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Research Article

Effects of Climate Variability on Evaporation in Dongping Lake, China, during 2003–2010

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Based on two long-term, hourly (10:30–11:30 and 13:10–14:10) meteorological over-lake observations and data from Shenxian meteorological station, nearby Dongping Lake, the Penman-Monteith equation and reference evaporation ratio algorithm were used to calculate lake evaporation in Dongping Lake, China, from 2003 to 2010. The variation trend of evaporation of Dongping Lake was analyzed, and the influences that caused changes in lake evaporation were also discussed. The results show that (1) the total annual evaporation in Dongping Lake increased at 18.24 mm/a during 2003–2010. The major climatic factors accounting for this increase are the rising net radiation and the rising air temperature; (2) the total annual evaporation in a particular hour (13:10–14:10) in Dongping Lake increased at 4.55 mm/a during 2003–2010—the major climate factors that accounted for this increase are rising net radiation, followed by air temperature, wind velocity, and air humidity; (3) against the background of global warming, the climate of Dongping Lake tended to be dry during 2003–2010; the largest contribution to this comes from air temperature, followed by wind velocity and relative humidity; and (4) the monthly evaporation in Dongping Lake has seasonal variability.

1. Introduction

Lakes and reservoirs store valuable fresh water and make them available for use in domestic, industrial, irrigation, hydropower, wetlands, and environmental applications [1]. The availability of fresh water stored in lakes and reservoirs is closely tied to variations in climate and human activities [2]. Evaporation is a key component in the water and energy cycles of lakes and reservoirs [2, 3]. In most situations, lake evaporation represents major water loss. Therefore, information on lake evaporation is essential for the water management of lakes and reservoirs. Climate variability affects lake evaporation, and in turn, evaporation also has an effect on the local climate [2, 4]. Some studies stated that lake evaporation can be considered to be a basic type of reference data for studies on land evaporation, climate changes, and water cycles [4].

The causes of lake evaporation changes have been extensively studied. For instance, hydrological models were used to calculate the water surface evaporations of many endorheic lakes and closed lakes, and how the regional climate changes affect the lake evaporation was analyzed [5, 6]. A Penman equation and CRLE (complementary relationship lake evaporation) model were used to calculate the evaporation of Ziway Lake in Africa, and how the air temperature and air humidity caused the lake evaporation change was discussed in paper of Vallet-Coulomb et al. [6]. Based on satellite observations, as well as meteorological and hydrological data, the lake water volume balance equation was used to conclude that global warming led to the decrease in lake evaporation, which contributed to the rapid surface expansion of Nam Lake in Tibet [7].

At present, calculation of lake evaporation is mainly based on climatology models or evaporation pans installed in land near the study area [8]. An evaporation pan that is exposed to air has a small area and shows small effects in the atmosphere. The atmospheric moisture deficit mainly depends on the surrounding environment being dry; in such conditions, the evaporation pan is more easily affected by advection and heat conduction [9]. The quantification of lake evaporation is ideally obtained from direct measurement through eddy covariance techniques [10]. However, the eddy covariance measurement requires expensive instruments and is difficult to operate in any given lake, thereby limiting its application in more lakes. Various indirect methods have been used to estimate lake evaporation, such as the water balance method, energy budget method, and mass transfer [11–13]. The widely used Penman-Monteith equation [14–16] takes turbulent transfer and energy balance into account, as well as meteorological factors, which can more accurately describe lake evaporation. Therefore, in this study, the Penman-Monteith equation was used to calculate the evaporation in Dongping Lake.

Dongping Lake is the second largest inland lake in the North China Plain. It bears the bleed-off tasks in river segments where the Yellow River transitions from wide channels to narrow channels and is also the last storage lake in the first-phase construction of the South-to-North Water Diversion Project's eastern route. After storage in Dongping Lake, water from the Yangtze River can be transferred to Tianjin and Jiaodong Peninsula by the South-to-North Water Diversion Project. Since 2003, we conducted long-term measurements directly over Dongping Lake. The meteorological data for 2-hour-long periods (10:30–11:30 and 13:10–14:10 in local time) over an 8-year period (from 2003–2010), as regional and meteorological representative of Dongping Lake, were consistently measured through man-boated tour observations over Dongping Lake.

The availability of consistent, long-term data motivated us to investigate the variations in lake evaporation and the climate variability that affected lake evaporation in this study. This study aims to gain better understanding of lake evaporation and its interactions with climate variability, thereby providing a scientific foundation for water resource assessment, hydrological studies, water conservancy project construction, and climate change studies in the North China Plain.

2. Study Area and Data Sources

2.1. Study Area. Dongping Lake (N 35.97°, E 116.18°) is located in the southwest Shandong Province in China. The location and shape of Dongping Lake are presented in Figure 1. Dongping Lake is the second largest inland lake in Shandong. Its surface area is 626 km^2. It has a perennial water area of 124 km^2 (180 km^2 in summer). The averaged depth is 2 m. The total water volume stored in Dongping Lake is about 40×10^8 m^3. Its elevation is 50 m above the averaged sea level. Dongping Lake locates in a humid and warm zone over midlatitude. It has a semihumid monsoon climate with four distinct seasons. The annual rainfall amount is 636 mm,

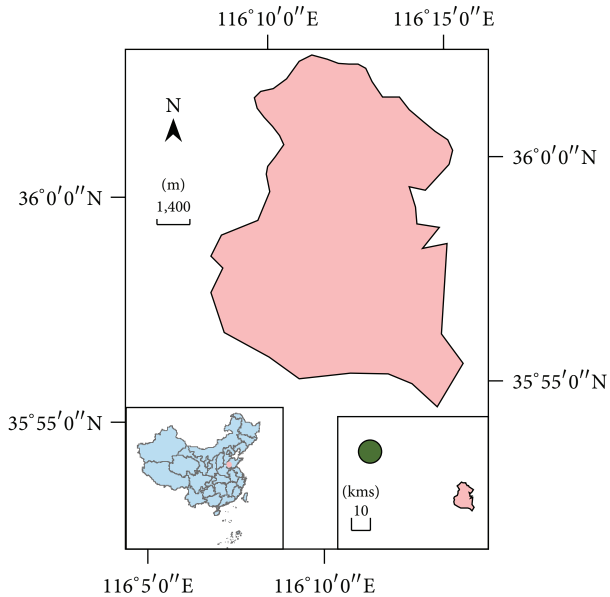

Figure 1: The location and shape of Dongping Lake in China.

which is concentrated in July and August. The annual averaged temperature is 13.4°C, and the annual sunshine hours are 2474.2 hours.

