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Evaporation variability of Nam Co Lake in the Tibetan Plateau and its role in recent rapid lake expansion

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SUMMARY

Previous studies have shown that the majority of the lakes in the Tibetan Plateau (TP) started to expand rapidly since the late 1990s. However, the causes are still not well known. For Nam Co, being a closed lake with no outflow, evaporation (E_L) over the lake surface is the only way water may leave the lake. Therefore, quantifying E_L is key for investigating the mechanism of lake expansion in the TP. E_L can be quantified by Penman- and/or bulk-transfer-type models, requiring only net radiation, temperature, humidity and wind speed for inputs. However, interpolation of wind speed data may be laden with great uncertainty due to extremely sparse ground meteorological observations, the highly heterogeneous landscape and lake-land breeze effects. Here, evaporation of Nam Co Lake was investigated within the 1979–2012 period at a monthly time-scale using the complementary relationship lake evaporation (CRLE) model which does not require wind speed data. Validations by *in-situ* observations of E601B pan evaporation rates at the shore of Nam Co Lake as well as measured E_L over an adjacent small lake using eddy covariance technique suggest that CRLE is capable of simulating E_L well since it implicitly considers wind effects on evaporation via its vapor transfer coefficient. The multi-year average of annual evaporation of Nam Co Lake is 635 mm. From 1979 to 2012, annual evaporation of Nam Co Lake expressed a very slight decreasing trend. However, a more significant decrease in E_L occurred during 1998–2008 at a rate of -12 mm yr^{-1}. Based on water-level readings, this significant decrease in lake evaporation was found to be responsible for approximately 4% of the reported rapid water level increase and areal expansion of Nam Co Lake during the same period.

1. Introduction

With more than a thousand lakes having a total free-water area of ca. 41,800 km^2, the Tibetan Plateau (TP) boasts the greatest concentration of high-altitude inland lakes in the world (Ma et al., 2011). These lakes form the headwaters of many large river basins of Asia and present themselves as important indicators of water resource availability during the ongoing climate change. Numerous studies have shown that the lakes of the inner Tibetan Plateau (iTP) (Fig. 1) have expanded substantially since the 1990s (Wu and Zhu, 2008; Zhu et al., 2010; Meng et al., 2011; Y. Zhang et al., 2011; B. Zhang et al., 2011; G. Zhang et al., 2011; Lei et al., 2012, 2013; Song et al., 2014; Wan et al., 2014; Wu et al., 2014) in contrast to the slight decline in lake volumes in the Himalayan region of Southern TP (Lei et al., 2014; Song et al., 2014). During the same period the glaciers in the iTP have significantly retreated (Yao et al., 2012) and precipitation rates have increased to some extent (Yang et al., 2014; Gao et al., 2015). Song et al. (2014) and Lei et al. (2014) found that the spatial patterns of precipitation variability are consistent with the observed changes in lake area across the entire TP, suggesting that precipitation variations play a dominant role in lake-area changes. However, basin-scale investigations over Linggo Co (Lei et al., 2012), Nam Co (Zhu et al., 2010) and Siling Co

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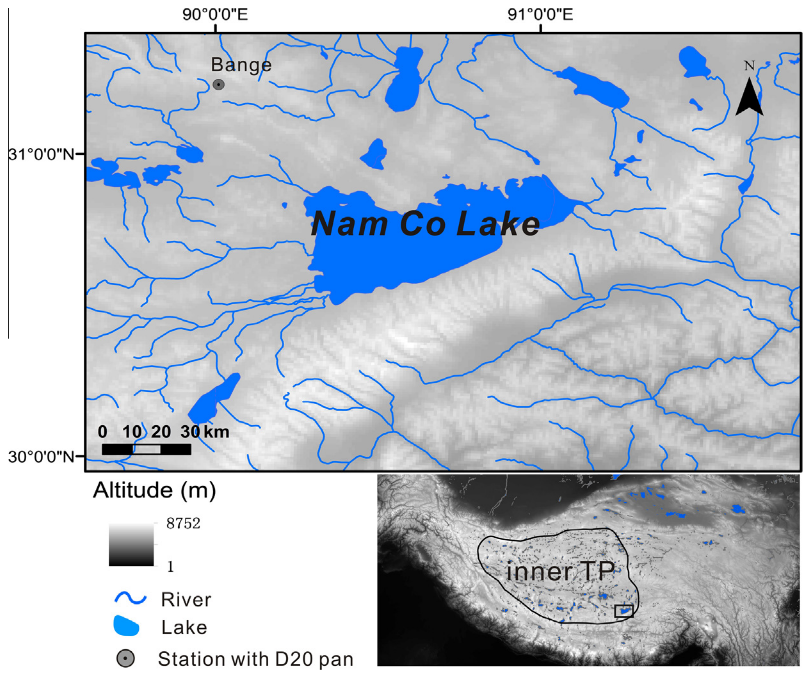

Fig. 1. Location of Nam Co Lake in the Tibetan Plateau and the meteorological station (Bange) with China 20-cm diameter (D20) pan evaporation measurements. The general boundary of the inner Tibetan Plateau (iTP) is basically modified from G. Zhang et al. (2013).

Lakes (Meng et al., 2011) using a water-balance method demonstrated that the increase in glacial melt-water into these lakes is the dominant factor in the observed lake expansions of the iTP. A recent inventory of Zhang et al. (2015) using Landsat products also suggested that the spatial variation of expansion of these glacier-fed lakes corresponds well with a warming temperature trend and glacier mass-loss patterns of the TP, highlighting the role glacier melting plays in areal extent changes of these lakes. Indeed, the mechanism of lake expansion is hard to quantify with inadequate hydro-meteorological observations due to the extremely harsh environment of these alpine regions. Additionally, the hydrological processes of these lakes within the TP may be more intricate than those in low-elevation regions. For example, quantifying water release from the degradation of frozen soils (Cheng and Wu, 2007) and runoff due to glacier melting (Lei et al., 2012; Zhang et al., 2015) is very challenging because of their limited accessibility. Regarding a closed lake without outflow, however, evaporation, E_L, from the lake is the only sink-term in the lake water balance that determines the response of lake water storage to variabilities in surface and subsurface runoff (including groundwater discharge into the lake) from precipitation and glacier melting (Wu et al., 2014).

