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Towards understanding the climate and landuse change impacts on hydrological cycle and water resources

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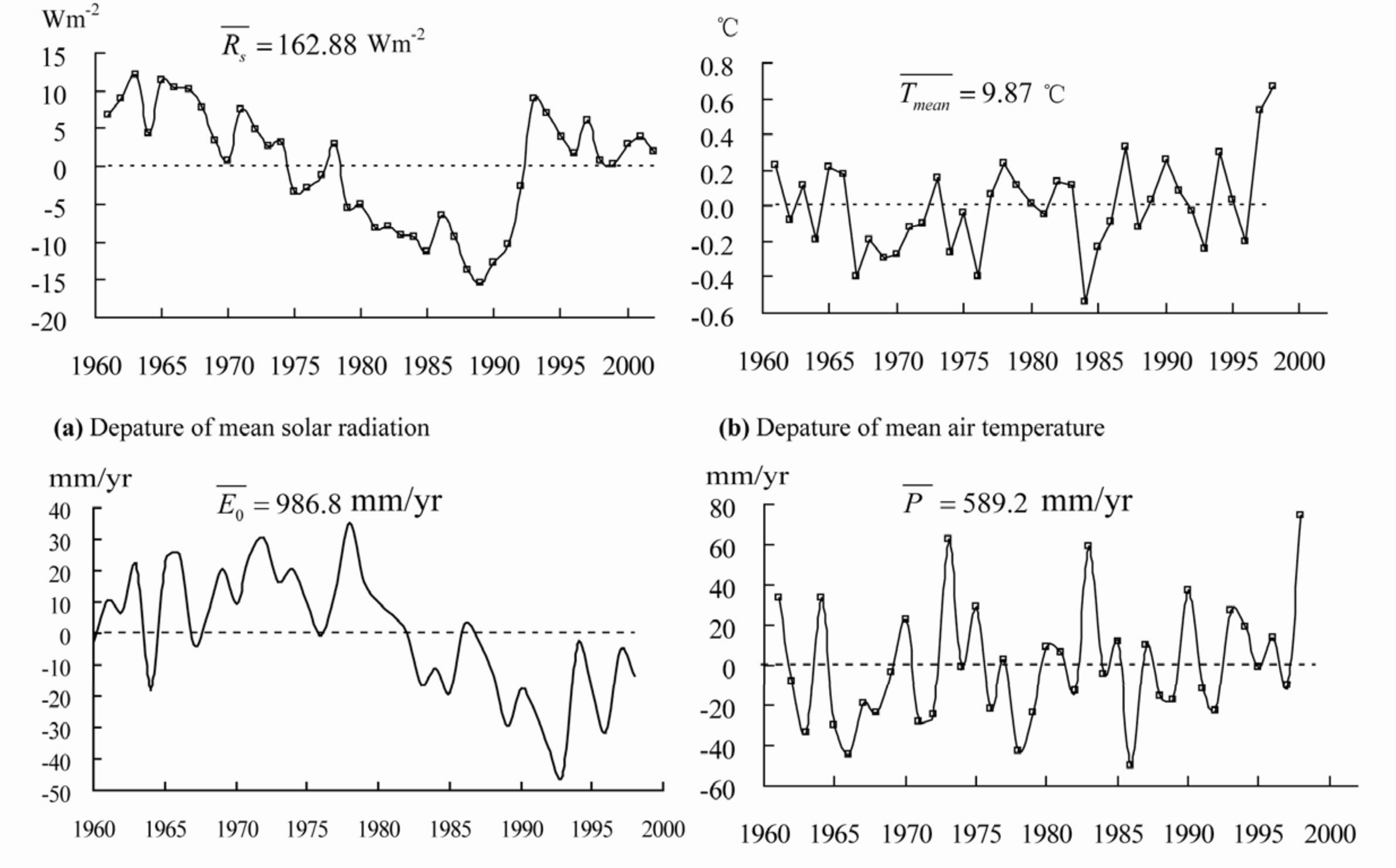
Outline

1. Climate change: global warming & dimming
2. What about the hydrological cycle?
3. Water balance analysis in 108 non-humid catchments in China
4. Results and discussions
5. Conclusion and future work

