Assessing the ability of potential evapotranspiration models in capturing dynamics of evaporative demand across various biomes and climatic regimes with ChinaFLUX measurements

ZHENG Han

Institute of Earth Environment, CAS, China

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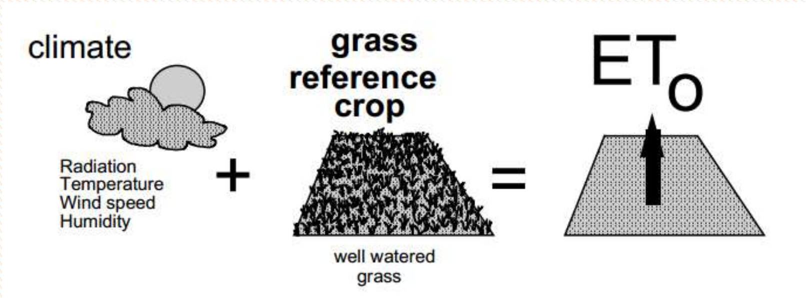
How to quantify Atmospheric Evaporative Demand?

Estimates of AED is widely required for hydrological analyses such as irrigation scheduling, water resources management, drought monitoring, hydroclimatologic variability……

Pan Evaporation (E$_{pan}$)

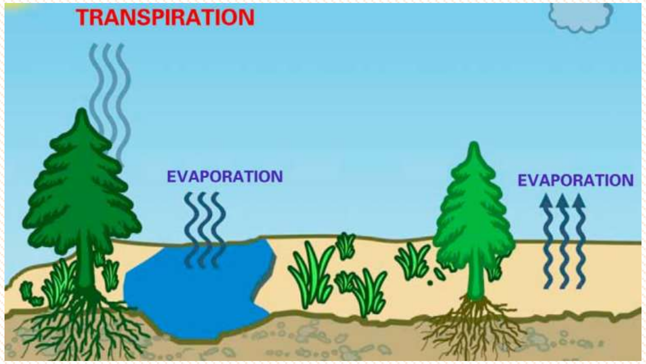
Open water surface

Reference evapotranspiration (ET$_0$)



Well-watered reference vegetated surface

Potential Evapotranspiration (PET)



Hypothetically well-watered actual vegetated surface

PET——the most suitable measure representing AED of actual land surfaces under given metrological conditions

How to choose right PET model from model pool for AED estimating?

PET could be estimated by some physical or empirical models. However, numerous PET models have been introduced, and there may exist significant differences among their estimates and variation trends.

Fully physical or combination model

$$PET_P = \frac{\Delta}{(\Delta + \gamma)} \frac{(R_n - G)}{\lambda} + \frac{\gamma}{(\Delta + \gamma)} \frac{6.43(1 + 0.536u)(e_s - e_a)}{\lambda}$$

Radiation-based Model

$$PET_{PT} = \alpha \times \frac{\Delta}{\Delta + \gamma} \times \frac{(R_n - G)}{\lambda}$$

Temperature-based Model

$$PET_L = \frac{\frac{500(T_a + 0.006z)}{100 - A} + 15(T_a - T_d)}{80 - T_a}$$

Therefore, it is necessary for us to determine the appropriate PET model(s) representing AED, especially for analyses on long-term dynamics in evaporative demand under global climate change.

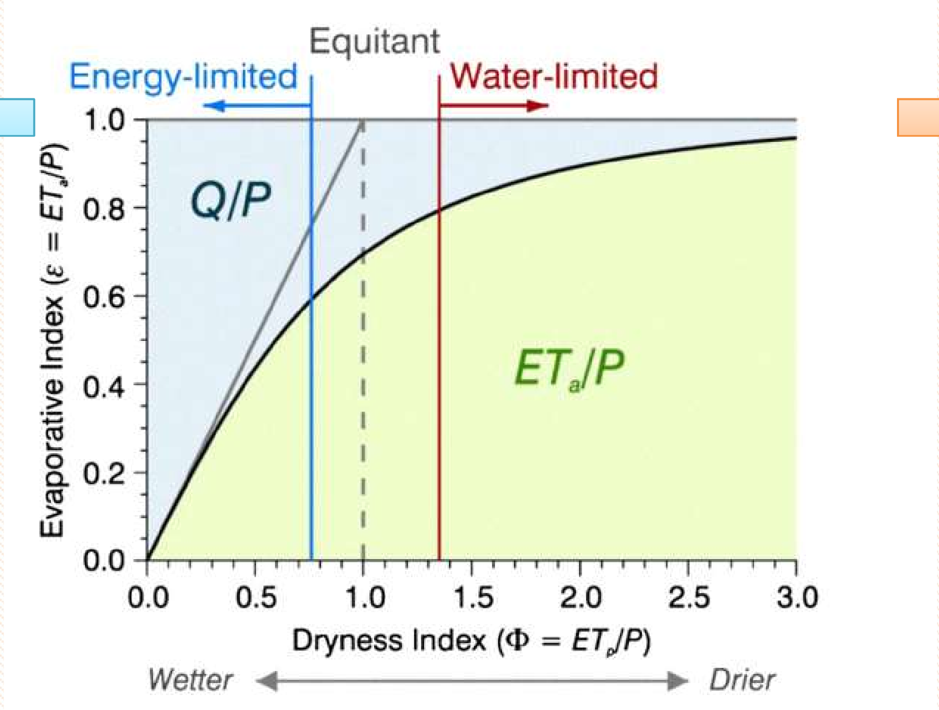
Water-limited vs. Energy-limited Evaporation

These two terms have long been used for understanding the role of evaporation in the water balance at various space-time scales

supply of water exceeds evaporative demand

Actual ET (AET) approaches PET

Proportional Principle



supply of water less than evaporative demand

Trends in PET and AET follows an inverse relationship

Complementary Principle

Therefore, it is necessary to find a feasible way to define the water- or energy-limited states in order to evaluate the capability of PET models in capturing dynamics in AED.

How to define Water- or Energy-limited conditions?

There also exist proportional or inverse relationships between AET trends and P trends for different hydroclimatological conditions. Thus, it is executable for us to define the states according to the observed relationships between AET trends and P trends, and hence obtain the 'realistic' equivalent trends in PET and evaporative demand.

