Journal of Environmental Radioactivity 127 (2014) 88–94

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

journal homepage: www.elsevier.com/locate/jenvrad

Hadley cell influence on ^{7}Be activity concentrations at Australian mainland IMS radionuclide particulate stations

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ARTICLE INFO

Article history:
Received 14 May 2013
Received in revised form
9 October 2013
Accepted 15 October 2013
Available online 27 October 2013

Keywords:
^{7}Be
Annual cycle
Hadley cell
CTBT
IMS
Australia

ABSTRACT

Beryllium-7 (^{7}Be) daily data from the four International Monitoring System (IMS) radionuclide particulate stations on mainland Australia are analysed over the period 2001 to 2011. The analysis indicates that levels of ^{7}Be in surface air at the stations follow annual cycles, with yearly peak activity concentrations occurring later at stations further south. The yearly peak migrates north–south at a rate of approximately 4.4° latitude per month. The change in phase of the ^{7}Be annual cycle between the stations corresponds with the seasonal migration of the Southern Hemisphere Hadley cell across mainland Australia. The implication is that the changing position of the downward limb of the Southern Hemisphere Hadley cell regulates the phase of the annual cycle in ^{7}Be activity concentrations in surface air in the Australian region.

1. Introduction

The International Monitoring System (IMS) established under the Comprehensive Nuclear-Test-Ban Treaty (CTBT) includes a global network of 80 radionuclide stations to monitor the air for anthropogenic radioactivity indicative of a nuclear explosion. Simultaneous with this CTBT verification role, IMS radionuclide stations produce data on naturally occurring radionuclides in surface air. One such radionuclide that is readily detected in routine gamma spectrometric analysis of daily particulate air monitoring samples is ^{7}Be, which is produced largely in the lower stratosphere and upper troposphere through the spallation of nitrogen and oxygen nuclei by cosmic-ray-produced neutrons and protons (Lal and Peters, 1967) and which decays to lithium-7 (^{7}Li) via electron capture and gamma emission (477.6 keV, 10.44%) with a half-life of 53.22 d (Tilley et al., 2002).

The production of ^{7}Be in the atmosphere is principally governed by the energy flux of cosmic-ray-produced neutrons and protons (which decreases with atmospheric depth) and the density of nitrogen and oxygen nuclei (which increases with atmospheric depth). The result is that ^{7}Be production rates are greatest in the lower stratosphere, less, but still substantial in the upper troposphere, and least in the lower troposphere (Lal and Peters, 1967). Height differences in production rates, together with atmospheric transport and removal processes, result in approximately order of magnitude activity concentration gradients between the lower stratosphere and upper troposphere and between the upper troposphere and surface air. Aircraft-based sampling indicates that typical ^{7}Be activity concentrations in the lower stratosphere are of the order of hundreds of mBq m^{-3} and that those in the upper troposphere are of the order of tens of mBq m^{-3} (Drevinsky et al., 1964; Dutkiewicz and Husain, 1985; Feely et al., 1989; Jordan et al., 2003). Typical ^{7}Be activity concentrations in surface air are only a few mBq m^{-3} at most locations worldwide (see, e.g., Feely et al. (1989) who give results of a global surface air sampling program).

The production of ^{7}Be in the atmosphere also varies temporally and latitudinally. Temporal variations occur over the ~11 y period of the solar cycle. Production rates are lower at sunspot maxima when the galactic cosmic-ray intensity to Earth is lowest (due to flooding of the interstellar medium with solar particles) and higher at sunspot minima (Lal and Peters, 1967; Masarik and Beer, 1999). The estimated solar effect on production rates of cosmogenic radionuclides in the atmosphere (including ^{7}Be) is a 15% increase (at sunspot minima) and decrease (at sunspot maxima) compared to the average production rate over a complete solar cycle (Masarik

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http://dx.doi.org/10.1016/j.jenvrad.2013.10.011

and Beer, 1999). Latitudinal variations in ^{7}Be production occur due to the deflection of incoming cosmic-rays by Earth's magnetic field. For any given height above sea level, production rates are lower above the equator (where the geomagnetic field is strongest) and higher above the poles (where the geomagnetic field is weakest) (Lal and Peters, 1967). Accounting for variations in tropopause height with latitude, the increase in production rates within the lower stratosphere and upper troposphere between the equator and mid-latitudes is by around a factor of two. No substantial additional increases in production rates occur within the lower stratosphere and upper troposphere between the mid-latitudes and the poles.

