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Impacts of inhomogeneous landscapes in oasis interior on the oasis self-maintaining mechanism by integrating numerical model with satellite data

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Abstract

Mesoscale meteorological modeling is an important tool to help understand the energy budget of the oasis. While basic dynamic and thermodynamic processes for oasis self-maintaining in the desert environment is well investigated, influence of heterogeneous landscapes of oasis interior on the processes are still important and remain to be investigated. In this study, two simulations are designed for investigating the influence of inhomogeneity. In the first case, land surface parameters including land-use types, vegetation cover fraction, and surface layer soil moisture are derived by satellite remote sensing data from EOS/MODIS, and then be used specify the respective options in the MM5 model, to describe a real inhomogeneity for the oasis interior. In the other run, land use types are set to MM5 default, in which landscapes in the oasis interior is relative uniform, and then surface layer soil moisture and vegetation fraction is set to be averages of the first case for the respective oasis and desert surface lying, to represent a relative homogeneity. Results show that the inhomogeneity leads to a weaker oasis "cold-wet island" effect and a stronger turbulence over the oasis interior, both of which will reduce the oasis-desert secondary circulation and increase the evaporation over the oasis, resulting in a negative impact on the oasis self-protecting mechanism. The simulation of homogeneity indicates that the oasis may be more stable even with relative lower soil moisture if landscapes in the oasis interior are comparatively uniform.

1 Introduction

The interaction between the atmosphere and the underlying surface, a phenomenon of great interest for climate theory and weather forecasting, is primarily manifested in the heat, moisture, and momentum exchanges between air masses and soil or water (Kukharets and Nalbandyan, 2006). Flying over a landscape in mid-latitudes presents a fantastic view of patchy fields with various surface properties and different sizes (Friedrich and Mölders, 2000). Obviously, this surface heterogeneity can result in more complicated interactions between the atmosphere and the underlying surface, affecting moist convection, producing or impacting the atmospheric circulations locally and even globally (Friedrich and Mölders, 2000; Mölders and Raabe, 1996; Chen and Avissar, 1994; Chen et al., 2003; Courault et al., 2007; Lynn et al., 1995; Patton et al., 2005; Reen et al., 2006; Yates et al., 2003; Zhang et al., 2010).

In many situations, these locally induced circulations are important in determining mesoscale weather conditions (Wu and Raman, 1997). Indeed, in the atmospheric boundary layer (ABL), surface heterogeneities affect the microscale to mesoscale circulations through non-linear processes (Patton et al., 2005; Mahrt et al., 1994; Baidya Roy and Avissar, 2002). Turbulent surface fluxes are strongly affected by the ability of the surface to redistribute the radiative energy absorbed from the sun and the atmosphere into sensible and latent heat fluxes (Mahrt et al., 1994; Chen et al., 2003). Surface heterogeneities thus induce spatial variability in surface heat fluxes that can create “inland breezes”, “oasis effect”, ““glacier wind” et al.” similar to sea-land breeze systems (Mahfouf et al., 1987; Mahrt et al., 1994; Chu et al., 2005; Gao et al., 2004; Lu et al., 2004; Sun et al., 2007). Such phenomena are known to contribute significantly to energy, water and matter transport (Bastin and Drobinski, 2006; Meng et al., 2009; Chu et al., 2005).

As unique intrazonal landscapes, oases surrounded by deserts and Gobi play important role in arid and semiarid regions of the world. In China, oases take up only 4–5 % of the total area of the region, but over 90 % of the population and over 95 % of the social wealth in northwest China is concentrated within the oases (Han, 2001; Gao et al., 2008). In the last half century, however, the rapid growth of population and the overexploitation of water, soil and biological resources have led to drought, salinization, and desertification and consequently have hindered the development of sustainable agriculture, resulting in an urgency to understand the oasis-desert interaction and processes (Liu et al., 2006, 2007; Li et al., 2011).

Studies have been done to investigate the land-atmosphere interaction over the oasis-desert system, indicating that the local circulations driven by the thermal heterogeneity between the oasis and desert is the key factor to maintain the oasis (Chu et al., 2005). Such thermally driven circulations similar as the sea breezes in the convective boundary layer are called as the non-classical mesoscale circulations (Segal and Arritt, 1992), and have been observed in the field experiment (Chen et al., 2005). In addition, the oasis is wetter and colder than the surrounded desert due to the evaporation and thermal processes in the afternoon on fair weather days, which will develop an inversion layer over the oasis. Both the mesoscale circulation and the inversion layer will help to prevent water vapor over the oasis flowing to the desert (Chu et al., 2005). These processes are totally called the oasis self-maintaining mechanism. However, the oasis interior are very inhomogeneous, constituting with water, cropland, urban, shelterbelt, natural vegetation, Gobi and desert, particularly when the cropland is irrigated during the growing season in Northwest of China (Fig. 1). While the basic dynamic and thermodynamic processes over the oasis-desert system is well investigated, the impacts of inhomogeneous oasis interior on oasis self-maintaining mechanism are still very important and remain to be investigated.

