

# Monsoon Variability in the Last Millennium: A model study

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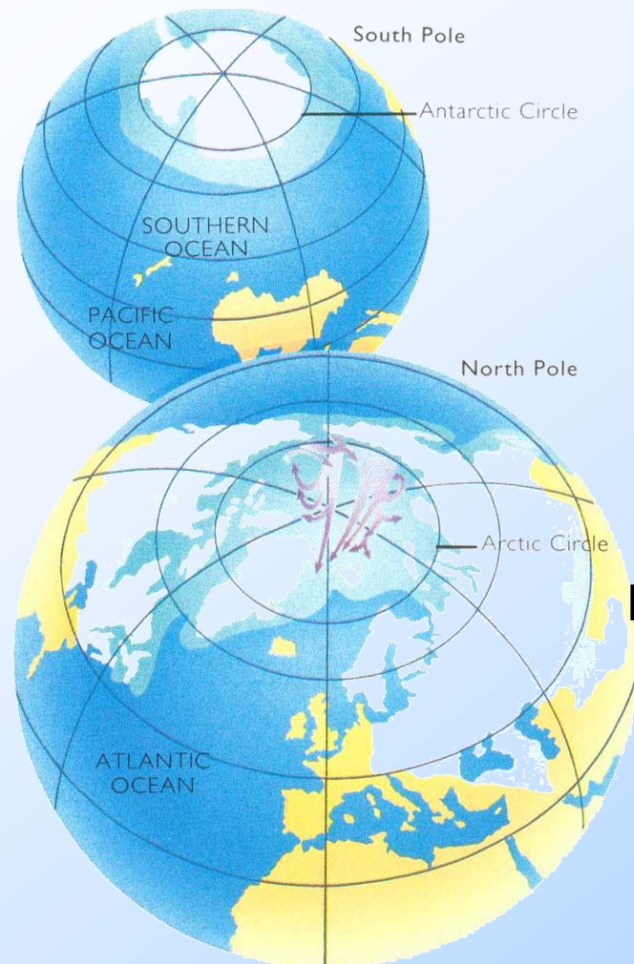
**University of Hawaii at Manoa, Honolulu**

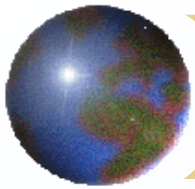
**Willie Soon**

**Harvard-Smithsonian Center for Astrophysics, Cambridge**

**Eduardo Zorita**

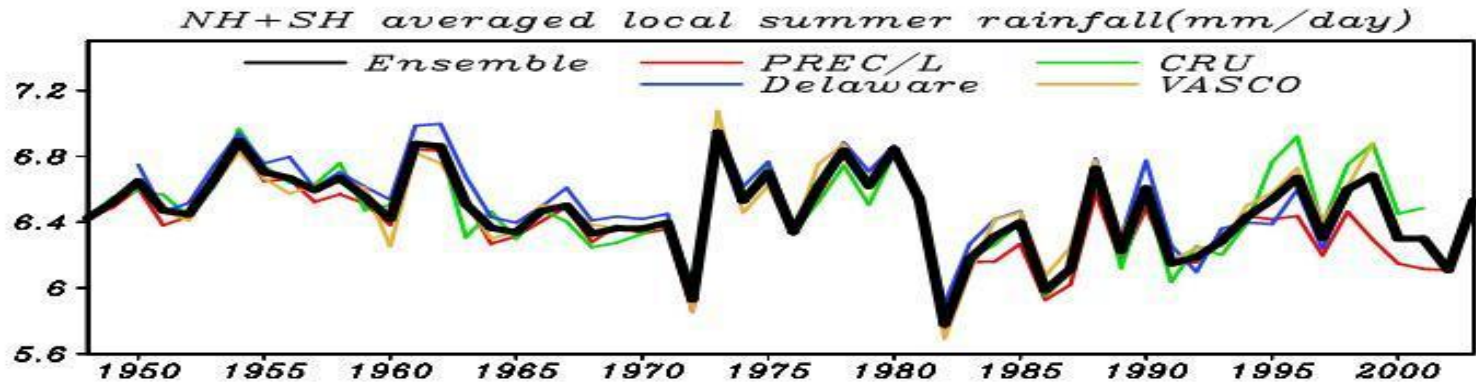
**GKSS Research Center, Germany**





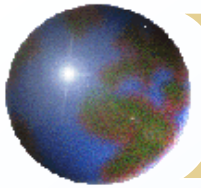
# Background

- Understanding multidecadal-centennial climate variability is essential for projection and attribution of climate change. But on this timescale very little is known.



