Preface

Progress in the study of oasis-desert interactions

A R T I C L E   I N F O

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A B S T R A C T

Within arid and semi-arid regions, deserts and oases generally act as the landscape matrix and mosaic, respectively. Oasis-desert interactions, i.e., the transport of mass and energy between the two, are very important for the stable co-existence of oasis and desert ecosystems. In recent decades, great progress has been made to advance our understanding of oasis-desert interactions. In this preface, we provide an overview of oasis-desert interaction studies available in the literature and our current understanding of the limitations and challenges of these studies. Future foci can be multiple-scale, high-accuracy observing matrices and seamless simulations from mesoscale circulations to large eddies, which are crucial for understanding small-scale structures of energy and water exchange and their connection with oasis-desert interaction.

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1. Significance of the study of oasis-desert interactions

Arid and semi-arid regions constitute approximately 41% of the world’s total land area, where the precipitation and water resources are scarce and the ecosystem is extremely fragile and very sensitive to anthropogenic disturbance. These regions are hot spots of climate change (GLP, 2005; Reynolds et al., 2007), where the most significant temperature increases have occurred over the past 100 years. In particular, arid and semi-arid regions account for 44.46% of the global warming trend of the mean land surface (Huang et al., 2012). Meanwhile, due to the effects of climate change and human activities, arid regions are expected to expand to up to 50% of the global land area by the end of this century (Huang et al., 2016c).

Arid and semi-arid regions generally exhibit basic landscape configurations, with deserts as the landscape matrix and oases as the landscape mosaic (Cheng et al., 1999; Cheng et al., 2014). Oases are the basis of human life and economic development, supporting more than 95% of the population in the arid regions of China although they cover less than 5% of the total area of arid regions (Han, 1999; Wang, 2009). Oases and deserts are two contradictions that are independent but interact. First, oases and deserts are different in terms of soil moisture conditions, vegetation type and distribution, energy budget, and the biological communities of the underlying surfaces, representing two independent ecosystems. Meanwhile, oases and deserts interact with each other. Numerous field observations and numerical simulation studies have demonstrated that water vapor and heat exchange occur between oases and deserts through air advection.

Oasis-desert interactions, i.e., the transport of mass (water vapor and CO$_2$) and energy between the two, are important topics when studying the atmosphere, ecology, and hydrology of oases. Exploring these interactions has important and profound significance for understanding the regional climate effects in oases, support oasis sustainability, and provide stable maintenance and development of oases ecosystems (Zhang and Huang, 2004). In recent decades, great progress has been made based on field observations (Li et al., 2009, 2013; Wang et al., 1993) and numerical simulations (Gao et al., 2004; Chu et al., 2005; Han et al., 2010; Jiang et al., 2005; Meng et al., 2009, 2012, 2015; Wen et al., 2012; Xue and Hu, 2001; Yan et al., 2001; Zuo et al., 2004b), which have revealed the mystery of the existence of oases in arid environments and their interactions with desert ecosystems.

As the preface to the issues surrounding oasis-desert systems, this study first examines observational evidence and the current understanding of oasis-desert interactions. Next, the paper summarizes a new advanced eco-hydrological observation network and presents perspectives for future research aimed at understanding small-scale water and energy exchange in fragmented oases. Finally, we highlighted some details of this special issue.

2. Observational evidence of oasis-desert interactions

2.1. Oasis effects from preliminary experiments

The “oasis effect” was first reported for an alfalfa field near Phoenix, Arizona, USA by Van Bavel (1967), who found that the daily latent heat flux after flood irrigation was much higher than the net radiation and that the daily average sensible heat flux and Bowen ratio were negative, representing a significant “oasis effect”. This field later experienced a drought, and the “oasis effect” disappeared. These observations recorded a complete cycle of the generation and disappearance processes of the “oasis effect”, revealing the impacts of soil moisture (irrigation or precipitation) on the “oasis effect”.