Numeric simulation is quite an efficient technique to study the mesoscale weather and boundary layer structure over the inhomogeneous landscape (Prabha et al., 2007; Kukharets and Nalbandyan, 2006; Ament and Simmer, 2006; Avissar and Liu, 1996; Chen and Avissar, 1994; Desai et al., 2006; Lynn et al., 1995; Mölders and Raabe, 1996). Ye and Jia (1995) investigated the impact of well watered mesoscale wheat over mid-latitude arid areas on mesoscale boundary layer structures and climate by modeling, indicating that a horizontal pressure gradient associated with mesoscale perturbations in temperature and humidity is created during the day, which results from more water transpired from the vegetation canopy and evaporated from underlying wet soil. Zhang et al. (2010) design a number of experiments to examine the effects of changes in heterogeneity patterns on numerical simulations of surface flux exchanges, near-surface meteorological fields, atmospheric planetary boundary layer (PBL) processes, mesoscale circulations, and mesoscale fluxes, indicating that the increased heterogeneity losses in the model lead to substantial, nonlinear changes in temporal evaluations and spatial patterns of PBL dynamic and thermodynamic processes. Meng et al. (2009) improved meteorological simulations in the Jinta oasis in Northwest China, especially for description of the inhomogeneous characteristics over the oasis by involving satellite data. This paper is a continuity of the work in Meng et al. (2009), in which they presented that the numerical simulation including satellite data can provide a better description for inhomogeneous underlying surface, while this work will make an attempt to understand the influence of heterogeneous oasis interior on the oasis self-maintaining mechanism.

The paper is structured as follows. Section 2 briefly presents a description of the study area and the datasets used in this work. Section 3 describes the MM5 model and the experimental design. Section 4 evaluates the simulation results and assesses the impact of the inhomogeneous landscape on the oasis self-maintaining mechanism. The final section summarizes the findings and identifies areas requiring future investigation.

2 Study area and datasets

2.1 Study area

The study area is Jinta oasis, situated between 98°39′ E and 99°08′ E and 39°56′ N and 40°17′ N in the middle of the Heihe river basin (Fig. 1) in northwestern China, with a yearly average precipitation of about 59.5 mm and an annual potential evapotranspiration of 2538.6 mm. The total area is about 165 212 km^2, mostly composed with farmland, natural grassland and desert-oasis transaction which are shown in Fig. 1. Jinta oasis is very flat, and the elevation difference is only 80 m. Its earthiness is very good, mainly including mud soil, tide soil (meadow soil), wind sand soil and typical gray brown soil which is distributed in the edge regions (Ma et al., 2002). The soil in the oasis is continuous and easy to reclaim, this region thus is considered as one of the national land resource developing and representative areas in China (Chen, 2000).

Jinta oasis is also a typical irrigation and agriculture oasis, which can represent the inhomogeneous oasis in northwest China well.

2.2 Datasets

Observational meteorological data were collected at Jinta oasis during the Jinta field experiment, which was performed through late spring to early autumn from 2003 to 2005. In the field campaign, meteorological elements measured with four automatic weather stations (AWSs), surface turbulent heat fluxes obtained from two Portable Automated Meso-net (PAM) stations (CSAT3/KH20, Campbell. Sci. Ins., Utah) and radar soundings were collected for the study of energy and water cycle over the oasis-desert system. The observations used in this study were obtained in July 2004. Details of the data can be found in the work of Meng et al. (2009) and Ao (2006).

Satellite data such as land use types, vegetation fraction cover and soil moisture are derived from the Moderate Resolution Imaging Spectro-radiometer (MODIS) gathers data in 36 spectral bands on the board the Terra (EOS AM) sensor. Details of the processing and application for the satellite data can be found in the work of Meng et al. (2009).

3 Numerical simulations

The nonhydrostatic MM5 (short for Fifth-Generation Penn State/NCAR Mesoscale Model) is a limited-area, nonhydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale atmospheric circulation. In this study, version 3 coupled by Noah land-surface model (LSM) was used in the simulation (Grell et al., 1994). Since Meng et al. (2009) have successfully simulated the oasis self-maintaining mechanism, this work is a continuity of that work. A triple-nested grid system with the same center located at 40.3° N, 98.9° E is used. The three systems extend 333 km, 120 km, 61 km and with grid spacing of 9 km, 3 km, and 1km respectively. Jinta oasis was located at the center of the third domain. In the vertical, 23 unevenly spaced full sigma levels are defined. The parameterization schemes are the same as the work of Meng et al. (2009). The model was initialized on 4 July 2004 at 12:00 UTC (20:00 Beijing Time) and ended on 5 July 2004 at 12:00 UTC, during which there is a strong oasis effect that has been observed in the field experiment (Chen et al., 2005).

