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Some Phenomena of the Interaction Between Vegetation and a Atmosphere on Multiple Scales

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ABSTRACT

This article studies the response of the distribution pattern and the physiological characteristics of the ecosystem to the spontaneous precipitation and the interaction between vegetation and the atmosphere on multiple scales in arid and semi-arid zones, based on measured data of the ecological physiological parameters in the Ordas Plateau of northern China. The results show that the vegetation biomass and the energy use efficiency of photosynthesis are especially sensitive to the annual precipitation; strong and complex interactions exist between the vegetation and the atmosphere on multiple scales leading to supernormal thermal heterogeneity of the underlying surface, the strong vortex movement and turbulence. This study can facilitate understanding of the land surface processes and the influences of global climate change as well as human activities on the human environment in the arid and semi-arid zones. It also aids in improving the parameterization schemes of turbulent fluxes of a heterogeneous underlying surface for land surface processes in climate models.

Key words: climate, arid zone, precipitation, ecosystem, climate change

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1. Introduction

The interaction of biological systems with the environment is over scales, that vary from the very small, such as that of plant components (Sogachev and Parferor, 2003), to scales as large as the global atmosphere (Ning Zeng et al., 1998). The BAHC (Biosphere Aspects of the Hydrological cycle) project, as a multidisciplinary interactive research project at a new level to probe into the interaction of the atmosphere-land ecological environment, was completed in December 2002 (BAHC Core Project Office, 1993; Bonan et al., 1996; Kabat et al, 2003). The achievements of BAHC over the past decade go well beyond its original, narrower plans; rather, they provide a new perspective on the interplay between two important components of the earth system–the hydrological cycle and the terrestrial biosphere. The relative (and often opposing) roles of biophysical and biogeochemical feedbacks of the terrestrial biosphere in the climate system have been outlined clearly (Betts et al., 1997; Bonan et al., 1992; Claussen et al., 1998; Brovkin et al., 1998). The rainfall-vegetation relationship is a result of the interaction between climate and vegetation. The vegetation plays an active role in determining the observed vegetation-rainfall distributions. Although the global vegetation distribution is largely controlled by the large-scale climate pattern, the observed vegetation-rainfall relationship is also influenced by vegetation feedback and climate variability. However, the underlying surface of sparse vegetation in arid and semi-arid grasslands, and desert regions, as an important constituent of the vulnerable climate zone of the global land surface, is one of the multifarious land surfaces of the Earth. The underlying surface of the sparse vegetation is a zone sensitive to climate change. In dry regions, the rainfall is the major factor in determining the vegetation distribution. The study of the interac-

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tion of this kind of underlying surface with the atmosphere is very important for enhancing our knowledge on the change of the global climate and environment. But the research on interaction of the underlying surface of sparse vegetation with the climate, especially with the arid climate, is still at the initial stage; and our understanding of it is quite shallow. Besides, the underlying surface of sparse vegetation is quite a frail ecosystem, and it easily degenerates into desert due to the negative influence of human activity under the arid climate. It is a grievous aftereffect that the oases of the Hexi region of Gansu province, which is a representative arid region in western China, degenerate into sparse vegetation; and the oases of the Mu Us desert of Inner Mongolia, which is another representative arid region in northern China, degenerate easily into desert as a result of the dual influences of the arid climate and the devastating effect of human activity. Without fail, the study of the interaction between the underlying surface of sparse vegetation and the atmosphere can establish a theoretical basis of the research on desertification.

In the aspect of theoretical study, many sensitivity numerical experiments with GCMs have shown that the global and regional climates are very sensitive to the processes occurring on the land surface with different properties (Mints, 1984; Chase et al., 1996). Meteorological models for numerical weather prediction or climate simulation require a description of land surface exchange processes. The strength of interaction among soil, plants, and the atmosphere also depends highly on scale (Anderson et al., 2003). The degree of complexity of these land-surface parameterization schemes, or Soil-Vegetation-Atmosphere Transfer models (SVATs), which are necessary for accurate model predictions, is yet unclear. Climate influences a variety of ecological processes. These effects operate through local weather parameters such as temperature, wind, rain, snow, and ocean currents, as well as through interactions among them. In the temperate zone, local variations in weather are often coupled over large geographic areas. These variations drive temporally and spatially averaged exchanges of heat, momentum, and water vapor that ultimately determine growth, recruitment, and migration patterns (Stenseth et al., 2002). Of the more than twenty parameterization frames of the land surface processes which are optional in GCMs, most are applicable only to the moist regions where there are underlying surfaces of dense and homogeneous vegetation. However, these underlying surfaces in the moist zone are vastly different from the heterogeneous underlying surfaces of sparse vegetation with irregular growth in the arid climate zone. The calibration of these SVATs for relatively complex terrain, such as sparse canopies, is also not completely resolved. It is important to study the interaction between the underlying surface of sparse vegetation and the atmosphere, along with the physical processes, the chemical processes, and the biological processes occurring between them. On the other hand, the majority of these parameterization frames of land surface processes describing physical processes of the vegetation and the atmosphere that are applicable to the moist region can hardly deal with important biochemical processes of CO_2 exchange. Consequently, the study of exchange processes of the matter and energy in the interface of the underlying surface of sparse vegetation and the atmosphere, and the study of the plant growth and biochemical processes of CO_2 exchange, are necessary for the research on the change of global climate and the environment, especially for the research on desertification and CO_2 increase. Although, at the present time, there are already many good studies about physiological ecology, probes into the relation of physiological ecology to the climate, especially the response of physiological ecology processes to the climate, are rare. The relation of vegetation with a single circumstance factor was been studied more, but probes into the characteristic variation of plant physiological ecology in the climate are rarer.