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Rosenberg (1969) conducted field experiments in an oasis in East Nebraska, USA. He found a strong local advection effect during the growing season, which caused the evapotranspiration flux to be significantly higher than the net radiation, with negative sensible heat flux. Flohn (1971) observed the same phenomenon when analyzing the water balance in Tunisian oases. Meanwhile, Su et al. (1987) conducted a field observational experiment in an oasis and gobi near Zhangye in northwest China. These authors found that a small oasis in a broad desert was acting as a source of cold air during the day and night under clear or slightly cloudy conditions during the summer growing season. They called the oasis a “cold island” and collectively called the micro-climate effects generated by the “cold island” the “oasis cold island effect.” The sensible heat flux inside the “cold island” was nearly zero or negative during the day due to thermal inversion.

Oke (1987) suggested that isolated cold, humid surfaces in arid, hot environments, such as a lake surface during a dry summer, isolated snow cover, parks in cities, and isolated trees along streets, could all exhibit this “oasis effect”, i.e., a latent heat flux higher than the net radiation flux, a negative Bowen ratio, and sensible heat transport from the atmosphere to the land surface.

Therefore, oasis effect, which means thermal inversion, and negative sensible heat flux appear over oases, are widespread over humid surfaces located in arid and hot environments.

2.2. Desert effect observed from HEIFE experiment

To thoroughly study the land–atmosphere exchange characteristics in arid regions, China and Japan initiated the Heihe River Basin Field Experiment (HEIFE) during 1988–1990. The experiment was the first international comprehensive field experiment about land-atmosphere interactions in arid regions.

The Heihe River Basin is located in the middle of the Hexi corridor in northwestern China (Fig. 1) and is the second largest inland river basin in northwestern China, covering an area of approximately 1,432,000 km² (Li et al., 2013). The basin is characterized by cryosphere (glaciers, frozen soil, alpine meadow forest) in its upper reaches, by irrigated cropland in its middle reaches and by riparian ecosystem and desert in its lower reaches (Cheng et al., 2014).

The HEIFE observation network included five micrometeorological stations and five automatic meteorological stations. The five micrometeorological stations were distributed on different underlying surfaces in oasis, gobi, and desert areas and in transitional zones between the desert and the oasis. The five automatic meteorological stations were established in a gobi, on a sand dune and surrounding the desert micrometeorological station. Meanwhile, observations were conducted at three radiosonde stations and four hydrological stations in the experimental region (Hu et al., 1994; Wang et al., 1993). This experiment provided a large, rich, and detailed dataset for studying oasis-desert interactions and greatly enhanced the understanding of oasis-desert interactions (Hu et al., 1994; Wang, 1999).

Through HEIFE, the oasis effect was confirmed and the so-called “desert effect” phenomenon was identified. The “desert effect” is characterized by moisture inversion and negative (downward) water vapor flux near the surface layer over the desert during the daytime and vice versa at night (Fig. 2(a) and b)). Both effects were frequently observed, as shown in Fig. 2(a and b) (Hu et al., 1990). The “desert effect” was also characterized by the following facts: the annual cumulative evaporation in deserts is greater than precipitation (a few dozen mm), and a layer of maximum soil moisture often appears at approximately 20 cm (Fig. 2(c)) below the hot, dry desert surface.

The mean water vapor transport downward was more than 0.1 mm per day (Wang et al., 1990). Although this amount of water is small, it potentially served as a source of water for desert vegetation (Zhang and Huang, 2004).

Additional intensified observations indicated that the air temperature profile over the oasis had a minimum value at some height before noon (10:00–12:00 a.m. at 4 m height in Fig. 2(a)). Meanwhile, the water vapor profile had a minimum value at some height over the desert near the oasis around noon (9:00, 10:00, 12:00, 13:00 a.m. in Fig. 2(b)) (Hu et al., 1993).

To further understand the characteristics of the atmosphere and the moisture and energy cycles during oasis-desert interactions, researchers conducted the “Experiment regarding energy and moisture transfer between the oasis and desert” in the Jinta Oasis, Jiuquan, which is located west of the Heihe River Basin, in June–August 2004. The Jinta Oasis was surrounded by desert and was less affected by macro topography (Chen et al., 2005). By analyzing the low-level wind field structure over the oasis and desert using data from the jinta experiment, Chen et al. (2005) observed that (1) the large temperature difference between the oasis and desert could stimulate secondary circulation between them and that (2) the background wind field strongly affected this secondary circulation. When the background wind field was strong, the local circulation was suppressed; otherwise, the local
circulation between the oasis and desert was significant. Wen et al. (2007) reached similar conclusions using data from automatic meteorological stations and sounding data from the Jinta experiment.