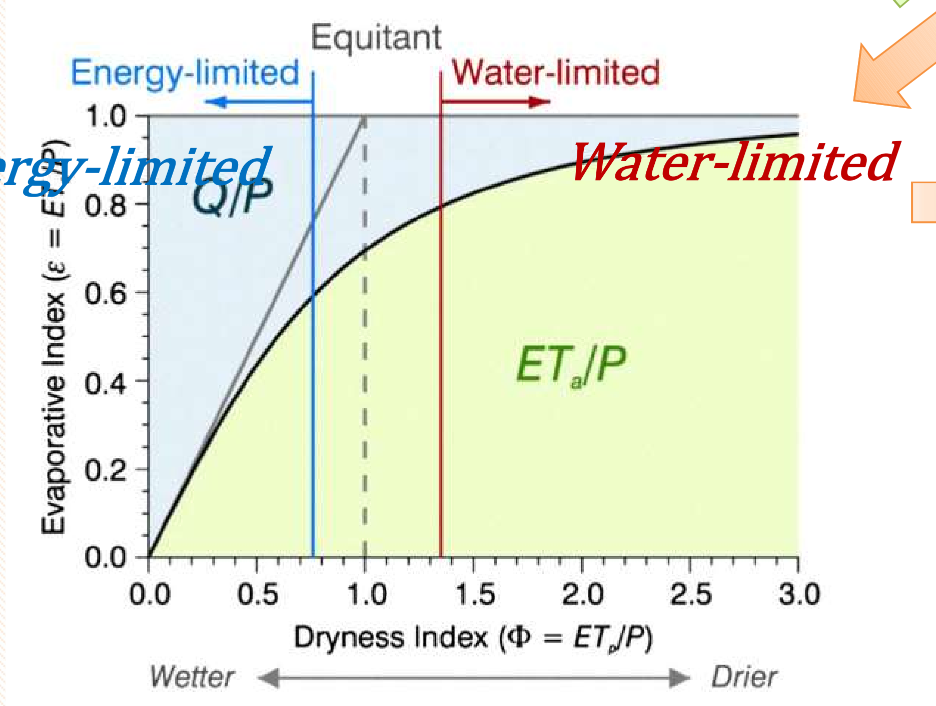
Inverse between trends of AET and P

Positive between trends of AET and P

Proportional Principle

positive relationship would be expected

Energy-limited



Water-limited

Complementary Principle

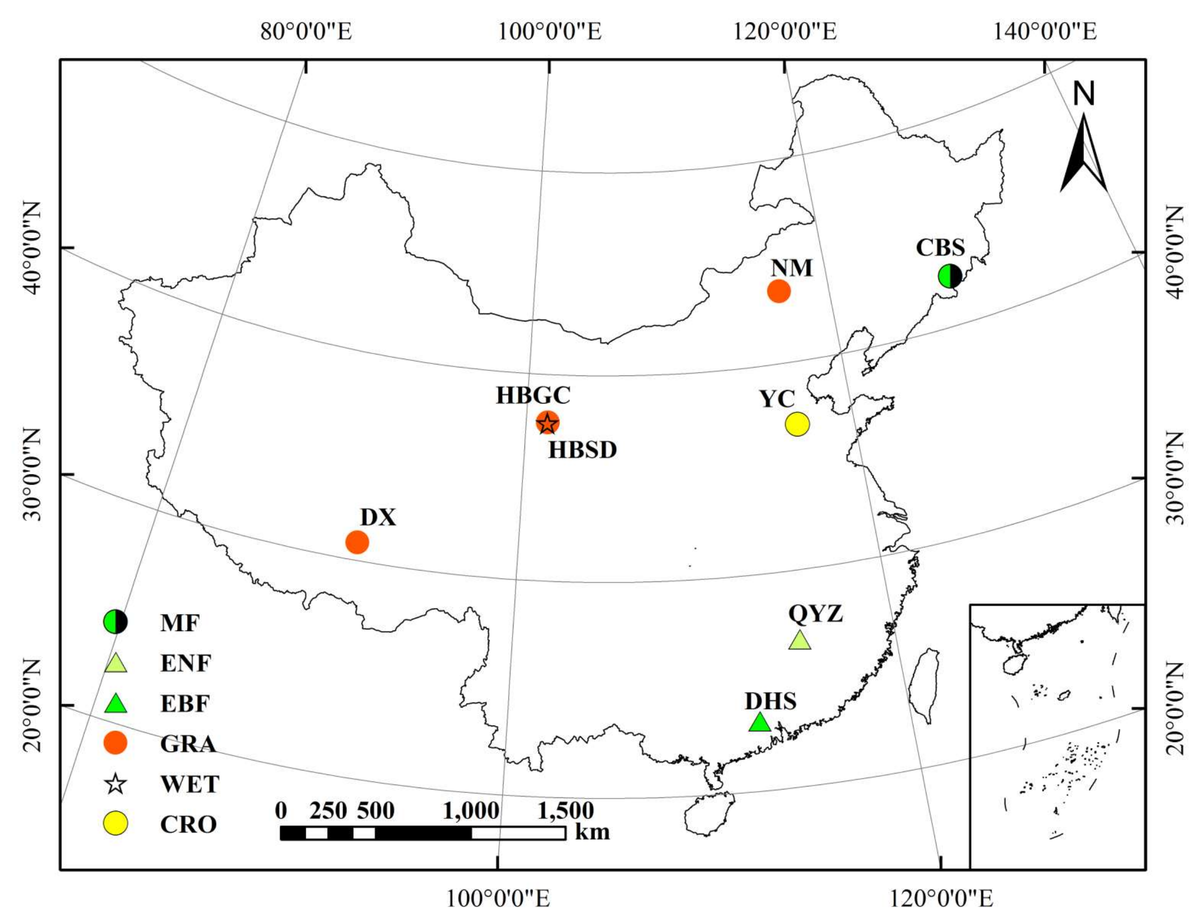
inverse relationship would be expected between the trends of PET and AET

Objectives

Therefore, this study aims to assess the utility of PET models in capturing annual and seasonal dynamics of evaporative demand, using the observed relationship between the trends of AET and P as an approach to define the corresponding hydroclimatological (i.e., water- or energy-limited) states.

