the atmosphere attached to fine aerosols (Dueñas et al., 2004; Heikkilä et al., 2008; Koch et al., 1996). The ^{7}Be downward transport to the Earth's surface is governed by the horizontal and vertical winds (Cristofanelli et al., 2006; Gerasopoulos et al., 2003).During this transport to the surface, high ^{7}Be specific activity typical of stratospheric air masses is decreased through radioactive decay, mixing with surrounding air of a lesser ^{7}Be concentration, and removal processes (Feely et al., 1989).

Due to arelatively long ^{7}Be half-life of 53.22 days, air masses that reach the Earth's surface in a fast subsidence from the UTLS region,can retain, to a certain extent, their signature of high ^{7}Be concentration (Husain et al., 1977). Since mixing diminishes the stratospheric properties of air within a few days (Appenzeller& Davies, 1992), the descent needs to occur fast enough so that the overall effect of mixing does not result in a complete loss of the ^{7}Be concentration gradient. Another condition that must hold is an absence of precipitation (Ajtić et al., 2013, 2016; Gerasopoulos et al., 2001), which has been shown to be the major removal mechanism of ^{7}Be from the atmosphere (Ioannidou& Papastefanou, 2006; Papastefanou &Ioannidou, 1991; Pham et al., 2011).

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The ^{7}Be specific activity in surface air shows an annual pattern with a maximum in the spring-summer season, which has been attributed to an increased vertical transport from the UTLS. In spring, relatively frequent stratospheric intrusions (Cristofanelli et al., 2006; Elbern et al., 1997; Feely et al., 1989) enrich the troposphere with air masses of high ^{7}Be concentration, while in summer, efficient vertical mixing brings ^{7}Be-rich air from the upper troposphere down to the surface (Gerasopoulos et al., 2001, 2003; Feely et al., 1989;).

Cases of high ^{7}Be surface concentration have been previously investigated, mostly in alpine stations in Europe (Cristofanelli et al., 2006; Elbern et al., 1997; Gerasopoulos et al., 2001; Stohl et al., 2000; Zanis et al., 1999). In some studies, a fixed limit of 8 mBq/m^{3} (Cristofanelli et al., 2006; Hernández-Ceballos et al., 2016b; Stohl et al., 2000) was used as a threshold defining the events of high ^{7}Be concentration. However, the abundance of ^{7}Be in surface air depends on the latitude (Doering&Saey, 2014; Feely et al., 1989; Hernández-Ceballos et al., 2015, 2016a; Kulan et al., 2006; Persson& Holm, 2014) and some locations show frequent measurements above this threshold (Buraeva et al., 2007; Hernández-Ceballos et al., 2016b; Petrova et al., 2009). Hence, a relative threshold that is specific for each measurement site, as introduced by Ajtić et al. (2016), could be more suitable for investigation of extremely high ^{7}Be concentrations over an extended geographical region.

Elevated ^{7}Be specific activities at the surface have been shown to occur outside the warm season (Ajtić et al., 2016; Hernández-Ceballos et al., 2016b), and the aim of this paper is to characterise temporal and spatial prevalence of extremely high ^{7}Be surface concentrations that occur during winter in northern Europe. Northern Europe has been identified as one of three distinct regions of ^{7}Be behaviour in surface air (Ajtić et al., 2015; Hernández-Ceballos et al. 2015,2016c), and although this radionuclide's records in Scandinavia have been previously studied (Leppänen et al., 2010, 2012; Leppänen&Paatero, 2013), the extremes in the ^{7}Be records have only been investigated for Helsinki, Finland (Ajtić et al., 2016).

Materials and Methods

Datasets

Measurements of the ^{7}Be specific activity in surface air are a part of the data stored in the Radioactivity Environmental Monitoring Database (REMdb) that encompasses a wider collection of different environmental radioactivity measurements in a large number of environmental sample types in Europe. The REMdb contains measurements since 1984. The ^{7}Be activity concentrations in surface air used in this study are a part of the sparse network consisting of high-sensitivity measurements performed in 34representative locations in Europe.

The REMdb is supported by REM group of the DG Joint Research Centre (JRC). The ^{7}Be measurements prior to 2007 are public, while the access to the data corresponding to the 2007–2011 period can be granted only after explicit request. More details on the REMdb and ^{7}Be specific activity measurements can be found in Hernández-Ceballos et al. (2015) and the REMdb monitoring reports (https://rem.jrc.ec.europa.eu/RemWeb/Reports.aspx).