3. Understanding oasis-desert interactions

Based on the data acquired during the HEIFE experiment, a physical picture of the basic processes of oasis-desert interactions is proposed (Hu et al., 1994; Zuo et al., 2004a) and shown in Fig. 3.

3.1. Physical picture of oasis-desert interactions

During the day, solar radiation heats the ground surface in desert regions. The surface temperature can reach up to 60 °C. The near-surface atmosphere develops super adiabatic and unstable stratification, which leads to the ascent of the near-surface air over the desert. In contrast, the surface temperature in the oasis is much lower because of vegetation transpiration and surface evaporation. The temperature difference between the two is 10–30 °C.

The strong thermal difference between the oasis and desert causes local circulation. In the near-surface layer, the air density and pressure over the desert are lower than over the oasis. The pressure difference drives moist and cold air flowing from the oasis to the desert, resulting in moisture inversion and a high temperature lapse rate of approximately 8–10 °C/100 m in addition to an updraft over the desert surface. In the upper-air, the air density and pressure over the desert are higher than that over the oasis. This pressure gradient drives dry and hot air over the desert flowing toward the oasis, forming a downdraft and a thermal inversion layer consisting of hot, dry air overlying the cold, moist air near the oasis surface. The thermal inversion gradient can reach 20.5 °C/100 m over the oasis (Zhang et al., 1992).

The airflow transfers heat from the desert to the oasis and provides extra energy to the oasis for evapotranspiration. The transferred energy can reach approximately 50% of the net radiation in terms of the daily total values. In the morning, due to the heating effect of solar radiation, the oasis will experience weak, upward sensible heat flux in the near-surface layer. When the oasis “cold effect” is very strong near noon and in the afternoon, the entire near-surface layer experiences temperature inversion, and the sensible heat flux is transferred downward to the surface.

Meanwhile, water vapor is transferred from the oasis to the desert near the surface. At night and in the morning, the direction of water vapor flux is upward due to surface evaporation in the desert soil layer (Hu et al., 1993). However, near noon and in the afternoon, moisture inversion occurs over the desert in the near-surface layer due to horizontal water vapor advection from the oasis. As a result, the direction of water vapor flux over the desert is downward.

In summary, the HEIFE experiment clarified the “oasis effect” and “desert effect” as well as the mass and energy budget exchange due to the mesoscale circulation between the oasis and desert, as shown in Fig. 3. The transfer of energy from the desert to the oasis can be used for productivity and evapotranspiration. The stability over the oasis inhibits, to some extent, water vapor diffusion from the oasis to the free atmosphere, decreases the water dissipation of the oasis-desert system, increases the water-use efficiency, and positively affects the sustainable development of the oasis. Simultaneously, the transfer of water vapor from the oasis to the near-surface layer of the desert, despite its small quantity, positively affects the maintenance of desert vegetation. The “oasis effect” and “desert effect” result in a positive feedback that is beneficial to the maintenance of the oasis ecosystem.
3.2. Theory of oasis-desert interactions

To quantify the advection of energy and mass between oases and deserts, Hu (1999) and Hu (2002) established equations for the non-equilibrium state of atmospheric systems. According to the theory, sensible heat and latent heat fluxes include two parts, i.e., the vertical gradient fluxes of heat or vapor and the corresponding coupled fluxes, respectively.

\[ \overline{\rho w' \theta} = -\rho c_p K_0 \frac{\partial \theta}{\partial z} + \rho c_p K_{0W} W \]  

\[ \overline{\rho w' q} = -\rho K_V \frac{\partial q}{\partial z} + \rho K_{VW} W \]  

(1) (2)

where \( \rho \), \( c_p \), and \( W \) represent the air density, heat capacity at constant pressure, and mean vertical velocity, respectively; \( K_0 \) and \( K_V \) are the turbulence diffusion coefficients of heat and vapor, respectively; and \( K_{0W} \) and \( K_{VW} \) are defined as the coupling coefficients of the vertical velocities to the heat and vapor turbulence fluxes, respectively.

