Comments to the Author:
Dear authors,

Thank you very much for responding to the review comments.
Given your suggested revision, I'd suggest that you submit your final revision for further review.

My own reading of the literature on this subject suggests that the use of evaporation, equilibrium evaporation (estimated by PT method), and potential evaporation (estimated by Penman method or observed by a pan) would make less confusion for the hydrological community, but I leave this to your preference.

Best wishes
Bob Su
editor HESS

Thank editor for your suggestions. We agree that using evaporation, equilibrium evaporation and potential evaporation would be an alternative way to categorize these three types of evaporation. Since we are following the definitions suggested in Brutasert and Parlange (1998) and Brutasert (2015), we would like to stay with their definitions of evaporation, potential evaporation and "apparent" potential evaporation. We added discussion about the different definitions of potential evaporation in the literature (Lines 57-59): "We acknowledge that there are different definitions of potential evaporation in the literature (Aminzadeh et al., 2016). Our study follows the definition of potential evaporation in Brutsaert and Parlange (1998) and Brutsaert (2015)."

We have revised the manuscript carefully based on the editor's and reviewers' helpful comments and suggestions. The major changes are:

(1) Table 1 is added to explain the definitions of evaporation, potential evaporation and "apparent" potential evaporation in different frameworks. The definition of potential evaporation is revised to be more clear (Lines 45-51): "Potential evaporation (E_p) is a widely used physical variable in hydrologic frameworks. It is the evaporation rate under unlimited land surface water supply (Thornthwaite, 1948). Pan evaporation (E_{pan}) measurement is often used as a surrogate of potential evaporation. However, these two variables are not the same (Brutsaert and Parlange, 1998; Roderick et al., 2009). A stipulation is added in the potential evaporation definition in Van Bavel (1966) and further clarified in Brutsaert (2015) that: 'the surface vapor pressure be saturated, so that it can be found from the surface temperature.'" The discussion about definition difficulties of evaporation terms is added (Lines 58-60): "We acknowledge that there are different definitions of potential evaporation in the literature (Aminzadeh et al., 2016). Our study will follow the definition of potential evaporation in Brutsaert and Parlange (1998) and Brutsaert (2015)."

(2) Process-based explanation about the complementary relationship and the Budyko framework is added (Lines 92-106): "Process-based speaking, the CR suggests a connection between

evaporation and "apparent" potential evaporation (Fig. 1a), which is driven by the energy feedbacks between atmosphere and land surface. During the drying process at the land surface, the excessive energy that is not used for evaporation will be available for the increase of sensible heat. The rise in air temperature will lead to an increase in the rate of "apparent" potential evaporation (Brutsaert and Parlange, 1998; Brutsaert, 2005; Aminzadeh et al., 2016). This connection between E_{pa} and E also suggests a connection between E_{pa} and P, since the water supply from precipitation will affect the rate of evaporation. In terms of the Budyko framework, E_p and P are used as the representations of energy supply and water supply respectively. The ratio between E_p and P is the primary controlling factor of the ratio of E over P in watersheds at long-term mean annual time scale (Fig. 1b). The ratio of E_p over P is also called the aridity index, which represents the dryness of the climate in a watershed. The ratio of E over P increases with the increase of aridity index, indicating that more water from precipitation will become evaporation rather than runoff under drier climate (Arora, 2002). No connection between E_p and P is suggested in the Budyko framework."

(3) Definition of "warm-season" is clarified (Lines 195-197): "Since pan evaporation is collected only during warm months (when temperatures remain above freezing), the weather stations at cold regions have less than 12 months of pan readings in a year. We call the period of warm months in a year 'warm-season'." (Lines 204-207): "For stations in the southern states with all 12 months of available data in a year, the full year will be considered as a warm-season. The northern state stations have fewer warm months, and, accordingly, the warm-season is much shorter."

(4) The discussion about the correlation analysis result is revised to be more quantitative and objective (Lines 243-252): "In the 259 weather stations, 93% of the stations have a negative correlation between P and E_{pa} (Fig. 4a), but only 43% of the stations are statistically significant ($p<0.05$; Fig. 4b). All significant P, E_{pa} correlations are negative. The weather stations located in the western region (regions with longitude higher than the weather station average longitude of W 94.81°) are more likely to have a significant P, E_{pa} negative correlation than those located in the east (regions with longitude lower than W 94.81°). This spatial difference may be related to climate characteristics: the eastern region has higher precipitation (averagely 105.5 mm/month) and lower "apparent" potential evaporation (averagely 145.3 mm/month), while the western region has lower precipitation (averagely 44.6 mm/month) and higher "apparent" potential evaporation (averagely 203.5 mm/month)." Also, the unnecessary discussion about the P and E_{pa} variability in different regions of the US is deleted.

(5) The need of collecting more data to further investigate the causal relationship and physical mechanism of behind the P, E_p and E_{pa} relationships is discussed (Lines 363-367): "It should be noted that the relationship between P and E_p and between P and E_{pa} found in this study are not direct causal relationships, but rather the result of interactions between a number of physical variables, such as net radiation, wind speed, humidity, and so forth. Further investigation into the physical mechanisms connecting these variables is underway."

(6) Figures 3 and 6 are revised following the reviewers' suggestions. Figure 3 highlights the four example weather stations from the four quadrants of the US. Scatter plots of P vs. E_{pa} are added in Figure 6 to better present the correlation between these two variables.

(7) A thorough proofreading is conducted to correct all the grammar errors and writing issues pointed out by the reviewers.

We believe the manuscript is substantially improved with the help of editor's and reviewers' comments and suggestions. The following section is point-by-point response to the reviews.

Response to Reviewer 1

In this research, by collecting and analyzing precipitation (P), pan evaporation (Epa) and potential evaporation (Ep) data at 259 stations in the US, the authors find that (1) Epa shows a negative correlation with P; (2) the negative correlation between P and Epa is more significant in arid region; (3) P and Ep are independent. These conclusions have been reported in many previous literatures (Hobbins et al., 2004; Ramírez et al., 2005; Kahler and Brutsaert, 2006; Brutsaert et al., 2015). It seems that what the authors did is to prove these findings without new perception or substantial contribution.

Thank you for your comments. According to the previous studies, Hobbins et al. (2004) studied the relationships between P, E_p, and E_{pa} at watershed scale; Ramírez et al. (2005) coupled site scale pan evaporation with watershed scale E and P; Kahler and Brutsaert (2006) and Brutsaert et al. (2015) used the site scale data at Flint Hills region of Kansas. By systematically investigating the relationships between P, E_p and E_{pa} with data from 259 weather stations across the US, our study is able to confirm the finding of these previous studies with field data at continental scale. Also, we combine the Bouchet's complementary relationship with Budyko's framework to generate the Bouchet-Budyko curves.

By combining Budyko equation and CR equation mathematically, they claim that they find the connection between the two frameworks. But except for putting the theoretical curves and data clouds together, no further analysis is provided. There are too many qualitative descriptions in the manuscript without quantified analysis and evidence.

Thank you for your comments. The connection between Budyko's framework and CR is essentially that the lower CR curve can be mathematically derived from Budyko equation (Eq. 4), assuming that we can use precipitation to represent moisture availability (Ramírez et al, 2005). Then based on the complementary relationship between E_{pa} and E, the upper CR curve can also be derived (Eq. 6). By putting the theoretical curves and data clouds together, we are able to show that the Bouchet-Budyko curves are following the trend of the data clouds, which will be the first step of validation of the mathematical derivations. We also added description of the process-scale explanation about the two frameworks in the manuscript to provide more information about this connection (Lines 92-106): "Process-based speaking, the CR suggests a connection between evaporation and "apparent" potential evaporation (Fig. 1a), which is driven by the energy feedbacks between atmosphere and land surface. During the drying process at the land surface, the excessive energy that is not used for evaporation will be available for the increase of sensible heat. The rise in air temperature will lead to an increase in the rate of “apparent” potential evaporation (Brutsaert and Parlange, 1998; Brutsaert, 2005; Aminzadeh et al., 2016). This connection between E_{pa} and E also suggests a connection between E_{pa} and P, since the water supply from precipitation will affect the rate of evaporation. In terms of the Budyko framework, E_p and P are used as the representations of energy supply and water supply respectively. The ratio between E_p and P is the primary controlling factor of the ratio of E over P in watersheds at long-term mean annual time scale (Fig. 1b). The ratio of E_p over P is also called the aridity index, which represents the dryness of the climate in a watershed. The ratio of E over P increases with the increase of aridity index, indicating that more water from precipitation will become evaporation rather than runoff under drier climate (Arora, 2002). No connection between E_p and P is suggested in the Budyko framework.”

L188-194: what’s the source of temperature (should be used to calculate _ and)?
what’s the spatial resolution of net radiation? did you take the Ep data for the grid
where the station is located as the Ep data for the station? It will caused great uncertainty.
Is there radiation data collected at the weather stations?

Thank you. The E_p calculation is done by Zhang et al. (2010). We collect Ep data from their dataset. In their paper, the data sources are explained in details. Temperature is derived from NCEP-NCAR Reanalysis (NNR). The spatial resolution of net radiation is 1° by 1°. Yes, we take E_p data based on the latitude and longitude of each weather station. The radiation data is not available at most of the weather stations in this study. We agree that the remote-sensing E_p data may not be as accurate as the field measurement data. In future studies, we will collect net radiation data to further validate our findings. The discussion about the accuracy of the remote-sensing E_p data is provided in the Discussion section (Lines 379-382): “The remote-sensing data of E_p may not have the same level of accuracy as the field measured P and E_{pa}. The value of α in the Eq. (7) may vary from location to location (Chen and Brutsaert, 1995; Brutsaert and Chen, 1995). Such factors may explain the deviation of some data points from the CR curve in Fig. 7.”

Line215-219: please provide detailed statistics to support your conclusion, like the percentage of significant P_Epa correlation, the mean P, the mean aridity index in the western and eastern regions. The same for L238-239, please provide the statistics for Ep variability and P variability.

Thank you for the suggestion. The percentage of significant P, E_{pa} correlation is 43%. The statistics information is added, including mean P and mean E_p of eastern and western regions, respectively (Lines 243-252): “In the 259 weather stations, 93% of the stations have a negative correlation between P and E_{pa} (Fig. 4a), but only 43% of the stations are statistically significant ($p<0.05$; Fig. 4b). All significant P, E_{pa} correlations are negative. The weather stations located in the western region (regions with longitude higher than the weather station average longitude of W 94.81°) are more likely to have a significant P, E_{pa} negative correlation than those located in the east (regions with longitude lower than W 94.81°). This spatial difference may be related to climate characteristics: the eastern region has higher precipitation (averagely 105.5 mm/month) and lower “apparent” potential evaporation (averagely 145.3 mm/month), while the western region has lower precipitation (averagely 44.6 mm/month) and higher “apparent” potential evaporation (averagely 203.5 mm/month).”

The discussion about P and E_{pa} variability in the eastern and western regions are deleted since the difference is not very distinguishable.

L219-220, L231-232 and L310: it seems that most of your results are similar to previous researches or have be reported before.

Thank you. Yes, these results are similar to the findings of previous studies, which is encouraging. By systematically investigating the relationships between P, E_p and E_{pa} with data from 259 weather stations across the US, our study is able to confirm the finding of these previous studies with field data at continental scale. We added discussion about the need of collecting more data to further our investigation on the physical mechanism and casual relationships between P, E_p and E_{pa} (Lines 363-367): "It should be noted that the relationship between P and E_p and between P and E_{pa} found in this study are not direct causal relationships, but rather the result of interactions between a number of physical variables, such as net radiation, wind speed, humidity, and so forth. Further investigation into the physical mechanisms connecting these variables is underway."

L244-245: As you classify the US into western and eastern parts, or northwestern, southwestern, northeastern and southeastern parts, I don't think there is any need to color the data points according to their latitudes and longitudes. Why not just use four colors?

Thank you. We use western/eastern or the four quadrants to discuss the results, but the color coding is able to show the continuous change of P, E_p and E_{pa} across the US. So with the color coding, more information can be presented, comparing with using four colors.

I cannot tell if "Southeastern region of the US has a wide range of precipitation; while points of the northeastern region are more concentrated" from fig5.

Thank you. This description is deleted.

L312: the boundary is 'Ep=Epa'

Thank you. The description is revised (Lines 339-341): "The horizontal solid black line in Fig. 7 is the boundary of the upper Bouchet-Budyko curve, above which E_{pa} exceeds E_p."

L344-345: please add quantitative analysis herein. Why it is 'when P/Ep is lower than 1' instead of 'when P/Ep is lower than 1.5'? how did you define 'signifcant E _Epa relationship'?

Thank you. We revised the discussion here (Lines 373-376): "The companion CR curves show that as the wetness index P/E_p decreases, the difference between E and E_{pa} grows. This indicates the complementary relationship between E and E_{pa} is most pronounced in arid environments; that is, the CR is more significant under water-limited condition." We will collect actual evaporation data to further validate this interpretation. With both E_{pa} and E data, more quantitative analysis will be conducted, but it is beyond the scope of this study.

L349-350: what does ‘fits with’ mean herein? In my point of view, you just provide some curves that located in the data clouds.

Thank you. We revised the statement (Lines 378-379): “The P, E_p and E_{pa} collected in this study are following the general trend of the upper Bouchet-Budyko curve (Fig. 7).”

L359-360: To use the combination of Budyko equation and CR equation, you must take care about the time scales, i.e., Budyko equation is merely applicable at long time scale.

Thank you. Yes, the Budyko framework is mainly applicable at long-term mean annual time scale. In recent years, there are studies trying to extend the Budyko framework to annual and intra-annual time scales (Wang and Alimohammadi, 2012; Zhang et al., 2008; Chen et al., 2013). Following their idea, we believe it is possible to link the Budyko framework with the CR. Description about the applicable time scale of the Budyko framework is added (Lines 68-71): “Furthermore, the Budyko framework, which is originally applicable at the long-term mean annual scale, has been extended to shorter time scales, such as annual (Wang and Alimohammadi, 2012; Zhang et al., 2008) and intra-annual periods (Chen et al., 2013).”