2.2. Data Sources. The 2-hour (10:30–11:30, 13:10–14:10) meteorological data obtained from man-boated tour observations [17] were used. A power-driven vessel was driven by observers from the shore to the middle, in edge-to-edge observations. The time when arriving to the lake's center was 11:00 or 13:40, and the observation time was for about 1 hour. This observation method is used to reduce the errors caused by warming and cooling of the lake surface and to minimize the errors caused by the temperature difference between the lake shore and lake center, when calculating the mean lake surface temperature. The measured parameters include air temperature, air humidity, wind velocity, net radiation flux 1.5 m above the lake surface, cloud cover, lake surface temperature, and water depth. Air temperature and air humidity were measured by dry and wet bulb thermometers; net radiation was measured by four-component table net radiation; wind velocity was measured by an anemorumbometer; and lake surface temperature was measured by a buoy-type thermometer. Observations in winter were impossible because of freezing, so data from December to February (the nongrowing season) were missing. The data from March to November in 2003–2010 were used.

Because it is difficult to calculate the daily evaporation of Dongping Lake from 2-hour meteorological data alone, meteorological data from a nearby weather station were also used. The nearby weather station is Shenxian meteorological station (N 36.23°, E 115.67°, 37.8 m high), which is 54.2 km away from Dongping Lake. The distance between Dongping Lake and Shenxian meteorological station is presented in Figure 1. The 2003–2010 observations from Shenxian meteorological station included daily maximum and hourly air temperature, hourly net radiation, sunshine duration, daily and hourly air humidity, and daily and hourly wind velocity.

3. Methods

3.1. Calculation of Hourly Evaporation in Dongping Lake. Because the FAO (Food and Agriculture Organization of the United Nations) modified Penman equation has empirical and regional limitations, it is not suitable for open and wide lakes [18]. This paper introduces the use of actually measured air temperature and air humidity, and Penman-Monteith equation fully considers turbulent transfer and energy balance with aerodynamic parameters. This allows the radiation driving force and air drying force to be better represented. The hourly potential evaporation LE_{dh} in Dongping Lake is calculated using the Penman-Monteith equation [14, 15], as follows:

$$LE = E_a + E_p = \frac{\Delta (R_n - G)}{\Delta + r(1 + (r_s/r_a))} + \frac{\rho_a c_p (e_s - e_a)/r_a}{\Delta + r(1 + (r_s/r_a))}. \quad (1)$$

In (1), LE is potential evaporation in mm; E_a is radiation driving force in mm; E_p is air drying force in mm; r is a psychrometric constant, usually set at 0.067, in kpa/°C [18]; c_p is the specific heat of the air in MJ/(kg·°C); ρ_a is the mean air density at constant pressure in kg/m^3; R_n is net radiation in MJ/(m^2·d); G is water heat flux in MJ/(m^2·d); Δ is the slope of the saturation vapor pressure-temperature relationship in kpa/°C; r_a is aerodynamic resistance in s/m [19]; and e_s and e_a are the saturated and actual vapor pressures, respectively, in kpa [20]. r_s is surface resistance in s/m—for water surfaces with enough water supply, water vapor is transported continuously upward; thus, the air close to the underlying surface with enough water supply is gradually saturated, so r_s is close to 0 [3].

Water heat flux G is generally calculated by using water temperature profiles because the temperature is different at different water depths, the so-called water temperature layering [2]. Dongping Lake is a shallow lake with an average depth of 2 m, so it could be considered to be a well-mixed lake with no water temperature layering. As a result, the lake surface temperature can satisfy the calculation of water heat flux. The water heat flux (G in MJ/(m^2·d)) was computed using (2), similar to Lenters et al. [2] and Likens and Johnson [21]:

$$G = c_s d_w (T_n - T_{n-1}) * \frac{1000}{86400}, \quad (2)$$

where c_s is water heat capacity (4.18 MJ/(m^3 · °C)), d_w is lake depth, and, T_n, T_{n-1} are lake surface temperature on times n and $n-1$, respectively.

3.2. Calculation of Evaporation Ratio and Daily Evaporation. The daily evaporation of Dongping Lake is calculated by using the reference ratio method [22]. The basic hypothesis is that, although meteorological factors change throughout the day, the ratio of hourly potential evaporation that accounts for the total daily amount is constant [22].

Dongping Lake is 54.2 km away from Shenxian meteorological station, but the major weather processes and the horizontal advections are basically the same; thus, their evaporation ratios are basically the same. Without direct evaporation records for Dongping Lake, the observation data from Shenxian County meteorological station were used to calculate the evaporation ratio (labeled as A), which was used as the evaporation ratio in Dongping Lake, similar to Zhu et al. [7]:

$$\frac{LE_{sh}}{LE_{sd}} \approx \frac{LE_{dh}}{LE_{dd}} = A, \quad (3)$$

where LE_{sd} is the daily potential evaporation at Shenxian meteorological station; LE_{sh} is the 1-hour (13:10–14:10) potential evaporation of Shenxian meteorological station; LE_{dd} is the daily potential evaporation of Dongping Lake; LE_{dh} is the 1-hour (13:10–14:10) potential evaporation of Dongping Lake; and A is the evaporation ratio.