Climate change: global warming & dimming

Climate change: A case study in China



(a) Depature of mean solar radiation

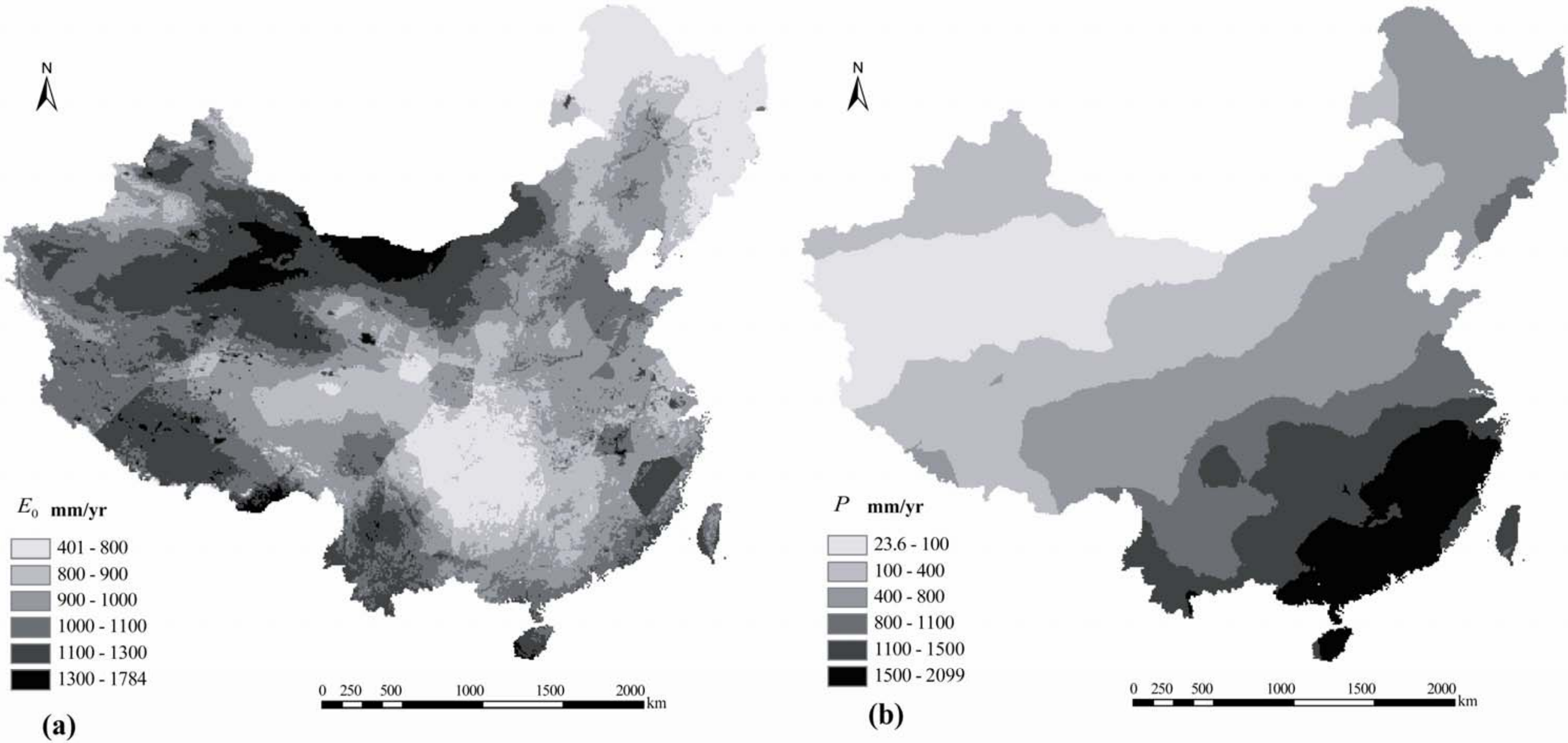
(b) Depature of mean air temperature

(c) Depature of annual potential evaporation

(d) Depature of annual precipitation

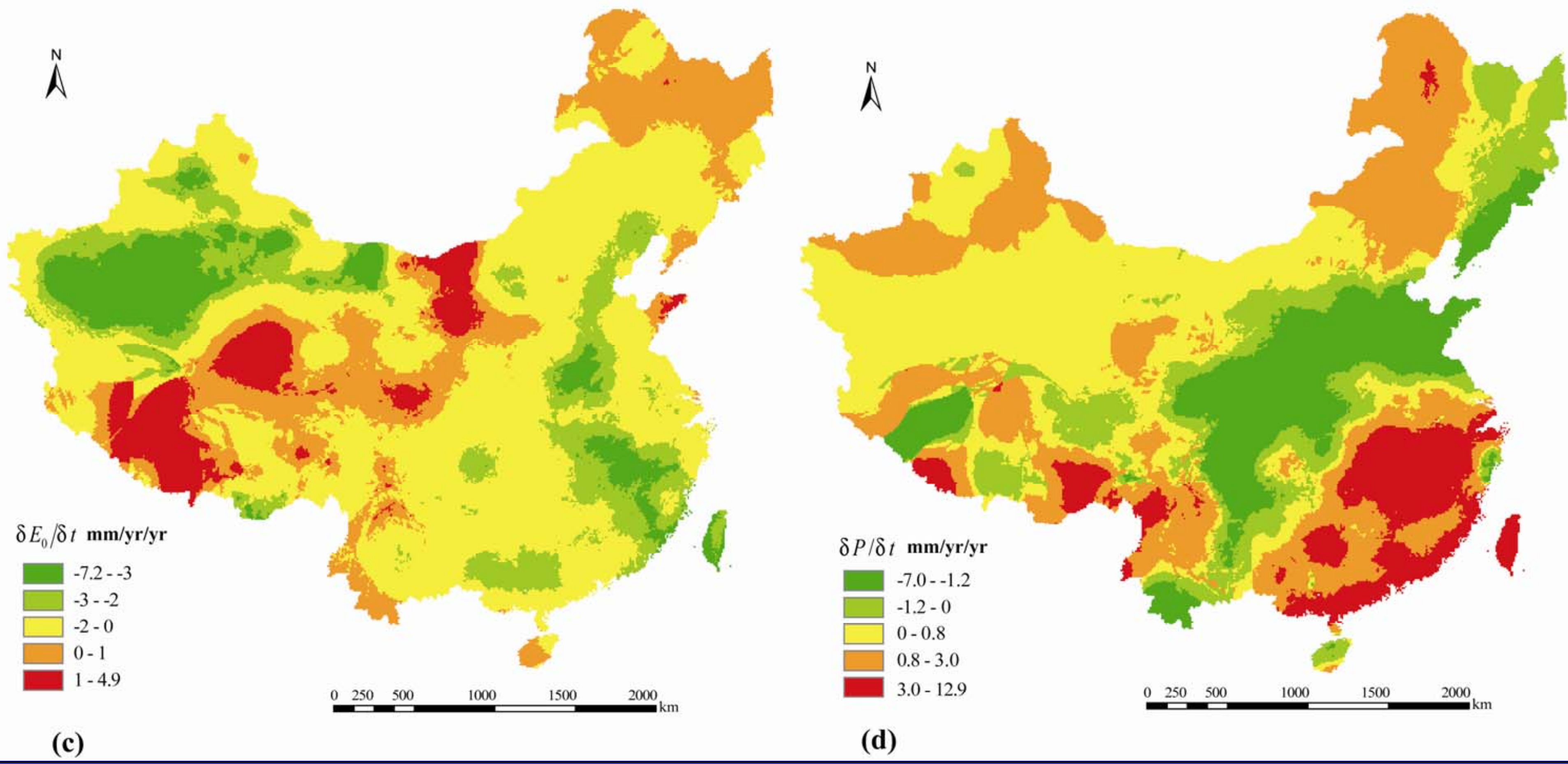
Note: (1) Potential evaporation is estimated by using Penman's equation;
(2) Solar radiation is averaged from 120 stations over China;
(3) Air temperature, potential evaporation, and precipitation is averaged using a 10-km gridded data interpolated from 740 stations over China.

Climate change: A case study in China (cont.)



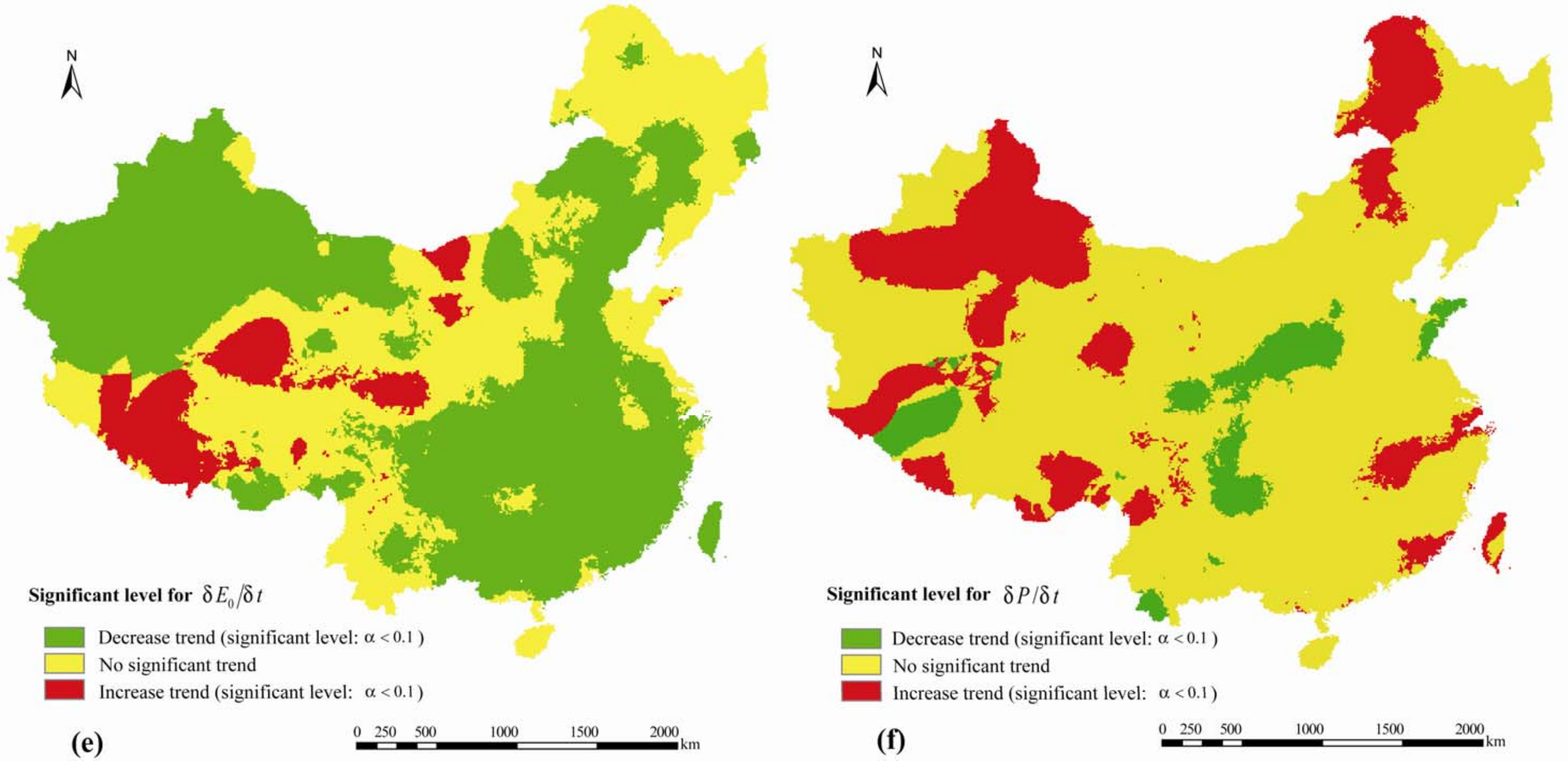
Spatial distributions of mean annual potential evaporation (E_0, estimated by Penman's equation) and mean annual precipitation (P) during 1960-2000.

Climate change: A case study in China (cont.)



