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Moisture sources of the Chinese Loess Plateau during 1979–2009

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ABSTRACT

The Chinese Loess Plateau (CLP) is one of the regions in China with the most serious water scarcity, and precipitation is a key issue in the CLP climate. To investigate the main sources of moisture for the CLP, we apply a Lagrangian particle dispersion model known as the flexible particle dispersion model (FLEXPART) to perform a 31-year transient simulation (1979–2009) with backtracking particles residing over the CLP for 10 days in this study. Further, a moisture source attribution method, the areal source–receptor attribution method, is employed to quantify the contributions of the moisture source regions to the CLP precipitation. The results show that in summer (June–July–August), the moisture transported into the CLP originates mainly from central–eastern China, northwestern China–eastern Central Asia, the South China Sea, the East China Sea, the Bay of Bengal, and the Arabian Sea. In contrast, in winter (December–January–February) the main moisture source regions are northwestern China–eastern Central Asia, central–eastern China, the sea around the Arabian Peninsula, the southern Tibetan Plateau–northwestern Indo-China Peninsula, and the Mediterranean Sea. Because of significant losses en route, such as those caused by terrain obstruction and the long path to the continental interior, the eventual moisture release to the CLP is much less than the original uptake. Of the above-mentioned sources, the continental moisture sources near the CLP are the main contributors to precipitation over the CLP in both summer and winter; of these, a high proportion is contributed by central–eastern China and northwestern China–eastern Central Asia, while the oceanic moisture sources make a very small contribution. The reasons for this phenomenon may include the great distance between the related oceans and the CLP; thus, the direct oceanic water vapor transport into the CLP encounters obstacles on conventional backtracking days. Furthermore, the indirect oceanic moisture sources of the CLP are also preliminarily discussed herein.

1. Introduction

Anthropogenic greenhouse gas emissions have been widely accepted as the primary cause of global climate change since the mid-20th century, and regional climate changes are usually inconsistent with the global mean and are more relevant for human and natural ecosystems (IPCC, 2013). Furthermore, the initial regional changes usually expand to a larger scale, which might even affect the large-scale change. Considering the complexity and scale-dependence of the Earth's climate system, the past, present and future climate changes at a regional scale are particularly worthy of study.

In recent years, increasing attention has been paid to climate change in China, where climatic types differ greatly in the eastern and western parts of the country. Particularly, the Chinese Loess Plateau (CLP), which lies between eastern and western China, has its own distinct climate variation in the context of global warming. Loess is highly susceptible to the forces of water and wind (Yoder, 1936; Zhao et al., 2013); thus, the CLP, which is mostly covered with loess, is one of the most erosion-prone places on Earth. This region is also notably characterized by limited water resources, as the annual precipitation averages 382 mm per year, which is mainly received in summer (Huang et al., 2008; Sui et al., 2013). Such a water deficit is a critical factor in influencing vegetation restoration and environmental reconstruction, among other ecological dynamics (Li and Shao, 2006). For these reasons, the CLP — a densely populated region classified as semi-arid continental climate — is not only an ecologically vulnerable region but also a sensitive region that responds to global climate change (Vörösmarty et al., 2000; Piao et al., 2010). Despite the importance of the CLP, very few studies have attempted to elucidate the physical mechanism of climate over the CLP as distinct from other regions, such as eastern China and the

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Tibetan Plateau. Thus, it is critically important to analyze the limited water resources of this region from various perspectives, including the question of the source of the water vapor (Stohl and James, 2004) because the actual moisture source regions of the CLP precipitation, particularly from a climatologic perspective, remain unclear.

Even more notable is the fact that loess, together with deep-sea sediments, ice cores, and stalagmites, is one of the most valuable archives of past climates. The loess and underlying red clay sediments carry an abundance of information of past environmental changes since the Miocene (e.g., Liu and Ding, 1998; Guo et al., 2002; Hao et al., 2012; Yang et al., 2015). Such long and consecutive records are essential for studying tectonic–climate interaction mechanisms and understanding the responses of climate system to external forces (Cronin, 2009), particularly for investigating Asian climate evolution and its driving mechanisms. Thus, exploring the modern moisture source regions of the CLP is helpful in gaining insight into past long-term climate change over the CLP.