Two simulations were performed in this work. In the first run, 1-km-resolution land use types, vegetation fraction and soil moisture data derived from MODIS are input in the coupled MM5-LSM system. This simulation is referred to as MOD, which has been shown to be a better run for simulating the meteorogical conditions and the oasis-desert heterogeneity (Meng et al., 2009). As land use types in this run include the oasis corridor, water, urban, farmland and grass (Fig. 2), it is taken as a "real" simulation for the heterogeneity of the oasis interiors. The other run is to present the relatively uniform, in which land use types come from the MM5 default (Fig. 2), showing that the oasis interior is mostly composed by vegetation. This run is referred to as EXP. In the EXP, vegetation fraction and surface layer soil moisture initials over the oasis and desert are replaced with the values of the averages of the oasis and desert respectively to present that both simulations have similar vegetation coverage and soil moisture conditions but different inhomogeneity.

4 Results and discussion

In the previous work of Meng et al. (2009), wind fields, land surface heat fluxes, land surface temperature and atmospheric profiles including potential temperature, specific humidity were evaluated by using the observational data, and the validation shows that MOD simulation is illustrated to be the best simulation for oasis self-maintaining mechanism and inhomogeneity. So, this work only focuses on the analysis of impacts on oasis self-protecting mechanism produced by heterogeneity versus the relative uniform of the oasis interior.

As is discussed in the introduction, studies have considered the mechanisms of oasis self-maintaining in a surrounded desert environment. Most of them focus on the oasis "cold-wet" effects and their driven mesoscale circulations and emphasizes the processes from the following ways. Firstly, the oasis is a cold-wet island comparing with the surrounded desert because of the oasis-desert heterogeneity caused vegetation and soil processes and their changes, producing a secondary circulation upward over the desert and downward over the oasis. The updraft over the desert reduces low-level hot, dry air flowing from the desert into the oasis and the downdraft increases the atmospheric static stability that reduces the oasis evaporation, both of which can prevent water loss and soil desertification over the oasis and protect it (Chu et al., 2005; Zhang and Huang, 2004; Lu et al., 2004). Secondly, the oasis with cropland, vegetation and protective forest can eliminate the wind from the desert, which helps to decrease the evaporation over the oasis and resist sandstorm (Meng et al., 2009). Thirdly, the moist air in the lower level over the oasis can be transferred to the higher level over the oasis and the surrounded desert by the secondary circulation, producing a moisture-inversion level over the oasis center and the desert neighboring the oasis, which can help reduce evaporation over the oasis and is good for the plant growing over the desert and creating a protecting belt around the oasis (Zhang and Huang, 2004). So, comparisons of these factors between the two simulations will be presented and discussed in this part.

4.1 Oasis effect

As the oasis effect and its self-protecting mechanism is the most evident in the afternoon (Chu et al., 2005; Chen et al., 2005), processes on 5 July 2004, 05:00 UTC (13:00 Beijing Time) will be analyzed and discussed in this work. Figures 3 and 4 show 2 m air temperature and specific humidity from the two simulations. Both simulations display that the oasis is a "cold island". In the MOD, the maximum of 2 m air temperature is around 35 °C in the north of the oasis, while the maximum in the EXP is slightly higher than MOD and in the west edge of the oasis. Comparing with land use types in

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Fig. 2, maximums in both simulations are around where bare soils are. Minimums in both simulations occurred in the lakes in the south. Focusing on the “cold island” effect, temperature difference between oasis and desert in the MOD is about 5 °C, which is about 1 °C less than it is in the EXP, indicating that “cold island” effect in the EXP is greater than MOD. Furthermore, minimums occur in the center of the oasis in the EXP simulation, while they happen along with the vegetation in the MOD simulation due to the influence of the inhomogeneity.

From 2 m specific humidity shown in Fig. 4, both simulations can simulate the oasis as a “wet island”. The driest region is over the desert, and the wettest is over the oasis. Similar as 2 m air temperature, specific humidity distributes along with the vegetation over the oasis in the MOD simulation, but concentrates and maximums occur in the northeast center in the EXP simulation. Humidity difference between oasis and desert is about 1.8 g kg^{-1} in the MOD simulation, and it is about 2.8 g kg^{-1} in the EXP run, showing that the “wet island” of the EXP is much greater than the MOD.

To furthermore investigate the influence of inhomogeneity on the “wet island” effect, the vertical latitudinal section of specific humidity in the middle of the oasis is shown in Fig. 5 (grid 18 to 50 from west to east is mainly oasis). Both simulations present the oasis as a “wet island”, with a maximum contour value of 4.6 g kg^{-1} in the MOD and 5.2 g kg^{-1} in the EXP run. The contour lines are more density over the oasis from surface to 700 hpa in EXP, and also appear with a deeper humidity inversion in 700-hpa layer than in MOD run. The humidity inversion is related with the oasis mesoscale circulation, and will be further discussed later. From the contours, the EXP run has a larger “wet island” comparing with the MOD simulation.

