Global Change Laboratory
School of Environmental Science and Engineering, SUSTech

Limiting global warming to 1.5°C restrains emerging aridification

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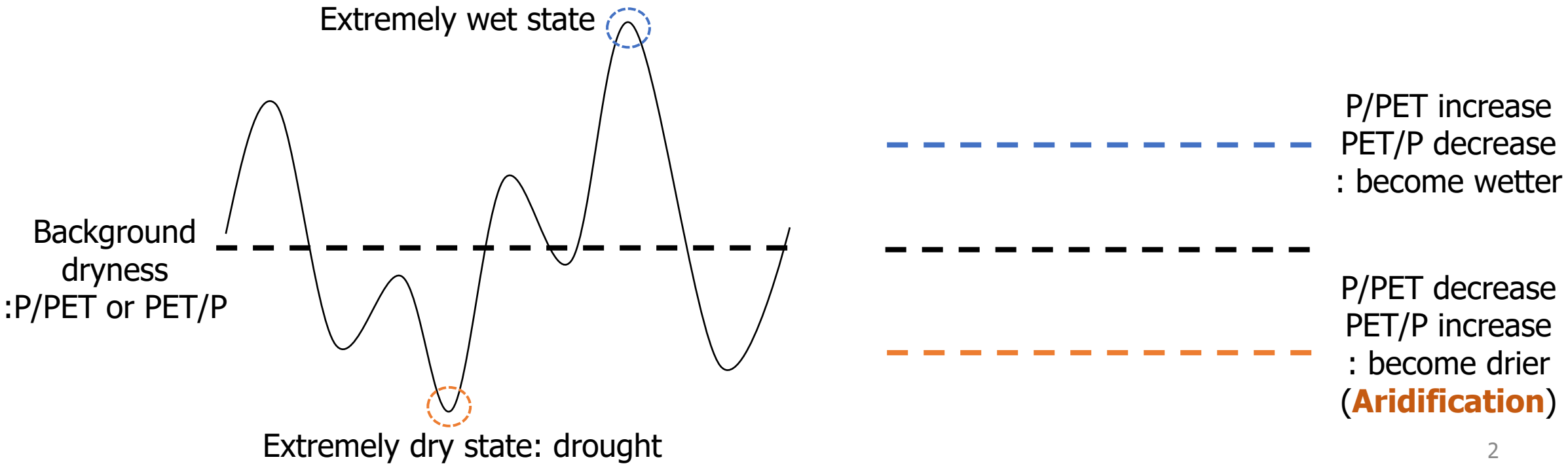
Apec Climate Center, 31 January, Busan, South Korea

Aridity and aridification

- Aridity indicate a background dryness at a location under specific climate conditions.
- Aridity index is used to examine the aridity.
  - The ratio of the atmospheric water supply (precipitation; P) and demands (potential evapotranspiration; PET): P/PET or PET/P



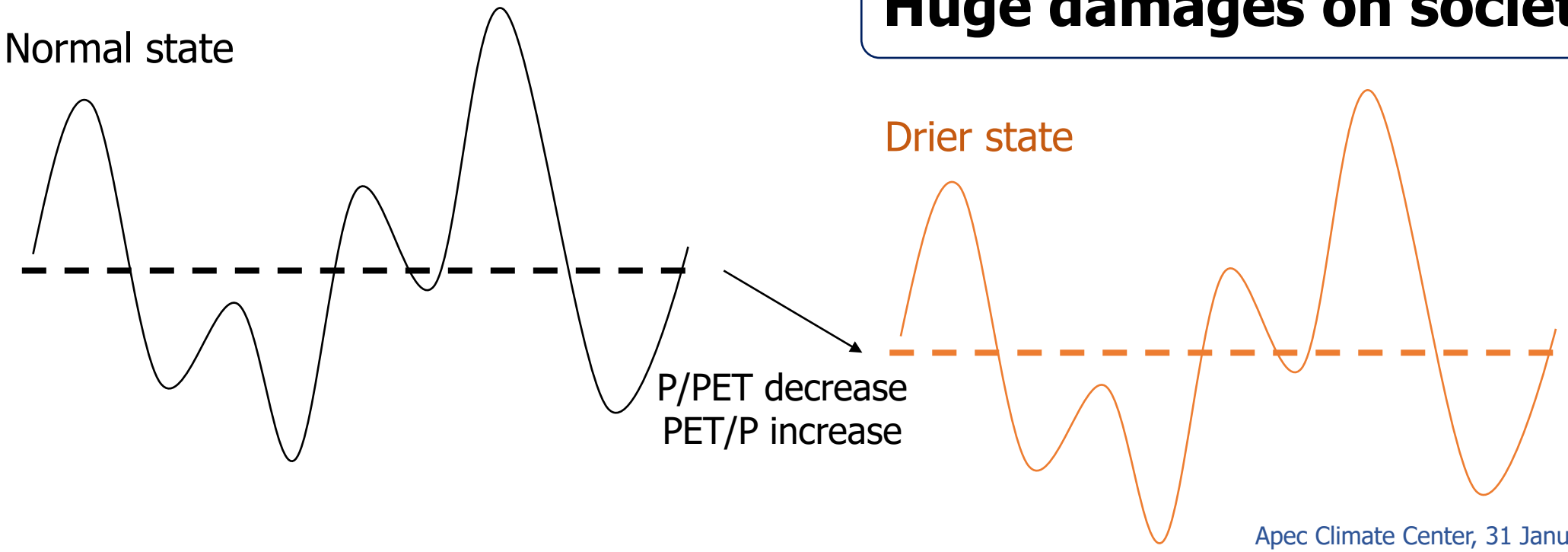
Impacts of aridification

- Desertification
- Increase in wildfire
- Increase in severe drought

Negative impacts

- Agriculture
- Water management
- Forest mortality

Huge damages on society



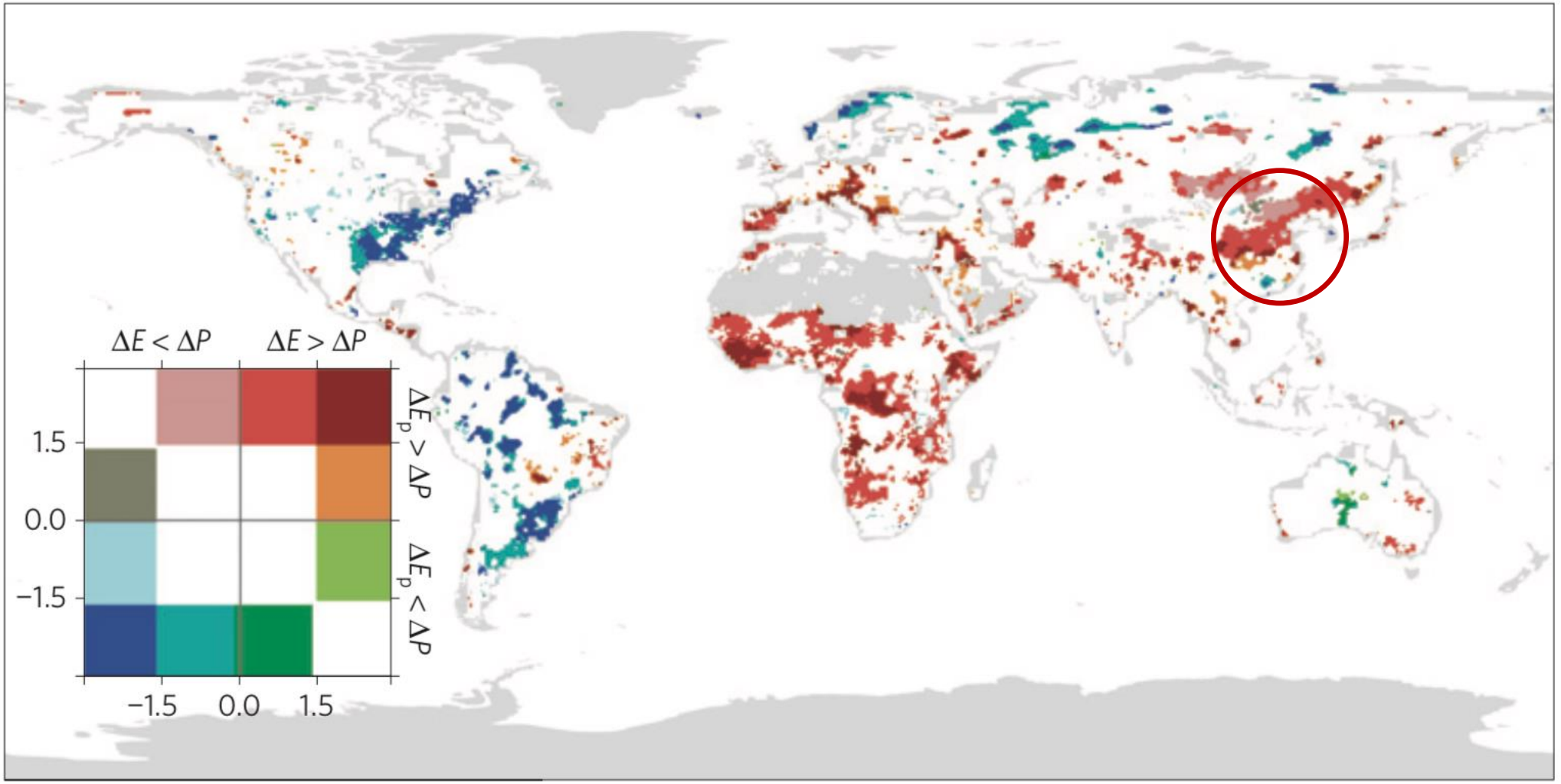
Two subjects

- Investigation of the observed drying trends in recent decades and underlying mechanism
  - Park et al., Dominance of climate warming effects on recent drying trends over wet monsoon regions, *Atmos. Chem. Phys.* **17** 10467-10476, 2017.

- Projection of the time at which substantial aridification will occur under future climate scenarios
  - Park et al., Keeping global warming 1.5 °C constrains emergence of aridification, *Nature Clim. Change* **8** 70-74, 2018.

Historical trends in dryness

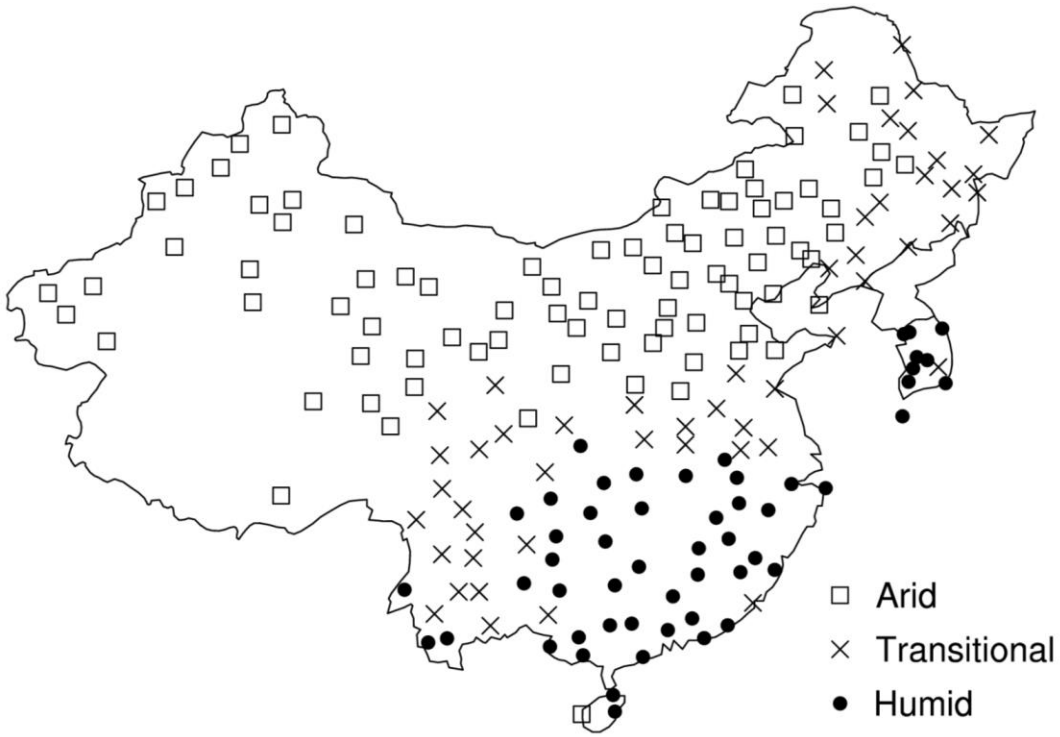
Drying and wetting trend: 1948-2005



*17 evaporation, 6 precipitation, and 21 PET data are used.

Greve et al. (2014)

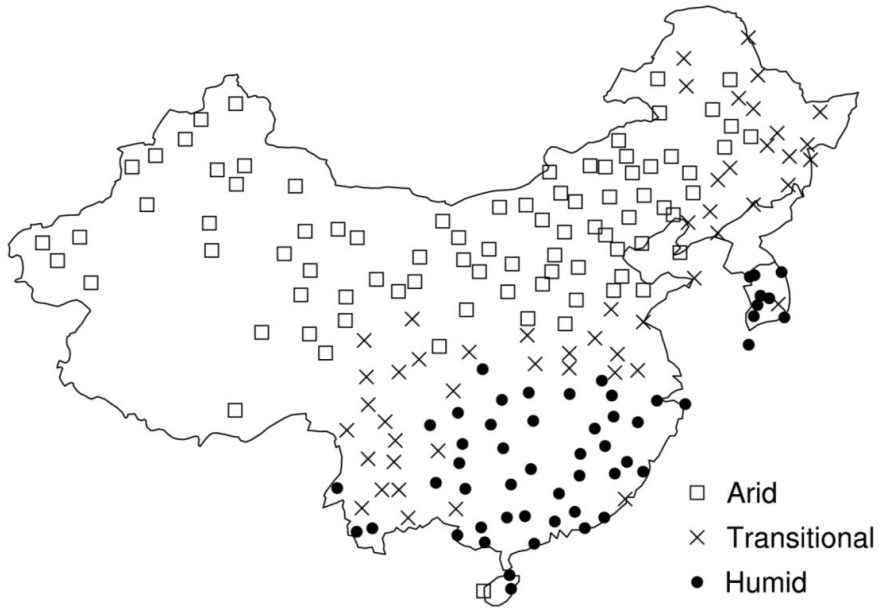
Target region: continental East Asia



Arid: 2 ≤ PET/P
Transitional: 1 ≤ PET/P < 2
Humid: PET/P < 1

- Abrupt climate change occurs.
  - Anthropogenic warming
  - Decadal variability in monsoon
- Various climate regimes exist.
- Impacts of aridification can be amplified in this region by
  - very large populations
  - fragile ecosystem
  - significant agricultural activities.

Objective

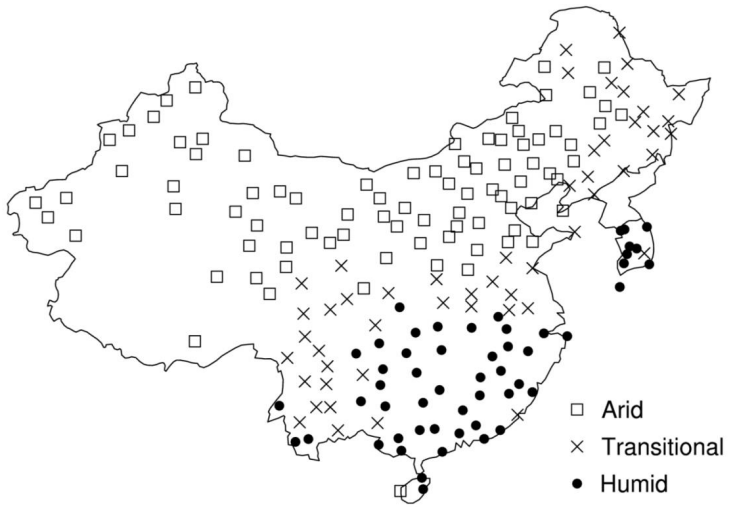


Arid: 2 ≤ PET/P
Transitional: 1 ≤ PET/P < 2
Humid: PET/P < 1

- Examining trends in aridity due to climate change
- Elucidating the mechanisms of aridity trends

- **Providing a concrete insight of the observed aridity trends over continental East Asia**

Climate data



Arid: 2 ≤ PET/P
Transitional: 1 ≤ PET/P < 2
Humid: PET/P < 1

- Daily mean climate data from 179 and 10 sites in China and South Korea for 1961-2010
  - 2m air temperature (T_a), precipitation (P), 10m wind speed (WS), relative humidity (RH), sunshine duration
  - T_a and Sunshine duration is used to compute net radiation (R_n) (FAO, 1998)
  - Computing daily PET following Penman-Monteith method (Allen et al., 1998)
  - Classifying each individual sites into three regimes based on 50-year climatology of PET/P
- Dividing entire period by two sub-periods due to monsoon variability
  - 1961-1983 and 1984-2010 based on three kinds of change-point method (Pettitt, 1980; Lund and Reeves, 2002; Beaulieu et al., 2012)

Contribution of each climate parameter

- To identify the climate variables that contribute most to the observed PET/P trends, relative influences of changes in P, Rn, WS, T_a, and RH on the PET/P trends are computed.