Global warming due to increasing concentration of atmospheric CO_2 is expected to cause higher evaporation rates and thus accelerate the warming via the water vapor feedback since it is a more potent green-house gas than CO_2 itself (Huntington, 2006). However, previous studies suggested that pan evaporation (Zhang et al., 2007; Yang et al., 2014; Xie et al., 2015) and reference evapotranspiration (Zhang et al., 2009; Yin et al., 2010; Gao et al., 2015) over the TP have decreased significantly in the past few decades. Therefore, the possible decrease of lake evaporation has been regarded as one of the reasons for recent rapid lake expansions in iTP (e.g. Lei et al., 2013; G. Zhang et al., 2011). This viewpoint, however, is built only on speculations, i.e., one would expect lake evaporation to show similar variability with pan evaporation and/or reference evapotranspiration because of the unimpeded access to water supply. In other words, quantitative evidence is needed to test this hypothesis. Besides, it is widely known that the release of sensible heat from the TP surface and the similar heat release of condensation of the evaporated water play a key role in Northern Hemispheric energy and water cycles at various temporal and spatial scales (Wu et al., 2015). Although the total lake (water) area only accounts for a small portion of the whole area of the TP, E_L is still crucial to the thermal control of the Asian monsoon system since the evaporation rate from water surfaces is usually much larger than that from the surrounding land area of the TP. Therefore, accurate estimation of E_L is not only vital to clarifying the mechanism of the reported rapid expansion of the lakes across the iTP, but it is also helpful to elucidate the role lakes play in regional climate change over this high-altitude region.

Admittedly, *in-situ* observations are the best approach to quantifying E_L. In recent years, for example, eddy covariance systems and large (surface area of 20 m^2) evaporation pans have been implemented over Ngoring Lake (Li et al., 2015) in the eastern TP, Erhai (Liu et al., 2015) and Yamdrok Yum Co (Yu et al., 2011) Lakes in the southeastern TP to more directly obtain E_L. These studies helped to clarify the short-term energy and water exchange regime between the lake and the atmosphere in high-altitude regions (Biermann et al., 2014; Wang et al., 2015) and provided a basis for understanding how the land surface processes of the TP impact the variability of the Southern Asian monsoon (Wu et al., 2015). Unfortunately, such *in-situ* observations are limited only to a few years. Therefore, longer term (e.g. multi-year or decadal) E_L estimations are still needed over the TP.

Previous multi-year studies of E_L for this region relied mainly on two approaches, i.e. the bulk-transfer, and combination-equation (Penman, 1948) based methods (e.g. Li et al., 2001; Xu et al., 2009; Zhu et al., 2010; Yu et al., 2011; Zhou et al., 2015). It should be noted that both the Penman and bulk transfer (Brutsaert, 1982) models require wind speed as input to estimate E_L. However, the heterogeneous landscape of the TP plus the site-specific lake-breeze systems that develop between the lake and its adjacent land surface (Liu et al., 2015; Gerken et al., 2014) make the spatial interpolation of the wind speed values measured by the sparse stations of the China Meteorological Administration (CMA) laden with higher uncertainty when compared with other metrological variables, e.g. air temperature and solar radiation. Consequently, lake evaporation models not requiring wind speed data may be preferable. In addition, previous studies mainly used data from meteorological stations at varying distances to the lakes to run the models. This may also lead to additional uncertainties if the estimation approach requires measurements over the lake due to the differences in surface and thermodynamic properties of the free water surface and the surrounding land (Szilagyi, 2008). Therefore, application of gridded meteorological data from grid-points located right above the lakes is preferable.

With an elevation of 4724 m above sea level (asl) [2009 data based on Y. Zhang et al. (2011)], Nam Co Lake is the highest large lake in the world. Remote-sensing based studies indicated that the lake expanded substantially since the 1970s to date (e.g. Lei et al., 2013; Zhu et al., 2010; Y. Zhang et al., 2011). In addition to quantifying the contribution of glacier-melting and precipitation to such areal-extent change, a more accurate estimation of E_L is still needed to an improved understanding of the mechanism of expansion. For example, Zhu et al. (2010) previously indicated that a decline of −30.7 mm in the multi-year averaged E_L value between the periods of 1992–2004 and 1971–1991 might contribute largely to the expansion of Nam Co Lake. Additionally, evaluation of an existing E_L estimation model that does not require wind data may be of interest to the scientific community for revealing long-term variations and/or trends in lake evaporation rates in such a hydro-meteorologically important but sparsely populated region as the TP. In the present study, the grid-based China Meteorological Forcing Dataset (CFMD) (He and Yang, 2011) and the complementary relationship lake evaporation (CRLE) model (Morton, 1983a, 1983b, 1986) were employed to estimate E_L over Nam Co Lake in the TP. The objectives of the present study are: (1) assessing the performance of the CRLE model in estimating lake evaporation of high-elevation lakes; (2) quantifying the temporal variability of E_L at Nam Co Lake and its role in the recent rapid expansion of lake surface area since the late 1990s. The present research differs from previous lake evaporation studies of the TP (Li et al., 2001; Xu et al., 2009; Zhu et al., 2010; Yu et al., 2011; B. Zhang et al., 2011; Wu et al., 2014) by followings: (i) the gridded meteorological data located above the lake area was used as forcing to avoid the impact of the land environment; (ii) the CRLE model which does not need wind speed data as input was used to estimate E_L, thereby expected to avoid uncertainties in wind speed required by the Penman and/or bulk transfer models; (iii) the simulated E_L rates were validated by observed E601B pan coefficient values on an annual scale as well as eddy-covariance-measured evaporation rates from an adjacent lake on a monthly scale.