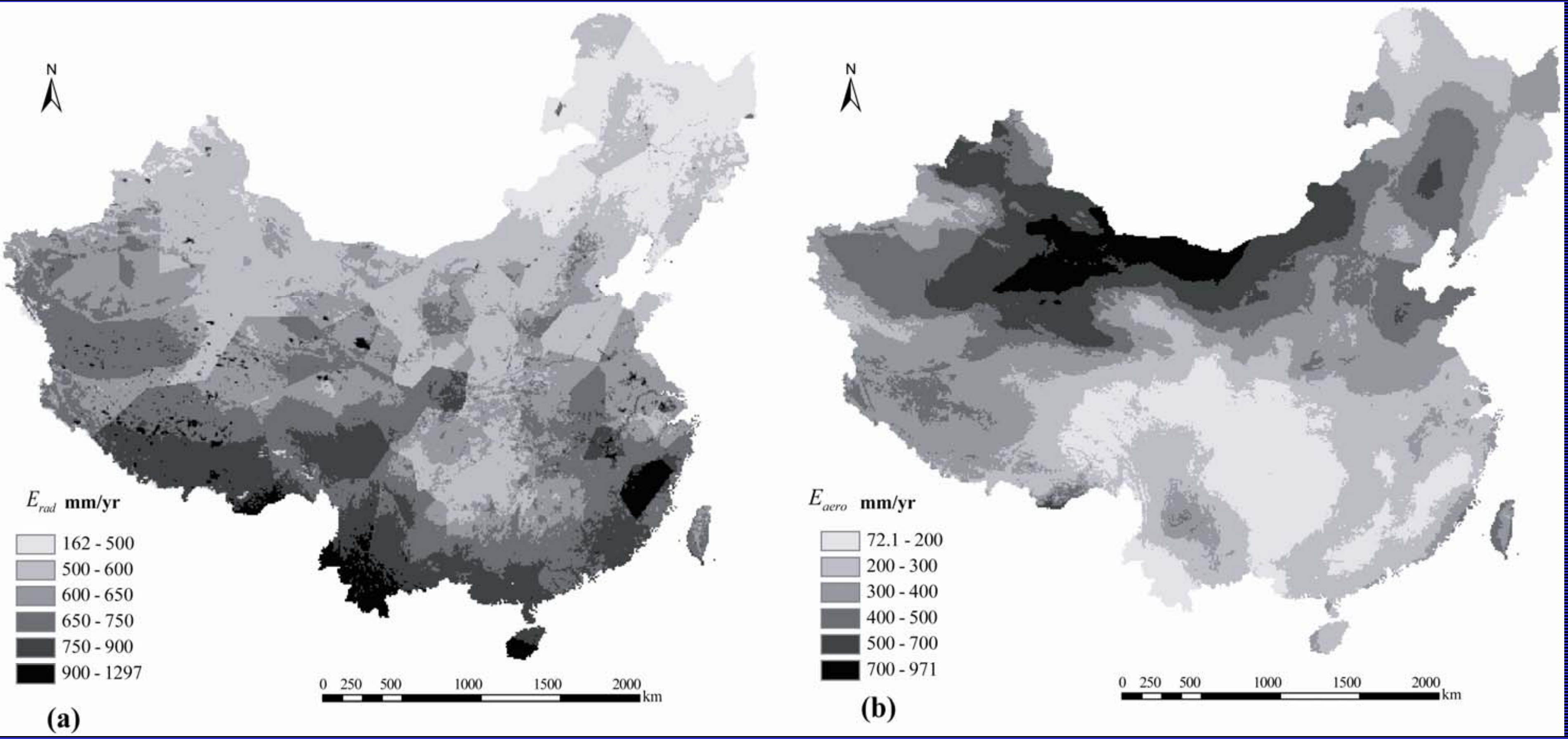
Trends of E_0 and P during 1960-2000

Climate change: A case study in China (cont.)



Significant level of the trends of E_0 and *P* during 1960-2000

Climate change: A case study in China (cont.)

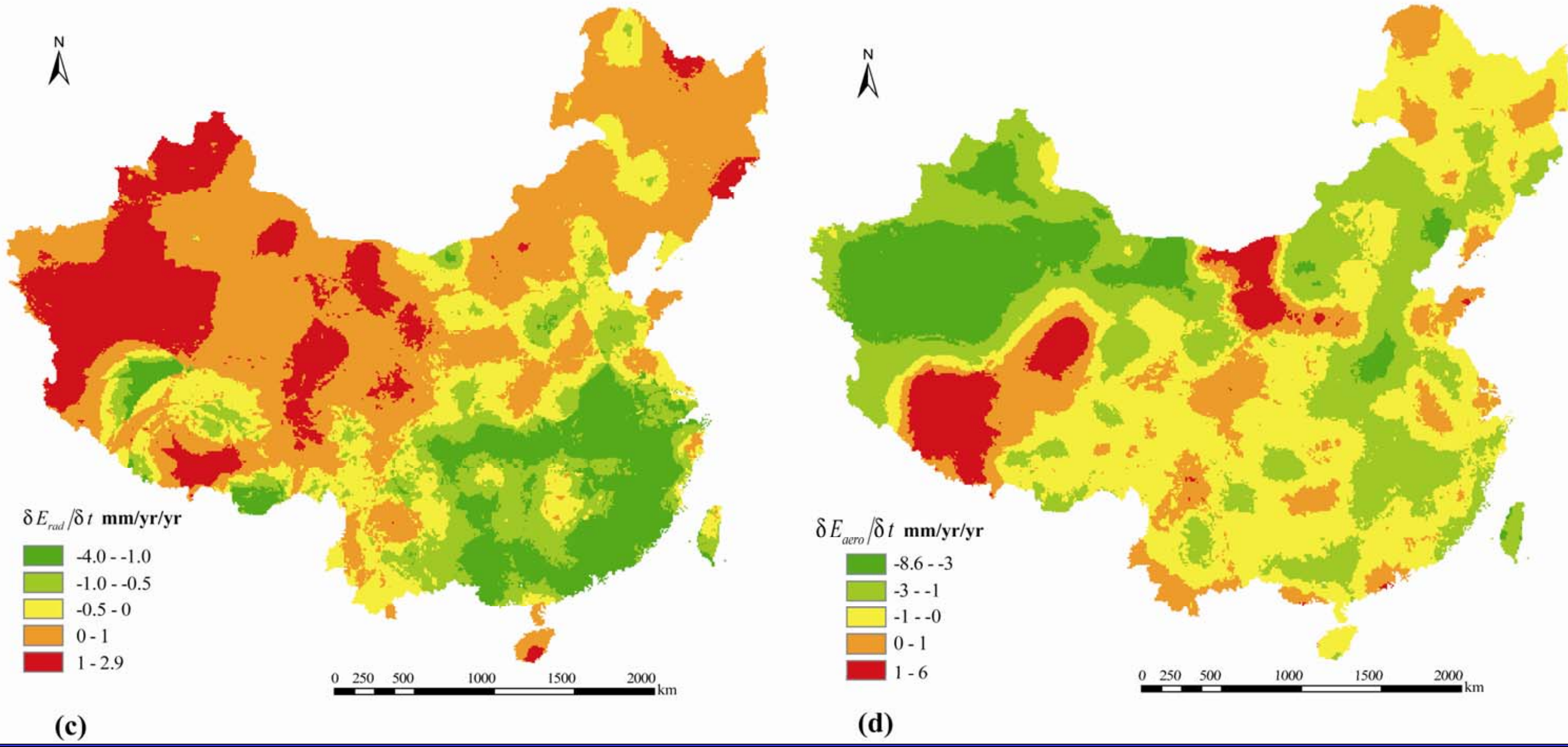


$$E_{rad} = \frac{\Delta}{\Delta + \gamma}(R_n - G)$$

$$E_{aero} = \frac{\gamma}{\Delta + \gamma} E_a$$

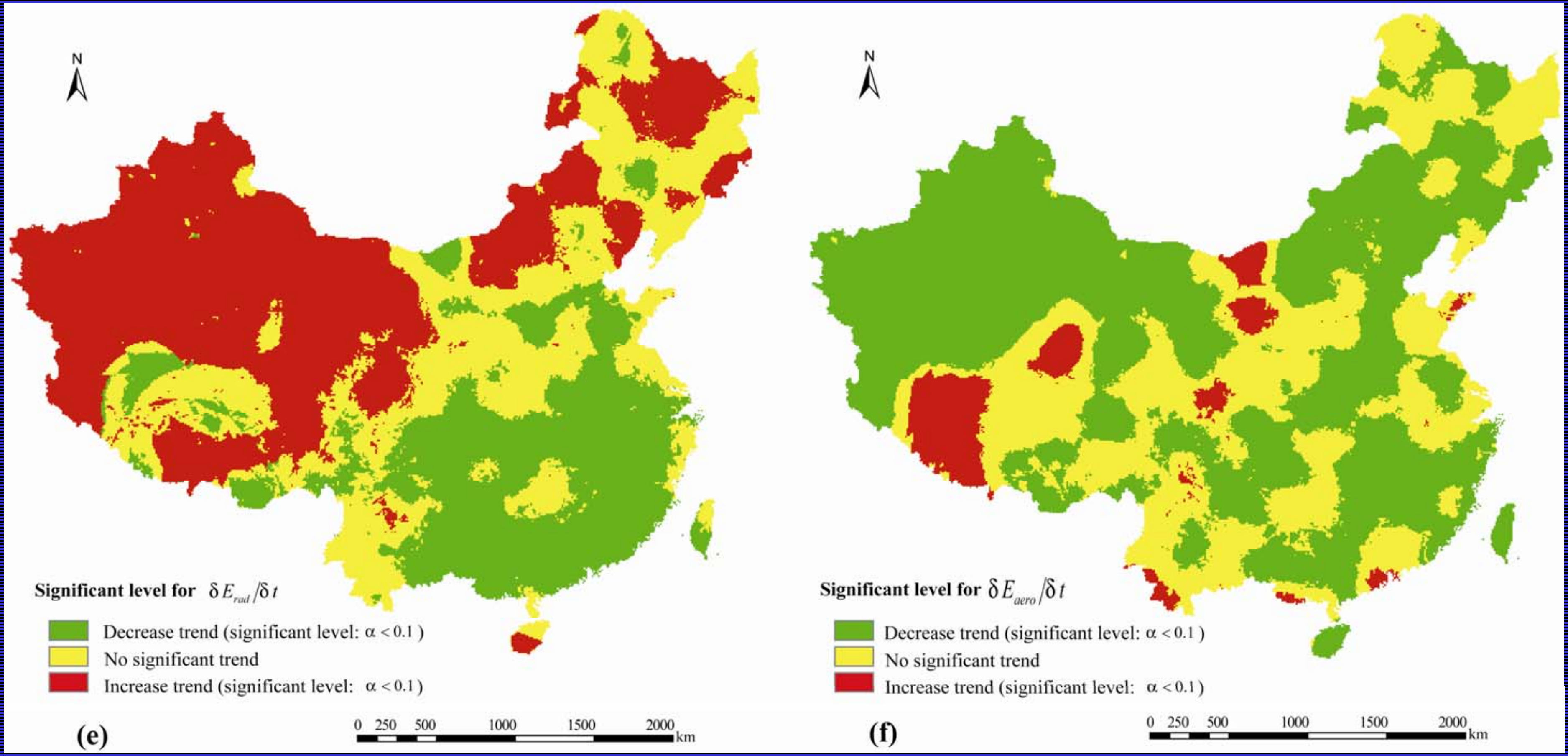
Spatial distributions of the mean annual radiation term (E_{rad}) and aero-dynamic term (E_{aero}) of the potential evaporation during 1960-2000.