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{PET}}{P}\right) = -\frac{\mathrm{PET}}{P^2}\frac{\mathrm{d}P}{\mathrm{d}t} + \frac{1}{P}\frac{\mathrm{dPET}}{\mathrm{d}t}$$

Applying multilinear regression method (Chattopadhyay and Hulme, 1997; Yin et al., 2010; Dinpashoh et al., 2011; Han et al., 2012)

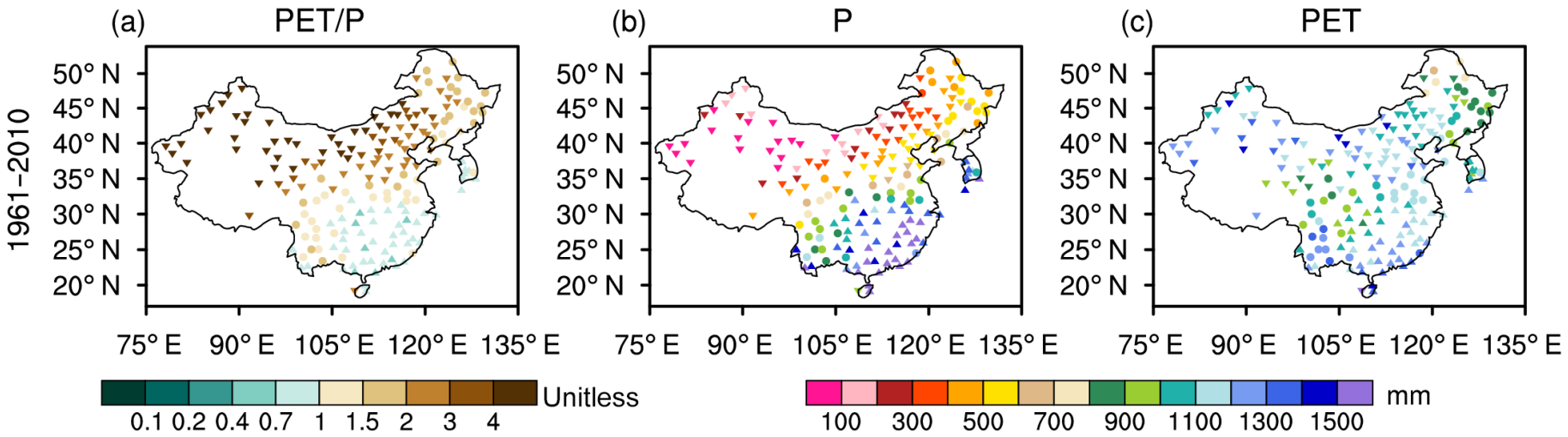
$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{PET}}{P}\right) \approx -\frac{\overline{\mathrm{PET}}}{\overline{P}^2}\frac{\mathrm{d}P}{\mathrm{d}t}$$ **Precipitation**

$$+\frac{1}{\overline{P}}\left(a_{R_\mathrm{n}}\frac{\mathrm{d}R_\mathrm{n}}{\mathrm{d}t} + a_{\mathrm{WS}}\frac{\mathrm{dWS}}{\mathrm{d}t} + a_{T_\mathrm{a}}\frac{\mathrm{d}T_\mathrm{a}}{\mathrm{d}t} + a_{\mathrm{RH}}\frac{\mathrm{dRH}}{\mathrm{d}t}\right)$$

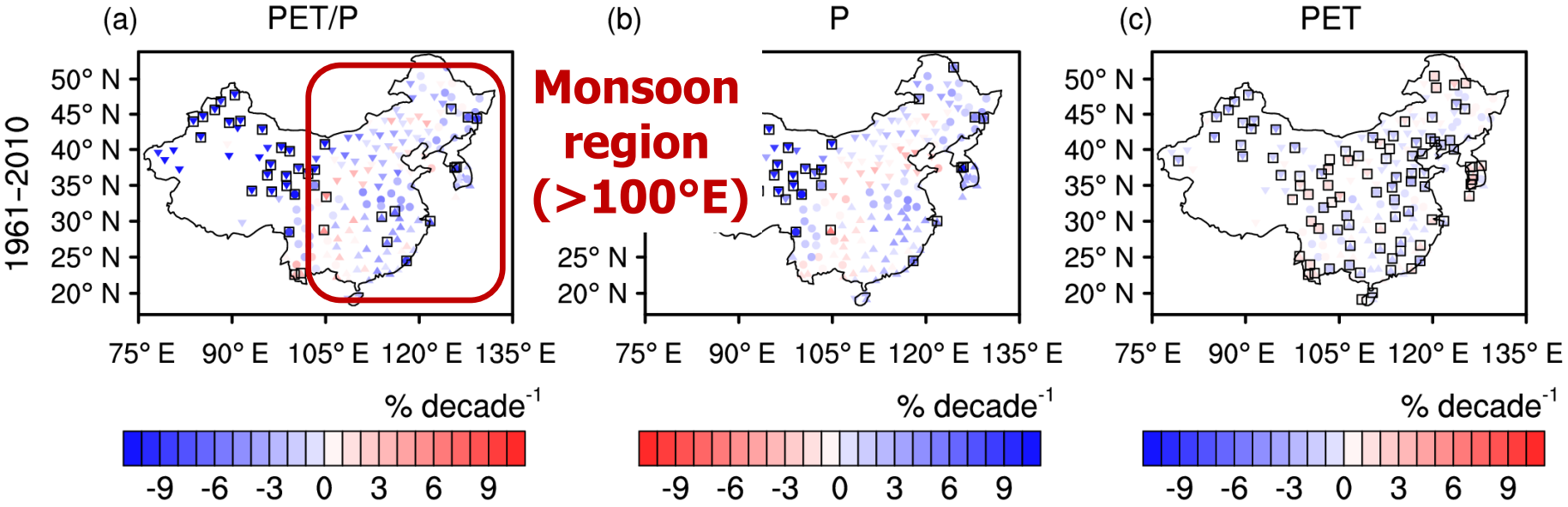
Net radiation **Wind speed** **Temperature** **Relative humidity**

Climatology and trends for entire period

Climatology

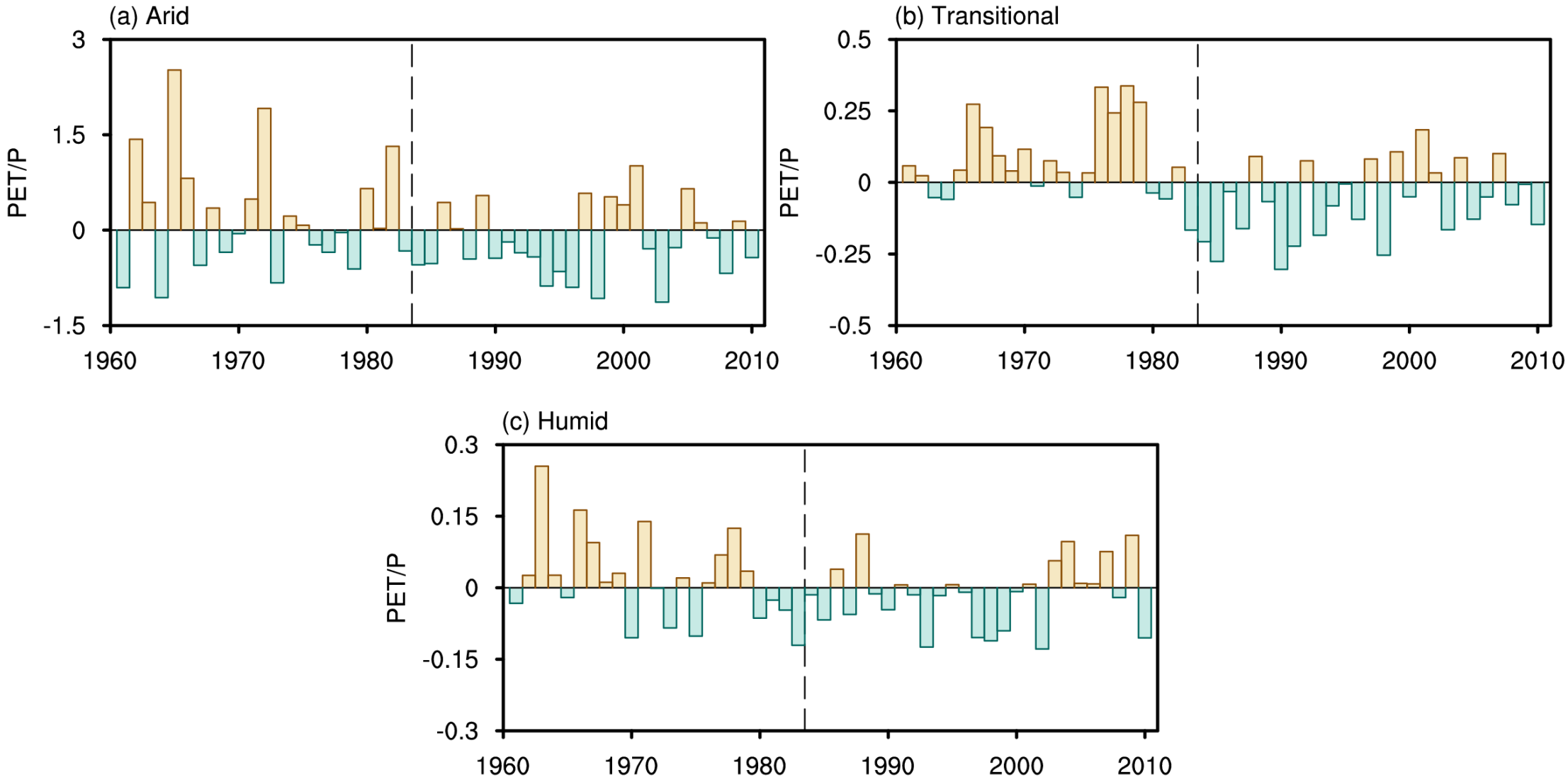


Trends



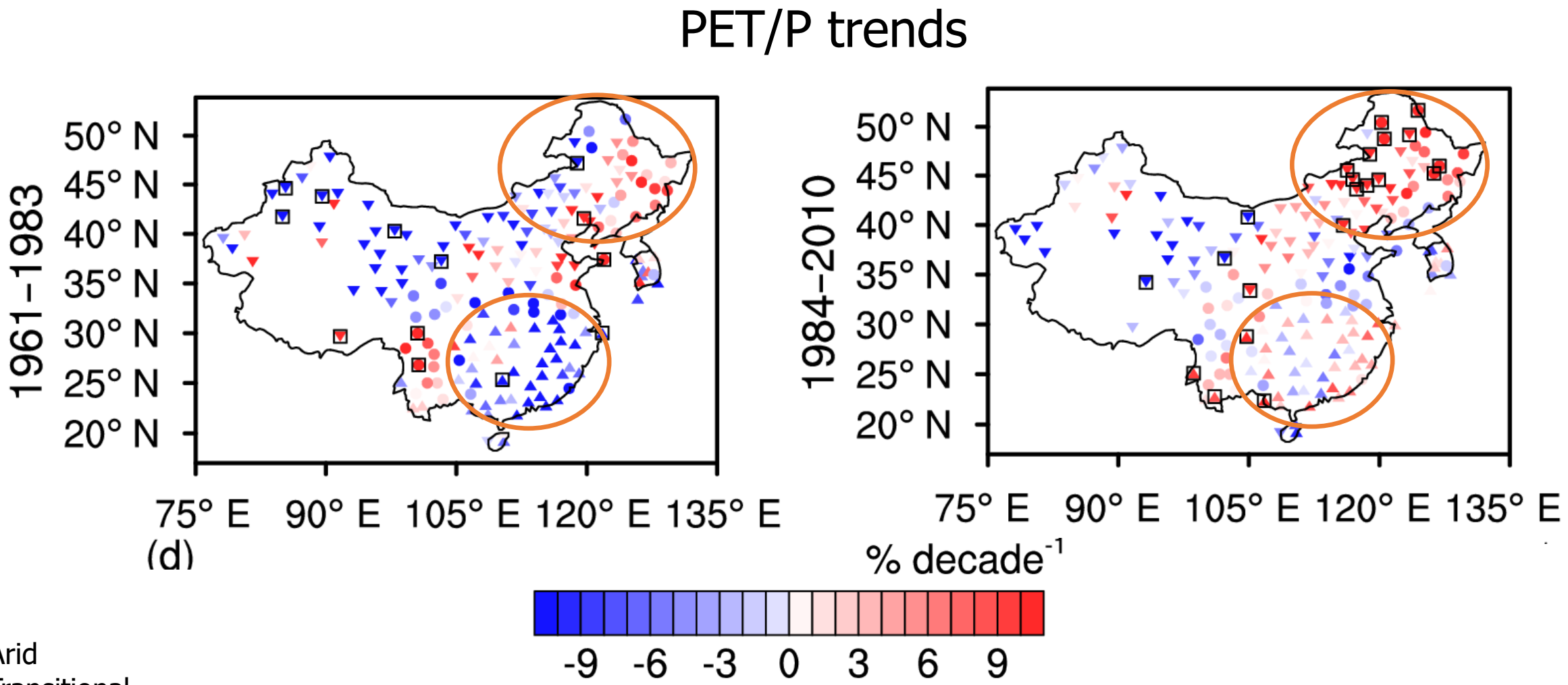
▼: Arid
●: Transitional
▲: Humid
□: trend is significant at 95% confidence level

Temporal anomalies of PET/P



Temporal anomalies are computed over the monsoon region (> 100°E)

PET/P trends for two periods



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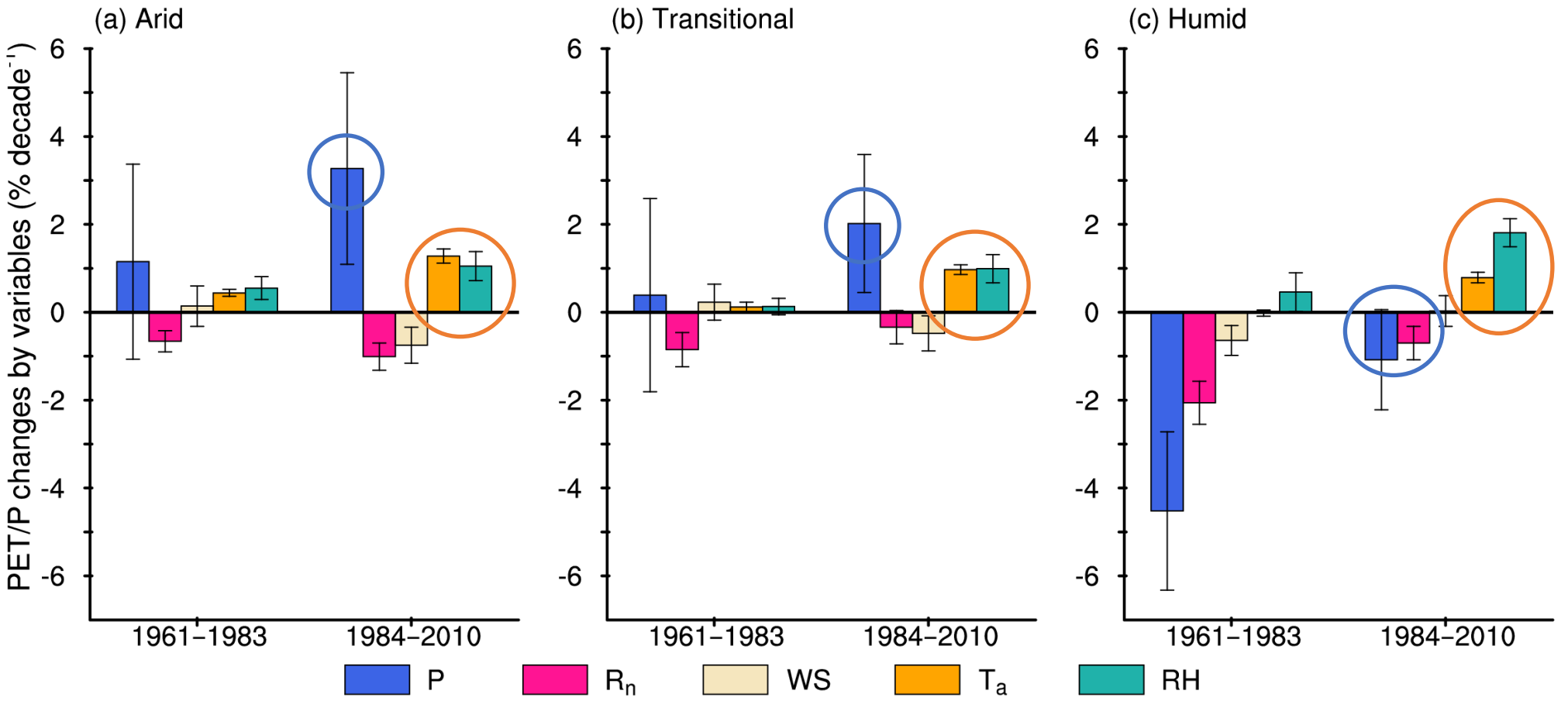
Contributions of climate parameters

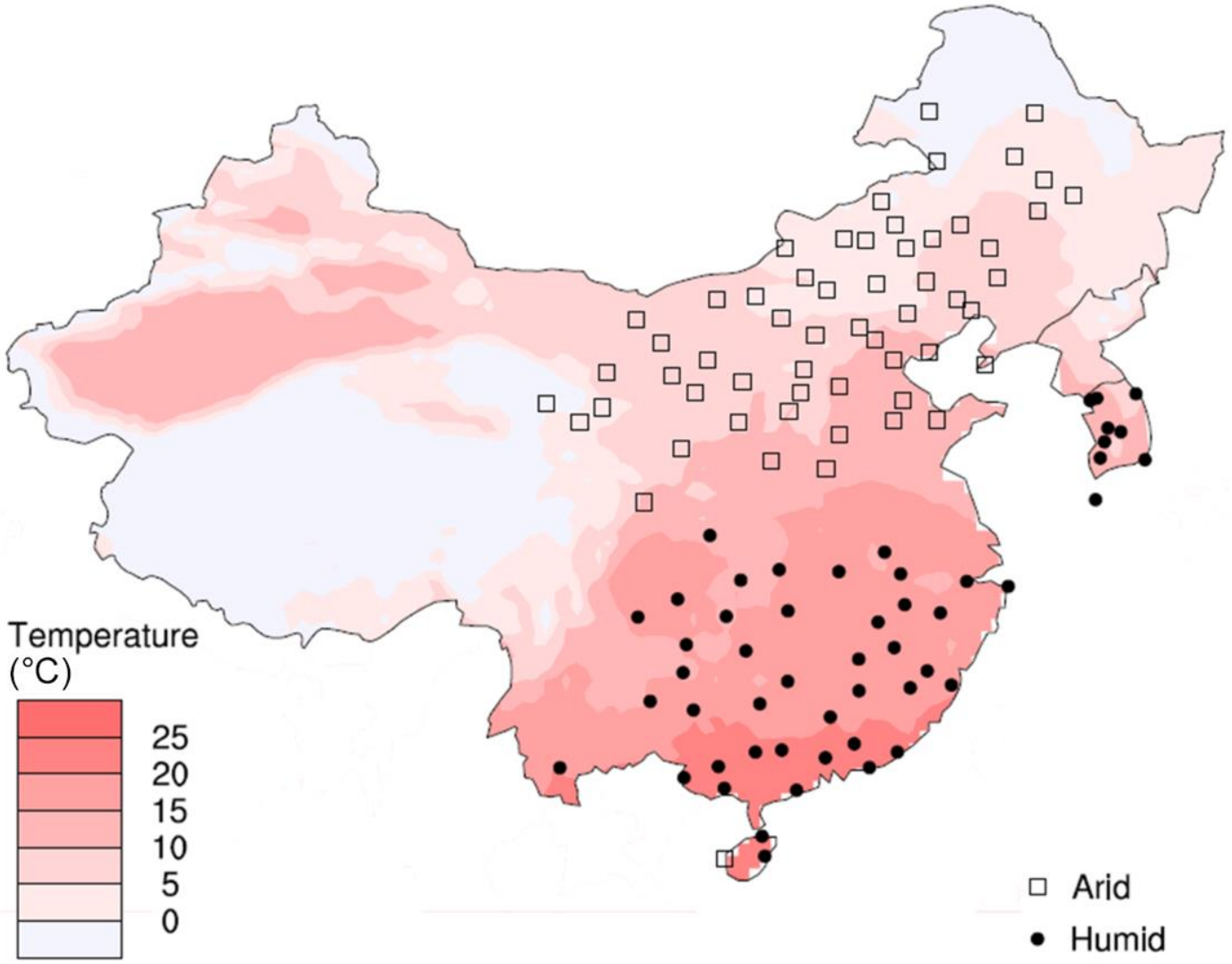


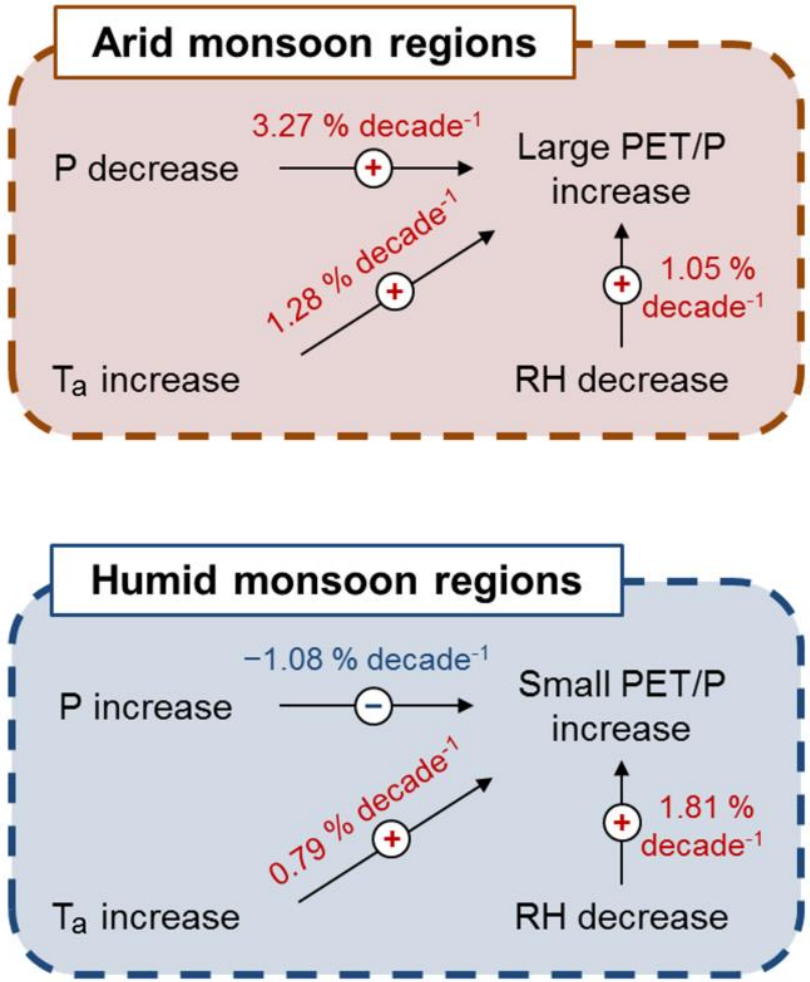
Positive values increase PET/P : drying effects