Chen et al. (2007, 2013) analyzed near-surface turbulence experiment observation data from Uppsala University at Lövsta in 1986 and provided the following approximate functions (Eqs. (3) and (4)) of the coupling coefficients:

\[ K_{0W} = \overline{uw_0} \ln \left( \frac{z_{w0}}{z_{w0}} \right) \left[ \ln \left( \frac{W}{u_*} \right) \right]^4 \]  

\[ K_{VW} = \overline{qv_0} \ln \left( \frac{z_{v0}}{z_{v0}} \right) \left[ \ln \left( \frac{W}{u_*} \right) \right]^4 \]  

(3) (4)

where \( u_* \) is the friction velocity, \( z_{w0} \) and \( z_{v0} \) are the zero-effect heights of coupled heat and vapor, respectively, and \( \overline{uw_0} \) and \( \overline{qv_0} \) are coupled vapor characteristic values related to the dynamic and thermodynamic characteristics of the underlying surface.

Based on the above studies on atmospheric non-equilibrium thermodynamics, Hu et al. (2012) stated that the integral terms of the convergence or divergence in the air column must contribute to the surface energy balance.

4. New observation era and research perspectives of oasis-desert systems

Integrated studies for understanding eco-hydrological processes across heterogeneous land surfaces urged researchers to upgrade the oasis-desert observing systems, e.g., the “Watershed Allied Telemetry Experimental Research” (abbreviated as WATER) and the “Heihe Watershed Allied Telemetry Experimental Research” (abbreviated as HiWATER), which were conducted in the Heihe River Basin in 2007–2009 and 2012–2015, respectively. These experiments provide new opportunities to advance our understanding of oasis-desert systems with highly heterogeneous surfaces.

4.1. WATER and HiWATER

The objectives of the WATER and HiWATER experiments were to establish an internationally recognized watershed observation system, improve the ability of researchers to observe ecological and hydrological processes and to apply remote sensing in integrated watershed ecology-hydrology studies and water resource management (Li et al., 2009, 2013).

In these experiments, comprehensive observations of the oasis and desert were made to study oasis-desert interactions. Particularly, the “Multi-scale Observation Experiment on Evapotranspiration over heterogeneous land surfaces” (MUSOEXE), which is a sub-experiment of HiWATER and a matrix observation method, was adopted, with dense distribution of eddy covariance systems (EC), large aperture scintillometers (LAS), and automatic meteorological stations (Fig. 3). This specific observation scheme included two nested experimental regions, one 30 km × 30 km region and one 5.5 km × 5.5 km region, in the central oasis region and in the midstream area of the Heihe River Basin. In the 30 km × 30 km experimental region, the observation system consisted of “one horizontal traverse and one vertical traverse”, including 1 superstation (within the oasis, cropland) and 4 ordinary stations (around the oasis), with underlying sandy desert, desert steppe, gravel desert, and wetland surfaces. In the 5.5 km × 5.5 km experimental region, the region was divided into 17 small regions based on the crop structure, orientations of the farmland shelter-belt and villages, distribution of roads, soil moisture content, and irrigation conditions. An eddy covariance system and an automatic meteorological station were installed in each small region. Three
pairs of LASs were mounted to span 2–3 km, which corresponded to the scale of 2–3 Moderate Resolution Imaging Spectroradiometer (MODIS) pixels. At the Daman superstation, a LAS spanning two MODIS pixels and a 40-m meteorological tower at the center of the light path of LAS, which served as a superstation, were constructed (Liu et al., 2016b; Xu et al., 2013). Stable isotope techniques were used to conduct single-point continuous and multi-point synchronized observations of soil evaporation and vegetation transpiration (Wang et al., 2016a; Wen et al., 2016). The thermal dissipation probes (TDP) were used to measure the transpiration of individual trees. In these experiments, the water and energy exchange between the desert and oasis was observed and the heterogeneous land fluxes were measured in individual areas within the oasis.