Shenxian meteorological observation station is covered by green grassland, so the FAO-modified Penman equation [18] could be used, since it is suitable for fully covered green land with a reference height of 0.12 m, reflectivity of 0.23, and enough water supply [18]. LE_{sd} and LE_{sh} are calculated as follows:

$$LE = \frac{0.408\Delta (R_n - G) + r (C_n/(T + 273)) u (e_s - e_a)}{\Delta + r(1 + C_d u)}, \quad (4)$$

where C_n is 900 (daily) and 37 (hourly) and C_d is 0.34 according to FAO 56 guidelines. However, according to ASCE-EWRI (The American Society of Civil Engineers-World Water & Environmental Resources Congress), canopy resistance in the daytime is 50 s/m and C_d in the daytime is 0.24. The C_d values standardized by FAO and ASCE-EWRI were validated by Allen et al. based on experiments conducted across U.S.A [23] and they concluded that 0.24 is suitable for calculation of hourly potential evaporation, while 0.34 is suitable for calculation of daily potential evaporation [23].

Daily potential evaporation in Dongping Lake is calculated based on A ((3) and (4)) and LE_{dh} ((1) and (2)). The potential evaporation, which is considered as the regional evaporation ability given sufficient water supply, that is, the theoretical upper limit of actual evaporation [24–26]. Since the water supply is sufficient in the lake, in most occasions, the lake's potential evaporation is equal to the actual evaporation [9].

3.3. Sensitivity Analysis. We performed a Mann-Kendall (M-K) test and contribution ratios analysis to study the variations in lake evaporations, as well as the effects of climate variability on lake evaporation. The details on the analysis procedures are described as follows.

(1) Variation Trend and Sudden Change Analysis. A trend judgment and significance test for evaporation in Dongping

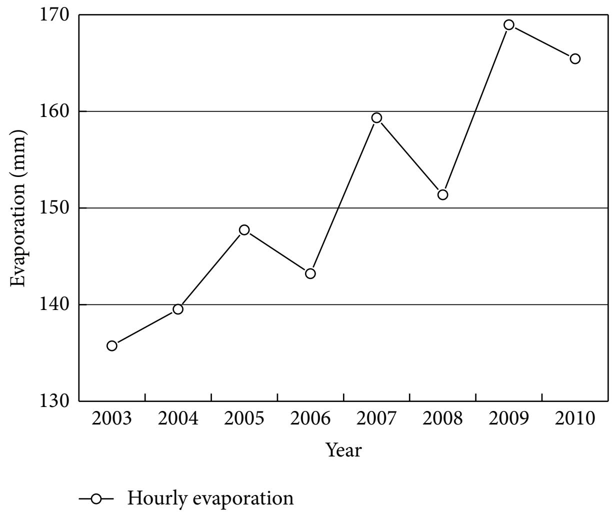

Figure 2: Variation trends of total annual hourly evaporation (13:10–14:10) in Dongping Lake from 2003 to 2010.

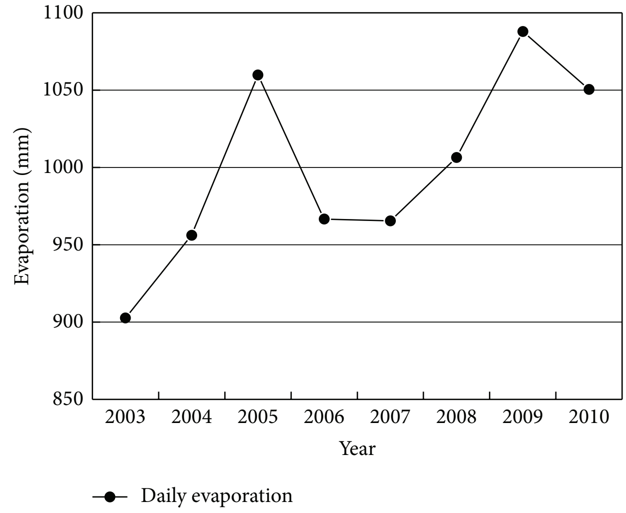

Figure 3: Variation trends of total annual daily evaporation in Dongping Lake from 2003 to 2010.

Lake and other climate factor series in Dongping Lake were performed by using the Mann-Kendall (M-K) test, following Li et al. [27]. The M-K test, which is considered as having low artificial influences and high quantitative degree, is widely used to assess the trends of hydrologic and climate time series. The formula for the test statistic is as follows:

$$S = \sum_{i=2}^{n}\sum_{j=1}^{i-1} \operatorname{sign}\left(X_i - X_j\right), \tag{5}$$

where sign() is a symbolic function and X_i, X_j mean the i and j values in time series; when $X_i - X_j$ is less than, equal to, or greater than zero, then $\operatorname{sign}(X_i - X_j)$ is −1, 0, and 1, respectively. The variation trend is given by z:

$$Z = \begin{cases} \dfrac{(S-1)}{\sqrt{n(n-1)(2n+5)/18}} & (S > 0) \\ 0 & (S = 0) \\ \dfrac{(S+1)}{\sqrt{n(n-1)(2n+5)/18}} & (S < 0); \end{cases} \tag{6}$$

when z is positive, it implies an uptrend; when z is negative, it shows a downtrend. The absolute value of z must be greater than or equal to 1.28, 1.96, and 2.32 to pass the 90%, 95%, and 99% significance tests, respectively.

(2) Calculation of Contribution Ratios. The effects of climate factors on evaporation in Dongping Lake were analyzed by using multiple regression, and their contribution ratios to the air drying force in Dongping Lake were analyzed, following Zhang et al. [28]. The significance levels of the independent variables (the climatic factor) into and out of the multivariate regression model were set at 0.05 and 0.1, respectively. In order to judge the relative contributions of the climate factors to evaporation from Dongping Lake, the data should be standardized between 0 and 1. Regression analysis was carried out on the standardized data, and the standardizing sequence of the regression equation data was obtained. The contribution by each independent variable to the changes in the dependent variable can be calculated as follows:

$$\begin{gathered} Y_s = aX_{1s} + bX_{2s} + cX_{3s} \cdots + nXns, \\ \eta_1 = \frac{|a|}{|a| + |b| + |c| + \cdots}, \\ \eta_2 = \frac{a\Delta X_{1s}}{\Delta Y_s}, \end{gathered} \tag{7}$$

where Y_s is the standardization of the dependent variable values; $X_{1s}, X_{2s}, X_{3s}, \ldots$ are the respective standardized values of the independent variables; a, b, and c are the regression coefficients of the standardized sequence; η_1 is the relative contribution of X_1 to Y; η_2 is the actual contribution of X_1 to Y; ΔY_s is the variable quantity of Y_s; and ΔX_{1s} is the variable quantity of X_{1s}.

