Characteristics of Oasis Effect in Zhangye, China and its Relationship with Agricultural Irrigation

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Abstract

Oases are important ecosystems that support life and agriculture in arid regions. However, they are ecologically fragile and are often threatened by both intensive agricultural production and climate change. To study the oasis effect and understand how the oases will respond to these pressures is crucial for sustainable development. Existing knowledge of oasis effect is insufficient to quantify the long-term trend of oasis effect during the past decades, and we are not yet clear what factors will impact the strength of oasis effect. In this study, data between 2001 and 2018 for Zhangye, Gansu, China was derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite and used to quantify the diurnal, annual and inter-annual oasis effect characteristics, and the normalized difference vegetation index (NDVI), evapotranspiration (ET), albedo and wind speed were analyzed for their correlation with oasis effect intensity. It is found that oasis effect in Zhangye has declined rapidly since 2012, and the decline of difference of ET between cropland and the surrounding desert could be a driver.

1. Introduction

Oasis is a kind of landscape in arid regions supported by natural or artificial rivers (Li et al, 2013). Compared with the arid surroundings, there is generally more intensive human activities
happening on oases, due to higher water availability. This makes oases the most important locations for agriculture in arid and semi-arid areas.

Due to water scarcity, irrigation has been a crucial supplement for rainfall in most oasis agricultural zones around the world. At present, 100% of the cultivated land is irrigated in Egypt, and 77% in Pakistan, 60% in Japan, and 48% in China (Fernández-Cirelli et al. 2009).

Irrigation makes it possible to cultivate on oasis. However, the water consumption is a heavy burden, which could bring about a series of problems, as groundwater exploitation, salinization of land and water resources and other environmental issues (Xiang et al. 2011), and sometimes even regional conflicts.

Better water management is essential to improve irrigation efficiency and reduce water consumption in oasis agricultural zones. However, since irrigation is a critical part to maintain the oasis ecosystem, will such a change in agricultural practice alter the regional climate? Meanwhile, due to the arid climate and significant water deficit, oasis is considered an ecologically fragile area which is sensitive to climate change. How will the future climate variation impact the oasis? Many of similar problems are still unresolved.

One of the most important indicator of oasis climate is the oasis effect. Oasis effect describes the evaporative cooling effect due to heat advection when a source of water exists in an otherwise arid area (Potchter et al. 2008). Due to oasis effect, the surface temperature and air temperature in an oasis is generally much cooler than the arid surroundings, making the oasis suitable for living and agriculture. This study tries to research on the characteristics of oasis effect in Zhangye, Gansu, China, based on the remote sensing data from past two decades, and attempts to determine the main drivers of the oasis effect in the region.
Oasis effect has been an active area of research in recent years (Taha et al., 1991; Chu et al., 2005; Potchter et al., 2005; Hao and Li, 2016). The research methods to approach oasis effect are generally twofold: some studies are based on ground-based temperature and flux measurements from specific projects or regular weather stations, while others resort to numerical simulation to study the phenomenon. Although field measurement is able to provide detailed information about a certain oasis, it is site-specific and limited by the number of stations. Numerical simulations have the advantage of broader scope and is able to deal with a longer time span, but most models can only generate estimation of coarse resolution, and lack the details to inform regional management. Currently, very few researches use satellite remote sensing as data source. Hao et al. (2016) combined the Moderate Resolution Imaging Spectroradiometer (MODIS) images and weather station data to study the oasis effect in Tarim Basin, Xinjiang, China for 13 years and determined that evaporative cooling is the main driver of oasis effect.

Among the scientific questions, one important issue is how to quantify the intensity of oasis effect. Traditionally, it is determined as the difference of temperature between the oasis and its surrounding arid region, so a negative value indicates the oasis is cooler. Since most of the existing research are based on ground measurement, screen-level temperature (1.5 or 2 m above ground surface) is often used. Other researchers using land surface temperature (LST) would determine the oasis effect intensity according to LST difference, which generally results in a stronger oasis effect.