L364-367: recommend to delete these nonsense.

Thank you. This part is deleted.

Fig1(a): the label of x axis should be ‘P’.

Thank you. We use the E/E_{pa} as the x axis in Fig. 1 to be consistent with the original CR. Later on in the paper, we discuss about the change of x axis in CR from E/E_{pa} to moisture availability, and then to P (Lines 164-169): “The x-axis of the complementary relationship is a ratio between E and E_{pa} (Bouchet, 1963). Ramírez et al. (2005) used the water-energy framework to link the CR with Budyko approach and changed the x-axis in the CR to moisture availability. Following this idea, several studies have used precipitation or wetness index (P/E_p) to represent moisture availability in the CR (Yang et al., 2006; Roderick et al., 2009). In this study, we also use P to represent moisture availability in the CR.”

Fig6: please mark the locations of these four stations in Fig3.

Thank you for the suggestion. Fig. 3a is modified to highlight the four example stations.

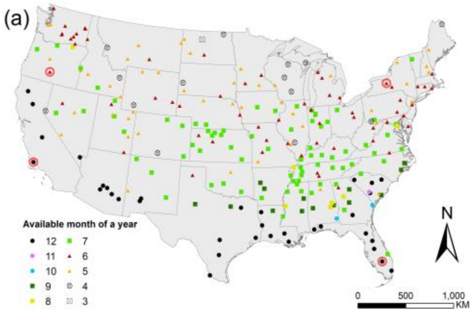


Fig. 3. **(a)** Map of 259 weather stations. The available month of a year of pan evaporation data for each weather station is presented using legends with different colors and shapes. Four representative weather stations are selected from the four quadrants of the US respectively, which are highlighted with red circles.

References:

Brutsaert, W.: A generalized complementary principle with physical constraints for land-surface evaporation, Water Resour. Res., 51, 8087-8093, doi:10.1002/2015WR017720, 2015.

Chen, X., Alimohammadi, N., and Wang, D.: Modeling interannual variability of seasonal evaporation and storage change based on the extended Budyko framework, Water Resour. Res., 49, 6067-6078, doi:10.1002/wrcr.20493, 2013.

Hobbins, M. T., Ramírez, J. A., and Brown, T. C.: Trends in pan evaporation and actual evapotranspiration across the conterminous U.S.: Paradoxical or complementary?, Geophys. Res. Lett., 31, doi:10.1029/2004GL019846, 2004.

Kahler, D. M., and Brutsaert, W.: Complementary relationship between daily evaporation in the environment and pan evaporation, Water Resour. Res., 42, W05413, doi:10.1029/2005WR004541, 2006.

Ramírez, J. A., Hobbins, M. T., and Brown, T. C.: Observational evidence of the complementary relationship in regional evaporation lends strong support for Bouchet's hypothesis, Geophys. Res. Lett., 32, L15401, doi:10:1029/2005GL023549, 2005.

Wang, D. and Alimohammadi, N.: Responses of annual runoff, evaporation, and storage change to climate variability at the watershed scale, Water Resour. Res., 48,W05546, doi:10.1029/2011WR011444, 2012.

Zhang, K., Kimball, J. S., Nemani, R. R., and Running, S. W.: A continuous statellite-derived global record of land surface evapotranspiration from 1983 to 2006, Water Resour. Res., 46, W09522, doi:10.1029/2009WR008800, 2010.

Zhang, L., Potter, N., Hickel, K., Zhang, Y., and Shao, Q.: Water balance modeling over variable time scales based on the Budyko framework— Model development and testing, J. Hydrol., 360, 117–131, 2008.

Response to Reviewer 2

GENERAL COMMENTS:
This paper is an observational study of the relationships between various idealized fluxes of evaporative demand as they are manifest in two paradigms: the Budyko framework and the complementary relationship between regional evapotranspiration and evaporative demand. While the paper does not break new theoretical ground beyond combining the complementary relationship and Budyko paradigms, it nevertheless provides essential, continental-scale verification of these relationships through observation, and, as such, should make a significant impact on the field. The authors are to be commended for avoiding the common pitfalls of working with pan evaporation data (for their Epa data): measurement uncertainty due to heterogeneity and the dataset's pronounced regional bias. To isolate the effects of artificial uncertainties introduced to their Epa analyses, they compare to a smaller, homogenized pan evaporation dataset. And they limit the period of analysis of their data to only those months for which they have complete data: they do not attempt to scale up to complete years, which would otherwise introduce spurious, unknown biases. The paper is written and structured well and requires only technical revisions.

Thank you for your comments and suggestions.

SPECIFIC COMMENTS: Following are the main issues to address:
1. In general, dealing with the hornet's nest of terminology is difficult but essential. The authors have done a tremendous job of introducing the various terms involved in the CR and the Budyko framework, and of keeping them distinct. However, to forestall initial confusion on the parts of readers who may already use different terminology (for example, what is called "apparent potential evaporation" here I call "potential evaporation," but what is called "potential evaporation" I call "wet environment evaporation"), they should state at the beginning of the Introduction that terms will be used in a way unfamiliar to some readers and then make reference to a table that compares them (I refer here to a table that was included in an earlier iteration of this manuscript).

Thank you for your suggestion. We added the table of terminology and description about the different evaporation terms (Lines 89-91): "The definitions of evaporation, potential evaporation and "apparent" potential evaporation in these different frameworks are summarized in Table 1."

Table 1. Types of evaporation in the Budyko framework and the original CR, and their redefined evaporation type based on generalized CR. The last column refers to the definitions of the three types of evaporation in the generalized CR provided in Brutsaert (2015).

Budyko Framework	Bouchet's Complementary Relationship	Generalized Complementary Relationship	Evaporation Definitions in Brutsaert (2015)
Actual evaporation (E)	Actual evaporation (E)	Actual evaporation (E)	The first type
Potential evaporation (E_p)	Wet environment evaporation (E_0)	Potential evaporation (E_p)	The second type

-	Potential evaporation (E_p)	"Apparent" potential evaporation (E_{pa})	The third type

2. This is the only outstanding comment from the previous review I gave to this manuscript: No process-scale explanation of either the surface-atmosphere feedbacks that drive the complementary relationship (including asymmetry vs. symmetry in the CR), nor the attribution of the water and energy budgets in the Budyko framework. This should be the text for their Figure 1. Also, the spatial scale-dependent homogeneity assumptions and the physical land-atmosphere feedbacks that underpin the CR need to be explained, as do the timescale-dependent assumptions of the Budyko framework. This would explain both the independence observed between P and Ep but also the dependence of Epa on P.

Thank you for the suggestion. Description about process involved in Budyko and CR are added (Lines 92-106): "Process-based speaking, the CR suggests a connection between evaporation and "apparent" potential evaporation (Fig. 1a), which is driven by the energy feedbacks between atmosphere and land surface. During the drying process at the land surface, the excessive energy that is not used for evaporation will be available for the increase of sensible heat. The rise in air temperature will lead to an increase in the rate of "apparent" potential evaporation (Brutsaert and Parlange, 1998; Brutsaert, 2005; Aminzadeh et al., 2016). This connection between E_{pa} and E also suggests a connection between E_{pa} and P, since the water supply from precipitation will affect the rate of evaporation. In terms of the Budyko framework, E_p and P are used as the representations of energy supply and water supply respectively. The ratio between E_p and P is the primary controlling factor of the ratio of E over P in watersheds at long-term mean annual time scale (Fig. 1b). The ratio of E_p over P is also called the aridity index, which represents the dryness of the climate in a watershed. The ratio of E over P increases with the increase of aridity index, indicating that more water from precipitation will become evaporation rather than runoff under drier climate (Arora, 2002). No connection between E_p and P is suggested in the Budyko framework"

3. While the authors have changed to using warm-season data only since the earlier iteration I reviewed, they should also use the full-year (annual) data where it is available, i.e., the southern states. This would only strengthen their observations and credibility.

Thank you for the suggestion. The full-year data is used as the warm season data in southern states. We added explanation about the warm-season definition (Lines 204-207): "For stations in the southern states with all 12 months of available data in a year, the full year will be considered as a warm-season. The northern state stations have fewer warm months, and, accordingly, the warm-season is much shorter."

4. They demonstrate the inter-relations of Ep, Epa and P through time at single points, although this analysis seems less than satisfying as currently presented. Below, I have suggested different graphics.

SPECIFIC COMMENTS: Minor issues to address:
L 47: Here, by "surface vapor pressure" I believe the vapor pressure directly at the

surface is meant here, rather than the more-familiar height of 2 m. If so, this should be specified.

Thank you. The “surface vapor pressure” here means the vapor pressure directly at the surface and adjacent near-surface area. The definitions of potential evaporation and surface vapor pressure are revised to be more clear in the manuscript (Lines 45-51): “Potential evaporation (E_p) is a widely used physical variable in hydrologic frameworks. It is the evaporation rate under unlimited land surface water supply (Thornthwaite, 1948). Pan evaporation (E_{pan}) measurement is often used as a surrogate of potential evaporation. However, these two variables are not the same (Brutsaert and Parlange, 1998; Roderick et al., 2009). A stipulation is added in the potential evaporation definition in Van Bavel (1966) and further clarified in Brutsaert (2015) that: ‘the surface vapor pressure be saturated, so that it can be found from the surface temperature.’”

LL 122-123: This is a little misleading as it makes it appear possible that Epa can be less than Ep in some circumstances.

Thank you. This sentence is revised (Lines 148-150): “‘Apparent’ potential evaporation will be higher than potential evaporation, especially under dry conditions; while it gradually approaches potential evaporation as the ratio of E over E_{pa} increases (Fig. 1a).”

LL 166-189: Nowhere is it specified what is meant by “warm-season.” Is it the period at each pan for which air temperatures are above freezing, or May through-October for all pans, or something else?

Thank you. The definition of warm-season is added (Lines 194-197): “We collect data for the period 1984-2015 from a total of 259 weather stations (Fig. 3a). Since pan evaporation is collected only during warm months (when temperatures remain above freezing), the weather stations at cold regions have less than 12 months of pan readings in a year. We call the period of warm months in a year ‘warm-season’.”

L 189: What is the value of the pan coefficient for Eq. (3), 0.7?

Thank you. The pan coefficient is set at 1.0.

L 190: That this is also called the “partial equilibrium evaporation rate” should probably be mentioned.

Thank you for the suggestion. The description about partial equilibrium evaporation rate is added (Lines 151-153): “As suggested by Morton (1976) and Brutsaert and Stricker (1979), potential evaporation can be estimated using the Priestley-Taylor equation (Priestley and Taylor, 1972), which is also called equilibrium evaporation (Brutsaert and Chen, 1995; Jiang and Islam, 2001).”

LL 193-195: What are the units, dimensions?

Thank you. The units are added (Lines 219-222): “where λ (J/kg) is the latent heat of vaporization; λE_p (W/m^2) is the latent heat flux; α is a coefficient to account for the effect of surface characteristics and vegetation, and is set to 1.26; Δ (Pa/°C) is the slope of the saturated vapor pressure curve; γ (Pa/°C) is the psychometric constant; R_n (W/m^2) is the net radiation; and G (W/m^2) is the heat flux into the ground.”

LL 247-248: There are many more reasons than this that this dataset was homogenized, and they bear mentioning here.

Thank you. The description of the homogenized dataset has been revised to provide more in-depth information about its reasoning behind homogenization (Lines 273-275): “In order to minimize the data heterogeneity caused by station move and human errors, this dataset compiled pan evaporation data from 247 stations across the US with thorough quality control.”

LL 275-276: I don’t think these different mechanisms are ever explained; they should be.

Thank you. The physical mechanism of the relationships between P, E_p and E_{pa} are discussed in the Discussion section (Lines 352-359): “The negative correlation between P and E_{pa} is linked by the humidity deficit. The formation of precipitation is positively related to the local level of humidity (Pal et al., 2000; Sheffield et al., 2006; An et al., 2017) while “apparent” potential evaporation is inversely related to humidity or positively related to the humidity deficit (Penman, 1948; Allen et al., 1998). As a result, precipitation and “apparent” potential evaporation will tend to exhibit a negative correlation. According to the Bouchet’s complementary relationship, this negative correlation between P and E_{pa} is more pronounced in arid regions than in humid regions.” and (Lines 361-367): “As a result, our study indicates that potential evaporation and precipitation, the representations of energy supply and water supply, are likely to be independent. This independence is currently under investigation with field data. It should be noted that the relationship between P and E_p and between P and E_{pa} found in this study are not direct causal relationships, but rather the result of interactions between a number of physical variables, such as net radiation, wind speed, humidity, and so forth. Further investigation into the physical mechanisms connecting these variables is underway.”

LL 282-290: See comment on Fig. (6) below.

LL 310-311: The reasoning behind the asymmetry should be summarized here. E.g., symmetry (when b = 1) implies that all energy released as increased sensible heat as latent heat declines goes to increase Epa by the same amount that latent heat declines.