The EXP simulation presents a stronger effect for both “cold” and “wet” condition, indicating that the concentration of vegetation in the oasis interior is more favorable for the production of the oasis effect. According to the land use types in Fig. 2, the area of oasis in EXP is larger than it is in the MOD, showing that a larger oasis can also be more stable for the oasis “cold-wet” island.

4.2 Mesoscale circulation

Figure 6 displays the modeled horizontal winds at 850 hPa in the two simulations. Both cases can simulate the pattern of low-level divergence and high-level convergence over the oasis, there is however difference in the two simulations: over the oasis, divergences occur in most time but convergence can be seen over the corridor in the MOD run, and divergence over the oasis in the EXP case is shown to be less affected due to the relative uniform of the oasis interior. Wind speed was reduced to be very small over the oasis interior due to the vegetation in both cases. No big differences in the wind speed in the two simulations, but over the patches in the oasis, indicating that the inhomogeneity does have influence on wind fields.

To co-operate the wind field, Figs. 7 and 8 display the divergence and vertical velocity at 850 hPa in the two simulations. In both simulations, the oasis area is a divergence region as an entirety comparing with the surrounded desert. As it is discussed in the introduction, the air flow divergent from the oasis to desert, produces downdraft at the edge of the oasis, and then convergent around the oasis-desert transition to updraft, holding water over the oasis and preventing it flowing into the desert. This is the favorable mechanism for protecting the oasis. However, comparing between the two cases, it shows that in the oasis, over the bare soil or the corridor, there is a convergent center in the MOD run but a divergence one in EXP. From the values of the divergent centers, the MOD simulation has stronger turbulence comparing with the EXP, which might be resulted by the relative lower soil moisture for using the oasis-averaged values in the EXP case. However, it should be noted that the interactional mechanism of divergence and convergence over the oasis in MOD case can result in the instability for the oasis interior and strengthen the turbulence and evaporation over the oasis. Once the turbulence is strong enough to break up the secondary circulation driven by the thermal heterogeneity between oasis and desert, water and heat exchange between the oasis and the desert will be enhanced and water vapor over the oases will flow

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into the surrounding deserts and make the oases drier and drier, even going into the vicious circle of water deficiency and soil desertification (Meng et al., 2009).

Figures 9 and 10 show the vertical section of divergence and vertical velocity from the two simulations. In Fig. 9, over the oasis (i.e. from grid 18 to 50), both divergence and convergence can be seen below 800 hPa in the MOD run, but mainly divergent at the edge and convergent in the center of the oasis in the EXP simulation. Responding with the turbulence, airflow has more up and down turbulence in the MOD run, but only goes up over the oasis interior in the EXP case, showing that the turbulence is stronger in lower-level atmosphere over the oasis interior in the MOD run.

Similar as the simulation for the oasis effect, both simulations show that the oasis-desert interactions can produce a secondary circulation in in the lower atmosphere for the oasis self-protecting. The MOD simulation with larger soil moisture and vegetation fraction seems to have a stronger circulation than it is in the EXP simulation, but the EXP simulation seems to be easier for oasis self-maintaining although it has relative lower soil moisture and vegetation fraction. The inhomogeneity of the MOD will lead to disturbances and water loss.

5 Conclusions

The influence of inhomogeneity of the oasis interior on oasis self-maintaining mechanism is investigated by using the mesoscale model MM5 (MOD) with satellite observations of land surface parameters from MODIS data. To do a comparison, the MM5 default land use types of the oasis are taken as a relatively homogeneous surface lying, surface soil moisture and vegetation fraction were replaced by using the averages of oasis and desert respectively in the comparative simulation (EXP) to represent the homogeneity. The results indicate the MOD simulation is a good case to describe the characters of the heterogeneous land surface lying in the oasis interior, and the EXP can simulate the homogeneity well.

Water and energy cycle is the most important factors for the oasis self-protecting. Comparison between the two simulations show that the "cold island" is decreased from 6 °C to 5 °C (2 m air temperature) due to the oasis-interior inhomogeneity and the "wet island" is reduced from 2.8 g kg^{-1} to 1.8 g kg^{-1} (2 m specific humidity). Vertical sections further indicate that the homogeneity in the oasis interior help to produce stronger humidity inversion over the oasis, preventing water in the oasis from evaporating.

For the oasis-desert secondary circulation, the moister and more heterogeneous landscapes make the secondary circulation stronger and also the convergent and divergent turbulences over the oasis interior. The stronger circulation is favorable for the oasis maintain, while the interactional mechanism of divergence and convergence can result in the instability over the oasis interior and strengthen the turbulence and evaporation over the oasis. Furthermore, the turbulence will decrease the "cold island" effect and then reduce the dynamic driver of the oasis-desert secondary circulation. Once the oasis-interior is inhomogeneous enough, the secondary circulation is easy to break up, water and heat exchange between the oasis and the desert will be enhanced and water vapor over the oases will flow into the surrounding deserts and make the oases drier and drier, even going into the vicious circle of water deficiency and soil desertification.