2. Materials and methods

2.1. Regional setting

Located in the northern foot of the Nyenchen Tanglha Mountain of the TP, Nam Co is a closed, semi-brackish lake (Wang et al., 2009) (Fig. 1). The lake is about 75 km long from east to west and 45 km wide from north to south. With an area of ca. 2013 km^2 [2009 data based on Y. Zhang et al. (2011)], it is the second largest lake in Tibet located in the Nam Co Lake Basin between 89°21′–91°23′E and 2 9°56′–31°70′N with a total watershed area of about 10,610 km^2 (B. Zhang et al., 2011). The main water supply to Nam Co Lake is precipitation and glacier meltwater. There are approximately 60 streams to flow into Nam Co Lake (Wang et al., 2009). The glacier meltwater mainly originates from the modern glacier on the Nyenchen Tanglha Mountain in the southeastern part of the basin. With a semi-arid sub-frigid monsoon climate, the mean annual temperature of the basin is about 0 °C, and the mean annual precipitation is approximately 450 mm (Zhu et al., 2010).

2.2. Data

In this study the gridded China Meteorological Forcing Dataset (CFMD) which was developed by the Institute of Tibetan Plateau Research, Chinese Academy of Sciences (He and Yang, 2011) was employed as lake-evaporation model input. CFMD contains near-surface air temperature, air pressure, wind speed, specific humidity, precipitation, downward shortwave as well as downward long-wave radiation. CFMD with a temporal resolution of 3 h covers the 1979–2012 time-period at a spatial resolution of 0.1°. It was constructed by merging direct measurements at 740 CMA meteorological stations with (a) Global Land Data Assimilation System (GLDAS); (b) GEWEX Surface Radiation Budget (GEWEX-SRB), and; (c) Tropical Rainfall Measuring Mission (TRMM) precipitation data (He and Yang, 2011). In a simulation of land surface temperatures over the arid region of China, Chen et al. (2011) demonstrated that the use of CMFD as model input was able to improve the Noah land surface model (Ek et al., 2003) results by reducing the mean bias by 2 °C from validations against MODIS daytime surface temperature data. Recently, Zhou et al. (2015) compared CFMD data with *in-situ* measurements of the CMA meteorological stations across the iTP. They suggested the following corrections to reduce systematic errors in the CFMD values, i.e.

$$T_{a_{\text{CFMD-cor}}} = T_{a_{\text{CFMD}}} + 3\ ^\circ\text{C} \tag{1}$$

$$q_{\text{CFMD-cor}} = 1.1 * q_{\text{CFMD}} \tag{2}$$

$$S_{\text{CFMD-cor}} = 0.8654 * S_{\text{CFMD}} \tag{3}$$

where T_a, q, and S are near-surface air temperature, specific humidity, and downward shortwave radiation, respectively. The subscript CFMD and CFMD-cor denote the original and corrected CFMD data, respectively. In this study the grid points of CFMD located right above the lake area of Nam Co were extracted and the resulting T_a, q, and S values corrected as shown above. While CRLE does not require wind speed records, such data of CFMD were also collected to analyze the relationship between simulated E_L and different measured meteorological variables, including wind speed (while it may bear some uncertainties as mentioned above, we just used it for comparisons).

For comparison of the trend in simulated E_L with that in pan evaporation, the daily China 20 cm diameter (D20) pan evaporation (E_{pan}) and precipitation data during 1979–2012 from a CMA meteorological station, Bange, in the vicinity of Nam Co Lake, were employed. The Bange station (Fig. 1) is located about 50 km to the northwest of Nam Co Lake. Partial model validation using a pan coefficient was based on daily E601B pan evaporation data of two other CMA stations, Maduo and Dali, during 2011–2012. These two stations situated in the relative vicinity of Ngoring Lake (4274 m asl) in the eastern TP and Erhai Lake (1978 m asl) in the southeastern TP, respectively (see Section 3.1).

2.3. Model description

There are numerous studies that investigated the performance of different models of open water evaporation (e.g. Winter et al., 1995; Sadek et al., 1997; Rosenberry et al., 2007; Majidi et al., 2015). While the methods that rely solely on air temperature and/or radiation data, e.g. those of Turc (1961), Hargreaves (1975) and Makkink (1957), can estimate wet surface evaporation, they primarily lack a rigorous physical basis and explicit consideration of subsurface heat storage, significant for deep lakes. The latter deficiency is also true for the widely employed physically-based Penman- and bulk-transfer-type methods, which have also been proven to be sensitive to wind speed data (Rosenberry et al., 2007; Majidi et al., 2015), hindering their applicability in the TP since the heterogeneous landscape and the sparse data collection network make it very difficult to obtain accurate wind speed data for a given lake.

The CRLE model was developed by Morton (1983a, 1983b, 1986) when he revised the symmetric complementary relationship (CR) of evaporation by Bouchet (1963) for estimating monthly E_L over lakes with time-varying water-column depth. The primary advantage of CRLE is that it does not need locally calibrated coefficients nor wind speed data. In this way, it may be superior to those models that rely on detailed observational data to calibrate their parameter values. For example, while the bulk transfer-type models do not need net radiation as input, their performance depends highly on explicit parameterization of the transfer coefficients using accurate momentum and water vapor roughness lengths as well as atmospheric stability data (Verburg and Antenucci, 2010; Wang et al., 2015), a great challenge in remote areas. In addition, CRLE explicitly takes into account month-to-month changes in subsurface heat storage by linearly routing the absorbed solar radiation via a hypothetical heat reservoir with delay times and storage constants related to the depth and salinity of the lake. Tested over 30 lakes in the United States, Andersen and Jobson (1982) demonstrated that E_L derived from CRLE was overall consistent with previous results of Kohler et al. (1955) who used the pan evaporation method to estimate lake evaporation. Sadek et al. (1997) evaluated the performances of the Penman, bulk transfer and CRLE models in simulating evaporation of the High Aswan Dam reservoir in Egypt and they found that the CRLE model showed the best agreement with the water budget method.