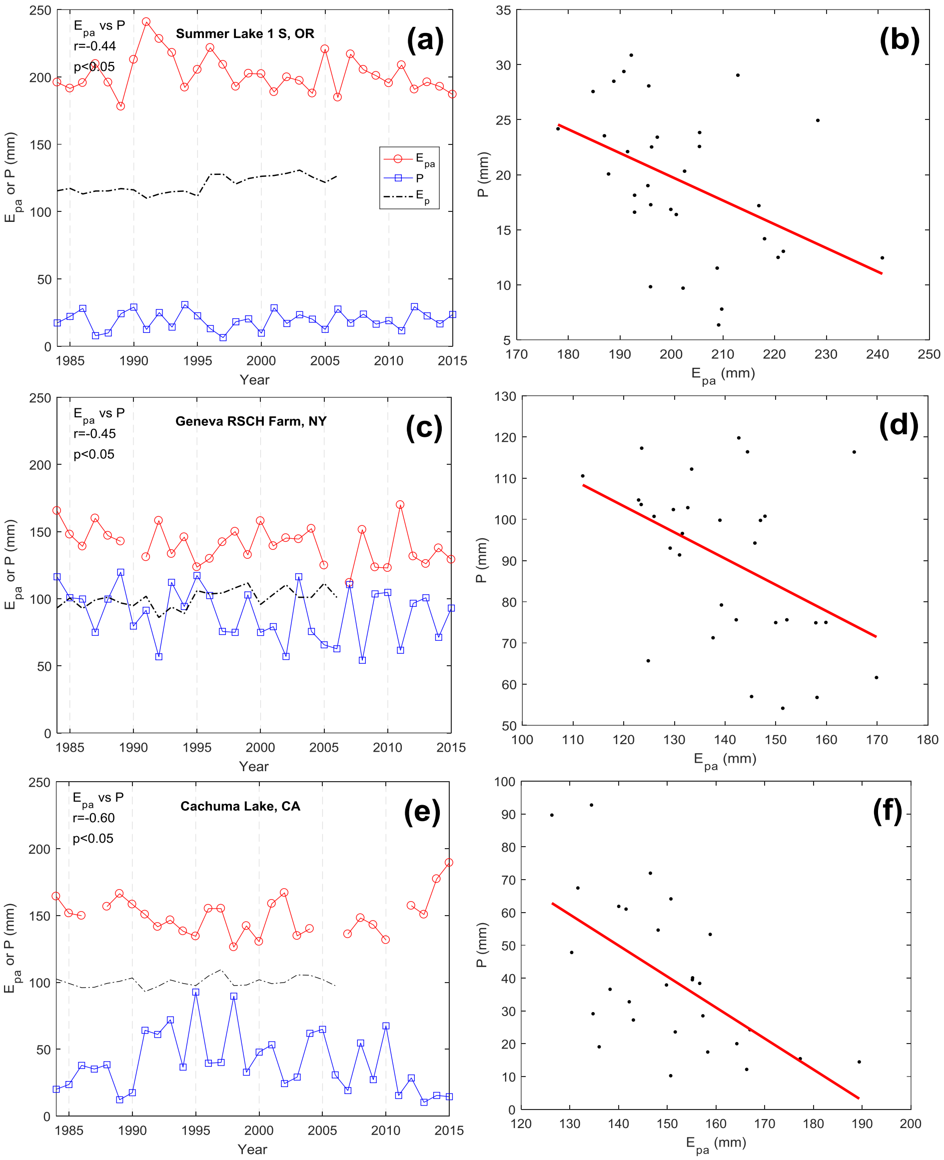
Thank you for the suggestion. Discussion about the asymmetry between E_{pa} and E is added (Lines 336-339): “This asymmetry is discussed in previous studies (Kahler and Brutsaert, 2006; Brutsaert, 2015). One explanation of this asymmetry between E and E_{pa} is that the evaporation pan will receive more heat than the surrounding area (Kahler and Brutsaert, 2006).”

LL 336-339: I think this thought needs more development: perhaps a hypothesis as to a causal relationship?

Thank you for the suggestion. We agree that this thought needs to be further developed. At the current stage, our data analysis is able to show the relationships between P, E_p and E_{pa}. We will collect more data and therefore to further investigate the causal relationship and physical mechanism in our future studies. The discussion about future studies is added (Lines 363-367): "It should be noted that the relationship between P and E_p and between P and E_{pa} found in this study are not direct causal relationships, but rather the result of interactions between a number of physical variables, such as net radiation, wind speed, humidity, and so forth. Further investigation into the physical mechanisms connecting these variables is underway."

Figure 6: I believe I called for these time-series plots in my review of an earlier version, but now I see that they are actually not that explicative. As presented these timeseries don't clearly demonstrate the inter-relations under discussion. In the long-term, multi-annual; complementarity is evident in Fig. (6c), but one has to look really hard to observe the CR at the inter-annual timescales, which is the scale to which the text refers. Perhaps it would be better to either plot these as X-Y scatterplots, or with each flux plotted as an anomaly around its climatological annual mean.

Thank you. Scatterplots are added in Fig. 6.


(a)
E_{pa} vs P
r=-0.44
p<0.05
Summer Lake 1 S, OR
E_{pa}
P
E_p
E_{pa} or P (mm)
Year
(b)
P (mm)
E_{pa} (mm)
(c)
E_{pa} vs P
r=-0.45
p<0.05
Geneva RSCH Farm, NY
E_{pa} or P (mm)
Year
(d)
P (mm)
E_{pa} (mm)
(e)
E_{pa} vs P
r=-0.60
p<0.05
Cachuma Lake, CA
E_{pa} or P (mm)
Year
(f)
P (mm)
E_{pa} (mm)

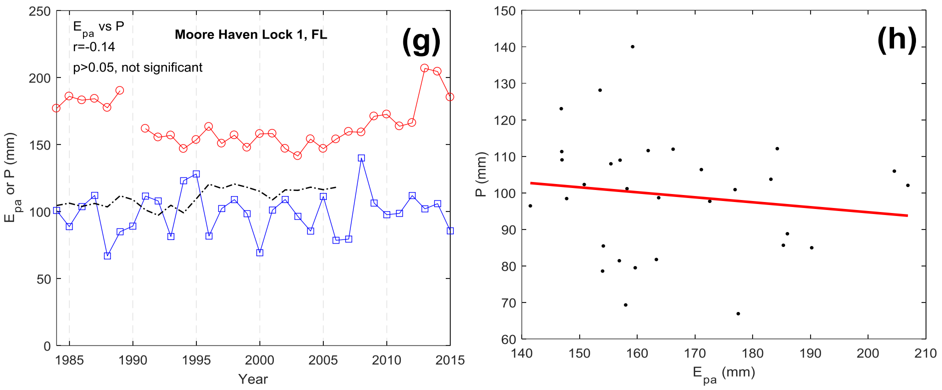


Fig. 6. Warm-season P, E_p and E_{pa} time series of four example weather stations in the study period of 1984-2015: **(a)** Summer Lake 1 S, OR (N 42°58’, W 120°47’); **(c)** Geneva RSCH Farm, NY (N 42°53’, W 77°20’); **(e)** Cachuma Lake, CA (N 34°35’, W 119°59’); **(g)** Moore Haven Lock 1, FL (N 26°50’, W 81°50’); and the scatterplots of P vs E_{pa} at the four example stations (**b**, **d**, **f**, **h**).

TECHNICAL COMMENTS: There are some hyphenation issues: there should be no hyphens after words ending in –ly, e.g., use “physically based” not “physically-based”; however, “warm season” should, in general, be hyphenatedâ˘A˘ Ti.e., “warm-season”â˘A ˘T particularly where it is used as a compound adjective (more often than not in this manuscript). “As well as” should always simply be “and.” I have pointed out a few points where there was repetition.

Thank you for the comment. We did a thorough revision to correct those mistakes.

L 1: “Warm season” should be hyphenated, here and wherever it is used as a compound adjective throughout the manuscript (which is almost everywhere).

Thanks. It is changed to warm-season.

L 30: “Missing word: use “. . .93% of the study weather stations. . .”

Thanks. The missing word is added.

L 65: Use “. . .the Budyko framework and Bouchet’s complementary. . .”

Thanks. This sentence is revised.

L 66: Use “. . .use the Fu equation. . .”

Thanks. This sentence is revised.

LL 78-81: This is repeated from earlier in this section.

Thanks. This part is deleted.

L 90 and 93: Use “relationships” – plural.

Thanks. It is corrected.

L 123: Use “conditions” – plural.

Thanks. It is corrected.

L 124: Missing word: use “. . .the ratio of E over Epa. . .”

Thanks. The missing word is added.

LL 142-147: To clean this section up to eliminate repetition and extraneous text, try: “Ep is a horizontal line in the CR that is parallel to the x-axis (Fig. 1a). Therefore, the modified CR indicates that P and Ep are independent. On the other hand, the upper curve of the CR, representing “apparent” potential evaporation Epa, declines along the x-axis, indicating that Epa and P are not â˘A´lindependent. For a dimensionless CR, we â˘A´lnormalize the x and y axes. The normalized CR describes the relationship between. . .”

Thanks. This section is revised (Lines 169-173): “E_p is a horizontal line in the CR that is parallel to the x-axis (Fig. 1a). Therefore, the modified CR indicates that P and E_p are independent. On the other hand, the upper curve of the CR, representing “apparent” potential evaporation E_{pa}, declines along the x-axis, indicating that E_{pa} and P are not independent. For a dimensionless CR, we normalize the x and y axes. The normalized CR describes the relationship between $\frac{E_{pa}}{E_p}$, $\frac{E}{E_p}$, and $\frac{P}{E_p}$ (Fig. 2).”

L 149: Try “To connect the Budyko framework with the normalized CR toward formulating the. . .”

Thanks. This sentence is revised (Lines 174-175): “To connect the Budyko framework with the normalized CR toward formulating the Bouchet-Budyko curves, we first transform Eq. (1) into a relationship between $\frac{E}{E_p}$ and $\frac{P}{E_p}$”.

L 196: Here, “long-term” needs a hyphen (as does “warm-season”).

Thanks. It is corrected.

LL 214-217: Try “In the 259 weather stations, 93% of the stations have a negative correlation between P and Epa (Fig. 4a), but only 43% are statistically significant (p<0.05; Fig. 4b). All significant P, Epa correlations are negative.”

Thanks. This sentence is revised (Lines 243-245): “In the 259 weather stations, 93% of the stations have a negative correlation between P and E_{pa} (Fig. 4a), but only 43% of the stations are statistically significant ($p<0.05$; Fig. 4b). All significant P, E_{pa} correlations are negative.”

L 219: Try “. . .climate characteristics: the eastern region. . .”

Thanks. This sentence is revised.

LL 223-235: This is repeated from above.

Thanks. This part is deleted.

LL 228-229: Try “All the warm-season P vs. Epa relations (i.e., all years, all seasons, for a total of 5312 data) are shown in Fig. 5a.”

Thanks. This sentence is revised (Lines 260-261): “All the warm-season P vs. E_{pa} relations (i.e., all years, all seasons, for a total of 5312 data points) are shown in Fig. 5a.”

LL 235-245: For clarity (and less superfluous text), try the following: “The right side of the cloud generally represents the northeastern and southeastern US (green and brown, respectively), while the left side of the cloud generally represents the northwestern and southwestern US (yellow and red, respectively). The left side cloud is more vertically oriented, indicating that the western US has higher Epa variability than P variability. The southwestern US has the highest Epa (red and orange). The northwestern US has much lower Epa (yellow). On the other hand, the right side of the cloud is more horizontally oriented, indicating that the eastern region has higher P variability than Epa. Unlike in the western US, the difference between the northeastern and southeastern regions is not clear. The southeastern region of the US has a wide P range; while points of the northeastern region are more concentrated.”

Thanks. This part is revised. Also, the unnecessary description about the P and E_{pa} variability in this part is deleted (Lines 267-270): “The right side of the cloud represents the northeastern and southeastern US (green and brown, respectively); while the left side of the cloud generally represents the northwestern and southwestern US (yellow and red, respectively).”

LL 252-253: Try “Only 41% of the stations have statistically significant relationship ($p< 0.05$); all negative.”

Thanks. This sentence is revised (Lines 277-278): “Of these, 41% of the stations have a statistically significant relationship ($p<0.05$); all negative.”

L 279: Try “. . .four weather stations from the four quadrants of the conterminous US to show the warm-season P,. . .”

Thanks. This sentence is revised (Lines 302-304): "…we select four weather stations from the four quadrants of the contiguous US (Fig. 3a), to show the warm-season P, E_p and E_{pa} in time series (Fig. 6)."

L 281: Use "Epa" for "pan evaporation."
Thanks. It is corrected.

LL 281-283: Try "...only have Epa data for six or seven months of each year,. . ."

Thanks. This sentence is revised (Line 305): "while the two stations in the northern regions only have E_{pa} data for six months of each year."

L 283: Delete "selected" here.

Thanks. It is deleted.

L 313: Try ". . .Bouchet-Budyko curve, above which Epa exceeds Ep."

Thanks. This sentence is revised (Lines 339-341): "The horizontal solid black line in Fig. 7 is the boundary of the upper Bouchet-Budyko curve, above which E_{pa} exceeds E_p."

L 329: Use "According to" instead of "Similar with."

Thanks. It is revised.

L 347: "Water-limited" should be hyphenated.

Thanks. It is corrected.

LL 370-372: This sentence is repeated from LL 354-356.

Thanks. This sentence is deleted.

L 377: Hyphenation: use "warm-season."

Thanks. It is corrected.

L 379: For ". . .in 93% of the study locations." just use ". . .at 93% of the stations."

Thanks. This sentence is revised.

LL 382-383: Delete the redundant phrase "on the relationship between warm season P and Ep"

Thanks. It is deleted.

Figure 3: The caption for panel (b) should specify that these are the homogenized data that overlap the 259-station dataset.

Thanks. The caption is revised (Lines 226-230): “Fig. 3. **(a)** Map of 259 weather stations. The available month of a year of pan evaporation data for each weather station is presented using legends with different colors and shapes. Four representative weather stations are selected from the four quadrants of the US respectively, which are highlighted with red squares. **(b)** Map of 93 weather stations with homogenized pan evaporation data that overlap the 259-station dataset.”

Figure 4: Hyphenation: use “point-scale” not “point scale” in the caption.

Thanks. It is corrected.

Figure 7: In the caption, state what the lower dotted line represents.

Thanks. The caption is revised (Lines 343-347): “Fig. 7. P/E_p vs. E_{pa}/E_p at 259 weather stations in the US for the period 1984 to 2015 for **(a)** warm-season data (N=5312), and **(b)** long-term average data (N=259). The data points are color coded based on their latitudes and longitudes. The three upper Bouchet-Budyko curves are plotted with different b values of b=1, b=2, and b=3, and with the same v value of v=2. The dashed line is the lower Bouchet-Budyko curve with v=2.”

Response to Reviewer 3

This manuscript describes an updated analysis of a combined Budyko-Bouchet complementary relation using data from across the US.

There has been a growing (and sometimes confusing) literature on the CR in recent years. Many of these difficulties have been described in a recent mini-review (see section 2 in Aminzadeh et al 2016 WRR).

The manuscript under consideration skips over the above-noted difficulties and in essence returns more closely to the original CR formulations by Brutsaert and co-workers. In that context, the manuscript adds some ideas and much useful data the literature.