The Ordas Plateau is a typical arid and semi-arid sandy land in China. The distribution pattern and the productivity of the terrestrial ecosystem are greatly affected by the climate change, especially the global precipitation change. An experimental result of the response of plant growth and the physiological ecological character to the simulated precipitation in the experimental greenhouse at the MU-US Ecological Station shows that the growth and the physiological character of seedlings of *Salix psammophila*, a dominant shrub in the Ordas Plateau, are sensitive to the artificially controlled water supply (Xiao et al., 2001). An important target of the SIUSSVA Project (Study of the Interaction between the Underlying Surface with Sparse Vegetation and the Atmosphere), which is a Key Subject supported by the Natural Science Foundation of China (NSFC), is to research the exchange processes of the matter and energy in the interface of the sparse vegetation of the underlying surface and the atmosphere, and on the plant growth and the biochemical processes of CO_2 exchange, using the Ordas Plateau as a study platform. This article tries to study the response of the distribution pattern and the productivity of the ecosystem to the spontaneous precipitation and the interaction between vegetation and the atmosphere on multiple scales in arid and semi-arid zones based on the results summarized mainly by the SIUSSVA Project, in order to understand the sensitivity of the ecolog-

Table 1. The distribution of annual precipitation at the routine meteorological stations in the Ih Ju Meng.

Banner	Otog Qian	Otog	Hanggin	Ejin Horo	Dong Sheng	Jungar	Dalad	Uxin
Precipitation (mm)	265.6	270.9	276.7	345.2	386.2	384.4	297.3	315.6

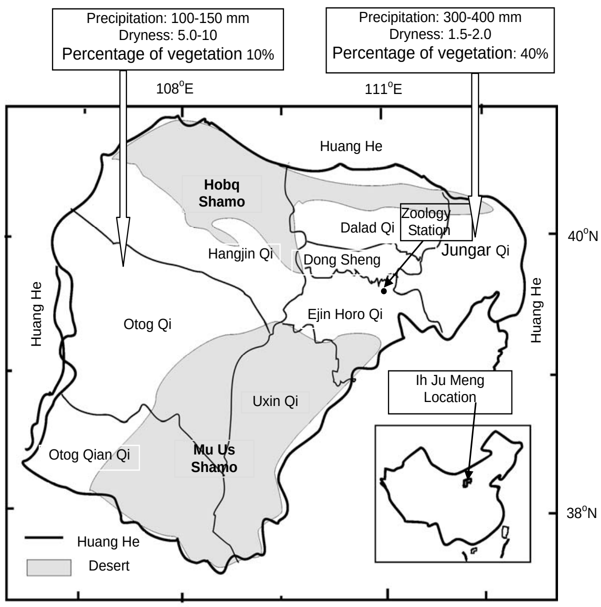

Fig. 1. The atlas of the Ih Ju Meng.

ical processes to the climate, and to improve parameterization of turbulent fluxes of heterogeneous underlying surfaces in the land surface processes of climate models.

2. Experimental site and method

The Ordas Plateau, which is chosen as a study platform, is situated south of Inner Mongolia in northern China. It is located at 37°35′24″–40°51′40″N and 106°42′40″–111°27′20″E, with an altitude of 1100–1500 m; the width from east to west is about 400 km and that from north to south is about 340 km, covering an area of about 130 000 km^2. It is a geographically distinctive area, with unique climate, geology and soils. The Ordas Plateau is a main center among desertification areas in China and a main source of raw sand sediment in the drainage area of the Yellow River. The physiognomy is comprised of a vulnerable ecological transition zone from sparse vegetation to desert. The Ih Ju Meng (Fig. 1) is bordered by the Yellow River (Huang He) in the west, north, and east. Two major desert areas, the Kubuqi Sandy Land (approx. 1500 km^2) and the 2/3 of the total Mu Us Sandy Land (approx. 4000 km^2) are located in the Ih Ju Meng. The majority of the Kubuqi Desert is in the Hanggin Qi, with smaller areas in the Dalad Qi and Jungar Qi, while the Mu Us Sandy land lies across four banners: Uxin Qi, Otog Qi, Otog Qian Qi, and Ejin Horo Qi.

