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

X. Meng, S. Lu, T. Zhang, Y. Ao, S. Li, Y. Bao, L. Wen, and S. Luo

Key laboratory of Land Surface Process and Climate Change in Cold and Arid Regions, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Science, 320 Donggang West Road, 730000 Lanzhou, Gansu, China

Abstract

The impacts of inhomogeneity of the oasis interior on oasis self-maintainance mechanism are investigated by using the mesoscale model MM5 with satellite observations of land surface parameters from MODIS data. Four simulations were performed, among which CTL (default simulation) and MOD (with parameters replaced with MODIS data) were used to validate the model results; and EXP1 and EXP2 were designed to study the inhomogeneity of oasis interior. Results show that the changes of oasis heterogeneity play roles in the surface heat-flux partitioning, and then lead to a larger "cold-wet" effect over the oasis. Vertical sections of humidity illustrate the existence of moisture-inversion level, and the deeper moisture-inversion in EXP1 and EXP2 further indicate that the relatively homogeneity in the oasis interior help to produce stronger humidity inversion over the oasis, preventing water over the oasis from evaporating. This is double verified by the analysis on the secondary circulation, which shows that the more homogeneous land surface conditions lead to stronger secondary circulation and less turbulent drafts over the oasis interior, playing a positive role in the oasis-self maintaining and development.

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). To some extent, the earth's surface is always heterogeneous (Marhrt, 2000; Friedrich and Mölders, 2000). Obviously, the surface heterogeneity can result in more complicated interactions between the atmosphere and the underlying surface, affecting moist convection, and systematically produce responses in the local circulation and regional climate (Courault et al., 2007; Reen et al., 2006; Yuan et al., 2008; 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”, similar to sea-land breeze systems (Mahfouf et al., 1987; 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).

As unique intrazonal landscapes, oases surrounded by deserts and Gobi play an 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 population growth 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 oasis-desert interaction and processes (Liu et al., 2006, 2007; Li et al., 2011).

Studies have investigated the land-atmosphere interactions between 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 to the sea breezes in the convective boundary layer are referred to as the non-classical mesoscale circulations (Segal and Arritt, 1992), and have been observed in the field (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 develops an inversion layer over the oasis. Both the mesoscale circulation and the inversion layer help to prevent water vapor over the oasis flowing to the desert (Chu et al., 2005; Meng et al., 2009). These processes are referred to as the oasis self-maintainance mechanism. However, the oasis interior is very inhomogeneous, constituted of water, cropland, urban, shelterbelt, natural vegetation Gobi and desert, particularly when the cropland is irrigated during the growing season in Northwest of China (Figure 1). While the basic dynamic and thermodynamic processes over the oasis-desert system is well investigated, a general understanding of the role of inhomogeneous oasis interior on oasis self-maintainance mechanism is still very important and remains elusive.

Numerical 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; Chen and Avissar, 1994). 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 was created during the day, which was resulted from more water transpired from the vegetation canopy and evaporated from underlying wet soil. Zhang et al (2010) designed 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 led 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 by involving satellite data, especially for description of the inhomogeneous characteristics over the oasis.

The objective of this paper is to examine the effects of oasis-interior heterogeneity in vegetation and soil moisture on the surface-atmosphere exchanges of mass and energy, and the oasis self-maintainance mechanism. Understanding the nature of surface atmosphere coupling over the oasis-desert system is vitally important for assessing local responses of water and energy transmission in an arid region in China.

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-maintainance 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 mainly includes mud soil, tide soil (meadow soil), wind sand soil and typical gray brown soil which distribute in the edge regions (Ma et al., 2002). The soil is continuous and easy to reclaim, resulting this region as one of the possible land resource developing (by reclaiming or by free development) and representative areas in China (Chen, 2000). It is also typical as an irrigated and agricultural oasis, representing the inhomogeneous oasis in northwest China.

2.2 Datasets

A field experiment was performed in summer 2004 in Jinta oasis. In the observations, meteorological parameters and surface turbulent heat fluxes obtained from the Portable Automated Meso-net (PAM) stations (CSAT3/KH20, Campbell.Sci. Ins., Utah) were collected for the study of energy and water cycle over the oasis-desert system. The data have been used widely for analyzing the atmosphere boundary layer characters and the water-energy budget over the oasis-desert landscapes (Chen et al, 2005). Details of the data can be found in the work of Ao (2006).

Satellite data such as land use types, vegetation fraction cover and surface-layer soil moisture were derived from the Moderate Resolution Imaging Spectro-radiometer (MODIS) gathers data in 36 spectral bands on board the Terra (EOS AM) and Aqua (EOS PM) satellites. 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 mesoscale, limited-area, terrain-following sigma-coordinate modeling system designed for atmospheric research (Grell et al., 1994). In this study, version 3 coupled by Noah land-surface model (LSM) was used in the simulation. A triple-nested grid system with the same center located at 40.3°N, 98.9°E was used. The three systems extend 333km, 120km, 61 km and with grid spacing of 9 km, 3km, and 1km respectively. Jinta oasis is located at the center of the third domain. In the vertical, 23 unevenly spaced full sigma levels were defined. MM5 was run with the MRF boundary layer scheme, the Kain-Frisch convection scheme, simple ice microphysics and cloud radiation scheme. The 0000 UTC Global Forecast System (GFS, provided by the National Centers for Environmental Predictions (NCEP)) gridded analysis fields and 6-h interval forecasts, at 1.25° lat/lon horizontal grid increment, were used to initialize the model and to nudge the boundaries of Grid 1. As a one-way strategy has been selected for the operational chain, Grid 2 used Grid 1 forecasts (at 2-h interval) and Grid 3 used Grid 2 forecasts (at 1-h interval) as boundary conditions.

The model was initialized on 4 July 2004 at 1200 UTC, i.e., 2000 BT (Beijing Time) and ended on 9 July 2004 at 1600 UTC, i.e., 0000 BT on 10 July 2004, during which the oasis effects have been observed in the field experiment (Chen et al., 2005). Referred to similar simulations for oasis-desert mesoscale circulation in other works (Chu et al., 2005; Lu et al., 2004; 2005), the first 30 hours of each simulation were skipped as spin-up time. Hereafter, the simulations from 0000 BT on July 6 2004 to 2300 BT on July 9 2004 were used for the analysis.