Monthly Scandinavia teleconnection indices (SCAND) were taken from the NOAA Climate Prediction Center (http://www.cpc.ncep.noaa.gov/data/teledoc/scand.shtml accessed 12 July 2016). The index values were standardised by the 1981–2010 climatology.

Study area

Four measurement sites, covering the northernmost region of Europe (55–69 °N; 12–28 °E), were chosen from the REM database. In these sites, approximately one measurement per week was performed over the 2001–2010 period, thus giving a total of approximately500 data points per each site. Table 1 shows the details of the chosen locations.

Table 1. *Measurement locations with their latitude and longitude, total number of measurements over 2001–2010, value of the 90th percentile, total number of extremes and extremes during winter.*

Measurement location	Latitude and longitude (°N; °E)	Total number of samples	90 % threshold (mBq/m^3)	Number of extremes	Number of winter extremes
Ivalo	(68.64; 27.57)	486	3.09	48	7
Umea	(63.85; 20.34)	496	3.39	49	5
Kista	(59.40; 17.93)	512	4.54	51	6
Risoe	(55.69; 12.10)	517	4.96	51	10

Methodology

In this analysis, the winter season was extended to four months: November, December, January and February (NDJF). Extremes in the ^{7}Be surface concentration were defined as measurements above the 90th percentile. The percentiles were calculated for each measurement locationcovering the whole period considered, thus obtaining an extreme criterion specific to each site (Ajtić et al., 2016). Table 1 also presents the 90% thresholds, along with the total number of extremes and winter extremes for each station.

Back-trajectory calculations

Hourly kinematic 3D backward trajectorieswere calculated over a 120-h period and at final heights of 500 m, 1500 m and 3000 m above ground level,using the Hybrid Single ParticleLagrangian Integrated Trajectory (HYSPLIT) modeldeveloped by the NOAA’s Air Resources Laboratory (Draxler et al.,2012). Model-calculated vertical velocities were used to compute backward trajectories, and the Global Data Assimilation System meteorological data set was used (information available online at http://ready.arl.noaa.gov/archives.php). These files have a spatial resolution of 1°x1° in latitude and longitude (111 km x 111 km), enough to resolve movement of air masses and its impact on the synoptic transport.

Since air masses with stratospheric properties, such as low temperature and low relative humidity, have been detected deep in the troposphere, at 3 km (Di Girolamo et al., 2009), we used this height as a tentative indication of stratospheric intrusion.

Potential vorticity anomaly calculations

Wind and temperature pressure level data from the NCEP/NCAR reanalysis (Kalnay et al., 1996) were used to calculate the potential vorticity (PV) anomalies at the 300 hPa level over the Northern Hemisphere. First, for each investigated month, November, December, January and February, long-term monthly mean PV over 1981–2010 was calculated, and then,for each day, the PV anomaly was obtained by subtracting daily PV field from the long-term mean for the corresponding month. For example, 31x30 (number of days in January x number of years over 1981–2010) anomaly PV fields were constructed for the month of January.

Further, for each grid point in the Northern Hemisphere and for each month, the 90th percentile in the PV anomaly series was calculated. This value was subsequently used in our analysis to separate areas with strong PV anomalies–a grid point was considered to have a “strong” PV anomaly if it was above the calculated 90th percentile for the given grid. This methodology enabled us to take into account the PV variability in the meridional direction, but also its month to month variability, as well as to avoid using a single fixed value as a threshold.

Results and Discussion

Table 1 shows the contribution of the winter extremes to the total number of extremes. The contribution rangedbetween 10 % in Umea, and 20 % in Risoe. Overall, for the four investigated measurements sites, there were 199 measurements above the 90th percentile, out of which 28 (14 %) occurred in (the four months of) winter.

The winter extremes were grouped according to the month in which they were registered,and two types of events were distinguished according to their spatial and temporal prevalence:

- type-1, when the number of extremes in a given month was less than three, and
- type-2,when at least three extremes occurred in a month – the extremes were either coincident (within a day) at three different sites, or consecutive extremesat one location with at least one extreme occurring elsewherein the region.

Table 2 shows the two types of the winter extremes and the corresponding monthly Scandinavia teleconnection index.