The experiments further advanced our understanding of the oasis-desert complex. Both the “oasis effect” and “desert effect” were confirmed by the EC observations and gradient observations. The daily average evapotranspiration from mid and late July to mid-August could exceed 10 mm/d. Under most conditions, the observed latent heat flux at the desert station was upward (0–50 W/m²). Although the heat flux was occasionally negative, the frequency and duration of these negative periods were smaller than those of the early HEIH experimental results. The failure of observing long-term negative latent heat flux likely resulted from the greater amount of precipitation that occurred in this area during the most recent decade.

4.2. Research perspectives

4.2.1. Observational techniques

Over the past 20 years, surface energy imbalance has become a core problem in the study of land-atmosphere energy exchange (Wang et al., 2009). Researchers have conducted multiple observation experiments around the world. However, the observed energy imbalance remains puzzling and requires further study. Energy advection by secondary circulation and the underestimation of low-frequency, large-scale turbulent flux may be the main reasons for the energy imbalance in EC observations (Foken, 2008; Wang et al., 2009). However, no conclusions have been reached regarding how to close the energy balance. Therefore, attempting to use a single EC observation station to represent the complex spatial coverage of a heterogeneous surface is not possible. Observations at multiple spatial points can probably capture the spatial average of turbulent fluxes (Chen et al., 2015). In this regard, the observation matrix in the HIWATER “multi-scale observation experiment on evapotranspiration over heterogeneous land surfaces” has great potential for providing a physical explanation or method for understanding energy closure over heterogeneous surfaces (such as oasis-desert systems) (Liu et al., 2016b). Additionally, as noted by Foken et al. (2011), using LES and higher-order closure models to study large-scale low-frequency turbulent eddies may also provide an approach for near-surface energy closure.

4.2.2. Advancing modeling and data assimilation techniques

Current simulation studies of oasis-desert interactions focus mainly on mesoscale circulation between an oasis and desert. However, small-scale energy and water exchange in oases and deserts as well as in oasis-desert transition zones were observed through HIWATER and require high-resolution simulations. Currently, most mesoscale numerical simulations solve the Reynolds-averaged Navier-Stokes equation (RANS). However, this method lacks the universality when describing unsteady turbulent motion, which involves complex geometric boundary conditions due to heterogeneous surfaces, and cannot be used to easily generate credible predictions (Cui et al., 2013). The LES method can obtain information regarding large-scale turbulent fluctuations and obtain higher resolution, more realistic simulation results than the RANS (Zhang et al., 2008). The LES can effectively simulate the atmospheric boundary layer of the micro-environment of complex underlying surfaces (such as cities) (Finnigan, 2000). Currently, the LES has become important for studying surface energy balance (Foken, 2008; Foken et al., 2011) and high-accuracy land-atmosphere exchange on heterogeneous underlying surfaces (Huang and Margulis, 2010; Lee et al., 2015; Liu et al., 2016a; Shao et al., 2013). One of the difficulties encountered when using the LES is the establishment of the lateral boundary conditions. In this regard, a multi-scale coupling method is often used. Multi-scale coupling methods are dynamic downscaling methods that use the output of mesoscale numerical simulations as lateral boundary conditions for an LES model. The LES results are fed back into the mesoscale numerical models. However, coarse-resolution simulation error and differences in the physical process parameterization at different resolutions can introduce extra error in LES models (Hong and Kanamitsu, 2014). Therefore, constructing a seamless method between mesoscale and large eddy numerical simulations or directly using Navier-Stokes simulation to reproduce small-scale fine structures of energy and water exchange will become important in meteorological studies of boundary layers (Foken et al., 2011; Lee et al., 2015).

Realistic parameterization schemes for land surface processes are very important for simulating oasis-desert interactions with high spatial heterogeneity (Jiang et al., 2005). These simulations partially rely on the retrieval of atmospheric parameters and land surface parameters from remote sensing data to obtain high-resolution and reliable data (Huang et al., 2016b; Song L S et al., 2016; Song Y et al., 2016). Meanwhile, data assimilation techniques can be used to assimilate observational data obtained from different sources and with different resolutions to the dynamic framework of atmospheric and land surface models and provide a better background for numerical models (Huang et al., 2016a).