This work only focuses on the analysis of inhomogeneity, and doesn't consider the influence of the oasis area. Land use types from MODIS data show a smaller area of the oasis than the MM5 default. And the area is also an important factor for the oasis self-maintaining mechanism. So, the results of this study may enlarge the influence of inhomogeneity. Further work will need to better constrain the heterogeneity and investigate the oasis area separately.

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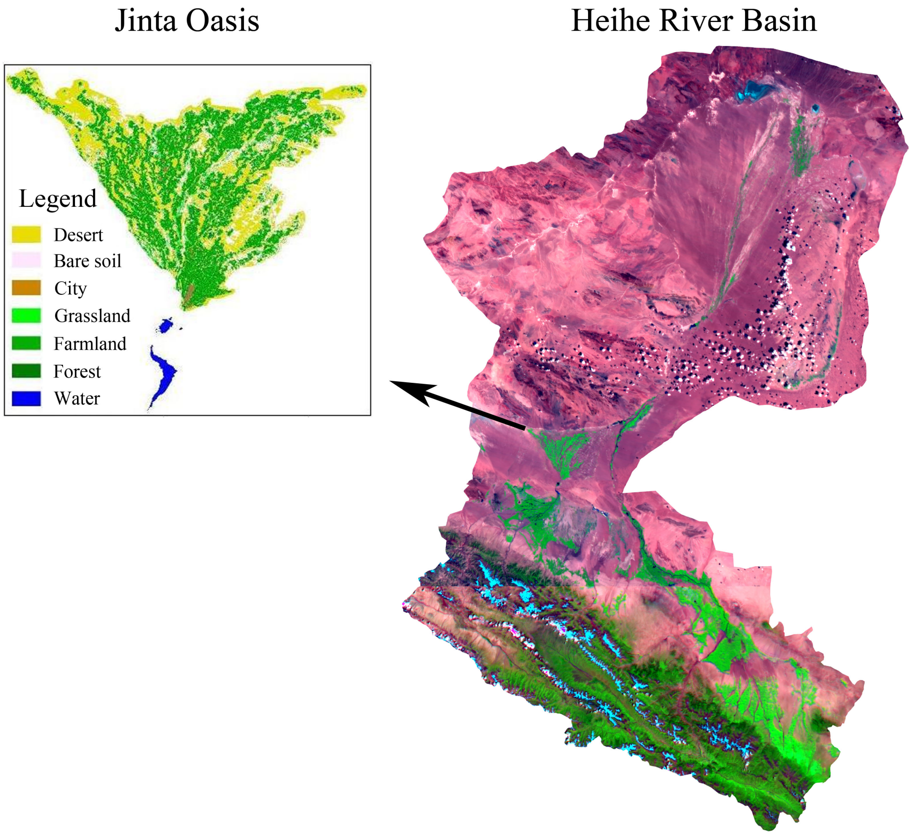

Fig. 1. Location of Jinta Oasis in Heihe River Basin (Geocover mosaics) and land use map of Jinta Oasis.

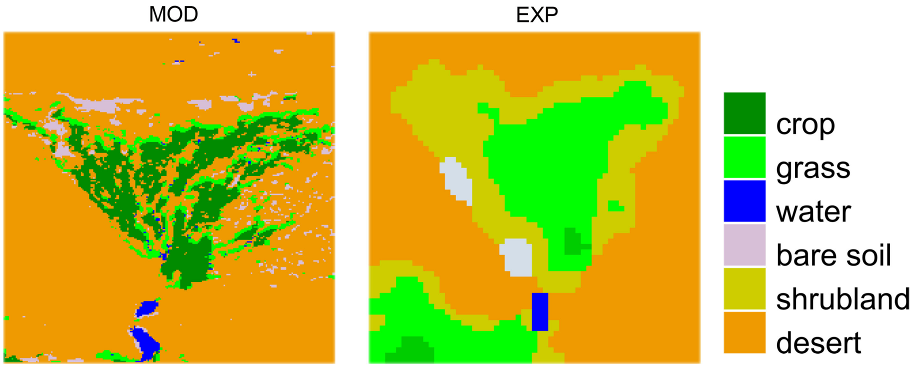

Fig. 2. Land-use maps for the third domain of the two simulations.