The manuscript is, in general, very clearly written, and with the extensive data, is a helpful addition to the literature.

Recommend: Accept subject to revision

Thank you for your comments and suggestions.

Comments:

1. Lines 45-57. I agree with the first condition for potential, i.e. no limit on the water supply. However, the second definition, i.e., saturated surface vapour pressure, is used by some scientists but the relevance is not clear. For example, in this manuscript, potential is actually defined by Priestley-Taylor and this does explicitly refer to saturated surface air. The comments here fall into the "difficulties" categories noted above. There is a vast range of definitions of potential E over the years …….. So what to do? Maybe drop the text about saturated vapour pressure at the surface and acknowledge some of the difficulties.

Thank you. We agree that there are different definitions of potential evaporation and we add discussion about the definition "difficulties" and add Aminzadeh et al (2016) as a reference (Lines 58-60): "We acknowledge that there are different definitions of potential evaporation in the literature (Aminzadeh et al., 2016). Our study follows the definition of potential evaporation in Brutsaert and Parlange (1998) and Brutsaert (2015)." We also revised the description of potential evaporation definition to make it more clear (Lines 45-51): "Potential evaporation (E_p) is a widely used physical variable in hydrologic frameworks. It is the evaporation rate under unlimited land surface water supply (Thornthwaite, 1948). Pan evaporation (E_{pan}) measurement is often used as a surrogate of potential evaporation. However, these two variables are not the same (Brutsaert and Parlange, 1998; Roderick et al., 2009). A stipulation is added in the potential evaporation definition in Van Bavel (1966) and further clarified in Brutsaert (2015) that: 'the surface vapor pressure be saturated, so that it can be found from the surface temperature.'"

2. Lines 45-57. I have advocated dropping the text about saturated vapour pressure in this paragraph. At any rate, it is also useful to note that for evaporation from a pure water surface (e.g. pan), the vapour pressure right at the evaporating surface is assumed to be saturated. I assume what you mean here is the vapour pressure of **adjacent near-surface air**. Please be specific.

Thank you. Yes, the “surface vapor pressure” include the vapor pressure at the water surface and at areas near the water surface. We revised the description of potential evaporation definition (Lines 45-51).

3. Line 56. TYPO. ….. by **an** evaporation pan

Thanks. The sentence is revised.

4. Line 79. See comment 2.

Thanks. This part is deleted since it is repetitive.

5. Line 130-135. You set a = 1. Why? I note that you say it does not make much difference to your results but it is nice to use a reasonable parameter value if you have one available. That would be 0.7 (instead of 1). The Class A pan (as used here) is elevated above the ground and the water surface evaporation is effected by heat exchange across the side walls. The meaning of the pan co-efficient relates to this additional heat. The traditional value for the pan co-efficient is around 0.7 (see Stanhill 1976 that you cite). Theoretical considerations suggest the value should be 0.65 to 0.9 with a mean close to 0.7 (see Fig. 10 in Lim et al 2013, AgForMet). So why not use 0.7?

Thanks. Yes, the pan coefficient is usually set at 0.7. Kahler and Brutsaert (2006) suggests a different value of 1.0 for mixed natural vegetation. They argued that 1.0 is not an unreasonable value for pan coefficient for mixed natural vegetation. We agree with their opinion and therefore set the pan coefficient value to 1.0.

6. Line 173. TYPO. for each year **at** each weather

Thanks. The sentence is revised.

7. Lines 188-196. I assume you set G to zero when calculation Ep? Please state how you did this calculation.

Thanks. The heat flux into the ground G is not set at zero. The calculation is done in Zhang et al. (2010). In their paper, they explained the calculation procedure:

$$G = R_n * [\Gamma_c + (1 - f_c) * (\Gamma_s - \Gamma_c)]$$

where R_n is the net radiation; Γ_c and Γ_s are ratios of G to R_n for full vegetation canopy and bare soil, respectively; and f_c is the fractional canopy coverage.

We collect E_p data from their dataset based on Zhang et al. (2010). We didn’t do any calculation related to the remote-sensing data. The description about the remote-sensing dataset is revised to be more clear (Lines 216-217): “The E_p data are collected from a remote-sensing dataset (Zhang et al., 2010), which is generated using the Priestley-Taylor equation with remotely sensed net radiation”.

References:

Kahler, D. M., and Brutsaert, W.: Complementary relationship between daily evaporation in the environment and pan evaporation, Water Resour. Res., 42, W05413, doi:10.1029/2005WR004541, 2006.

Zhang, K., Kimball, J. S., Nemani, R. R., and Running, S. W.: A continuous statellite-derived global record of land surface evapotranspiration from 1983 to 2006, Water Resour. Res., 46, W09522, doi:10.1029/2009WR008800, 2010.

Exploring the relationship between warm-season precipitation, potential evaporation, and "apparent" potential evaporation at site scale

Xi Chen[1] and Steven G. Buchberger[2]

[1]College of Arts and Sciences, Department of Geography and Geographic Information Science, University of Cincinnati

[2]College of Engineering and Applied Science, Department of Civil Engineering and Architectural Engineering and Construction Management, University of Cincinnati

Corresponding author: Xi Chen (xi.chen@uc.edu)

Abstract

Bouchet's complementary relationship and the Budyko hypothesis are two classic frameworks that are inter-connected. To systematically investigate the connections between the two frameworks, we analyze precipitation, pan evaporation and potential evaporation data at 259 weather stations across the United States. The precipitation and pan evaporation data are from field measurement and the potential evaporation data are ~~computed~~collected from a remote-sensing dataset. We use pan evaporation to represent "apparent" potential evaporation, which is different from potential evaporation. With these data, we study the correlations between precipitation and potential evaporation, and between precipitation and "apparent" potential evaporation. The results show that 93% of the study weather stations exhibit a negative correlation between precipitation and "apparent" potential evaporation. Also, the aggregated data cloud of precipitation versus "apparent" potential evaporation with 5312 warm-season data points from 259 weather stations shows a negative trend in which "apparent" potential evaporation decreases with increasing precipitation. On the other hand, no significant correlation is found in the data cloud of precipitation versus potential evaporation, indicating that precipitation and potential evaporation are independent. We combine a Budyko-type expression, the Turc-Pike equation, with ~~the~~ Bouchet's complementary relationship to derive upper and lower Bouchet-Budyko curves, which display a complementary relationship between "apparent" potential evaporation and actual evaporation. The observed warm-season data follow the trend of the Bouchet-Budyko curves ~~well~~. Our study shows the consistency between Budyko's framework and Bouchet's complementary relationship, with the distinction between potential evaporation and "apparent" potential evaporation. The formulated complementary relationship can be used in quantitative modeling practices.

1. Introduction

Potential evaporation (E_p) is a widely used physical variable in hydrologic frameworks. It is the evaporation rate under ~~two conditions: firstly, the~~ unlimited land surface water supply ~~is unlimited~~ (Thornthwaite, 1948~~); secondly, the surface vapor pressure is saturated (Van Bavel, 1966; Brutsaert, 2015~~). Pan evaporation (E_{pan}) measurement is often used as a surrogate of potential evaporation. However, these two variables are not the same (Brutsaert and Parlange, 1998; Roderick~~, et al., 2009). The~~ et al., 2009). A stipulation is added in the potential evaporation definition in Van Bavel (1966) and further clarified in Brutsaert (2015) that: "the surface vapor pressure be saturated, so that it can be found from the surface temperature." Therefore, the main difference between potential evaporation and pan evaporation is that pan evaporation is not measured under saturated surface vapor pressure. As a result, potential evaporation can be considered to depend only on the energy supply of climate while pan evaporation is driven by both energy supply and humidity deficit in the atmosphere (Rotstayn~~,~~ et al., 2006). In Brutsaert and Parlange (1998), the term "apparent" potential evaporation (E_{pa}) is introduced to distinguish pan evaporation from potential evaporation. "Apparent" potential evaporation can be measured by an evaporation pan, while potential evaporation cannot. We acknowledge that there are different definitions of potential evaporation in the literature (Aminzadeh et al., 2016). Our study follows the definition of potential evaporation in Brutsaert and Parlange (1998) and Brutsaert (2015).

Because potential evaporation is energy-driven, it can be used as a physical variable to describe the energy supply in a hydrologic system. For instance, the well-established Budyko framework (Budyko, 1958; 1974) uses ~~the relationship between~~ precipitation (P) and potential evaporation to represent the relationship between water supply and energy supply~~.~~, and therefore to describe the impact of long-term climate on the hydrologic cycle. The Budyko framework has been extensively used to analyze interactions between hydrology, climate, vegetation and other elements in watersheds (Milly, 1994; Zhang et al., 2001; Yang et al., 2007; Donohue et al., 2007; Yang~~,~~ et al., 2011; Xu~~,~~ et al., 2014; Zhou et al., 2015; Zhou et al., 2016). Furthermore, the Budyko framework, which is originally applicable at the long-term mean annual scale, has been extended to shorter time scales, such as annual (Wang and Alimohammadi, 2012; Zhang et al., 2008) and intra-annual periods (Chen et al., 2013).

Several studies have made connections between the Budyko framework and ~~the~~ Bouchet's complementary relationship (CR) (Bouchet, 1963). Yang et al. (2006) used the ~~Fu's~~Fu equation (Fu, 1981), which is one of the commonly used equations to represent the Budyko~~'s~~ curve, to describe the relationship between actual evaporation and potential evaporation in the CR. Roderick et al. (2009) presented a complementary relationship normalized by net irradiance and compared it with the Budyko framework. Lhomme and Moussa (2016) combined Turc-Pike equation (Turc, 1954; Pike, 1964), which is another commonly used Budyko-type equation, with the CR to show the dependence of Budyko curve on the drying power of the air.

When linking the Budyko framework with the CR, it is crucial to have a clear definition of different types of evaporation used in these two frameworks. Brutsaert and Parlange (1998) and Brutsaert (2015) generalized the CR and provided definitions of the evaporation terms in the CR, namely actual evaporation (E), potential evaporation (E_p), and "apparent" potential evaporation (E_{pa}, see Fig. 1a). ~~As described previously, potential evaporation, following the original potential evaporation definition (Thornthwaite, 1948; Van Bavel, 1966), is the evaporation rate under saturated surface vapor pressure and unlimited land surface water supply;~~

~~while "apparent" potential evaporation, which can be measured by evaporation pan, is the evaporation rate under unlimited land surface water supply, but not under saturated vapor pressure. It is clarified in Brutsaert and Parlange (1998)~~Brutsaert and Parlange (1998) point out that the complementary relationship is between actual evaporation and "apparent" potential evaporation, not between actual evaporation and potential evaporation. In the Budyko framework (Fig. 1b), the definition of potential evaporation ~~is also following the original~~follows Van Bavel (1966)'s potential evaporation definition that it is under unlimited land surface water supply ~~and saturated vapor pressure~~without the effect of humidity deficit (Budyko, 1974~~).~~), which is the same as the E_p definition in the generalized CR. The definitions of evaporation, potential evaporation and "apparent" potential evaporation in these different frameworks are summarized in Table 1.

Process-based speaking, the CR suggests a connection between evaporation and "apparent" potential evaporation (Fig. 1a), which is driven by the energy feedbacks between atmosphere and land surface. During the drying process at the land surface, the excessive energy that is not used for evaporation will be available for the increase of sensible heat. The rise in air temperature will lead to an increase in the rate of "apparent" potential evaporation (Brutsaert and Parlange, 1998; Brutsaert, 2005; Aminzadeh et al., 2016). This connection between E_{pa} and E also suggests a connection between E_{pa} and P, since the water supply from precipitation will affect the rate of evaporation. In terms of the Budyko framework, E_p and P are used as the representations of energy supply and water supply respectively. The ratio between E_p and P is the primary controlling factor of the ratio of E over P in watersheds at long-term mean annual time scale (Fig. 1b). The ratio of E_p over P is also called the aridity index, which represents the dryness of the climate in a watershed. The ratio of E over P increases with the increase of aridity index, indicating that more water from precipitation will become evaporation rather than runoff under drier climate (Arora, 2002). No connection between E_p and P is suggested in the Budyko framework.

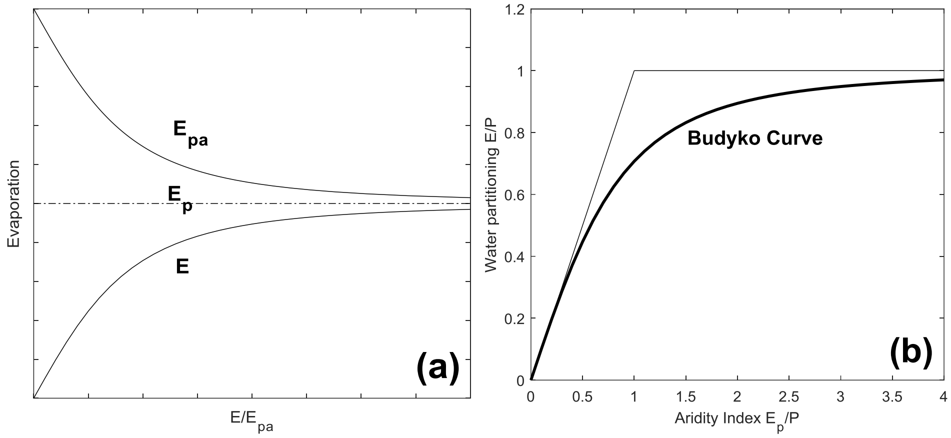


Fig. 1. Conceptual representations of **(a)** the complementary relationship and **(b)** Budyko framework.

~~Our~~Table 1. Types of evaporation in the Budyko framework and the original CR, and their redefined evaporation type based on generalized CR. The last column refers to the definitions of the three types of evaporation in the generalized CR provided in Brutsaert (2015).