Four simulations were performed in this work. In the first one, all parameters were from MM5 default, which is referred to as CTL. The second experiment is referred to as MOD, in which 1-km-resolution land use types, vegetation fraction and 10cm soil moisture were replaced by the values derived from MODIS data, with a more “realistic” land-surface condition than CTL. CTL and MOD simulations were used to evaluate the model results. In addition, land use types in MOD include the oasis corridor, water, farmland and grass (Fig. 2), it was taken as a “realistic” simulation for the heterogeneity of the oasis interiors. The other two simulations present the relatively uniform, in which the bare soil and desert patches in the oasis interior in MOD simulation were replaced by cropland or grass, showing that the oasis interior was mostly composed by vegetation. The replacement with cropland is referred to as EXP1, and the replacement with grass is referred to as EXP2. In EXP1 and EXP2, vegetation fraction and soil moisture initials over the substitute area were replaced with the values of the averages of the crop and grass respectively to present two possible ways of the oasis development (reclaiming farmland and free development). Land use map and 10cm soil moisture distribution of the four simulations are shown in Fig. 2 and 3 (vegetation fraction maps omitted). As testing experiments, EXP1 and EXP2 were designed to study the inhomogeneity of oasis interior; CTL and MOD were used to validate the model results.

4 Results and Discussion

4.1 Evaluation of simulation results

2m air temperature, specific humidity, sensible and latent heat flux outputs from CTL and MOD simulations were evaluated against with the observations (Fig. 4). Bias and root mean square error (RMSE) are shown in Table 1. According to the statistics, MOD experiment produces better simulations for all parameters than CTL, although slightly larger errors exist in the simulations for surface heat fluxes. The time series of the four parameters from CTL, MOD simulations and observations are shown in Fig.4. Both simulations can simulate the diurnal variations of the parameters well. MOD simulation performs better than CTL, particularly for sensible and latent heat flux. As a result, MOD simulation represents a more “realistic” and “inhomogeneous” situation in the follow-up study, while EXP1 and EXP2 indicate relatively “uniform” land-surface conditions.

4.2 Impacts of inhomogeneity on oasis-self maintaining mechanism

As was discussed in the introduction, studies have considered the mechanisms of oasis self-maintainance in a surrounded desert environment. Most of them focused on the oasis “cold-wet” effects and their driven mesoscale circulations. In general, these studies emphasized the processes from the following ways. Firstly, the oasis is a cold-wet island comparing with the surrounded desert due to the inhomogeneous partitioning of water and energy, 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 (Chu et al., 2005; Zhang and Huang, 2004; Lu et al., 2004). Secondly, the oasis with cropland, vegetation and forest can eliminate the wind from the desert, slowing down 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 (moisture content of the air increases with height) level, reducing evaporation over the oasis, benefiting the plant growing over the desert and creating a protecting belt around the oasis (Zhang and Huang, 2004). Comparisons of these factors among the simulations will be presented and discussed in this part.

4.2.1 Surface heat-flux heterogeneity

According to land surface energy balance, the equations over the oasis and desert can be expressed as (Holloway and Manabe, 1971; Lu et al, 2004; Chu et al, 2005):

$$R_n{}^O = H^O + \lambda E^O + G^O$$

$$R_n{}^D = H^D + \lambda E^D + G^D \qquad (1)$$

Where R_n, H, λE and G are the net radiation, sensible heat-flux, latent heat-flux, and soil heat-flux at the oasis (denoted as ^{O}) and desert (denoted as ^{D}), respectively. The difference of the surface energy balance between oasis and desert is represented by

$$R_n{}^D - R_n{}^O = \left(H^D - H^O\right) + \left(\lambda E^D - \lambda E^O\right) + \left(G^D - G^O\right) \qquad (2)$$

According to the analysis on observations from Heihe river basin in China, it was found that the soil hear flux is almost the same in the oasis and desert (Kai et al, 1997), i.e., $G^D \approx G^O$, then equation (2) can be written as:

$$R_n{}^D - R_n{}^O = \left(H^D - H^O\right) + \left(\lambda E^D - \lambda E^O\right) \qquad (3)$$

The characteristics of the surface radiation balance over desert $R_n{}^D$ and oasis $R_n{}^O$ are analyzed and compared in the HEIFE area by use of the data observed at the desert and oasis (Zhangye station). Shen et al. (1995) found that under the clear sky, the instantaneous fluxes of downward shortwave and longwave radiation reaching the surface and their diurnal variations are nearly the same over desert and oasis. However, due to the surface albedo difference, $R_n{}^O$ is always larger than $R_n{}^D$. In summer,

$$R_n{}^O - R_n{}^D \approx 129.6 \text{ W/m}^2 \qquad (4)$$

Kai et al. (1997) found that the latent heat-flux is smaller over the desert (67 W/m^2) than over the oasis (634 W/m^2) in the HEIFE region

$$\lambda E^O - \lambda E^D \geq 530 \text{ W/m}^2 \qquad (5)$$

Combining equations (3), (4) with (5), the difference of sensible heat flux between the oasis and desert can be expressed as

$$H^O - H^D \le -400 \text{ W/m}^2 \tag{6}$$

The differential sensible heat fluxes over the oasis and the surrounding desert regions drive the secondary circulation with the downdraft over the oasis and the updraft over the desert. And the large evaporation over the oasis consumes lots of energy, leading to evident lower temperature and higher humidity over the oasis.

Fig.5 shows the time series of sensible and latent heat flux differences between the oasis and the desert from MOD, EXP1 andEXP2 simulations (averaged over oasis minus over desert). It indicates that big difference between the oasis and the desert in sensible and latent heat flux occurred during the daytime (0600 to 1800 BT). For sensible heat flux, the maximum of the difference happened around 13:00 BT with a value about -150~-220 W/m^2 in different days. And the latent heat flux is similar to the sensible heat, expect the maximums are between 120~180 W/m^2. Comparing EXP1 and EXP2 with MOD simulation, the changes of oasis heterogeneity play roles in the surface heat-flux partitioning, but the influence degree of EXP1 is larger than EXP2.