- Assessing the magnitudes of PET;
- Assessing the annual trends of PET;
- Assessing the per-month trends of PET.

Study Sites



Eight typical ecosystems with eddy covariance flux towers, as part of ChinaFLUX

Three forest sites, three grassland sites, one wetland site and one cropland site.

These eight sites are separated along a broad geographical distribution and encompass the most prevalent climate and ecosystem types in China

Selected PET models

PET models selected for this study.

Classification	No.	Common model name	Input variables	Reference
Fully physical	1	Penman	R_n, T_a, e_a, u	Penman (1948)
Radiation-based	2	Makkink	R_s, T_a	Xu and Singh (2002)
	3	Turc	R_s, T_a, RH	Lu et al. (2005)
	4	Jensen-Haise	R_s, T_a	Jensen and Haise (1963)
	5	Stephens-Stewart	R_s, T_a	McGuinness and Bordne (1972)
	6	Priestly-Taylor	R_n, T_a	Priestley and Taylor (1972)
	7	Hargreaves	R_s, T_a	Hargreaves (1975), Xu and Singh (2000)
Temperature-based	8	Blaney-Criddle	T_a, p	Xu and Singh (2002)
	9	Romanenko	T_a, e_a	Romanenko (1961)
	10	Hamon	T_a, L_{day}	Hamon (1960), Oudin et al. (2005)
	11	Linacre	T_a, T_d	Linacre (1977)
	12	Hargreaves-Samani	T_a, T_{max}, T_{min}, R_a	Hargreaves and Samani (1982)
	13	Thornthwaite[a]	T_a, L_{day}	Thornthwaite (1948)
	14	Kharrufa[a]	T_a, p	Xu and Singh (2001)

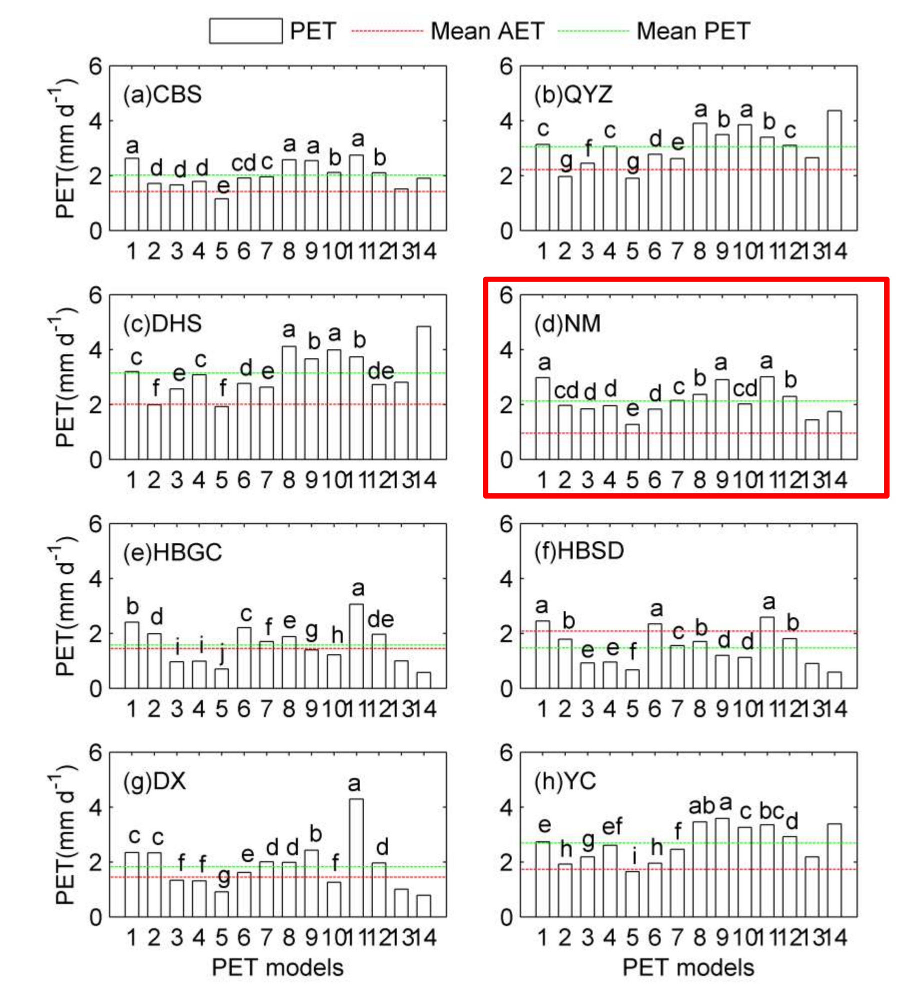
R_n, net radiation; T_a, mean air temperature; T_{max} and T_{min}, maximum and minimum air temperature, respectively; VPD, vapor pressure deficit; e_a, actual vapor pressure; u, wind speed; R_s, incident solar radiation; RH, relative humidity; L_{day}, maximum possible duration of sunlight or daylight hours; p, daily percentage of total annual daytime hours; R_a, extraterrestrial radiation. The units of the input variables for each model were shown in the Appendix.

[a] These two models were applied to monthly scale, while other models were applied to daily scale.

containing one fully physically based method, six radiation-based models and seven temperature-based models

RESULTS *Assessing PET magnitudes*

AET should never exceed PET at a long-term scale (e.g., annual time step), i.e., PET≥AET on average.



- Differences in the daily PET values estimated from different PET models were significant for all the eight sites (p-values<0.05), and no models gave consistently low or high PET averages.
- Mean daily PET from all the fourteen PET models were always larger than mean daily AET only at the NM site .

Assessing PET magnitudes

Reasonable PET models representing magnitudes of evaporative demand for different sites. Reasonable PET models refer to the models that give larger mean daily PET values than mean daily AET values according to the definition of PET (i.e., PET ≥ AET on average). The PET models with grey shadows are models which could give reasonable PET estimates for all the eight ecosystems.