Table2. *Two types of winter ^{7}Be extremes and the corresponding monthly value of the SCAND index.*

Extreme type	Date (YYYYMM)	Site andthe end date of the measurement period in parenthesis	SCAND
Type-1	200502	Ivalo (13), Umea (28)	0.74
	200511	Risoe (14)	0.49
	200712	Kista (25), Risoe (21)	0.43
	200801	Ivalo (07), Kista (06)	0.46
	200901	Ivalo (19), Umea (12)	0.06
	200902	Ivalo (09), Umea (09)	0.53
	200911	Ivalo (09)	0.82
	200912	Kista (21)	0.86
Type-2	200302	Ivalo (23), Umea (24), Risoe (24)	1.55
	200601	Ivalo (23), Kista (23), Risoe (09, 23)	2.11
	201001	Kista (25), Risoe (18, 26)	1.23
	201002	Umea (01), Kista (01), Risoe (01, 08, 15)	1.04

It should be noted here that the end day of the ^{7}Be measurement period (the usual duration of the measurement periods for the four sites was six to eight days) was taken as the representative day of the whole period. In other words, a time stamp corresponding to the last day of the measurement period was given to the observed occurrence of extremely high ^{7}Be surface concentration. For example, three ^{7}Be extremes, in Ivalo, Umea and Risoe, were detected during February 2003 (Tab. 2), and we marked these events with the last day of the observation period for each of the sites, which was 23 February for Ivalo, and 24 February for Umea and Risoe.

The SCAND pattern consists of a primary circulation centre over Scandinavia, with weaker centres of opposite sign over western Europe and eastern Russia / western Mongolia (Barnston&Livezey, 1987). Over Scandinavia, the positive phase of the SCAND pattern is associated with: positive height anomalies, sometimes reflecting major blocking anticyclones; below-average temperatures; and below-average precipitation. These characteristics of the SCAND positive phase can be favourable for a stratospheric intrusion and an ensuing fast descent of air masses (Davies &Schuepbach, 1994; Di Girolamo et al., 2009; Kentarchos et al., 1998; Zanis et al., 2003).

For type-1 events (Tab. 2), except the one that occurred in January 2009, SCAND was close to or higher than 0.5 (the values of SCAND greater than 0.5 fall into the 66th percentile). For type-2 events, SCAND was above 1 (the 95th percentile). During February 2003, when a type-2 event was registered (Tab. 2), an extreme ^{7}Be occurrence was also noted in Helsinki, Finland (Ajtić et al., 2016).

Over 2001–2010, the winter SCAND index greater than 1 was observed in other two instances: in January 2001 and November 2003, when the SCAND index was 1.45 and 1.51, respectively. However, they were not accompanied by an extreme ^{7}Be occurrence.

We performed back-trajectory calculations to further analyse the transport conditions associated with the extreme ^{7}Be events. Figure 1 gives an example forthe type-2 event in February 2003, with 23 and 24 February taken as the representative days of the extremes (as briefly described above), and thus the starting days for the back-trajectory calculations.The trajectories for Umea and Risoe on 24 February 2003 had a clear anticyclonic movement, as expected in a situation with a high-pressuresystem over Scandinavia (corresponding to high values of SCAND), which further implied that sources of high ^{7}Be concentrations were located in a wider area on the edges of this high-pressure system. In each measuring location, there were trajectorieswith altitudes above 3000 m, some of which passed through grids of anomalously high PV values.