Negative values decrease PET/P : wetting effects

*Mean contributions of each climate parameters over the monsoon region (> 100°E)

Mechanism behind recent drying trends



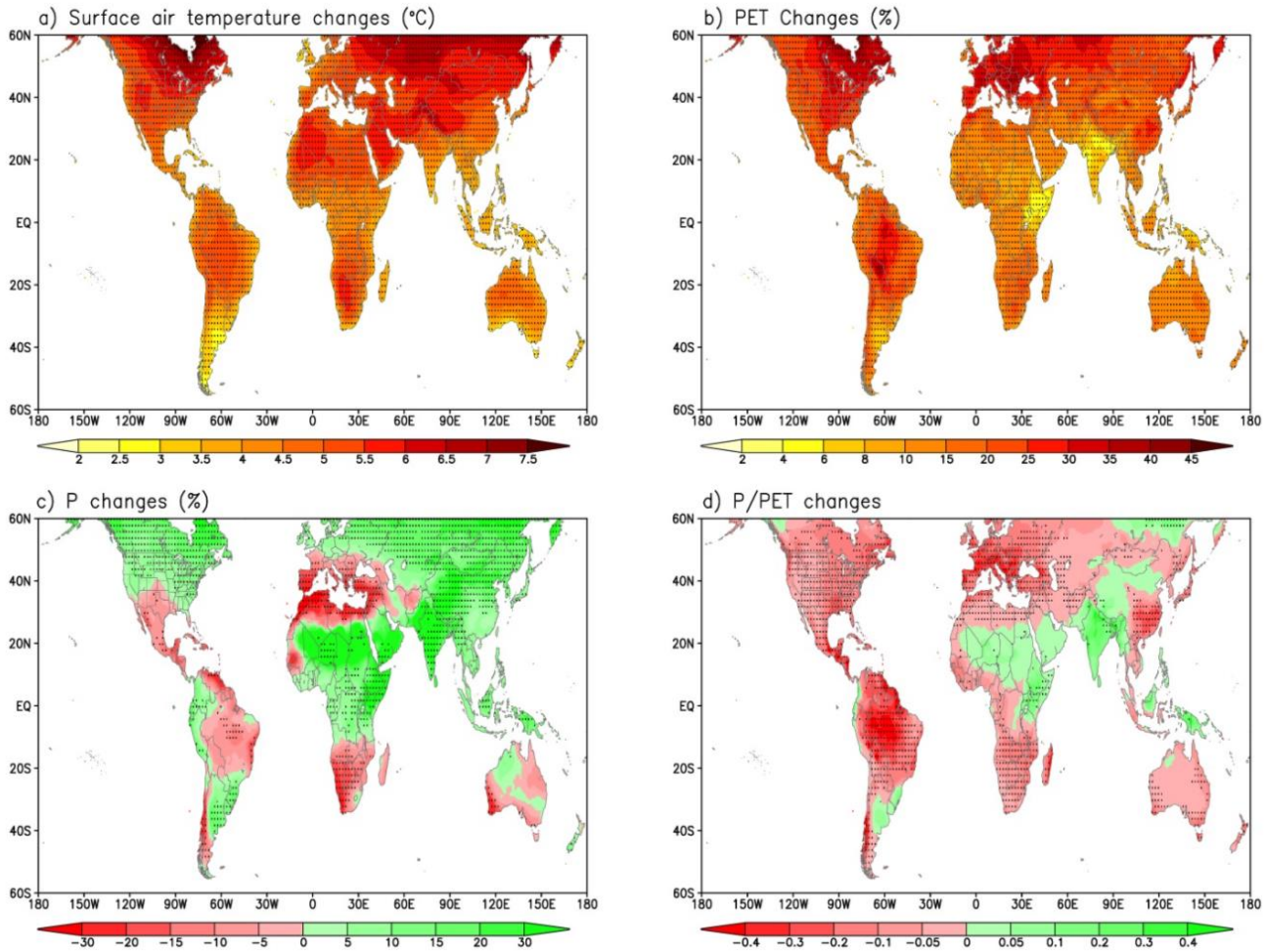


Summary

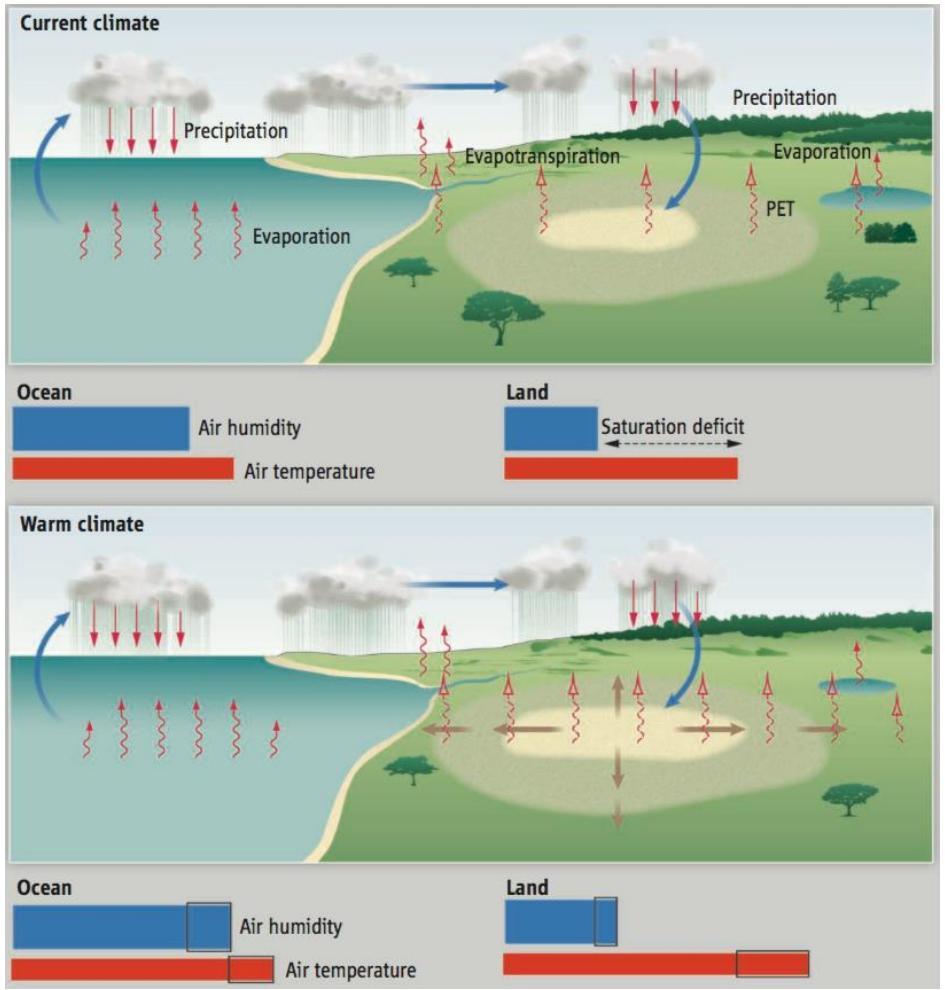
- In the earlier period (1961-1983), changes in P generally leads to wetting trends regardless of climate regimes.
- Aridity trends are turned to drying in recent period (1984-2010), especially in the arid and humid monsoon region.
  - In the arid monsoon region, combined impacts of P, T_a, and RH leads to significant drying trends.
  - The drying trends are relatively small in the humid monsoon region because of the positive effects of T_a and RH are offset by the negative effects of P and Rn.
- Over all climate regimes, effects of warming (T_a and RH) rises in recent period. This can be a observed precursor of projected drying trends.

Aridification in the warming climate

RCP8.5: 2071-2100 minus 1961-1990



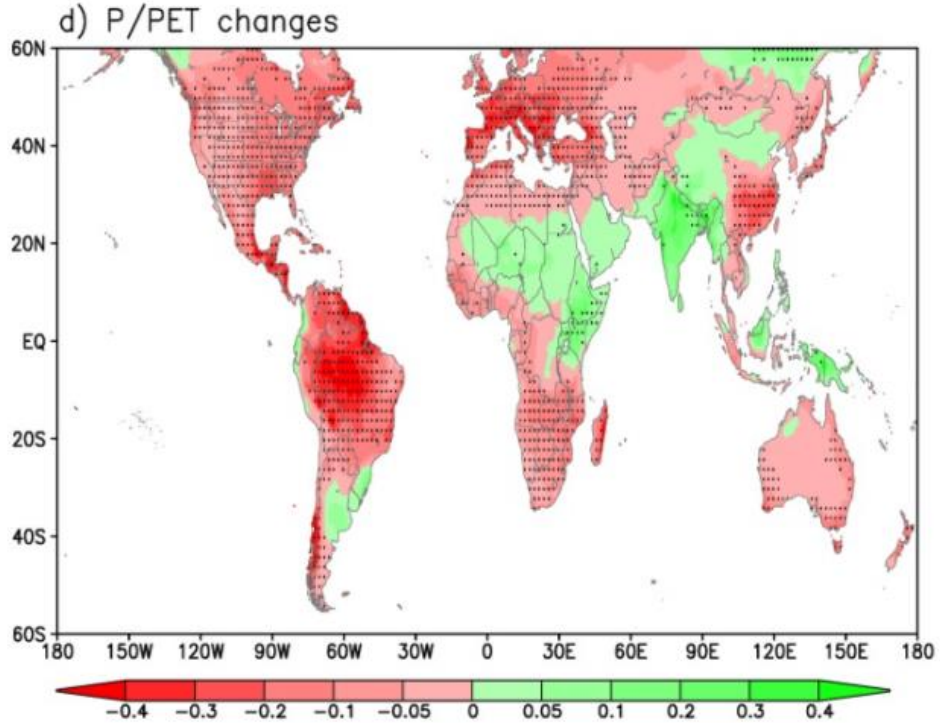
Feng and Fu (2013)



Sherwood and Fu (2014)

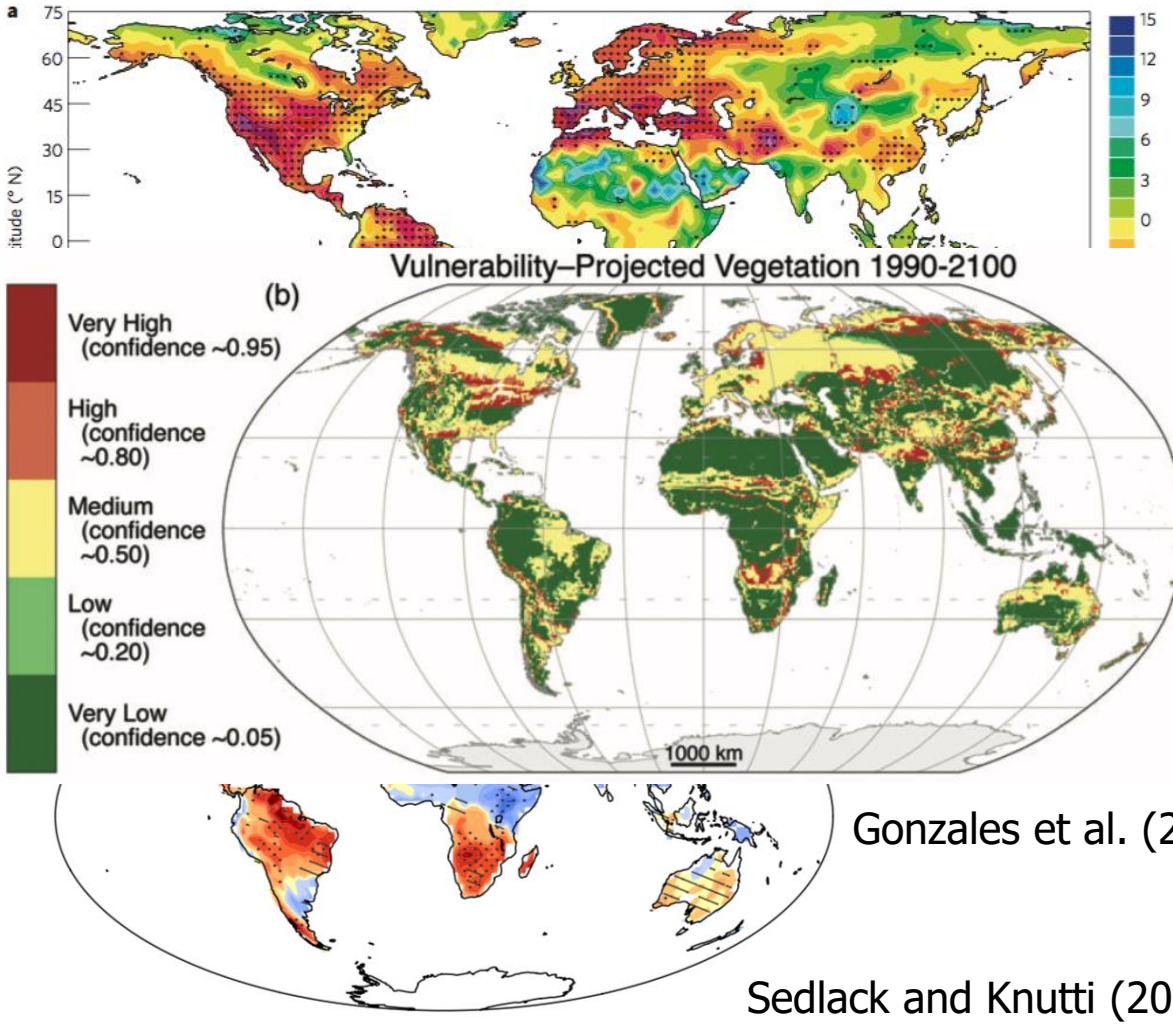
Future aridification and potential risks

RCP8.5: 2071-2100 minus 1961-1990



Feng and Fu (2013)

RCP4.5: 2080-2099 minus 1981-1999

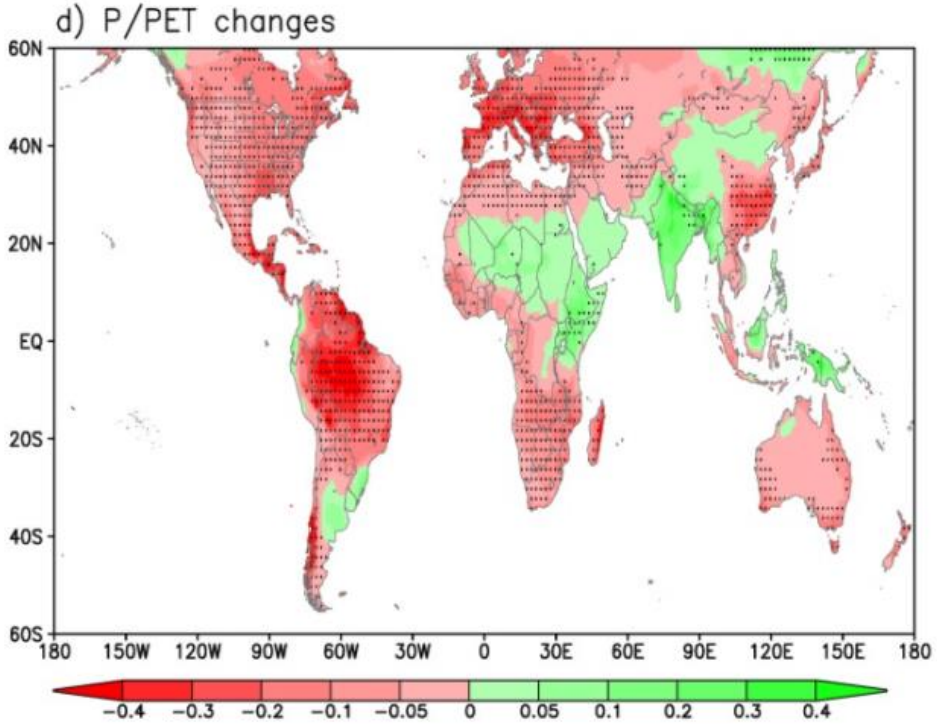


Gonzales et al. (2010)

Sedlack and Knutti (2014)

Missing information in previous studies

RCP8.5: 2071-2100 minus 1961-1990



Feng and Fu (2013)