Another issue is the diurnal, annual and inter-annual characteristics of oasis effect. Most research based on ground measurements show that the oasis effect is stronger during the day than at night. Naot and Mahrer (1991) showed that an oasis in Kibbutz Gilgal, Jordan Valley, Israel is 7°C cooler than the surroundings in the early afternoon hours and only 5°C cooler at midnight.
Taha et al. (1991) reported a site in Davis, CA, USA that is 4.5 ~ 6 °C cooler during day while 1 ~ 2 °C warmer at night. As for annual and inter-annual patterns, since most research did not have observation for multiple years, only Hao et al. (2016) showed with remote sensing data that oasis effect in Tarim Basin is strongest in summer and has been declining since 2001.

Finally, the mechanism of oasis effect is controversial. Some field measurement studies conclude that evaporative cooling is the main cause of oasis effect (Becker et al, 2003; Hao and Li, 2016). Others add that wind speed is an important factor, but the impact is uncertain. Oke (1987) and Sporken-Smith and Oke (1998) conclude that high wind speed would increase the oasis effect intensity, while Potchter et al (2008) show that oasis effect is stronger with mild or no wind. Other factors include albedo (Jauregui, 1990; Grimmond et al, 1996), shading (Potchter et al, 2008) and vegetation types (Han, 2010).

To answer the questions above in the context of Zhangye and to clarify the mechanism of oasis effect there, this research first detected the change of agricultural zone distribution in Zhangye based on land use data from multiple sources and determined the core zone that maintained agricultural activities throughout 2001 to 2018. We used satellite remote sensing data and products to track the oasis effect in the period, and studied related biophysical factors including NDVI, evapotranspiration (ET), albedo and meteorological factors including wind speed and precipitation, and built a correlation model to explain the trend of oasis effect with these factors. The work showed that the oasis effect in the agricultural zones of Zhangye has diminished among the years we studied, especially after 2010. The oasis effect is correlated with the difference of ET between cropland and desert, while none of the meteorological factors proved a significant contributor to oasis effect. Here we concluded that the declining ET in recent years, which is likely
to be the result of decreased water consumption due to improved irrigation techniques, is the main
driver of such diminishing oasis effect in Zhangye.

2. Materials and Methods

2.1. Study Site

Zhangye oasis is a major agricultural oasis located in Gansu province, northwest China,
which is in the middle of the Hexi Corridor. Zhangye oasis is a part of the Heihe River Basin, an
inland endorheic river basin in Northwest China, which covers an area of approximately 78,600
km² (Brizga, 2010). The Heihe River is the main source of irrigation for Zhangye and supports the
oasis in the middle of desert and Gobi Desert.

The annual mean air temperature is approximately 6°C, and the warmest month is July.
The annual mean precipitation is approximately 114.9 mm; more than 70% of this precipitation is
accumulated during the growing season from June to September (Zhang et al., 2015). The growing
season of crops in Zhangye is between May and September.

Located in the middle of desert, Zhangye oasis has a very arid climate, and the agriculture
depends heavily on irrigation. Agricultural irrigation consumes approximately 80% of the total
river water of Heihe River. As a result of the aggressive water extraction, too little water flows
into Juyanhai Lake downstream, and the lake dried out in 1992, turning an area of 200 km² around
the lake into a desert (Zhang et al., 2009). In order to supply enough water to the ecosystems along
the Heihe River, the city of Zhangye has been implementing various policies and infrastructure to
reduce water consumption by irrigation.
Figure 1: Map of study area. The study area locates in Zhangye, Gansu, China, covering the agriculture zone and the surrounding arid areas. Two land cover types were chosen as regions of interest in this study: barren or sparsely vegetated area as reference region, and cropland as study region of oasis effect.