Prior to the application of the CR, originally developed for actual areal evapotranspiration estimation, one needs to determine the appropriate CR pattern (i.e. symmetric or asymmetric) (Szilagyi, 2007; Ma et al., 2015a) based on the type of potential evaporation rates applied. Such a determination may rely on calibrating either a proportionality coefficient (Kahler and Brutsaert, 2006; Szilagyi, 2015) or certain components (Ma et al., 2015a) within the CR theory. The avenue of Morton's (1983a) method belongs to the latter approach. Specifically, by introducing the concept of "equilibrium temperature" (T_p) to calculate the potential evaporation ($E_{P\text{-}CRLE}$) and the wet-environment ($E_{W\text{-}CRLE}$) evaporation rates, Morton (1983a) proposed a symmetric CR model. Here, T_p (°C) refers to the temperature at which Morton's (1983a) energy budget and mass transfer methods produce the same potential evaporation rate from a small moist surface, i.e.

$$E_{P-CRLE} = \frac{1}{\lambda}\{Q_W - [\gamma f_t + 4\varepsilon\sigma(T_p + 273.15)^3](T_p - T_a)\} \tag{4}$$

$$E_{P-CRLE} = \frac{1}{\lambda}[f_t(e_p - e_a)] \tag{5}$$

where λ is the latent heat of vaporization (J kg^{-1}), Q_W is the available energy at the evaporating surface at air temperature (W m^{-2}), γ the psychrometric constant (kPa °C^{-1}), ε the surface emissivity (taken as 0.97), σ the Stefan–Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), e_p (kPa) the saturation vapor pressure at T_p, and e_a (kPa) the measured actual vapor pressure at T_a. f_t (W m^{-2} kPa^{-1}) is the vapor transfer coefficient, which is a function of the dimensionless air stability factor, ζ, i.e.

$$f_t = (p_s/p)^{0.5} f_z/\zeta \tag{6}$$

where p_s and p are atmospheric pressure at sea and lake surface levels, respectively. f_z is an empirical constant (= 250 W m^{-2} kPa^{-1}). For the inverse of ζ, Morton (1983a) derived

$$1/\zeta = 0.28(1 + e_p/e_o) + \Delta Q_w/[\gamma(p_s/p)^{0.5} b_o f_z(e_o - e_p)] \tag{7}$$

where b_o is another empirical constant (= 1.12), Δ (kPa °C^{-1}) the slope of the saturation vapor pressure curve at T_a and e_o (kPa) the saturation vapor pressure at T_a. By equating (4) and (5), T_p can be solved through iterations (see Morton (1983a), pages 64–65).

The wet-environment evaporation under the equilibrium temperature is then calculated as

$$E_{W-CRLE} = \frac{1}{\lambda}\left[b_1 + b_2 \frac{\Delta_p}{\Delta_p + \gamma} Q_{WP}\right] \tag{8}$$

where b_1 and b_2 are constants having default values of 13 W m^{-2} and 1.12, respectively (Morton, 1983a). It should be noted that b_1 accounts for energy advection and is significant only during seasons of very low net radiation. Ma et al. (2015b) argued that it should be taken as zero in the summer season to improve the performance of Morton's model in the TP, thus $b_1 = 0$ in the present study. Δ_p (kPa °C^{-1}) is the slope of the saturation vapor pressure curve at T_p and Q_{WP} (W m^{-2}) the available energy for an evaporating surface at T_p. In particular, the ultimate goal of Morton's (1983a) "equilibrium temperature" is to build a symmetrical complementary model for estimating areal evaporation via the CR theory, and the $E_{W\text{-}CRLE}$ based on this equilibrium temperature (Eq. (8)) is regarded as the wet-surface evaporation rate (Morton, 1986). The connection of the CRLE model to the CR is via employing the T_p value for the estimation of the wet-environment evaporation rate. The available energy, Q_{WP}, for evaporation over the lake surface in Eq. (8), includes the heat storage change (ΔS_H) of the lake calculated by a routing method (Morton, 1986). Within this procedure, the net shortwave radiation received by the lake surface in the first month of the simulation period is set as the initial value of ΔS_H to iteratively solve for consecutive ΔS_H values (see Morton (1986), page 376 for more details) for a year when the model is restarted two more times with the last value of ΔS_H. While the assumption that heat storage in the first month equals the net shortwave radiation is arbitrary, the error quickly dissipates as the iteration converges in a few steps, similar to an arbitrary initial storage condition of a linear storage element employed for flow routing (Morton, 1986; Szilagyi and Szollosi-Nagy, 2010).

The CRLE model was designed for a monthly time-step. The forcing inputs are monthly mean air temperature, relative humidity (calculated via the specific humidity data) and sunshine duration hours. In the original CRLE model the downward shortwave radiation is estimated via the sunshine duration hours (McMahon et al., 2013). As CFMD contains the downward shortwave radiation data, we modified the model to use it directly. However, estimation of the net longwave radiation in the CRLE still requires sunshine durations and the actual water vapor pressure, therefore the scheme of Yin et al. (2013) was applied to calculate the sunshine durations from the measured downward shortwave radiation data of CFMD. In addition, the model also requires the mean lake depth and salinity as inputs. Based on Wang et al.'s (2009) extensive survey in Nam Co Lake, the mean lake depth in 2008 was set at 55 m. Then a monthly time series of average lake depth for 1979–2012 was constructed from relative water level changes between 1976 and 2010 as documented by Lei et al. (2013). The salinity of Nam Co Lake was set as a fixed value of 1.7 g L^{-1} according to Wang et al. (2009).

