Evaluation of five complementary relationship models for estimating actual evapotranspiration during soil freeze-thaw cycles

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ABSTRACT

The actual evapotranspiration (ETa) estimated models based on the complementary relationship (CR) theory have been applied in various climatic conditions around the world. However, in cold regions, the evaluation of the adaptability of the CR models was performed through complete freeze-thaw cycles, and the adaptability during various periods of soil freeze-thaw cycles has not been evaluated separately. Daily ETa was measured by lysimeters on alpine grassland in the Qilian Mountains from 2010 to 2017, and the measurements were used to evaluate five CR models during the thawing, thawed, freezing, and frozen periods, respectively. The five models comprised the advection-aridity (AA) model of Brutsaert and Stricker, the GG model proposed by Granger and Gray, Morton’s CR areal evapotranspiration (CRAE) model, the Han model, and Brutsaert model. The results show that all five CR models were only able to estimate daily ETa during the thawed period. None of the models could estimate the daily ETa during the thawing, freezing, or frozen periods. The basic assumptions of the CR may not be suitable for non-thawed periods with complex energy processes, and no complementary behavior was shown in the non-thawed periods. The CR models must be applied with caution during freeze-thaw cycles in cold regions.

Key words | complementary relationship, estimation, evaluation, evapotranspiration, freeze-thaw cycle

HIGHLIGHTS

- Actual daily evapotranspiration (ETa) from 2010 to 2017 was measured in alpine grassland in the Qilian Mountains.
- Complementary relationship evapotranspiration models could estimate ETa only during the thawed period.
- No complementary behavior was shown during the thawing, freezing, or frozen periods in the cold regions.
INTRODUCTION

Evapotranspiration (ET) is an important part of the global hydrothermal balance, consuming about 60% of precipitated water on land back to the atmosphere and more than 50% of the net radiation available on land (Oki & Kanae 2006; Jung et al. 2010; Hirschi et al. 2017; Panwar et al. 2019). It is the core link of surface water, carbon, and energy exchange (Wang & Dickinson 2012) and an important indicator of regional climate change and water cycle research (Wang et al. 2013; Sörensson & Ruscica 2018). However, direct observations of actual evapotranspiration (ETa) remain unavailable in many locations around the globe (Han et al. 2014; Liljedahl et al. 2017; Kim et al. 2019), and reliable estimates of ET are crucial for a better understanding of current and future water/energy/carbon budgets (Sörensson & Ruscica 2018).

Several methods have been proposed for estimation of ETa (McMahon et al. 2016), but the models based on the complementary relationship (CR) proposed by Bouchet (1965) are usually preferred because they require only standard meteorological variables and avoid extremely detailed knowledge of the complex processes and interactions between the soil, the vegetation, and the near-surface boundary layer (Xu & Singh 2005; Huntington et al. 2011). A variety of models based on the CR have been developed in recent decades, and examples of widely known models include the advection-aridity (AA) model proposed by Brutsaert & Stricker (1979), the Granger and Gray (GG) model (Granger & Gray 1989), and the CR areal evapotranspiration (CRAE) model derived by Morton (1985). All three models are linear function for CR. Han et al. (2012) developed a nonlinear approach and extended it to a sigmoid generalized complementary function (hereafter referred to as the Han model) (Han & Tian 2018). Inspired by Han et al. (2012), Brutsaert (2015) proposed a generalized nonlinear form of the CR with physical boundary conditions (hereafter referred to as the Brutsaert model).

These five CR models have been used and discussed in various climatic conditions throughout the world. However,
compared with warm regions, those five models are rarely discussed in cold regions, where the soil freeze-thaw process affects the hydrothermal processes including ET. Approximately 66 million km$^2$ (~52.5%) of the global land area undergoes a seasonal transition of freezing-thawing conditions every year (Kim et al. 2012; Rowlandson et al. 2018), and a soil freeze-thaw process refers to the physical geological phenomenon that the surface soil temperature drops below 0 °C and then rises above 0 °C (Zhao et al. 2021). The freeze-thaw process of the active layer in the permafrost region could be divided into four stages: summer thawing stage, autumn freezing stage, winter cooling stage, and spring warming stage (Zhao et al. 2000). And in the seasonal frozen region, the soil freeze-thaw process could be divided into four periods: thawing, thawed, freezing, and frozen (Ding et al. 2017). Ma et al. (2015a) evaluated several CR models in the alpine steppe of the Tibetan Plateau, but only during the warm season when the soil had thawed. Hu et al. (2018) evaluated the Brutsaert model across four vegetation types on Mount Gongga in southwestern China. The model evaluation was on a daily scale for a full year, with no respective evaluation of different periods during the soil freeze-thaw cycles. Some researchers have used CR models to calculate ET$_a$ on regional and continental scales (Zhu et al. 2016; Kim & Kaluarachchi 2017; Szilagyi et al. 2017; Liu et al. 2018; Szilagyi & Jozsa 2018; Ma et al. 2019), portions of where certainly must have undergone freeze-thaw cycles. Still, no separate evaluation of the adaptability of the CR models in different periods during soil freeze-thaw cycles has been performed.