4.2.2 Oasis “cold-wet” effect

Fig.6 and 7 shows the time series of 2m air temperature and specific humidity differences between the oasis and the desert (averaged over oasis minus over desert) from MOD, EXP1, EXP2 simulations. All simulations show negative difference for temperature and positive difference for humidity during the daytime, indicating that the oasis is a “wet-cold” island in the daytime. Among the three simulations, EXP1 produces the maximums of the temperature- and humidity- difference, while values in EXP2 are close to that in MOD.

As the surface energy heterogeneity and “cold-wet” effect occurr during the daytime (0600 to 1800 BT shown in Fig.5), and the oasis effect and its self-protecting mechanism are the most evident in the afternoon (i.e., around 1300 BT) (Chu et al., 2005; Chen et al., 2005). Distributions of 2m air temperature and its differences between MOD and EXP1, EXP2 simulations on 6 July 2004, 1300 BT are shown in Fig. 8. The maximums of 2m air temperature are around 36.5 °C in the north of the oasis for all the three simulations, while the area of maximums in the MOD is slightly larger than EXP1 and EXP2. The minimums of temperature are around 32 °C (water region excluded) in the south of the oasis, with the largest low-temperature region produce by EXP1. According to land use types shown in Fig.2, maximums in all simulations are around where bare soil and desert are. Except over the lakes, minimums in all simulations occurr over the regions where the vegetation is density. Furthermore, minimums occur in the west of the oasis in EXP1 simulation, while they follow by the vegetation in the MOD and EXP2 simulations. Considering the temperature changes, 2m air temperature over the oasis decreased about -2.5°C in EXP1 comparing with MOD, while it was about -1.5°C, in EXP2.

Focusing on the "cold island" effect, 2m air temperature differences between oasis and desert (oasis minus desert) averaged during the day time in each day for the three simulations are shown in Table 2. It shows that "cold island" effect of the oasis was increased in EXP1 (making the oasis 0.08 °C colder than that in MOD simulation, which is about 7% of MOD), while it was reduced in EXP2 (making the oasis 0.11 °C warmer than that in MOD).

2m specific humidity and their differences between MOD and EXP1, EXP2 simulations on 6 July 2004, 1300 BT are shown in Fig.9. All simulations can simulate the oasis as a "wet island". The driest region is over the desert, and the wettest is over the oasis. Similar to 2m air temperature, 2m specific humidity distributes along with the vegetation over the oasis in the MOD simulation, but concentrates and maximums occur in the west center in the EXP1 and EXP2 simulations, with a higher "wet" island in EXP1 than EXP2. Compared with MOD simulation, 2m specific humidity over the oasis increases about 1.0 g/kg in EXP1, while it enhances about 0.5 g/kg in EXP2.

2m specific humidity differences between oasis and desert (oasis minus desert) averaged during the day time in each day for the three simulations are shown in Table 3. Both EXP1 and EXP2 display a stronger “wet island” effect than MOD simulation (increasing about 19% in average in EXP1 and 6% in EXP2 comparing with MOD).

4.2.3 Moisture-inversion level

As was discussed above, the moisture-inversion level is also one of the protecting mechanisms to decrease the oasis evaporation. The vertical latitudinal section of specific humidity in the middle of the oasis is shown in Fig.10 (grid 18 to 50 from west to east is mainly oasis). All simulations present the oasis as a “wet island”, with a maximum contour value of 5.0 g/kg, 5.4 g/kg and 5.2 g/kg for MOD, EXP1 and EXP2 simulations respectively. The moisture is higher over the oasis from surface to 770 hPa in EXP1 and EXP2 than that in MOD simulation. All simulations produce deep humidity inversions above 700-hpa layer, preventing water loss from evaporation over the oasis. The depth of the moisture-inversion level is the deepest in EXP1, and it is deeper in EXP2 than in MOD. Totally, both EXP1 and EXP2 have stronger “wet island” and deeper moisture-inversion level comparing with the MOD simulation, leading to a positive role in the oasis. self-maintainance mechanism.

4.2.4 Mesoscale circulation

Fig. 11 displays the modeled horizontal winds and air temperature at 850 and 750 hPa in the two simulations on 6 July 2004, 1300 BT. All simulations show that the oasis is a "cold island" at these two levels. The horizontal winds are divergent in all three simulations at both levels, but affected by the background winds at 750hPa. Comparing EXP1 and EXP2 with MOD simulation, divergences occur in most time but slight convergence can be seen over the bare soil and desert patches in the oasis interior in the MOD simulation, and divergences over the oasis in EXP1 and EXP2 are shown to be less affected due to the relatively uniform of the oasis interior. Furthermore, divergent wind speeds in EXP1 and EXP2 are larger than that in MOD, and are reduced to be weaker over the oasis interior due to inhomogeneity in MOD simulation. Comparing EXP1 with EXP2, the divergent wind speeds in EXP2 are smaller than EXP1 over the oasis interior.

To co-operate the horizontal wind field, Fig.12 displays the vertical latitudinal section of vertical velocity for the three simulations on 6 July 2004, 1300 BT. Positive values indicate rising motion. All simulations show updraft airflows are produced over the oasis (i.e., from grid 18 to 50), while downdrafts exist at the edge of the oasis (i.e., around grid 20 and 45 in MOD, grid 20 and 50 in EXP1 and EXP2). From 750 to 600 hPa, EXP1 shows a stronger and wider downward motion than EXP2 and MOD, and the downdrafts in EXP1 are stronger than MOD as well. In the lower levels from 850 to 750 hPa, airflow has more up and down turbulences in the MOD simulation, but only goes down over the oasis interior in EXP1 and slightly goes up and down in EXP2, which is consistent with characters of the horizontal winds shown in Fig. 11.