2.2. Data

Land cover and land use data: MODIS MCD12Q1, which consists of annual land use classification in six different classification schemes (Friedl and Sulla-Menashe, 2019); GlobeLand30, a 30-m resolution land-cover map for the years 2000 and 2010 (Jun, et al., 2014) and European Space Agency’s 3-epoch series (1998-2002, 2003-2007, 2008-2012) of global land cover maps at 300-m spatial resolution (ESA Climate Change Initiative - Land Cover project, 2017). In addition, Landsat Surface Reflectance Images of three different dates (July 23, 2002, July 21, 2013 and July 18, 2018) were downloaded from United States Geological Survey (USGS) to validate the land use classification.
The land surface temperature (LST) dataset used in the research is from the MOD11A2 Version 6 product. The product provides an average 8-day per-pixel Land Surface Temperature at 1-km spatial resolution, with each pixel value a simple average of all the corresponding MOD11A1 LST pixels collected within that 8-day period that satisfy the quality criteria.

The biophysical features we studied including NDVI, ET and albedo. For NDVI, we used the MOD13Q1 MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V006 dataset, which provides Normalized Difference Vegetation Index (NDVI) data at 16-day intervals and 250-m spatial resolution. This NDVI data is derived from the MODIS reflectance bands 1 (red) and 2 (near-infrared) and is processed to the best available pixel value from all the acquisitions during the 16-day period, based on criteria including low clouds, low view angle and the highest NDVI value.

For ET, we used the MOD16A2 Version 6 Evapotranspiration/Latent Heat Flux product. The product is an 8-day composite dataset at 500-m spatial resolution, and the ET data is derived based on the Penman-Monteith equation, which includes inputs of daily meteorological reanalysis data along with MODIS products such as vegetation property dynamics, albedo, and land cover.

For albedo, we used the MCD43A3 Version 6 Albedo Model dataset, which offers daily albedo values 500-m resolution, derived from 16 days of Terra and Aqua MODIS data. The albedo values are given as black-sky albedo (directional hemispherical reflectance) and white-sky albedo (bihemispherical reflectance) data at local solar noon and is given for each MODIS spectral bands as well as three broadbands (visible, near infrared (NIR), and shortwave). In this study we used the shortwave broadband values and determined the daily albedo with black-sky albedo, white-sky albedo and the diffusion fraction given in the NCEP/NCAR Reanalysis Derived Variables Dataset (Kalnay et al., 1996). Isotropic incident radiation from all directions assuming no direct sunlight...
produces white-sky albedo $\alpha^{ws}$. Direct radiation from only a given incident solar geometry ($\Omega_i$) defines black-sky albedo $\alpha^{bs}(\Omega_i)$. The albedo that reflects the actual illumination condition, known as blue-sky albedo $\alpha(\Omega_i)$, can be simply calculated from the linear combination of black-sky and white-sky albedos (Lewis and Barnsley, 1994):

$$\alpha(\Omega_i) = \alpha^{ws}p + \alpha^{bs}(\Omega_i)(1-p)$$

where $p$ is the ratio of the surface downward diffuse shortwave radiation to the surface downward total shortwave radiation. In the NCEP/NCAR Reanalysis dataset, the ratio is calculated as:

$$p = \frac{Q_{D,\text{Vis}} + Q_{D,\text{NIR}}}{Q_{B,\text{Vis}} + Q_{B,\text{NIR}} + Q_{D,\text{Vis}} + Q_{D,\text{NIR}}}$$

where $Q_{D,\text{Vis}}$, $Q_{D,\text{NIR}}$, $Q_{B,\text{Vis}}$ and $Q_{B,\text{NIR}}$ refer to downward diffuse visible radiation, diffuse near IR radiation, beam visible radiation and beam near IR radiation, respectively. The long-term average monthly values for $p$ are:

<table>
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<tr>
<th>Month</th>
<th>1</th>
<th>2</th>
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<th>5</th>
<th>6</th>
<th>7</th>
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<th>9</th>
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<td>0.250</td>
<td>0.269</td>
<td>0.265</td>
<td>0.276</td>
<td>0.299</td>
<td>0.285</td>
<td>0.268</td>
<td>0.271</td>
<td>0.252</td>
<td>0.255</td>
<td>0.278</td>
</tr>
</tbody>
</table>