Soil freeze-thaw processes are common on the earth’s land surface. Permafrost covers approximately one-quarter of the Northern Hemisphere’s land area (Obu et al. 2019), and seasonal frozen ground appears throughout the world. Cold regions in which soil freezing-thawing processes are significant and severe are usually located at high elevations and high latitudes. High elevation areas such as the Tibetan Plateau and other mountainous regions are generally important sources of freshwater (Dettinger 2014), and high latitude areas such as the arctic show remarkable change in the water cycle under climate changing (Bring et al. 2016). ET and the water cycle are poorly understood in these cold regions because their extremely harsh natural environmental conditions lead to a scarcity of measurement data (Liljedahl et al. 2017; Yang et al. 2019). Although less ET may occur in the cold season with frozen soil than in the warm season when soil is thawed, it is an integral and indispensible part of the overall ET and water cycle, and it is necessary to evaluate the estimated ET$_a$ throughout the freeze-thaw processes.

Consequently, using in situ long sequence daily artificial lysimeters data and automatic meteorological observations in Qilian Mountains, the aims of this study are (1) to quantify ET$_a$ in a cold high elevation mountainous area and (2) to evaluate the ability of five CR models to estimate daily ET$_a$ during soil freeze-thaw cycles in cold regions.

**MATERIALS AND METHODS**

**Study area**

The experiment was conducted at the Qilian Alpine Ecology and Hydrology Research Station, located in the headwaters region of Heihe River in the Qilian Mountains (Figure 1). A standard meteorological observation field (99°52.9'E, 38°16.1'N, 2,980 m) was constructed at the station on 20 June 2009, and an automatic meteorological tower was installed to record half-hourly measurements of meteorological variables including air temperature, relative humidity, wind speed and direction, radiations, soil heat flux, and multiple layers of soil temperature and water content. According to the meteorological data from the observation field and automatic meteorological tower, from 2010 to 2017, the mean air temperature and relative humidity were approximately 0.9 °C and 54.0%, respectively. The mean annual precipitation was 487.1 mm; more than 90% of which occurred during the plant growing season (May to September). Rainfall was the main form of precipitation, and snowfall accounted for about 9.6% of the total precipitation. According to field observation, even if there was snowfall, snow was difficult to accumulate, and most of them melt in 1 day. The existence of snow cover was rare, so the effect of snow was not considered in this study. The research site was classified as seasonal frozen soil, and the maximum frozen soil depth was about 240 cm. The dominant species in the area were Kobresia capillifolia (Decne.) C.B. Clarke and Carex moorcroftii (Falc. ex Boott). The canopy cover
exceeded 98%, and the vegetation root depth was nearly 35 cm. Following the method recommended by Allen et al. (1998), the half-hour meteorological data were processed into daily mean values for this study.

Methods

Background of the CR

The complementary principle involves the relationship between ETa, potential ET (ETpo), and ‘apparent’ potential ET (ETpa) (Brutsaert 2015). The CR theory proposed first as a symmetric linear function by Bouchet (1965), and Brutsaert & Parlange (1998) broadened it to an asymmetric linear function:

$$\frac{ET_{pa}}{C_0} \frac{ET_{po}}{C_0} = b \left( \frac{ET_{po}}{C_0} \frac{ET_{a}}{C_0} \right)$$

where ETpa is the ‘apparent’ potential evaporation, which describes the ET that occurs from a small saturated surface; ETpo is the potential ET or the wet environment ET, which describes the ET that takes place from the extensive well-watered surface; and ETa is the actual evapotranspiration. Definitions of and differences between the three ET were given by Brutsaert (2015). $b$ is the proportionality.

By normalizing Equation (1) with ETpa, Equation (1) can be expressed as follows:

$$y = (1 + 1/b)x - 1/b$$

$$y = ET_a/ET_{pa}$$

Han et al. (2012); Han & (Tian 2018) argued that a non-linear formulation of the CR would be more appropriate, and Brutsaert (2015) suggested that $y$ should be a more general function of $x$, as follows:

$$y = f(x)$$

where $f$ is a function of the quantity inside the brackets. The differences in the CR models are (1) how to define function $f$ and (2) how to calculate ETpa and ETpo.

AA model. Based on the consideration of ‘advection-aridity’, Brutsaert & Stricker (1979) derived the AA model, which can be expressed as follows:

$$ET_{AA} = 2ET_{po} - ET_{pa}$$

where $ET_{AA}$ is ETa estimated by the AA model and ETpa is calculated by combining information from the energy budget and water vapor transfer in the equation proposed by Penman (1948):

$$ET_{pa} = \Delta \frac{R_n - G}{\lambda} + \frac{\gamma}{\Delta + \gamma} f(U)(e_s - e_a)$$

where $\Delta$ is the slope of the saturation vapor pressure curve at the air temperature (kPa/°C), $\gamma$ is the psychometric constant
(kPa/°C), \(R_n\) is the net radiation (MJ/m²/day), \(G\) is the soil heat flux (MJ/m²/day), \(\lambda\) is the latent heat of vaporization (MJ/kg), and \(e_s\) and \(e_a\) are the saturation and actual vapor pressure at air temperature (kPa), respectively. \(f\) (U) is the wind function, which includes the 2-m wind speed \((U_2, \text{m/s})\), and should be derived via the Monin-Obukhov similarity theory as follows:

\[
f(U) = \frac{0.622 \kappa^2 \rho U_2}{P_a \ln \left( \frac{z - d_0}{z_{ov}} \right) \ln \left( \frac{z - d_0}{z_{om}} \right)}
\]

where \(t = 86,400\) s/day, \(\kappa\) is the von Karman constant \((0.4)\), \(\rho\) is the density of air \((\text{kg/m}^3)\), \(P_a\) is the air pressure (kPa), \(z\) is the measurement height of wind speed and humidity (2 m), \(d\) is the displacement height (m), and \(z_{om}\) and \(z_{ov}\) are the roughness lengths of momentum and water vapor (m), respectively. \(z_{om}\) and \(d_0\) are correlated with the effective roughness height, \(h\) (Guo & Shen 2015). In this study, \(z_{om} = 0.123 h\), \(d_0 = 0.67 h\), and \(z_{ov} = 0.1 z_{om}\) (Allen et al. 1998; Han et al. 2012; Ma et al. 2015; Zhang et al. 2017).

