Science of the Total Environment 557–558 (2016) 861–868

Contents lists available at ScienceDirect

Science of the Total Environment

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

A 20-year simulated climatology of global dust aerosol deposition

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HIGHLIGHTS

- Annual dust deposition of 1161 Mt is averaged from a 20-year global dust simulation.
- Dry deposition of dust aerosol is globally greater than dust wet deposition.
- A decreasing trend in modeled global dust deposition exists over 1991–2010.
- Dust deposition shifts from high in spring and summer to low in fall and winter.

ARTICLE INFO

Article history:
Received 31 January 2016
Received in revised form 11 March 2016
Accepted 12 March 2016
Available online xxxx

Editor: D. Barcelo

Keywords:
Climate model
Dust aerosol deposition
Interannual variations
Seasonal cycle

ABSTRACT

Based on a 20-year (1991–2010) simulation of dust aerosol deposition with the global climate model CAM5.1 (Community Atmosphere Model, version 5.1), the spatial and temporal variations of dust aerosol deposition were analyzed using climate statistical methods. The results indicated that the annual amount of global dust aerosol deposition was approximately 1161 ± 31 Mt, with a decreasing trend, and its interannual variation range of 2.70% over 1991–2010. The 20-year average ratio of global dust dry to wet depositions was 1.12, with interannual variation of 2.24%, showing the quantity of dry deposition of dust aerosol was greater than dust wet deposition. High dry deposition was centered over continental deserts and surrounding regions, while wet deposition was a dominant deposition process over the North Atlantic, North Pacific and northern Indian Ocean. Furthermore, both dry and wet deposition presented a zonal distribution. To examine the regional changes of dust aerosol deposition on land and sea areas, we chose the North Atlantic, Eurasia, northern Indian Ocean, North Pacific and Australia to analyze the interannual and seasonal variations of dust deposition and dry-to-wet deposition ratio. The deposition amounts of each region showed interannual fluctuations with the largest variation range at around 26.96% in the northern Indian Ocean area, followed by the North Pacific (16.47%), Australia (9.76%), North Atlantic (9.43%) and Eurasia (6.03%). The northern Indian Ocean also had the greatest amplitude of interannual variation in dry-to-wet deposition ratio, at 22.41%, followed by the North Atlantic (9.69%), Australia (6.82%), North Pacific (6.31%) and Eurasia (4.36%). Dust aerosol presented a seasonal cycle, with typically strong deposition in spring and summer and weak deposition in autumn and winter. The dust deposition over the northern Indian Ocean exhibited the greatest seasonal change range at about 118.00%, while the North Atlantic showed the lowest seasonal change at around 30.23%. The northern Indian Ocean had the greatest seasonal variation range of dry-to-wet deposition ratio, at around 74.57%, while Eurasia had the lowest, at around 12.14%.

1. Introduction

Dust aerosol is the main component of atmospheric aerosols. It is estimated that, globally, annual dust aerosol emissions into the atmosphere total 1000–3000 Mt, which basically accounts for about half of the total tropospheric aerosol amount (Charlson et al., 1995; Houghton et al., 2001; Zender et al., 2004). Dust aerosol has important influences on the ecological environment and climate change within regions, and even globally (Sokolik et al., 2001; Ackerman et al., 2000; Chiapello et al., 2005). Long-distance transport and deposition of dust aerosol have significant effects on global biogeochemical cycles. The

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http://dx.doi.org/10.1016/j.scitotenv.2016.03.086
0048-9697/

deposition of dust aerosol can change the surface albedo, affect loess accumulation, provide nutrients (Fe^{2+}) to marine plankton, and affect oceanic absorption of CO_2 (Martin, 1990). Therefore, dust aerosol can link biogeochemical cycles through sand emissions, atmospheric transport and deposition, which has become a vital aspect in the study of global change with its environmental effects (Goudie et al., 2006).

Observational data with respect to dust aerosol are deriving mainly from ground-level meteorological observation systems, allowing the basic characterization of temporal and spatial distribution of dust aerosol (Cowie et al., 2014; Flamant et al., 2012). With the development of remote sensing technology and the use of ground radar, solar spectrometers and other instruments, the large area and vertical structure of dust aerosol can also be studied (Wang et al., 2013). In recent times, with the operation of a variety of satellites, high spatial and temporal resolution and multi-channel remote sensing observation of dust aerosol have become a reality (Ginoux et al., 2012; Karyampudi and Carlson, 1988). Nevertheless, due to the short records of high-quality observations of dust aerosol, the model-based analysis still plays a key role.

Based on a study of the variations of dust aerosols, Sun (2002) suggested that the formation of the Loess Plateau in China was affected by sand storms releasing, transporting and depositing dust, and the many years of soil regeneration and accumulation. Martin et al. (1990) revealed that strong dust storms can transport aeolian Fe^{2+} from inland dust source areas to the oceans, triggering the biological pump and raising the productivity of phytoplankton. This enhancement of marine primary productivity can reduce the concentration of CO_2 in the atmosphere. Dust aerosols act as a refrigerant for the planet and are a key link in the global material cycle and climate change (Coale et al., 1996; Watson et al., 2000).

