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Causes for the increases in both ET and water yield over vegetated mainland China during the last two decades

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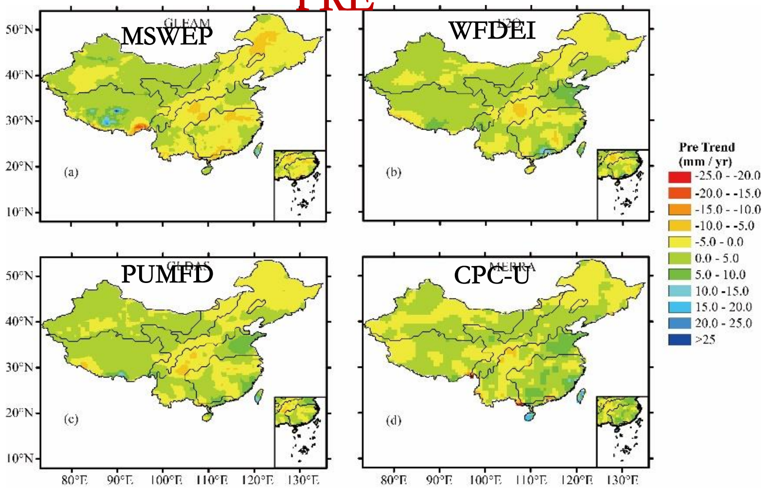
目录

CONTENTS

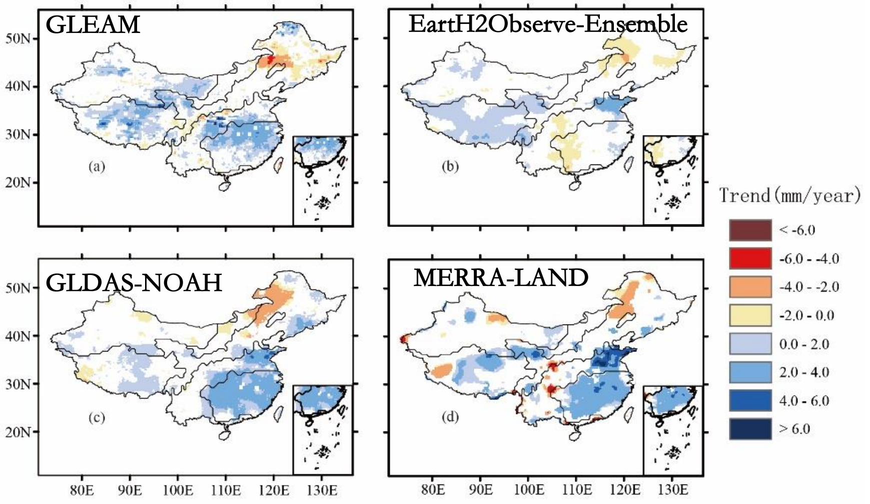
1. Introduction

- Hydrological cycle have significantly changed across the globe under the context of global warming and exacerbation of human activities
- **ET** is arguably a **central component** of the terrestrial water cycle, and functions as a vital link between the **land surface and the atmosphere**

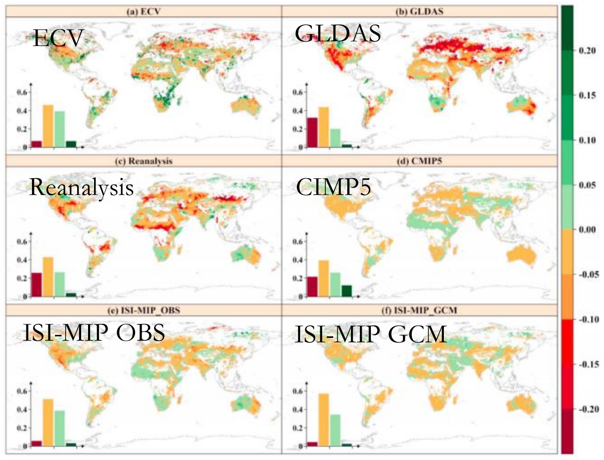
PRE



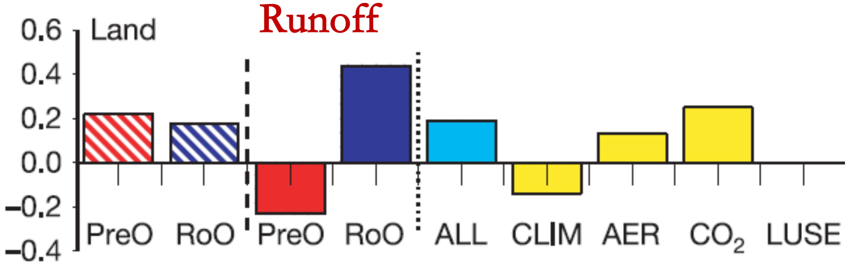
ET

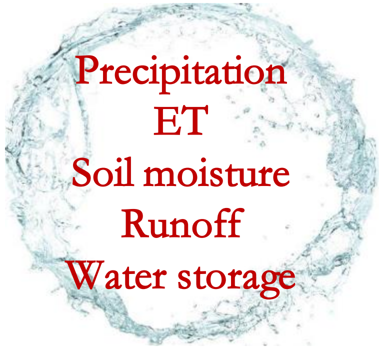


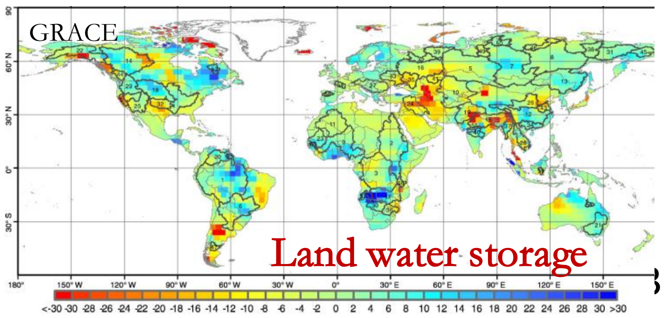
Soil moisture



Runoff

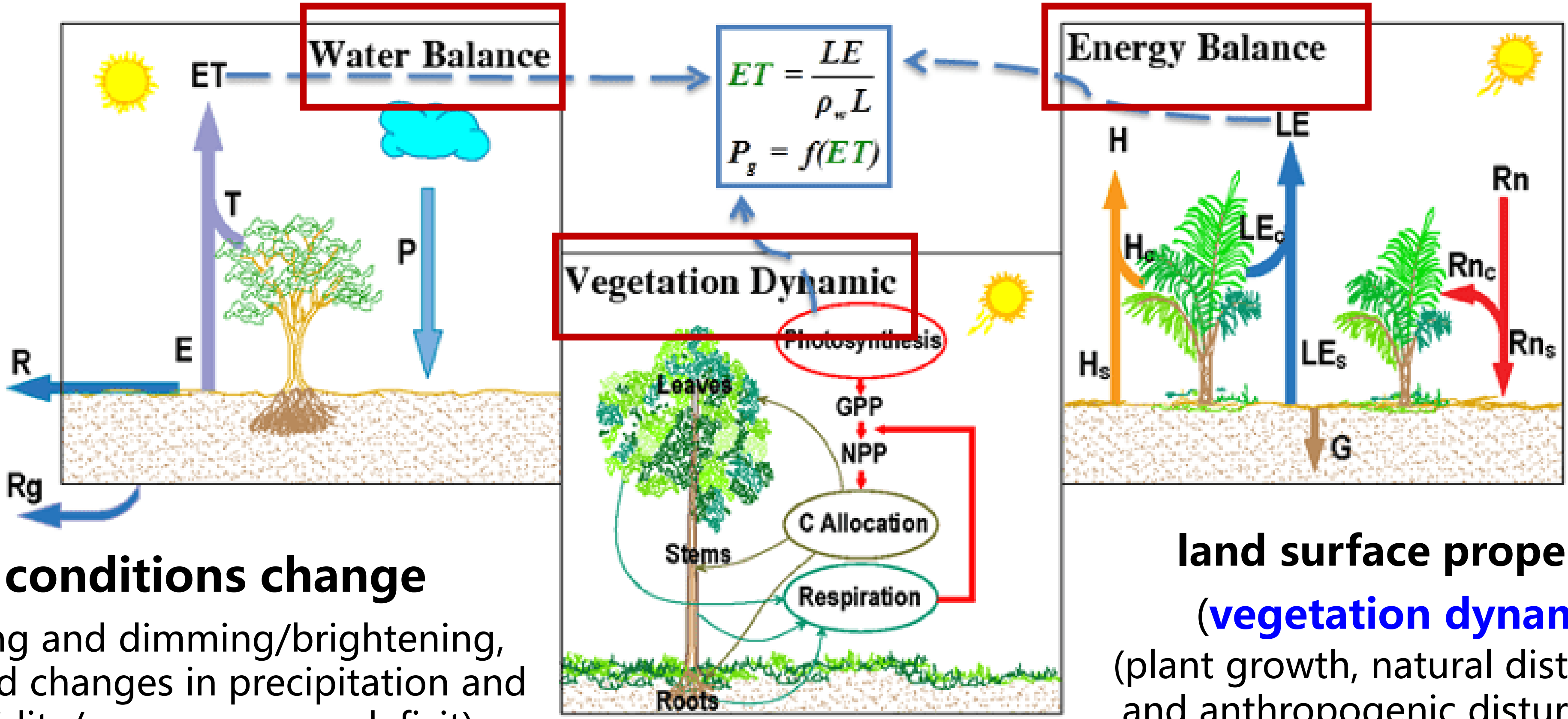






1. Introduction

- The mechanisms behind the changed ET have been extensively elucidated from global to regional scales, however, vegetation-induced hydrological effects remain controversial