\(\text{ET}_{\text{AA}}\) is calculated by the Priestley–Taylor equation (Priestley & Taylor 1972):

\[
\text{ET}_{\text{AA}} = \alpha \frac{\Delta}{\Delta + \gamma} \frac{(R_n - G)}{\lambda}
\]

where \(\alpha\) is the parameter and other symbols are as defined previously.

**GG model.** For the GG method, Granger & Gray (1989) introduced the concepts of relative ET \((G^*)\) and showed that an equation similar to that of Penman could also be derived following the CR approach:

\[
\text{ET}_{a}^{\text{GG}} = \frac{\Delta G^*}{\Delta G^* + \gamma} \frac{(R_n - G)}{\lambda} + \frac{\gamma G^* - E_a}{\Delta G^* + \gamma} E_a
\]

where \(\text{ET}_{a}^{\text{GG}}\) is \(\text{ET}_{a}\) estimated by the GG model, \(E_a\) is the drying power of the air, which in general can be written as follows:

\[
E_a = f(U)(e_s - e_a)
\]

Based on daily estimated values of \(\text{ET}_{a}\) from the water balance, Granger & Gray (1989) showed that a unique relationship exists between \(G^*\) and a parameter that they called the relative drying power \(D\), given as follows:

\[
D = \frac{E_a}{E_a + (R_n - G)/\lambda}
\]

\[
G^* = \frac{1}{1 + 0.028e^{0.045D}}
\]

Later, Granger (1998) modified Equation (13) to

\[
G^* = \frac{1}{0.793 + 0.20e^{-0.902D} + 0.006D}
\]

**CRAE model.** For the CRAE method, \(\text{ET}_{a}\) can be estimated using Equation (15):

\[
\text{ET}_{a}^{\text{CRAE}} = 2 \text{ET}_{pa}^{\text{CRAE}} - \text{ET}_{pa}^{\text{CRAE}}
\]

where \(\text{ET}_{a}^{\text{CRAE}}\) is \(\text{ET}_{a}\) estimated by the CRAE model; however, the calculation of \(\text{ET}_{pa}\) and \(\text{ET}_{po}\) is different. To calculate \(\text{ET}_{pa}\), Morton (1985) decomposed the Penman equation into two separate parts to describe the energy balance and the vapor transfer process. The most prominent advantage of CRAE is that it does not require wind speed as an input (Ma et al. 2015b)). The ‘equilibrium temperature’, \(T_p\), which is defined as the temperature at which the energy balance equation and the vapor transfer equation for a moist surface give the same result, was introduced to calculate the potential ET.

\[
\text{ET}_{pa}^{\text{CRAE}} = \frac{1}{\kappa} [f_v(e_p - e_d)]
\]

where \(f_v\) is a vapor transfer coefficient \((\text{W/m}^2/\text{mbar})\), \(\epsilon\) is the surface emissivity, \(p\) is the atmospheric pressure \((\text{mbar})\), \(\sigma\) is the Stefan–Boltzmann constant \((\text{W/m}^2/\text{K}^4)\), \(T_p\) and \(T_a\) are the equilibrium and air temperatures \((\text{°C})\), \(e_p\) is the saturation vapor pressure \((\text{mbar})\) at \(T_p\), \(e_d\) is the saturation
vapor pressure (mbar) at dew point temperature, \( \lambda \) is the latent heat of vaporization (W day/kg), \( \gamma \) is the psychometric constant (mbar/°C), and \( R_n \) and \( G \) are as defined previously but in units of W/m². \( T_p \) can be obtained via iterations from Equations (16) and (17). Note that the units used in the CRAE model are adopted here to ensure that the correct values of the empirical constants are included.

\[
f_v = (f_z/\xi)(p_s/p)^{0.5}
\]

where \( p_s \) is the sea-level atmospheric pressure (mbar), \( f_z \) is a constant, and \( \xi \) is a dimensionless stability factor estimated from:

\[
\frac{1}{\xi} = 0.281 + 0.0120 + \frac{\Delta(R_n - G)}{[\gamma p(p_s/p)^{0.5}b_0f_z(e_a - e_d)]}
\]

where \( e_a \) is the saturation vapor pressure (mbar) at air temperature, \( \Delta \) is the slope of the saturation vapor pressure curve (mbar/°C) at air temperature, and \( b_0 = 1.0 \) for the CRAE model.