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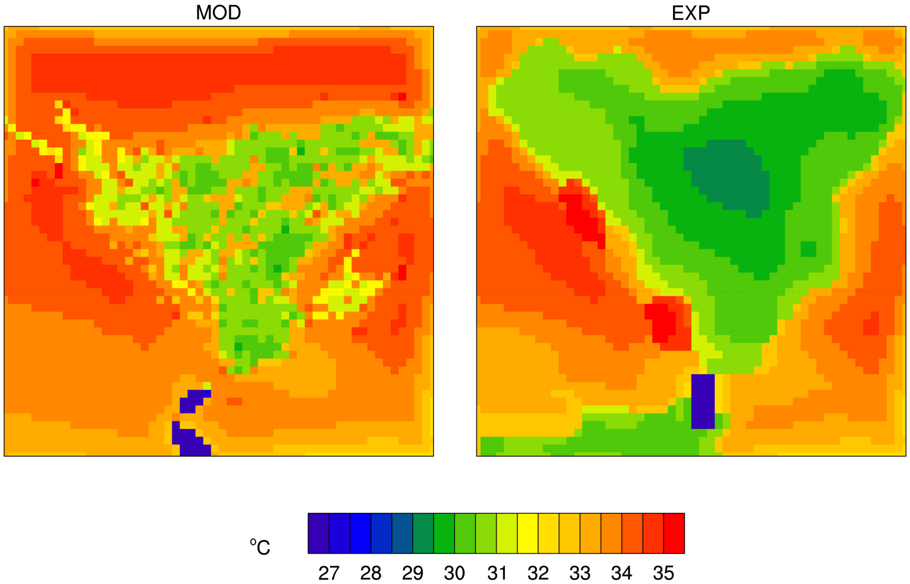

Fig. 3. 2 m air temperature on 5 July 2004, 05:00 UTC (13:00 Beijing Time) of the two simulations.

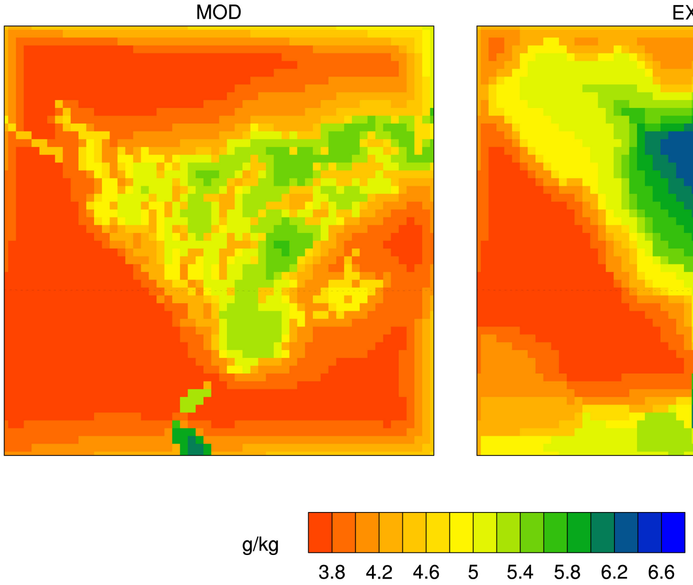

Fig. 4. 2 m specific humidity of the two simulations (the same time as Fig. 3).

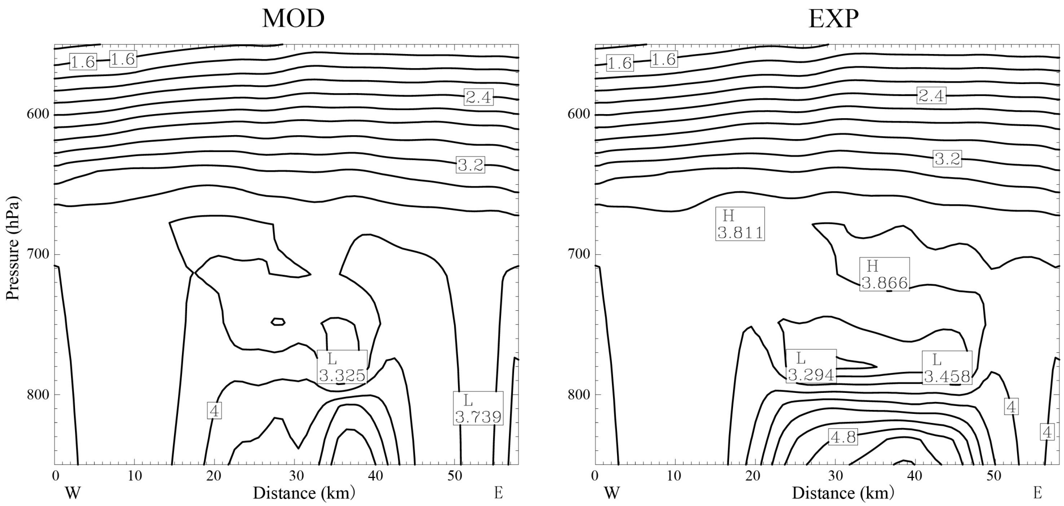

Fig. 5. Vertical latitudinal section of specific humidity in the middle of the oasis for the two simulations (the same time as Fig. 3). Unit is $g\,kg^{-1}$, and interval is 0.2.