climate conditions change

(global warming and dimming/brightening, wind stilling, and changes in precipitation and relative humidity/vapor pressure deficit)

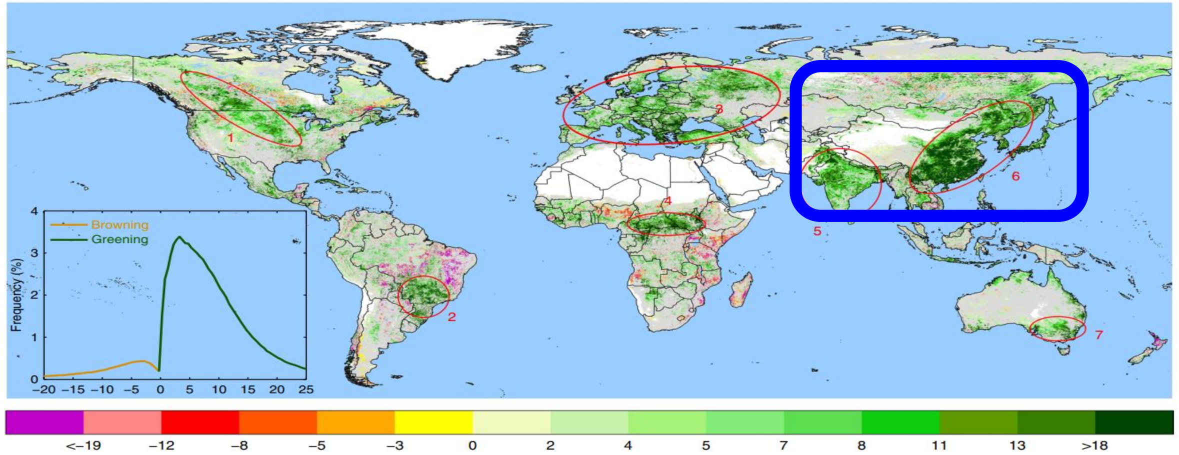
land surface properties

(**vegetation dynamics**

(plant growth, natural disturbances, and anthropogenic disturbances))

1. Introduction

- The apparent vegetation greening and climate change across China during the past decades provide a good research opportunity to examine the hydrological responses to changes in vegetation and climate



Chen et al. (2019)

Indirect factors: plant growth under the natural environmental conditions, such as CO_2 fertilization and nitrogen deposition……

Direct factors: human disturbances, such as afforestation/reforestation, and croplands abandonment……

- Only a few studies have separated the contributions of human-disturbed and natural vegetation to the variations of key hydrological variables across China, and identified the dominant factor among climate variables, human-disturbed vegetation and natural vegetation

1. Introduction

- **Due to no considerations of the impacts of interactions among the influential factors, there often exist uncertainties and even errors for the contributions estimated by the traditional separation methods**

✓ Regression analysis (xie et al., 2020),

✓ Sensitivity method (sun et al., 2013; zhang et al., 2020),

✓ Differential equation approach (yang et al., 2009, 2014; zhang et al., 2018),

✓ Traditional numerical experiment approach (comparing the simulations under different scenario settings; e.G., Liu et al., 2016; bai et al. 2020; zhang et al., 2020)

- Sun et al. (2014, 2017, 2021) developed a joint-solution method with multiple sensitivity numerical experiments.
- This method can eliminate the combined effects of the influential factors' interactions, and provides an efficient tool for accurately estimating the contributions of each factor to changes in the hydrological variables (Li et al. 2021; Wang et al. 2023).

1. Introduction

☐ Objective

1: Investigate the trends in **ET, water yield** (i.e., precipitation minus ET) over mainland China during 2001-2020

2: Quantify the **contributions of climate variables and vegetation dynamics** (including human-disturbed and natural vegetation) to the trends in ET and water yield

2. Data and methodology

☐ Boreal ecosystem production simulator (BEPS):

process-based, diagnostic terrestrial biosphere model

A process-based boreal ecosystem productivity simulator using remote sensing inputs

J Liu, JM Chen, J Cihlar, WM Park - Remote sensing of environment, 1997 - Elsevier

This paper describes a boreal ecosystems productivity simulator (BEPS) recently developed at the Canada Centre for Remote Sensing to assist in natural resources management and to estimate the carbon budget over Canadian landmass (106–107 km2). BEPS uses principles of FOREST biogeochemical cycles (FOREST-BGC)(Running and Coughlan, 1988) for quantifying the biophysical processes governing ecosystems productivity, but the original model is moth fled to better represent canopy radiation processes. A numerical scheme is …

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Daily canopy photosynthesis model through temporal and spatial scaling for remote sensing applications

JM Chen, J Liu, J Cihlar, ML Goulden - Ecological modelling, 1999 - Elsevier

Because Farquhar's photosynthesis model is only directly applicable to individual leaves instantaneously, considerable skill is needed to use this model for regional plant growth and carbon budget estimations. In many published models, Farquhar's equations were applied directly to plant canopies by assuming a plant canopy to function like a big-leaf. This big-leaf approximation is found to be acceptable for estimating seasonal trends of canopy photosynthesis but inadequate for simulating its day-to-day variations, when compared with …

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[HTML] Vegetation structural change since 1981 significantly enhanced the terrestrial carbon sink

JM Chen, W Ju, P Ciais, N Viovy, R Liu, Y Liu… - Nature …, 2019 - nature.com

Satellite observations show that leaf area index (LAI) has increased globally since 1981, but the impact of this vegetation structural change on the global terrestrial carbon cycle has not been systematically evaluated. Through process-based diagnostic ecosystem modeling, we find that the increase in LAI alone was responsible for 12.4% of the accumulated terrestrial carbon sink (95±5 Pg C) from 1981 to 2016, whereas other drivers of CO2 fertilization, nitrogen deposition, and climate change (temperature, radiation, and precipitation) …

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Net primary productivity of China's terrestrial ecosystems from a process model driven by remote sensing

X Feng, G Liu, JM Chen, M Chen, J Liu, WM Ju… - Journal of environmental …, 2007 - Elsevier

The terrestrial carbon cycle is one of the foci in global climate change research. Simulating net primary productivity (NPP) of terrestrial ecosystems is important for carbon cycle research. In this study, China's terrestrial NPP was simulated using the Boreal Ecosystem Productivity Simulator (BEPS), a carbon-water coupled process model based on remote sensing inputs. For these purposes, a national-wide database (including leaf area index, land cover, meteorology, vegetation and soil) at a 1km resolution and a validation database …