Several studies have aimed at identifying the moisture source regions for the sub-regions of China, not including the CLP, based on isotopic composition (Tian et al., 2007; Liu et al., 2008; Wen et al., 2010), but the isotope data are not normally available for the selected regions for a long-term period (Stohl and James, 2004). On the other hand, a great deal of work has been performed using the conventional Eulerian method to investigate moisture source regions and moisture transport (e.g., Simmonds et al., 1999; Zhou et al., 2011; Sun and Wang, 2013). However, the Eulerian method has limitations in its ability to track the water vapor from the potential moisture source regions to the target region because it only depends on the variations of the meteorological elements over the regions (Sun and Wang, 2014). Recently, a Lagrangian flexible particle dispersion model (FLEXPART) was developed (Stohl and James, 2004, 2005); it was originally applied to track the transport of air pollutants and radioactive constituents (Stohl, 1998) and has been used extensively to estimate moisture transport and its source regions (e.g., Sodemann et al., 2008; Stohl et al., 2008; Sodemann and Stohl, 2009; Gimeno et al., 2010, 2013; Drumond et al., 2011; Chen et al., 2012, 2013; Sun and Wang, 2014, 2015; Huang and Cui, 2015). In comparison with the Eulerian method mentioned previously, FLEXPART can be used for tracking moisture from the potential moisture source regions to the target region or backtracking in reverse. Moreover, the changes of the water vapor in the transport path can be accurately calculated. Recently, Drumond et al. (2011) examined the moisture source regions that affect the major regimes of summer precipitation in China during 2000–2004. Sun and Wang (2014) investigated the moisture source regions of semi-arid grassland in China on precipitation days in summer and winter during 2000–2009. Among the abovementioned studies, however, most have undertaken short-term simulations, which may be inappropriate to address the mean state of the climatology. To consider the moisture transport for a relatively long-term period that can be regarded as a standard window at the climatological scale, here we perform a relatively long-term simulation, covering a 31–year period (1979–2009) that is longer than earlier experiments, configured with high spatial and temporal resolutions.

The article is organized in the following manner. The FLEXPART model and the method used in this study are described in Section 2. Section 3 describes the moisture source regions of the CLP and the contribution of potential moisture source regions to the precipitation in the CLP. The conclusions and discussions are presented in Section 4.

2. Method, data and region

2.1. Data and model

The FLEXible PARTicle dispersion model (FLEXPART) is applied here, which was established on the basis of the Lagrangian equations of atmospheric motion and the Langevin equations for Gaussian turbulence (Stohl and James, 2004, 2005). Unlike other models in view of Eulerian viewpoint, different parameters can be tracked for the entire atmosphere along individual trajectories in the FLEXPART. This model has been applied widely to amount of studies involving the transport of air pollutant, water vapor, and radioactive constituents from the source to the target region. Moreover, FLEXPART has also been used in large studies of moisture transport by case study or climatology (e.g., Sodemann et al., 2008; Stohl et al., 2008; Sodemann and Stohl, 2009; Sun and Wang, 2014, 2015; Huang and Cui, 2015). The latest version — FLEXPART 9.02 has been initialized in a forward mode to track atmospheric moisture for the entire atmosphere along trajectories from the source regions using NCEP–CFSR 6–h data (Saha et al., 2010), including land cover, temperature, relative humidity, and three-dimensional winds at 42 levels with a horizontal resolution of 0.5° × 0.5° (http://rda.ucar.edu/datasets/ds094.0/). This configuration is used here due to the data length and the simulation target, although FLEXPART can also be used to simulate in a backward mode to backtrack atmospheric moisture from given target regions (Drumond et al., 2011; Chen et al., 2012, 2013) or used with input data from the European Centre for Medium-Range Weather Forecasts (ECMWF) (Simmons et al., 2007). In this study, FLEXPART was run in the domain filling mode with one million particles released globally and moved freely in the atmosphere over a 31–year period from 1979 to 2009. In the domain filling mode, the entire atmosphere is divided homogeneously into particles of equal mass, which are distributed in proportion to the air density. The model outputs were recorded in 6 intervals, including the identity of the particles, three–dimensional position of the particles (latitude, longitude, and altitude), specific humidity, air density, and mass of each particle.

2.2. Target region

The CLP is located within 34–39°N and 103–113°E in north-central China, covering an area of ~360,000 km^2 (Li and Lu, 2010) that is composed of the majority of the Shaanxi and Shanxi provinces and a part of other administrative regions, including Henan province, Gansu province, the Inner Mongolia Autonomous Region and the Ningxia Hui Autonomous Region. The CLP potentially contains ~25 Ma of loess accumulation (Qiang et al., 2011), is the longest and most continuous dust archive on the planet (Liu and Ding, 1998; Guo et al., 2002), and is known for its topographic variations within the loess hills and gully landforms. It is also the largest semi-arid zone in China. The regional scale of the CLP is designated by the black polygon in Figs. 1–3 and 5.

2.3. Identification of moisture source regions and quantification of contribution

With respect to the FLEXPART output, the water budget equation in Lagrangian form is widely used to calculate the net rate of change of the water vapor content (e.g., Stohl and James, 2004, 2005; Sodemann et al., 2008; Stohl et al., 2008; Sodemann and Stohl, 2009; Gimeno et al., 2010, 2013; Drumond et al., 2011; Chen et al., 2012, 2013; Sun and Wang, 2014, 2015; Huang and Cui, 2015). First, the atmosphere is assumed to divide into a large number of particles (number: N), which are homogeneously distributed. Given a total atmospheric mass (m_a), each particle therefore represents a mass $m = m_a/N$. A particle is advected using the trajectory equation (Stohl, 1998):

$$\frac{dx}{dt} = v[x(t)] \tag{1}$$

where x is the particle's position, and $v[x(t)]$ is the wind velocity interpolated in space and time from the analysis grid to $x(t)$.

By interpolating q to $x(t)$, the change of the water vapor content of a particle in Lagrangian form is:

$$e - p = m\frac{dq}{dt} \tag{2}$$

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