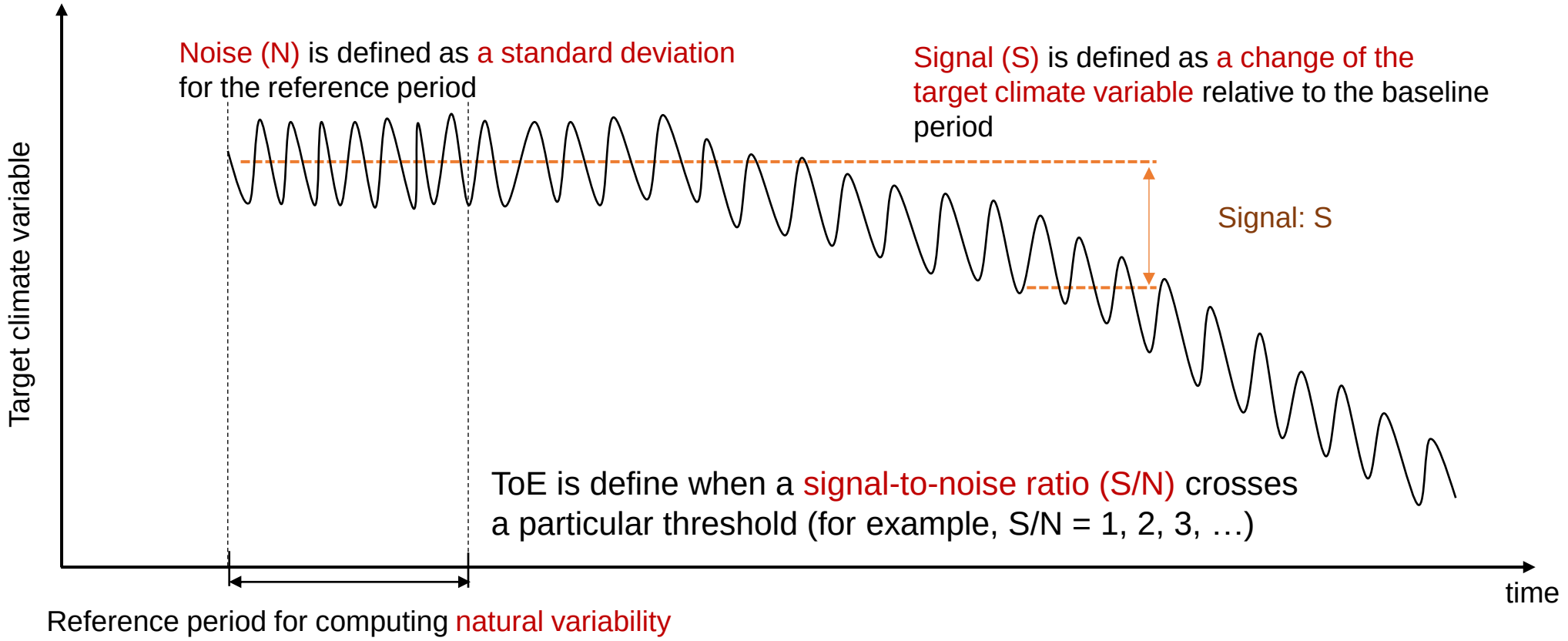
- Projection of aridification usually provided by a spatial map of difference in aridity index, which hides temporal aspects.
- For climate adaptation, a question when the degree of aridification will reach a significant level is important.

↓

Time of emergence for aridification (ToEA)

Time of emergence (ToE)

- ToE, the time at which the signal of climate change emerges from the noise of natural climate variability is a key variable for climate prediction and risk assessments. (Hawkins and Sutton, 2012).



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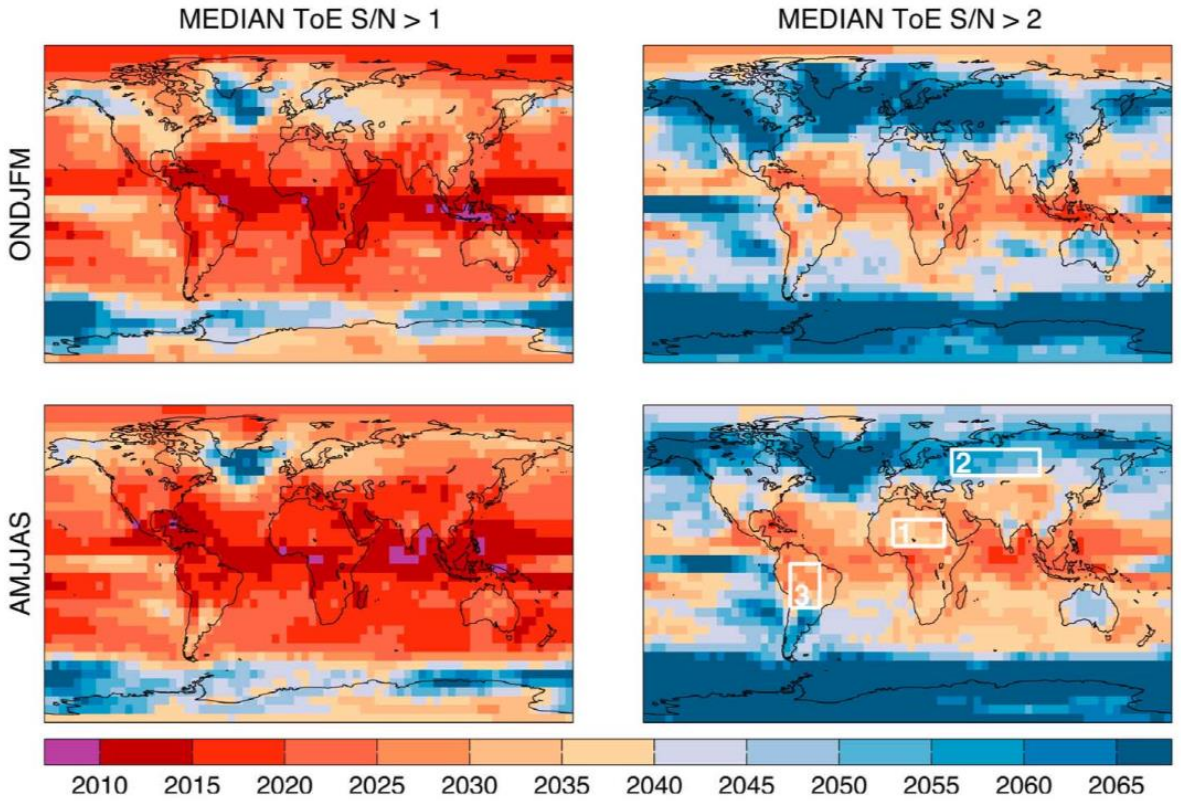


Median ToE for surface air temperature

Hawkins and Sutton (2012)

Temperature goals of the Paris agreement

- "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels"
- It is important information for regional climate policy whether ToEA is earlier or later than the projected time of 1.5 °C and 2 °C global warming ($t_{1.5}$ and t_2).

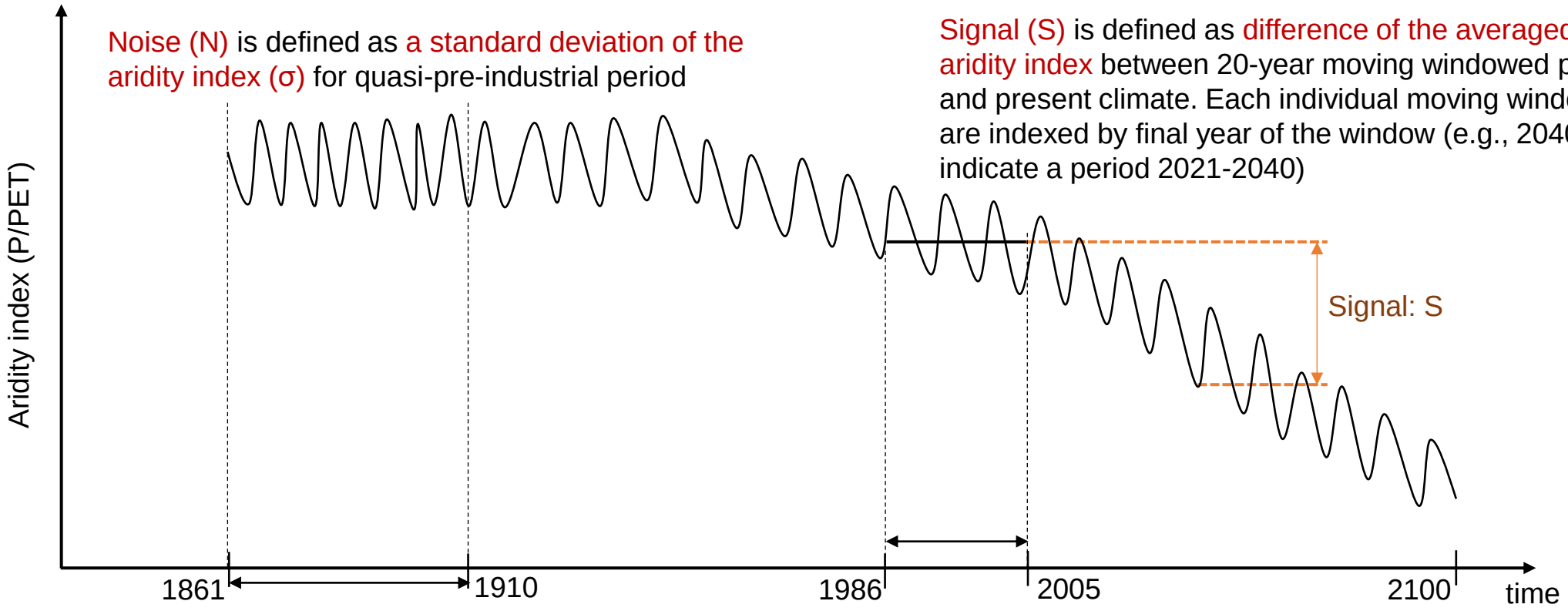
Objectives

- Estimating ToEA
- Determining whether a ToEA is arrived at earlier than global temperature changes of 1.5 °C and 2 °C warming target

1. Verifying the effectiveness of the temperature goals on preventing emerging aridification
2. Providing vital information on regional climate mitigation

A schematic diagram for estimating ToEA

- ToEA is determined the first time when a decrease in the 20-year mean aridity index (S) is less than a half of interannual standard deviation (N), that is, S/N<−0.5.



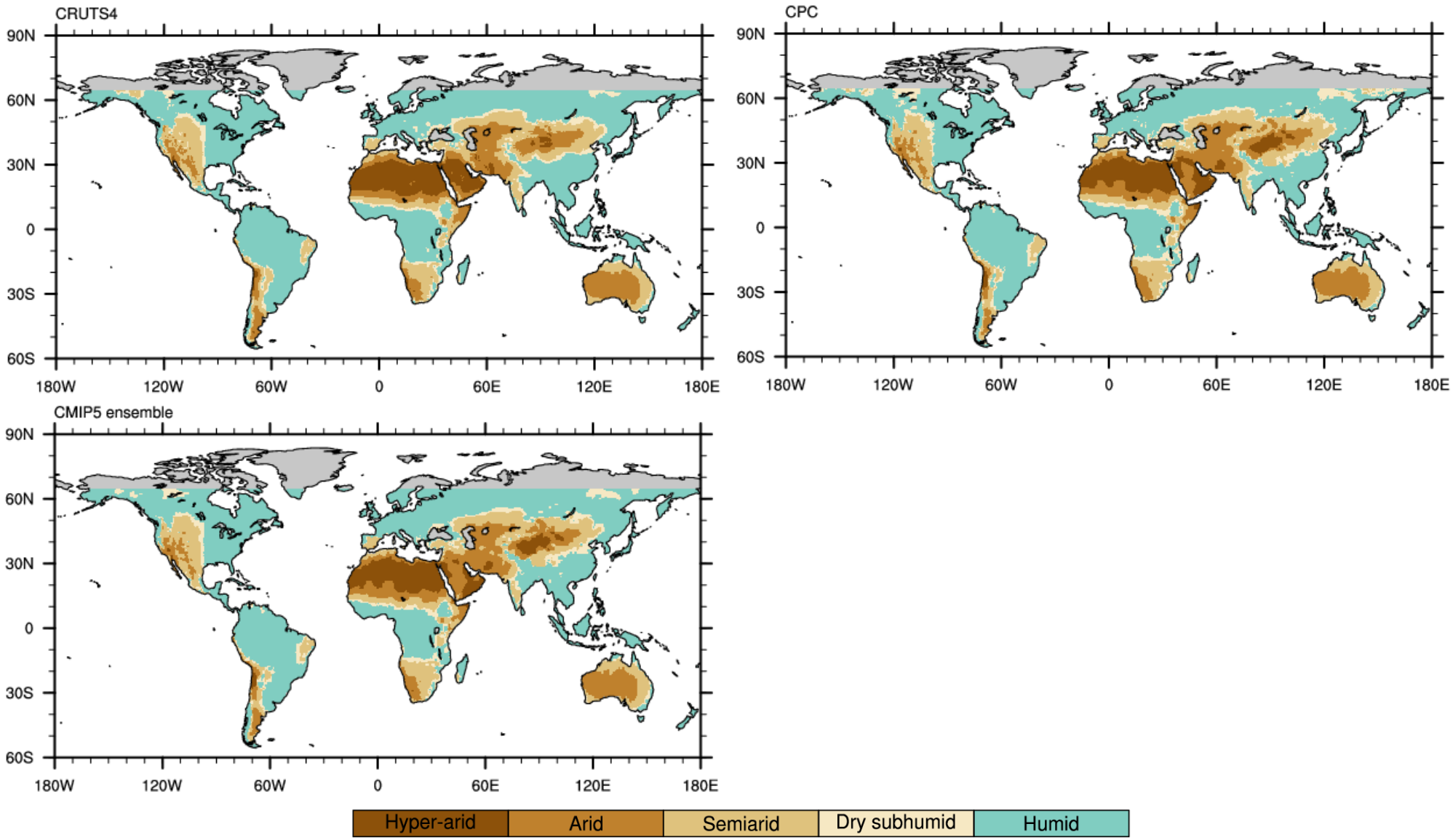
Quasi-pre-industrial period: 1861-1910
Computation of natural variability (King et al. 2015)

Baseline period: 1986-2005
Representing present climate

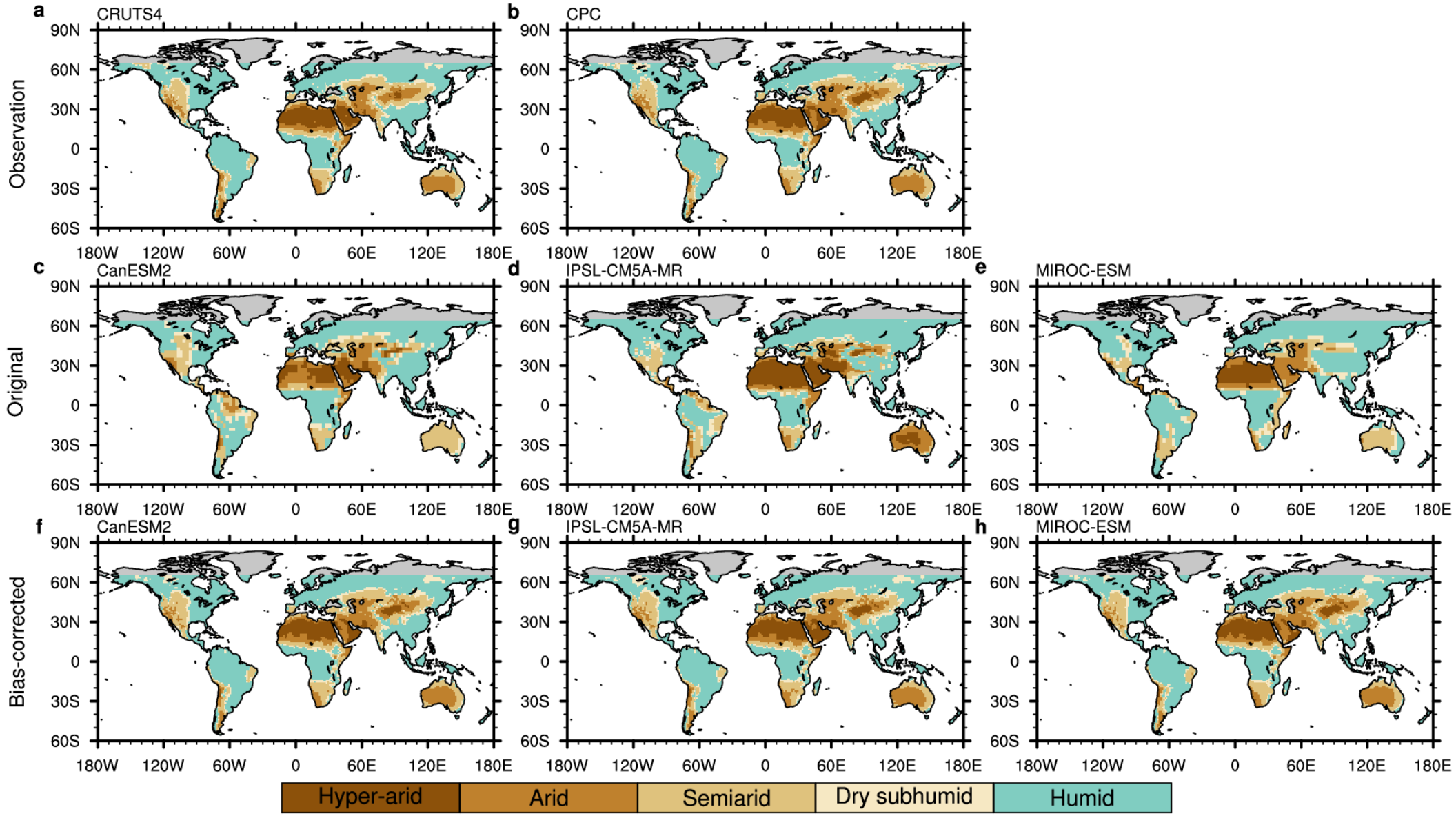
Data

- Climate simulations from 27 global climate models
  - Monthly precipitation, surface air temperature, wind speed, solar radiation, and relative humidity
    - Surface air temperature, wind speed, solar radiation, and relative humidity are used to compute PET following Penman-Monteith method (Allen et al. 1998).
  - Historical (1861-2005) and RCP4.5 and RCP8.5 (2006-2100)
  - Regridded into 0.5°×0.5° horizontal resolution over the land only based on a bias-correction method (Feng and Fu, 2013)
- Reanalysis data for model evaluation
  - Climate Research Unit time series version 4.0 (CRUTS4)
  - Climate Prediction Center (CPC)

Evaluation of the ensemble mean P/PET



Bias-correction on P/PET

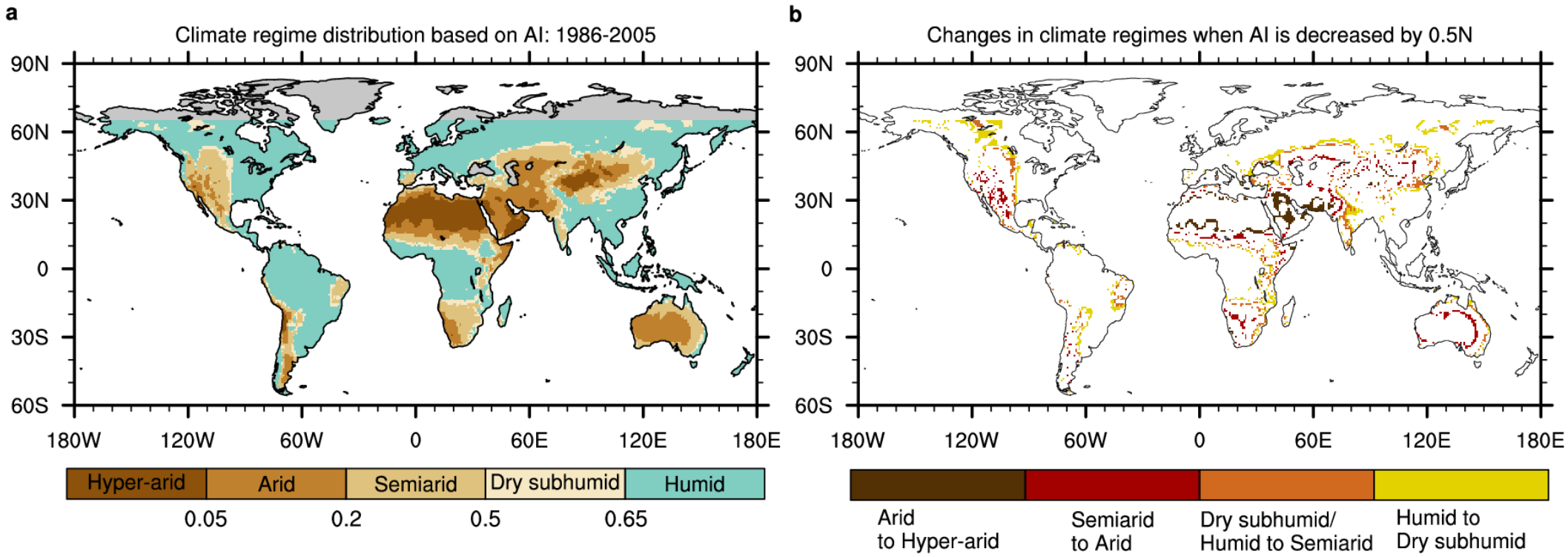


Considerations for the threshold, S/N<−0.5

- Any threshold for ToE is subjective, but two considerations are necessary.
  - The threshold should be large enough to represent a change with important implication.
  - The threshold should be not so large that it is equivalent to the events that have little chance of occurring during the timescale of interest.