As was discussed in the introduction, the air flow diverges from the oasis to desert, produces downdrafts over the oasis, and then converges around the oasis-desert transition at the edge to updrafts, holding water over the oasis and preventing it flowing into the desert. This is a favorable mechanism for protecting the oasis. Comparisons among the three simulations show that the inhomogeneity of MOD simulation produces a slighter divergence than EXP1 and EXP2. The interactions of divergence and convergence (Fig.11), updrafts and downdrafts (Fig.12) 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 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).

5 Conclusions

The influence of inhomogeneity of the oasis interior on oasis self-maintainance mechanism was investigated by using the mesoscale model MM5 with satellite derived land surface parameters from MODIS data. Four simulations were performed, among which CTL (default simulation) and MOD (with parameters replaced with MODIS data) were used to validate the model results to present that the input of MODIS-derived parameters can produce a better simulation; EXP1 and EXP2 were designed to study the inhomogeneity of oasis interior with inhomogeneous landscape and its related parameters replaced with crop in EXP1 and substituted with grass in EXP2. The results indicate that the MOD simulation can produce a better simulation than CTL. EXP1 and EXP2 were designed to present the future development of oasis, i.e., EXP1 reduces the inhomogeneity by farmland reclaiming, while EXP2 by free development. As more “realistic” and “possible” conditions, results of MOD, EXP1 and EXP2 were compared to investigate the influence of heterogeneity on oasis self-maintainance mechanism.

Surface heat flux heterogeneity was explored first. Big difference between the oasis and the desert in sensible and latent heat flux occurred during the daytime, resulting in the oasis as a “cold island”. For sensible heat flux, the maximum of the difference happened around midday in each day with the value about -150~-220 W/m^2 in different days. And the maximums of latent hear fluxes are between 120~180 W/m^2. Comparisons among the simulations show that the changes of oasis heterogeneity play roles in the surface heat-flux partitioning, but it is larger in EXP1 than that in EXP2.

Water and energy cycle is the most important factors for the oasis self-protecting. All simulations show negative difference for temperature and positive difference for humidity during the daytime, indicating that the oasis is a “wet-cold” island in the daytime. Among the three simulations, EXP1 produces the strongest “cold-wet” island, while EXP2 has a stronger “wet” island, but close “cold” island as MOD. Vertical sections of humidity illustrate the existence of moisture-inversion level, and the deeper moisture-inversion in EXP1 and EXP2 further indicate that the relatively homogeneity in the oasis interior help to produce stronger humidity inversion over the oasis, preventing water over the oasis from evaporating.

For the oasis-desert secondary circulation, the more homogeneous land surface conditions make the secondary circulation stronger, and the inhomogeneity creates both updrafts and downdrafts over the oasis interior. The stronger circulations in EXP1 and EXP2 are favorable for the oasis maintain and development, while the interactional mechanism of divergence and convergence in MOD 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, and the water and heat exchange between the oasis and the desert will be enhanced, which may allow water vapor over the oases flowing 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 ensemble analysis of the model designs, and doesn’t consider the influence of soil moisture. However, EXP1 and EXP2 with different land surface parameters present that the influence degree of the relatively “uniform” are not identical, which might be affected much by the influence of soil moisture distribution. Such a hypothesis can raise another question in its turn, i.e., the influence of irrigation on the oasis development. Located in a very dry region, lots of oases like Jinta oasis in northwest China depend on irrigation; the impacts of irrigation on oasis self-maintainance mechanisms are important and still need to be investigated. Further work will need to better constrain this question in advance.

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Table 1. Statistics of 2m air temperature, specific humidity, sensible and latent heat flux between CTL, MOD simulations and observations.

Statistics	Air temperature (°C)		Specific humidity (g/kg)		Sensible heat flux (W/m^2)		Latent heat flux (W/m^2)	
	CTL	MOD	CTL	MOD	CTL	MOD	CTL	MOD
Bias	-0.79	-0.34	-0.861	-0.585	93.1	58.5	-78.8	-38.3
RMSE	3.03	2.79	1.373	1.234	152.8	98.4	120.1	76.6

Table 2. Averaged 2m air temperature difference between oasis and desert (oasis minus desert) during the time period of 06:00 to 18:00 BT in each day for MOD, EXP1 and EXP2 simulations (°C)

	Jul 6	Jul 7	Jul 8	Jul 9
MOD	-1.36	-1.21	-0.89	-0.97
EXP1	-1.47	-1.35	-0.92	-1.01
EXP2	-1.19	-1.14	-0.77	-0.88

Table 3. Averaged 2m specific humidty difference between oasis and desert (oasis minus desert) during the time period of 06:00 to 18:00 BT in each day for MOD, EXP1 and EXP2 simulations (g/kg)

	Jul 6	Jul 7	Jul 8	Jul 9
MOD	0.747	0.65	0.462	0.503
EXP1	0.835	0.754	0.541	0.683
EXP2	0.721	0.659	0.49	0.612