Beryllium-7 produced in the atmosphere quickly becomes an aerosol associated specie. Its transport in the atmosphere is governed by the same processes governing that of the aerosol. The typical behaviour of ^{7}Be in surface air at most locations worldwide is for activity concentrations to follow an annual cycle. This behaviour is generally considered indicative of seasonal stratosphere-to-troposphere exchange and vertical air mass transport from the upper to the lower troposphere (Feely et al., 1989). The vertical concentration profile of ^{7}Be in the atmosphere is similar to that of ^{137}Cs and other particulate-bound fission products that were previously present in the atmosphere due to the global circulation via the stratosphere of radioactive debris from above ground nuclear weapons testing; the atmospheric reservoir of these fission products is now effectively depleted due to deposition and decay. Past measurements of ^{7}Be and weapons-produced fission products show strong similarities between their behaviour in surface air (Gustafson et al., 1961; Parker, 1962; Rangarajan and Gopalakrishnan, 1970), including in the phase of their annual cycles, suggesting that the same atmospheric transport processes govern the surface air behaviour of both. Natural and renewable ^{7}Be has the potential to be used as a surrogate to develop and refine models of the likely surface air behaviour of ^{137}Cs and other fission products from future nuclear events with global fallout consequences and to investigate the regional atmospheric transport processes controlling this behaviour. The utility of ^{7}Be to reconstruct the surface air ^{137}Cs signal from historical nuclear weapons testing has also been demonstrated (Alonso Hernández et al., 2004).

Australia hosts seven IMS radionuclide stations in its territories. All seven stations have radionuclide particulate monitoring capability and two also have noble gas (radioxenon) detection systems. The stations are currently maintained by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) under contract with the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organisation (CTBTO). Four of the stations are located on the Australian mainland and have been in routine IMS operation for several years. This paper presents a first analysis of the ^{7}Be data from these stations. The aim is to investigate the surface air behaviour of ^{7}Be activity concentrations at the stations (primarily the annual cycles) and reconcile this behaviour with known atmospheric processes. This paper also demonstrates the complementary role of the IMS in providing data for natural radionuclides that are of no CTBT verification significance but which can be used to predict the surface air behaviour of aerosol associated radioactive species from future nuclear events with global fallout consequences.

2. Station locations and climate information

Location details of the four Australian mainland IMS radionuclide particulate stations are given in Table 1. The stations are geographically well spread. They are located at Darwin, Townsville, Perth and Melbourne. Darwin is in the north of Australia, Townsville is on the northern part of Australia's east coast, Perth is on the southern part of Australia's west coast and Melbourne is in the southeast corner of Australia. Table 2 summarises general climate information for each station location for the most recent 30 y climate reporting period (1981–2010) using data obtained from the Australian Government Bureau of Meteorology. Darwin and Townsville have a tropical climate with strong seasonality in rainfall and high year-round temperatures. Perth and Melbourne have a temperate climate with distinct seasonal temperature variations. Perth experiences a seasonal pattern in rainfall, whereas Melbourne does not.

Table 1
Location details and date of entry into IMS operation of the four Australian mainland radionuclide particulate stations.

IMS station code	Location	Latitude (°S)	Longitude (°E)	Elevation (m)	Date of entry into IMS operation
AUP09	Darwin	12.43	130.89	10	31 March 2002
AUP06	Townsville	19.25	146.77	7.5	30 November 2001
AUP10	Perth	33.93	115.97	15	28 July 2000
AUP04	Melbourne	37.72	145.10	44	28 July 2000

3. Methods

IMS radionuclide particulate stations use high volume air samplers to collect daily (~24 h) aerosol samples from the surface air and high resolution gamma spectrometry to analyse the samples. The minimum requirements for both the sampling and detection systems of an IMS radionuclide particulate station have been previously defined by the Preparatory Commission for the CTBTO and are summarised in Schulze et al. (2000). The four Australian mainland stations have been certified by the Provisional Technical Secretariat for the CTBTO as meeting these requirements.

Daily data of ^{7}Be activity concentrations in surface air were obtained from the International Data Centre (IDC) (Matthews and De Geer, 2005). The measurement periods considered were complete calendar years, from 1 January after the date of entry into IMS operation of each station as given in Table 1 to 31 December 2011. Analysis was made of the ^{7}Be annual averages and annual cycles.

4. Results and discussion

4.1. Annual averages

Table 3 gives the annual average and standard deviation of ^{7}Be activity concentrations in surface air at the four Australian mainland IMS radionuclide stations for each year of measurement. The annual averages suggest systematic differences in typical ^{7}Be activity concentrations in surface air between stations located in different climate zones during comparable years. The significance of these differences was investigated using *t*-test analysis at the

Table 2
Climate information summary for Australian mainland IMS radionuclide station locations for the climate reporting period from 1981 to 2010.

BoM station code[a]	Location	Climate type	Mean maximum temp (°C)		Mean annual rainfall (mm)	
			Summer	Winter	Amount	Distribution
014015	Darwin	Tropical	33.5	30.8	1811.4	Nov–Apr ~ 94%
032040	Townsville	Tropical	31.8	25.3	1071.7	Nov–Apr ~ 88%
009021	Perth	Temperate	32.1	18.1	725.0	May–Sep ~ 78%
086282	Melbourne	Temperate	26.5	13.0	518.9	Fairly uniform

[a] Refers to the Australian Government Bureau of Meteorology weather station used for climate information.