Impact of P/PET decrease by −0.5N

- Decrease in P/PET by −0.5N induce substantial aridification along the boundaries of existing climate regimes, implying profound climatic impacts.
  - For example, 15% of semi-arid regions would become arid regions.



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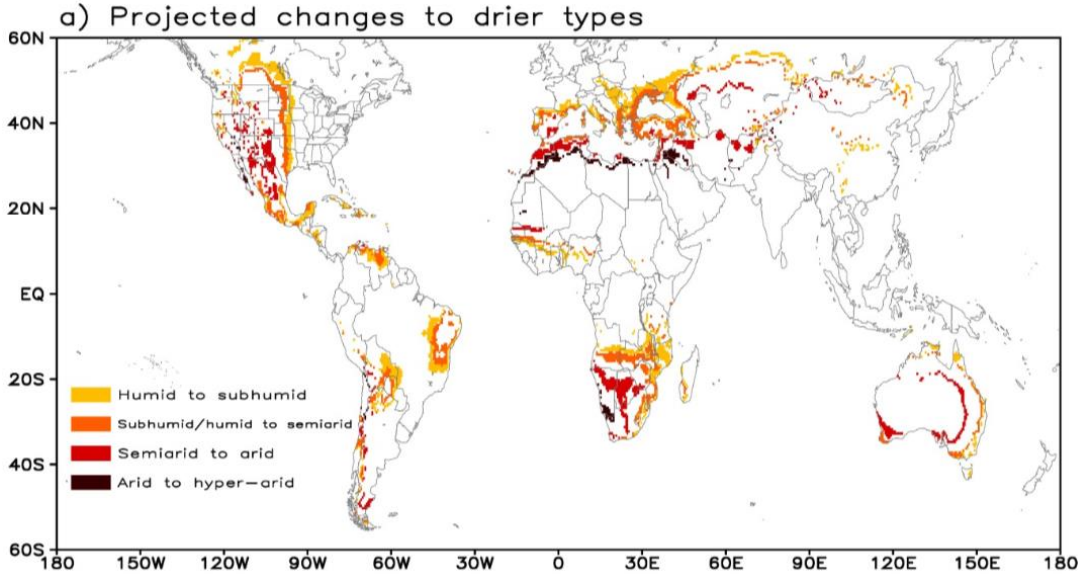
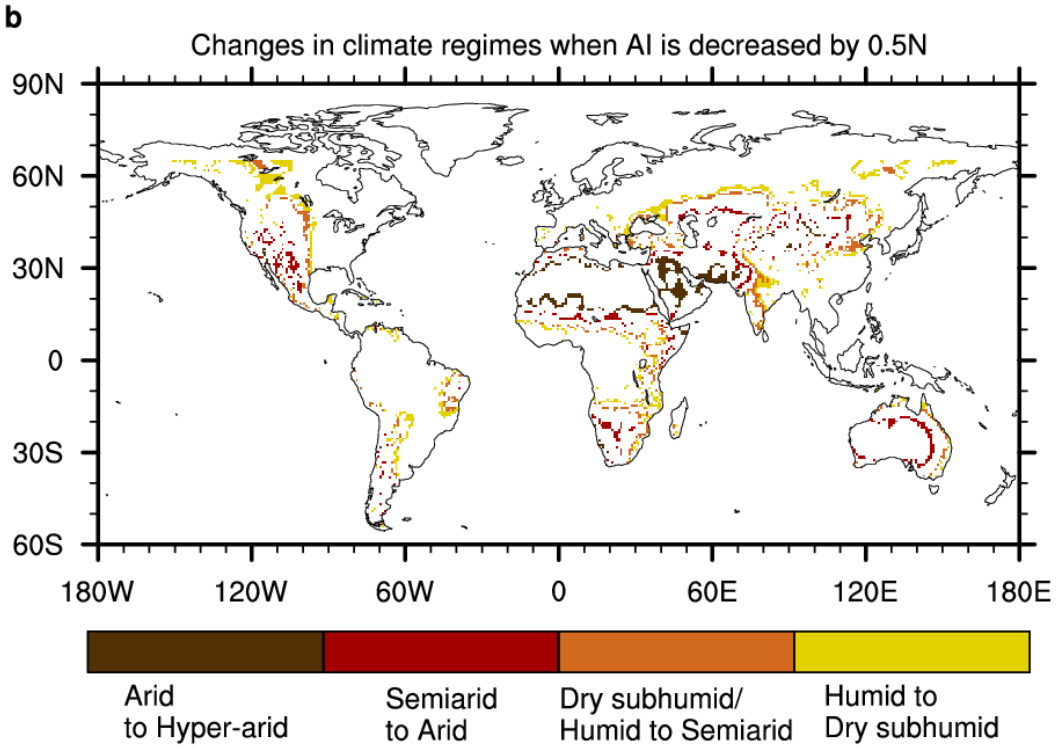
2071-2100 minus 1961-1990

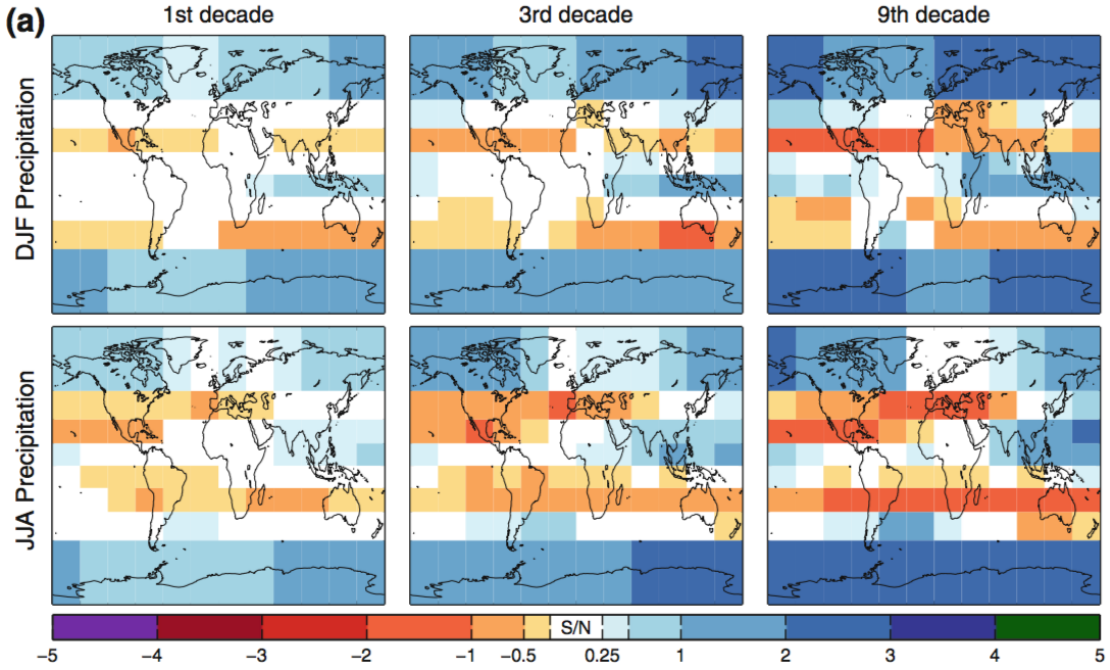


Feng and Fu (2013)

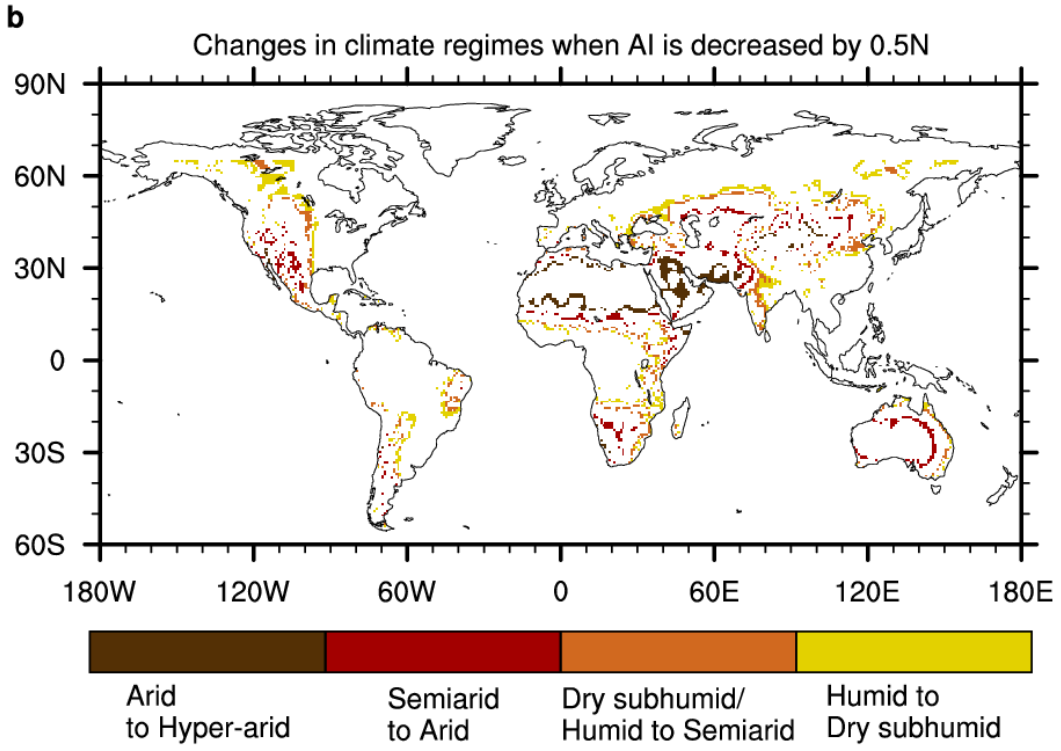


Realization of aridification by S/N=−0.5

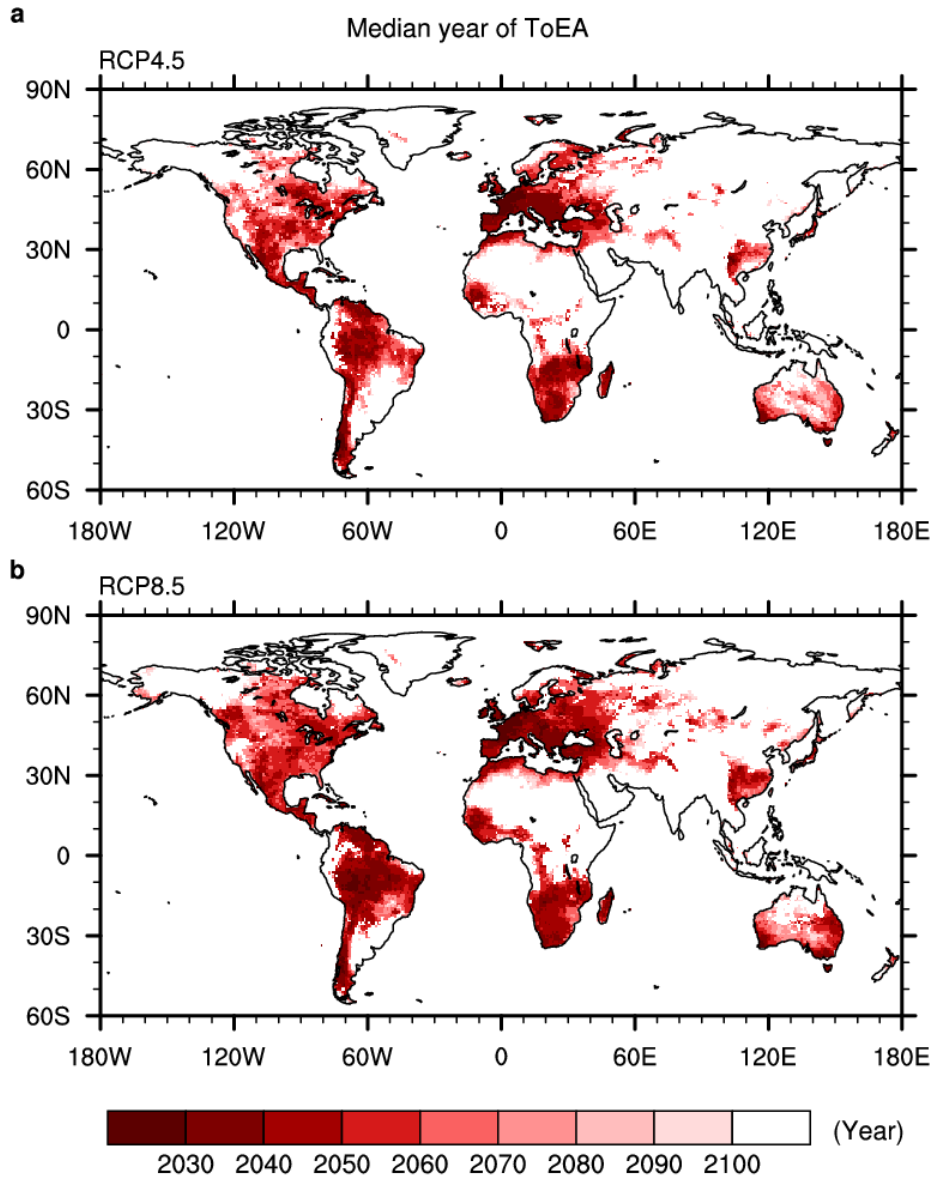
- A choice of S/N=−0.5 is small enough that anomalous years having an aridity index lower than the twentieth century aridity index −0.5N are actually likely to be experienced.



Hawkins and Sutton (2011)

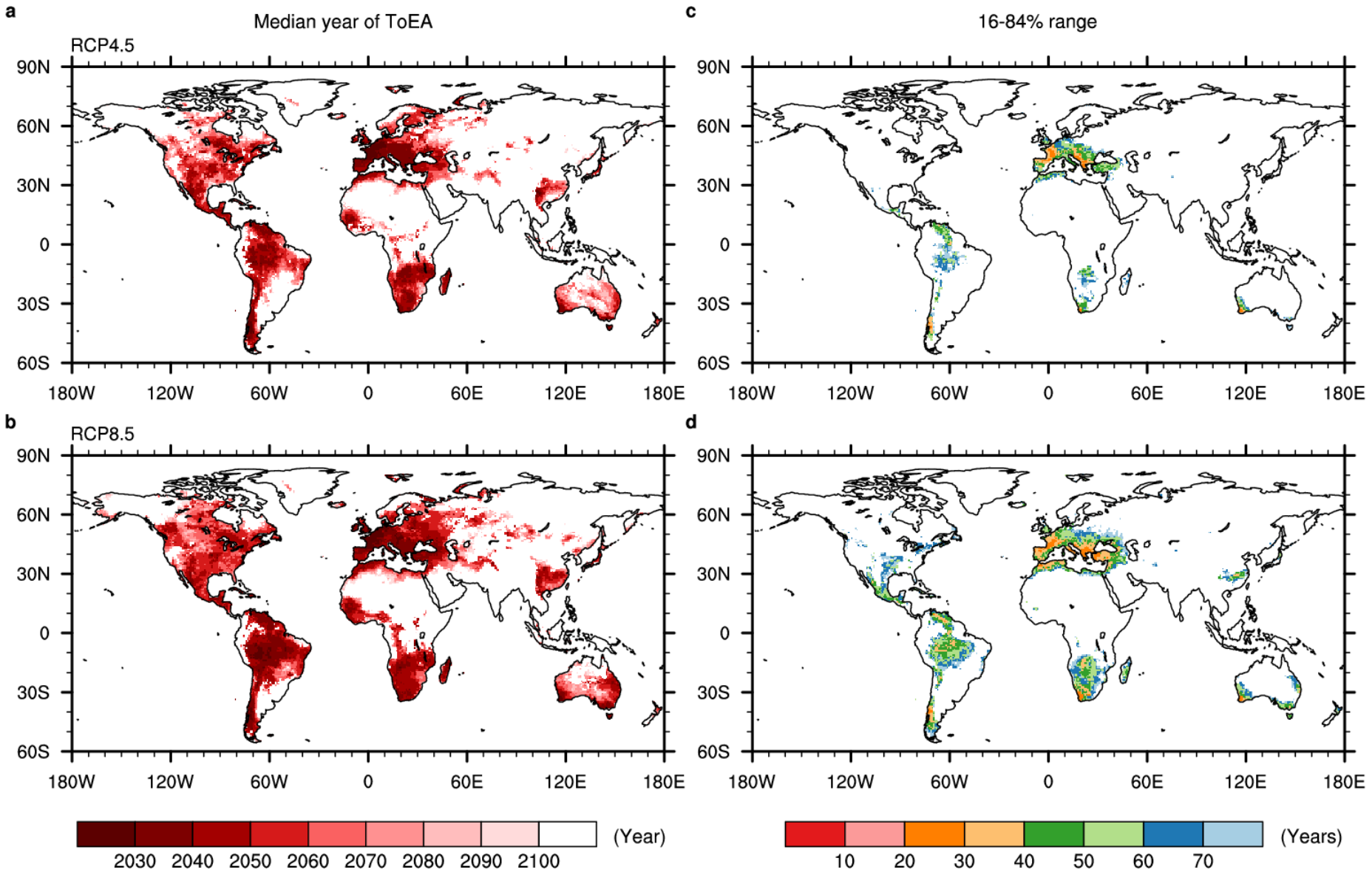


Estimated the ensemble median ToEA



- ToEA is determined over 42% and 49% of total land surface under RCP4.5 and RCP8.5.
- Spatial patterns of ToEA is similar under both RCP scenarios.
  - Earlier ToEA (<2050) over South America, Central America, southern Europe, western and southern Africa, coastal Australia, and southern China
  - Later ToEA (>2050) over North America and northern Europe.
- ToEA is generally earlier in RCP8.5 than RCP4.5.
  - High emissions of GHGs increase the likelihood of significant aridification.