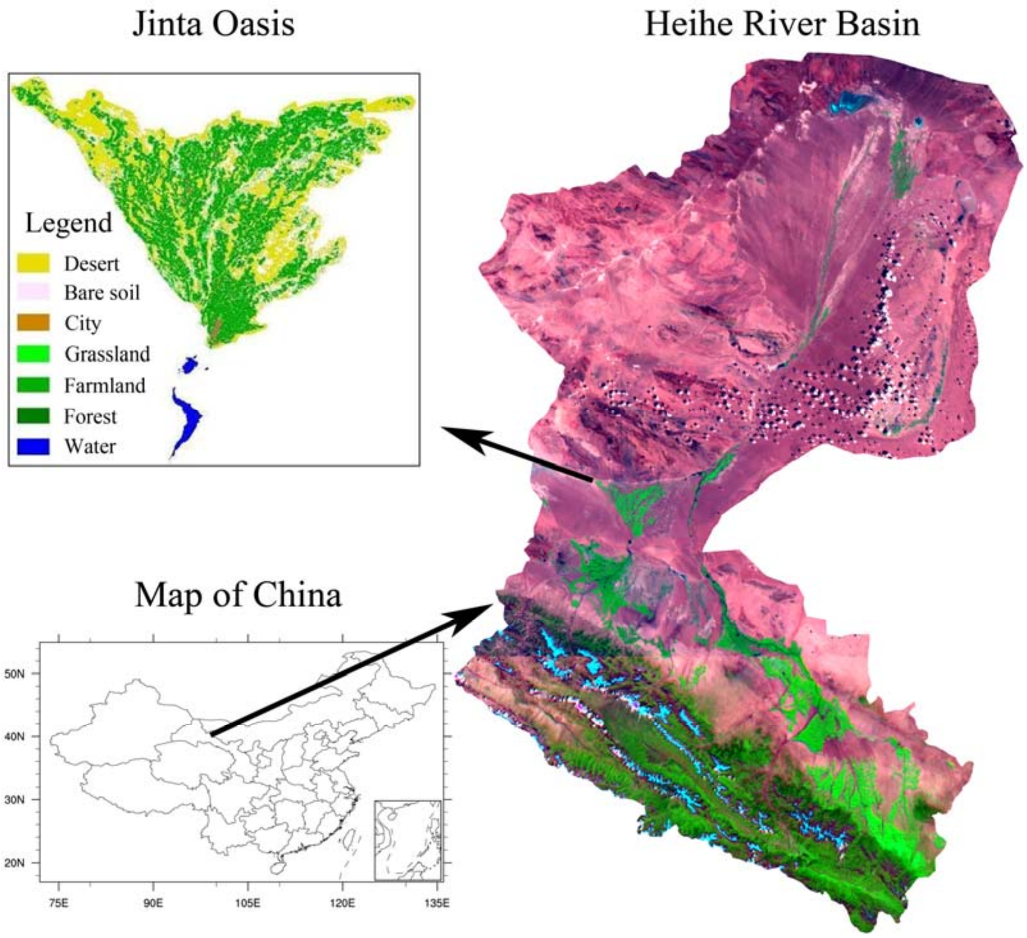

Fig. 1. Location of Jinta Oasis in Heihe River Basin (Geocover mosaics) and land use map of Jinta Oasis.

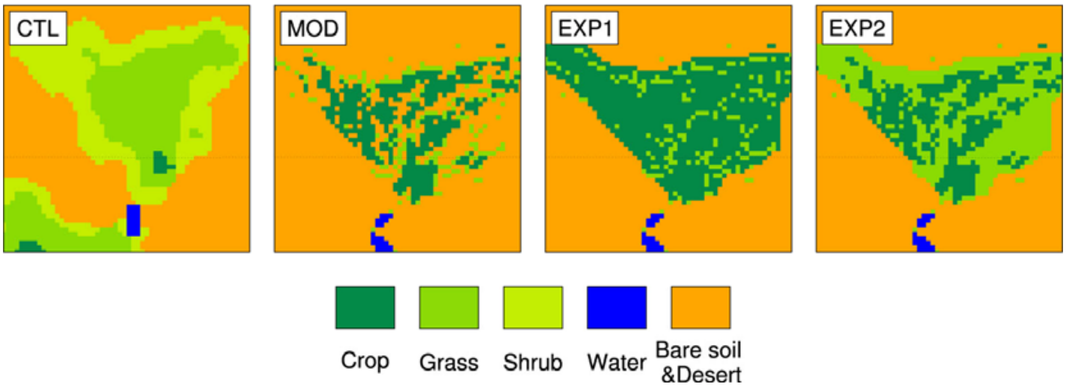

Fig. 2. Land-use maps for the third domain of the four simulations.

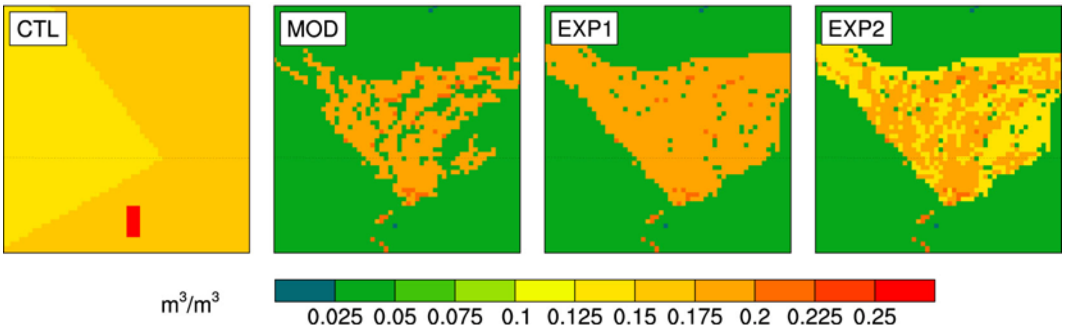

Fig. 3.10cm soil moisture distributions for the third domain of the simulations.

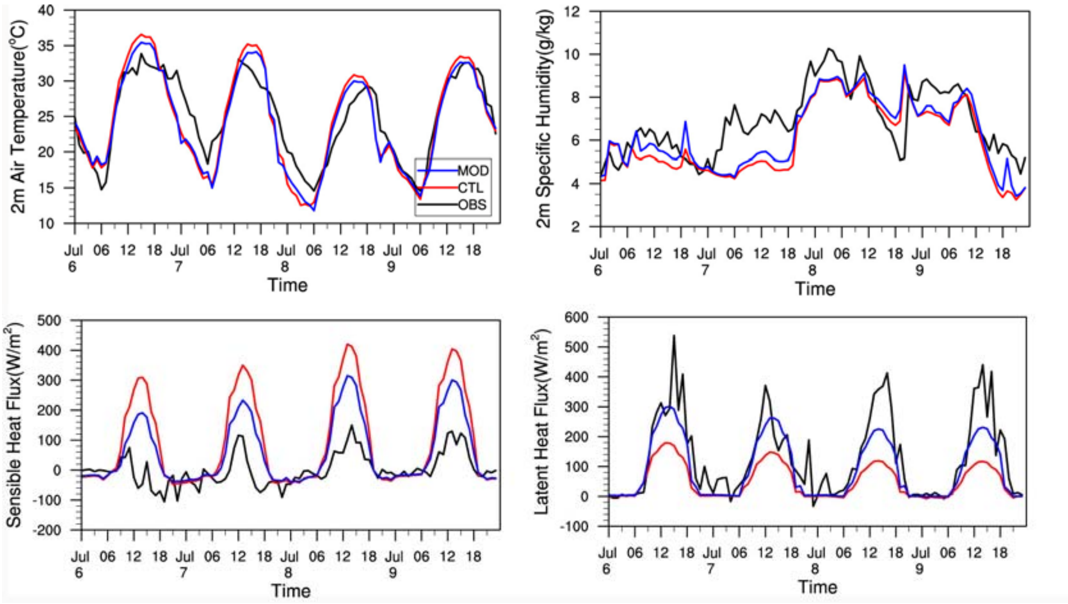

Fig.4. Observations of 2m air temperature, 2m specific humidity, sensible and latent heat fluxes versus CTL and MOD simulations.