4. Results and Discussion

4.1. Interannual Variability

4.1.1. Varying Characteristics of Hourly and Daily Evaporation in Dongping Lake from 2003 to 2010. The yearly accumulation of the hourly (13:10–14:10) and daily evaporation shown in Figures 2 and 3 is calculated based on descriptions in Sections 3.1 and 3.2. The total annual hourly and yearly evaporation both have increased from 2003 to 2010. They passed the M-K test at $\alpha = 0.05$ and $\alpha = 0.01$, and their variation trends were consistent and significant. Table 1 shows the Z values of the M-K trend tests for total annual hourly and daily evaporation in Dongping Lake during 2003–2010.

Figure 3 shows that the total annually daily evaporation from 2003 to 2010 was increased at the rate of 18.24 mm/a, within a range between 902 mm in 2003 and 1088 mm in

Table 1: Z values of the M-K trend tests for total annually hourly and daily evaporation in Dongping Lake during 2003–2010.

	Hourly evaporation	Daily evaporation
Z values of M-K tests	1.98	2.72
Change of rate (mm/a)	18.24	4.55

Remark: mm/a means the increasing rate per year.

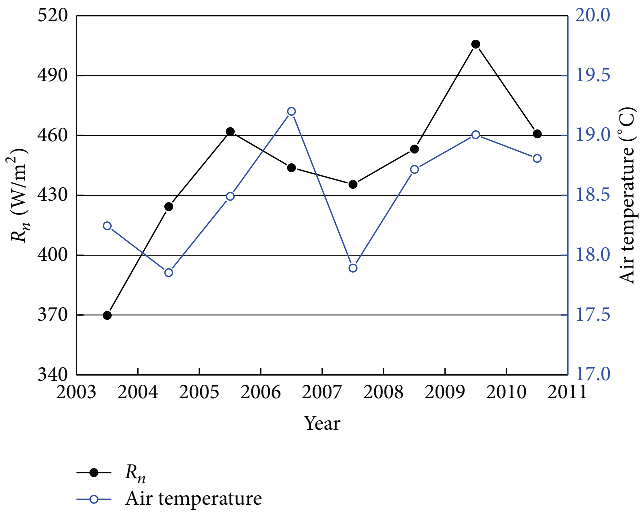

Figure 4: The variation trends of annually averaged air temperature and net radiation in Dongping Lake during 2003–2010 (open circle means air temperature, dot means net radiation).

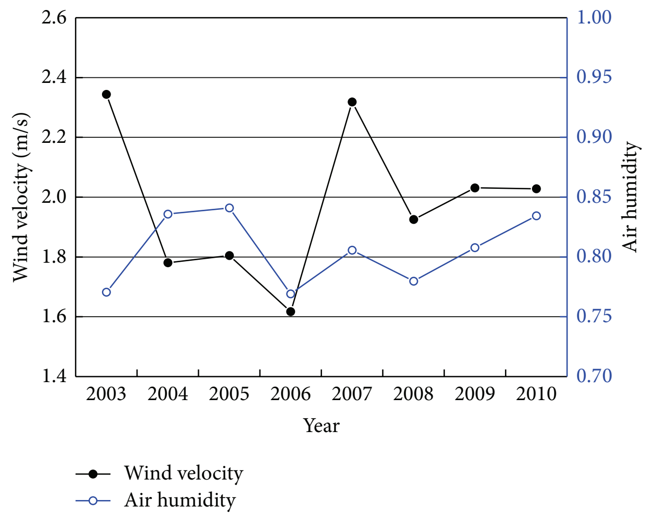

Figure 5: The variation trends of annually averaged air humidity and wind velocity in Dongping Lake during 2003–2010 (open circle means air humidity, dot means wind velocity).

2009; Figure 2 shows that the hourly evaporation at 13:20 was increased at the rate of 4.55 mm/a, within a range between 123 mm in year 2003 and 153 mm in year 2009; the increase of 1-hour (13:10–14:10) evaporation accounted for 24.9% of the annual increase in evaporation, which indicates that the hourly meteorological data (13:10–14:10) can be used to analyze the response of evaporation in Dongping Lake evaporation to climate variability. This is because the evaporation and main influence factors of evaporation, including solar radiation, land surface temperature, and air temperature, at most time can reach their maximum value during 13:10–14:10. The lake surface absorbs heat and transports long-wave radiation upwards to the air through turbulent transport and advection movement after sunrise, which increases air temperature and net radiation. At 12:00 noon, the solar altitude angle and solar radiation received by the lake surface are at their maximum. However, the received heat is still greater than the upward emitted long-wave radiation, so lake surface temperature and net radiation are still rising. Close to 13:00, the heat stored and discharged by land reaches a balance, so net radiation and air temperature both reach the daily maximum [17].