To estimate \( ET_{po} \), Morton (1983) also modified Equation (9) by Priestley & Taylor (1972) to account for the equilibrium temperature dependence of both the available energy and the slope of the saturation vapor pressure curve:

\[
ET_{po}^{CRAE} = \frac{1}{\lambda} \left[ b_1 + b_2 \frac{\Delta p}{\Delta_p + \gamma} (R_n - G) \right]
\]

where \( (R_n - G) \) is the net available energy for the surface at \( T_p \) (°C), \( \Delta p \) is the slope of the saturation vapor pressure curve (mbar/°C) at \( T_p \), \( b_1 \) (=14 W/m²) and \( b_2 \) (=1.20) are empirical coefficients, and the other variables are as defined previously. Note that the original time step of the CRAE model was advocated as being at least 5 days because of subsurface heat storage changes (Morton 1983). However, the model was permitted on daily time-step analysis so long as the daily values are accumulated to a week or longer (McMahon et al. 2013), and recent researches indicated that \( ET_a \) can be estimated on a daily scale by the CRAE model (McMahon et al. 2013; Ma et al. 2015b). Considering that the present in situ observation site includes soil heat flux measurement and comparison with other models, the CRAE model was applied on a daily timescale in this study.

**Han model.** Based on the CR, Han et al. (2012) proposed a nonlinear function approach for the normalized CR ET model, and Han & Tian (2018) extended the previous development to a sigmoid generalized complementary function to estimate \( ET_a \), and the Han model can be expressed as follows (Han & Tian 2018):

\[
\gamma_{Han} = \frac{1}{1 + m \left( \frac{x_{max} - x_{Han}}{x_{Han} - x_{min}} \right)^n}
\]

\[
x_{Han} = \frac{ET_{rad}}{ET_{po}^{Han}}
\]

where \( ET_{rad} \) is the proportion of the radiation term in \( ET_{po}^{Han} \):

\[
ET_{rad} = \frac{\Delta}{\Delta + \gamma} \left( R_n - G \right)
\]

Considering comparison with other models, Equation (22) was derived a modified form:

\[
\gamma_{Han} = \frac{1}{1 + m \left( \frac{x_{max} - x_{Han}'}{x_{Han'} - x_{min}} \right)^n}
\]

\[
x_{Han'} = \frac{ET_{po}^{Han}}{a}
\]

\[
ET_{po}^{Han} = a \left( R_n - G \right)
\]

In Equations (22) and (27), \( m \) and \( n \) are empirical coefficients:

\[
m = \frac{4\alpha(1 + b^{-1})(x_{0.5} - x_{min})(x_{max} - x_{0.5})}{(x_{max} - x_{min})}
\]
Actual evapotranspiration measurement

The lysimeter is the standard instrument used to measure ET\textsubscript{a} without assumptions and is considered to provide the most accurate determination of ET\textsubscript{a} (Holmes 1984; Vaughan et al. 2007; Seneviratne et al. 2010; Wang & Dickinson 2012). To reduce the measurement error from soil heterogeneity and vegetable difference in the lysimeters, two lysimeters of same size were designed to repeat the ET\textsubscript{a} measurement, and the mean values from the two lysimeters were taken as the ET\textsubscript{a} at the research site. The two lysimeters chosen for this work with the size of 40 cm in depth and 31.5 cm in diameter were installed in a flat pasture in the standard meteorological observation field on 25 June 2009. Each was weighed daily at 20:00 (China Standard Time), with a balance of 2 g in precision, which corresponds to 0.026 mm. More information regarding lysimeters can be seen in Yang et al. (2017). ET\textsubscript{a} was calculated using the following equation:

\[ \text{ET}_a = 10\Delta W/\rho S + P - 10I/\rho S \]  

where \( \Delta W \) is the weight difference measured by the lysimeter (g/day), \( \rho \) is the water density (1 g/cm\textsuperscript{3}), \( S \) is the surface area of the soil within it (cm\textsuperscript{2}), \( P \) is the precipitation (mm/day), and \( I \) is the infiltration (g/day), measured by weighing daily, as with the lysimeters.

Period division

The complete soil freeze-thaw cycle can be divided into four periods: thawing, thawed, freezing, and frozen. The soil temperatures at depths of 0 and 40 cm were chosen to divide the periods. The soil temperature at 0 cm was used to indicate whether the surface soil was frozen or thawed. The soil temperature at 40 cm was selected because ET basically occurs near the surface and because of the vegetation root depth and the size of the lysimeters. The criteria for division were as follows:

\[
\begin{align*}
T_0 &> 0 \text{ and } T_{40} > 0 & \text{Thawed} \\
T_0 &\leq 0 \text{ and } T_{40} > 0 & \text{Freezing} \\
T_0 &\leq 0 \text{ and } T_{40} \leq 0 & \text{Frozen} \\
T_0 &> 0 \text{ and } T_{40} \leq 0 & \text{Thawing}
\end{align*}
\]
where $T_0$ and $T_{40}$ represent the soil temperature at depths of 0 and 40 cm ($^\circ$C), respectively. Figure 2 shows an example of the four-period division in 2017.