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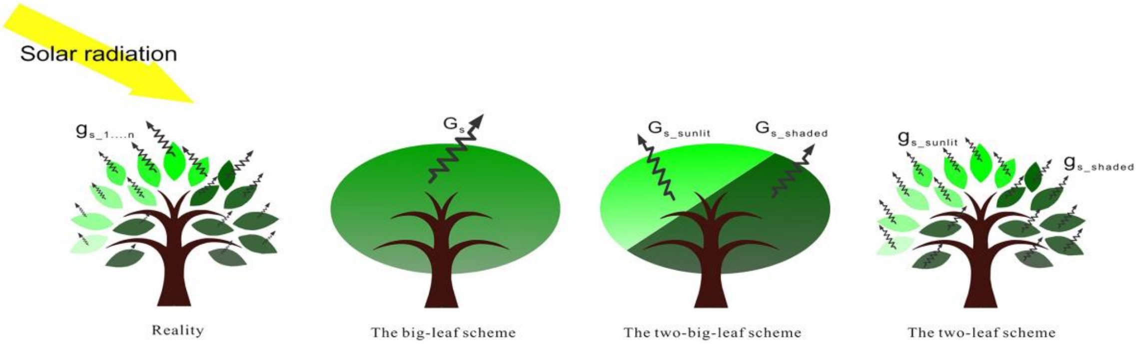
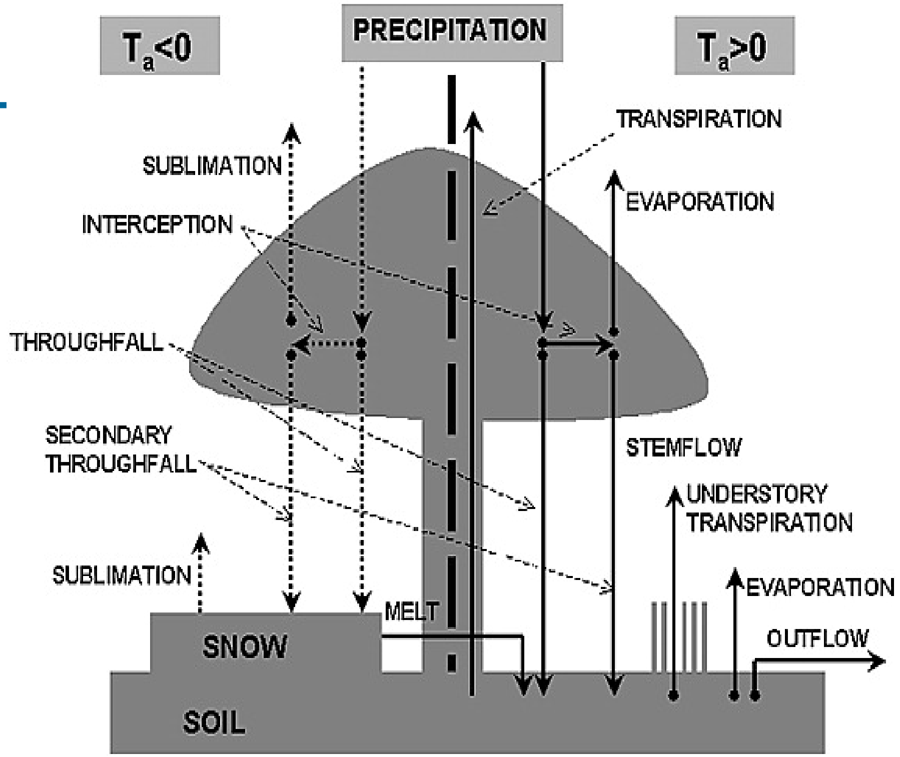
2. Data and methodology

☐ Boreal ecosystem production simulator (BEPS)

- ✓ Originally stemmed from the FOREST-BGC model with **a new temporal and spatial scaling scheme**, and stratified whole canopies into sunlit and shaded leaves to calculate daily carbon fixation and water consumption (Liu et al., 2003; Chen et al., 1999; Ju et al., 2006)
- ✓ Its **superiority and successful applications** in estimating terrestrial carbon and water fluxes in various ecosystems in different regions (China, North America, Europe, East Asia, and the globe)





- ✓ ET

$$ET = T_{ran} + E_{plant} + E_{soil} + S_{plant} + S_{ground}$$

- ✓ Canopy transpiration

$$T_{ran} = T_{ran.sunlit} LAI_{sunlit} + T_{ran.shaded} LAI_{shaded}$$

- ✓ Transpiration of sunlit and shaded leaves

$$T_{ran,j} = \frac{\Delta R_{n,j} + \rho c_p VPD / r_a}{[\Delta + \gamma(1 + r_{s,j}/r_a)\lambda_v]}$$

2. Data and methodology

Major inputs for the BEPS model

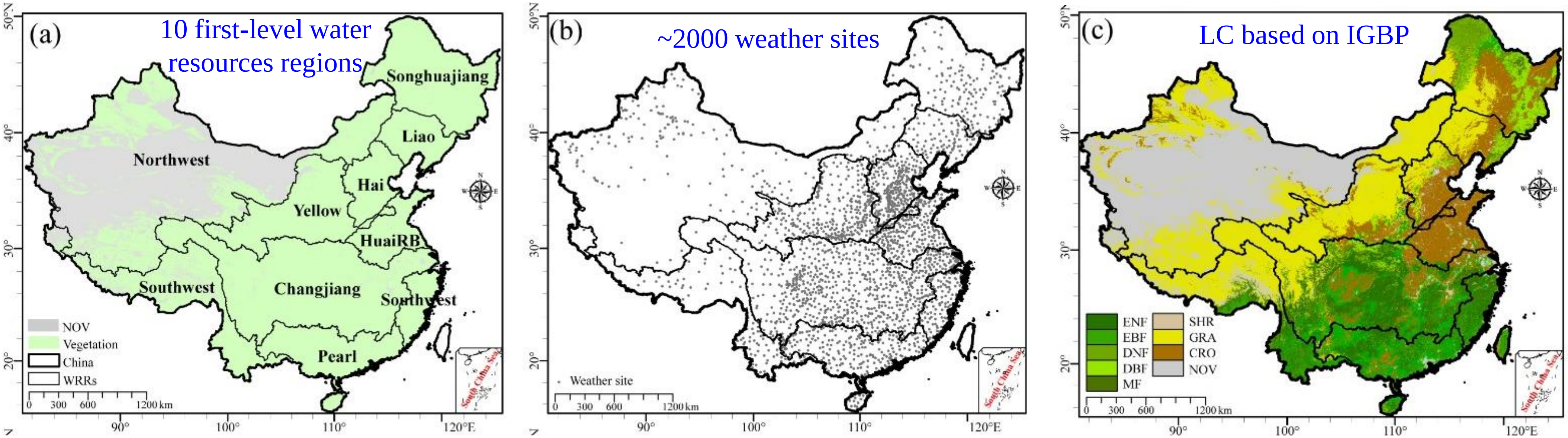
✓ **Meteorological observations:**

Precipitation, maximum and minimum temperatures, relative humidity, and sunshine duration

✓ **Land surface inputs：**

Land use/cover (LC): MCD12Q1, GLOBMAP LAI, Soil texture

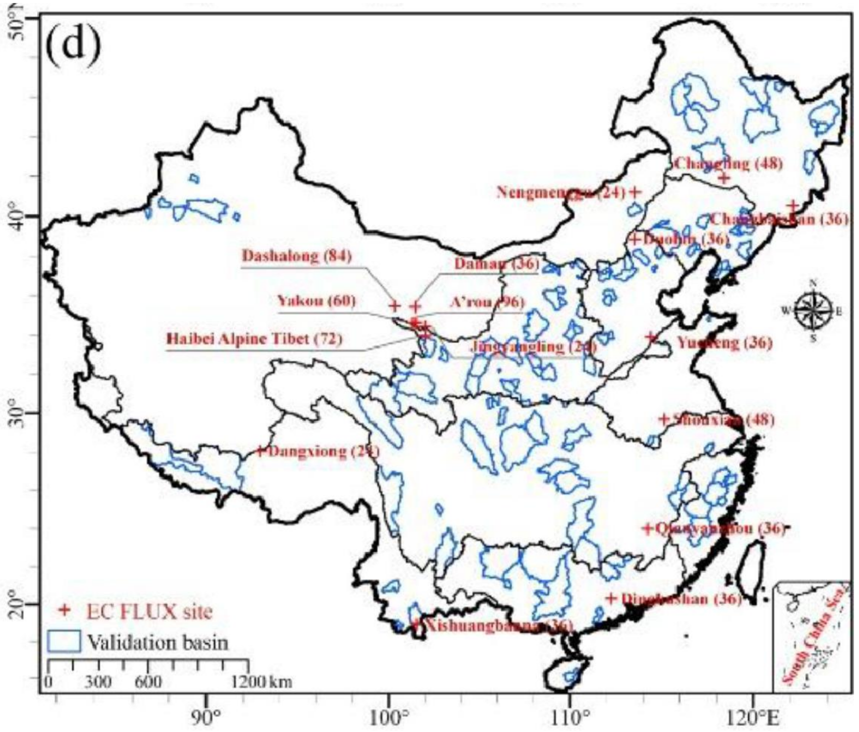
	Resolutions	Time span
Meteorological data	txt, daily	2001-2020
MODIS LC	500 m, annually	2001-2019
GLOBMAP LAI	500 m, 8-day	2001-2020
Soil data	0.00833°	--
CO2 concentration	txt, annually	2001-2020