Additionally, meteorological data are obtained from National Climatic Data Center (NCDC) Global Surface Summary of the Day (GSOD) dataset. That including daily average temperature, average wind speed and precipitation for Zhangye weather station (ID: 526520), located in the city of Zhangye.
2.3. Methods

**Remote sensing analysis.** The three different land use classification products are validated against three Landsat Images. Through visual comparison, the MODIS land cover classification failed to represent the change of urban area, while GlobeLand30 did not capture the correct border of urban region and classified most of the desert and Gobi Desert around Zhangye Oasis as grassland. The ESA CCI classification showed a reasonably accurate result and is used to detect the change of land use and land cover in Zhangye. Then, The Landsat Surface Reflectance Images and classification maps were used to determine the representative regions of cropland and barren land, within which the LST would be extracted. The criteria for such regions are that they should maintain the same land cover throughout the study period, and there should be a buffer zone of 1-km wide between these regions and the neighboring land use type. Three barren area (“reference”) and one agricultural area (“cropland”) were determined.

**Data preprocessing.** All remote sensing data are preprocessed with Google Earth Engine. All data products are filtered by the quality control indicators and all abnormal values are excluded. Then, data are downloaded as raster files and extracted as matrices with Harris Geospatial Solutions’ Environment for Visualizing Images (ENVI) Interactive Data Language (IDL) scripts. The datasets are then loaded into MATLAB, where all data of finer spatial resolutions are aggregated to 1-km resolution to match the LST data. Meanwhile, daily data are averaged to 8-day periods and 16-day datasets are linearly interpolated to 8-day.

**Statistical analysis.** The following computation and statistical analysis were conducted in R. Oasis effect intensity of each cropland pixel is calculated as the difference between the pixel’s LST and the average LST of the pixels in the reference regions. To study the temporal trend of oasis effect, we determine Zhangye’s average oasis effect for a certain date as the average of oasis
effect across all cropland pixels on that date. Additionally, to analysis the spatial variation of oasis effect, we define a pixel’s mean growing season oasis effect as the average of oasis effect for the given pixel across all dates between May and September during the studied years.

Similarly, we defined the difference of NDVI, ET and albedo between cropland and reference regions, and note these values as $\Delta$NDVI, $\Delta$ET and $\Delta\alpha$.

First, we studied the time series of Zhangye’s average oasis effect intensity to find out whether there is a significant trend across the years. The trends of $\Delta$NDVI, $\Delta$ET and $\Delta\alpha$, as well as average wind speed are also studied.

Then, we applied pixel-by-pixel correlation between oasis effect and each of the four factors mentioned above. The correlation was on three different levels: on data record level, where each data point represents a pixel in a 8-day period; on date level, where each data point represents the whole oasis in one 8-day period; and on pixel level, where each data point represents a pixel’s average state across all the growing seasons. The second and third levels intend to reflect temporal and spatial variation, respectively.

Finally, we concluded based on the correlation model to determine which factors among wind speed, $\Delta$NDVI, $\Delta$ET and $\Delta\alpha$ are more closely related to the oasis effect.

3. Results and discussion

3.1. Land use change and expansion of agricultural zone in Zhangye

Zhangye city is in the center of the oasis. According to the Landsat Images, agricultural zone surrounds the urban area and is mostly located to the south of the city, occupying the major part of the oasis. To the north of the urban area is a mosaic of cropland and wetland. The oasis extends to the northwest of the study region, where cropland and natural vegetation coexist. Sparse
vegetation and desert are the main land cover type to the other directions of the oasis. Heihe River flows through the west of the oasis.