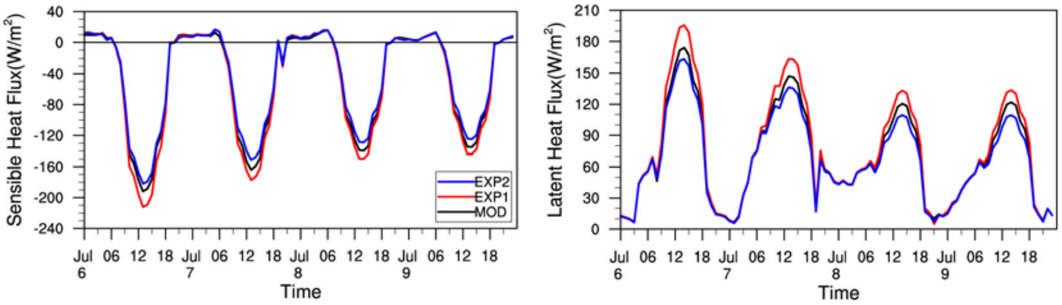

Fig. 5. Time series of sensible and latent heat flux differences between the oasis and desert (averaged over oasis minus over desert) from MOD, EXP1 and EXP2 simulations.

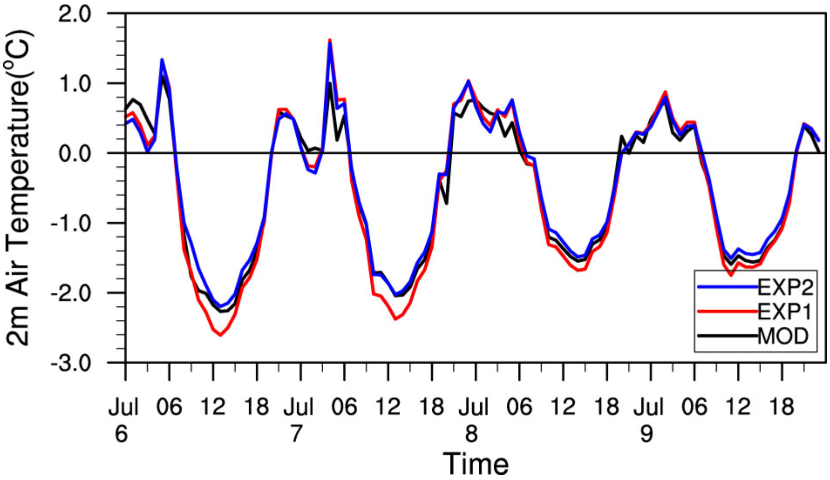

Fig. 6. Time series of 2m air temperature differences between the oasis and the desert (averaged over oasis minus over desert) from MOD, EXP1 and EXP2 simulations.

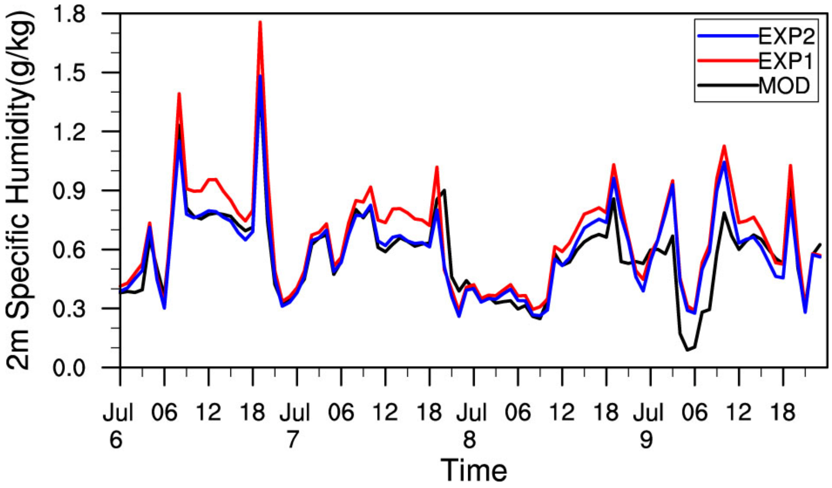

Fig. 7. Time series of 2m specific humidity differences between the oasis and the desert (averaged over oasis minus over desert) from MOD, EXP1 and EXP2 simulations.