4.1.2. The Effects of Climate Factors on Daily Evaporation in Dongping Lake. Climate factors directly affect radiation driving force and air drying force and thus indirectly affect evaporation in Dongping Lake. Based on (2), net radiation directly affects radiation driving force, while air temperature, air humidity, and wind velocity directly affect air drying force. The annual means of 10:30–11:30 and 13:10–14:10 meteorological data were used to analyze the variation trends in the monthly evaporation of Dongping Lake. Table 2 lists the Z values of the M-K trend test for annually averaged net radiation, averaged air temperature, averaged air humidity, and averaged wind velocity in Dongping Lake during 2003–2010. Figure 4 shows the variation trends of annual mean air temperature and annual mean net radiation, and Figure 5 shows the variation trends of both annual mean air humidity and annual mean wind velocity during 2003–2010. Based on Figures 4 and 5 and Table 2, the annual mean net radiation and mean air temperature in Dongping Lake both showed an increasing trend and the increasing trend of mean net radiation and mean air temperature passed the significance test at $\alpha = 0.05$ and $\alpha = 0.1$. Namely, the annual mean net radiation and annual mean air temperature in Dongping Lake increased significantly from 2003 to 2010, although annual mean air humidity and annual mean wind velocity increased at a insignificant trend. The annual mean air temperature, annual mean net radiation, and annual mean wind velocity increased at 0.11°C/a, 12.01 W/m^2/a, and 0.001 m/s/a, respectively. Annual mean air humidity fluctuated between 0.77 and 0.84. From the variation trend in annual change, the increased evaporation in Dongping Lake was mainly caused by the increasing air temperature and increasing net radiation.

The underlying surface of Dongping Lake is a homogeneous water body. When solar radiation increases, the solar shortwave net radiation received by the lake surface is greater than that received by land due to the small albedo of the lake surface. Water bodies have larger heat capacity and higher heat conduction ability than land, so changes in lake surface temperature are less rapid than those of land surface temperatures. Thus, long-wave radiation emitted by the lake to atmosphere is less than that emitted by land.

Table 2: Z values of the M-K trend tests for annually averaged net radiation, averaged air temperature, averaged relative humidity, and averaged wind velocity in Dongping Lake during 2003–2010.

	Net radiation	Air temperature	Air humidity	Wind velocity
Z values of M-K tests	1.98	1.48	0.50	0.25
Change of rate	12.01	0.11	0.001	0.001

Table 3: Z values of M-K tests and contribution ratios for annual air drying force and radiation driving force in Dongping Lake during 2003–2010.

	Radiation driving force	Air drying force
Z values of M-K tests	2.47	0.99
Contribution ratios	75%	25%
Change of rate	0.012	0.004

The increase in net radiation is the combined result of multiple factors. When air temperature increases, the long-wave radiation emitted from the atmosphere to the lake surface also increases, which increases net radiation. However, based on Figure 5, net radiation does not show a similar variation trend as T_a, because R_n is affected by other factors. Cloud cover can also lead to the increase of R_n by changing the solar radiation received by the Earth-atmosphere system [29]; an increase of wind velocity can also change the external horizontal advection of Dongping Lake and thereby indirectly alter the net radiation by directly changing air temperature.

The increase of global CO_2 content has led to the decrease of long-wave radiation emitted from the Earth-atmosphere system, to the increase of downward long-wave radiation in the atmosphere, to the increase of energy stored in the Earth-atmosphere system, and thus to the increase of R_n [30]. Multiple factors interact in the climate system, which is a profound scientific problem to be studied in the future.

4.2. Hourly (13:10–14:10) Evaporation through Climate Variation

4.2.1. Variation Trends of Hourly Evaporation, Radiation Driving Force, and Air Drying Force in Dongping Lake during 2003–2010. Based on (2), Dongping Lake's evaporation was affected by two main factors: (1) radiation driving force from net radiation and water heat flux and (2) air drying force, namely, the horizontal advections driven by weather factors, such as air temperature, air saturation difference, and wind velocity.

The annual 1-hour (13:10–14:10) air drying force, annual 1-hour (13:10–14:10) radiation driving force, and annual 1-hour (13:10–14:10) evaporation in Dongping Lake were calculated using (2) and are shown in Figures 6 and 7. Table 3 lists the changing rate and M-K Z values of the annual 1-hour (13:10–14:10) evaporation, the annual 1-hour (13:10–14:10) radiation driving force, and the annual 1-hour (13:10–14:10) air drying force and contribution ratios for annual air drying force and radiation driving force in Dongping Lake during 2003–2010. Table 3 and Figures 6 and 7 show that the annual 1-hour (13:10–14:10) radiation driving force increased at the rate of 0.012 mm/day/a during 2003–2010, while annual 1-hour (13:10–14:10) air drying force fluctuated but increased at 0.004 mm/day/9a. Annual 1-hour (13:10–14:10) lake evaporation passed the M-K test at $\alpha = 0.1$, and radiation driving force passed the M-K test at $\alpha = 0.01$. Therefore, the annual radiation driving force increased significantly from 2003 to 2010. However, air drying force did not pass the M-K test indicating the increasing trend is not significant.

The annual air drying force decreased during 2003–2006 but experienced a fluctuant increase during 2006–2010; overall its increasing trend during 2003–2010 was not significant. This could be because the radiation driving force was influenced by net radiation, which was mainly influenced by solar radiation and water heat flux. And the water heat flux was mainly influenced by the water depth and the rise value of the surface temperature over an hour. In addition, in the same month, the lake depth did not change much. Because water has a large heat capacity, the rising value of the surface temperature over an hour was mainly influenced by solar radiation and the increase of net radiation was also mainly influenced by solar radiation. However, the air drying force was the result of nonlinear interactions between meteorological and nonmeteorological factors. Table 3 shows the relative contribution ratios of radiation driving force and air drying force to the uptrend of evaporation in Dongping Lake. The contribution ratio of radiation driving force (75%) was significantly higher than that of air drying force (25%). These results indicate that (1) the major cause of increasing evaporation in Dongping Lake during 2003–2010 was the increased radiation driving force, while the air drying force could promote or offset the uptrend of evaporation and (2) the climate around Dongping Lake became drier from 2003 to 2010.

4.2.2. Contribution Rate to Air Drying Force from Climate Factors. Based on the results in Section 4.2.1, against the background of global warming [30], the climate around Dongping Lake tended to slowly become drier from 2003 to 2010. From (2), air drying force is a result of the nonlinear interaction between air temperature, wind velocity, and relative humidity. The spatial distribution of the relative contribution ratios of climate factors to air drying force (Table 4) shows that the largest contribution comes from air temperature (51%), followed by wind velocity (32%) and the smallest contribution comes from relative humidity (16%).