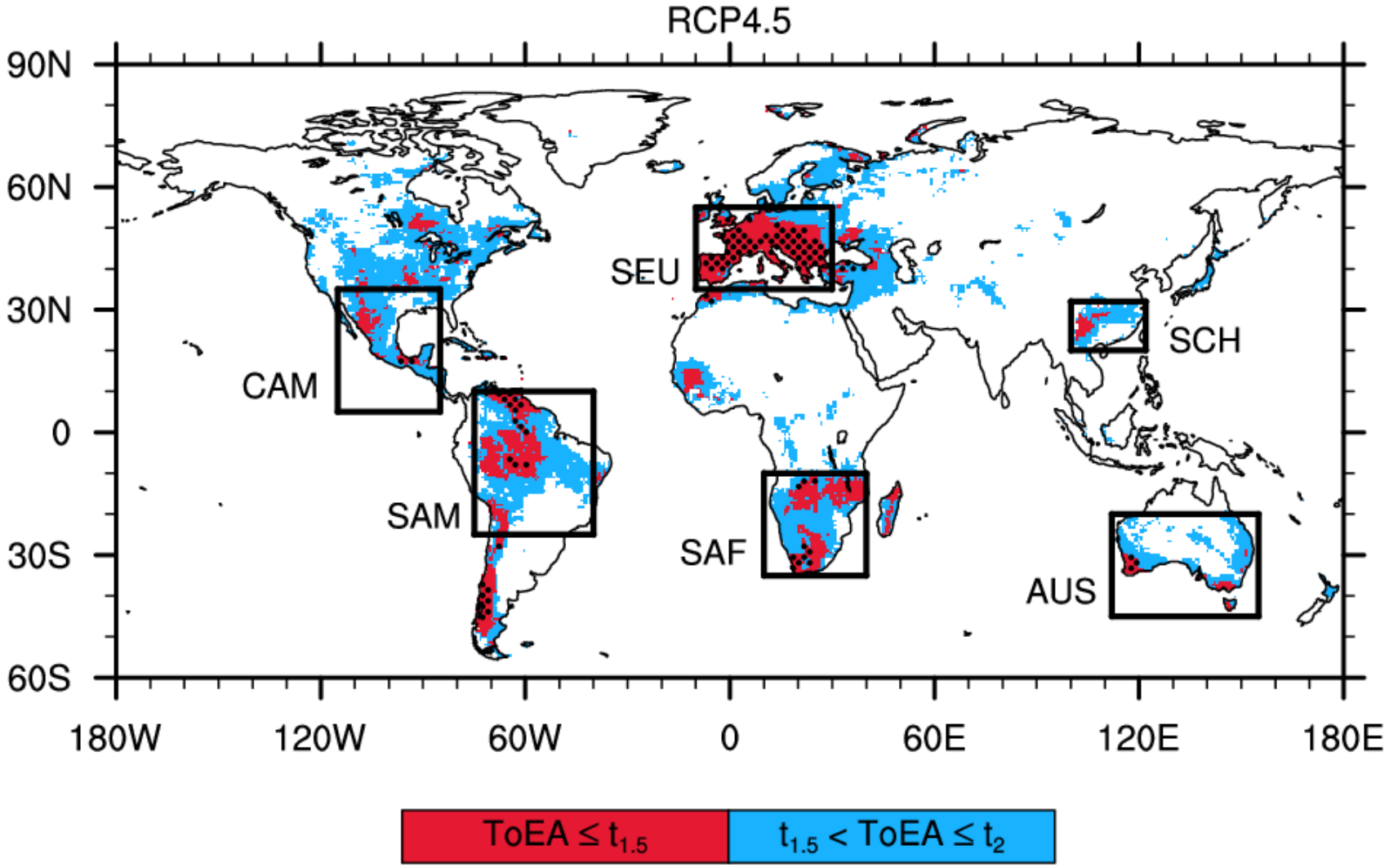
Median ToEA with uncertainty range



Comparing ToEA to temperature goals

- $t_{1.5}$ and t_2 are computed as the times at which global mean temperature reaches 0.9 °C and 1.4 °C above 1986–2005, respectively, as this period was probably at least 0.6 °C warmer than the pre-industrial level.
- The median year of ToEA is compared to that of $t_{1.5}$ and t_2.
  - '<' means 'earlier than'
  - '≤' mean 'earlier than or at the same time as'.
- Two kinds of regions are determine under RCP4.5 and RCP8.5
  - ToEA ≤ $t_{1.5}$ and $t_{1.5}$ < ToEA ≤ t_2
  - ToEA ≤ $t_{1.5}$ indicates 50% likelihood (based on the CMIP5 ensemble spread) that aridification emerges before a 1.5 °C global temperature change is reached.

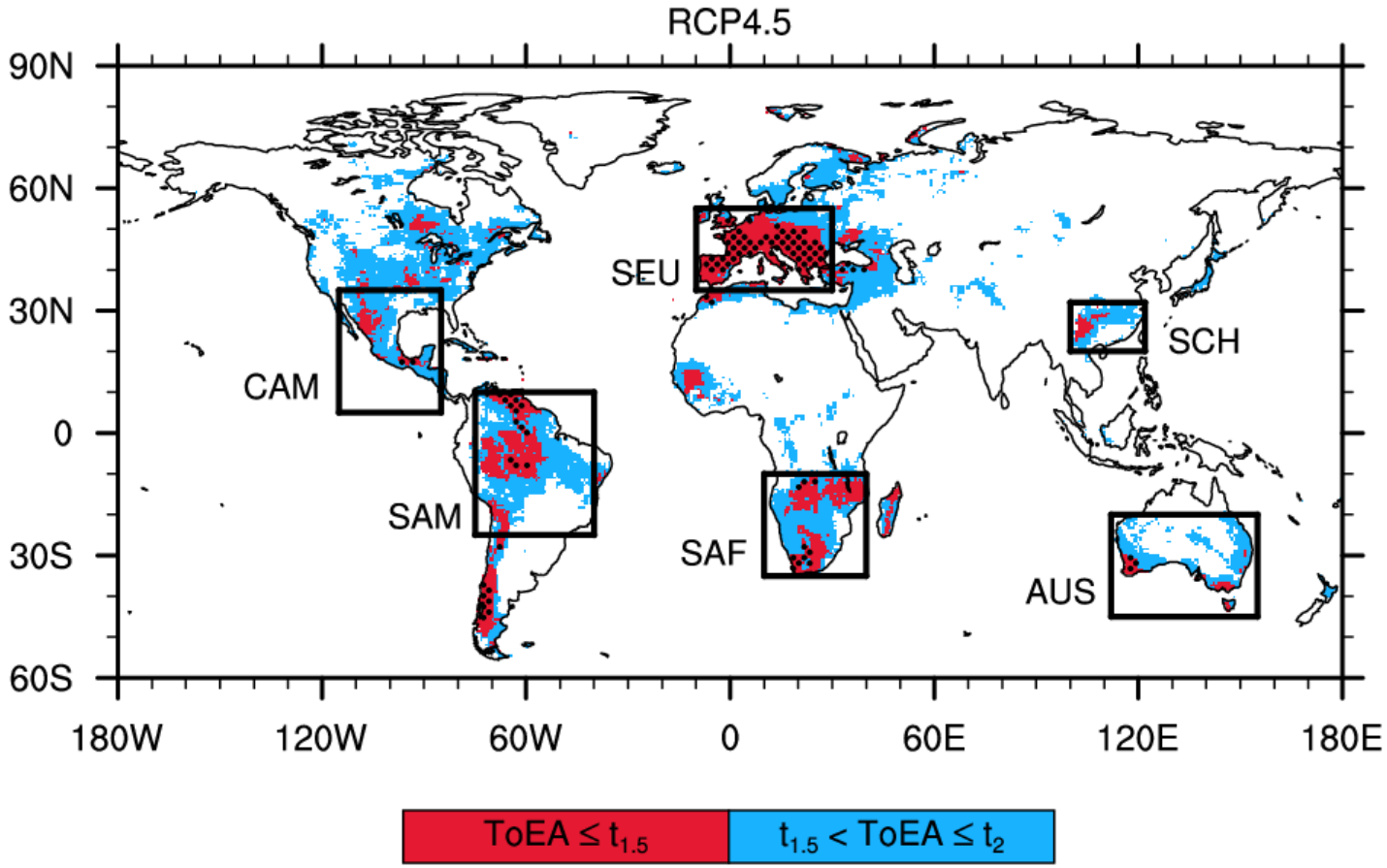
ToEA Vs. $t_{1.5}$ and t_2



CAM: Central America
SAM: South America
SEU: Southern Europe
SAF: Southern Africa
SCH: Southern China
AUS: Coastal Australia

* Stippled areas indicates that 84th percentile year of ToEA is earlier than median of t_2
* White areas indicates that median of ToEA is later than that of t_2

ToEA Vs. $t_{1.5}$ and t_2



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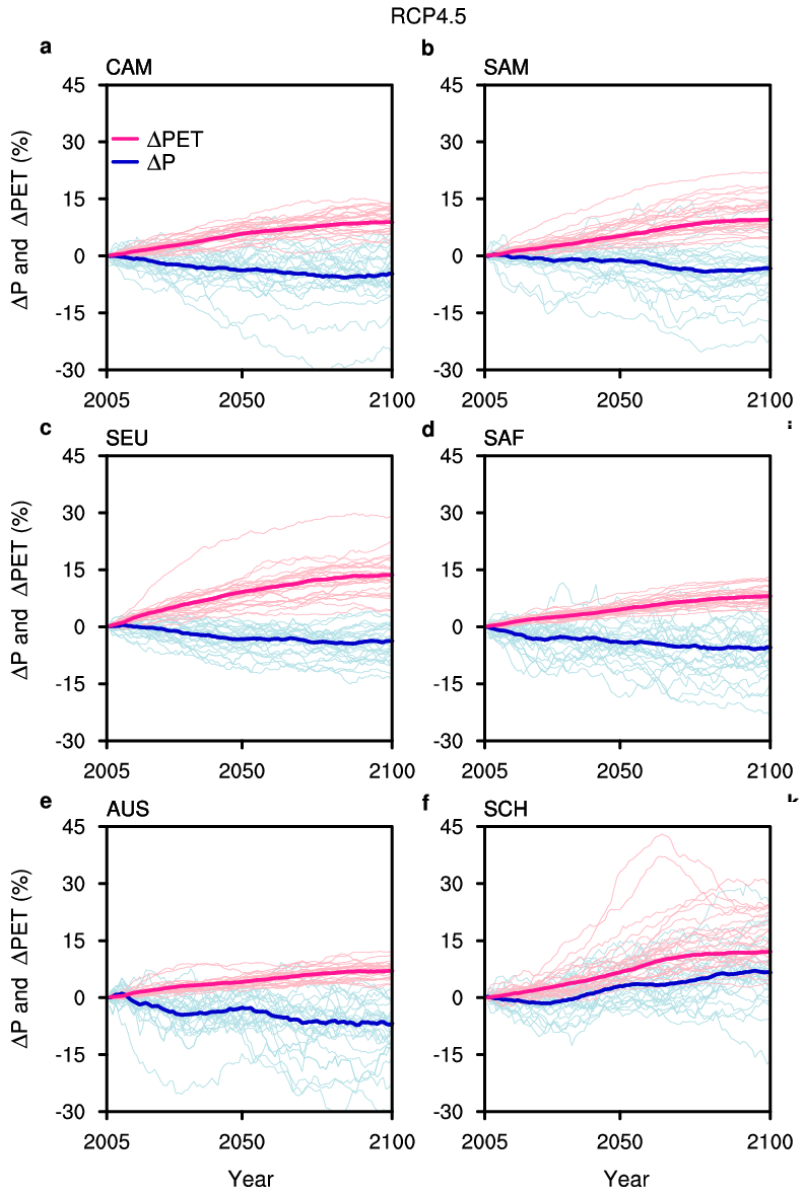
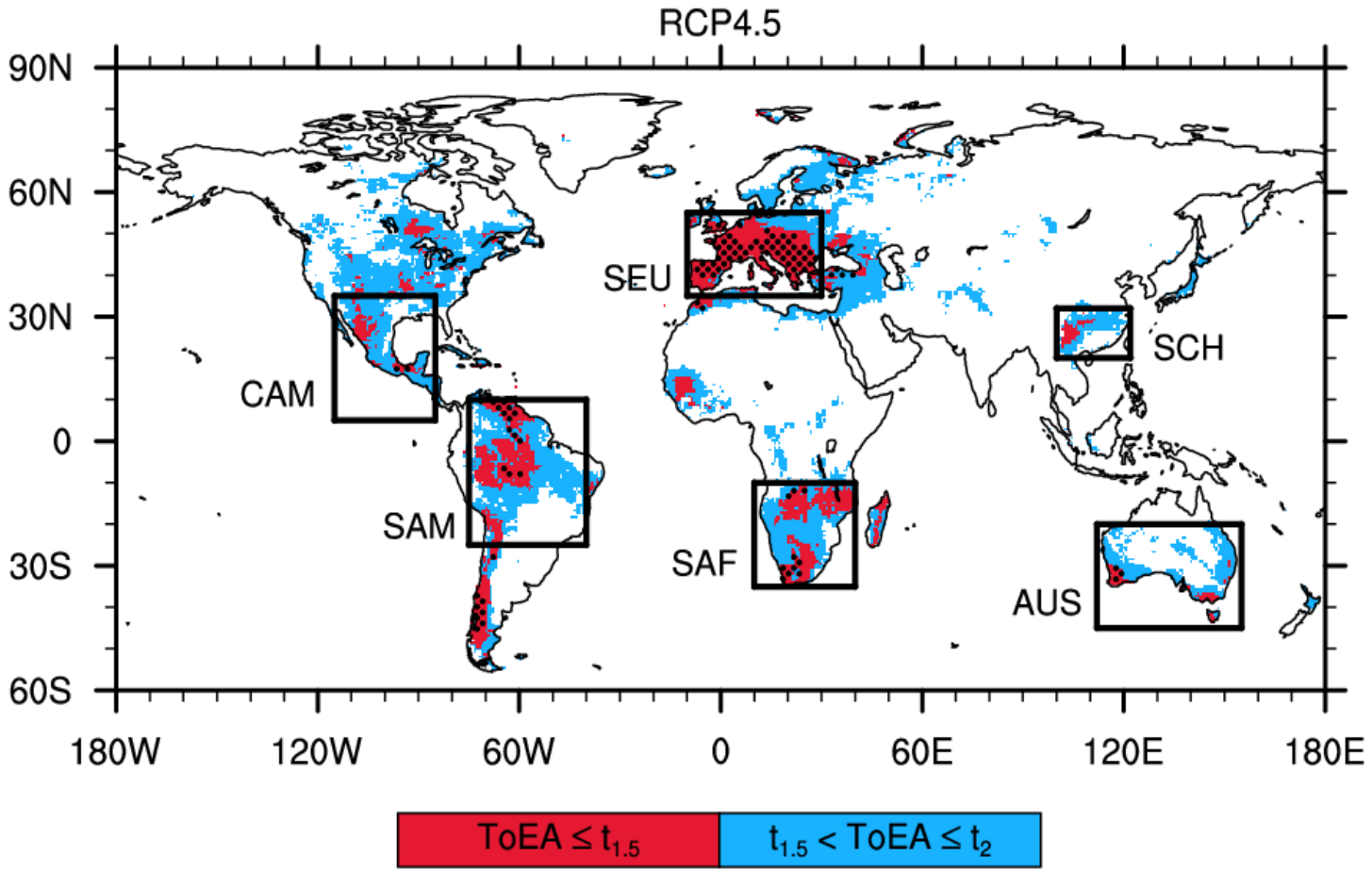
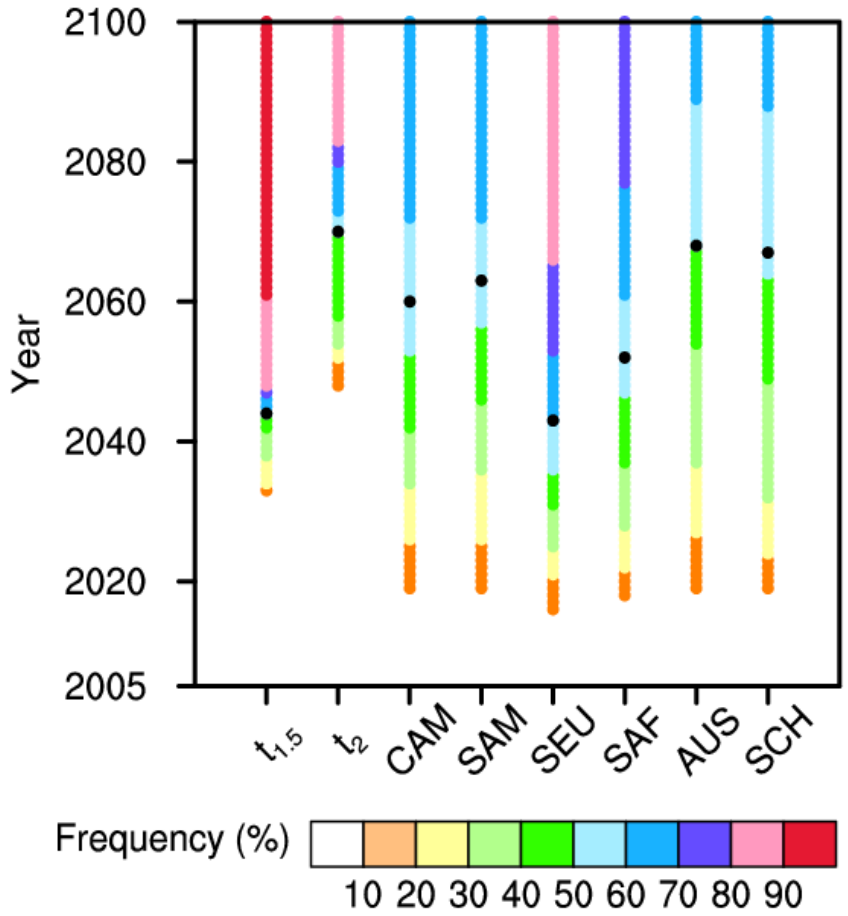