Sublimation from the lake ice may be considered negligible due to very low temperatures in the winter. Lake evaporation rates were estimated for the ice-free periods which were determined with the help of the daily minimum (T_{min}) and maximum (T_{max}) air temperature values. Specifically, the 3 h temporal resolution of the CFMD's air temperature values made it possible to consider T_a at 06:00 and 15:00 to represent T_{min} and T_{max}, respectively. When T_{min} > 0 °C occurred over the first consecutive three days during the first half of the year, then the fourth day was considered as the start of the ice-free period. Similarly, when $T_{max} < 0$ °C took place over the first consecutive three days during the second half of the year, then the last day before this 3-day period was considered as the end of the ice-free period. The so-determined ice-free periods were overall consistent with the results of Zhang et al. (2014a). For months with partial ice-free periods, the "monthly" evaporation rates were downscaled by the length of the ice-free period.

3. Results and discussions

3.1. Model validation

Zhou et al. (2013) conducted an *in-situ* E601B pan evaporation study at the shore of Nam Co Lake during 2007–2011. Their observations were mainly carried out from mid-May to mid-October in each year (see the Table 4 in Zhou et al. (2013) for specific dates). The E601B pan is made of fiberglass with a depth of 68.7 cm and a diameter of 61.8 cm (Ma et al., 2015a). Unlike the CMA D20 above-ground pan, the E601B pan was buried in the soil with its orifice 30 cm above the ground surface. Therefore, the E601B pan belongs to the sunken-pan category according to the World Meteorological Organization (WMO) classifications (Xiong et al., 2012). We summed the CRLE-derived E_L estimates during the same period of Zhou et al.'s (2013) observations. As seen in Fig. 2, the CRLE-simulated E_L values display an interannual variation very similar to that of the E601B-measured E_{pan} values but at a lower evaporation rate. The reason for the lower lake evaporation rates is two-fold. (i) While the E601B pan was buried in the soil to reduce the solar radiation intercepted by its sidewall, the evaporating area is still only 3000 cm^2. Therefore, local energy advection around the pan enhanced its evaporation rate in comparison to that of the lake with a surface area several magnitudes larger (Ma et al., 2015a). (ii) The heat storage of the pan water displays greater diurnal variation, thereby affecting its evaporation rate, as was highlighted by Roderick et al. (2009).

There exists a rich literature investigating the ratio of lake evaporation to pan evaporation (called pan coefficient) since the 1950s. For instance, it is widely reported that the mean annual ratio of E_L in North America to the U.S. class-A pan evaporation rate is approximately 0.7 (Kohler et al., 1955; Lapworth, 1965). From

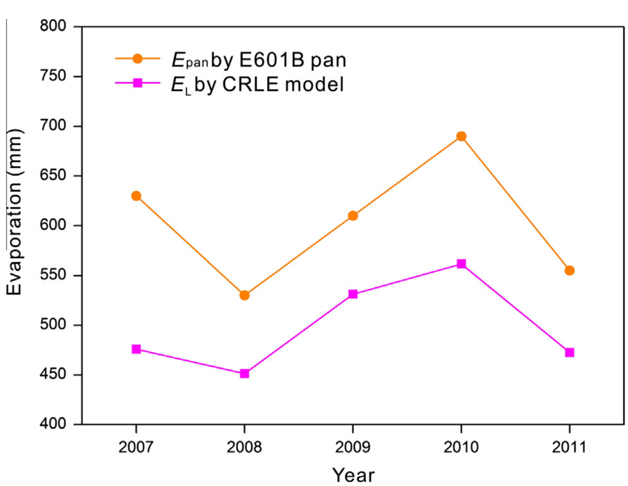

Fig. 2. Lake evaporation (E_L) simulated by CRLE and pan evaporation (E_{pan}) measured by Zhou et al. (2013) using an E601B sunken pan at the shore of Nam Co Lake. Note that E_L for each year in this figure was recalculated based on the dates (mainly from mid-May to mid-October) of Zhou et al. (2013) since their dates did not cover the whole ice-free period.

in-situ observations over Neusiedl Lake with a surface area of 320 km^2 in Austria, Neuwirth (1973) indicated a pan coefficient value within the range of 0.70–0.75 from May to October, with an average of 0.72, while using a class-A pan. Also, Morton (1986) compared CRLE-simulated annual E_L over 16 lakes in North America and Africa with class-A pan evaporation rates and found the former 0.69 times that of the latter on average. The diameter and depth of the US class-A pan are 120.7 cm and 25.4 cm, respectively. It belongs to the above-ground pan category since it is placed on a 3–5 cm high hollow wooden platform. This way class-A pans suffer a significant sidewall effect due to solar radiation (i.e. shortwave radiation is intercepted by the side of the pan) (Riley, 1966). The energy balance experiment of Lim et al. (2013) using the class-A pan also suggested that the extra radiation at the sidewall is an important factor that affects the pan coefficient. Under the same environmental conditions, evaporation rates from an above-ground pan are expected to be larger than those from a sunken pan. Therefore, the pan coefficient of a class-A pan should be slightly lower than that of an E601B pan. Using eddy covariance instrumentation, Li et al. (2015) and Liu et al. (2015) carried out E_L observations during the ice-free periods over Ngoring Lake in eastern TP (from 2011 to 2012) and Erhai Lake in southeastern TP (only in 2012), respectively. For validation, we calculated the ratio of their observed E_L to the E601B pan evaporation at the corresponding nearest CMA station (i.e. Maduo station for Ngoring Lake and Dali for Erhai Lake) in the same period. The results show that the ratios are between 0.75 (2011) and 0.77 (2012) for Ngoring Lake and 0.93 (2012) for Erhai Lake, respectively. In the present study, the ratio of Nam Co Lake evaporation to that of the E601B pan of Zhou et al. (2013) ranges from 0.76 to 0.85 in Fig. 2 with an average of 0.83. Taking possible spatial differences in climate across the TP into consideration, the E601B pan coefficients obtained for Nam Co Lake indicate that the annual E_L values of the CRLE of the present study are reasonable.