Table 5 lists the Z values of the M-K trend test for annual net radiation, air temperature, relative humidity, and wind velocity in Dongping Lake (13:10–14:10) during 2003–2010. The variation trends in annual 1-hour (13:10–14:10) air temperature, net radiation, air humidity, and wind velocity are shown in Figures 8 and 9, respectively. According to Tables 4 and 5 and Figures 6, 7, 8, and 9, the increase in wind speed and air temperature decreases the air drying force,

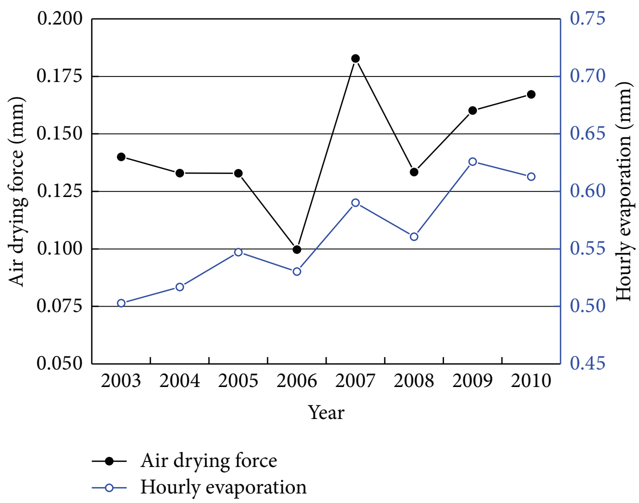

FIGURE 6: The variation trends of annual mean of 1-hour (13:10–14:10) air drying force and hourly evaporation in Dongping Lake during 2003–2010 (open circle means hourly evaporation, dot means air drying force).

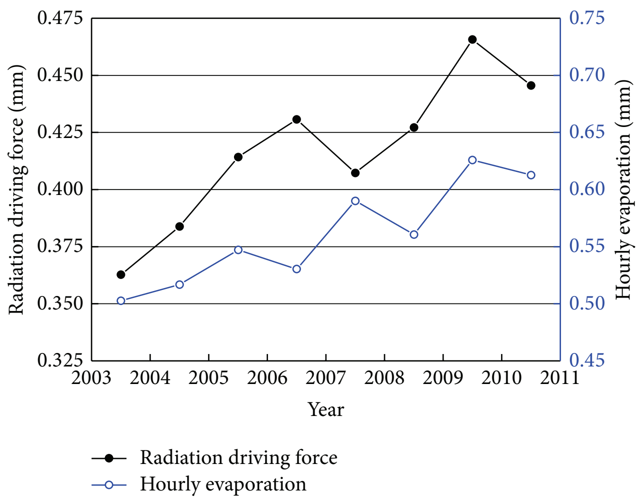

FIGURE 7: The variation trends of annual mean of 1-hour (13:10–14:10) radiation driving force and hourly evaporation in Dongping Lake during 2003–2010 (open circle means hourly evaporation, dot means radiation driving force).

but the increase in air humidity decreases air drying force. However, the forces which caused air drying force to increase were larger than the forces which caused air drying force to decrease, finally resulting in the increasing trend of air drying force from 2003 to 2010. Climate in Dongping Lake region tends to be drier during 2003 to 2010 due to global warming based on the observed trend in annual change of air temperature (Tables 4 and 5).

Air temperature not only decides the diffusion rate of water vapor above water surface, as well as the receiving ability of vapors, but its stratification effect also directly affects the gradient of air humidity. A higher air temperature will result in greater air saturation differences and air drying

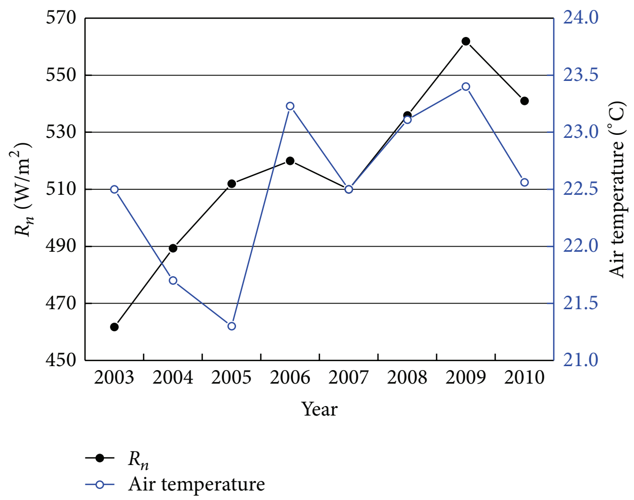

FIGURE 8: The variation trends in annual mean of 1-hour (13:10–14:10) air temperature and net radiation in Dongping Lake during 2003–2010 (open circle means air temperature, dot means net radiation).

force. Based on the observation data in this paper (Figures 4 and 8), the air temperature in Dongping Lake during 2003–2010 showed a fluctuant increasing trend. This is because Dongping Lake is an ecological island for tourism; thus, polluting industries were forbidden, so the air was clear. Even with global warming, its air temperature during 13:10–14:10 fluctuated but slowly increased.

With enough water supply, the air close to the underlying surface with enough water supply is gradually saturated. Thus, the action from horizontal advections, the large input, and mixing with unsaturated air will result in air temperature unsaturation at a height of 1.5 m. The observation data indicate that, at 1.5 m high, the relative humidity of the air fluctuated stably. The wind velocity at 1.5 m high was increasing slowly. An increase in wind velocity would strengthen turbulence, so the exchange between dry and wet air increased. Not only did long-wave radiation in the atmosphere increase, but the air saturation difference above the water surface also increased. This increase in wind velocity would also directly lead to a decrease in aerodynamic resistance. These combined processes would lead to the increase of air drying force.