The previous studies demonstrated the importance of dust aerosols at large spatial and temporal scales; and yet, thus far, most studies in this field have focused on a specific time and region, with few considering global climate change over long periods of dust deposition. In the present study, based on a 20-year (1991–2010) simulation of dust aerosol deposition with the global climate model CAM5.1 (Community Atmosphere Model, version 5), the interannual and seasonal variations of dust deposition at the global scale were investigated, with a focus on the differences in the characteristics of major land and sea areas.

2. Methods

2.1. CAM5.1 and its dust aerosol deposition scheme

CAM5.1 is the atmospheric model component of the Community Earth System Model developed by the National Center for Atmospheric Research, USA. The aerosol module in the model contains atmospheric aerosol emissions, transport, transformation, dry and wet depositions, and aerosol–cloud interaction. The mass conservation equation of aerosol is expressed as follows (Gong et al., 2003):

$$\frac{\partial x_{ip}}{\partial t} = \frac{\partial x_{ip}}{\partial t}\bigg|_{SOURCES} + \frac{\partial x_{ip}}{\partial t}\bigg|_{TRANSPORT} + \frac{\partial x_{ip}}{\partial t}\bigg|_{CLEAR\text{-}AIR} + \frac{\partial x_{ip}}{\partial t}\bigg|_{DRY} + \frac{\partial x_{ip}}{\partial t}\bigg|_{IN\text{-}CLOUD} + \frac{\partial x_{ip}}{\partial t}\bigg|_{BELOW\text{-}CLOUDS}.$$

In this equation, x_{ip} is the aerosol mass, in which p is the type of aerosol particle and i indicates the different bin of aerosol particle size distributions. The local variation in aerosol mass is determined by aerosol emissions, transport, chemical transformation, wet growth and collision and coalescence growth, dry deposition, in-cloud scavenging and the wash-out process below cloud. Based on current scientific understanding, dust aerosol emissions are derived from natural wind erosion, and dust aerosol deposition is a nonlinear complex process and has numerous factors of influence. The dry deposition process is affected by gravitational settling and dispersion and transportation of turbulence, which is closely related to aerosol particle size, atmospheric stability and the physical and chemical characteristics of the underlying surface (Sievering, 1967; Chamberlain, 1967; Slinn et al., 1980; Wedding et al., 1980; Peters et al., 1992; Gallagher et al., 2002). Wet deposition involves in-cloud and below-cloud scavenging processes, and is affected by factors such as aerosol particle size, size distribution and solubility (Greenfield, 1957; Lai et al., 1978). The mineral dust entrainment and deposition (DEAD) model was introduced as dust emission and deposition schemes in the model (Zender et al., 2003).

2.2. Simulation and analysis

The resolution of the horizontal grid in CAM5.1 was 2.5° × 1.9°, consisting of 144 zonal grid points and 96 meridional grid points. The σ-p mixed coordinate system was used in the vertical direction. The model top was at approximately 3.64 hPa, and the entire vertical column was divided into 30 layers. The simulation time was from 1 January 1990 to 31 December 2010 with spin-up in the first year of 1990, providing a 20-year (1991–2010) set of global simulated aerosol deposition data to be analyzed. The model performance evaluation and validation (Liu et al., 2012; Liu et al., 2015; Albani et al., 2014) confirmed that the climate model CAM5.1 can simulate global dust emissions in a reasonable range, although a large uncertainty in dust emission modeling still existed due to the current dust fluxes schemes and predicted meteorological parameters. This study focused on the 20-year climate modeling of global dust aerosol depositions to characterize the climatology of dust aerosol deposition. The dust deposition are the total amount of dust dry and wet depositions, and the ratio of dry to wet deposition was defined as the deposition ratio. To quantitatively characterize the interannual and seasonal variations of dust deposition and deposition ratio, the ratios of the standard deviations of interannual (monthly) changes to the annual (monthly) averages of dust deposition and deposition ratio over the 20-year period are defined as the interannual (seasonal) variation range. The trend of global dust aerosol deposition was also analyzed, by using the linear trend statistical method. The land and sea deposition areas selected for analysis are detailed in Table 1. The annual and seasonal variations of total deposition and dry-wet deposition ratio in these areas were also discussed in the following sections.

Dust emission source areas are concentrated over the desert regions, including Sahara, Arabia, Karakum, Gobi, Taklimakan, Australian and Great Sandy deserts (Prospero et al., 2002). The global climate model CAM5.1 used in this study has been successfully applied in many other studies (e.g., Gates et al., 1999; Ghan, 2013; Wehner et al., 2014). Based on the model performance evaluation and validation (Liu et al., 2012;; Liu et al., 2015; Albani et al. 2014), the 20-year global dust aerosol deposition dataset produced by the model in the present study could be sufficiently reliable for climate analysis.

3. Results

In the CAM5.1, the dry deposition scheme considered the gravitational settling and turbulent Mix-Out of aerosols, and the wet deposition scheme treated the nucleation in clouds and wash-out scavenging by convective and for stratiform precipitation below clouds (Liu et al., 2012.). By analyzing the total amount of dry and wet depositions of

Table 1
Details of the land and sea areas selected for analysis in this study.

Region	Latitude	Longitude
North Atlantic	5°S–42°N	18°W–100°W
Eurasia	28°N–78°N	10°W–150°E
North India ocean	5°S–24°N	54°E–100°E
North Pacific	20°N–65°N	140°E–120°W
Australia	3°S–53°S	84°E–180°E