For validation at a monthly scale, we used data of Wang et al. (2015) who implemented eddy covariance instruments in the summer of 2012 over a small lake (surface area of ca. 1 km^2) located only 1 km to the southeast of Nam Co Lake (see Fig. 1 in Wang et al. (2015) for specific location of this adjacent small lake). For July and August of 2012, they obtained monthly evaporation rates of 105.7 and 123.3 mm, respectively. During the same period, the CRLE-simulated E_L rates over Nam Co Lake were 110.6 and 122.0 mm, respectively, which are very close to Wang et al. (2015)'s observed values. This comparison suggests that the CRLE model is able to simulate E_L accurately over Nam Co Lake on a monthly scale.

3.2. Model sensitivity analysis

To check CRLE's sensitivity to its input variables (i.e. downward shortwave radiation, air temperature and relative humidity), each time series was systematically disturbed by a constant ±10% while keeping the other two variables unchanged during model runs. As seen in Table 1, the CRLE is most sensitive to downward shortwave radiation, i.e. a 10% increase would lead to an about 14.6% increase in annual E_L. This is followed by air temperature where a 10%

Table 1
Relative change in the mean annual E_L value due to ±10% changes in the input variable while leaving the other two inputs unchanged.

Input variable	−10% change of input (%)	+10% change of input (%)
Downward shortwave radiation	−14.1	14.6
Air temperature	−2.4	1.7
Relative humidity	0.1	−1.1

decrease resulted in a 2.4% decrease in annual E_L. CRLE is the least sensitive to the relative humidity value since a 10% variation only resulted in ~1% change of the simulated annual lake evaporation. Similar sensitivity analysis by Vallet-Coulomba et al. (2001) for the Penman model suggested that a 10% change in solar radiation, air temperature and relative humidity would lead to 11.2%, 4.8% and 2.9% variation for the simulated evaporation rates over Lake Ziway, Ethiopia, respectively, indicating an overall sensitivity larger than that of CRLE.

3.3. Evaporation variability of Nam Co Lake

From CRLE the maximum annual evaporation rate of Nam Co Lake during 1979–2012 was 719.0 mm in 1998, while the minimum of 542.8 mm took place in the previous year (Fig. 3) (see Appendix for detailed data). The multi-year (from 1979 to 2012) average of annual evaporation is 635.2 mm. Within the year, the largest monthly evaporation rates are found in August (two months after radiation peaks) with an average of about 120.6 mm (not shown), accounting for about 19% of the annual E_L value. Eddy-covariance-measured evaporation rates over Ngoring Lake in eastern TP by Li et al. (2015) also indicate that monthly evaporation rates peak in August, supporting the CRLE results of the present study.

Annual evaporation of Nam Co Lake declined very slightly between 1979 and 2012 with an overall rate of -0.03 mm yr^{-1} (Fig. 3). It displays a slight increasing trend from the 1980s to the mid-1990s, followed by a significant decreasing trend with a rate of -12.0 mm yr^{-1} between 1998 and 2008, replaced by overall increased evaporation values from 2009 to 2012. Using the multi-year average of annual E_L as a baseline, the decadal mean anomalies in the 1980s, 1990s and 2000s were -1.0 mm, 4.2 mm and -19.8 mm, respectively.

Theoretically, evaporation from a natural water body is mainly controlled by three factors: available energy, aerodynamic conductance and vapor pressure deficit. Therefore, the average values of downward shortwave radiation, air temperature, wind speed and vapor pressure deficit of each year from 1979 to 2012 were standardized using the extremum standardization method (i.e. $V_{std,i} = (V_i - V_{min})/(V_{max} - V_{min})$, $i = 1,2,\ldots,n$, where $V_{std,i}$ and V_i are standardized and original values of the given variable, V_{max} and V_{min} are its maximum and minimum values, and n the number of observations) for a comparison with the similarly standardized annual lake evaporation rates (Fig. 4). E_L correlates best with wind speed (the correlation coefficient, R, is 0.137) among the meteorological variables (Fig. 4), suggesting to be the main driver of the observed interannual variability of lake evaporation. By the PenPan model of

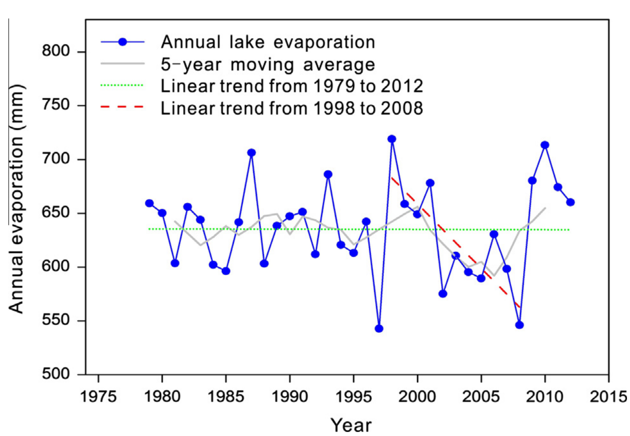

Fig. 3. CRLE-simulated annual evaporation rates of Nam Co Lake (1979–2012).

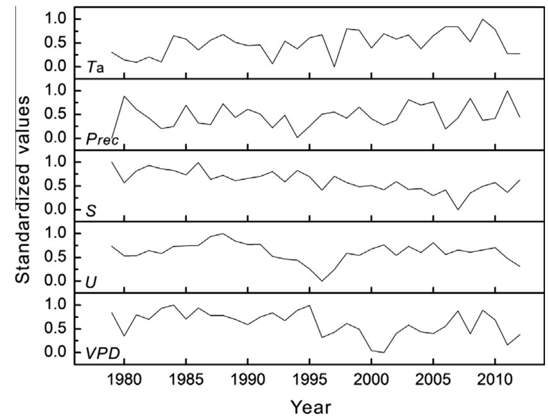

Fig. 4. Standardized values of annual air temperature (T_a), precipitation (*Prec*), downward shortwave radiation (S), wind speed (U), vapor pressure deficit (*VPD*) over Nam Co Lake (1979–2012). The precipitation data is from Bange station.