Among the land use classification schemes, ESA CCI shows the most accurate oasis boundary. However, most part of agriculture is categorized as rainfed cropland, which is actually irrigated agriculture. Besides, a large part of the barren land surrounding the oasis is classified as grassland, which according to Pan et al (2018) should be more accurately classified as desert or sand. However, this set of classification does show a change of urban and cropland over the past decades. In the center of the oasis, cropland was lost due to urbanization, while on the edges, small patches of barren land were reclaimed to grow crops. Overall, area for cropland has a net increase of 1.39% from 2001 to 2015.

Figure 2: Land cover and land use classification of study area. Data from ESA CCI Project phase 2.

3.2. Characteristics of oasis effect in Zhangye

The oasis effect in Zhangye, in terms of the difference of land surface temperature between oasis and desert, is most prominent during the daytime of growing season.
During the day, the cropland is generally more than 5 °C cooler than desert, while at night the oasis effect is around -2 ~ 2 °C, which means the cooling on oasis is minimal and sometimes reversed. This result is in accordance with many existing researches that found nighttime oasis effect is smaller.

Throughout a year, the oasis effect has its lowest value in peak growing season, which is often in late July or early August. During the growing season (May to September), the cropland is generally 10 ~ 20 °C cooler than barren land. In other months, the oasis effect is not as significant and is often a small negative value. On certain days after snow, the oasis effect is positive, indicating the desert is warmer than cropland.

Across the study period of 18 years, the annual mean oasis effect intensity is shown in the figure below. Fig. (A) and (B) represent daytime and nighttime oasis effect, respectively. Red lines indicate annual average, while green lines show the average of growing season. Both daytime and nighttime oasis effect is generally negative, indicating a cooler oasis. However, the intensity of cooling during night is very limited, and in recent years the effect is stronger than early.

For daytime, both annual and growing season average show a general trend of diminishing oasis effect. The growing season oasis effect actually has a slight trend of intensifying before 2010 but has been diminishing since 2010. The trend is especially obvious after 2015, as the oasis effect changes from -11 to -8 °C.
Figure 3: Oasis effect during 2001-2018. (A) shows annual daytime oasis effect (DA) and daytime oasis effect of growing season (DG). (B) shows annual nighttime oasis effect (NA) and nighttime oasis effect of growing season (NG). Oasis effect is most obvious during the day. The daytime oasis effect is diminishing over time (especially after 2010), while nighttime trend does not show significant change.

Such change could be a result of change in agricultural practices. In 2010, Zhangye completed the Water Users’ Association (WUA) policies and water quotas for irrigation (Akiyama et al., 2018), and installed precision irrigation facilities to replace the flood irrigation systems, which is estimated to waste at most 67.9% of the water (Yang et al., 2015). The policies and infrastructures could have reduced the irrigation to the fields, thus reducing the ET of cropland.

3.3. Characteristics of biophysical and meteorological parameters

3.3.1. NDVI

The NDVI of Zhangye oasis fluctuates between 0.1 and 0.7 during a year and is generally above 0.5 during growing seasons. The barren regions have an NDVI of 0.05 ~ 0.15 and has higher values during growing seasons, possibly due to the sparse vegetation.
The difference of NDVI between cropland and reference regions is shown in the figure. Over the past 18 years, $\Delta$NDVI shows a declining trend and decreased from around 0.45 to 0.35.

![Figure 4: Annual growing season average NDVI difference between cropland and barren regions, showing a trend of decline.](image)

3.3.2. **Evapotranspiration**

ET of cropland in Zhangye has its peak value of $2.5 \sim 4.5 \text{ kg} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$ during the growing season, while ET for sparse vegetation around the oasis is generally no more than $1.5 \text{ kg} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$ around the year.

The difference of ET between cropland and reference region is shown in the figure below. $\Delta$ET shows a slight increase from around 1.8 in 2001 to around 1.9 $\text{ kg} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$ in recent years. Since 2012, annual mean $\Delta$ET shows a decline.

![Figure 5: Time series of annual mean evapotranspiration (ET) difference between oasis and desert.](image)
3.3.3. Albedo

Albedo for the barren regions around Zhangye has not changed significantly over the past 18 years, remaining at around 0.22. The albedo for cropland, however, has been increasing from 0.18 to 0.20. As a result, the difference of albedo between cropland and barren land has narrowed from around -0.03 to -0.02. The trend is shown below.