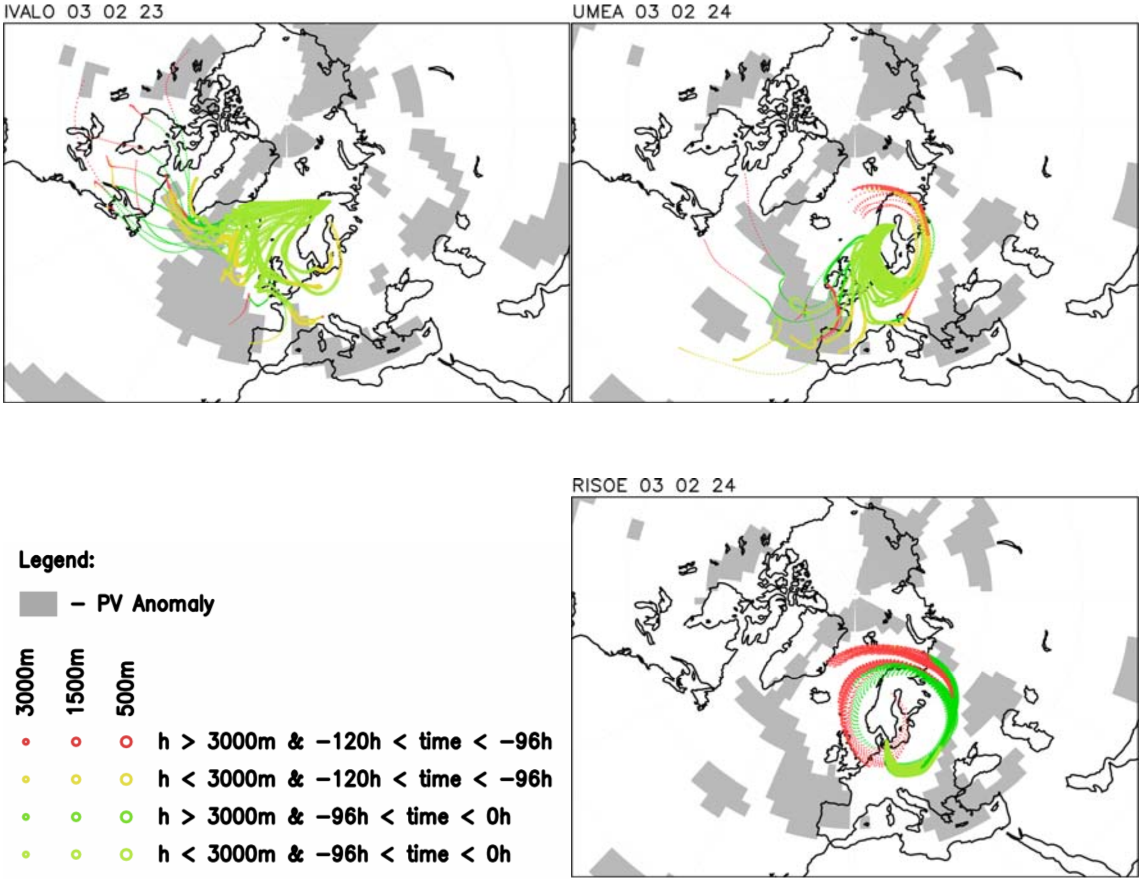

Figure 1.*Back trajectories for Ivalo, Umea and Risoe. The trajectories started on therepresentative daysof the ^{7}Be extremes detected in February 2003, and were run backwards for five days. Three starting altitudes were chosen: 3000 m (small circles), 1500 m (medium-sized circles) and 500 m (large circles). The altitudes of the trajectories are colour coded: red and yellow if on the last day of calculations (between -96hours and -120hours), the altitude was higher or lower than 3000 m, respectively; dark and light green ifat any time during the first four days of calculations (between 0hours and -96hours), the altitude was higher or lower than 3000 m, respectively.Given in grey are areas whereinthe PV anomaly was above the 90th percentile threshold for the fourth (-96 hours) and fifth (-120 hours) day of the back-trajectory calculations in corresponding reanalysis grid points.*

Although our approach needs a stricter statistical analysis of backtrajectories, their overall pattern for all the identified ^{7}Be extreme events showed a number of anticyclonictrajectories passing through fields of anomalously high potential vorticity above 3000 m.

Conclusions

Our results showed thatextremely high ^{7}Be surface concentrations in northern Europe occur over the November–February months. These winter extremes contributed between 10 % (in Umea) and 20 % (in Risoe) to the total number of extremes observed over the 2001–2010 period.

Two types of the ^{7}Be extremes were distinguished:isolated events detected in one or two stations (type-1), and extremes grouped within four months (February 2003, January 2006, and January and February 2010), when at least three ^{7}Be extremes per month were observed (type-2). In the case of type-1 extreme events, the monthly SCAND was positive and, with only one exception, larger than 0.4, while for type-2 events, the monthly SCAND was very high (larger than 1). This finding implies that in northern Europe during winter, the atmospheric conditions associated with a high SCAND index facilitate an occurrence of extreme ^{7}Be surface concentrations.The analysis of backtrajectories run for five days backwards from the representative dates of the extreme occurrences showed a prevailing pattern withanticyclonic trajectories passing through areas of anomalously high potential vorticity fields above 3000 m.

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