Rotstayn et al. (2006), Xie et al. (2015) demonstrated that waning winds were the main cause of the observed overall pan evaporation decline of the TP between 1970 and 2012. Other studies (e.g. Zhang et al., 2009; Yin et al., 2010; Xie and Zhu, 2013) similarly found that variation in wind speed was the primary factor that led to depressed reference evapotranspiration rates across the TP in past few decades.

While CRLE does not require wind measurements, it accounts for the effect of it through the air stability factor, ζ. The smaller the difference in T_a and T_p, and thus in the corresponding saturation vapor pressure terms, e_o and e_p, respectively, the larger becomes the vapor pressure coefficient, f_t, as evidenced from Eq. (7). This is so because the stronger the wind (therefore f_t) the larger the heat and moisture transfer capability of the air becomes, thus for the same energy and moisture fluxes it requires a smaller difference in the temperatures between the air and the free water surface, as indicated in Fig. 5.

3.4. Comparison with other lakes and D20 pan evaporation studies

The interannual variability of E_L over Nam Co matches that of E_{pan} from the D20 pan of the nearby CMA station, Bange (Fig. 6), around a mean value significantly smaller than for the pan mainly because the D20 above-ground pan was strongly influenced by evident energy advection (Ma et al., 2015a), additional radiant energy

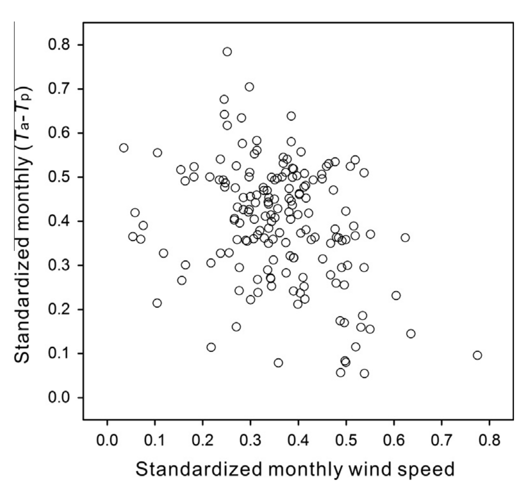

Fig. 5. Standardized monthly wind speed vs standardized monthly difference in air (T_a) and equilibrium temperatures (T_p).

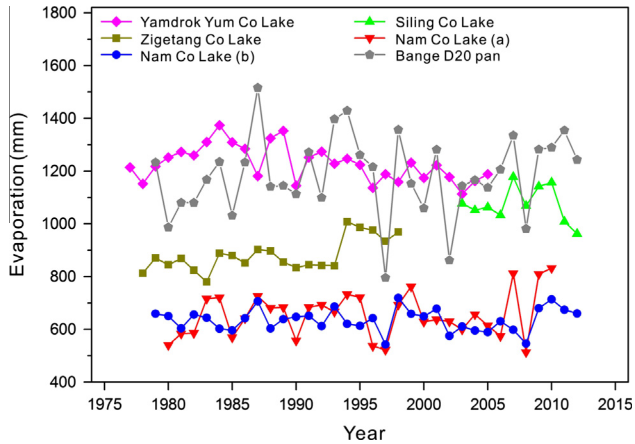

Fig. 6. Estimates of lake evaporation in the Tibetan Plateau. Yamdrok Yum Co Lake is from Yu et al. (2011) by a bulk transfer model. Siling Co Lake is from Zhou et al. (2015) by the Penman model. Zigetang Co Lake is from Li et al. (2001) also by the Penman model. Nam Co Lake is from (a) Wu et al. (2014) by the Penman–Monteith model; (b) CRLE model of the present study. The Bange D20 data are from the China D20 above-ground pan of CMA meteorological station and are the accumulation of daily values according to the dates of ice-periods of Nam Co Lake in every year.

intercepted by the pan's sidewall (Lim et al., 2013; Xiong et al., 2012), and diurnal variation of heat storage in the pan water (Roderick et al., 2009). Note that in addition to its obvious "sidewall effect", the area of D20 pan is only 314.2 cm^2, roughly 0.1 times of the area of E601B pan, the evaporation rate of the former is therefore expected to be much larger than that of the latter, as was highlighted by Xiong et al. (2012) and also shown in Figs. 2 and 6.

Despite not using wind speed as input, the CRLE-simulated E_L values overall compare well with those of the modified Penman–Monteith model (Wu et al., 2014) (Fig. 6) with $R = 0.439$. The two means are 632.3 and 655.5 mm, respectively for the common 1980–2010 period. It should be noted however that some difference in the results of the two models did occur in some years which may be caused by different model physics. Taking the E_L estimates of Wu et al. (2014) during 2007–2010 as an example, its inter-annual variability in this period was obviously inconsistent with that of the E601B pan evaporation rates (see Fig. 2) at the shore of Nam Co Lake measured by Zhou et al. (2013), indicating some challenges for the Penman–Monteith model when estimating evaporation rates of Nam Co Lake.

Regarding a spatial comparison, it can be seen that annual E_L values over different lakes display obvious differences due mainly to differences in elevation. That is, elevation of Yamdrok Yum Co, Siling Co, Zigetang Co, and Nam Co Lakes are 4441, 4535, 4575, and 4724 m asl, respectively. Mean annual evaporation from these lakes decrease with increasing elevation (Fig. 6). Temporal variability of E_L for Zigetang Co Lake (Li et al., 2001) is similar to that of Nam Co Lake, displaying an overall increasing trend during the 1980s–1990s period. These two lakes also behaved consistently with the overall increasing evaporation trend of the D20 pan from adjacent CMA station, Bange, during the same period (Fig. 6). Although the E_L values of Siling Co Lake (Zhou et al., 2015) were only available from 2003 to 2012, it also showed similar trends with the CRLE-simulated values of Nam Co Lake. With regard to Yamdrok Yum Co Lake (Yu et al., 2011), evaporation increased slightly from the late 1970s to late 1980s, but decreased gradually afterwards. Note that Yamdrok Yum Co Lake is located in the southeastern TP, while the other three lakes are situated in the inner TP. Hence the differences in E_L trends may be attributable to differences in the manifestation of local climate variability, among other possible factors.