PET model	CBS	QYZ	DHS	NM	HBGC	HBSD	DX	YC
Penman	√	√	√	√	√	√	√	√
Makkink	√			√	√		√	√
Turc	√	√	√	√				√
Jensen-Haise	√	√	√	√				√
Stephens-Steward				√				
Priestly-Taylor	√	√	√	√	√	√	√	√
Hargreaves	√	√	√	√	√		√	√
Blaney-Criddle	√	√	√	√	√		√	√
Romanenko	√	√	√	√			√	√
Hamon	√	√	√	√				√
Linacre	√	√	√	√	√	√	√	√
Hargreaves-Samani	√	√	√	√	√		√	√
Thornthwaite	√	√	√	√				√
Kharrufa	√	√	√	√				√

- only three models selected in this study could produce reasonable magnitudes of evaporative demand (i.e., PET⩾AET on average) for all the eight sites, including the Penman, Priestly-Taylor and Linacre models, while the other 11 PET models have different degrees of inadequacies along with different ecosystems

RESULTS *Assessing the annual and seasonal trends of PET*

Three (kinds of) models were further considered to assess their ability in reproducing annual and seasonal dynamics of evaporative demand.

Fully physically Penman Equation

$$PET_P = \frac{\Delta}{(\Delta + \gamma)} \frac{(R_n - G)}{\lambda} + \frac{\gamma}{(\Delta + \gamma)} \frac{6.43(1 + 0.536u)(e_s - e_a)}{\lambda}$$

Radiation-based Priestly-Taylor Model

$$PE_{PT} = \alpha \times \frac{\Delta}{\Delta + \gamma} \times \frac{(R_n - G)}{\lambda}$$

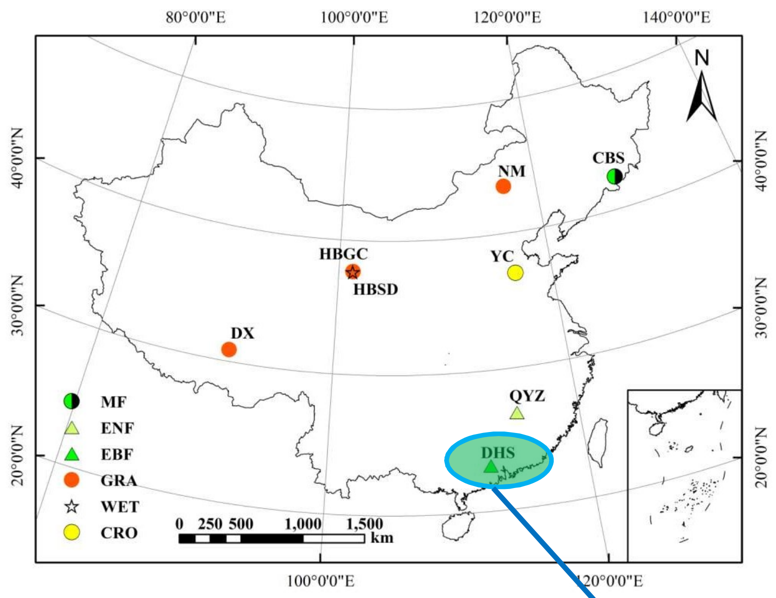
Temperature-based Linacre Model

$$PET_L = \frac{\frac{500(T_a + 0.006z)}{100 - A} + 15(T_a - T_d)}{80 - T_a}$$

Monthly trends: **Linear trends of PET rates for each month over the observational periods with the method of ordinary least square regression. mm mth-1 yr-1**

Annual trends: sum of twelve monthly trends to minimize the biases caused by timing of gaps within the data records **mm yr-2**

Annual trends of PET at DHS site



Subtropical evergreen broadleaf forest

	PET model	A Annual-average rate (mm yr^{-1})	B Annual trend (mm yr^{-2})
	Penman	960.15	−2.86(0.74)
	Priestly-Taylor	695.95	3.20(0.48)
	Linacre	1000.70	−7.37(0.40)
	Precipitation	736.51	22.62(0.35)
	AET	524.40	−3.91(0.34)
	Penman	1143.22	−12.39(0.13)
	Priestly-Taylor	1014.11	−1.11(0.84)
	Linacre	1239.69	−15.67(0.06)
	Precipitation	1363.74	34.28(0.30)
	AET	809.62	13.14(0.33)
DHS	Penman	1165.60	−15.10(0.24)
	Priestly-Taylor	1008.26	−7.82(0.45)
	Linacre	1364.23	−16.84(0.08)
	Precipitation	1702.03	78.48(0.20)
	AET	733.21	−3.27(0.66)

AET ↓
P ↑

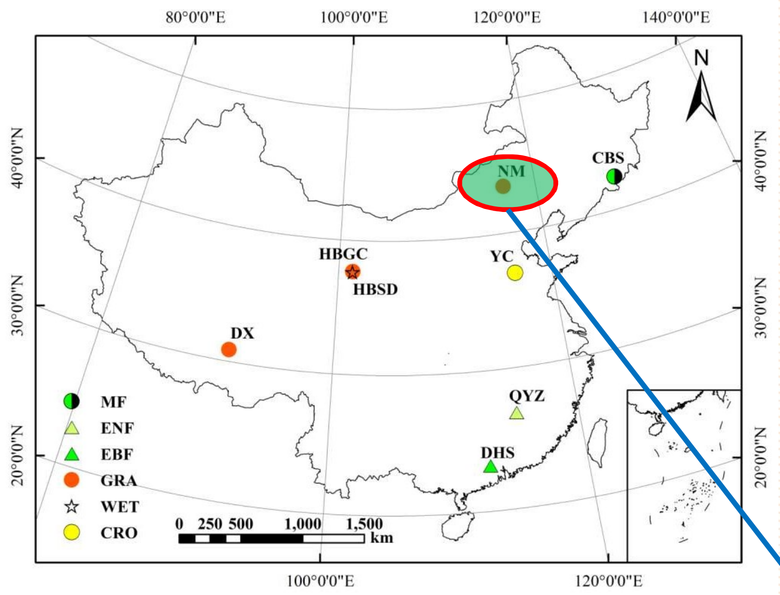
DHS
Energy-limited site

Proportional
Principle

AET ↓
PET ↓

Penman
Priestly-Taylor
Linacre

Annual trends of PET at NM site



Typical temperate steppe

Site	PET model	A Annual-average rate (mm yr^{-1})	B Annual trend (mm yr^{-2})
CBS	Penman	960.15	−2.86(0.74)
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	Linacre	1364.23	−16.84(0.08)
	Precipitation	1702.03	78.48(0.20)
	AET	733.21	−3.27(0.66)
NM	Penman	1087.41	−1.66(0.81)
	Priestly-Taylor	668.70	7.98(0.22)
	Linacre	1097.47	−10.60(0.11)
	Precipitation	289.00	3.93(0.74)
	AET	347.51	9.76(0.18)

