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Simulation of ^{210}Pb and ^{7}Be scavenging in the tropics by the LMDz general circulation model ☆

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ABSTRACT

A new formulation of aerosol scavenging by convective precipitations, consistent with the Emanuel convective mass-flux scheme, is implemented into the Laboratoire de Météorologie Dynamique general circulation model, LMDz. The aerosols ^{210}Pb and ^{7}Be are used as inert tracers to evaluate LMDz performance in terms of atmospheric transport in the tropics. Wind fields are calculated over 2007 in a regular grid with a resolution of 1.875° in longitude, 1.24° in latitude and 40 vertical levels. The first part of the paper addresses the sensitivity of LMDz simulations to convective schemes and to scavenging parameterizations. Results are analyzed at two tropical stations and one mid-latitude station by comparing simulated aerosol concentrations with available data, collected at surface stations. On a daily scale, the observed variations of concentrations are poorly reproduced by any considered model at both tropical stations. Nevertheless, fluctuations at timescales longer than a few days may be captured over periods of a few weeks to a few months by the new formulation.

The second part of this paper focuses on the new implemented parameterization of convective scavenging. The objective is to interpret mismatches of simulated concentrations with observed data and to determine which transport mechanisms are responsible for peaks of ^{7}Be concentrations recorded at tropical stations. Typical meteorological situations in Polynesia are analyzed in view of convective transport and scavenging of ^{7}Be. In particular, the sensitivity to the location of the South Pacific Convergence Zone is examined on concentrations in Polynesia. Results demonstrate that ^{7}Be plumes are brought downward in the middle atmosphere by large-scale subsidence associated to the subtropical jet, in a 35°–25°S band. At surface, ^{7}Be plumes are associated either to shallow convection or to deep convection with moderate precipitations. Within moderate convective events, surface concentrations are enhanced by surface release due to re-evaporation of precipitations. Most ^{7}Be surface plumes reaching the Polynesian stations are produced locally in the neighborhood of stations and advected over one or two days by surface large-scale winds. The largest mismatches may be attributed to uncertainties in the simulation of precipitations within deep convective cloud systems that develop along troughs.

1. Introduction

In the tropics, deep convection transports warm and moist air parcels from surface to upper troposphere within strong updrafts. As it rises, moist air condensates giving birth to convective precipitations. At the cloud top, horizontal transport of condensate produces laterally sheared clouds in the form of anvils. Convective precipitations are generally more intense than stratiform precipitations resulting either

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from cloud anvils or from stratified clouds formed in the large-scale circulation. Deep convection efficiently contributes to the vertical mixing of aerosols and to their removal from the atmosphere by precipitations. Aerosol particles present near a convective cloud are entrained inside the strong updrafts, a part of them being scavenged by convective precipitations and anvil precipitations. Whereas the aerosols transport time between surface and the higher troposphere may reach several days to weeks in large-scale circulation, the high vertical velocities in convective cells shorten this time to a few hours (Tost et al., 2010). The upward motion of aerosols is compensated by the downward motion within precipitations as well as by large-scale subsidence outside the convective cell. Precipitations may partially or totally re-evaporate as they fall through unsaturated atmospheric layers, releasing a fraction of aerosols.

In this paper, two natural radionuclides whose sources are global in extent and relatively known, ^{210}Pb and ^{7}Be, are used as passive tracers in order to investigate the effect of tropical convection on aerosol transport. ^{210}Pb, with a half-life of 22.3 years, is the decay daughter of ^{222}Rn that is an inert gas released into the atmosphere from porous soils containing uranium (Turekian et al., 1977). ^{7}Be, with a half-life of 53 days, is produced in a nuclear reaction by cosmic rays in the upper atmosphere. Soon after their production, the two radionuclides become attached to submicron aerosols and are transported with them, until aerosols are removed from the atmosphere by dry or wet deposition (e.g. Turekian and Graustein, 2003). As the only source of ^{210}Pb is decay of radon, emitted from continents, its detection at remote locations indicates intercontinental air motions. Due to its origin, concentrations of ^{7}Be are much higher in the stratosphere than in the lower troposphere due both to the largest production in the upper atmosphere and to long residence times of beryllium isotopes in the stratosphere, estimated at around one year (Heikkilä and Smith, 2012). Hence, the introduction of ^{7}Be in the lower troposphere is controlled by mass exchanges between stratosphere and troposphere, large-scale subsidence and convective circulation. In the tropics, both radionuclides are removed primarily from the troposphere by wet removal processes, in both large-scale systems and convective clouds (e.g. Guelle et al., 1998). In the published studies, the estimated mean residence times in the troposphere depend on the modeling of scavenging and range from 18 to 23 days for ^{7}Be and from 4 to 11 days for ^{210}Pb (e.g. Feichter et al., 1991; Koch et al., 1996; Liu et al., 2001; Heikkilä and Smith, 2012).