ToEA Vs. $t_{1.5}$ and t_2 with uncertainty range





* Stippled areas indicates that 84th percentile year of ToEA is earlier than median of t_2
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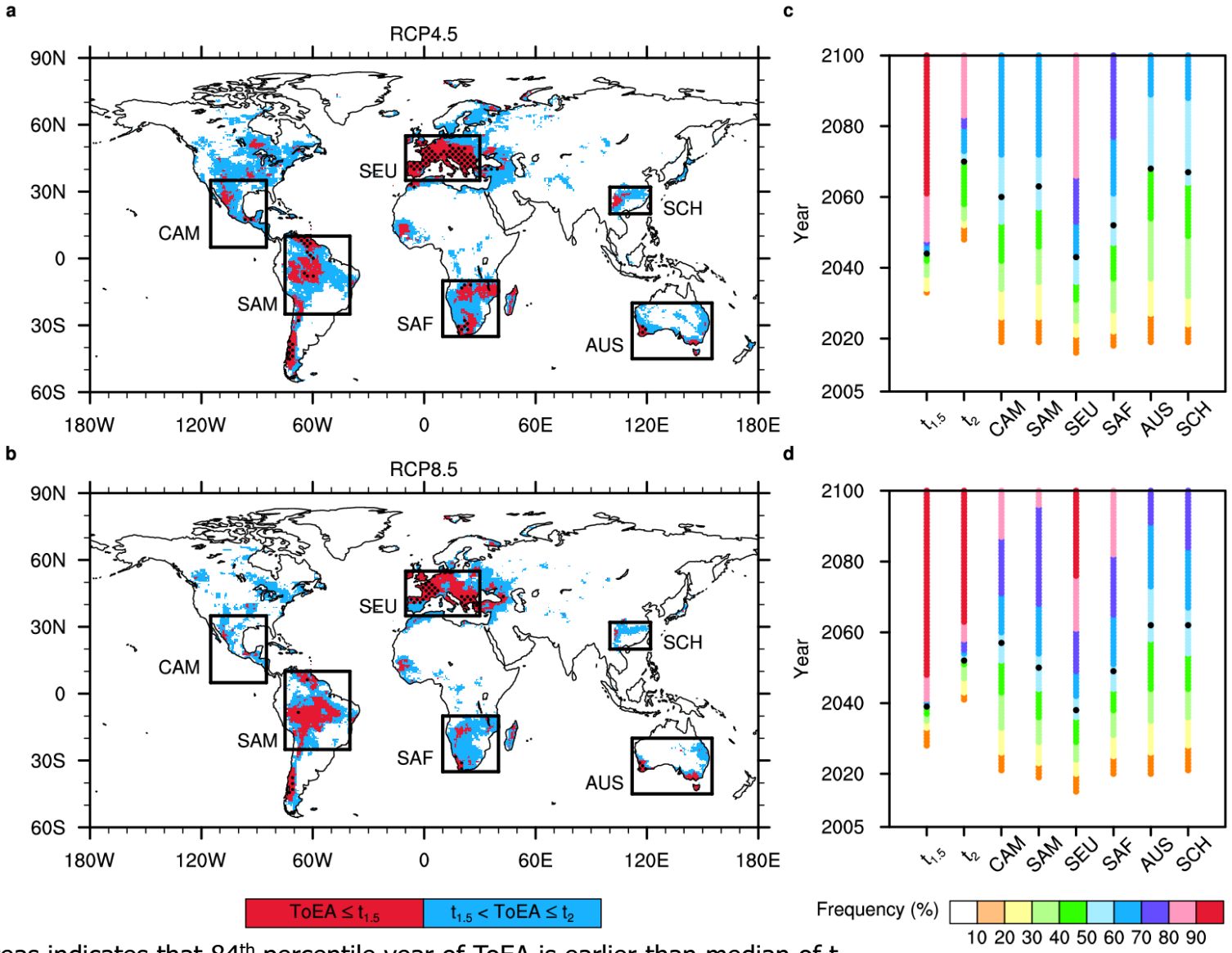
ToEA Vs. $t_{1.5}$ and t_2: RCP4.5 and RCP8.5



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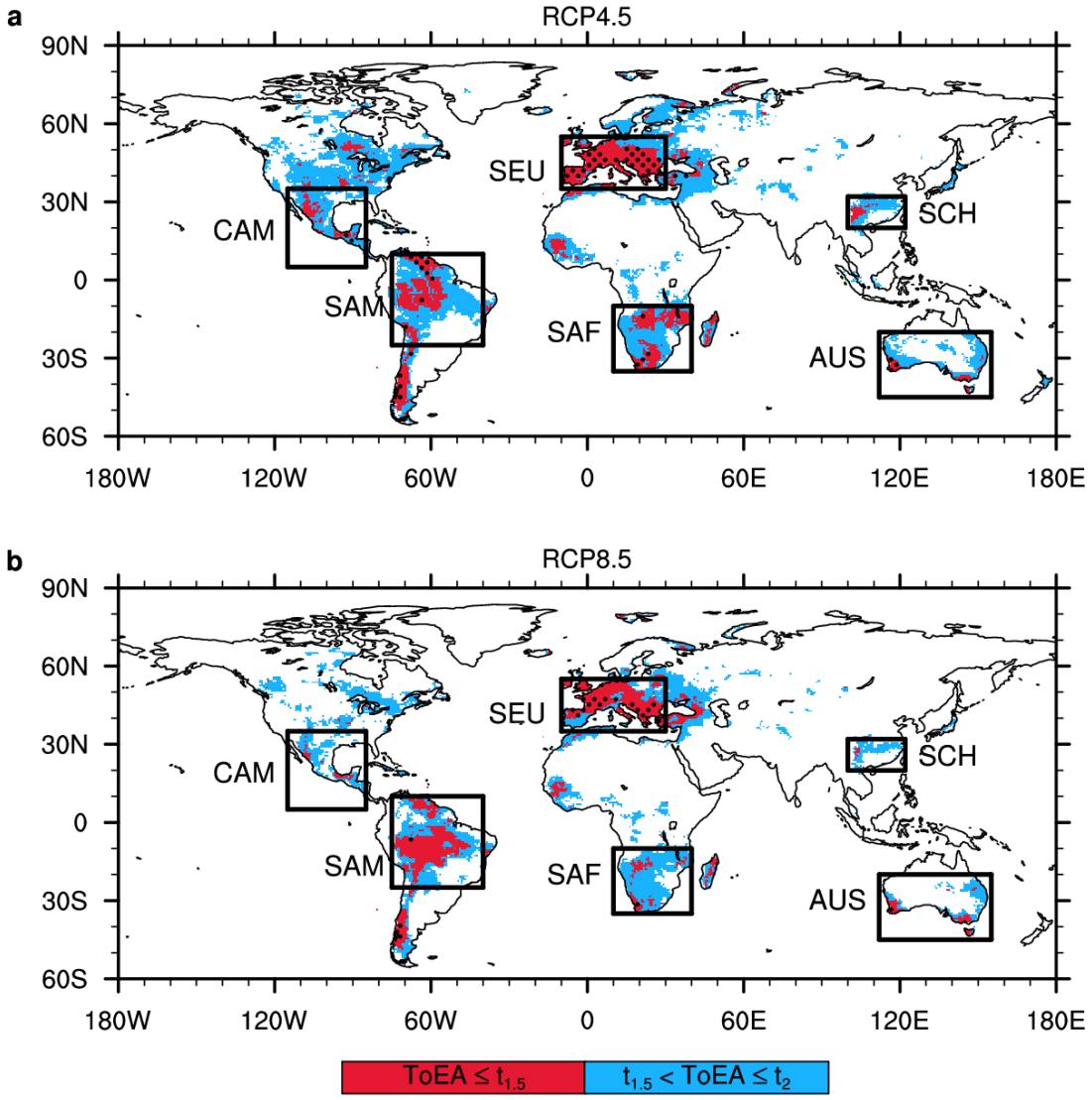
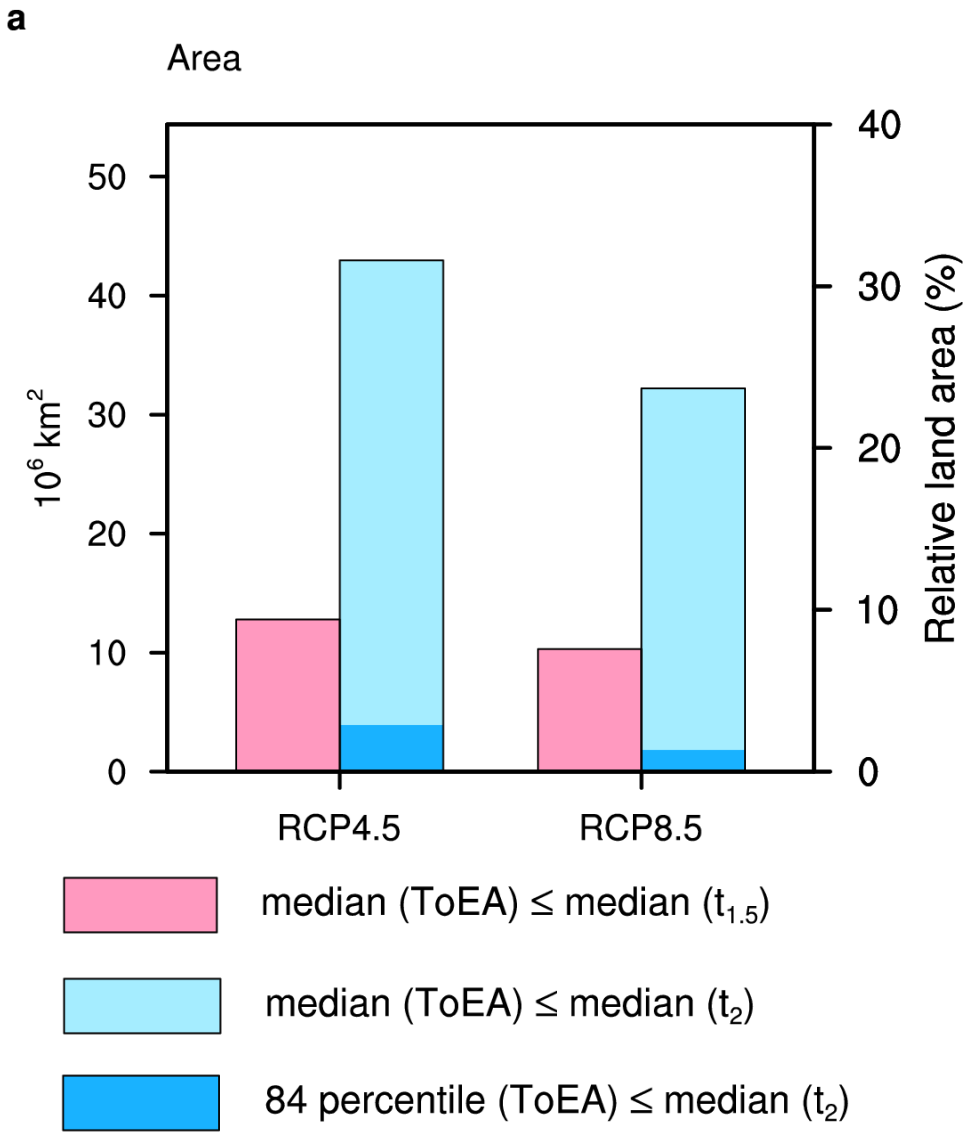
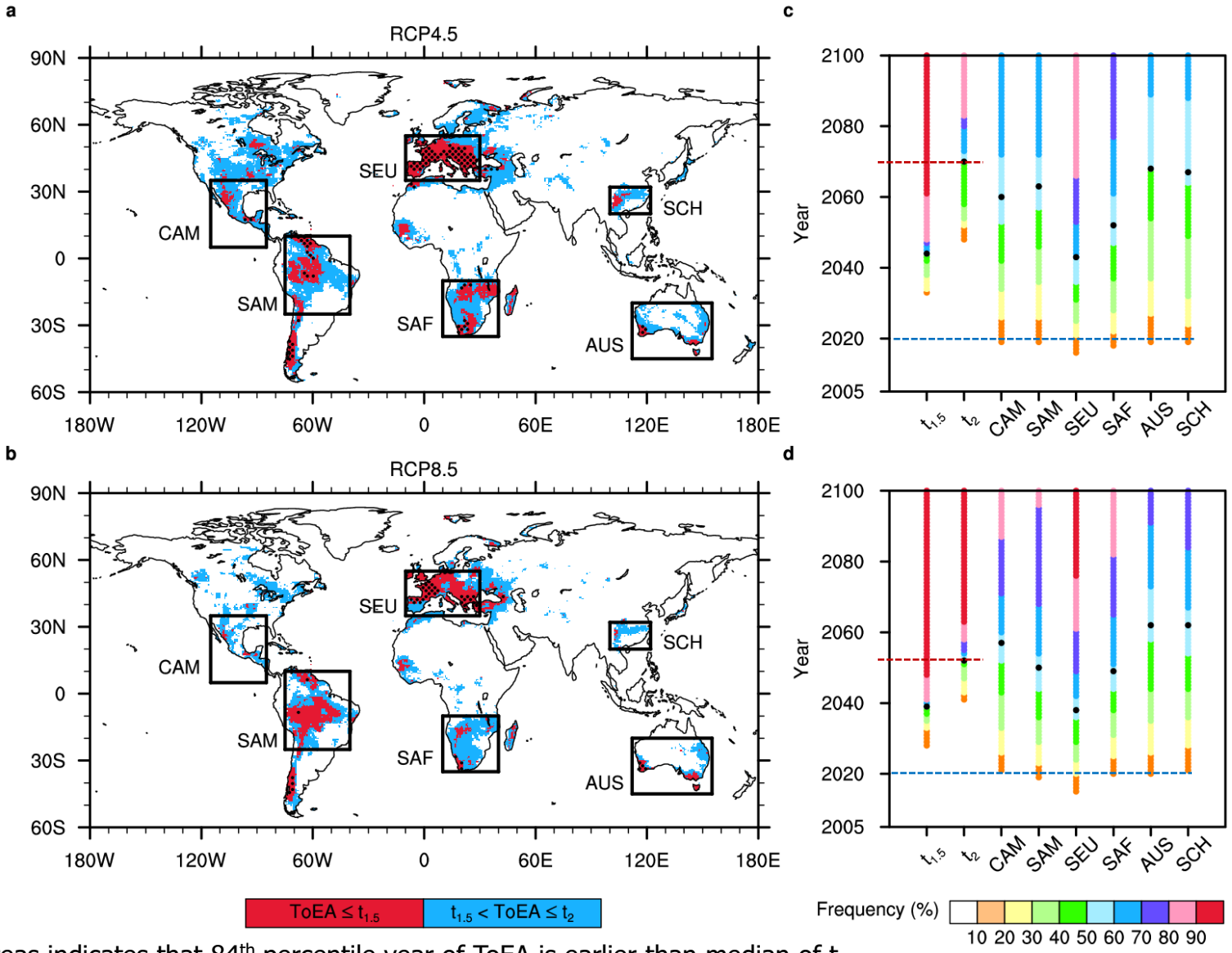
Areal occupation





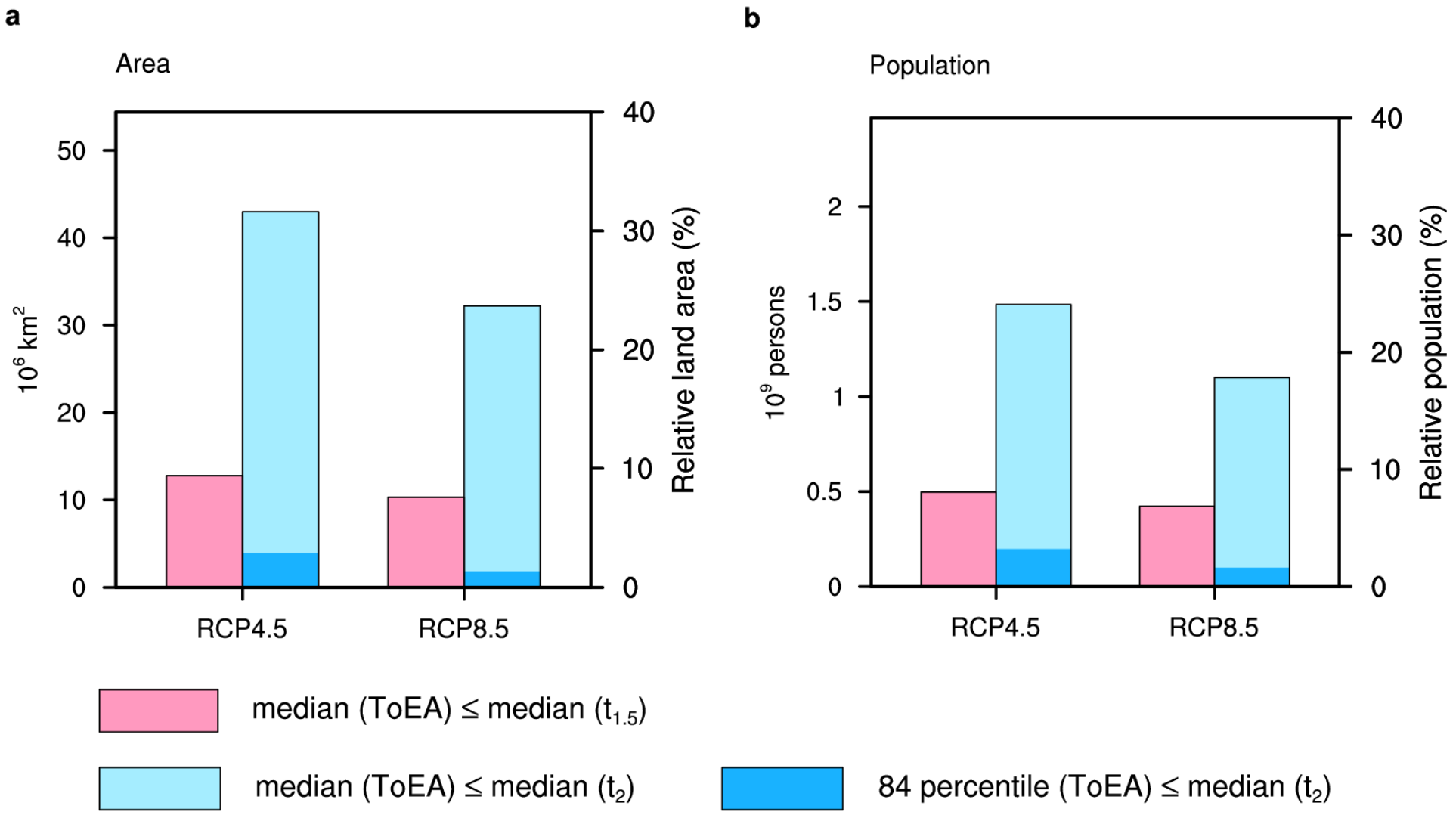
* Stippled areas indicates that 84th percentile year of ToEA is earlier than median of t_2
* White areas indicates that median of ToEA is later than that of t_2