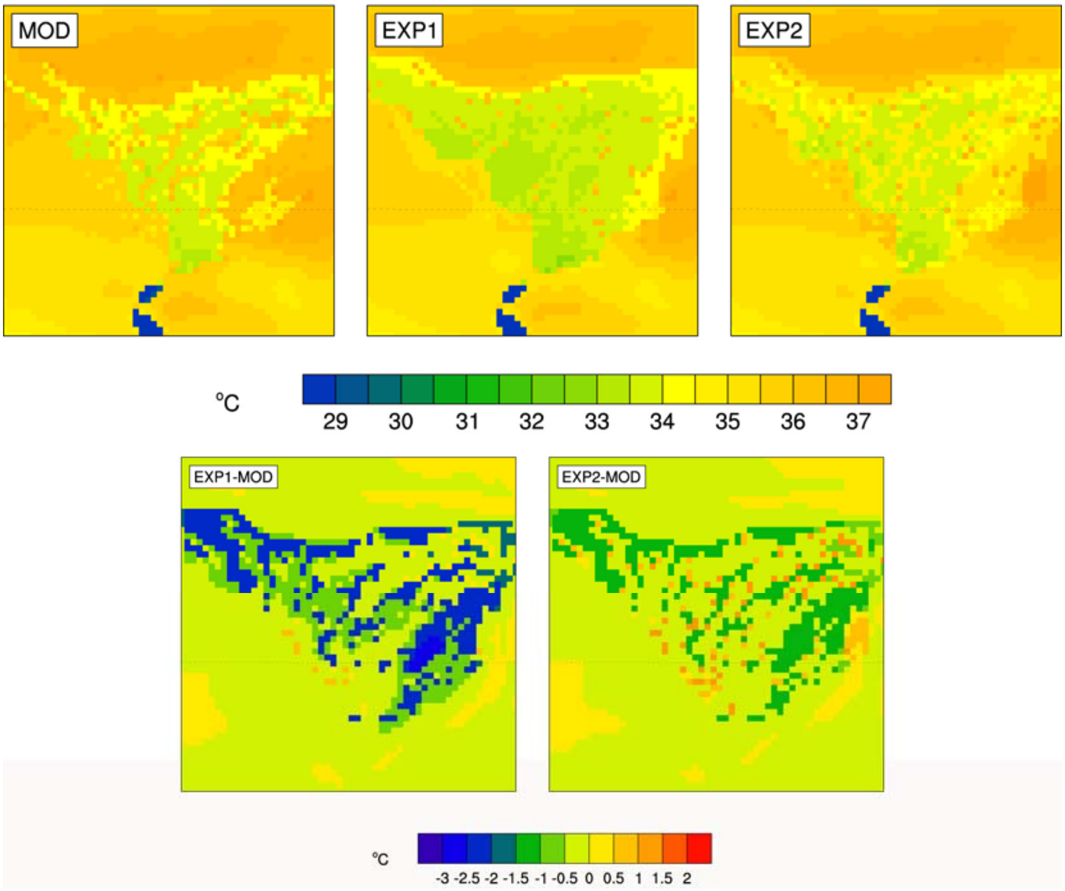

Fig. 8. 2m air temperature and its differences between MOD and EXP1, EXP2 simulations on 6 July 2004, 1300 BT.

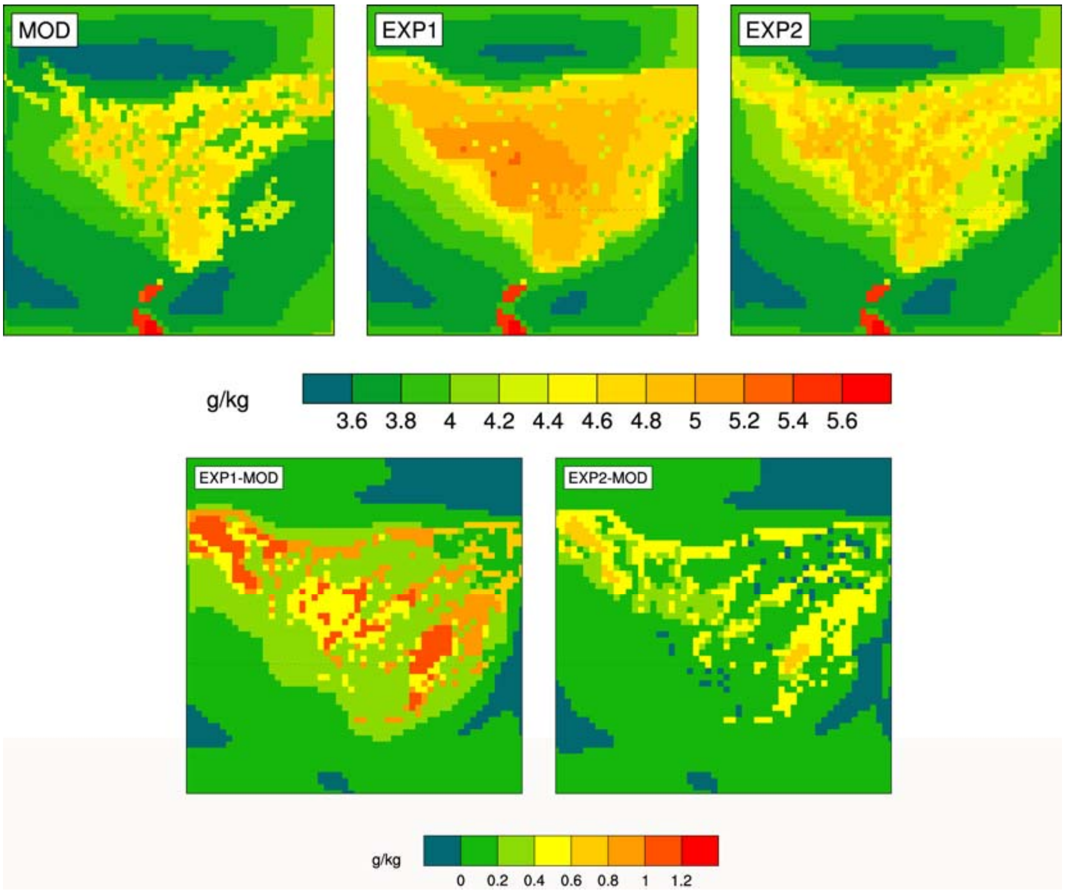

Fig. 9. 2m specific humidity and its differences between MOD and EXP1, EXP2 simulations on 6 July 2004, 1300 BT.