The climate of the Ordas Plateau is typically continental with low rainfall and extreme variation of seasonal and diurnal temperature. The continental nature of the climate decreases markedly from west to east. The distribution of annual precipitation decreases dramatically from 300–400 mm in the east to only 100–150 mm in the west in the limited 400 km wide range, but the mean temperature in the summer, which is the plant growth season, is about 20°C from the east to the west with no variation; the distribution of dryness increases dramatically from only 1.5–2.0 in the east to 5–10 in the west; And the percentage of vegetation varies from 40% in the east to only 10% in the west (see Liu, 1997). Figure 1 marks the annual precipitation, dryness, and percentage of vegetation in the west and east of the Ih Ju Meng. Table 1 gives the distribution of annual precipitation at the routine meteorological stations in each banner of the Ih Ju Meng. The above facts show that the annual precipitation increases basically from the west to the east and from the north to the south; the climate consists of a transition zone, which is vulnerable, from a wet climate to an arid climate.

Dissimilarity of the physiognomy, the climate, the soil, the vegetation, and the ecosystem in the range of a width of only 400 km from the east to the west reflects different responses of the ecosystem to different climates in order to incarnate fully the aftereffect and the character of the interaction between the underlying surface of sparse vegetation and the arid and semi-arid climate. This area is a typical background for us to study responses of the ecosystem to the spontaneous precipitation.

Caragana intermedia is a typical plant in the arid zone. The physiological ecological parameters of *Caragana intermedia* are measured in the sunshine in summer 2001, in each banner. These parameters include temperature $T_{\rm air}$ of the leaf air hole and temperature $T_{\rm suf}$ of the leaf surface, the net photosynthesis rate $P_{\rm r}$ (μmol CO_2 m^{-2} s^{-1}), the transpiration rate E (mmol H_2O m^{-2} s^{-1}), the air hole conductivity R, the carbon dioxide concentration $CO_{2\rm out}$ of the leaf cell vent, the carbon dioxide concentration $CO_{2\rm int}$ in the leaf cell, and the effective photosynthetic radiation (PAR). At the same time, the percentages of vegetation and vegetation biomass are directly measured, and the relative humidity RH (%) and the wind speed V (m s^{-1}) are also observed. In order to study the influence of vegetation on the microclimate in the semi-arid zone, the surface temperature on the ground is measured around a chosen individual plant of *Caragana intermedia* and *Artemisia Ordosica* with an infrared thermometer.

The photosynthesis and transpiration are the foremost processes of plant, thus the photosynthesis, the transpiration, and the energy use efficiency of photosynthesis are the foremost indexes of plant physiological ecology. We can study the characteristics of vegetation physiological ecology in the arid region using the above measured data. The net photosynthesis rate $P_{\mathrm{r,CO_2}}$ (μmol CO_2 m^{-2} s^{-1}) expresses how much carbon diozide the plant absorbs in the photosynthesis process. The photosynthesis latent energy $L_{\mathrm{CO_2}}$=478 kJ mol^{-1} is the amount of stored energy of the plant that absorbs 1 mol of carbon dioxide in the photosynthesis process. Then the stored energy $P_{\mathrm{L,CO_2}}$ (mJ m^{-2} s^{-1}) of the vegetation photosynthesis is

$$P_{\mathrm{L,CO_2}} = P_{\mathrm{r,CO_2}} \cdot L_{\mathrm{CO_2}} \,. \qquad (1)$$

The plant transpiration rate E (mmol H_2O m^{-2} s^{-1}) expresses how much water vapor the plant transpires in the photosynthesis process. The molecular weight of the water is $M_{\mathrm{H_2O}}$=18 g mol^{-1}. The transpiration latent heat $L_{\mathrm{H_2O}}$ of the plant is

$$L_{\mathrm{H_2O}} = [2.501 - 0.00237 \cdot T_{\mathrm{air}}] \cdot 10^6 \qquad (2)$$

Here, T_{air} is the temperature of the leaf air hole of the plant. Then the energy consumed (J m^{-2} s^{-1}) by the plant in the photosynthesis process is

$$E_{\mathrm{L,H_2O}} = E \cdot M_{\mathrm{H_2O}} \cdot L_{\mathrm{H_2O}} = E_{\mathrm{H_2O}} \cdot 18 \cdot [2.501 - 0.00237 \cdot T_{\mathrm{air}}] \,. \qquad (3)$$

The energy use efficiency η (‰) of photosynthesis, viz., the ratio of the stored energy to the consumed energy in the photosynthesis process, is

$$\eta = P_{\mathrm{L,CO_2}} / E_{\mathrm{L,H_2O}} \,. \qquad (4)$$

3. Sensitivity of the ecological processes to local climate in the semi-arid zone

The climate influences the vegetation succession. The most obvious components in the climate factors impacting the vegetation are the precipitation and temperature. The precipitation influences the vegetation productive power under different administrative levels of the global range, the regional range, and the site range. For a desert area, a primary factor of influence on the percentage of the vegetation and density of vegetation community is the precipitation, because there is an abundance of solar radiation there.