2. Data and methodology

☐ Data for validating the BEPS model

- ✓ 16 **EC flux sites**: ChinaFlux, FLUXNET, NCO-CMA, and HiWATER
- ✓ 127 **basins** annual **streamflow** records (2001-2010)
- ✓ 7 widely-used **ET products**



ET products	Resolutions	Time span
GLEAM3.5a	0.25, daily	1980-2020
ERA5	0.25°, monthly	1979-present
ERA5-Land	~9 km, monthly	1950-present
MERRA2	2/3°×1/2°, monthly	1980-present
MERRA-Land	2/3°×1/2°, monthly	1980-present
GLDAS_NOAH025_V2.1	0.25°, monthly	2000-present
MOD16A2.006	500 m, 8-day	2001-present

☐ Kling-Gupta Efficiency (KGE):

a widely-used combined validation metric

$$KGE = 1 - \sqrt{(R-1)^2 + (\beta-1)^2 + (\gamma-1)^2}$$

$$R = \frac{\sum_{i=1}^{N}[(E_i-\mu_e)(O_i-\mu_o)]}{\sqrt{\sum_{i=1}^{N}(E_i-\mu_e)^2}\sqrt{\sum_{i=1}^{N}(O_i-\mu_o)^2}}$$

correlation coefficient

$$\beta = \frac{\mu_e}{\mu_o}$$

average tendency (larger/smaller)

$$\gamma = \frac{\sigma_e/\mu_e}{\sigma_o/\mu_o}$$

variability (underestimate/overestimate)

2. Data and methodology

- **The attribution method (Joint-solution method** with **multiple sensitivity numerical experiments)** was employed to estimate the contribution of each driving factor (Sun et al., 2014, 2017, 2021)
- 6 numerical simulations were performed based on the concept and influential factors, including 1 **control** simulation and 5 **experimental** simulations

	Description
EXPCTL	Daily climate variables, 8-day LAI, and annual LC maps during 2001-2020
EXPPRE	All settings are the same as EXPCTL, except that **precipitation** is fixed at the value of the year 2001. For example, the precipitation on June 1, 2001, is used for June 1 for every year from 2001 to 2020.
EXPRAD	All settings are the same as EXPCTL, except that **incoming solar radiation** is fixed at the value of the year 2001.
EXPTEM	All settings are the same as EXPCTL, except that **temperature** is fixed at the value of the year 2001.
EXPRH	All settings are the same as EXPCTL, except that **relative humidity** is fixed at the value of the year 2001.
EXPVEG	All settings are the same as EXPCTL, except that 8-day **LAI** and annual **LC** map are fixed at the value of the year 2001.

2. Data and methodology

- **☐** Contribution of each factor to the annual ET trends was estimated at each grid cell in the study area using the separation algorithm

✓ With the assumption that the changed factors induced the EXPx ET trends:

$$\sum_{K\neq x}^{N} C_{ET}^{K} = T_{ET}^{EXP_x}$$

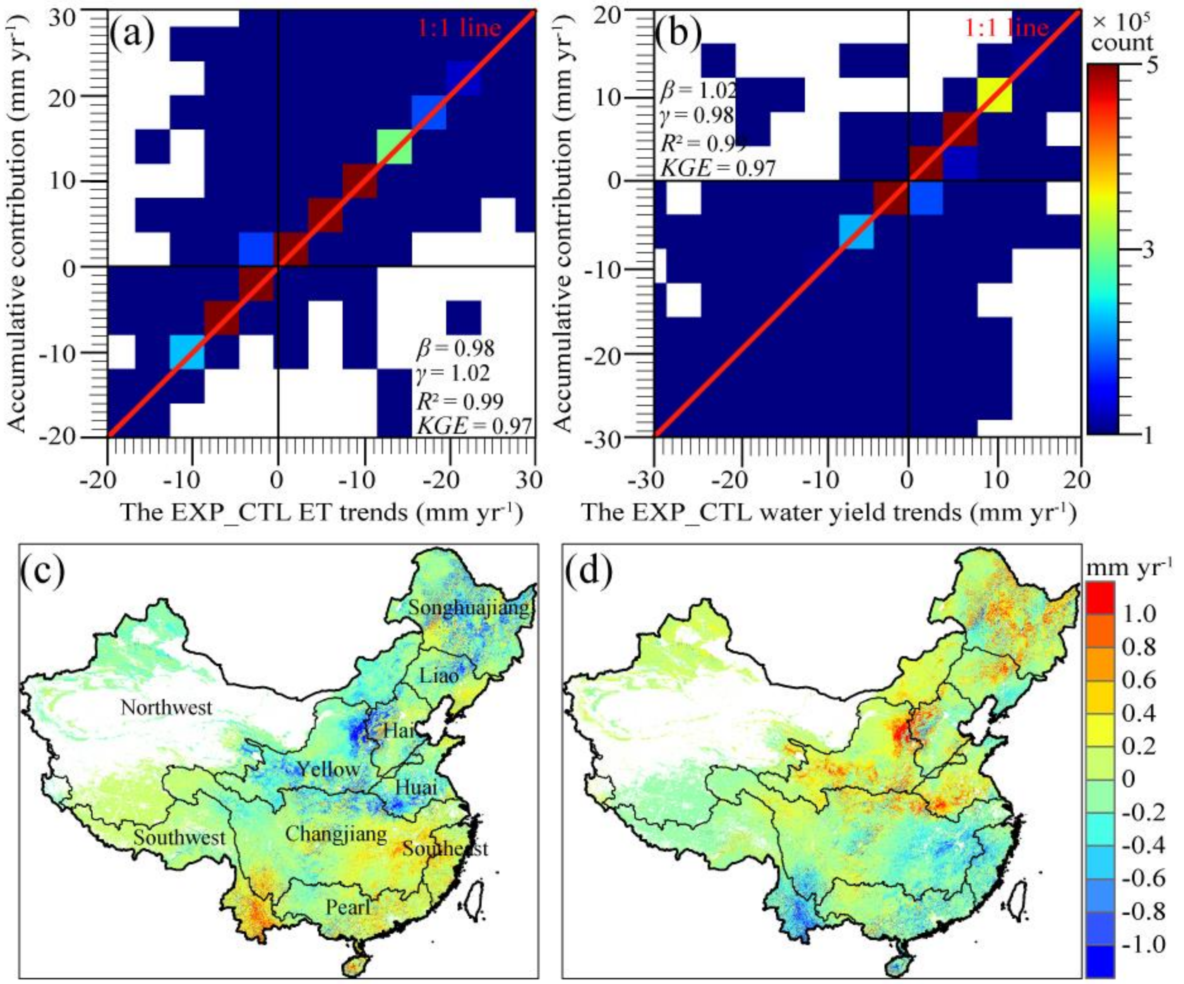
✓ Get a set of simultaneous equations with 5 unknown numbers

✓ By solving these equations, the respective contribution for each factor:

$$C_{ET}^{K} = \frac{\sum_{K\neq i}^{N} T_{ET}^{EXP_K} - (N-2)T_{ET}^{EXP_x}}{(N-1)}$$

Sun et al. (2014, 2017, 2021)

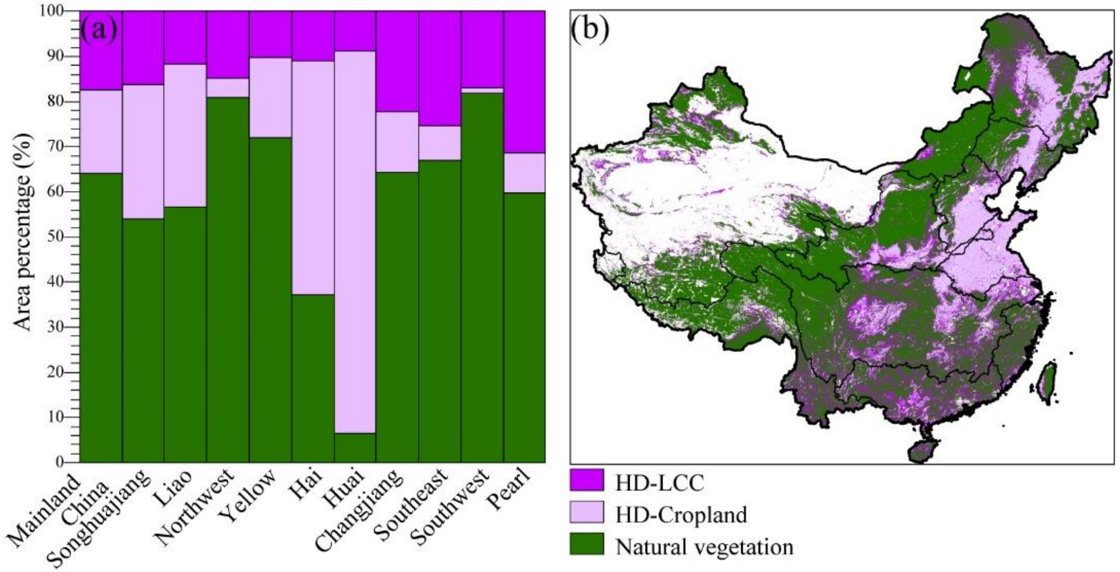
Attributing ET and water yield trends across vegetated mainland China effectively