Budyko Framework	Bouchet's Complementary Relationship	Generalized Complementary Relationship	Evaporation Definitions in Brutsaert (2015)
Actual evaporation (E)	Actual evaporation (E)	Actual evaporation (E)	The first type
Potential evaporation (E_p)	Wet environment evaporation (E_0)	Potential evaporation (E_p)	The second type
-	Potential evaporation (E_p)	"Apparent" potential evaporation (E_{pa})	The third type

In order to explore the connections between the Budyko framework and the CR, our study investigates the ~~relationship~~relationships between precipitation and potential evaporation as well as between precipitation and “apparent” potential evaporation. We collect warm~~–~~-season precipitation, potential evaporation and pan evaporation data from 259 weather stations across the contiguous US. Studying the ~~relationship~~relationships between P, E_p and E_{pa}, advances our understanding of the well-established classic Budyko framework and the CR. Furthermore, based on insights provided by previous studies (Yang et al., 2006; Roderick et al., 2009; Lhomme and Moussa, 2016), we use a Budyko-type expression to develop a new formulation for the CR.

2. Methodology

2.1 Theoretical development

2.1.1 Budyko framework

The Budyko curve (Fig. 1b) describes the relationship between long-term water partitioning, represented by the ratio of actual evaporation over precipitation, and long-term climate, represented by the ratio of potential evaporation over precipitation, namely aridity index (Budyko, 1958; 1974). In recent decades, the Budyko framework has been examined with annual data (e.g. Yang et al., 2007; Potter and Zhang, 2009; Cheng et al., 2011). A number of Budyko-type functions have been developed to mathematically describe the Budyko curve (Turc, 1954; Fu, 1981; Zhang~~,~~ et al., 2001; Yang et al., 2008; Wang and Tang, 2014). Within these functions, the Turc-Pike equation is a parsimonious single parameter equation (Turc, 1954; Pike, 1964):

$$\frac{E}{P} = \left[1 + \left(\frac{E_p}{P}\right)^{-v}\right]^{-\frac{1}{v}} \qquad (1)$$

where E is actual evaporation, E_p is potential evaporation, P is precipitation, and v is a parameter to represent landscape properties such as vegetation coverage and soil properties (Zhang~~,~~ et al., 2001; Yang~~,~~ et al., 2008). The parameter v needs to be a positive number, and its typical value is 2.0.

2.1.2 Generalized complementary relationship

Bouchet's complementary relationship (Bouchet, 1963) ~~is to describe~~describes the relationship between actual evaporation E and potential evaporation E_p. Brutsaert and Parlange (1998) introduced the term "apparent" potential evaporation E_{pa} and clarified that the CR is between E and E_{pa}, not E and E_p (Fig. 1a). They also proposed a generalized complementary relationship:

$$bE + E_{pa} = (1+b)E_p \quad 0 \le E \le E_p \le E_{pa} \qquad (2)$$

where b is a proportionality parameter not less than one. When b is equal to one, Eq. (2) represents the original complementary relationship (Kahler and Brutsaert, 2006). "Apparent" potential evaporation will be higher than potential evaporation, especially under dry ~~condition~~conditions; while it gradually approaches potential evaporation as the ratio of E over E_{pa} increases (Fig. 1a). As suggested by Morton (1976) and Brutsaert and Stricker (1979), potential evaporation can be estimated using the Priestley-Taylor equation (Priestley and Taylor, 1972~~).~~), which is also called equilibrium evaporation (Brutsaert and Chen, 1995; Jiang and Islam, 2001). "Apparent" potential evaporation can be estimated using the Penman equation (Penman, 1948; Linacre, 1994; Rotstayn et al., 2006) or using data measured at evaporation pans (Brutsaert, 1982; Brutsaert and Parlange, 1998):

$$E_{pa} = aE_{pan} \qquad (3)$$

where E_{pan} is the pan evaporation and a is the pan coefficient. The pan coefficient varies from location to location (Stanhill, 1976; Linacre, 1994). In Kahler and Brutsaert (2006), a pan coefficient of $a = 1.0$ is recommended for mixed natural vegetation, which will be used in this study. It should be noted that the linear relationship between E_{pa} and E_{pan} given in Eq. (3) and the choice of "a" value will not affect the correlations between P, E_p and E_{pa}.

2.1.3 Relationships between P, E_p and E_{pa}

The x-axis of the complementary relationship is a ratio between E and E_{pa} (Bouchet, 1963). Ramírez et al. (2005) used the water-energy framework to link the CR with Budyko approach and changed the x-axis in the CR to moisture availability. Following this idea, several studies have used precipitation or wetness index (P/E_p) to represent moisture availability in the CR (Yang et al., 2006; Roderick et al., 2009). In this study, we also use P to represent moisture availability in the CR. ~~The E_p~~E_p is a horizontal line in the CR that is ~~in~~ parallel ~~with~~to the x-axis (Fig. 1a~~), which is now represented by P.~~). Therefore, the modified CR ~~is indicating~~indicates that ~~P~~P and ~~E_p~~E_p are independent. On the other hand, the upper curve of the CR, ~~which is~~ representing "apparent" potential evaporation ~~E_{pa}, is declining~~E_{pa}, declines along the x-axis, indicating that ~~E_{pa}~~E_{pa} and ~~P~~P are not independent. ~~After changing the x-axis in the CR to P, to have~~For a dimensionless CR, we normalize the x and y axes ~~in the CR~~. The normalized CR describes the relationship between $\frac{E_{pa}}{E_p}$, $\frac{E}{E_p}$, and $\frac{P}{E_p}$ (Fig. 2).

To connect the Budyko framework with the normalized CR~~, and therefore to formulate~~ toward formulating the Bouchet-Budyko curves, we first transform Eq. (1) into a relationship between $\frac{E}{E_p}$ and $\frac{P}{E_p}$:

$$\frac{E}{E_p} = \left[\left(\frac{P}{E_p}\right)^{-v} + 1\right]^{-\frac{1}{v}} \qquad (4)$$

Yang et al. (2006) did similar transformation using ~~Fu's~~the Fu equation (Fu, 1981). Dividing both sides of Eq. (2) by E_p yields:

$$b\frac{E}{E_p} + \frac{E_{pa}}{E_p} = 1 + b \qquad (5)$$

Combining Eqs. (4) and (5), gives a relation between $\frac{P}{E_p}$ and $\frac{E_{pa}}{E_p}$:

$$\frac{E_{pa}}{E_p} = b + 1 - b[(\frac{P}{E_p})^{-v} + 1]^{-1/v} \qquad E_{pa} \geq E_p \qquad (6)$$

Equations (4) and (6) represent the lower and upper curves of the normalized CR respectively (Fig. 2). Roderick et al. (2009) presented a similar framework, without the formulation of the curves. To verify the relationships between ~~precipitation, potential evaporation~~P, E_p, and ~~“apparent” potential evaporation~~E_{pa}, and to examine the Bouchet-Budyko curves in Eqs. (4) and (6), we analyze climate data from 259 weather stations across the contiguous US.

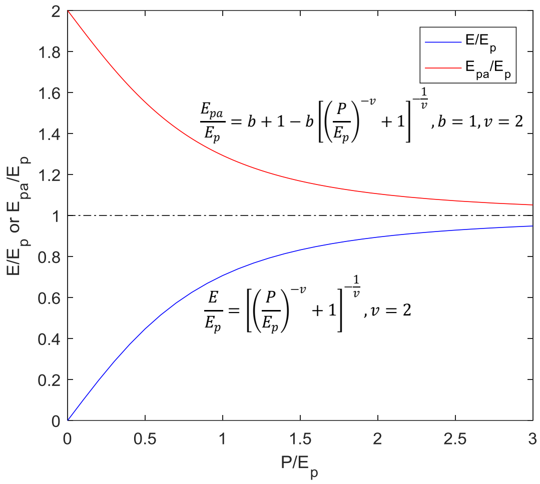


Fig. 2. Dimensionless Bouchet-Budyko curves in the normalized complementary relationship.

2.2 Data sources

Monthly precipitation and pan evaporation are collected from the National Oceanic and Atmospheric Administration (NOAA) at the National Climatic Data Center (NCDC). The data can be downloaded at: https://www.ncdc.noaa.gov/IPS/cd/cd.html . The precipitation data are measured using standard rain gauge and the pan evaporation data using Class A evaporation pans. We collect data for the period 1984-2015 from a total of 259 weather stations (Fig. 3a). Since pan evaporation is collected only during warm months (when temperatures remain above freezing), the weather stations at cold regions have less than 12 months of pan readings in a year. We call the period of warm months in a year “warm-season”. We calculate the monthly average ~~of~~ pan evaporation and precipitation using only the warm months ~~with available pan evaporation data~~ for each year at each weather station. ~~The calculated warm month averages are used to represent warm season pan evaporation and precipitation in each year.~~ For short, it is called warm-season data (i.e., warm-season pan evaporation, warm-season precipitation). We also calculate the annually averaged warm~~-~~-season data to represent the long~~-~~-term average level of pan evaporation and precipitation at each station. For short, it is called long~~-~~-term average data. Over the 259 selected stations, there is an average of seven months per year with ~~warm season~~available pan evaporation data. As Fig. 3 shows, the number of available months decreases from ~~Southern~~the southern regions to ~~Northern~~the northern regions. For stations in the southern states with all 12 months of available data in a year, the full year will be considered as a warm-season. The northern state stations have fewer warm months, and, accordingly, the warm-season is much shorter. On the other hand, not all 259 weather stations have the full record from 1984 to 2015, the average number of years with available data for each location is 18. A complete summary of the information available at all 259 weather station is provided in Table S1. In order to minimize the uncertainty from various warm periods in a year from station to station, we repeat the analysis using an alternative source of pan evaporation in the NCDC dataset containing homogenized warm month data from May to October (Hobbins, et al., 2017). A total of 93 weather stations overlap both sets of pan evaporation data for the period 1984 to 2001 (Fig. 3b). ~~After data collection, we~~We convert pan evaporation in the NCDC dataset to "apparent" potential evaporation using Eq. (3). ~~The potential evaporation E_p data are generated using the Priestley-Taylor equation with remotely sensed net radiation (Zhang et al., 2010):~~

The E_p data are collected from a remote-sensing dataset (Zhang et al., 2010), which is generated using the Priestley-Taylor equation with remotely sensed net radiation:

$$\lambda E_p = \alpha \frac{\Delta}{\Delta+\gamma}(R_n - G) \qquad (7)$$

~~where~~where λ (J/kg) is the latent heat of vaporization; λE_p (W/m^2) is the latent heat flux; α is a coefficient to account for the effect of surface characteristics and vegetation, and is set to 1.26; Δ

(Pa/°C) is the slope of the saturated vapor pressure curve; γ (Pa/°C) is the psychometric constant; R_n (W/m^2) is the net radiation; and G (W/m^2) is the heat flux into the ground. The E_p data cover the period 1983-2006. Similar with P and ~~E_{pan}~~E_{pa}, we calculate the warm~~-~~-season E_p and long~~-~~-term annually averaged~~ warm season~~ E_p based on the monthly E_p data.

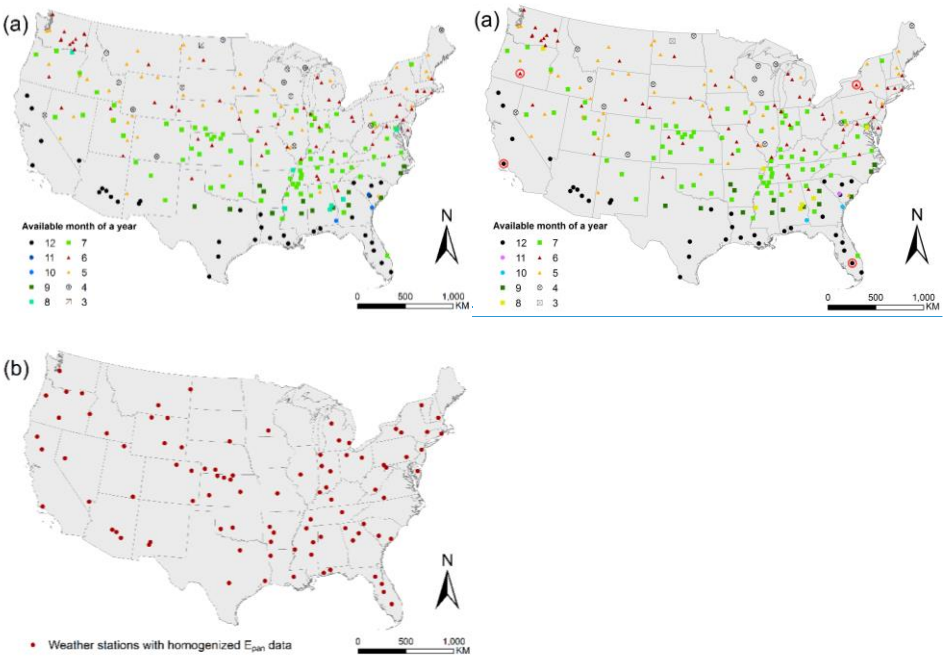


Fig. 3. **(a)** Map of 259 weather stations. The available month of a year of pan evaporation data for each weather station is presented using legends with different colors and shapes. Four representative weather stations are selected from the four quadrants of the US respectively, which are highlighted with red circles. **(b)** Map of 93 weather stations with homogenized pan evaporation data that overlap the 259-station dataset.

2.3 P, E_p and E_{pa} correlation analysis

Using the collected weather station data of precipitation and pan evaporation for the period 1984 to 2015, we first calculate the Pearson correlation coefficient between warm~~-~~-season P and warm -season E_{pa} for each location (Fig. 3a). We then perform the same correlation analysis of P and E_{pa} using the homogenized pan evaporation dataset (Hobbins et al., 2017) (Fig. 3b). Secondly, we use data of warm~~-~~-season P and warm~~-~~-season E_p for the period of 1984 to 2006, which is the period both P and E_p data are available, to investigate the correlation between P and E_p. Finally, to validate the newly derived Bouchet-Budyko curves, the relationship between $\frac{P}{E_p}$ and $\frac{E_{pa}}{E_p}$ is plotted using the collected data at both seasonal and long~~-~~-term average time scales.