Climate change: A case study in China (cont.)



Trends of E_{rad} and E_{aero} during 1960-2000

Climate change: A case study in China (cont.)



Significant level of the trends of E_{rad} and E_{aero} during 1960-2000

Climate change impact on potential evaporation

- Thornthwaite's equation (1948)

$$E_0 = 16d(10T / I)^a$$

The effect of air temperature has been magnified !

- Penman's equation (1948)

Radiative forcing

Drying power of atmosphere

$$E_0 = \frac{\Delta}{\Delta + \gamma}(R_n - G) + \frac{\gamma}{\Delta + \gamma}E_a$$

Correlation analyses between pan evaporation and related variables
(*Zuo et al.* 2005; *Gao et al.* 2006)
Sensitivity analyses of Penman equation
(*Gifford et al.* 2005; *Gong et al.* 2006)

Key factors affecting potential evaporation: net radiation, wind speed and humidity, the extents of which differ from region to region.

What about the hydrological cycle?

Climate change: global warming & dimming

•Global Warming
greenhouse-gas-induced

potential evaporation increase (expected)
(*Rind et al*. 1990; *IPCC* 2001)

precipitation increase (measured & expected)
(*Dai et al*. 1997; *IPCC* 2001)

Evaporation paradox

•Pan evaporation decrease (measured) worldwide

the complementary hypothesis

***Brutsaert & Parlange* 1998**

actual evaporation increase (expected)

(e.g., *Peterson et al*. 1995; *Chen et al*. 2005; *Chattopadhyay et al.* 1997; *Quintana-Gomez*, 1998; *Moonen et al.* 2002; *Cohen et al.* 2002; *Tebakari et al.* 2005; *Xu et al*. 2005; *Roderick & Farquhar* 2004, 2005)

•Global Dimming: solar radiation decrease (measured)

pollution-induced

***Stanhill & Cohen* 2001; *Ramanathan et al*. 2001; *Liepert et al*. 2002**

How to estimate the actual evaporation?

Hypothesis on the relationship between potential and actual evaporation

- **Penman hypothesis**

$$E = f(\theta)E_0$$

(*Penman*, 1948; *Shuttleworth*, 1993; *Allen et al.*, 1998)

$$f(\theta) = 0 \sim 1 \quad E \text{ and } E_0 \textit{ are in proportional relation}$$

- **Bouchet hypothesis**

$$E + E_0 = 2 \times E_w$$

(*Bouchet* 1963; *Brutsaert & Parlange*, 1998)

E_0: potential evaporation (by Penman equation or pan data)

E_w: wet-surface evaporation (or equilibrium evaporation by Priestley-Taylor equation)

$$\Rightarrow dE + dE_0 = 0 \quad E \text{ and } E_0 \textit{ are in complementary relation}$$

The discrepancy between the Penman and Bouchet hypotheses is especially highlighted in non-humid regions!

Theory– Budyko's coupled water-energy balance equation

Water balance: $$P = E + R$$

Energy balance: $$R_n = \lambda E + H$$

Coupled water- energy balance

$$\frac{E}{P} = \varphi\left(\frac{R_n}{\lambda P}\right) = \varphi\left(\frac{E_0}{P}\right)$$

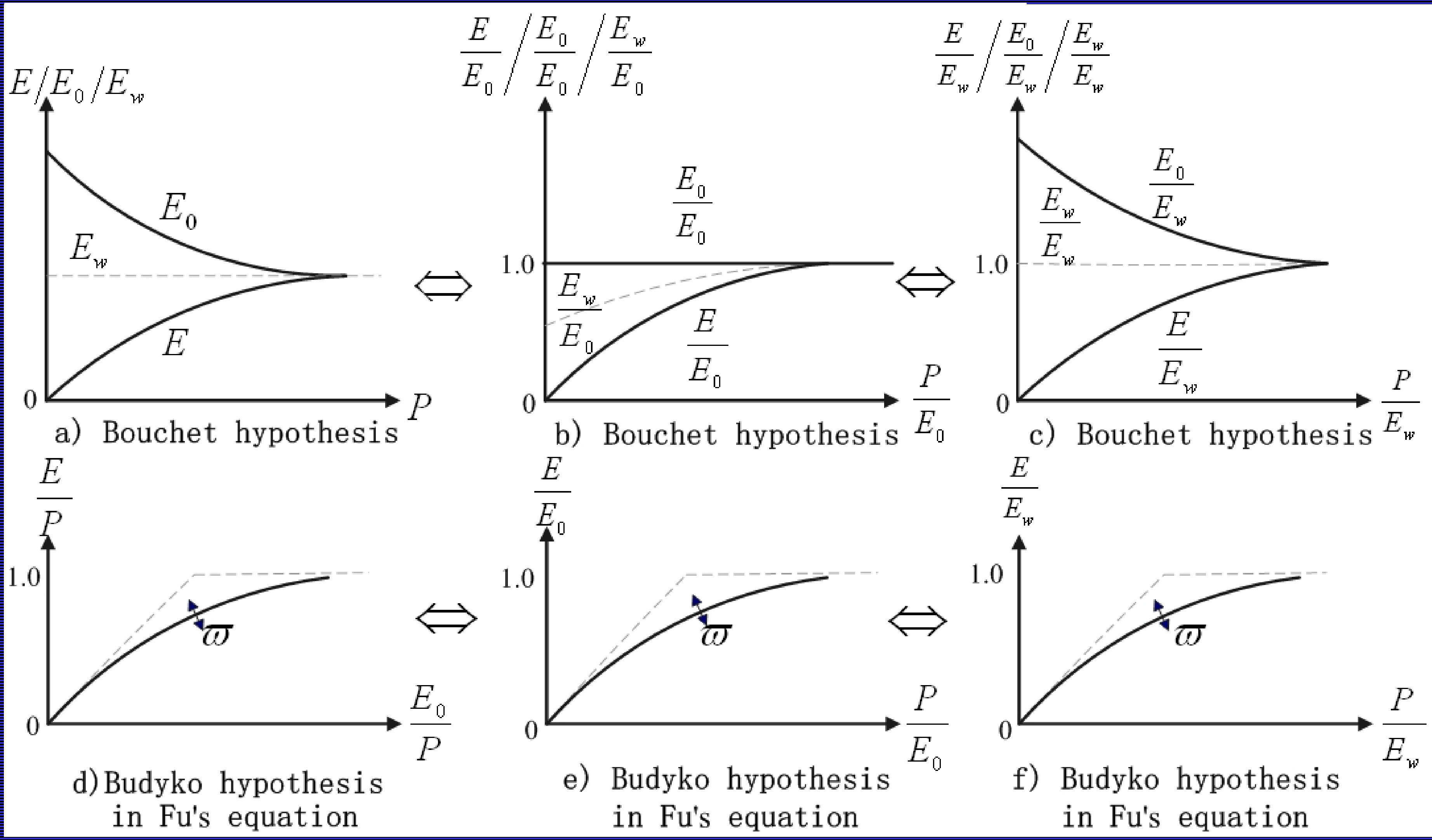
(*Budyko*, 1974)

Based on phenomenological considerations and dimensional analysis, *Fu* (1981) theoretically derived the analytical solution to the Budyko hypothesis

$$\frac{E}{P} = 1 + \frac{E_0}{P} - \left[1 + \left(\frac{E_0}{P}\right)^{\varpi}\right]^{1/\varpi}$$

(*Fu*, 1981)

Consistency between the Bouchet and Budyko hypotheses



(*Yang et al.* 2006, *GRL*)

Consistency between the Bouchet and Budyko hypotheses

Physics of the Bouchet hypothesis (***Brutsaert & Parlange*, 1998, *Science***)

$$E_0 - E_w = E_w - E$$

- For a given available energy (E_w), (E_0-E) is the additional sensible heat under water-limited conditions (E_0-E=0 under wet conditions), and this is the energy that would be potentially consumed as evaporation if the environment becomes wetter.