AET ↑
P ↑

NM
Water-limited site

Complementary Principle

AET ↑
PET ↓

Penman
Linacre

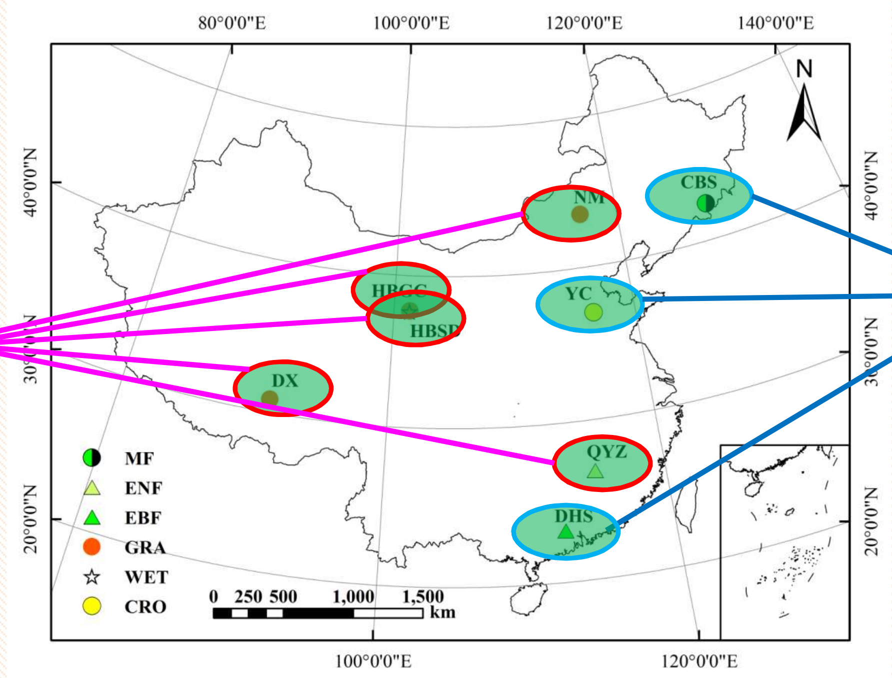
Assessing Annual Trends of PET

Water-limited sites

Complementary Principle

Penman

Linacre



Energy-limited sites

Proportional Principle

Penman

Priestly-Taylor

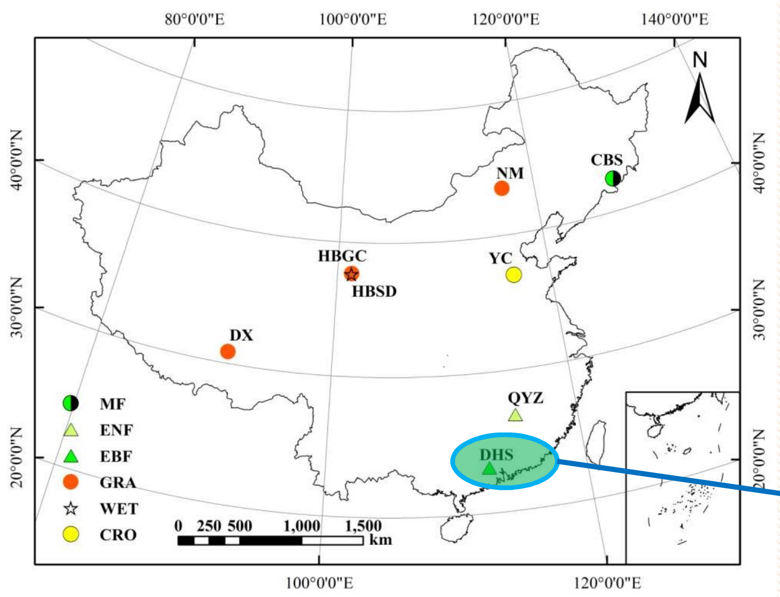
Linacre

- All the three PET models could faithfully reproduce the dynamics in evaporative demand for the energy-limited conditions at the annual time scales.
- Only the Penman and Linacre models could represent dynamics in evaporative demand for the water-limited conditions.

Seasonal trends of PET in DHS site

Correlation coefficients between Per-month trends (i.e., trend for Januaries, for Februaries, etc.) of each PET model estimates with equivalent trends in AET and P for each site