**Estimation of parameters**

The five models can be divided into two groups: (1) uncalibrated models (GG and CRAE models), all of the parameters were used according to the values measured or recommended by the existing models; (2) calibrated models (AA, Han, and Bursaert models), key parameters need to be calibrated. The Priestley–Taylor parameter $\alpha$ is an important parameter for the AA, the Han, and the Bursaert models; and it is not quite the Priestley–Taylor parameter but is merely a weak analog of it (Crago & Qualls 2018; Hu et al. 2018). It is usually has a default value of 1.26 (Priestley & Taylor 1972; Ma et al. 2015a; Zhang et al. 2017), and the values of $\alpha$ range between 0.87 and 1.44 in various climatic conditions in China (Liu et al. 2016). Since the original AA model version was selected in this study, the $\alpha$ was an only parameter need to be calibrated. In addition to Priestley–Taylor parameter $\alpha$, $b$ of the Han model in Equations (30) and (32) and $c$ of the Bursaert model in Equation (34) need to be calibrated, respectively. Considering the seasonal variability of $\alpha$ in the CR (Yang et al. 2013; Liu et al. 2016), the monthly variation in the mean parameters were calibrated, with parameters optimized by minimizing the mean absolute error (MAE) of the estimated actual evaporation (Legates & McCabe 1999; Han & Tian 2018).

The measured $E_{Ta}$ and the corresponding meteorological data from 2010 to 2011 were selected to calibrate the model parameters, and the data from 2013 to 2017 were selected to evaluate the five CR models (the data for 2012 were excluded because of gaps). The model parameters were calibrated daily and then processed into monthly mean values. During the calibration, the parameter $b$ of Han and $c$ of Brutsaert were unconstrained, and the parameters of $\alpha$ of AA, Han, and Bursaert models were bounded between 0.87 and 1.44. The calibrated monthly parameters values are shown in Table 1.

**Evaluation criteria**

Statistical indices were used for the quantitative analysis of the $E_{Ta}$ modeling performance. The $E_{Ta}$ values measured by the lysimeters and estimated by five CR models were compared using a series of statistics. The errors were calculated as follows:

$$R^2 = \frac{\text{cov}(E, M)}{\sigma_E \sigma_M}$$

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^{n} |E_i - M_i|$$

![Figure 2](image-url) | Period division of soil freeze-thaw cycle at research site in 2017 (P1, frozen; P2, thawing; P3, thawed; P4, freezing).
Table 1 | Monthly values of calibrated parameters for research site

| Month | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | Mean |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| AA    | α   | 1.28| 1.16| 1.08| 0.96| 1.03| 1.19| 1.17| 1.14| 1.12| 1.06| 1.30| 1.23 | 1.14 |
| Han   | b   | 0.2 | 0.28| 0.31| 0.59| 0.87| 1.12| 1.86| 1.49| 1.05| 0.07| 0.72| 0.77 |
|       |     |     |     |     |     |     |     |     |     |     |     |     |      |
|       | α   | 0.95| 0.96| 0.94| 0.94| 1.00| 1.15| 1.12| 1.07| 1.09| 0.98| 0.99| 0.96 | 1.01 |
|       | b   | 0.2 | 0.28| 0.31| 0.59| 0.87| 1.12| 1.86| 1.49| 1.05| 0.07| 0.72| 0.77 |
| Brutsaert | α | 0.87| 0.87| 0.87| 0.87| 1.01| 1.11| 1.18| 1.06| 1.06| 0.9 | 0.99| 0.87 | 0.97 |
|       | c   | 2.95| 3.51| 3.93| 5.32| 4.62| 2.03| 7.91| 4.77| 5.02| 4.78| 2.31| 3.52 | 4.22 |

Figure 3 | Precipitation and evapotranspiration in various freeze-thaw periods from 2013 to 2017 at research site.

Figure 4 | Measured daily evapotranspiration measured by lysimeters and estimated by the five CR models from 2013 to 2017 in the research site. Please refer to the online version of this paper to see this figure in colour: [http://dx.doi.org/10.2166/nh.2021.093](http://dx.doi.org/10.2166/nh.2021.093).
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (E_i - M_i)^2}

(43)

\[ \text{NSE} = 1 - \frac{\sum_{i=1}^{n} (E_i - M_i)^2}{\sum_{i=1}^{n} (M_i - \bar{M})^2} \]

(44)

where $R^2$, MAE, RMSE, and NSE are the coefficient of determination, the mean absolute error (mm/day), the root-mean-square error (mm/day), and the Nash–Sutcliffe efficiency, respectively. $n$ is the number of statistical days, and $\text{cov}$ and $\sigma$ are the covariance and standard deviation, respectively, $E$ is the estimated $ET_a$ values by CR models (mm/day), and $M$ represents the $ET_a$ values measured by the lysimeters (mm/day).

Note that, to avoid the possible influence of precipitation events and snow sublimation on evaluation, $ET_a$ measurements from days with precipitation were not considered in the evaluation of the five CR models.

**Figure 5** | Comparison of the daily actual evapotranspiration ($ET_a$) measured by lysimeters and estimated by the five CR models for (a) thawed, (b) freezing, (c) frozen, and (d) thawing periods from 2013 to 2017 at research site. The black line indicates the $y=x$ line.
RESULTS

Actual evapotranspiration during soil freeze-thaw cycles

The mean values of ETa, measured by two lysimeters, were taken as the ETa at the research site, and Figure 3 shows the variations in ETa and precipitation in various periods of the soil freeze-thaw cycles from 2010 to 2017. The mean annual ETa was 441.5 mm. ETa accounted for 91.7% of precipitation in the corresponding period and represented the largest loss of water cycle on the research site. In the years with low precipitation, such as 2010 and 2012, ETa even exceeded precipitation because soil freezing could store precipitation in abundant years for ET in the next year (Sugimoto et al. 2003; Ohta et al. 2008). The vast majority of ETa and precipitation both occurred during the thawed period. The mean of the ratio of ETa during the thawed period and for the whole year was 91.4%, and that value for precipitation was 93.5%. The mean daily ETa values for the thawed, freezing, frozen, and thawing periods were 2.19, 0.28, 0.16, and 0.41 mm/day, respectively.