Figure 2 shows the observed percentage of vegetation and biomass of vegetation and the distributions of annual precipitation in the Ih Ju Meng. It shows obvious responses of the biomass and percentage of vegetation to the annual precipitation. In this figure, the annual precipitation gradually increases across four banners and one city from west to east: Otog, Otog Qian, Hangjin, Jungar, and Dong Sheng city, and it also increases across three banners: Dalad, Uxin, and Ejin Horo, from north to south. The increasing trend of vegetation biomass is especially obvious along with the increase of the annual precipitation in the corresponding banner; generally speaking the percentage of vegetation maintains the upward trend along with annual precipitation, but it fluctuates up and down from time to time. Of course, this increasing trend is not linear due to the influence of other factors, e.g. the soil and soil moisture content, on the biomass and percentage of vegetation.

Figure 3 gives the distributions of the net photosynthesis rate and transpiration rate of vegetation from west to east in the Ih Ju Meng. Figure gives the distributions of the stored energy $P_{L,\mathrm{CO_2}}$ (mJ m^{-2} s-1) of absorbing carbon dioxide in the photosynthesis process, and the consumed energy $E_{L,\mathrm{H_2O}}$ (J m^{-2} s^{-1}), viz., the transpiration latent heat of the vegetation. The energy use efficiency η(‰) is also given in Fig. 4. Figure 3 shows that the transpiration rate of the vegetation is about 3–4 orders of magnitude greater than the net photosynthesis rate; they seem to increase in a manner from west to east. Figure 4 shows that the energy stored by the vegetation due to absorbing carbon dioxide in the photosynthesis process also seems to increase from west to east, while the energy consumed by the vegetation decreases from

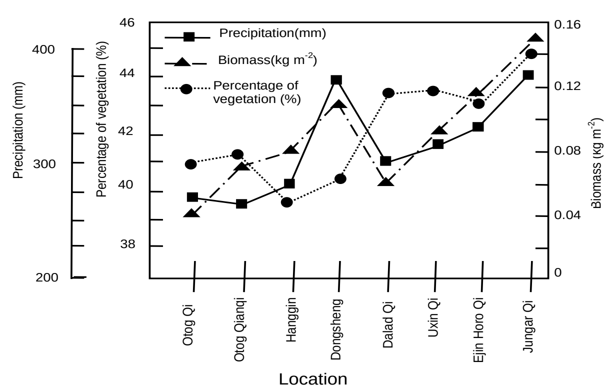

Fig. 2. Distributions of the annual precipitation, the biomass and vegetation coverage in the Ih Ju Meng.

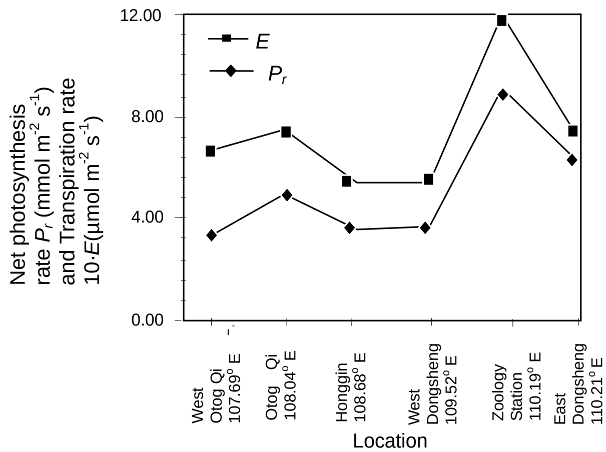

Fig. 3. Distributions of the net photosynthesis rate and transpiration rate of vegetation in the Ih Ju Meng.

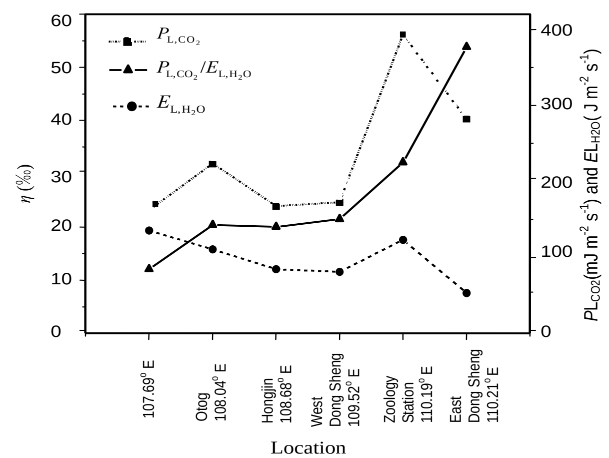

Fig. 4. Distributions of the stored energy P_{L,CO_2} (mJ m^{-2} s^{-1}) of absorbing carbon dioxide in the photosynthesis, and the consumed latent energy (viz. transpiration latent heat) (J m^{-2} s^{-1}) of the plant, along with the energy use efficiency η (‰) in the Ih Ju Meng.

west to east. But it is interesting that the energy use efficiency dramatically increases from west to east. In the arid and semi-arid zone, the increase of the energy use efficiency along with the increase of annual precipitation leads to an increase of the vegetation biomass of shrub plants; furthermore, the increase of annual productivity finally leads to an increase of the percentage of vegetation and density of vegetation.