Subtropical evergreen broadleaf forest



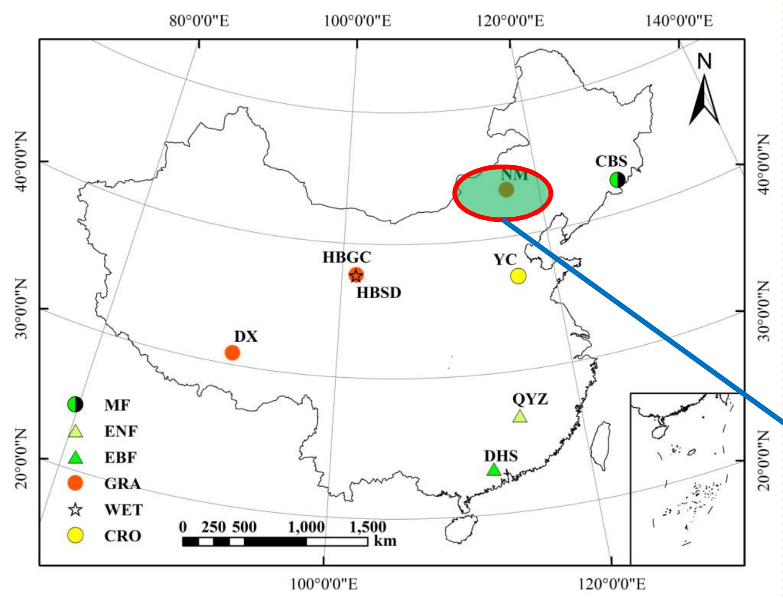
Site	PET model	C Correlation with per-month AET trends
CBS	Penman	0.07(0.84)
	Priestly-Taylor	0.05(0.87)
	Linacre	0.02(0.95)
	Precipitation	−0.11(0.73)
	AET	
QYZ	Penman	−0.10(0.76)
	Priestly-Taylor	0.31(0.33)
	Linacre	−0.40(0.20)
	Precipitation	0.07(0.83)
	AET	
DHS	Penman	0.93(< 0.001)
	Priestly-Taylor	0.89(< 0.001)
	Linacre	0.73(0.01)
	Precipitation	−0.81(0.002)
	AET	

AET − ***P*** → *DHS* Energy-limited → Proportional Principle → **AET** + **PET** → Penman Priestly-Taylor Linacre

seasonality of AET mainly determined by energy supply

Seasonal trends of PET at NM site

Typical temperate steppe



Site	PET model	C Correlation with per-month AET trends
CBS	Penman	0.07(0.84)
	Priestly-Taylor	0.05(0.87)
	Linacre	0.02(0.95)
	Precipitation	−0.11(0.73)
	AET	
QYZ	Penman	−0.10(0.76)
	Priestly-Taylor	0.31(0.33)
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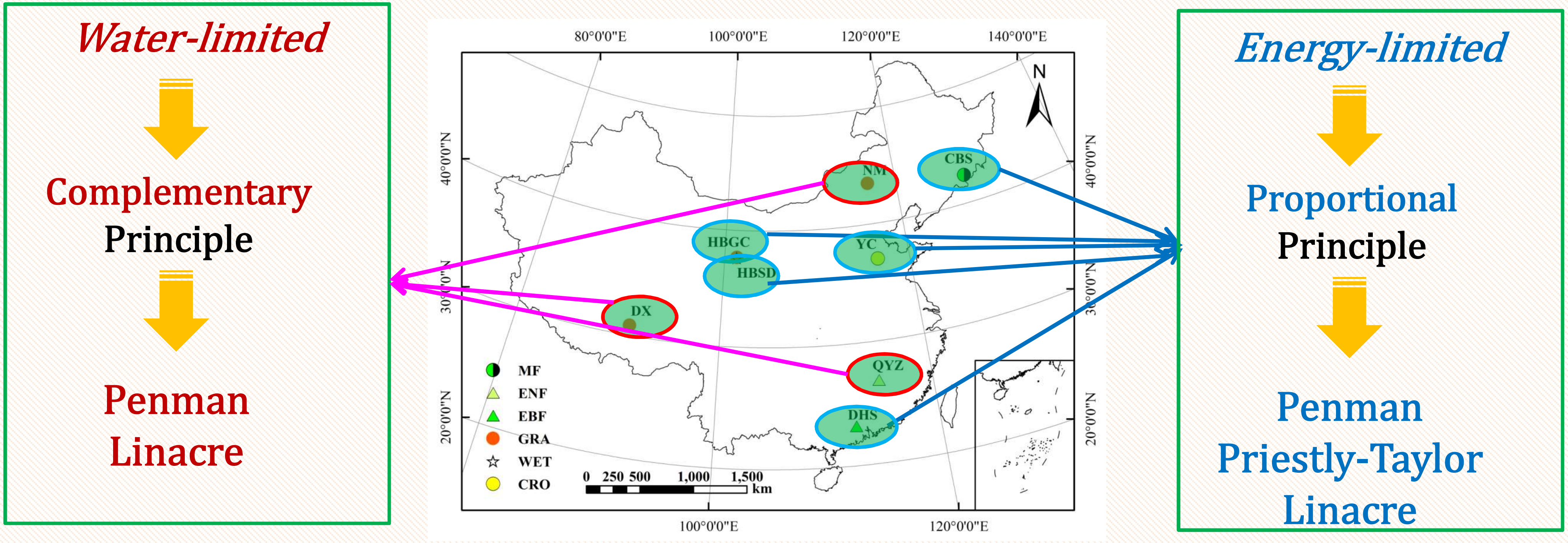
DHS	Penman	0.93(< 0.001)
	Priestly-Taylor	0.89(< 0.001)
	Linacre	0.73(0.01)
	Precipitation	−0.81(0.002)
	AET	
NM	Penman	−0.23(0.48)
	Priestly-Taylor	0.56(0.06)
	Linacre	−0.42(0.17)
	Precipitation	0.43(0.16)
	AET	

AET + ***P*** → *NM* Water-limited → Complementary Principle → **AET** − **PET** → Penman Linacre