4.2.3. Theoretical recognition

Through systematic observations and numerical simulations, the large-scale interactions and mechanisms between oases and deserts are generally clear. However, the following problems remain:

(1) The effects of internal heterogeneity within an oasis on the oasis-desert interactions. Particularly, it is not clear how small-scale energy and water exchange and their impacts on oasis-desert interactions are altered by the kinetic heterogeneity caused by farmland shelterbelts and by the thermal heterogeneity caused by irrigation within oases. Solving this problem requires high-resolution observational data and high-accuracy numerical simulation studies.

(2) The control of different irrigation schemes on evapotranspiration and crop productivities. How the irrigation schemes and management operations (biodegradable plastic mulches and so on) regulate the crop stomatal conductance, carbon assimilation and allocation between above/below-ground biomass remains unknown. The optimized irrigation scheme and management operation, which lead to a high water use efficiency (WUE), is the final goal. Solving this problem requires long-term field observations and high-accuracy numerical simulation studies.

(3) The complexity of the water collection and use systems of desert plants. Desert plants possess highly evolved water collection and use systems, which include root structures that maximize soil water absorption and leaf structures that minimize leaf surface area (Pan et al., 2016). How the desert plants collect and use water from humid air advected from the near oasis to survive has not been completely revealed.
5. Introduction to the special issue

As introduced in the above four sections, large scale oasis-desert interactions have been investigated based on oasis effect and desert effect hypotheses. However, small scale energy and water exchanges within the oasis, caused by farmland shelterbelt-induced kinetic heterogeneity and irrigation-induced thermal heterogeneity, have rarely been studied. Deep investigations of these effects would, from a fundamental scientific viewpoint, help improve the understanding of land surface processes of fragmented heterogeneous surfaces and, from an oasis management viewpoint, help manage the system to maximize the benefits to oasis agriculture and the desert ecosystem and therefore sustain the precious oases ecosystems distributed in arid regions around the world.

We organized the special issue titled “energy balance and water cycle of the oasis-desert system” to better understanding oasis-desert interactions while focusing on small-scale energy and water exchanges within an oasis. Previously published papers mainly focus on observations and modeling of latent heat and sensible heat fluxes in oases or arid regions using newly developed approaches (Song LS et al., 2016; Song Y et al., 2016; Zhu et al., 2016; Zhang et al., 2016; Zhang and He, 2016), river basin-scale remote sensing products for energy balance (Huang et al., 2016b), partitioning of soil evaporation and vegetation transpiration (Wang et al., 2016a; Wen et al., 2016), scale effect analysis considering pixel-scale heterogeneity (Liu et al., 2016b; Ran et al., 2016; Wang et al., 2016b), and model-observation fusion (data assimilation) to improve the estimation of turbulent fluxes under heterogeneous surfaces (Huang et al., 2016a). These papers focused on small scale heterogeneity and scaling issues and could be helpful for further understanding the aforementioned scientific questions. However, this special issue does not include relevant papers discussing numerical simulations of oasis-desert interactions at finer resolutions and does not propose new theories for understanding oasis-desert interactions and small-scale energy and water exchange within oases. In addition, this study does not include physical interpretations or the development of methods to close the energy balance. These important questions should be addressed in the future using HiWATER data.

6. Summary

Understanding water and energy exchange within oasis-desert systems is important for oasis ecosystem maintenance and water resource management in arid regions. Previous studies have identified typical oasis and desert effects. A conceptual model of oasis-desert interactions has been established. Nevertheless, actual oasis-desert systems are more complex, with high kinetic and thermodynamic heterogeneity. It is anticipated that dense observation networks and advanced numerical modeling tools may contribute to the development of theories for understanding the small-scale energy and water exchange within an oasis and their impacts on the mesoscale interactions between the oasis and the desert and provide guidance for irrigation planning.

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