Model performance during soil freeze-thaw cycles

Figures 4 and 5 show the performance of the estimation of daily ETa using five CR models for the various freeze-thaw periods, and Table 2 shows the values of the evaluation criteria. The performance of the five models was significantly better during the thawed period than during the other three periods, with significant more $R^2$ and NSE. In summary, during the thawed period, the calibrated models, with mean MAE, RMSE, and NSE of 0.67 mm/day, 0.83 mm/day, and 0.76, respectively, showed the better performances than uncalibrated models, with mean MAE, RMSE, and NSE of 0.79 mm/day, 1.02 mm/day, and 0.65, respectively. There were slight differences in the model performance of the calibration models. The Han and Brutsaert models with two calibrated parameters showed the better performance than the AA model with one calibrated parameter, and the Han model showed slight better performance than the Brutsaert model. The performance order of the five models during the thawed period was Han model, Brutsaert model, AA model, GG model, and CRAE model. In the freezing,

| Periods | n | Models | $a$ | $b$ | $R^2$ | MAE | RMSE | NSE | Mean ETa | Mean ETe |
|---------|---|--------|----|----|------|-----|------|-----|-------|-------|
| Thawed  | 482 | GG     | 0.58 | 1.24 | 0.75 | 0.79 | 0.96 | 0.69 | 2.40  | 2.64  |
|         |     | CRAE   | 0.58 | 0.45 | 0.84 | 0.79 | 1.02 | 0.65 | 2.40  | 1.84  |
|         |     | AA     | 0.73 | 0.21 | 0.79 | 0.73 | 0.91 | 0.72 | 2.40  | 1.96  |
|         |     | Han    | 0.87 | -0.14| 0.86 | 0.64 | 0.78 | 0.79 | 2.40  | 1.96  |
|         |     | Brutsaert | 0.87 | -0.03| 0.82 | 0.64 | 0.81 | 0.78 | 2.40  | 2.05  |
| Freezing| 147 | GG     | 0.78 | 0.42 | 0.13 | 0.38 | 0.46 | -9.15| 0.28  | 0.64  |
|         |     | CRAE   | -0.03| 0.53 | 0.00 | 0.29 | 0.34 | -4.58| 0.28  | 0.52  |
|         |     | AA     | 0.41 | -0.12| 0.02 | 0.38 | 0.51 | -11.60| 0.28  | -0.01 |
|         |     | Han    | 0.18 | 0.05 | 0.08 | 0.19 | 0.24 | -1.66| 0.28  | 0.10  |
|         |     | Brutsaert | 0.12 | 0.17 | 0.01 | 0.17 | 0.23 | -1.58| 0.28  | 0.20  |
| Frozen  | 553 | GG     | 1.74 | 0.51 | 0.26 | 0.62 | 0.76 | -26.92| 0.15  | 0.77  |
|         |     | CRAE   | 0.47 | 0.39 | 0.09 | 0.33 | 0.39 | -6.22| 0.15  | 0.46  |
|         |     | AA     | 1.41 | -0.16| 0.24 | 0.29 | 0.38 | -5.88| 0.15  | 0.04  |
|         |     | Han    | 0.54 | 0.06 | 0.22 | 0.12 | 0.16 | -0.29| 0.15  | 0.14  |
|         |     | Brutsaert | 0.50 | 0.02 | 0.23 | 0.12 | 0.16 | -0.24| 0.15  | 0.10  |
| Thawing | 84  | GG     | 1.75 | 1.16 | 0.57 | 1.49 | 1.59 | -23.97| 0.43  | 1.93  |
|         |     | CRAE   | 0.93 | 0.23 | 0.37 | 0.34 | 0.44 | -0.90| 0.43  | 0.63  |
|         |     | AA     | 2.19 | -0.09| 0.53 | 0.72 | 0.87 | -6.55| 0.43  | 0.86  |
|         |     | Han    | 0.86 | 0.27 | 0.55 | 0.25 | 0.33 | -0.05| 0.43  | 0.64  |
|         |     | Brutsaert | 1.29 | -0.10| 0.55 | 0.27 | 0.38 | -0.44| 0.43  | 0.46  |

Note: n, number of statistical days; $a$, $b$, and $R^2$, slope, intercept, and coefficient of determination values, respectively, for the linear regressions; MAE, mean absolute error (mm/day); RMSE, root-mean-square error (mm/day); NSE, Nash–Sutcliffe efficiency; Mean ETa, mean measured daily evapotranspiration (mm/day); and Mean ETe, mean estimated daily evapotranspiration (mm/day).
frozen, and thawing periods, none of the five models were able to estimate the daily ETa at the research site.

**CR during soil freeze-thaw cycles**

Based on the fact that the calibration models showed better performances than the uncalibrated models, the CRs of different periods of the freeze-thaw cycle were analyzed by the calibration models. Figure 6 shows the dimensionless form of the CR for the four freeze-thaw periods. The observed daily ETa showed significant complementary behavior only during the thawed period; no linear or nonlinear CR was seen in the other three periods.

Figure 7 shows the scaled daily rates of actual evapotranspiration (ETa/ETpo) and scaled apparent potential evapotranspiration (ETpa/ETpo) against the moisture index (ETa/ETpa) for the four freeze-thaw periods. Still, complementary behavior was only shown during the thawed period, not in the other three periods.