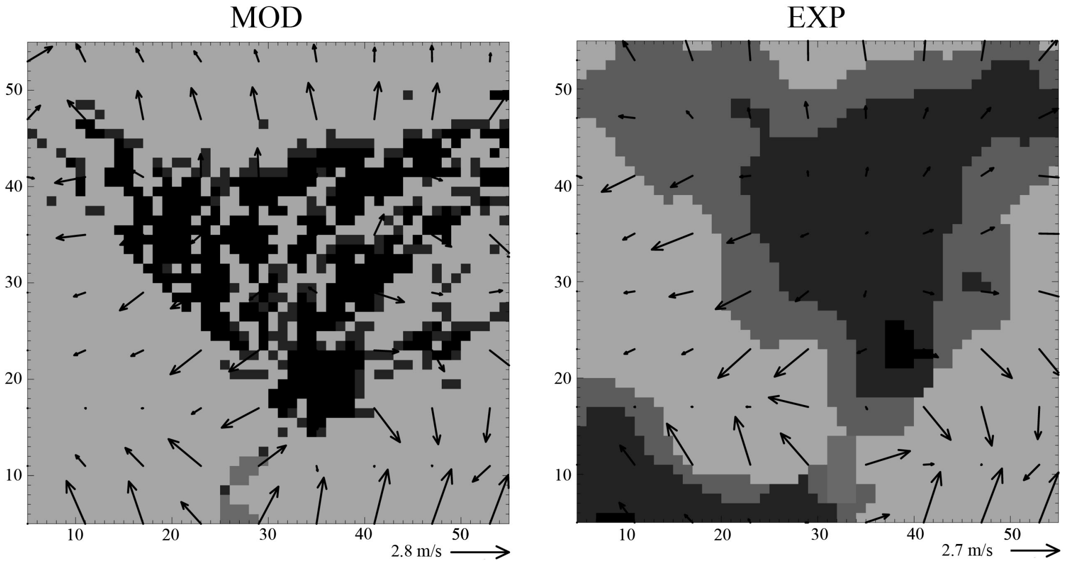

Fig. 6. Horizontal winds at 850 hPa in Jinta oasis for the two simulations (the same time as Fig. 3).

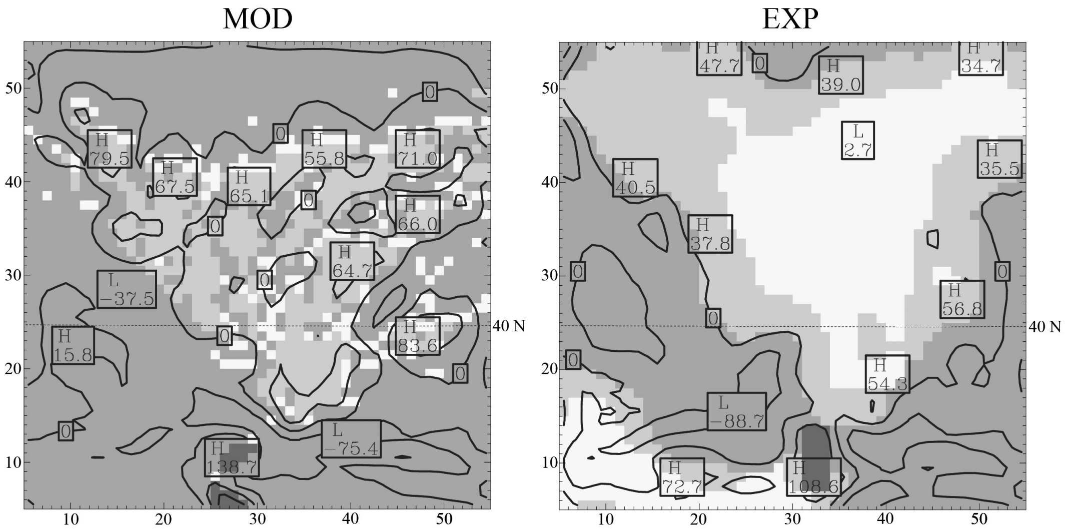

Fig. 7. Horizontal divergence at 850 hPa in Jinta oasis for the two simulations (the same time as Fig. 3). Unit is $10^{-5}\,\mathrm{s}^{-1}$, and interval is 50.00.

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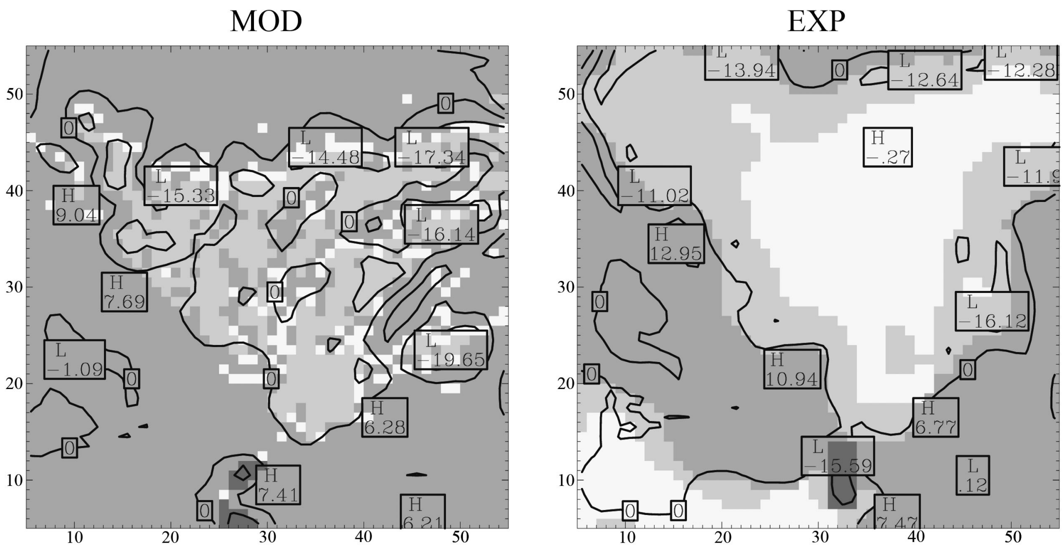