3.5. The role of interannual E_L variability in recent rapid expansion of Nam Co Lake

To investigate what possible role the modeled E_L variation plays in the expansion of Nam Co Lake, a synthesis of available studies (Chen et al., 2009; Kropáček et al., 2012; Lin et al., 2012; Ma et al., 2012; Shao et al., 2007; Wan et al., 2014; Wu and Zhu, 2008; Y. Zhang et al., 2011; B. Zhang et al., 2011, 2013; Zhang et al., 2014b; Zhu et al., 2010) on recent lake-area change is presented in Fig. 7a. Despite differences in remote sensing data source and image processing applied by different studies, all research reported a rapid expansion of Nam Co Lake from the late 1990s to late 2000s (Fig. 7a). However, the contributing factors are still debated. Zhu et al. (2010) stated that glacier meltwater contributed the most to the water storage increase of the lake, whereas Ma et al. (2012) maintained that an increase in precipitation is the main reason for the expansion. While an exact determination of the water balance of Nam Co Lake is beyond the scope of the present study, the significant decrease in the annual E_L values of Nam Co Lake (see Fig. 3) during this period may indeed be one of the factors contributing to this rapid expansion.

Nam Co Lake is a closed lake with no outlet (Fig. 1). As the area of Nam Co Lake is about 2000 km^2, the incremental increase of about 60 km^2 (Fig. 7a) in lake area from the late 1990s to the late 2000s only accounts for ca. 3% of the total area. Therefore, for a given relatively short time interval, t (e.g. 1998–2008 as shown below), the change of water level (H) can be assumed as (Wu et al., 2014)

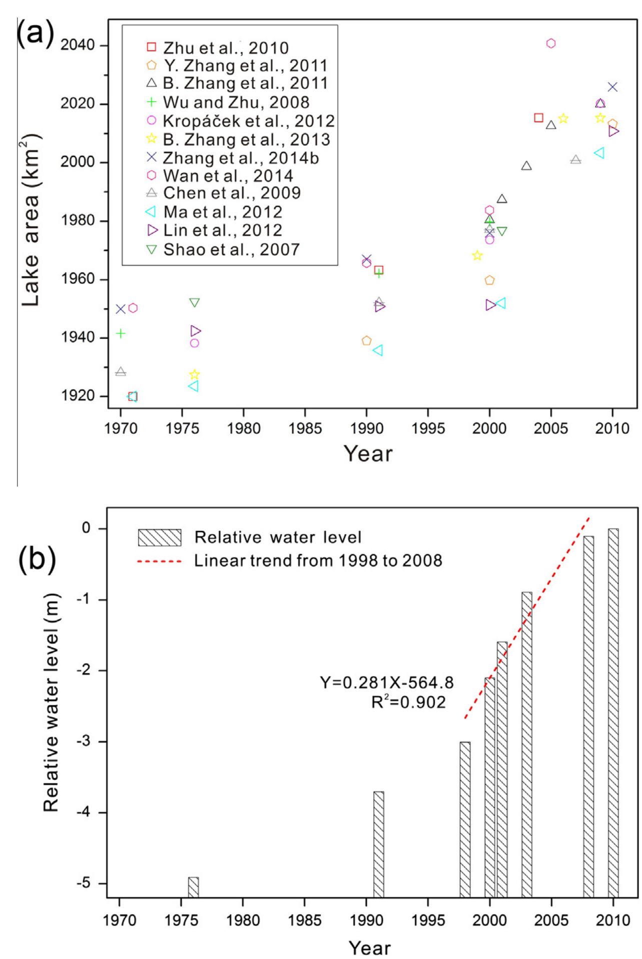

Fig. 7. Annual change in (a) lake area, and; (b) water level of Nam Co Lake. The relative water level data is from Lei et al. (2013).

$$\frac{dH}{dt} = \frac{dP}{dt} + \frac{dR_g}{dt} + \frac{dR_s}{dt} + \frac{dG}{dt} - \frac{dE_L}{dt} + \varepsilon \quad (9)$$

where P is precipitation over the lake surface, R_g glacier/snow meltwater runoff, R_s non-glacial/snow runoff, G net groundwater recharge to the lake, and ε a possible random error term.

From current bathymetric investigations and information of historical shoreline positions, Lei et al. (2013) reconstructed the relative water level variation in Nam Co Lake from 1979 to 2010 (Fig. 7b). Similar to the changes of lake area in Fig. 7a, the water level also increased rapidly and significantly with a rate of 0.281 m yr^{-1} during the period of 1998–2008. In the same period, annual E_L of Nam Co Lake decreased with a rate of -12 mm yr^{-1} (Fig. 3), indicating that about 4% of the rapid expansion of Nam Co Lake may be attributed to the decrease of E_L during the same period.

4. Conclusions

In this paper the CRLE model was run with gridded meteorological data input to simulate the free water evaporation of Nam Co Lake during ice-free periods. Results indicate that lake evaporation in a highly heterogeneous landscape can be estimated by the model without requiring wind data. This is because CRLE implicitly considers the effect of wind on evaporation through the calculation of a vapor transfer coefficient. This property of CRLE reported here is of significance in a harsh environment (i.e. Tibetan Plateau) where ground meteorological observations are sparse and large uncertainties in spatial interpolation of the wind speed data exist.

The 34-year average of free water evaporation of Nam Co Lake is 635 mm yr^{-1}. Annual evaporation rates overall decreased slightly during the 1979–2012 period, while interannual variability is mainly attributed to similar variability in wind speed. A significant decrease in annual lake evaporation was witnessed for the 1998–2008 period with a rate of -12 mm yr^{-1} which is thought to be responsible for about 4% of the recent rapid expansion of Nam Co Lake.

Acknowledgements

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2016.03.030.

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