Physics of the Budyko hypothesis using Fu's equation (***Yang et al.*, 2006, *GRL***)

- Change in actual evaporation is determined by the balance between the precipitation and potential evaporation.
- In non-humid regions, this change is dominated by change in precipitation rather than in potential evaporation, and the Bouchet complementary relationship between actual and potential evaporations comes about because actual and potential evaporations are correlated via precipitation.
- In humid regions, this change is controlled by change in potential evaporation rather than precipitation, and this is identical to the Penman hypothesis.

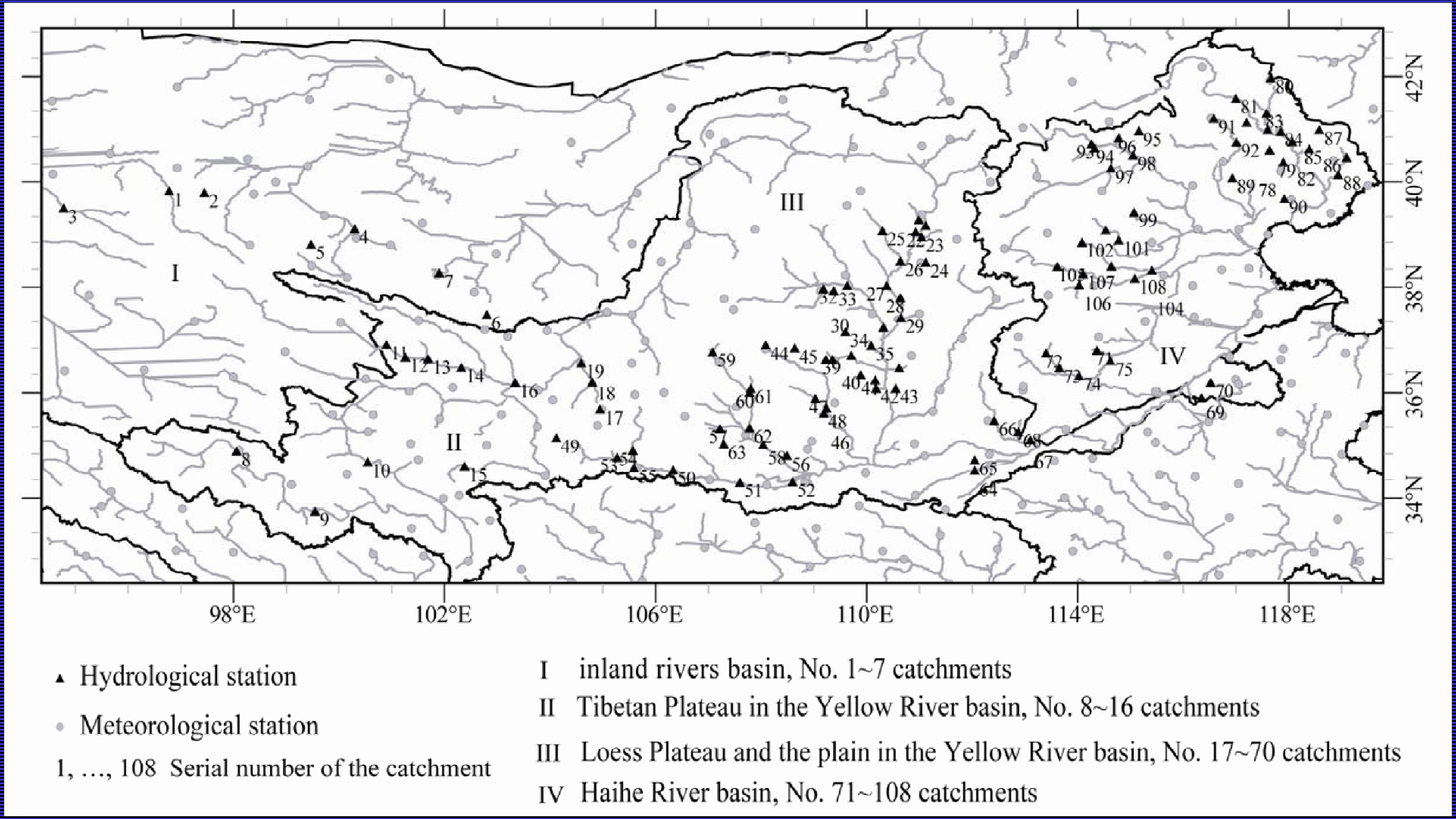
Water balance analysis in 108 non-humid catchments in China

Objective: Understanding the change of hydrological cycle

Invoke Budyko's coupled water-energy balance equation to

- **understand the relationship between the coupled water-energy balance with landscape characteristics;**
- **predict the temporal and spatial variability of actual evaporation;**
- **Improve our understanding of the hydrological cycle implication of climate change.**

108 Catchments in non-humid regions were used in this Study



Monthly discharge data in 108 catchemnts which have less human activity;
Daily meteorological data are available at 238 stations in which 47 stations have solar radiation;
Catchment area varies 271~98414 km^2;
Time period ranges 1951-2000;
Runoff coefficient (*R*/*P*): 0.02~0.32; Dryness index (E_0/*P*): 1.16~6.80

Procedure of Water Balance Analysis

① The catchment extent was extracted from 1-km DEM and re-sampled to 10-km resolution;

② A 10-km gridded climate dataset has been interpolated from the gauge data;

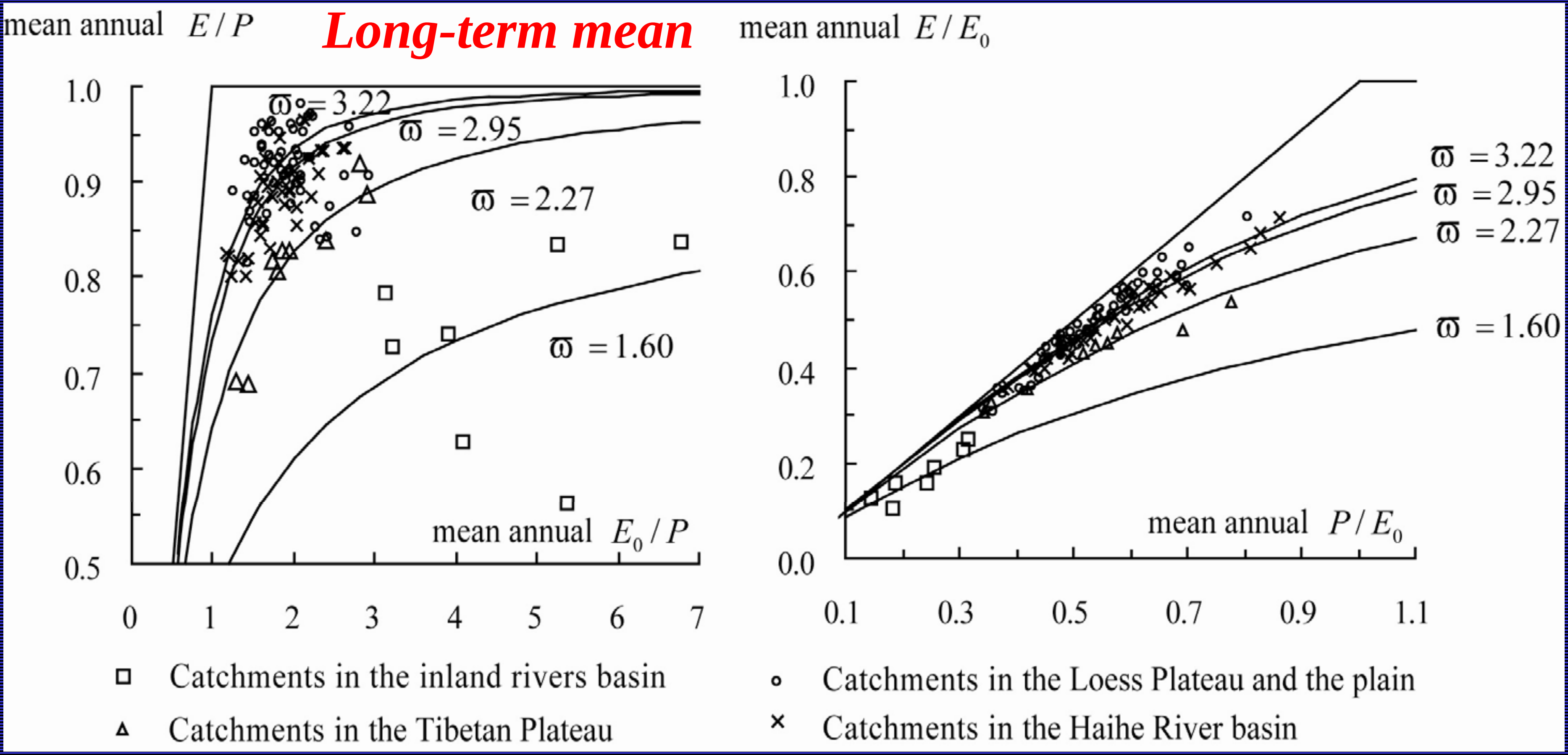
③ Potential evaporation was estimated for each grid using Penman equation and averaged on catchment;

④ Wet surface evaporation was estimated for each grid by the Priestley-Taylor equation (α=1.26) and averaged on catchment scale;

⑤ Actual evaporation was estimated from annual water balance $P = E + R$.