4. Influence of the ecological processes on the microenvironment in the semi-arid zone

4.1 *Distribution of surface temperature around individual plants in the desert*

In order to study the influence of the ecological processes on the microenvironment in the semi-arid zone, the surface temperature (°C) of vegetation is measured around a chosen individual plant of Caragana intermedia and Artemisia Ordosica, which is a sand-fixation plant of savageness sand phytobiocoenose and widely distributed preferably in the Ordas Plateau, through an infrared thermometer over ten days in mid July 2001. The height and diameter of the individual plant are 1.1 m and 1.5 cm respectively. The measured points include the shadow of the plant and also in direct sunlight in order to probe into the influence of vegetation on the surface temperature. The measurement is taken at different distances (cm) in eight directions around the center of a chosen individual plant of Caragana intermedia and Artemisia Ordosica, and the measurement is done 6 times during 0800–1800 LST in one day to observe the diurnal variation of temperature on the ground surface around the plant.

Figure 5 is the diurnal variation of isotherms on the ground surface around the individual plant of Caragana intermedia. In the figure, the labels H and L denote respectively the high temperature center and low temperature center on the ground surface. It shows that the surface temperature around an individual plant dramatically forms a gradient, and the temperature gradient gradually increases with the rising sun; e.g., at 1400 LST, the maximum of the surface temperature reaches 70°C, the lowest temperature is only 42°C, and the temperature gradient reaches 32°C between the places with the highest and lowest temperature. A surface temperature of 86°C was measured on the exposed soil; there exists a supernormal thermal heterogeneity of the underlying surface around the individual plant. The measured result also shows that the vegetation influences not only the temperature in the plant shadow, but also apparently the temperature of the surface not overshadowed by the plant: that is it lowers the surface temperature around the individual plant. Besides, the high surface temperature on the exposed soil might cause a strong unstable stratification of the atmosphere.

The great heterogeneity of the underlying surface and the strong unstable stratification of the atmospheric surface layer may result in strong vortex movement and turbulence. This will be discussed below.

4.2 *Vortex movement and turbulence intensity in the neighbourhood of an individual plant in the desert*

The velocity vortex theorem was proved by atmospheric linear thermodynamics (Hu, 2002):

$$\nabla \times \boldsymbol{U} = \frac{1}{\theta}\boldsymbol{U} \times \nabla\theta \, . \qquad (5)$$

