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Numerical simulation of the impact of reforestation on winter meteorology and environment in a semi-arid urban valley, Northwestern China

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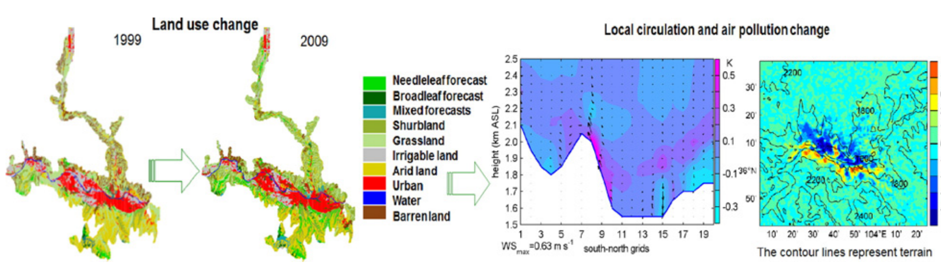
HIGHLIGHTS

- Obvious land use change due to reforestation in the north and south mountains.
- Effect on local meteorology and pollutant distribution studied by WRF and FLEXPART.
- Mountain-valley wind circulation was enhanced by reforestation.
- Air exchange between valley and outside was enhanced and urban air quality improved.
- Spatial extent and magnitude of effect depend on time of a day and weather conditions.

GRAPHICAL ABSTRACT



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ABSTRACT

Since 1999 Chinese government has made great effort to reforest the south and north mountains surrounding urban Lanzhou – a city located in a river valley, Northwestern China. Until 2009 obvious land use change occurred, with 69.2% of the reforested area been changed from grasslands, croplands, barren or sparsely vegetated land to closed shrublands and 20.6% from closed shrublands, grasslands, and croplands to forests. Reforestation changes land-surface properties, with possible impact on the evolution of atmospheric variables. To understand to what extent the local meteorology and environment could be affected by reforestation in winter, and through what processes, two sets of simulations were conducted using the Weather Research and Forecasting model (WRF) and the FLEXible PARTicle (FLEXPART) dispersion model for a control case with high-resolution remotely sensed land cover data for 2009 and a scenario assuming no reforestation since 1999. Results suggested that the changes in albedo, surface exchange coefficient and surface soil heat conductivity related to reforestation led to the changes in surface net radiation and surface energy partitioning, which in turn affected the meteorological fields and enhanced the mountain-valley wind circulation. Replacement of shrublands and grassland with forest in the south mountain through reforestation play a dominant role in the enhancement of mountain-valley wind

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circulation. Reforestation increased the amount of air exchanged between the valley and the outside during the day, with the largest hourly increase of 10% on calm weather days and a monthly mean hourly increase of 2% for the study period (Dec. 2009). Reforestation affected the spatial distribution of pollutants and slightly improved the urban air quality, especially in the eastern valley. Results from this study provide useful information for future urban air quality management and reforestation plan, and some experience for cities with similar situations in the world.

1. Introduction

Anthropogenic modification of land cover, e.g. reforestation, is one of the most important sources of global land cover change. In the 1970s, Charney (1975) studied the Sahel desertification and found that earth surface vegetation change altered surface albedo and thus the surface energy balance and regional climate. Since then, many studies have been carried out to investigate the impact of land surface characteristics on boundary layer meteorology and, more recently, on atmospheric environment. For example, Juang et al. (2007) experimentally investigated the impact of the conversion of abandoned agricultural land to forests in the southeastern United States on surface temperature. They found significant difference in near surface temperatures among three adjacent ecosystems (grass-covered old-field, planted pine forest, and hardwood forest), which indicate that anthropogenic modification of land surface characteristics through, for example reforestation, in limited area could affect local meteorology and atmospheric circulation. Using modified Regional Climate Model, Ding et al. (2005) revealed that reforestation in northwestern China might alter the intensity of East-Asian monsoon. Numerical simulations also reveal that changes of land surface properties in limited area, such as urban expansion and greening, modifies surface thermal properties and related secondary circulation, and thus air quality (Middel et al., 2014; Papangelis et al., 2012; Tao et al., 2015; Zhang et al., 2009). Reforestation changes land-surface properties, such as surface albedo, emissivity, roughness length, soil thermal conductivity and others, and have possible impact on the evolution of atmospheric variables through modifying the surface radiation budget and exchanges of heat, water, and momentum (Hu et al., 2015; Notaro et al., 2006; Wang et al., 2010), which in turn may affect air quality (Tao et al., 2013). Knowledge of how reforestation affects meteorological conditions and atmospheric environment would be valuable for assessing urban air quality management and provide guidance for government decision-making.