4.3. Monthly Variability

4.3.1. Variation Trends of Monthly Evaporation of Dongping Lake. The hourly evaporation was calculated by (2); the ratio to relate the hourly evaporation into daily evaporation was calculated by (3); and finally, the total daily evaporation for each given month was computed. The averages of the 10:30–11:30 and 13:10–14:10 meteorological data were used to analyze the variation trends of monthly evaporation in Dongping Lake.

Table 6 presents the monthly lake evaporations in Dongping Lake for all years during 2003–2010. It can been seen that lake evaporations were at their maximum in summer (157.87, 162.75, and 129.51 mm in May, June, and July, resp., accounting

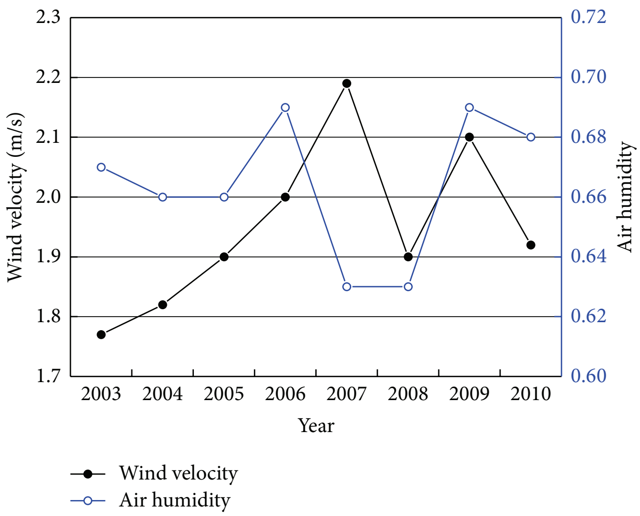

FIGURE 9: The variation trends of annual mean of 1-hour (13:10–14:10) air humidity and wind velocity in Dongping Lake during 2003–2010 (open circle means air humidity, dot means wind velocity).

TABLE 4: The spatial distribution of relative contribution ratios of climate factors to air drying force.

Air temperature	Wind velocity	Air humidity
51%	32%	16%

TABLE 5: Z values of M-K trend tests for annual mean of 1-hour (13:10–14:10) net radiation, air temperature, relative humidity, and wind velocity in Dongping Lake during 2003–2010.

	Air temperature	Relative humidity	Wind velocity
Z values of M-K test	1.37	0.12	0.37
Change of rate	0.16	0.000	0.031

for more than 40% of yearly evaporation), followed by spring (101.91 and 113.05 mm in March and April, resp.), fall (110.77, 89.40, and 80.57 mm in August, September, and October, resp.), and winter (November, 53.67 mm). Table 7 lists the M-K test results; lake evaporation increased in all months (except an insignificant downtrend in October), especially in July ($\alpha = 0.01$), followed by May, August, and November ($\alpha = 0.1$); the uptrend was not significant in March, April, June, or September period.

The intra-annual variability of meteorological factors affected the relevant changes in lake evaporation. The rising trends of air temperature and net radiation from April to August have several influences, including the thawing of frozen water, the gradual recovery of water level, and the activation of air molecules. This resulted in an enhanced energy exchange. From April to August, solar radiation, air temperature, and wind speed are gradually enhanced, finally resulting in an increasing trend of evaporation. However, the variations of wind speed can cause the evaporation to fluctuate. But from September to November, the trends of these variables exhibited just reverse trends compared to those of April to August.

The intra-annual distribution of precipitation and the changing characteristics of water level corresponded to the intra-annual changes of evaporation distribution. In the rainy season between July and August, precipitation and the rise of water level will affect the water exchange between Dongping Lake and the Yellow River. The annual precipitation was concentrated in July and August, while evaporation was centered between May and July in Dongping Lake. So, the phase difference between precipitation and evaporation will induce the changes of water level of Dongping Lake. Before April, the water levels in Dongping Lake and the Yellow River were both low but largely different, and their water exchange was weak. From May to June, the water levels were increased in both Dongping Lake and the Yellow River and water exchange between them was also strengthened. From June to August, water exchange between Dongping Lake and the Yellow River reached its peak, and evaporation will also reach the maximum during this period. After September, precipitation will gradually decrease in the following months and evaporation in Dongping Lake will be low.

4.3.2. Monthly Evaporation of Dongping Lake through Climate Variation. Table 8 presents the Z values of M-K test on rate of air and lake temperature change, air humidity, and wind velocity. It can be seen from Table 8 that the net radiation increased in all months except April. The increasing trend was evident in May (11.60 w/m^2/month/a), July (11.02 w/m^2/month/a), and October (18.38 w/m^2/month/a) and they all passed the $\alpha = 0.01$ M-K test; the trend was prominent in June (16.34 w/m^2/month/a) and passed the $\alpha =$ 0.5 M-K test; the trend was significant in August and passed the $\alpha = 0.1$ M-K test.

Wind speed can indirectly affect water surface evaporation speed through eddy exchange, and wind can move water vapor molecules away from the water surface, thus thinning the surface saturated layer and maintaining a high transport rate. High wind speed can result in small aerodynamic resistance and large water surface evaporation, while low wind speed can result in high aerodynamic resistance and small water surface evaporation. Under the background of global warming [30], air temperature increased in all months except in April. Furthermore, there is no large fluctuation of air humidity, and the change of wind speed is a little complex. Low air humidity means low water vapor content in the air, which would promote water surface evaporation and vice versa.

In March, there is a balance between the increase of lake evaporation caused by the insignificant increases in net radiation (12.45 w/m^2/month/a) and air temperature (0.09°C/month/a) and the change of lake evaporation caused by an insignificant increase in air humidity (−0.02/month/a) and an insignificant decrease in wind speed (0.02 m/s/a); this induced the smooth fluctuation of lake evaporation in March. In April, an increase in wind speed (0.05 m/s/a) compensated for a decrease in lake evaporation caused by a

Table 6: Monthly evaporation of Dongping Lake (unit: mm).