3. Results

3.1 Correlations among P, E_p, and E_{pa}

In the 259 weather stations, 93% of the stations have a negative correlation between P and E_{pa} (Fig. 4a~~). However,~~), but only 43% of the stations ~~have~~are statistically significant ~~correlation~~ ($p<0.05$~~) between P and E_{pa} (~~; Fig. 4b). All ~~the weather stations with~~ significant P, E_{pa} ~~correlation have~~correlations are negative ~~correlation~~. The weather stations located in the western region (regions with longitude higher than the weather station average longitude of W 94.81°) are more likely to have a significant P, E_{pa} negative correlation than those located in the east~~.~~ (regions with longitude lower than W 94.81°). This spatial difference may be related to climate characteristics~~ that~~: the eastern region has higher precipitation ~~and lower aridity index,~~(averagely 105.5 mm/month) and lower “apparent” potential evaporation (averagely 145.3 mm/month), while the western region has lower precipitation ~~and higher aridity index.~~(averagely 44.6 mm/month) and higher “apparent” potential evaporation (averagely 203.5 mm/month). The

Bouchet’s complementary relationship is more significant in arid regions (Ramírez et al., 2005), corresponding to the left side of the CR curves; while it is less significant in humid regions, corresponding to the right side of the CR curves (Fig. 1a). As a result, the negative correlation between precipitation and “apparent” potential evaporation is more significant in the west than in the east.

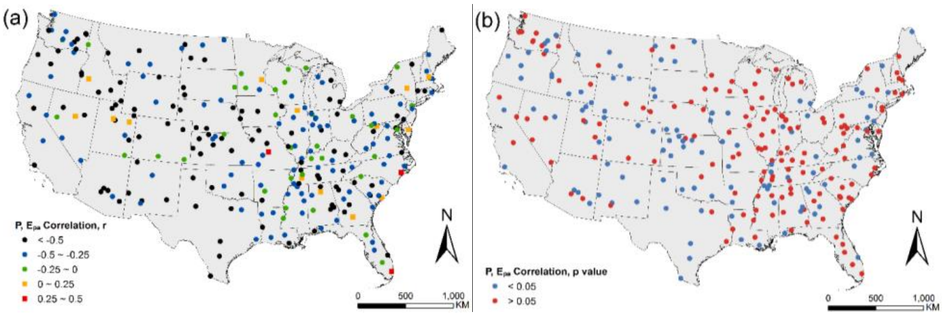


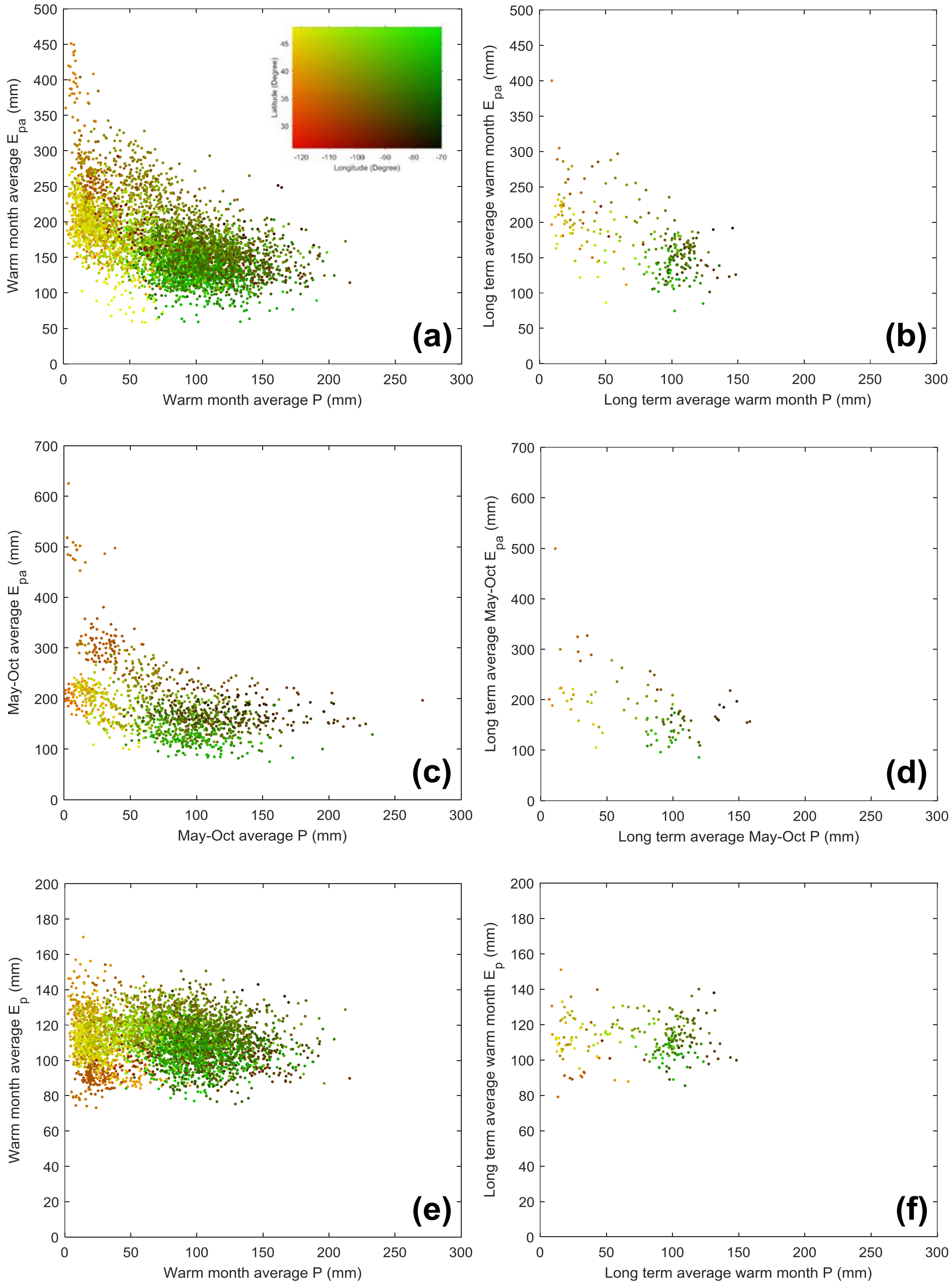
Fig. 4. Map of point~~-~~-scale annual P, E_{pa} correlation at 259 weather stations, **(a)** r value and **(b)** p value.

~~We then plot all~~ All the warm~~-~~-season ~~data~~P vs. E_{pa} relations (i.e., all years, all seasons, for a total of ~~each year each station, totally~~ 5312 data points~~, on a P vs. E_{pa} figure (~~) are shown in Fig. 5a~~)~~.. The data cloud shows a negative trend in general. We also plot the long~~-~~-term annually averaged values of warm~~-~~-season P and E_{pa} of the 259 weather stations (Fig. 5b), which shows a similar negative trend. Hobbins et al. (2004) showed a similar negative trend between ~~P~~precipitation and ~~E_{pan}~~pan evaporation with watershed scale data. To represent the spatial distribution of the weather stations, we color code the data points based on their spatial coordinates of latitude and longitude. The climate in the eastern US is much wetter than the western US, and therefore the data cloud of E_{pa} vs. P is separated into two parts horizontally. The right side of the cloud ~~is mostly green and brown, representing~~represents the northeastern and southeastern ~~areas of the~~ US (green and brown, respectively~~;~~); while the left side of the cloud ~~is mostly yellow and red, representing~~generally represents the northwestern and southwestern ~~areas,~~ US (yellow and red, respectively~~. The left side cloud is more vertically oriented, indicating that the western region has higher E_{pa} variability than P variability. Southwestern region has the highest E_{pa} in the US, represented by the red and orange points. Northwestern region has much lower E_{pa}, represented by the yellow points. On the other hand, the right side cloud is more horizontally oriented, indicating that the eastern region has higher P variability than E_{pa}. Unlike the western region, the difference between the northeastern and southeastern regions are not very distinguishable. Southeastern region of the US has a wide range of precipitation; while points of the northeastern region are more concentrated.~~).

As explained before, we also use an alternative pan evaporation dataset (Hobbins et al., 2017) to further validate our analysis result. This dataset is homogenized to have the same period of pan evaporation data record in each year from May to October ~~and therefore~~. In order to minimize the ~~uncertainty~~data heterogeneity caused by station move and human errors, this dataset compiled pan evaporation data from 247 stations across the ~~various length of warm period from station to station~~US with thorough quality control. It is derived from the same dataset as our data, namely the NCDC dataset. Based on the homogenized pan evaporation data, 85 stations out of 93 (91%) have a negative correlation between P and E_{pa}. ~~Only~~Of these, 41% of the stations have a statistically significant ~~correlation~~relationship ($p<0.05$~~). All the significant correlations are~~); all negative. This result is consistent with the analysis result based on our collected data from 259 weather stations. We also use the data cloud to show the relationship between P and E_{pa} in the warm period of May to October in each year at each of the 93 stations (Fig. 5c), as well as the relationship of long-term annually averaged warm period P and E_{pa} (Fig.

5d). The trend of data cloud is similar with the data cloud trend using our collected data at both seasonal and long~~-~~-term average time scales. In other words, both datasets show a negative relationship between P and E_{pa}.

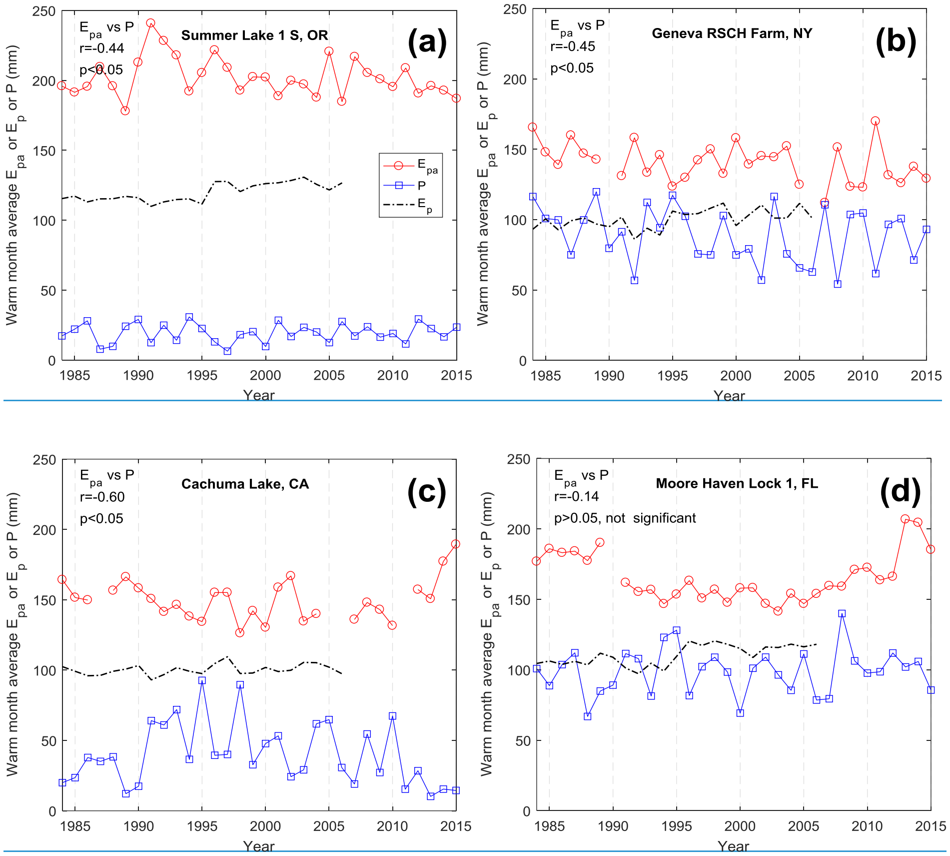
~~We then plot the relationship between~~ The P and E_p ~~(Fig.~~data are shown in Figures 5e and 5f~~), using the E_p data generated by a remote-sensing algorithm based on the Priestley-Taylor equation as explained previously (Zhang et al., 2010).~~. At both seasonal and long~~-~~-term average time scales, there is no clear relationship shown between P and E_p, confirming the independence between P and E_p discussed in Section 2.1.3. This result shows the difference between E_p and E_{pa}, that E_p is independent from P but E_{pa} is not. Therefore, it is important to distinguish E_{pa} from E_p and to understand the different physical mechanisms of the two processes (Brutsaert, 2015).