Results and Discussions

Spatial variability of the coupled water-energy balance



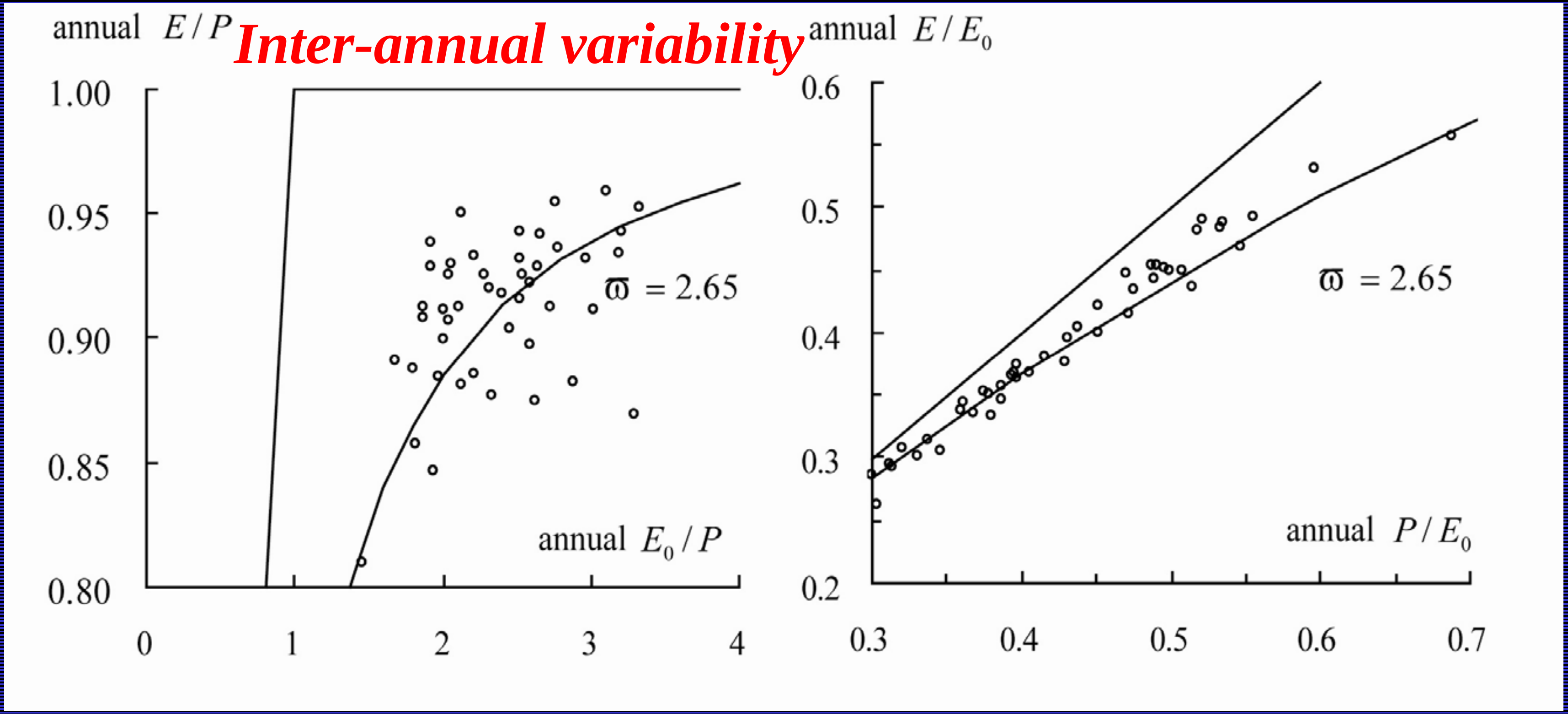
with respect to Precipitation:

$$\frac{E}{P} = 1 + \frac{E_0}{P} - \left[1 + \left(\frac{E_0}{P}\right)^{\varpi}\right]^{1/\varpi}$$

with respect to Potential Evaporation:

$$\frac{E}{E_0} = 1 + \frac{P}{E_0} - \left[1 + \left(\frac{P}{E_0}\right)^{\varpi}\right]^{1/\varpi}$$

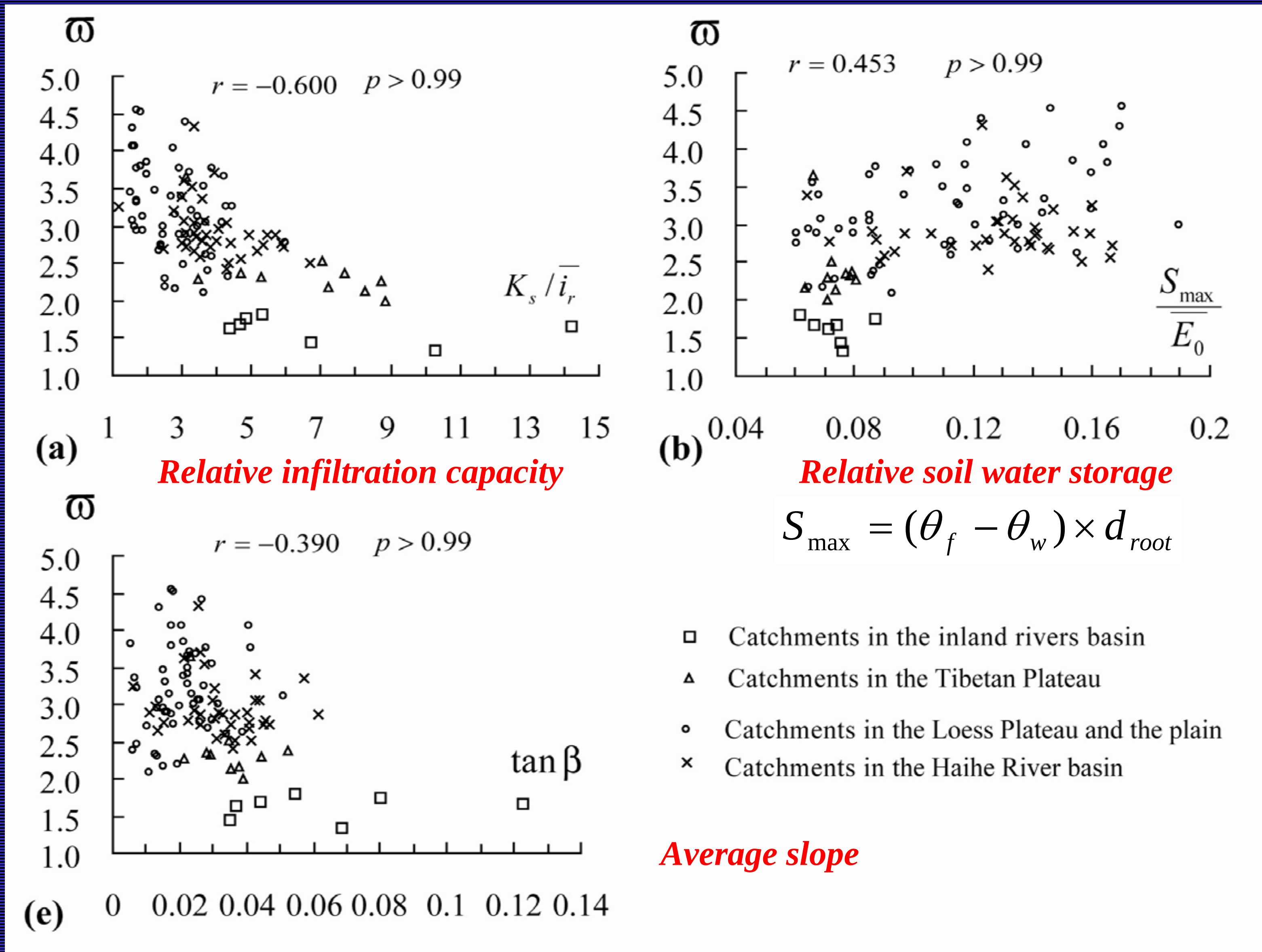
Inter-annual variability of the coupled water-energy balance



One typical catchment in the Haihe River basin (No. 76)

The Budyko hypothesis has been examined to be valid based on annual water balance for each individual catchment.