Fig. 8. Horizontal vertical velocity at 850 hPa in Jinta oasis for the two simulations (the same time as Fig. 3). Unit is cm s^{-1}, and interval is 10.

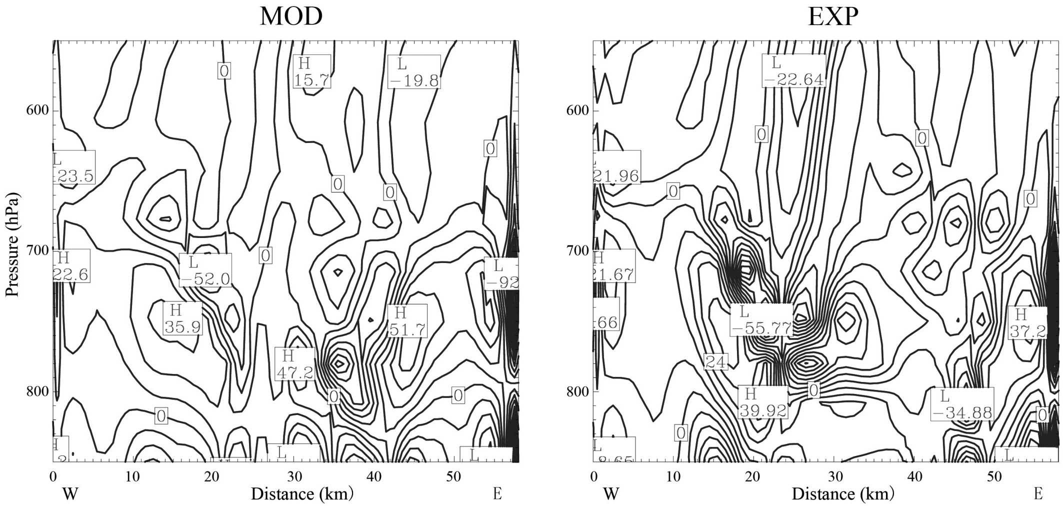

Fig. 9. Vertical latitudinal section of divergence in the middle of the oasis for the two simulations (the same time as Fig. 3). Unit is $10^{-5}\,\mathrm{s}^{-1}$, and interval is 10.00.

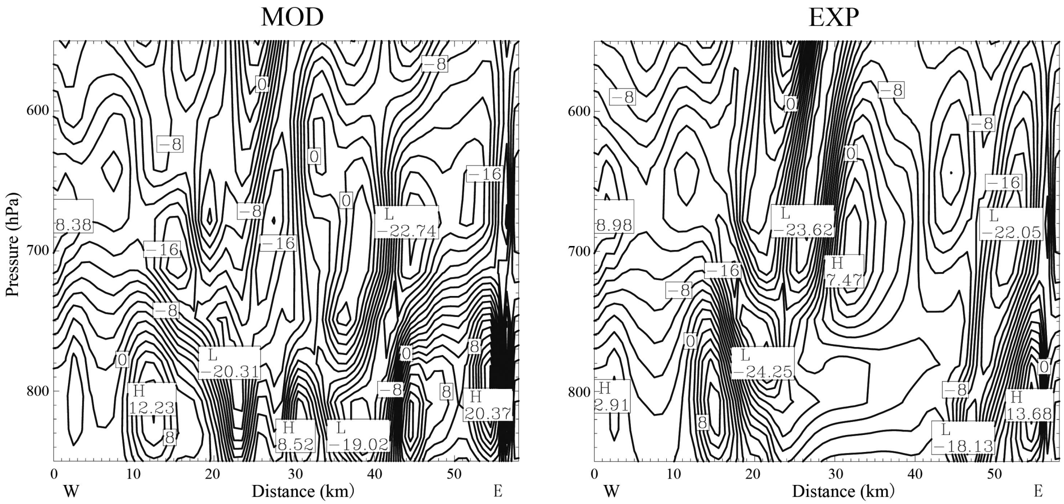

Fig. 10. Vertical latitudinal section of vertical velocity in the middle of the oasis for the two simulations (the same time as Fig. 3). Unit is cm s^{-1}, and interval is 10.