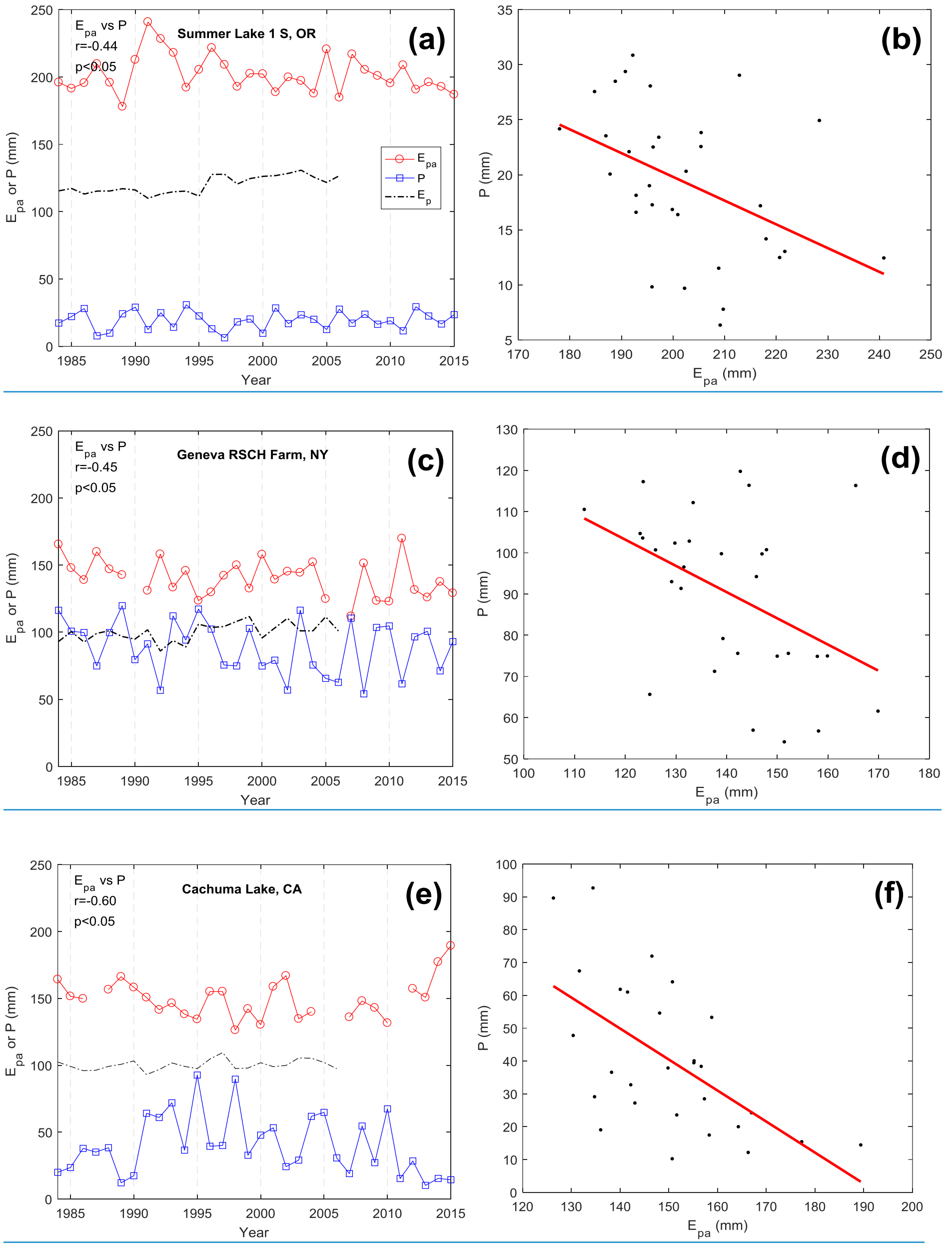
(a)
Warm month average E_{pa} (mm)
Warm month average P (mm)
Latitude (Degree)
45
40
35
30
-120
-110
-100
-90
-80
-70
Longitude (Degree)
(b)
Long term average warm month E_{pa} (mm)
Long term average warm month P (mm)
(c)
May-Oct average E_{pa} (mm)
May-Oct average P (mm)
(d)
Long term average May-Oct E_{pa} (mm)
Long term average May-Oct P (mm)
(e)
Warm month average E_p (mm)
Warm month average P (mm)
(f)
Long term average warm month E_p (mm)
Long term average warm month P (mm)
0
50
100
150
200
250
300
350
400
450
500
600
700
20
40
60
80
120
140
160
180

Fig. 5. P vs. E_{pa} at 259 weather stations in the US for the period 1984 to 2015 for **(a)** warm~~-~~-season data (N=5312), and **(b)** long~~-~~-term annually averaged warm~~-~~-season data (N=259). The data points are color coded based on their latitudes and longitudes. P vs. E_{pa} at 93 weather stations in the US for the period 1984 to 2001 using the homogenized pan evaporation dataset for **(c)** warm period May-Oct in each year (N=1214), and **(d)** long~~-~~-term annual average warm period May-Oct data (N=93). P vs. E_p at the 259 weather stations for the period of 1984 to 2006 for **(e)** warm~~-~~-season data (N=5312) and **(f)** long~~-~~-term annual average warm~~-~~-season data (N=259).

To present the P, E_p and E_{pa} ~~relationship~~relationships at individual locations and therefore to further investigate the dependence between the three variables, we select four weather stations from the ~~northwest, northeast, southwest, and southeast regions respectively~~four quadrants of the contiguous US (Fig. 3a), to show the warm~~-~~-season P, E_p and E_{pa} in time series (Fig. 6). The two stations in the southern regions have data in all 12 months of a year; while the two stations in the northern regions only have ~~pan evaporation~~E_{pa} data ~~in warm~~for six months of ~~6 or 7 months of a~~each year. All four stations show negative correlations between P and E_{pa}. This negative correlation at the ~~selected~~ weather station in Florida is not statistically significant (~~Fig. 6d~~Figs. 6g and 6h). As mentioned before, the P and E_{pa} correlation is less significant in the eastern region than in the west, because of the ~~higher humidity~~wetter climate in the east. On the other hand, at the other three locations, the warm~~-~~-season P and E_{pa} are relatively symmetric to each other (~~Fig~~Figs. 6a~~, 6b, and 6c~~ to 6f). During years when one series is above average, the other tends to be below average and vice versa. In terms of the relationship between P and E_p, all four locations show no significant correlations between the two variables (p>0.05). This is consistent with the independence of P and E_p shown in Fig. 5e and 5f.



(a)
Summer Lake 1 S, OR
E_{pa} vs P
r=-0.44
p<0.05
E_{pa}
P
E_p
(b)
Geneva RSCH Farm, NY
E_{pa} vs P
r=-0.45
p<0.05
(c)
Cachuma Lake, CA
E_{pa} vs P
r=-0.60
p<0.05
(d)
Moore Haven Lock 1, FL
E_{pa} vs P
r=-0.14
p>0.05, not significant
Warm month average E_{pa} or E_p or P (mm)
Year
0
50
100
150
200
250
1985
1990
1995
2000
2005
2010
2015



(a)
Summer Lake 1 S, OR
E_{pa} vs P
r=-0.44
p<0.05
E_{pa}
P
E_p
E_{pa} or P (mm)
Year
(b)
P (mm)
E_{pa} (mm)
(c)
Geneva RSCH Farm, NY
E_{pa} vs P
r=-0.45
p<0.05
E_{pa} or P (mm)
Year
(d)
P (mm)
E_{pa} (mm)
(e)
Cachuma Lake, CA
E_{pa} vs P
r=-0.60
p<0.05
E_{pa} or P (mm)
Year
(f)
P (mm)
E_{pa} (mm)

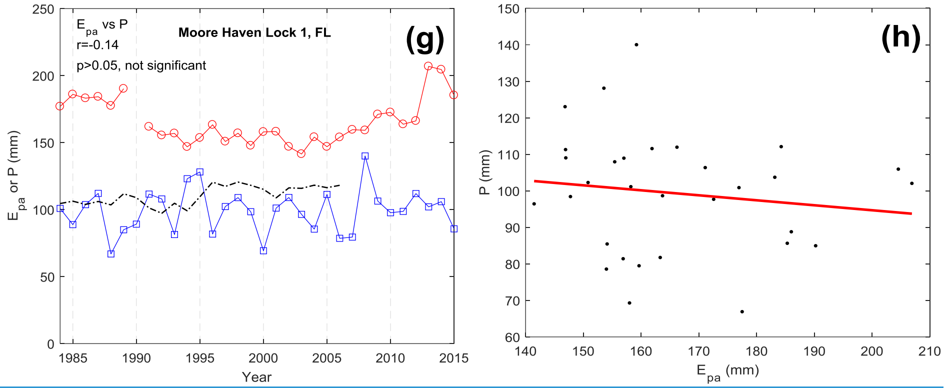


Fig. 6. Warm~~–~~-season P, E_p and E_{pa} time series of four example weather stations in the study period of 1984-2015: **(a)** Summer Lake 1 S, OR (N 42°58’, W 120°47’); **(~~b~~c)** Geneva RSCH Farm, NY (N 42°53’, W 77°20’); **(~~c~~e)** Cachuma Lake, CA (N 34°35’, W 119°59’); ~~and (**d**~~**(g)** Moore Haven Lock 1, FL (N 26°50’, W 81°50’); and the scatterplots of P vs E_{pa} at the four example stations (**b**, **d**, **f**, **h**).

3.2 Bouchet-Budyko curves

There are two Bouchet-Budyko curves (Fig. 2). The upper curve describes the relationship between E_{pa}, E_p and P (Eq. 6) and the lower curve describes the relationship between E, E_p and P (Eq. 4). The lower curve is derived from the Budyko curve based on Turc-Pike equation. This relationship between E, ~~P~~E_p and ~~E_p~~P has been studied extensively following the Budyko framework~~,~~ and~~ it is,~~ therefore, it is not the focus of this study. This study investigates the relationship between E_{pa}, E_p and P, which is represented by the upper Bouchet-Budyko curve. Since the collected weather station data of P and ~~E_{pan}~~E_{pa} are available 1984 to 2015 and the E_p data ~~generated~~collected from the remote-sensing ~~algorithm~~dataset are available 1983 to 2006, we

~~study~~examine the relationship between P/E_p and E_{pa}/E_p in the overlapping period of 1984 to 2006~~. Based on warm season data of P, E_p and E_{pan}, we plot the relationship between P/E_p and E_{pa}/E_p~~ (Fig. 7). ~~We draw~~ Using Eq. (6) three curves ~~using Eq. (6)~~ with different *b* values ~~of~~ (1, 2, and 3~~.~~) are shown in Figure 7. The *v* value is set at 2, which is ~~a~~ commonly used ~~value~~ in the Budyko framework. When *b* equals one, the two CR curves are symmetric. When *b* exceeds one, the two CR curves are asymmetric. This asymmetry is discussed in previous studies (Kahler and Brutsaert, 2006; Brutsaert, 2015). One explanation of this asymmetry between E and E_{pa} is that the evaporation pan will receive more heat than the surrounding area (Kahler and Brutsaert, 2006). Brutsaert (2015) reports an even higher *b* values ~~around~~of 4.5. The horizontal solid black line in Fig. 7 is the boundary of the upper Bouchet-Budyko curve ~~that~~, above which E_{pa} ~~≥~~ exceeds E_p.

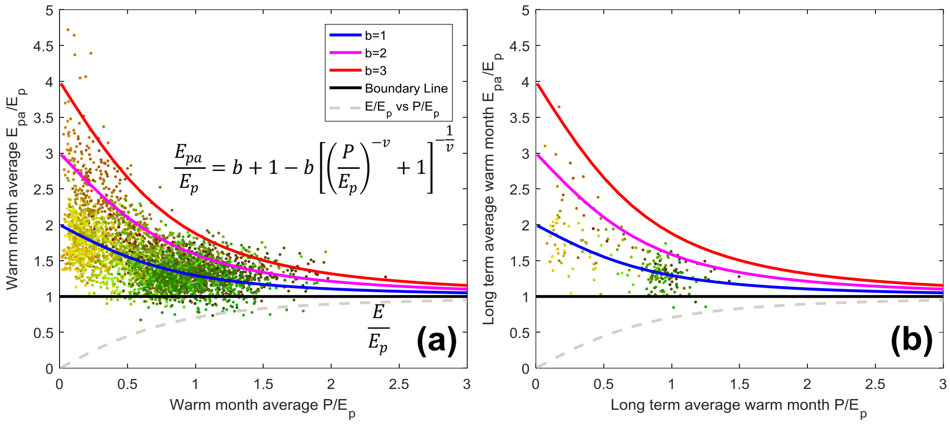


Fig. 7. P/E_p vs. E_{pa}/E_p at 259 weather stations in the US for the period 1984 to 2015 for **(a)** warm-season data (N=5312), and **(b)** long~~-~~-term average data (N=259). The data points are color coded based on their latitudes and longitudes. The three upper Bouchet-Budyko curves are

plotted with different b values of b=1, b=2, and b=3, and with the same v value of v=2. The dashed line is the lower Bouchet-Budyko curve with v=2.

4. Discussion

4.1 Relationship between P and E_{pa}, and between P and E_p

With the weather station data, a negative correlation between warm~~-~~-season ~~precipitation~~P and ~~“apparent” potential evaporation~~E_{pa} is shown in 242 out of 259 weather stations (93%). The negative correlation between P and E_{pa} is linked by the humidity deficit. The formation of precipitation is positively related to the local level of humidity (Pal et al., 2000; Sheffield et al., 2006; An et al., 2017) while “apparent” potential evaporation is inversely related to humidity or positively related to the humidity deficit (Penman, 1948; Allen et al., 1998). As a result, precipitation and “apparent” potential evaporation will tend to exhibit a negative correlation. ~~Similar with~~According to the Bouchet’s complementary relationship, this negative correlation between P and E_{pa} is more ~~significant~~pronounced in arid regions than in humid regions.

On the other hand, P and E_p shows no significant correlation at both the seasonal and the long-term average time scales. ~~Potential evaporation is driven by energy supply, which is quantified by the Priestley-Taylor equation using the remote-sensing data (Zhang, et al., 2010).~~ As a result, our study indicates that ~~energy supply~~ potential evaporation and precipitation, the ~~representation~~representations of energy supply and water supply, are likely to be independent. This independence is currently under investigation with field data. It should be noted that the relationship between ~~P~~P and ~~E_p~~E_p and between ~~P~~P and ~~E_{pa} we find~~E_{pa} found in this study are not direct causal ~~relationship~~relationships, but rather the result of interactions between a number

Formatted: Font: Italic

of physical variables~~. We will collect more data~~, such as net radiation, wind speed, humidity, and ~~further investigate~~so forth. Further investigation into the physical mechanisms ~~of~~connecting these ~~relationships in future studies~~variables is underway.

4.2 The Bouchet-Budyko curve and its applications

Combining the Bouchet's complementary relationship and the Budyko framework leads to two dimensionless CR curves, normalized by E_p (Fig. 2). The upper Bouchet-Budyko curve is derived from the connection between Budyko framework and the CR, and the lower Bouchet-Budyko curve is derived directly ~~derived~~ from the Budyko framework, based on the Turc-Pike equation. The ~~two~~companion CR curves show that ~~when~~as the wetness index P/E_p ~~is lower than one,~~decreases, the difference between E and E_{pa} grows. This indicates the complementary relationship between E and E_{pa} is ~~more significant. In other words~~most pronounced in arid environments; that is, the CR is more significant under water~~-~~ limited condition. As discussed in Ramírez et al. (2005), the CR can be considered as an extension of the Budyko framework. ~~With the Bouchet-Budyko curves shown in Fig. 2, this connection can be quantitatively analyzed, which will be our future study direction.~~

The P, E_p and E_{pa} collected ~~data of P, E_p and E_{pan} fits with~~in this study are following the general trend of the upper Bouchet-Budyko curve (Fig. 7). The remote-sensing data of E_p may not have the same level of accuracy as the field measured P and ~~E_{pan} and the~~E_{pa}. The value of α in the Eq. (7) may vary from location to location (Chen and Brutsaert, 1995; Brutsaert and Chen, 1995). ~~This~~Such factors may explain the deviation of some data points from the CR curve in Fig. 7.