General circulation models (GCMs) do not explicitly resolve individual convective clouds. Transport of aerosols in global models requires a representation of both convection and aerosol scavenging by precipitations. These two parameterizations lead to large uncertainties in the transport of aerosols and make it difficult to interpret mismatches of the simulated concentrations with observations.

The adequate formulation of convection in GCMs is one of the major uncertainties in simulations of tropical weather. The pioneer work of an intercomparison of convection schemes was performed by Mahowald et al. (1995) who investigated the influence of seven convection schemes on tracer transport in a chemical transport model. More recently, Tost et al. (2010) examined the sensitivity on the trace gases transport to five different convection schemes in a GCM. In this paper, transport of radionuclides is simulated over one year by the GCM LMDz, in which two convection schemes are implemented, Tiedtke's (1989) and Emanuel's (1991) schemes. The originality of this latter scheme is the introduction of a precipitating downdraft governed by evaporation of rain that plays a key role in the downward transport of ^{7}Be. Moreover, better results are expected using this scheme since it is better adapted to model tropical deep convection and improves significantly the large-scale distribution of tropical precipitation (Hourdin et al., 2006).

Convective scavenging in GCMs has been the object of numerous studies, in which the natural radionuclides ^{210}Pb and ^{7}Be are used as passive tracers (e.g. Balkanski et al., 1993; Guelle et al., 1998; Koch et al., 1996; Liu et al., 2001; Hauglustaine et al., 2004; Heinrich and Jamelot, 2011). So far, LMDz simulations by Heinrich and Blanchard (2009) or by Heinrich and Jamelot (2011) used traditional convective scavenging schemes developed independently of the convective scheme. As regards ^{210}Pb and ^{7}Be transport, they found that LMDz was able to reproduce over the globe the characteristic patterns of horizontal distribution and their maps of monthly averaged concentrations (Heinrich and Jamelot, 2011) were similar to those calculated by Guelle et al. (1998) or Liu et al. (2001). Their simulations were also evaluated by comparing daily-averaged surface concentrations to high quality data from stations, which belong to the International Monitoring System (IMS) of the Comprehensive Test Ban Treaty Organization and collect airborne aerosols on a daily routine (Schulze et al., 2000). At a timescale of a few days, agreement with recorded time series was considered as satisfactory for stations at mid- and high-latitudes. By contrast, simulated time series at tropical stations indicated a large sensitivity to convection parameterizations and were in poor agreement with data. In particular, an exaggerated release of radionuclides due to re-evaporation was modeled in simulations using the Emanuel's scheme and a traditional convective scavenging scheme. These results have led us to develop a new parameterization of scavenging.

Convective scavenging and convective transport are two processes that compete with respect to transport of aerosols. The originality of this formulation, implemented by Pilon et al. (submitted for publication), is to be fully consistent with air and water motions within the Emanuel's (1991) convective scheme. Validation of this parameterization has been based on single-column simulations of the TOGA COARE experiment (Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment) and has been followed by an extension of the parameterization to the three-dimensional model. The first results from 3D simulations are presented in this paper, with a focus on the comparison of recorded and simulated concentrations at two tropical stations. In the literature, most numerical studies by GCM consist in comparing measured and simulated concentrations on a monthly or seasonal scale. Recently, Usoskin et al. (2009) simulated ^{7}Be transport using a nudged GCM for one solar particle event occurring at high latitudes. Simulated daily averaged concentrations were compared over 50 days with data from 11 stations of the IMS. They found that ^{7}Be time series were satisfactorily reproduced at timescales longer than 4 days but that shorter time fluctuations were unevenly captured.

This paper is focused on the atmospheric transport of ^{7}Be and ^{210}Pb in Polynesia at different timescales. Its purpose is twofold. The first is to address the sensitivity of LMDz simulations to the