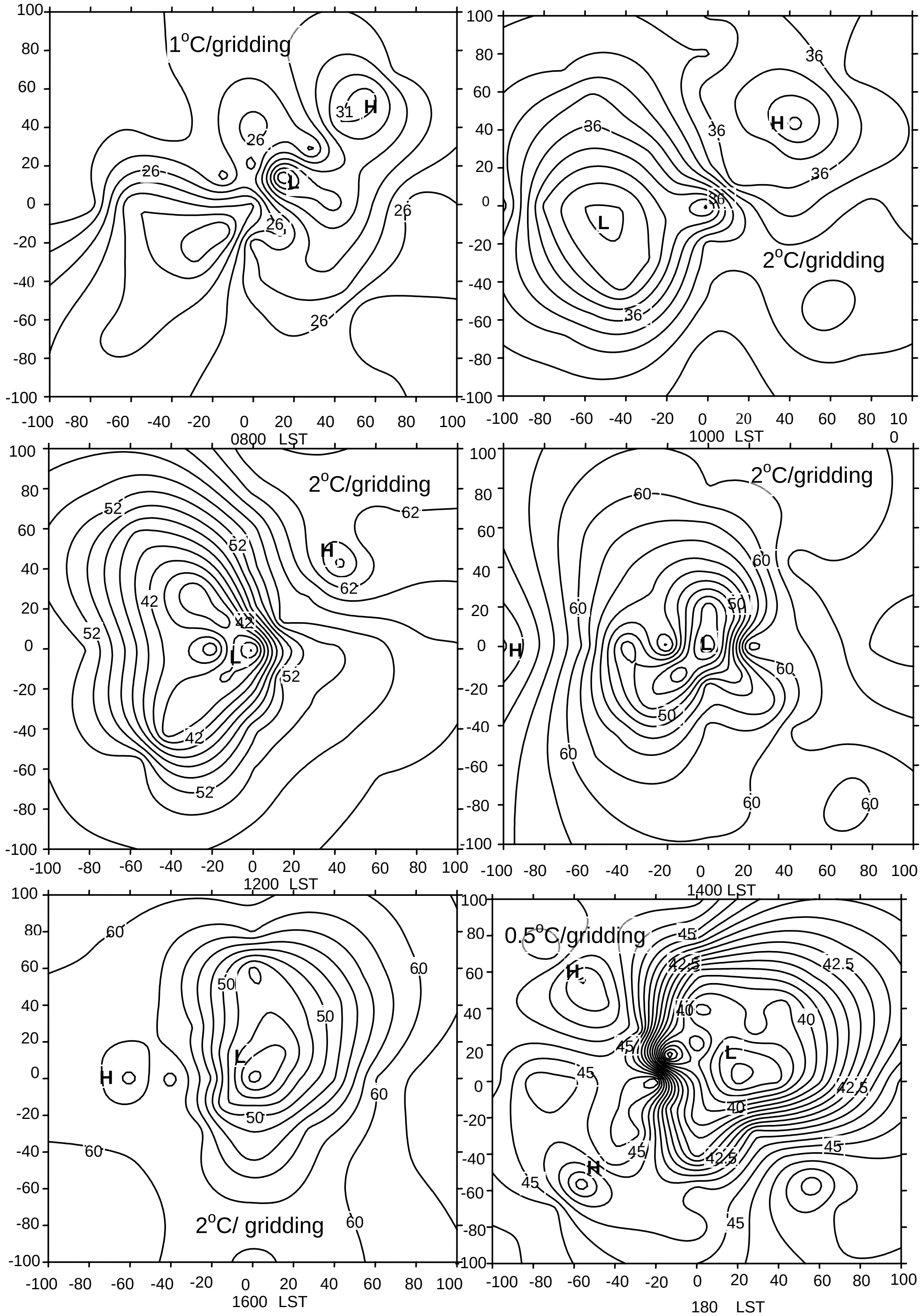

Fig. 5. Diurnal variation of isotherms on the ground surface around the plant. The vertical ordinate and horizontal ordinate are the distance (cm) from the plant center.

Here, the velocity vorticity $\boldsymbol{\Omega}$ is defined as

$$\boldsymbol{\Omega} = \nabla \times \boldsymbol{U} = (\xi, \eta, \zeta) \, . \tag{6}$$

The vortex theorem specifies that the velocity vorticity equals the vector product of the velocity and the relative gradient of potential temperature. The vortex theorem indicates that the potential temperature gradient forms a vortex movement or a circulation movement in the atmospheric velocity field. It is a well-known fact that the heterogeneity of atmospheric temperature and pressure causes vortex movement in the atmospheric velocity field. The three components of the velocity vorticity are, respectively,

$$\begin{cases} \xi = \dfrac{\partial W}{\partial y} - \dfrac{\partial V}{\partial z} = \dfrac{1}{\theta}\left(W\dfrac{\partial \theta}{\partial y} - V\dfrac{\partial \theta}{\partial z}\right) \, , \\ \eta = \dfrac{\partial U}{\partial z} - \dfrac{\partial W}{\partial x} = \dfrac{1}{\theta}\left(U\dfrac{\partial \theta}{\partial z} - W\dfrac{\partial \theta}{\partial x}\right) \, , \\ \zeta = \dfrac{\partial V}{\partial x} - \dfrac{\partial U}{\partial y} = \dfrac{1}{\theta}\left(V\dfrac{\partial \theta}{\partial x} - U\dfrac{\partial \theta}{\partial y}\right) \, . \end{cases} \tag{7}$$

The two horizontal components (ξ, η) of the velocity vorticity represent the vortex movement caused by the vertical circulation in the atmosphere. The vertical circulation is an important type of circulation movement in the atmosphere, such as the land and sea breeze, the mountain and valley winds, the lake and land breeze, etc. The vertical vorticity ζ describes the horizontal vortex movement, such as atmospheric cyclones or anticyclones, typhoons and tornadoes etc. It shows that the horizontal gradient of potential temperature causes the vertical vortex movement.

The strong vortex movement may offer enough energy through the energy cascade transportation to develop turbulence. The thermal stratification of the atmosphere is too unstable in the desert to offer the necessary condition to develop turbulence. The turbulence intensity theorem was also proved by atmospheric linear thermodynamics (Hu, 2002)

$$(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) = K_{ii}\frac{1}{\theta}U_i\frac{\partial \theta}{\partial x_i} = K_m\frac{1}{\theta}\boldsymbol{U} \cdot \nabla\theta \, . \tag{8}$$