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**Figure 6** | Values of ETa/ETpa plotted against ETpo/ETpa for (a) thawed, (b) freezing, (c) frozen, and (d) thawing periods from 2013 to 2017 at research site. The black, red, and blue curves are complementary relationships in dimensionless form AA (Equation (6)), Han (Equation (27), a = 1.01, b = 0.77), and Brutsaert (Equation (34), c = 4.22) models, respectively. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2021.093.
DISCUSSION

Model performance relative to variation in parameter $\alpha$

As the Priestley–Taylor parameter $\alpha$, an important parameter for the AA model, Han model, and Brutsaert model, was calibrated using local meteorological data, it is necessary to analyze the sensitivity of this parameter. The calibrated monthly $\alpha$ in this study ranged from 1.02 to 1.08, which is similar to the values reported in other studies in which this formulation was used in high elevation regions (Ma et al. 2015a; Hu et al. 2018) and ranged from 0.87 and 1.44 in various climatic conditions in China (Liu et al. 2016). To analyze the influence of $\alpha$ on the model’s performances, a series of values from 0.87 to 1.44, at intervals of 0.01, were introduced to Equations (9), (29), and (38), and $ET_a$ was then estimated using the AA, Han, and Brutsaert models. Figure 8 shows
the variation in NSE produced by the AA, Han, and Brutsaert models relative to changes in \( \alpha \) for various freeze-thaw periods. During the thawed period, the NSE from all three models could approach 1 with a reasonable \( \alpha \). During the other three periods, with \( \alpha \) values from 0.87 to 1.44, the NSE from all three models were less than 0. This sensitivity analysis of \( \alpha \) indicated that the CR models could not estimate ET\(_a\) during the freezing, frozen, and thawing periods for any value of \( \alpha \).

**Effects of soil freeze-thaw cycles on CR**

The goal of this study was to evaluate the use of CR models to estimate daily ET\(_a\) in cold regions, and the results show that the CR models were applicable only during the thawed period; in other words, the CR was only shown during the thawed period. The CR theory was first proposed by Bouchet (1965), and later broadened by Brutsaert & Parlange (1998). The core assumption is that when water is limited, the energy difference between ET\(_{pa}\) and ET\(_{po}\) has a linear or
nonlinear relationship with the energy difference between ET_{pa} and ET_{a}. However, this assumption was proposed on intuitive grounds, and its validity has never been rigorously justified (Brutsaert 2013). When the soil is thawed, the ET_{a} process in cold regions may be similar to that in warm regions, and the assumption is suitable for this condition. During the freezing and thawing periods, the prominent characteristic of the cold region is the intraday freeze-thaw cycles (Guo et al. 2014); thus the energy was used not only to evaporate the water into vapor but also in the phase change of ice-water. When the soil was frozen, unfrozen liquid water content in soil was very low, and the sublimation of solid water, whose physical and energy consumption processes differ from those of evaporation, was the main composition of ET (Knowles et al. 2012). In general, the energy consumption pattern during the non-thawed periods differs from that during the thawed period because in addition to soil evaporation, energy is used for the phase change of ice-water and sublimation. The altered plant transpiration affected by freeze-thaw cycles can also change the energy balance in cold regions (Cable et al. 2014). These complex energy processes may be inconsistent with the basic assumptions of the CR, which may explain why none of the five CR models could estimate the daily ET_{a} during the freezing, frozen, and thawing periods.

Statistics traps in model performance

Although the applicability of the CR models during various periods of the freeze-thaw cycles in cold regions has not been evaluated separately, some studies have compared the estimated and measured daily ET_{a} values for the complete freeze-thaw cycles, and the results showed good model performance (Zhu et al. 2016; Hu et al. 2018; Liu et al. 2018). However, a statistics trap may apply to these results because they evaluated the models across the complete freeze-thaw cycle. The results of this study show that the CR models were not able to estimate the daily ET_{a} during the non-thawed periods (Figure 5; Table 2). When the statistics were extended to all of the data, all five models could estimate the daily ET_{a} at the research site very well. The model performance for the complete freeze-thaw cycle was even better than that for the thawed period, with a larger $R^2$, lower MAE and RMSE values, and a larger NSE values (Figure 9; Table 3). The reason for this statistical trap is that the ET that occurred during

![Figure 9](image)

**Figure 9** Comparison of the daily evapotranspiration (ET_{a}) measured by lysimeters and estimated by five CR models for complete freeze-thaw cycle from 2013 to 2017 at research site. The black line indicates the $y = x$ line.

| Models | $a$ | $b$ | $R^2$ | MAE | RMSE | NSE | Mean ET_{a} | Mean ET_{e} |
|--------|-----|-----|-------|-----|------|------|-------------|-------------|
| GG     | 0.70| 0.81| 0.77  | 0.72| 0.89 | 0.66 | 1.04        | 1.54        |
| CRAE   | 0.60| 0.38| 0.88  | 0.50| 0.70 | 0.79 | 1.04        | 1.00        |
| AA     | 0.79| 0.00| 0.82  | 0.50| 0.68 | 0.80 | 1.04        | 0.82        |
| Han    | 0.84| −0.01| 0.91 | 0.33| 0.51 | 0.89 | 1.04        | 0.86        |
| Brutsaert | 0.86| −0.02| 0.89 | 0.33| 0.53 | 0.88 | 1.04        | 0.88        |