Located deep in the hinterland of China, the Lanzhou Valley has a continental arid and semi-arid climate. The annual average temperature is 9.3 °C, and the annual average wind speed is 0.8 m s^{-1}, with 62% calm wind conditions and a prevailing easterly wind near the surface. The annual precipitation is 327.7 mm, of which 50% falls during July–September (Wang et al., 2009b). With more than three million populations, Lanzhou is one of the most polluted cities in China (Qu et al., 2010), especially in winter when 50% of days exceed the national grade II standard (Chen et al., 2010). Long-lasting boundary layer temperature inversion and calm wind conditions has been identified as the main reasons for the severe air pollution in winter in Lanzhou and reforestation has been suggested as one possible mitigation measure (Hu and Zhang, 1999). In 1999, the local government of Lanzhou launched the "reforestation in the north and south mountains" project which involves a total investment of 660 million Yuan. By the end of 2009, the afforested area over the southern and northern mountains increased to about 593 km^2. This supplies a case for studying the impact of reforestation. Some previous studies have investigated the possible effect of reforestation on meteorological conditions in Lanzhou (An et al., 2003; Chu et al., 2008; Yang et al., 2009), however these studies have relied on assumptions regarding the area and extent of the afforested area. Their purpose was more towards identifying the potential effect. While such approach fits the goal of their studies, it cannot be used to explain the real situation of land use change due to reforestation in recent years. Thus, it is necessary to evaluate the impact of the extensive reforestation in the north and south mountains surrounding urban Lanzhou on local meteorology and environment using more realistic land cover data.

In this study, remotely sensed land cover over the north and south mountains of Lanzhou for 1999 and 2009 was used with WRF (Weather Research and Forecasting) and FLEXible PARTicle (FLEXPART) models to assess the effects of reforestation on local meteorology and air quality in urban Lanzhou during winter. Specifically, the study seeks to understand the processes by which reforestation may lead to variations in local meteorology and pollutant distribution. Section 2 describes the model configuration and land surface data. Section 3 presents the evaluation of model simulations followed by discussions on the effects of reforestation on surface energy partitioning, meteorological condition and air quality. Conclusions are presented in Section 4.

2. Data and methods

2.1. Model description and configuration

2.1.1. WRF model

The WRF is a next-generation mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs. The effort to develop WRF has been a collaborative partnership, principally among the National Center for Atmospheric Research (NCAR), the National Centers for Environmental Prediction (NCEP), and other research institutions and universities. It has two dynamical cores: ARW and NMM, and WRF ARW v3.3 was used in this study. The WRF ARW has been widely used in applications with scales ranging from meters to thousands of kilometers, including idealized simulations (e.g. LES, convection, baroclinic waves), and researches on parameterization schemes, data assimilation, forecasting, etc. More information on WRF was documented in Skamarock and Klemp (2008).

In this study, WRF was configured to have four nested domains with 27, 9, 3, and 1 km resolution (Fig. 1a). The coarsest domain covers most of China and its adjacent continents and the finest domain (domain 4) covers the urban area of Lanzhou and most areas of the north and south mountains. In the vertical, there are 35 vertical levels extending from the surface to 50 hPa, with 12 levels in the lowest 1 km. The initial and lateral boundary conditions were obtained from the 6 h Final (FNL) Operational Global Analysis data by the National Centers for Environmental Prediction (NCEP) at $1° \times 1°$ horizontal resolution (http://rda.ucar.edu/datasets/ds083.2/). Analysis nudging from the Four-Dimensional Data Assimilation (FDDA) system was used to ensure that the upper-air model predictions do not drift too far away from the reanalysis conditions (Carvalho et al., 2012).

The WRF is coupled with the Noah land surface model (LSM) with single-layer urban canopy model to link the surface conditions with the atmosphere. An overview of the selected physical parameterization schemes in WRF is given in Table 1. This study focuses on December, the most polluted winter month in the study area (Wang et al., 2009b). One month simulation for December 2009 was conducted using different land surface representations to investigate the potential impact of reforestation on local meteorology. The simulation was integrated from