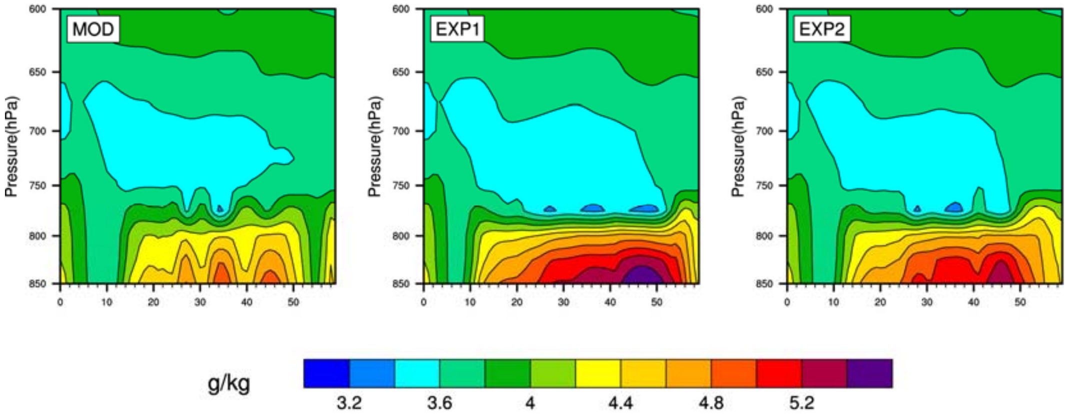

Fig.10. Vertical latitudinal section of 2m specific humidity (g/kg) from MOD, EXP1 and EXP2 simulations on 6 July 2004, 1300 BT.

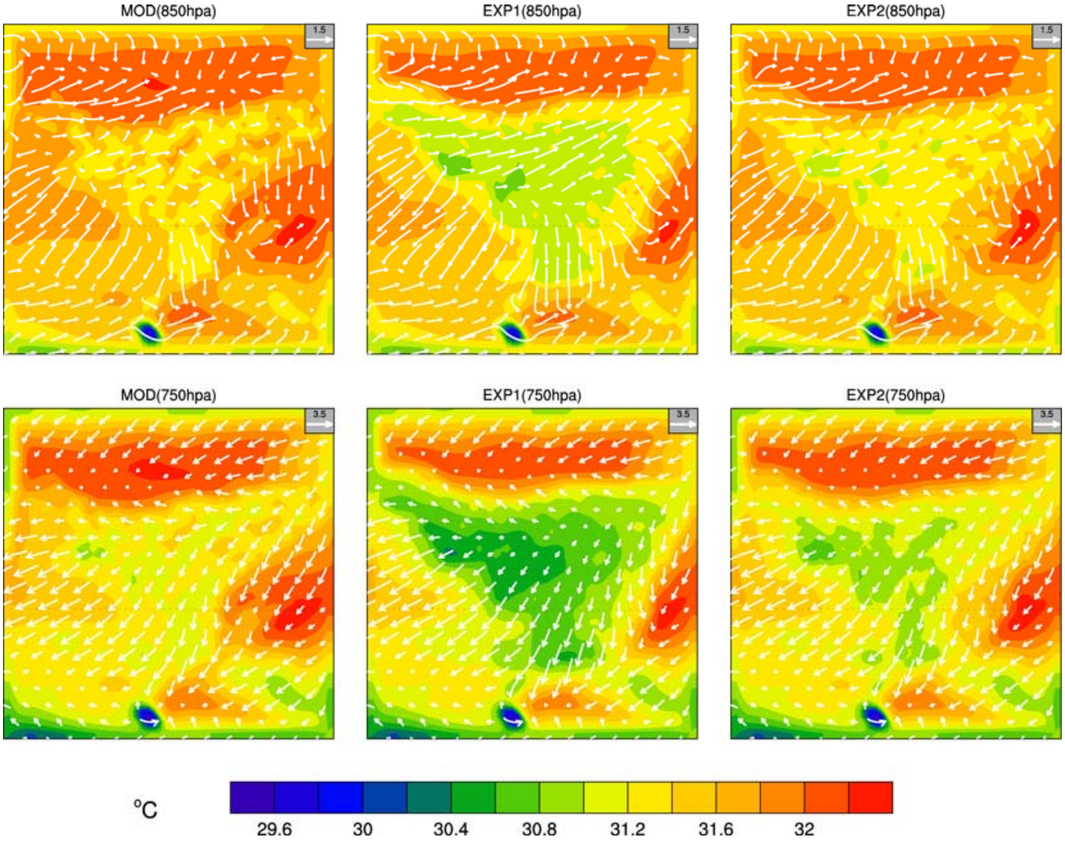

Fig.11. Simulated horizontal winds (m/s) and air temperature (°C) at 850 hPa from MOD, EXP1 and EXP2 simulations on 6 July 2004, 1300 BT.

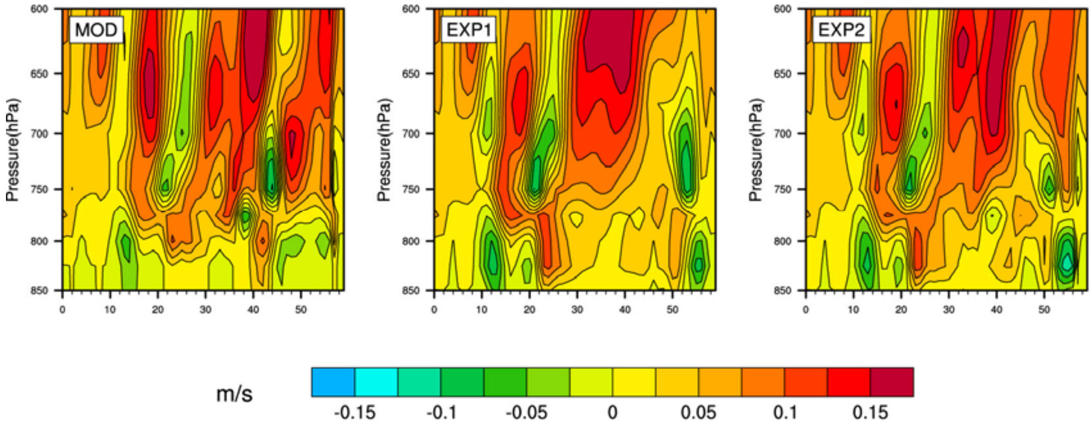

Fig.12. Vertical latitudinal section of vertical velocity (m/s) from MOD, EXP1, EXP2 simulations on 6 July 2004, 1300 BT.