2. Data and methodology

☐ Human-disturbed (HD) and natural vegetation identification

- ✓ **HD-LCC:** HD vegetation with LCC
- ✓ **HD-Cropland**: consistent cropland
- ✓ **Natural vegetation**: consistent non-agricultural LC during 2001-2020



(Chen et al., 2019; Chen et al., 2021)

☐ Identifications of dominant factors for the annual ET and water yield trends

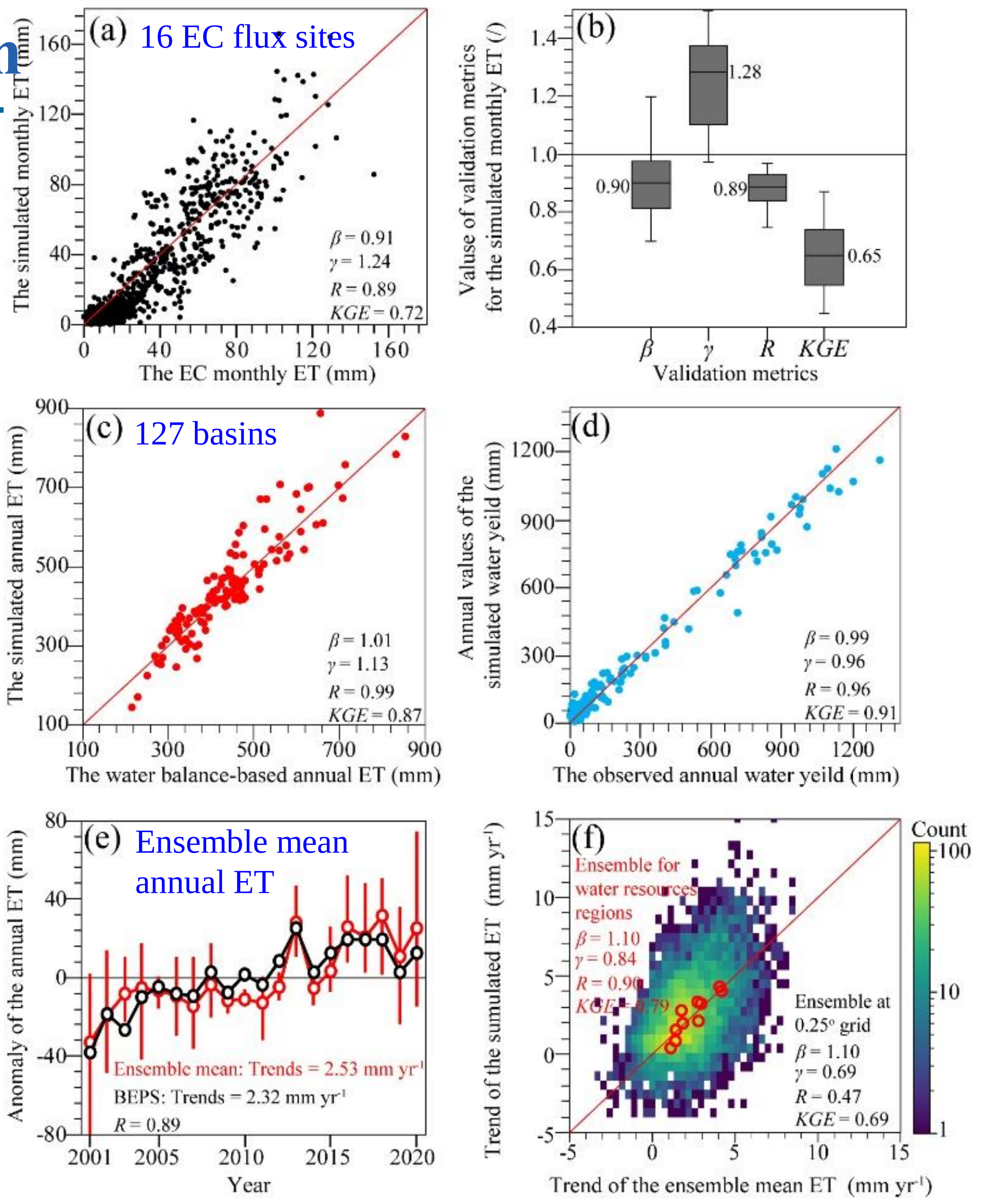
① estimate the vegetation contributions to the ET (water yield) trends for a certain region by summing up area-weighted contributions from HD-LCC, HD-Cropland, and natural vegetation.

② by comparing the contributions of each climate factor and vegetation, the dominants for vegetated mainland China and each water resources region can be determined.

③ Furthermore, if vegetation is dominant for a given region, we further determine the dominant factor to be HD-LCC, HD-Cropland, and natural vegetation based on their contributions.

3. Results—Evaluation of simulation

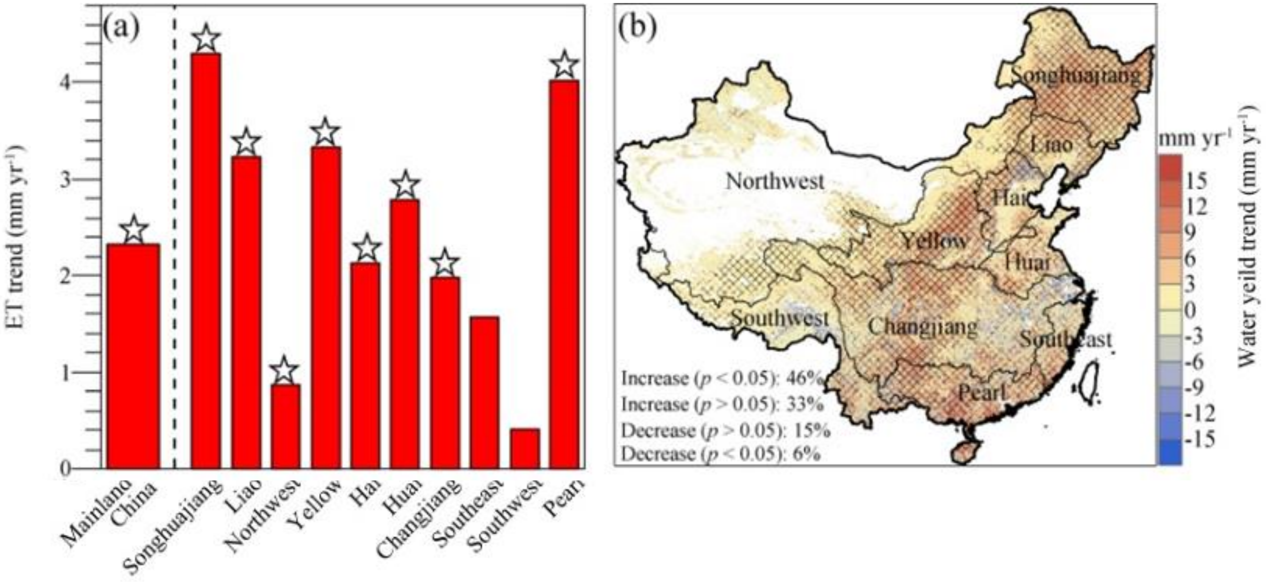
- The performance of the BEPS model was **reasonably well in simulating ET and water yield**, which gave us confidence in the following sensitivity experiments
  - ✓ Agreed reasonably well with **monthly** ET measurements from the flux **site**s, though the mean value and the temporal variability were slightly underestimated and overestimated, respectively
  - ✓ Reasonably capture the magnitudes and spatial patterns of the observed multi-**year** mean ET and water yield in these 127 **basin**s
  - ✓ The **inter-annual fluctuation** of the simulated ET over vegetated mainland China closely agreed with the **ensemble mean**
  - ✓ Capture the ET trends on regional and 0.25° grid scales