Reasons for larger area under RCP4.5



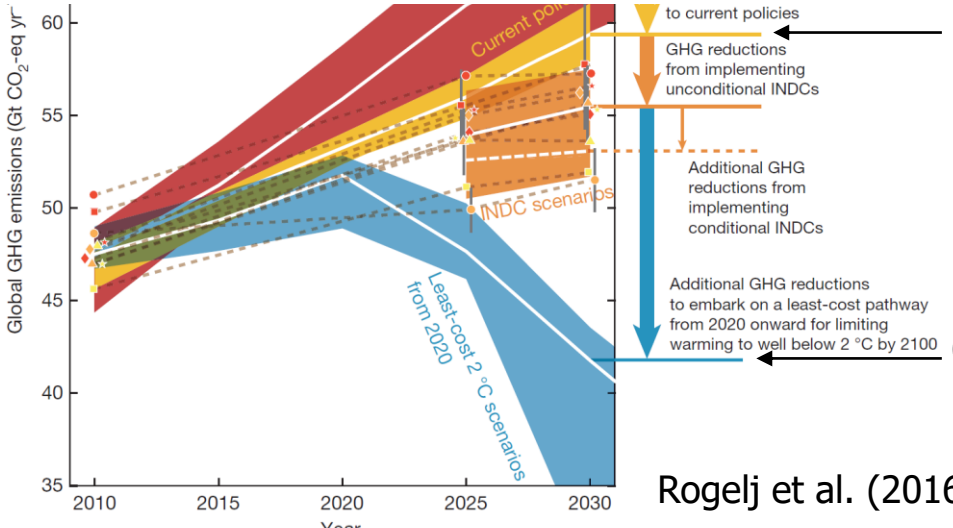
* Stippled areas indicates that 84th percentile year of ToEA is earlier than median of t_2
* White areas indicates that median of ToEA is later than that of t_2

Area and population under emerging aridification



Summary and take-home message

- Under RCP4.5 and RCP8.5, aridification will emerge at 2 °C warming level relative to the pre-industrial level in sizable fractions of the world measured by both area (32% and 24%) and population (24% and 18%).
- **Efforts to mitigate global warming are urgently needed to reduce significant aridification, as well as aridity-related risks.**



GHG emission at current climate policies

GHG emission for 2ºC warming above pre-industrial level

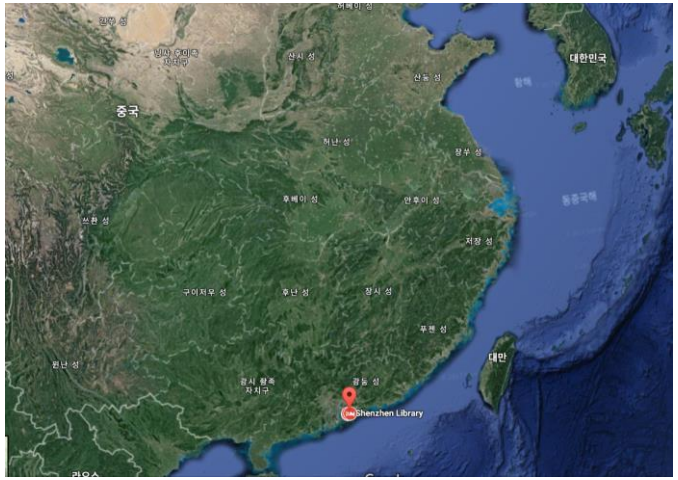
Rogelj et al. (2016)

Thank you for your attention

- Supplementaries

Shenzhen, SUSTech

- Southern University of Science and Technology (南方科技大学)

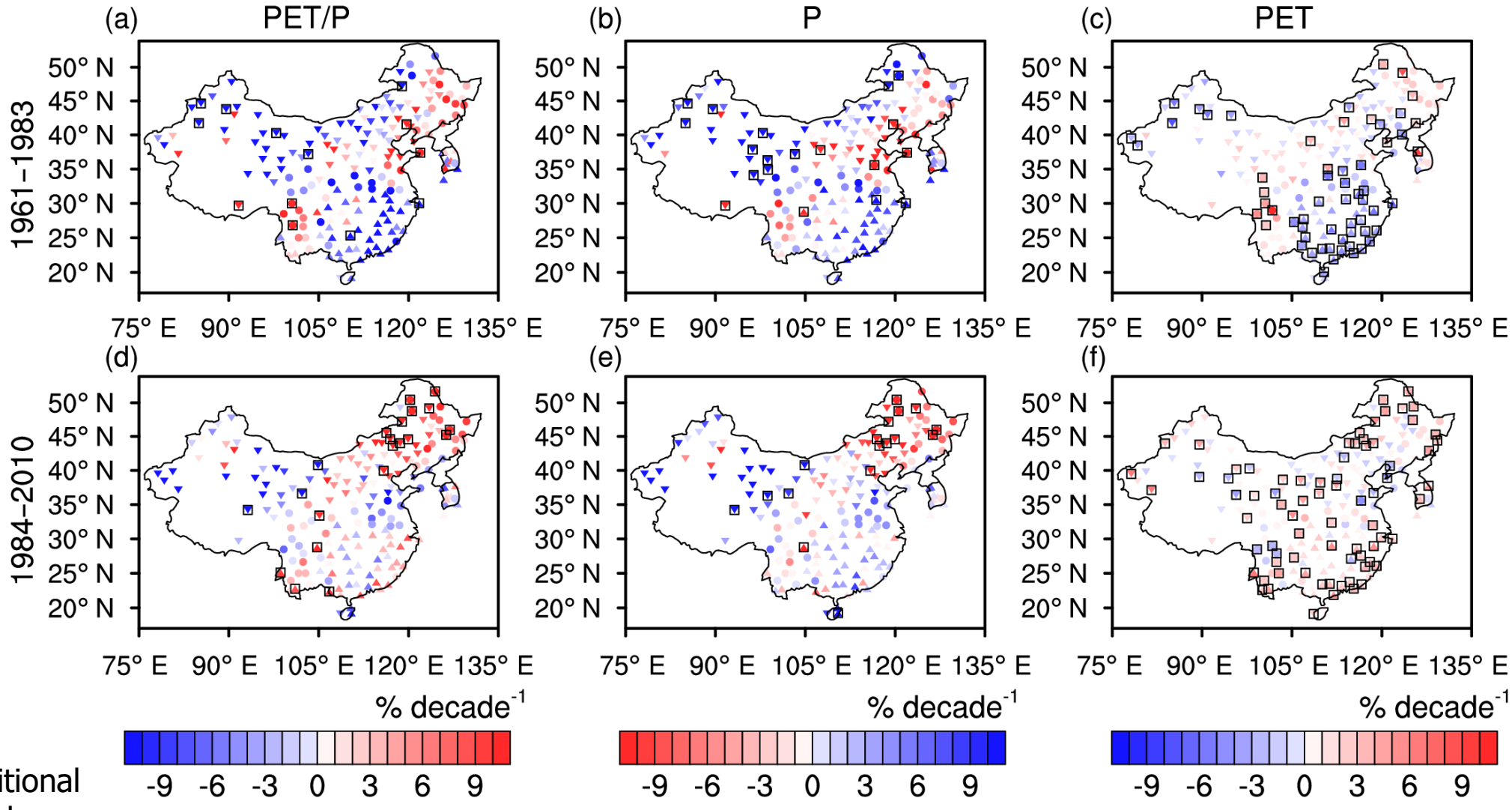


Objectives

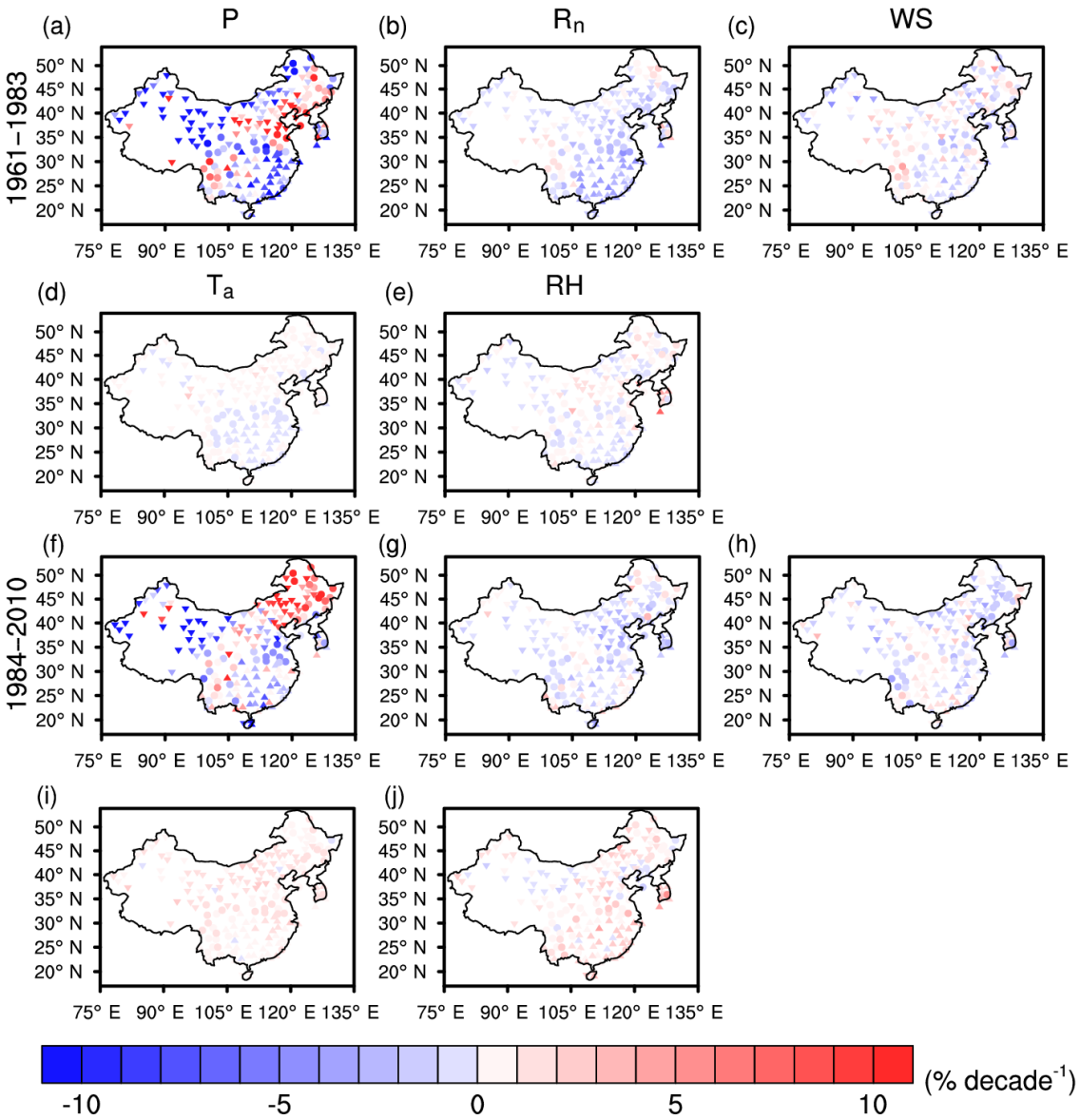
- Examining trends in aridity due to climate change
- Elucidating the mechanisms of aridity trends

- **Providing a concrete insight of the observed aridity trends in continental East Asia**

Trends for two periods



▼: Arid
: Transitional
▲: Humid
□: trend is significant at 95% confidence level


(a)
P
(b)
R_n
(c)
WS
1961–1983
(d)
T_a
(e)
RH
1984–2010
(f)
(g)
(h)
(i)
(j)
50° N
45° N
40° N
35° N
30° N
25° N
20° N
75° E 90° E 105° E 120° E 135° E
-10
-5
0
5
10
(% decade^{-1})

Objectives

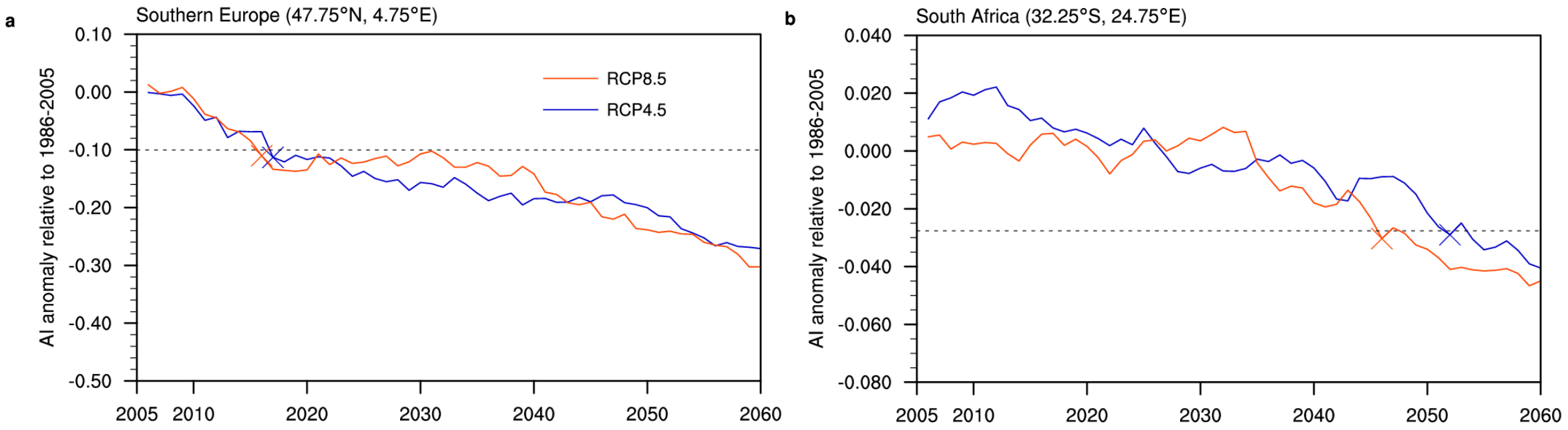
- Estimating ToEA
- Determining whether a ToEA is arrived at earlier than global temperature changes of 1.5 °C and 2 °C warming target

1) Verifying the effectiveness of the temperature goals on preventing emerging aridification
2) Providing vital information on regional climate mitigation

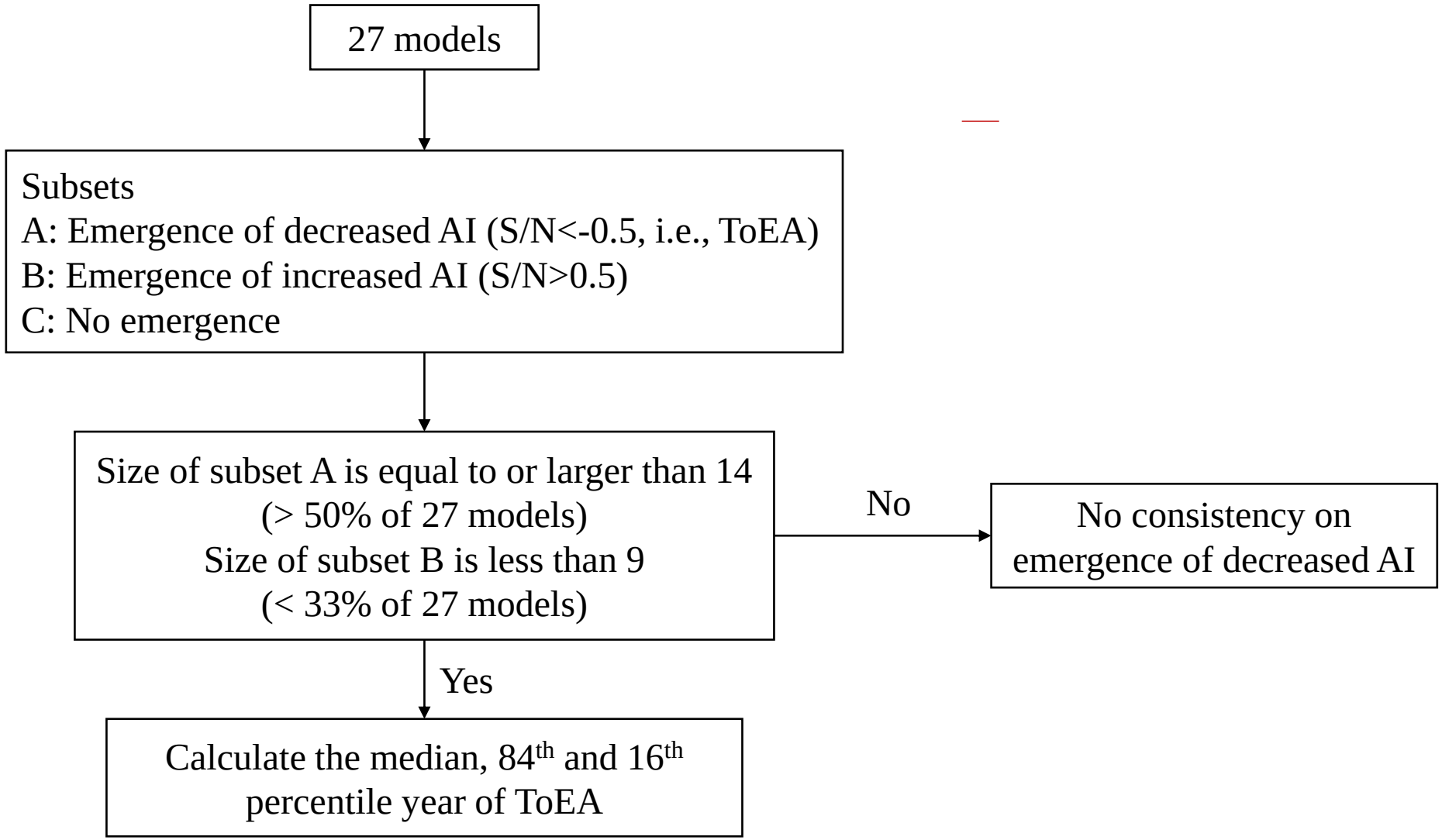
Examples of ToEA

- ToEA is determined the first time when the S/N is less than –0.5.

Ex) CSIRO-Mk3.6.0



Calculation of ensemble quantiles



Changes in P and PET