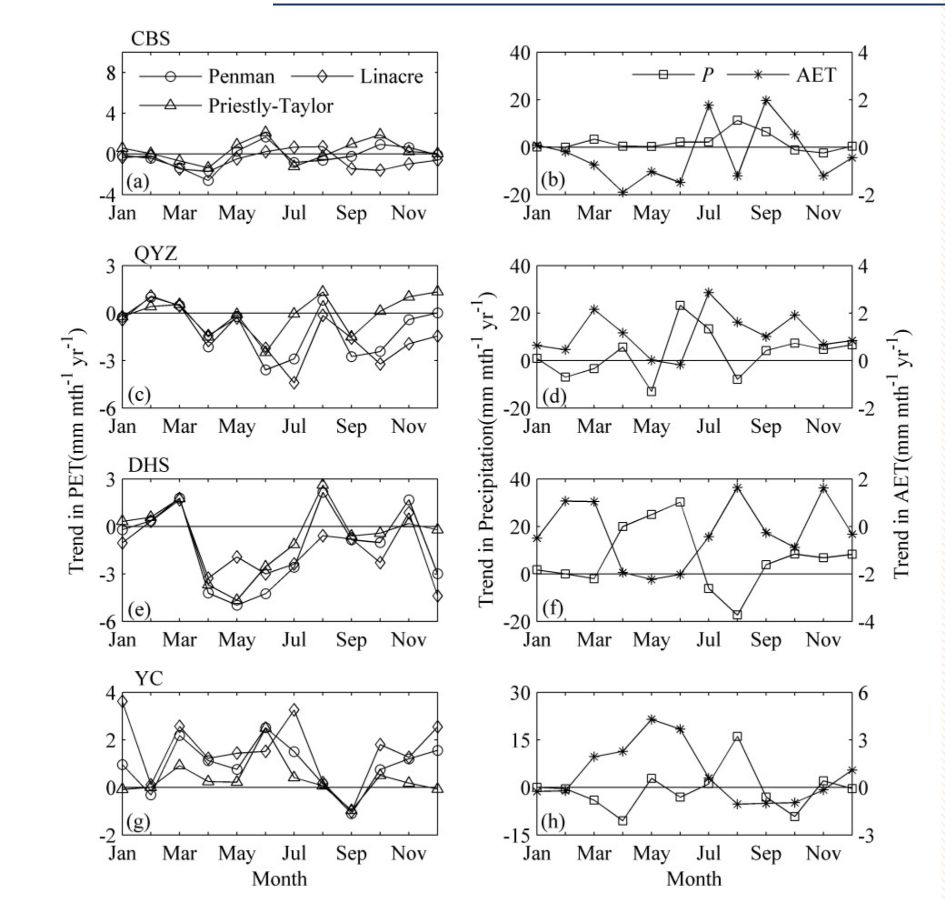
seasonality of AET mainly determined by WATER supply

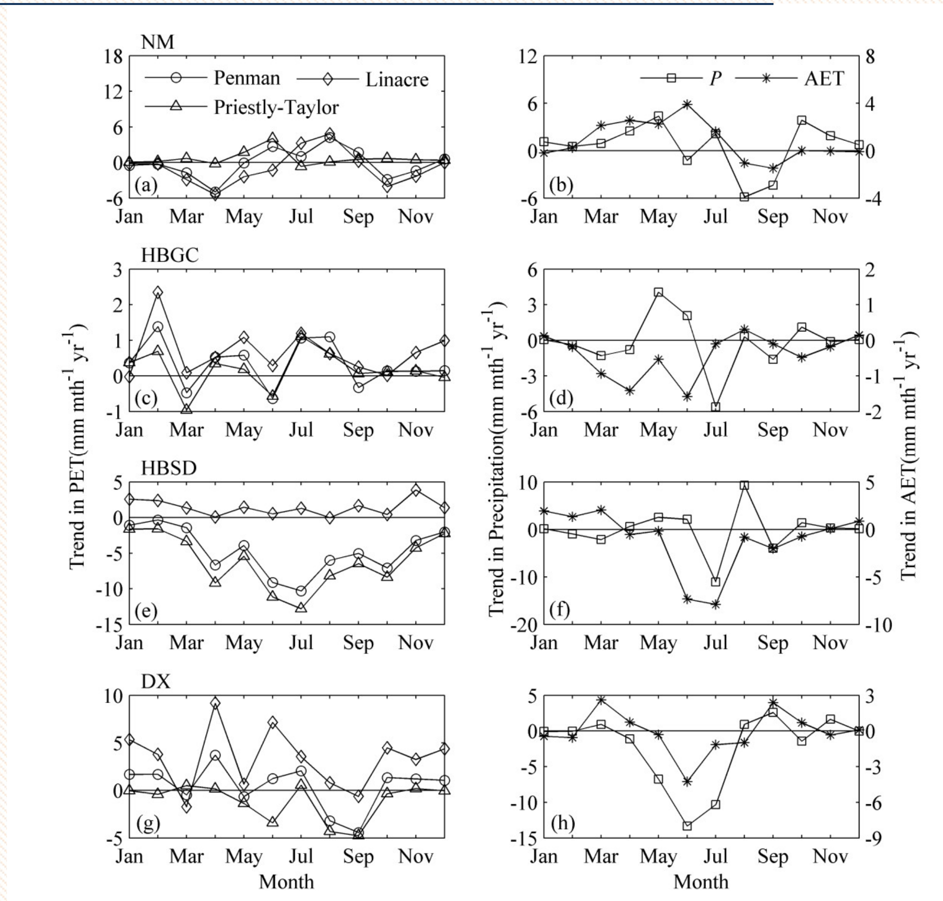
Assessing Seasonal Trends of PET



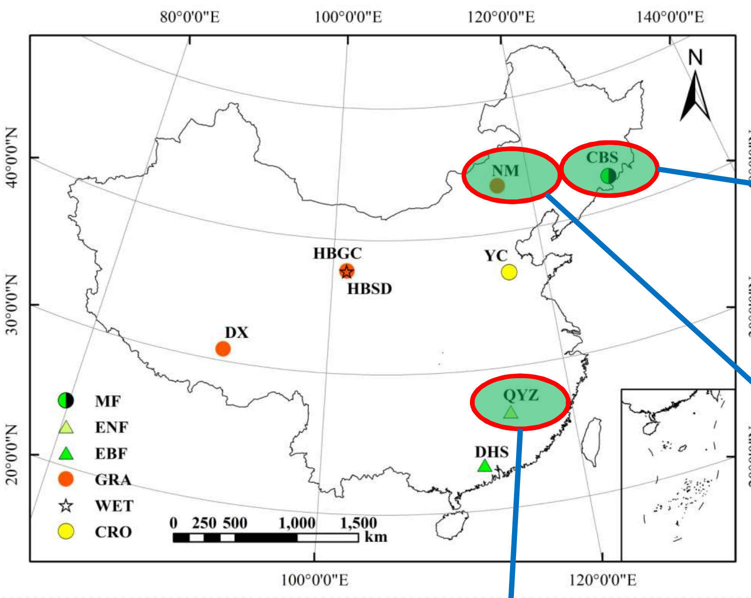
- All the three PET models could faithfully reproduce the dynamics in evaporative demand for the energy-limited conditions at the seasonal scales.
- Only the Penman and Linacre models could represent dynamics in evaporative demand for the water-limited conditions.