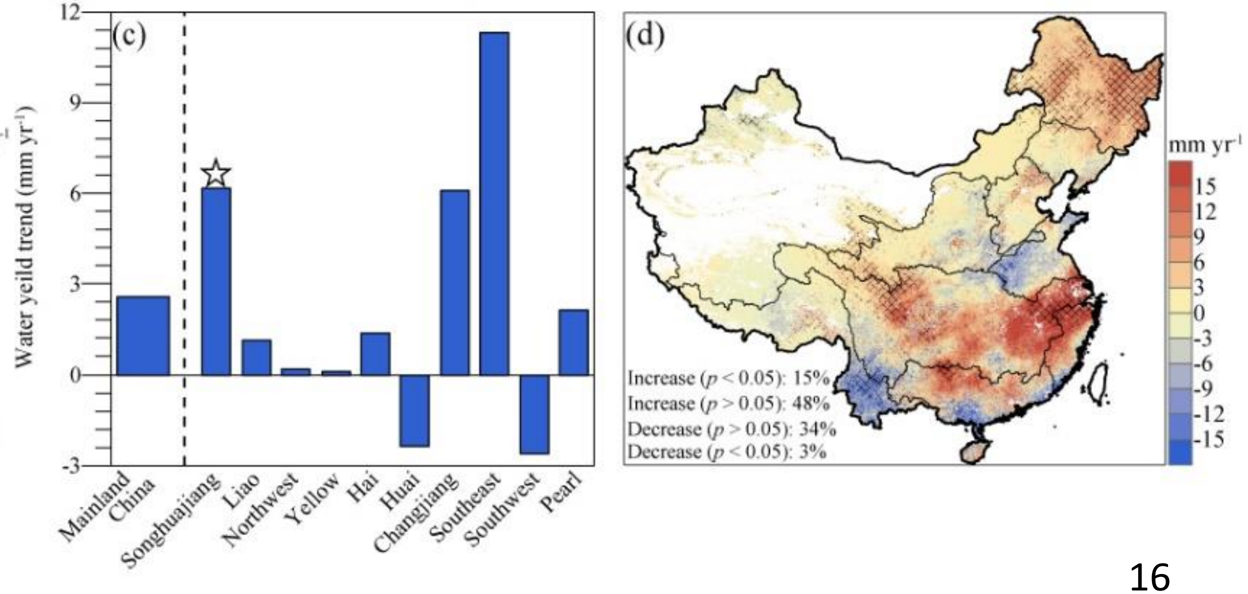


3. Results--Trends in ET and water yield

- On average, a significant increasing **ET** trend (2.3 mm y^{-1}) was detected over vegetated mainland China
- Spatially, 46% of the study area experienced significant upward trends of ET, with the highest values (>6.0 mm y^{-1}) mainly observed in central, northeast, and southeast China

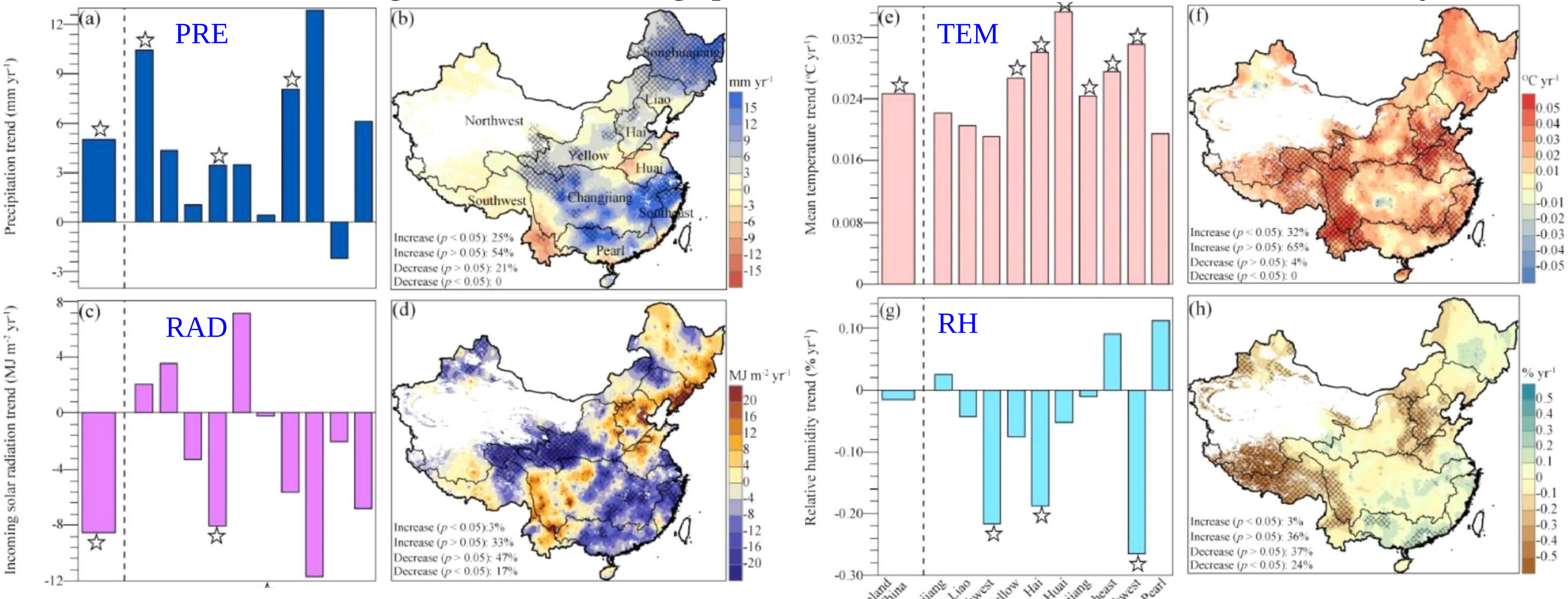
- The annual **water yield** averaged over vegetated mainland China increased by 2.6 mm y^{-1} (p>0.05) during 2001-2020
- Although the trends in water yield seemed stronger than those in ET, the trends in water yield were insignificant over 80% of vegetated mainland China