Relationship between the coupled water-energy balance with landscape characteristics



$$S_{max} = (\theta_f - \theta_w) \times d_{root}$$

Relationship between the coupled water-energy balance with landscape characteristics

Using stepwise regression analysis, it has obtained the parameter ϖ in Fu's equation:

$$\frac{E}{P} = 1 + \frac{E_0}{P} - \left[1 + \left(\frac{E_0}{P} \right)^{\varpi} \right]^{1/\varpi}$$

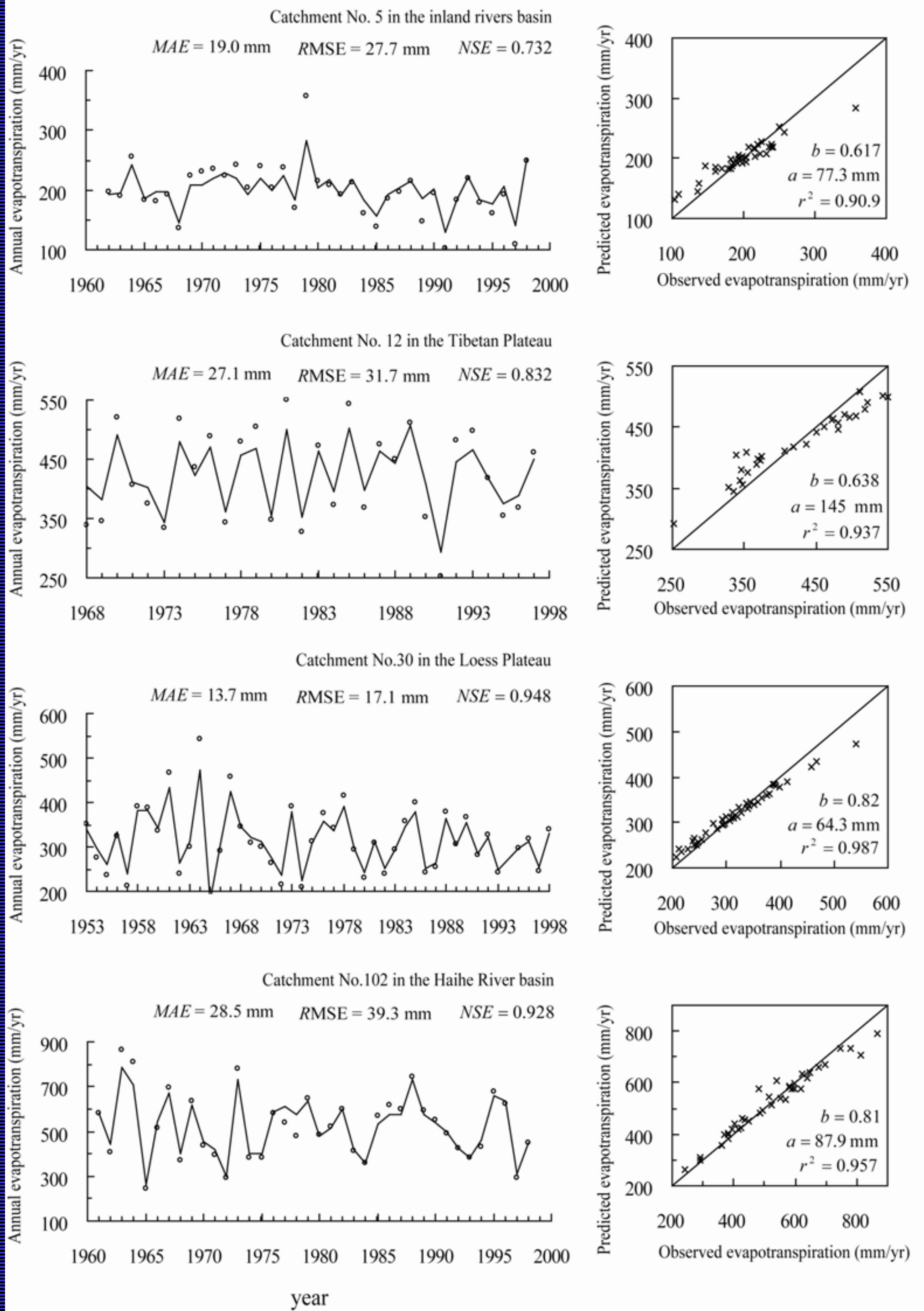
$$\varpi = 1 + 8.652 \left(K_s / \overline{i_r} \right)^{-0.368} \left(S_{\max} / \overline{E_0} \right)^{0.436} \exp\left(-4.464 \tan \beta \right)$$

Relative infiltration capacity

Relative soil water storage capacity

Average slope

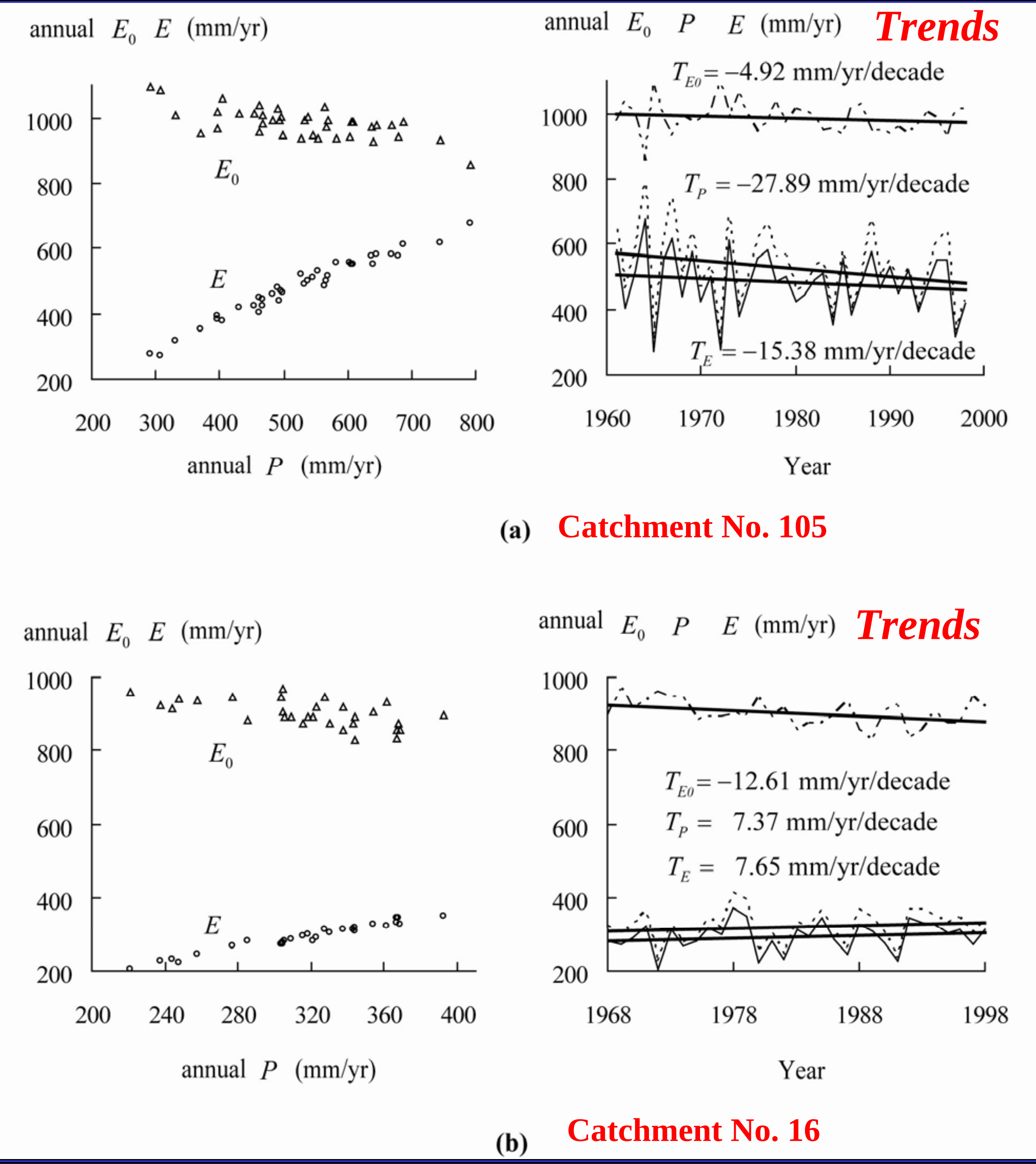
Inter-annual predictability of Fu's equation with an empirical formula of ω



(*Yang et al.*, 2007, *WRR*, *in press*)