This upper Bouchet-Budyko curve can be used to estimate the ~~"apparent" potential evaporation~~E_{pa} based on the data of ~~precipitation~~P and ~~potential evaporation~~E_p. The "apparent" potential evaporation can be measured by evaporation pan, but this measurement has its limitations. For example, it is only ~~functional in~~available for warm ~~period~~periods. The collected data with time averaged pan evaporation levels over weeks, months, and years may lead to systematic error in surface flux calculations (Brutsaert, 1982; Kahler and Brutsaert, 2006). The Bouchet-Budyko curve can help us to estimate E_{pa} without the ~~limitation~~limitations of evaporation pans. Comparing with more physically~~-~~ based E_{pa} quantification approaches, such as Penman equation (Penman, 1948) and "PenPan" model (Rotstayn et al., 2006), our model is derived from conceptual frameworks and therefore may provide top-down insights about the E_{pa} level in hydrologic systems.

~~In addition, the lower Bouchet-Budyko curve is based on an alternative form of Budyko-type equation (Eq. 4), derived from the Turc-Pike equation. This curve can be used to show the relationship between E and E_p under varying climate characteristic. We will collect field evaporation data to investigate this curve in future studies.~~

Similar to the Budyko framework, the Bouchet-Budyko curves can be used in hydrologic models and climate models. ~~Furthermore, the upper and lower curves can be used to estimate the trend of "apparent" potential evaporation and actual evaporation respectively, based on the level of precipitation and potential evaporation. These Bouchet-Budyko curves can also~~These Bouchet-Budyko curves can be used to examine the fidelity of simulated precipitation and evaporation sequences routinely produced by general circulation models to drive climate change investigations.

5. Conclusions

We ~~collect~~collected warm~~-~~-season precipitation, potential evaporation, and ~~pan~~“apparent” potential evaporation data at 259 weather stations in the US to investigate the correlation among these three physical variables. The results ~~show~~showed a negative correlation between P and E_{pa} ~~in~~at 93% of the ~~study locations.~~stations. The physical reason ~~of~~for the P, E_{pa} negative correlation could be related to the humidity variability. When humidity increases, the likelihood for precipitation increases while the rate of ~~pan~~“apparent” potential evaporation decreases. On the other hand, our study results ~~on the relationship between warm season P and E_p~~ ~~support~~supported the assumption that P and E_p are independent. ~~By combining~~Combining the CR with a Budyko-type equation, we ~~formulate~~formulated the companion CR curves, showing the connection between the ~~two~~Bouchet and Budyko frameworks. ~~As a result, this research~~These insights may encourage hydrologists to ~~generate new ideas on the interpretation of~~further explore the strong link between the Budyko framework and the CR, promoting new ways of hydrologic modeling. Future work will investigate the physical ~~mechanism~~mechanisms behind the newly-derived Bouchet-Budyko curves and explore the application of ~~Bouchet-Budyko~~these companion curves.

Acknowledgment

We thank the Editor and the three anonymous reviewers for their insightful and critical comments and valuable suggestions. The data of precipitation and pan evaporation measurements can be downloaded from the National Climatic Data Center website: https://www.ncdc.noaa.gov/IPS/cd/cd.html. The homogenized pan evaporation data can be

downloaded from the USGS ScienceBase: https://www.sciencebase.gov/catalog/. The data of remote-sensing based potential evaporation ~~is~~are provided by the Numerical Terradynamic Simulation Group at University of Montana, based on the study of Zhang et al. (2010). The data can be downloaded from their website: http://www.ntsg.umt.edu/about/default.php.

References

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (Eds.): Crop evapotranspiration: Guidelines for computing crop water requirements, Irrig. Drainage Pap. 56, Food and Agric. Org., Rome, 1998.

Aminzadeh, M., Roderick, M. L., and Or, D.: A generalized complementary relationship between actual and potential evaporation defined by a reference surface temperature, Water Resour. Res., 52, 385-406, doi:10.1002/2015WR017969, 2015.

An, N., Wang, K., Zhou, C., and Pinker, R. T.: Observed variability of cloud frequency and cloud-based height within 3600 m above the surface over the contiguous United States, J. Climate, 30, 3725-3742, doi:10.1175/JCLI-D-16-0559.1, 2017.

Arora, V. K.: The use of the aridity index to assess climate change effect on annual runoff, J. Hydrol., 265, 164-177, 2002.

Bouchet, R.: Evapotranspiration reelle et potentielle, signification climatique, IAHS Publ., 62, 134-142, 1963.

Brutsaert, W.: Hydrology: An Introduction, Cambridge Univ. Press, N. Y., 2005.

Brutsaert, W. and Chen, D.: Desorption and the two stages of drying of natural tallgrass prairie, Water Resour. Res., 31, 1305-1313, 1995.

Brutsaert, W. and Parlange, M. B.: Hydrologic cycle explains the evaporation paradox, Nature, 396(5), 300, 1998.

Brutsaert, W. and Stricker, H.: An advection-aridity approach to estimate actual regional evapotranspiration, Water Resour. Res., 15(2), 443-450, 1979.

Brutsaert, W.: A generalized complementary principle with physical constraints for land-surface evaporation, Water Resour. Res., 51, 8087-8093, doi:10.1002/2015WR017720, 2015.

Brutsaert, W.: Evaporation into the Atmosphere: Theory, History and Applications, 299 pp., Springer, New York, 1982.

Budyko, M. I.: Climate and Life, translated from Russian by D. H. Miller, Elsevier, New York, 1974.

Budyko, M. I.: The Heat Balance of the Earth's Surface, U.S. Dep. of Commer., Washington, D. C, 1958.

Carmona, A. M., Poveda, G., Sivapalan, M., Vallejo-Bernal, S. M., and Bustamante, E.: A scaling approach to Budyko's framework and the complementary relationship of evapotranspiration in humid environments: case study of the Amazon River basin, Hydrol. Earth Syst. Sci., 20, 589-603, 2016.

Chen, D. and Brutsaert, W.: Diagnostics of land surface spatial variability and water vapor flux, J. Geophys. Res., 100, 25,595-25,606, 1995.

Chen, X., Alimohammadi, N., and Wang, D.: Modeling interannual variability of seasonal evaporation and storage change based on the extended Budyko framework, Water Resour. Res., 49, 6067-6078, doi:10.1002/wrcr.20493, 2013.

Cheng, L., Xu, Z., Wang, D., and Cai, X.: Assessing inter-annual variability of ET at the catchment scale using satellite-based ET datasets, Water Resour. Res., 47, W09509, doi:10.1029/2011WR010636, 2011.

Donohue, R. J., Roderick, M. L., and McVicar, T. R.: On the importance of including vegetation dynamics in Budyko's hydrological model, Hydrol. Earth Syst. Sci., 11, 983-995, doi:10.5194/hess-11-983-2007, 2007.

Fu, B. P.: On the calculation of the evaporation from land surface [in Chinese], Sci. Atmos. Sin., 5, 23-31, 1981.

Hobbins, M. T., Barsugli, J. J., Dewes, C. F., and Rangwala, I.: Monthly pan evaporation data across the continental United States between 1950-2001, doi:10.21429/C9MW25, 2017.

Hobbins, M. T., Ramírez, J. A., and Brown, T. C.: Trends in pan evaporation and actual evapotranspiration across the conterminous U.S.: Paradoxical or complementary?, Geophys. Res. Lett., 31, doi:10.1029/2004GL019846, 2004.

Jiang, L. and Islam, S.: Estimation of surface evaporation map over surthern Great Plains using remote sensing data, Water Resour. Res., 37(2), 329-340, 2001.

Kahler, D. M., and Brutsaert, W.: Complementary relationship between daily evaporation in the environment and pan evaporation, Water Resour. Res., 42, W05413, doi:10.1029/2005WR004541, 2006.

Lhomme, J. and Moussa, R.: Matching the Budyko functions with the complementary evaporation relationship: consequences for the drying power of the air and the Priestley-Taylor coefficient, Hydrol. Earth Syst. Sci., 20, 4857-4865, doi:10.5194/hess-20-4857-2016, 2016.

Linacre, E. T.: Estimating U.S. class A pan evaporation from few climate data, Water Int., 19(1), 5-14, 1994.

Milly, P. C. D.: Climate, soil water storage, and the average annual water balance, Water Resour. Res., 30, 2143-2156, 1994.

Morton, F. I.: Climatological estimates of evapotranspiration, J. Hydraul. Div., 102(3), 275-291, 1976.

Pal, J. S., Small, E. E., and Eltahir, E. A. B.: Simulation of regional-scale water and energy budgets: Representation of subgrid cloud and precipitation processes within RegCM, J. Geophys. Res., 105, 29,579-29,594, 2000.

Penman, H. L.: Natural evaporation from open water, bare and grass, Proc. R. Soc., Ser. A, 193, 120-145, 1948.

Pike, J. G.: The estimation of annual run-off from meteorological data in a tropical climate, J. Hydrol., 2(2), 116-123, 1964.

Potter, N. J., and Zhang, L.: Interannual variability of catchment water balance in Australia, J. Hydrol., 369, 120-129, 2009.

Priestley, C. H. B. and Taylor, R. J.: On the assessment of surface heat flux and evaporation using large-scale parameters, Mon. Weather Rev., 100(2), 81-92, 1972.

Ramírez, J. A., Hobbins, M. T., and Brown, T. C.: Observational evidence of the complementary relationship in regional evaporation lends strong support for Bouchet's hypothesis, Geophys. Res. Lett., 32, L15401, doi:10:1029/2005GL023549, 2005.

Roderick, M. L., Hobbins, M. T., and Farquhar, G. D.: an evaporation trends and the terrestrial water balance. II. Energy balance and interpretation, Geogr. Compass, 761-780, doi:10.1111/j.1749-8198.2008.00214.x, 2009.

Rotstayn, N. D., Roderick, M. L., and Farquhar, G. D.: A simple pan-evaporation model for analysis of climate simulations: Evaluation over Australia, Geophys. Res. Lett., 33, doi:10.1029/2006GL027114, 2006.

Sheffield, J., Goteti, G., and Wood, E. F.: Development of a 50-year high-resolution global dataset of meteorological forcings for land surface modeling, J. Climate, 19, 3088-3111, 2006.

Shuttleworth, W. J.: Evaporation, in Handbook of Hydrology, edited by D. R. Maidment, pp. 4.1-4.53, McGraw-Hill, New York, 1993.

Stanhill, G.: The CIMO international evaporimeter comparisons, Publication 449, World Meteorological organization, Geneva, 38 pp, 1976.

Thornthwaite, C. W.: An approach toward a rational classification of climate, Geogr. Rev., 38, 55-94, 1948.

Turc, L.: Le bilan d'eau des sols: Relation entre les precipitations, l'evaporation er l'ecoulement, Ann. Agron., 5, 491-569, 1954.

Van Bavel, C. H. M.: Potential evaporation: The combination concept and its experimental verification, Water Resour. Res., 2, 455-467, doi:10.1029/WR002i003p00455, 1966.

Wang, D. and Alimohammadi, N.: Responses of annual runoff, evaporation, and storage change to climate variability at the watershed scale, Water Resour. Res., 48, W05546, doi:10.1029/2011WR011444, 2012.

Wang, D. and Tang, Y.: A one-parameter Budyko model for water balance captures emergent behavior in Darwinian hydrologic models, Geophys. Res. Lett., 41, 4569-4577, doi:10.1002/2014GL060509, 2014.

Xu, X., Yang, D., Yang, H., and Lei, H.: Attribution analysis based on the Budyko hypothesis for detecting the dominant cause of runoff decline in Haihe basin, J. Hydrol., 510, 530-540, doi:10.1016/j.jhydrol.2013.12.052, 2014.

Yang, D., Sun, F., Liu, Z., Cong, Z., and Lei, Z.: Interpreting the complementary relationship in non-humid environments based on the Budyko and Penman hypotheses, Geophys. Res. Lett., 33, L18402, doi:10.1029/2006GL027657, 2006.

Yang, D., Sun, F., Liu, Z., Cong, Z., Ni, G., and Lei, Z.: Analyzing spatial and temporal variability of annual water-energy balance in nonhumid regions of China using the Budyko hypothesis, Water Resour. Res., 43, 1-12, doi:10.1029/2006WR005224, 2007.

Yang, H. and Yang, D.: Derivation of climate elasticity of runoff to assess the effects of climate change on annual runoff, Water Resour. Res., 47, doi:10.1029/2010WR009287, 2011.

Yang, H., Yang, D., Lei, Z., and Sun, F.: New analytical derivation of the mean annual water-energy balance equation, Water Resour. Res., 44, W03410, doi:10.1029/2007WR006135, 2008.

Zhang, K., Kimball, J. S., Nemani, R. R., and Running, S. W.: A continuous statellite-derived global record of land surface evapotranspiration from 1983 to 2006, Water Resour. Res., 46, W09522, doi:10.1029/2009WR008800, 2010.

Zhang, L., Dawes, W. R., and Walker, G. R.: Response of mean annual evapotranspiration to vegetation changes at catchment scale, Water Resour. Res., 37, 701-708, 2001.

Zhang, L., Potter, N., Hickel, K., Zhang, Y., and Shao, Q.: Water balance modeling over variable time scales based on the Budyko framework – Model development and testing, J. Hydrol., 360, 117-131.

Zhou, S., Yu, B., Huang, Y., and Wang, G.: The complementary relationship and generation of the Budyko functions, Geophys. Res. Lett., 42, 1781-1790, doi:10.1002/2015GL063511, 2015.

Zhou, S., Yu, B., Zhang, L., Huang, Y., Pan, M., and Wang, G.: A new method to partition climate and catchment effect on the mean annual runoff based on the Budyko complementary relationship, Water Resour. Res., 52, doi:10.1002/2016WR019046, 2016.