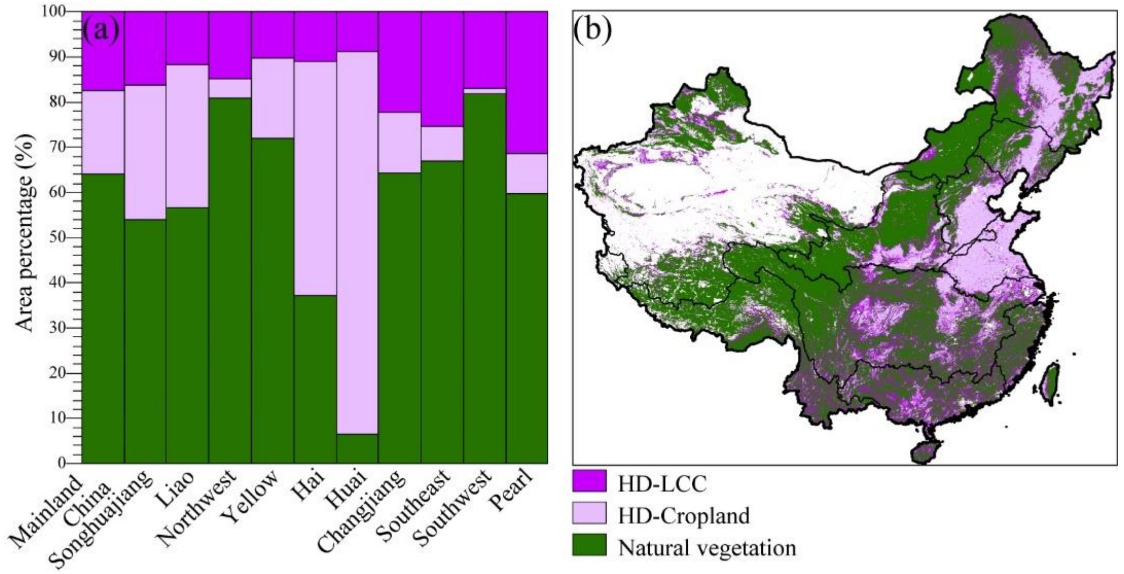
3. Results--Trends in climate variables

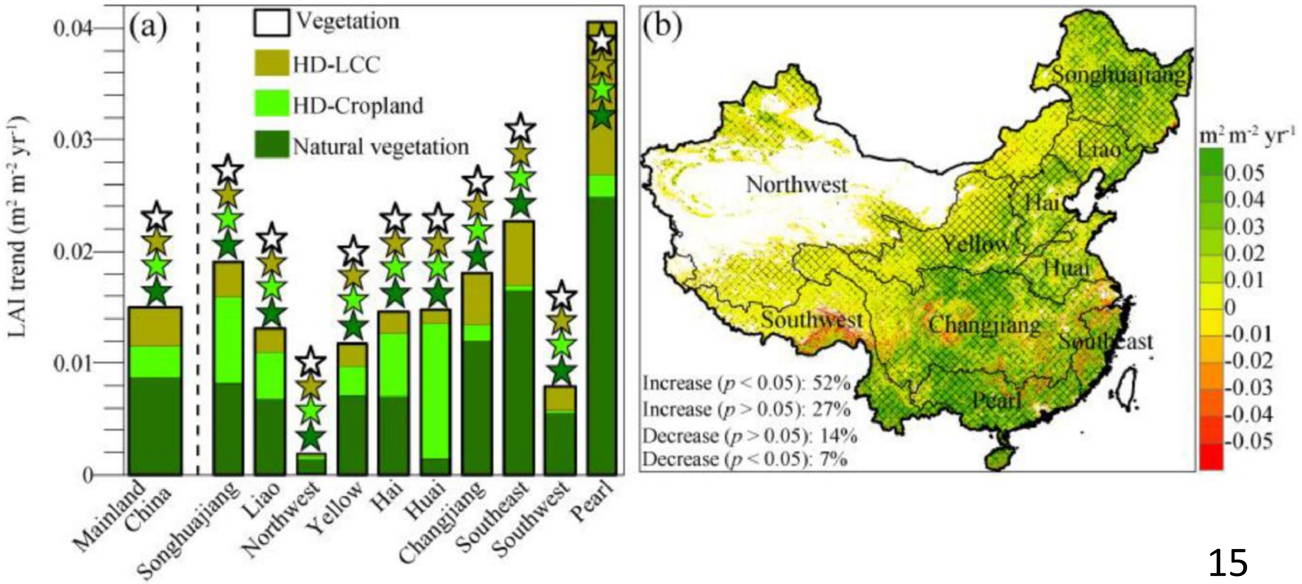
- The annual **precipitation** showed a significant increase trend of 5.0 mm y^{-1}; The annual **incoming solar radiation** experienced a significant decreasing trend (8.6 MJ m^{-2} y^{-1})
- The mean **temperature** had a significant warming trend of 0.025 °C y^{-1}; The **relative humidity** trend was close to zero, although there were strong spatial variations in the trends in relative humidity



3. Results--Trends in LAI

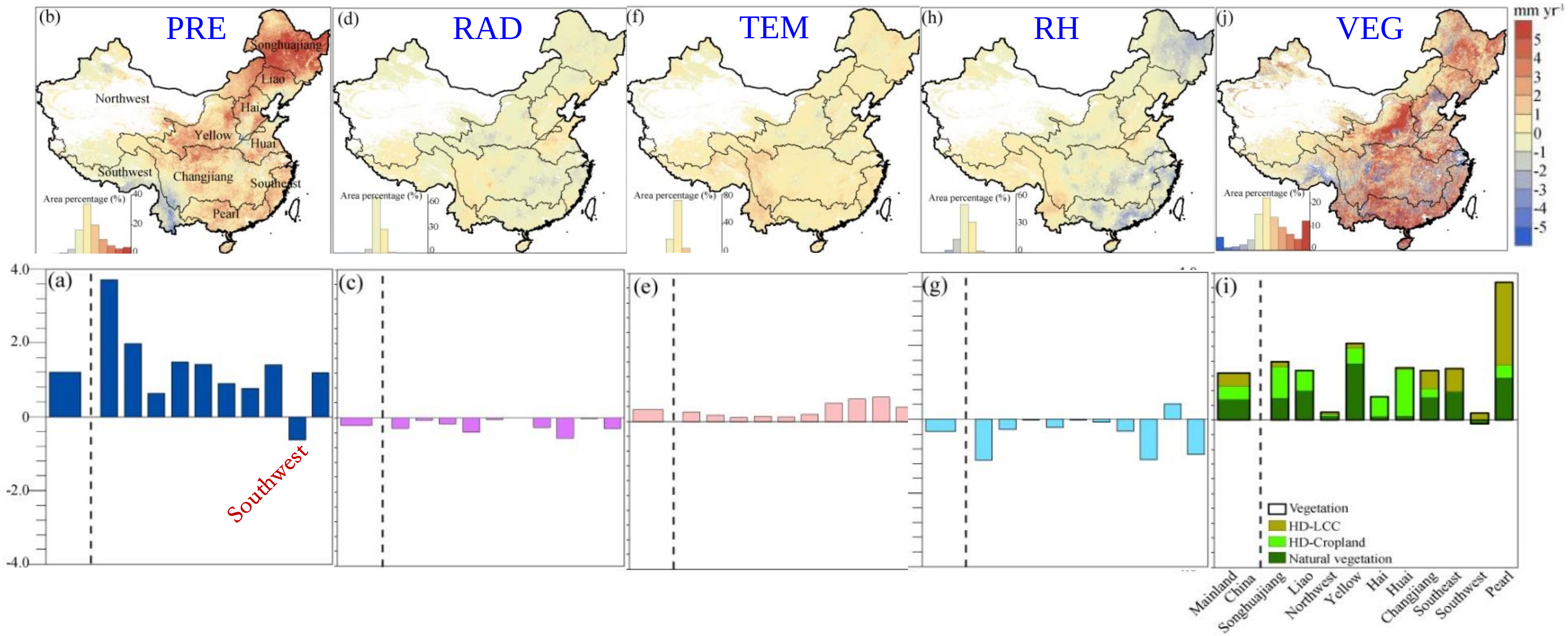
- The annual nation-averaged LAI experienced a significant ($p<0.05$) greening trend of 0.015 during the past two decades
- The widespread greening trends were observed over ~80% of vegetated mainland China, with more than half of the study area showing significant ($p<0.05$) greening trends
- The nation-averaged HD-LCC, HD-Cropland and natural vegetation LAI significantly increased by 0.0035, 0.0029, and 0.0089, respectively
- The **natural vegetation** played a decisive role in the significant greening trends over mainland China except Huai RB (HD-Cropland dominated)





3. Results--Attributions for the trends in ET

- **Precipitation and vegetation** contributed similarly to the ET trends (1.20 versus 1.29 mm y^{-1}), natural vegetation made the largest contribution (0.56 mm y^{-1})
- However, the contributions of incoming solar radiation (-0.20 mm y^{-1}), temperature (0.33 mm y^{-1}), and relative humidity (-0.33 mm y^{-1}) were much lower than precipitation and vegetation



3. Results--Attributions for the trends in water yield

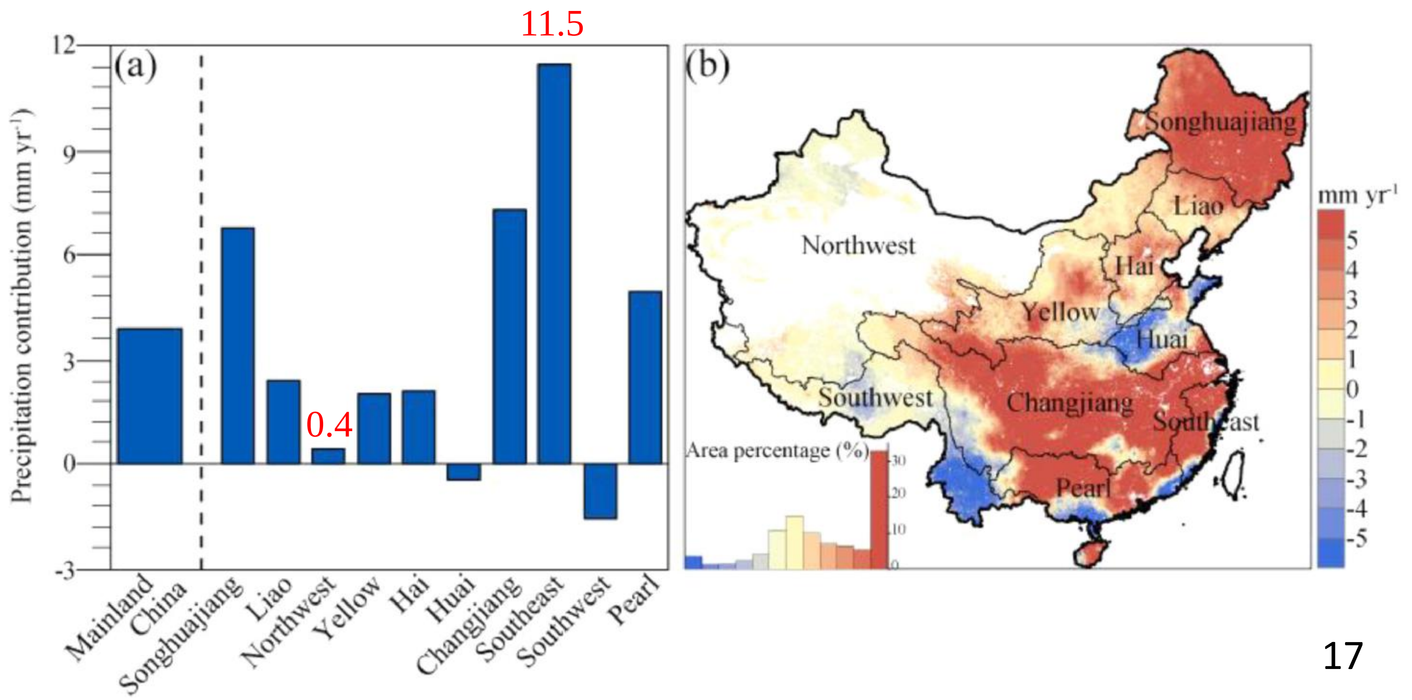
- The **precipitation contributions** to each grid cell's annual **water yield** trends:

$$(PRE_{trend}) \ - \ (\text{precipitation contributions to the } ET_{trend})$$

- The contribution of the **remaining factors**:

$$-1.00 * (\text{the factor's contribution to the } ET_{trend})$$

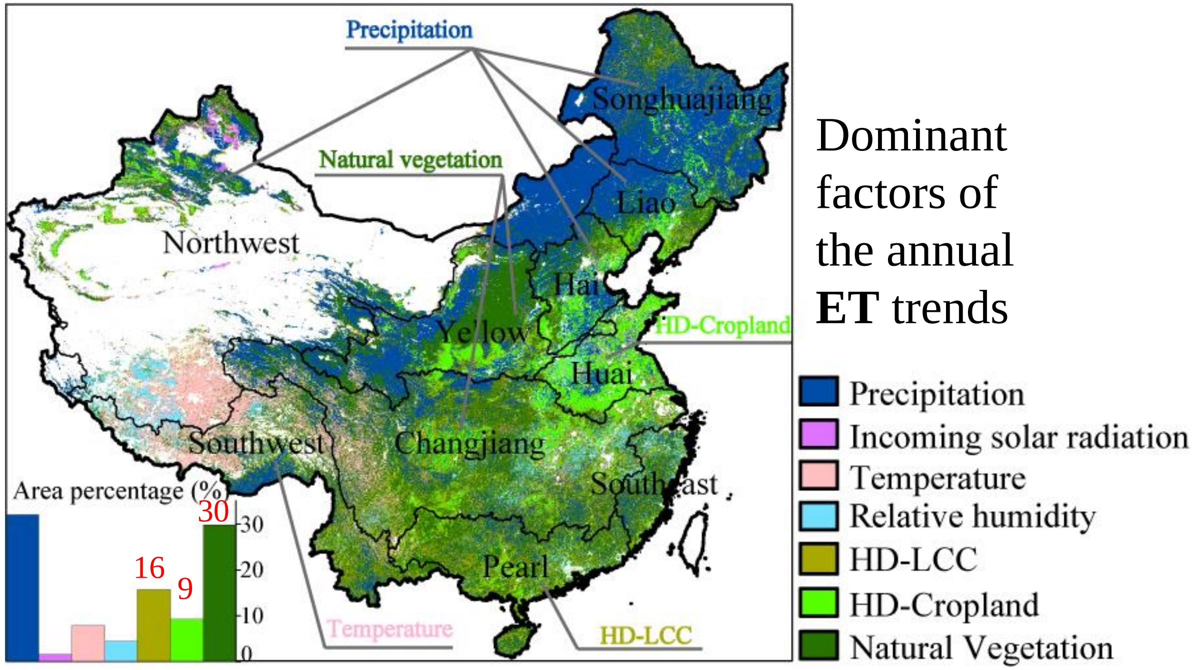
- The contribution of precipitation was positive for **8/10** water resources regions, ranging from 0.4 mm y^{-1} in Northwest RB to 11.5 mm y^{-1} in Southeast RB
- Positive precipitation contributions were found over **76%** while negative contributions covered 24% areas (mainly in southwestern and central-east China)



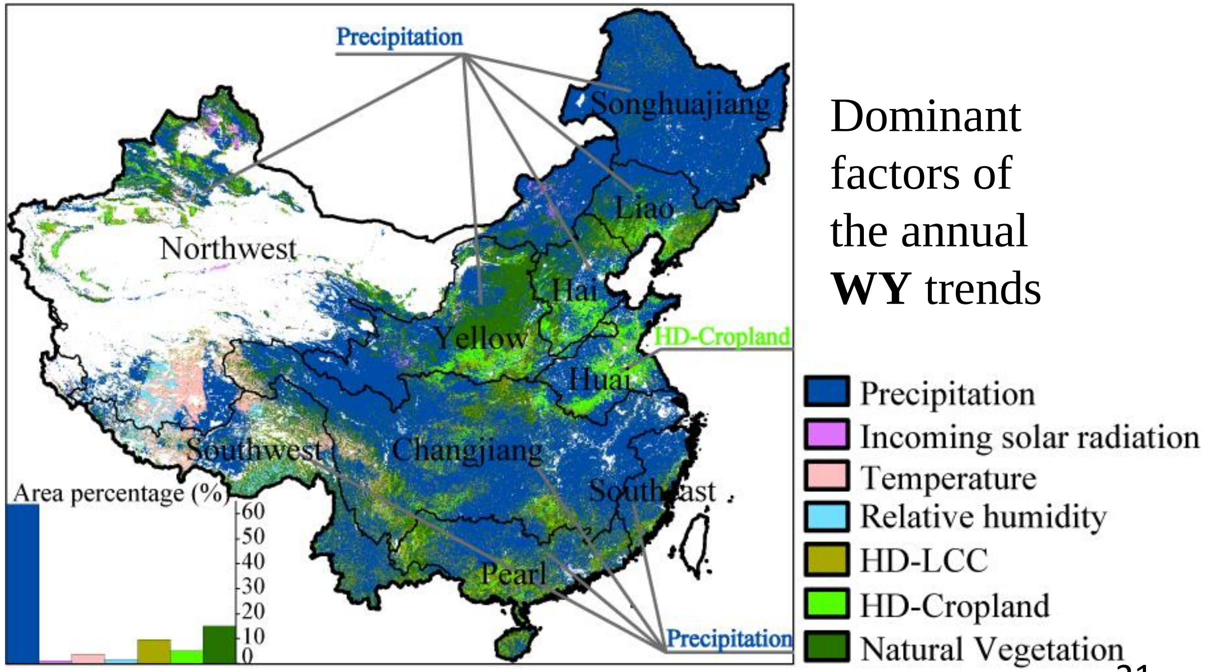
3. Results--Dominant factors of the trends in ET and water yield

- **Precipitation and vegetation together** dominate **9/10** water resources regions, and the temperature was the driver for ET trends in Southwest RB
- Spatially, precipitation and vegetation were the dominant factors over **32%** and **55%** of vegetated mainland China

- **Precipitation** was the driver for water yield trends for **9/10** water resources regions, while HD-LCC was the dominant factor for Huai RB
- Spatially, precipitation dominated **64%** of vegetated mainland China, while vegetation dominated 30%, mainly located in northern China



Dominant factors of the annual **ET** trends



Dominant factors of the annual **WY** trends

4. Conclusions

- 46% of the study area experienced significant increases in ET, with an overall increase of 2.3 mm y^{-1}. The overall trend in WY was 2.6 mm y^{-1} but insignificant
- Vegetation and precipitation dominated ET trends over 55% and 32% of study area, respectively
- Human-distributed vegetation and natural vegetation combined explained water yield trends over 30% areas
- Vegetation (particularly for human-distributed vegetation) greening was crucial for the hydrological cycle changes

5. Uncertainties

BEPS model

- Does not account for lateral movement of soil water, cryospheric hydrological processes, lakes, and reservoirs, and anthropogenic water use interventions

Other uncertainties

- Input datasets (i.e., meteorological, LAI, and LC datasets) can be propagated to the simulation results
- There existed two-way interactions between vegetation and the atmosphere. The contributions of vegetation (climate change) to the ET and water yield trends in this study **partially involves** the effects of climate change (vegetation)

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