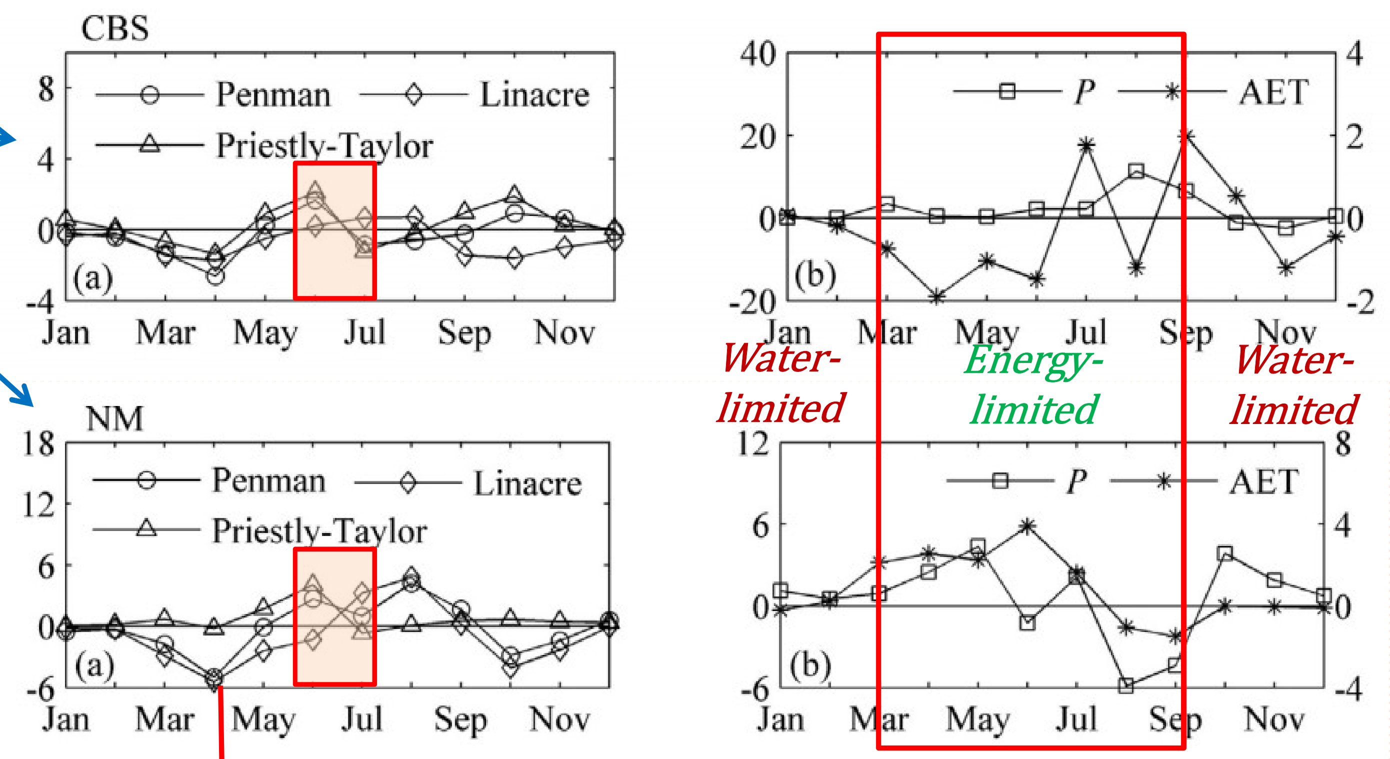
Per-month trends in PET, AET and *P*

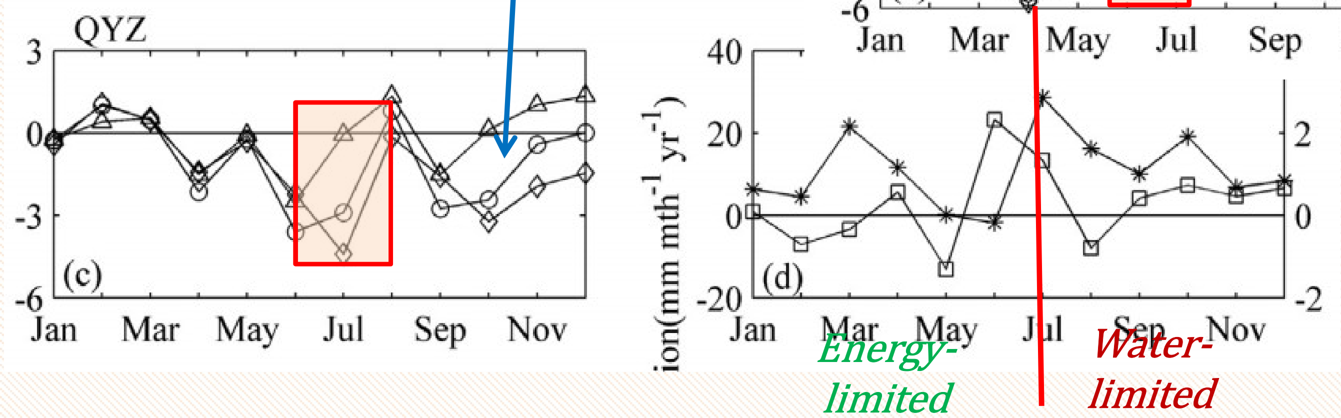




There exist seasonal switches between water- and energy-limited states for many sites !
How the three models work in reproducing the seasonal switches ?







Linacre model was unable to capture the PET dynamics during June to July at these sites

Take home messages

Through assessing the ability of 14 PET models in capturing long-term (typically 2003-2011) dynamics of evaporative demand at eight ecosystems across various biomes and climatic regimes in China, we could conclude that:

- 3 of 14 PET models could represent the magnitudes of evaporative demand.
- Priestly-Taylor model was best suited for energy-limited conditions.
- Linacre model may fail to capture seasonal switch between water- and energy-limited states.
- Penman equation works best across the range of conditions tested.

Thanks for your attention!

ZHENG Han
zhenghanmarch@sina.com