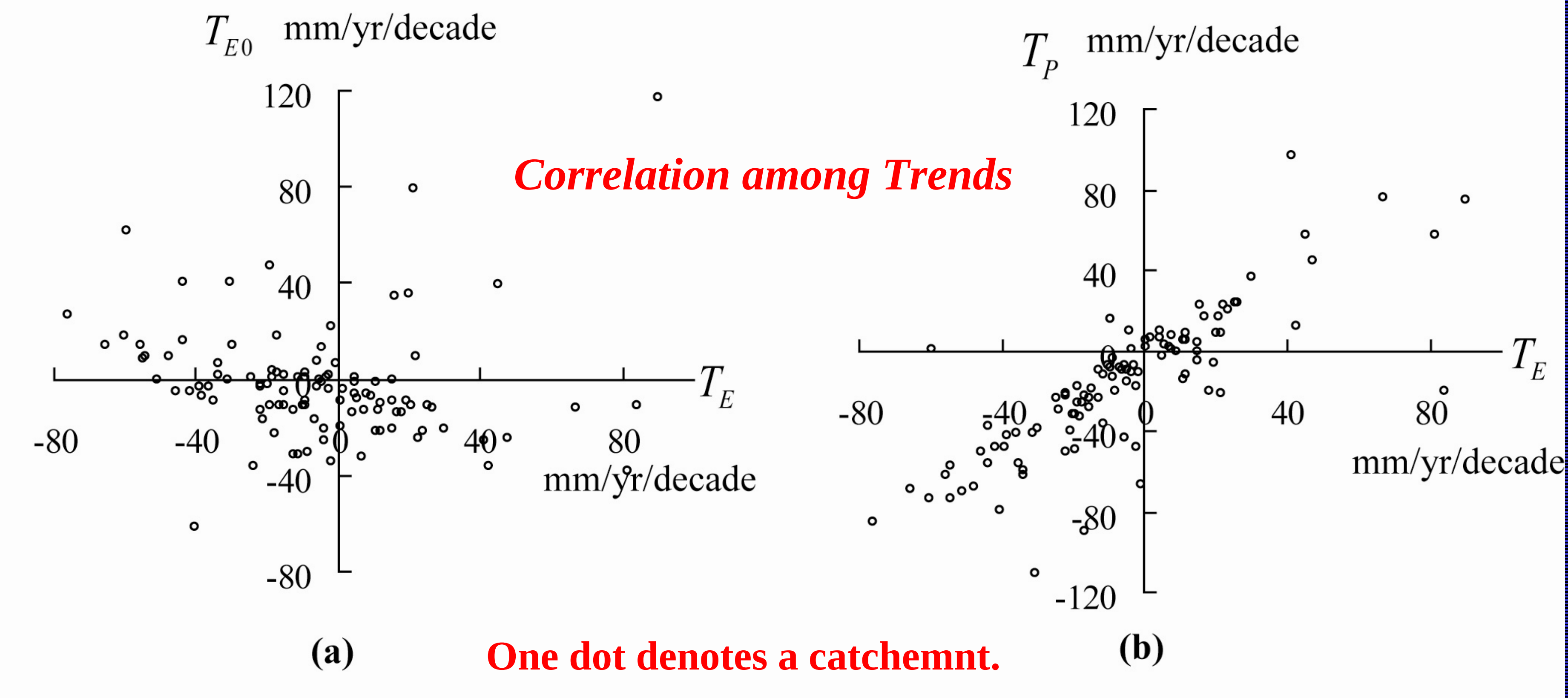
Four typical catchments

Relationship between actual and potential evaporation with respect to annual precipitation and time, respectively.



T_p, T_{E0}, T_E denote the trends of precipitation, potential and actual evaporation.

Correlation analysis among the trends of potential evaporation, actual evaporation and precipitation



Both positive and negative correlations have found between the potential and actual evaporation.

Most correlations between the actual evaporation and precipitation have been found to be positive.

Explanation of the changes in potential and actual evaporation, and precipitation in a perspective of coupled water-energy balance

The total differential of actual evaporation can be given as

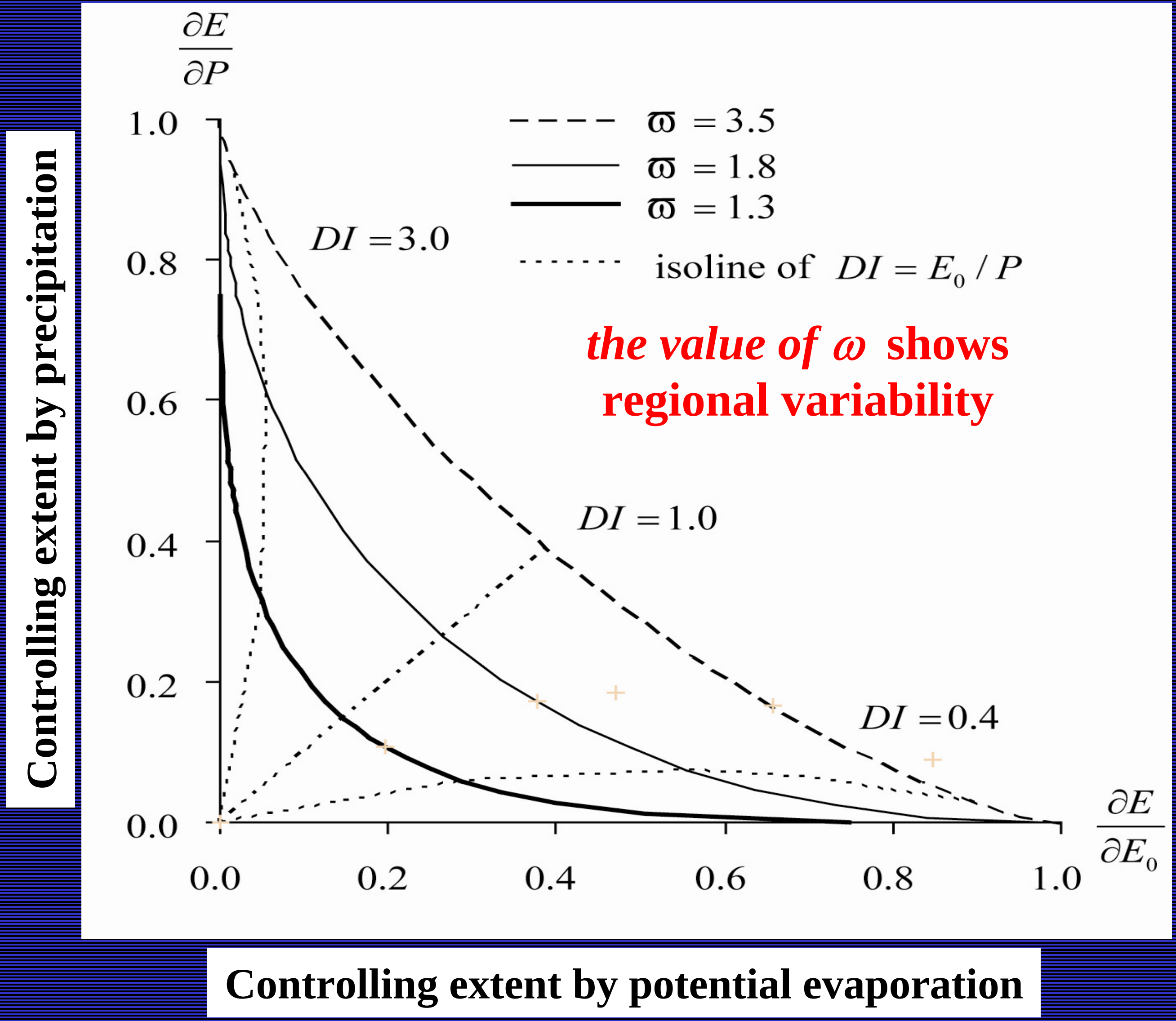
$$\frac{\delta E}{\delta t} = \frac{\partial E}{\partial E_0}\frac{\delta E_0}{\delta t} + \frac{\partial E}{\partial P}\frac{\delta P}{\delta t} + \frac{\partial E}{\partial \varpi}\frac{\delta \varpi}{\delta t}$$

Since the vegetation needs much longer time to adapt to the steady change of climate (*Eagleson*, 2002), the landscape characteristics are relatively stable, we assume: $\delta\varpi / \delta t = 0$

$$\frac{\delta E}{\delta t} = \frac{\partial E}{\partial E_0}\frac{\delta E_0}{\delta t} + \frac{\partial E}{\partial P}\frac{\delta P}{\delta t}$$

Using Fu's equation, we can estimate the controlling extents on the actual evaporation by the potential evaporation and precipitation.

$$\frac{E}{P} = 1 + \frac{E_0}{P} - \left[1 + \left(\frac{E_0}{P}\right)^{\varpi}\right]^{1/\varpi}$$



- In non-humid regions, actual evaporation is controlled mainly by precipitation;
- In humid regions, actual evaporation is controlled mainly by potential evaporation;
- Landscape affects to the controlling extent of climate on the water balance.

Conclusions

- **Controversy on Hydrological cycle implication of global climate change is a on going hot topic.**
- **Globally, the complementary idea can explain that the decrease in pan evaporation (potential evaporation) indicates increase in actual evaporation.**
- **However, water balance analysis in many regions of the world don’t fully support this explanation.**

Conclusions (cont.)

- **Analysis in 108 non-humid catchments in China tell us that the change in actual evaporation is dominated by change in precipitation rather than in potential evaporation. Thus the effect of potential evaporation (solar radiation) on hydrological cycle has been overestimated.**
- **In addition, previous studies have not illustrate the geographical variability in hydrological cycle response to climate change. And this is important for understanding the regional characteristics of hydrological cycle and for prediction in ungauged basins.**
- **Fu’s equation derived from the Budyko hypothesis provides us a useful theoretic framework for investigating the spatial and temporal variations in hydrological cycle regarding to the global climate change.**

Future Research

- We are continuing the water balance analysis over different climate regions and geographical settings.
- This analysis is aimed to understand the control factors on the basic characteristics of catchment hydrological response.
- We will also look at the changes in vegetation during the past 30 years for understanding the regional ecohydrological response to the global climate change.
- By this top-down analysis, we hope to be able to predict the water balance in the ungauged basins.

Acknowledgements

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Thank you for your kind attention !