This theorem reveals the material fact that the turbulence intensity is in proportion to the scalar product of the velocity and the relative gradient of potential temperature. From this theorem, one knows that the root of turbulence is the potential temperature gradient. It reveals the spacial heterogeneity of temperature, which is a fountainhead of the turbulence. This turbulence caused by the spatial heterogeneity of the temperature is called Reyleogh-Benard turbulence. From formula (8), the velocity variances are obtained respectively as

$$\begin{cases} \overline{u'^2} = -K_{11}\left(\dfrac{\partial U}{\partial x} - \dfrac{U}{\theta}\dfrac{\partial \theta}{\partial x}\right) \\ \overline{v'^2} = -K_{22}\left(\dfrac{\partial V}{\partial y} - \dfrac{V}{\theta}\dfrac{\partial \theta}{\partial y}\right) \\ \overline{w'^2} = -K_{33}\left(\dfrac{\partial W}{\partial z} - \dfrac{W}{\theta}\dfrac{\partial \theta}{\partial z}\right) \end{cases} \tag{9}$$

From the above analyses and the measured results of surface temperature around the plant, we can easily understand that the great heterogeneity of the underlying surface and the unstable stratification of the atmosphere in the desert may cause strong vortex movement and turbulence. If the horizontal temperature gradient is the same in each direction, we can take the x-direction as the wind direction, viz. the wind velocity is $U > 0$ and $V = 0$, and then the velocity vorticity (7) is transformed to

$$\begin{cases} \xi = \dfrac{1}{\theta}\left(W\dfrac{\partial \theta}{\partial y}\right) \, , \\ \eta = \dfrac{1}{\theta}\left(U\dfrac{\partial \theta}{\partial z} - W\dfrac{\partial \theta}{\partial x}\right) \, , \\ \zeta = -\dfrac{1}{\theta}U\dfrac{\partial \theta}{\partial y} \, . \end{cases} \tag{10}$$

Based on the above measured results, the temperature is very heterogenous; the thermal stratification is strongly unstable, thus the magnitude of the parameters near the ground surface in the surface layer can be assumed as follows

$$\begin{aligned} &U \sim 3\ \mathrm{m\ s^{-1}} \, , \quad W \sim 0.5\ \mathrm{m\ s^{-1}} \, , \quad \theta \sim 310\ \mathrm{K} \, , \\ &\frac{\partial \theta}{\partial x} \sim \frac{\partial \theta}{\partial y} \sim 10^{\circ}\mathrm{C\ m^{-1}} \, , \ \frac{\partial \theta}{\partial z} \sim 2^{\circ}\mathrm{C\ m^{-1}} \, , \end{aligned} \tag{11}$$

From formula (10) and magnitude (11) of the parameters, the magnitudes of velocity vorticity are estimated as

$$\begin{aligned} &\zeta \sim 1.6 \times 10^{-2}\ \mathrm{m^2\ s^{-1}} \, , \\ &\xi \sim 1.9 \times 10^{-1}\ \mathrm{m^2\ s^{-1}} \, , \\ &\eta \sim -9.7 \times 10^{-2}\ \mathrm{m^2\ s^{-1}} \, . \end{aligned} \tag{12}$$

We often see a whirlwind in the desert. This whirlwind seems similar to a mini-tornado; it laps up abundant dust and holds quite a strong capability of transporting energy and matter. This whirlwind is formed if the horizontal vortex develops enough strength when $\boldsymbol{\Omega} = (\xi, \eta, \zeta)$ is large enough. The strong vortex movement and turbulence in the desert consequently cause a strong exchange of energy and matter near the ground surface which leads to a stronger physiological process, such as the photosynthesis and transpiration of plants, and which forms a complex interaction between vegetation and its living environment.

4.3 *Interaction between vegetation and its living environment in the desert*

There exists an obviously complex interaction between the vegetation and its living environment. The vegetation changes its surrounding environment; in turn the environment changes as well as spurs the vegetation change. The vegetation lowers the intensity of solar radiation reaching the ground surface, which causes the temperature in an overshadowed range to become lower than in the open range. As a result, the temperature difference between an overshadowed range and the open range causes the supernormal thermal heterogeneity of the ground surface around the individual plant to develop a vortex movement and turbulence. On the other hand, the soil temperature is lower due to the influence of vegetation overshadow, but the air temperature over the vegetation is higher, with the result that the soil absorbs heat from the air through energy exchange. As a result, the air temperature falls in the neighborhood of vegetation overshadow, and it further affects the photosynthesis and transpiration in the physiological process of the plant.

The interaction between soil heterogeneity and shrubs induced an autogenic development of "fertile islands" and an increased spread of shrubs in the grassland ecosystems (Garner and Steinberger, 1989; Chen et al., 2003). The "fertile island" is also called a "resource island" (Reynolds et al., 1999). The development of fertile islands around individual shrubs could change the vegetation composition and structure, as well as the distribution patterns of soil resources, and thus, could reinforce the changes of the ecosystem function and structure from a relatively stable grassland ecosystem to a quasi-stable shrub land ecosystem (Klemmedson and Barth, 1975; Kieft et al., 1998; Whitford et al., 1997; Thompson et al., 2005). Due to the inclemency of climate and soil conditions, and to the intense disturbances of human beings, the soil resource heterogeneity in arid and semi-arid grassland ecosystems has gradually increased worldwide during the last century. The study of the fertile island phenomenon would help us to understand the causes, consequences and processes of desertification in arid and semi-arid areas.