![Albedo difference over time](image)

Figure 6: Time series of annual average albedo difference between cropland and reference region during growing season.

3.3.4. Wind speed

Weather data was collected from Zhangye weather station. Here the daily average wind speed and maximum wind speed during the growing season were analyzed (red: maximum wind speed; green: mean wind speed). The wind speed in recent years are higher than in previous years.
3.4. Correlation analysis

First, we studied the relationship between oasis effect and vegetation in Zhangye oasis. Two factors are considered separately: NDVI and ET. There correlation with oasis effect is shown in the figure below.

The correlation was studied from both spatial and temporal perspectives. For the temporal correlation, figure A shows that on days that $\Delta$NDVI is greater, oasis effect tends to be stronger (more negative). Meanwhile, according to figure C, higher $\Delta$ET is associated with greater oasis effect intensity. For spatial correlation, the conclusions are similar: for those pixels that keep high $\Delta$NDVI and $\Delta$ET, the cooling effect is stronger.
Figure 8: Correlation between daytime oasis effect and Normalized Difference Vegetation Index (NDVI) difference (A and B), or between daytime oasis effect and evapotranspiration (ET) (C and D). Daytime oasis effect intensity is significantly correlated with NDVI difference and ET between cropland and desert (p<0.01). A and C show the temporal correlation, with each point representing the average value for the whole cropland on a specific growing season date, while B and D show the spatial correlation, with each point representing average value for a cropland pixel across the growing seasons in the 18 years.

We also studied the correlation between oasis effect and difference of albedo ($\Delta \alpha$) between oasis and desert. On days when oasis albedo is much lower than desert, the oasis effect tends to be stronger. Similarly, for those pixels that has relatively lower albedo, the cooling is more
significant. This correlation could indicate that albedo difference is not a major driver of oasis effect.

![Figure 9: Correlation between oasis effect and difference of albedo (Δα) between oasis and desert. P < 0.01 for both correlations.](image)

Finally, the correlation between oasis effect and wind speed is shown below ((A) for mean wind speed, (B) for max wind speed). Wind speed would decrease the intensity of oasis effect and limit the cooling effect, but the correlation is limited.
4. Conclusions

This study overviewed the land use change in Zhangye and detected the agricultural expansion since 2001. A representative agricultural zone was selected in the oasis, and three desert or sparsely vegetated region were selected as reference. The oasis effect for Zhangye is then calculated from MODIS LST data from 2001 to 2018, generating a 1-km resolution, 8-day interval dataset.

We then examined the diurnal, annual and inter-annual characteristics of oasis effect of Zhangye. The oasis is most significant during the day and in growing season, averaging to around $-10^\circ C$. The annual mean growing season oasis effect showed a trend of diminishing after 2010, especially after 2015. During the same period, $\Delta NDVI$ decreased, $\Delta ET$ first increase and then decreased after 2012, and $\Delta \alpha$ increased. Wind speed in Zhangye showed a slight increase, but the pattern is not clear.

Each of the factors above were fit to a correlation model with oasis effect. Both $\Delta NDVI$
and ΔET had a strong negative correlation with oasis effect, with higher ΔNDVI and ΔET associated with stronger cooling effect. Δα had a positive correlation with oasis effect, which is contrary to the hypothesis that higher albedo leads to cooler climate. This implies that albedo is not a main driver of oasis effect. Wind speed has a weak positive correlation with oasis effect, showing that oasis effect could decrease under higher wind speed.

Overall, the change of oasis effect has roughly the same pattern as ΔNDVI, showing the possibility that vegetation in the oasis is impacting the oasis effect. Meanwhile, the decrease of oasis effect after 2012 could partly attribute to the decrease of ΔET. Change of ΔET could be a result of new policies and techniques which promotes to save water when irrigate.

Bibliography


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