Note: $n$, number of statistical days; $a$, $b$, and $R^2$, slope, intercept, and coefficient of determination values, respectively, for the linear regressions; MAE, mean absolute error (mm/day); RMSE, root-mean-square error (mm/day); NSE, Nash-Sutcliffe efficiency; Mean ET_{a}, mean measured daily evapotranspiration (mm/day); and Mean ET_{e}, mean estimated daily evapotranspiration (mm/day).
the thawed period accounted for the vast majority of the total ET for the entire freeze-thaw cycle (Figure 3). If the model performance was tested on a monthly scale, all five models could estimate ETa for the thawed months (May, June, July, August, and September), but not the non-thawed months (January, February, March, April, October, November, and December) (Figure 10; Table 4). Like the daily scale, a statistical trap was found when the statistics were extended to all months, and the model performance for the complete freeze-thaw cycle was better than that for the thawed period. The evaluation of the model performance for the complete freeze-thaw cycle does not indicate

Table 4 | Performance of the GG, CRAE, AA, Han, and Brutsaert models in estimating monthly evapotranspiration during soil freeze-thaw cycles from 2013 to 2017 at research site

| Periods          | n   | Models | a   | b   | $R^2$ | MAE  | RMSE | NSE  | Mean ETa | Mean ETe |
|------------------|-----|--------|-----|-----|-------|------|------|------|----------|----------|
| Thawed months    | 25  | GG     | 0.46| 23.79| 0.37  | 9.47 | 12.74| 0.34 | 42.11    | 42.98    |
|                  |     | CRAE   | 0.51| 10.21| 0.83  | 11.75| 13.59| 0.25 | 42.11    | 31.54    |
|                  |     | AA     | 0.62| 8.79 | 0.73  | 9.66 | 11.10| 0.50 | 42.11    | 34.88    |
|                  |     | Han    | 0.78| 4.02 | 0.89  | 6.17 | 7.60 | 0.77 | 42.11    | 36.93    |
|                  |     | Brutsaert | 0.74| 6.45 | 0.75  | 6.80 | 8.90 | 0.68 | 42.11    | 37.80    |
| Non-thawed months| 35  | GG     | 1.15| 16.34| 0.34  | 17.47| 20.09| −9.86| 7.57     | 25.04    |
|                  |     | CRAE   | 0.43| 10.57| 0.54  | 6.83 | 7.53 | −0.52| 7.57     | 13.79    |
|                  |     | AA     | 1.03| −2.90| 0.38  | 6.96 | 8.39 | −0.89| 7.57     | 4.86     |
|                  |     | Han    | 0.15| 3.64 | 0.04  | 5.06 | 7.40 | −0.47| 7.57     | 4.81     |
|                  |     | Brutsaert | 0.43| 1.46 | 0.43  | 5.51 | 5.44 | 0.20 | 7.57     | 4.70     |
| All months       | 60  | GG     | 0.54| 20.73| 0.54  | 14.14| 17.41| 0.27 | 21.96    | 32.52    |
|                  |     | CRAE   | 0.51| 10.04| 0.92  | 8.88 | 10.49| 0.73 | 21.96    | 21.19    |
|                  |     | AA     | 0.82| −0.54| 0.83  | 8.08 | 9.61 | 0.78 | 21.96    | 17.37    |
|                  |     | Han    | 0.85| −0.53| 0.90  | 5.52 | 7.49 | 0.86 | 21.96    | 18.19    |
|                  |     | Brutsaert | 0.88| −0.78| 0.91  | 4.88 | 7.09 | 0.88 | 21.96    | 18.49    |

Note: n, number of statistical days; a, b, and $R^2$, slope, intercept, and coefficient of determination values, respectively, for the linear regressions; MAE, mean absolute error (mm/month); RMSE, root-mean-square error (mm/month); NSE, Nash–Sutcliffe efficiency; Mean ETa, mean measured month evapotranspiration (mm/month); and Mean ETe, mean estimated month evapotranspiration (mm/month).
that the CR models can calculate the daily or monthly ET$a$ values separately for different periods.

**CONCLUSIONS**

Daily ET$a$ during the thawed period is significantly higher than that during the freezing, frozen, and thawing periods, and ET$a$ that occurs during the thawed period accounts for the vast majority of the total ET$a$. All five CR models can estimate daily ET$a$ for the thawed period. The performance order of the five models were Han model, Brutsaert model, AA model, GG model, and CRAE model. The basic assumptions of the CR may not be suitable for the non-thawed periods with complex energy processes. None of the five models could estimate the daily ET$a$ value for the freezing, frozen, and thawing periods, and no complementary behavior was seen during the non-thawed periods.

The environment in cold areas is extremely harsh, and ET$a$ measurements in such regions are seriously lacking. Although CR models cannot estimate daily ET$a$ during the non-thawed periods, estimated ET$a$ remains an alternative means of understanding ET and water cycle in cold regions because CR models can effectively calculate ET$a$ during the thawed period, which accounts for most of the total ET$a$ in those regions. It should be noted, however, that estimations of ET$a$ from CR models during the non-thawed periods must be treated with caution.

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**DATA AVAILABILITY STATEMENT**

All relevant data are available from an online repository or repositories (https://doi.org/10.6084/m9.figshare.9901151.v2).

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