	March	April	May	June	July	August	September	October	November	Year (mm)
2003	80.71	125.96	130.35	160.61	106.62	84.60	73.65	87.33	52.81	902.64
2004	110.19	96.78	142.97	150.19	117.01	109.05	103.37	74.16	52.45	956.16
2005	117.75	151.93	161.98	197.99	104.81	101.94	86.32	84.04	53.06	1059.82
2006	130.18	80.13	160.06	133.08	120.45	124.43	96.26	78.25	43.84	966.69
2007	87.87	106.15	150.06	161.01	137.03	113.55	71.98	81.69	56.12	965.48
2008	82.99	106.19	188.65	132.51	150.35	117.01	95.27	76.06	57.38	1006.41
2009	105.21	121.73	168.65	188.22	153.25	120.48	92.36	80.22	58.25	1088.37
2010	100.35	115.56	160.23	178.36	146.56	115.12	96.12	82.78	55.46	1050.42
Average	101.91	113.05	157.87	162.75	129.51	110.77	89.40	80.57	53.67	

Table 7: Z values of M-K tests and rate of monthly evaporation change.

	March	April	May	June	July	August	September	October	November
Evaporation	0	0.25	1.73^{a}	0.25	2.47^{b}	1.73^{a}	0.24	−0.24	1.73^{a}
Change of rate (mm/a)	−0.404	0.70	4.85	1.74	7.31	3.63	1.24	−0.26	0.87

Remark: a and b mean passing the 90%, and 99% confidence levels.

decrease in air temperature (0.12°C/month/a), which will lead to an insignificant increasing trend in lake evaporation of Dongping Lake. From May to August, the significant increase of net radiation (11.60 w/m^2/month/a, 16.34 w/m^2/month/a, 11.02 w/m^2/month/a, and 14.93 w/m^2/month/a for May, June, July, and August, resp.) compensated for a decrease in lake evaporation, which was caused by a variation in air humidity (−0.014/month/a in July, 0.005/month/a in August) and a decrease in wind velocity (−0.09 m/s/month/a, −0.09 m/s/month/a, −0.02 m/s/month/a, and −0.01 m/s/month/a, for May, June, July, and August, resp.) and thus caused the increase of lake evaporation. Though both net radiation (10.19 w/m^2/month/a, 18.38 w/m^2/month/a, resp.) and air temperature (0.05°C/month/a, 0.34°C/month/a, resp.) increased in September and October, an insignificant decrease in wind speed and an insignificant increase in air humidity inhibited lake evaporation; thus, lake evaporation decreased insignificantly in September and October. A significant increase of wind speed (0.16 m/s/month/a) and an insignificant increase of net radiation (11.73 w/m^2/month/a) led to the significant increase in lake evaporation in November.

5. Conclusions and Discussion

Based on the various meteorological elements observed in Dongping Lake and the nearby weather station, the total annual daily and hourly evaporations from 13:10 to 14:10 in Dongping Lake from 2003 to 2010 were calculated using the Penman-Monteith equation. The variables trends in evaporation were analyzed. The relationship between climate factors and evaporation was then further discussed. The conclusions are as follows.

(1) The total annual evaporation in Dongping Lake increased at 18.24 mm/a during 2003–2010. The major climate factor that accounted for this increase was the rising net radiation and air temperature.

(2) Against the background of global warming [30], the climate around Dongping Lake tended to become drier during 2003–2010; the largest contribution to this came from air temperature, followed by wind velocity and relative humidity.

(3) The yearly hourly (13:10–14:10) evaporation in Dongping Lake increased at 4.55 mm/a during 2003–2010. This increasing rate of evaporation from 13:10 to 14:10 accounted for 24.9% of the increases in yearly evaporation. The major climate factor that accounted for this increase was the rising net radiation, followed by air temperature, wind velocity, and air humidity.

(4) The monthly evaporations of Dongping Lake have seasonal variability. There is an important relationship between the lake's evaporation and seasonal changes in the water level. The largest increases in rate of lake evaporation were in May, July, and August. The major climate factor that accounted for this increase was the increasing net radiation.

The variation trend of evaporation in Dongping Lake during 2003–2010 was calculated, and the contributions of climate factors to the climate around Dongping lake were studied quantitatively. The results will help to better understand the effects of climate change on Dongping Lake, as well as to provide insights for studies on the variation trends of terrestrial evaporation in the North China Plain. The air temperature in Dongping Lake showed an uptrend during 2003–2010, and the warming trend in the future will be a concern for us all. The increasing evaporation of Dongping Lake in 2003–2010 was mainly caused by increased net radiation, while the increase of net radiation was mainly caused by an increase in CO_2 concentrations. Because the climate system is complex and has many interactions among multiple factors, more data are needed for further studies. However, for deep lakes, the water heat flux should take water temperatures at different depths into account [2]. Obtaining

Table 8: Z values of M-K tests on rate of monthly evaporation change, air and lake temperature, air humidity, and wind velocity.

	March	April	May	June	July	August	September	October	November
Air temperature	0.25	−1.24	1.98^b	0	0.99	1.24	0.50	1.73^a	0.50
Change of rate (°C)	0.09	−0.12	0.24	0.05	0.09	0.20	0.05	0.34	0.03
Air humidity	-1.98^b	0.25	−0.25	0	1.48^a	0.25	0.25	2.23^b	0
Change of rate	−0.02	0.00	0.00	0.00	0.014	0.005	0.002	0.014	−0.002
Wind velocity	0.74	0.74	−0.74	−1.24	0	-1.48^a	−0.25	−0.50	1.98^b
Change of rate (m/s)	0.02	0.05	−0.09	−0.09	−0.02	−0.01	−0.01	−0.002	0.16
Net radiation	0.99	0	2.72^c	1.98^b	2.47^c	1.48^a	1.24	2.48^c	1.04
Change of rate (w/m^2)	12.45	1.43	11.60	16.34	11.02	14.93	10.19	18.38	11.73

Remark: a, b, and c mean passing the 90%, 95%, and 99% confidence levels.

meteorological data needs to consume more human and financial resources. In addition, applying the remote sensing method to the estimation of lake evaporation will also be a hot topic for studies on lake evaporation in the future.

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