The results of the above study show that multiple influences of vegetation on the environment are not only in response to the temperature modulation of the air and soil, but they also could form the "fertile islands" in an arid region to cause the heterogeneity of soil fertility in the local ecological environment. In the arid region, decomposed emarcid things of plants are congregated around individual shrubs through the transportation of the wind, vortexes, and turbulence and results in the "fertile island effect". Figure 6 illustrates the "fertile island" phenomenon, which was observed in a field investigation of the SIUSSVA Project, in an arid and semi-arid zone in China. Figure 6a is a fertile island photo from the Ordas Plateau in a semi-arid region of northern China; Fig. 6b is another fertile island photo from the Hexi Corridor in an arid region of western China. The figures show that the fertile island is a sand stack with an abundant plant cluster. The plants on the sand stack of the "fertile islands" grow easily due to soil fecundity; moreover, the plant growth causes the decomposed emarcid substances of the plant to congregate easily around the lush plant cluster through transportation of the wind, vortexes, and turbulence. This is a positive feedback process. Consequently, the fertile island effect is a result of the interaction between vegetation and the atmosphere at the micro-scale in the arid and semi-arid zone. The plant cluster of a fertile island is larger than the individual plant; accordingly the fertile islands increase the scale of the heterogeneity of the underlying surface in the desert. Figures 6a and b also show that although the soil and climate have an incomplete homology in the Hexi Corridor and Ordas Plateau, the fertile islands in the two regions have analogous configurations and the same dynamical reasons for their formation.

These complex interaction processes of the vegetation with the atmosphere influence the transportation and balance of energy and matter in the arid and semi-arid zone. The theoretical basis of the parameterization of turbulent fluxes is a homogeneous underlying surface. The great heterogeneity caused by the interaction processes of vegetation with the atmosphere is a challenging problem for the parameterization of turbulent fluxes in land surface processes in the climate system.

5. Conclusion and discussion

There exists vehement and complex interaction between the vegetation and atmosphere on multiple scales. Firstly, local climate evidently influences the vegetation state. The energy use efficiency of photosynthesis, the vegetation biomass, and net productivity of vegetation are especially sensitive to the annual precipitation, because there is abundant solar radiation in the arid and semi-arid zone. These results in the plant inheriting unusual characteristics of plant physiological ecology via adapting to circumstances in

Fig. 6. The "fertile island" phenomenon in arid and semi-arid zone in China. (a) "Fertile island" of Ordas plateau in semi-arid region of northern China. (b) "Fertile island" of Hexi Corridor in arid region of western China.

a long evolutionary process. The vegetation can adjust for air temperature and soil temperature, and it enhances its maintenance and utilization of rainwater. The ground surface is heated under strong sunshine to result in extraordinarily high surface temperature, which may reach 60–80°C, to form strong thermal unstable stratifications of the atmosphere. The effect of plant overshadowing lowers the soil temperature to affect the photosynthesis and transpiration in the physiological process of the plant; this effect of plant overshadowing also leads to a supernormal thermal heterogeneity of the underlying surface around the plants in the desert to cause the surface temperature gradient to exceed 30°C m^{-1}. Strong vortex movement and turbulence are developed under the conditions of the supernormal thermal heterogeneity of the underlying surface and a strong unstable thermal stratification. On the other hand, through transportation of the wind, strong vortex movement and turbulence, abundant decomposed emarcid substances of the plant congregate around the plant cluster to result in a "fertile island effect" that forms a heterogeneous field of soil fertility in the local ecological environment. The fertile islands further increase the scale of thermal heterogeneity of the underlying surface.

The interaction between vegetation and the atmosphere occurs in a cascade of different scales, e.g. the GCM-scale (1000 km), viz. the macro-scale, the mesoscale (100 km), the patch scale (100 m–10 km) of the interaction between one patch and another patch, and the micro-scale (1 m–100 m) of vegetation coverage. The fluxes of current SVAT models of land surface processes are measured on these scales, too. The interaction between vegetation and the atmosphere should be studied on different scales, moreover on manifold scales. Studying the sensitivity of the ecological processes to the regional climate in the arid and semi-arid zone is beneficial to understanding the land surface processes and influences of global climate change and human activity on man's environment in the arid and semi-arid zone. The great heterogeneity of the underlying surface is a challenging problem for the parameterization and theoretical basis of a homogeneous underlying surface, and of turbulent fluxes in land surface processes of the climate system. It is necessary to further the study of interactive processes of vegetation with the atmosphere on multiple scales.

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