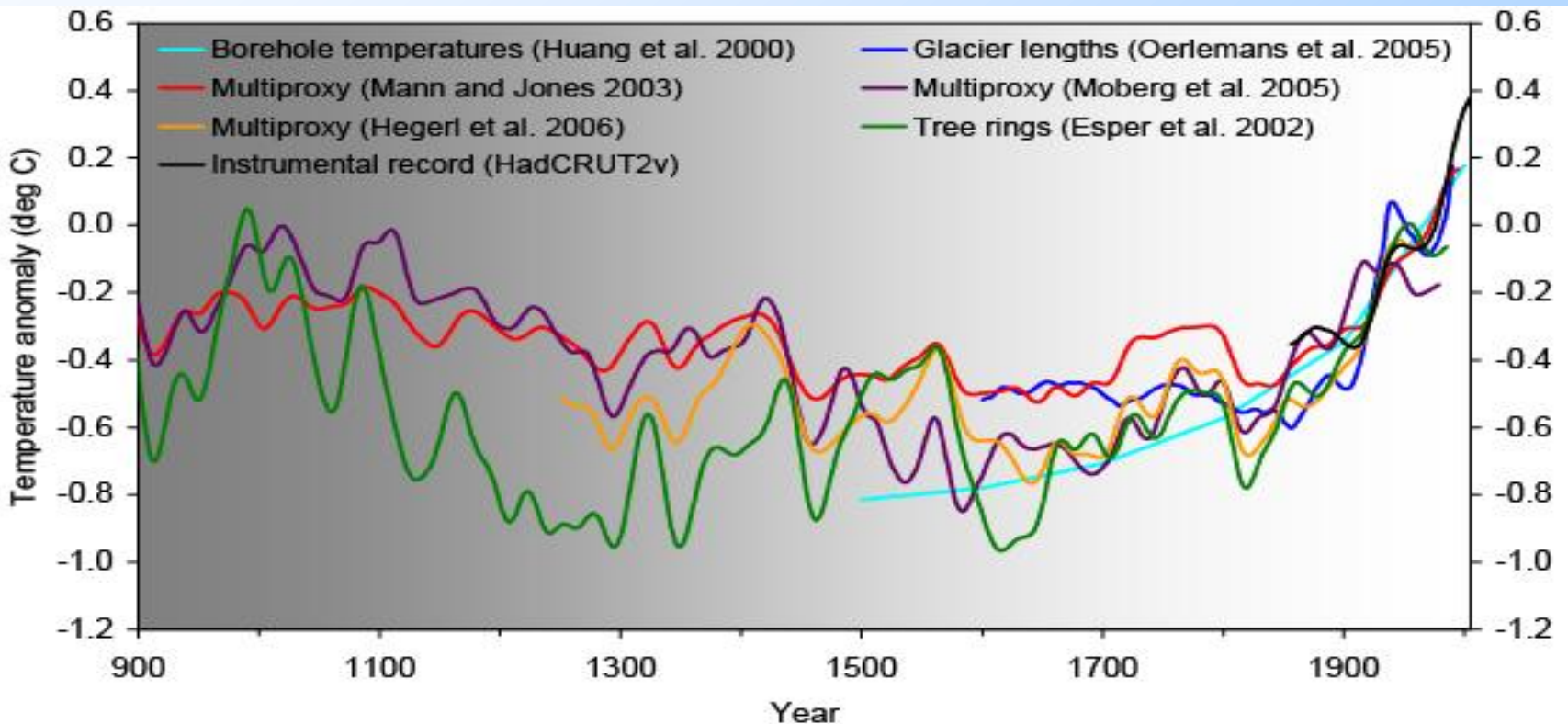
Global land monsoon rainfall decreases over the last 60 years based on observed data (Wang and Ding, 2008).

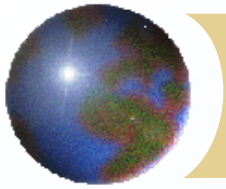




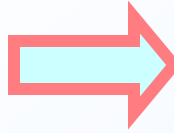
# Background

- Centennial-millennial variability has been studied mainly based on proxy data (tree ring, stalagmite, ice core, lake sediment, coral, historical document). Climate simulation is needed to explain its causes and mechanisms.





# Outline-GM and EAM



Motivation



Scientific Questions



Model and validation



Results



Conclusion

Liu et al. *Journal of Climate*, 2009.

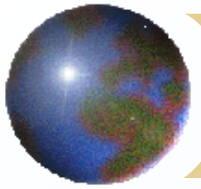
Global Monsoon (GM)

Liu et al. *Climate Dynamics*, 2009.

East Asian Monsoon (EAM)

Precipitation



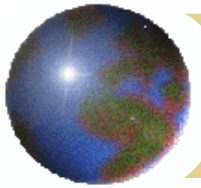


# Motivation-GM

## Why Global Monsoon?

- ⊕ GM is a response of the global coupled atmosphere-land-ocean system to annual variation of the solar forcing.
- ⊕ GM precipitation (GMP) is a major water resource to more than two thirds of the world's population. The future spatio-temporal change in GM precipitation is one of the deepest concerns worldwide.
- ⊕ The centennial-millennial variability of the GMP has not been studied. The characteristics, causes and mechanisms of the variability remain unknown.



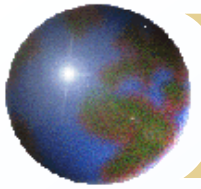


# Motivation-EAM

## Why East Asian Monsoon?

- ✚ EAM is a submonsoon system of the Asian Monsoon. It has the largest meridional extent (including tropics, subtropics and midlatitude).
- ✚ EAM precipitation (EAMP) relates to droughts and floods in China, Japan and Korea. It influences agriculture, economy and daily life of people.
- ✚ The behavior and causes of EAMP variation on the centennial-millennial time scale is little known.

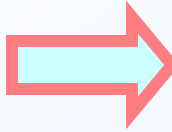




# Outline-GM and EASM



**Motivation**



**Scientific Questions**



**Model and validation**

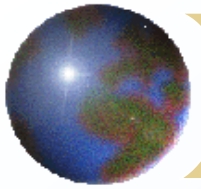


**Results**



**Conclusion**



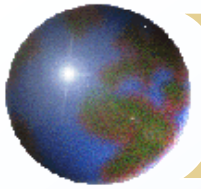


# Scientific Question-GM

## Global Monsoon:

- ⊕ How does the GMP change on centennial-millennial timescale?
- ⊕ What factors give rise to these changes? What physical processes are involved?



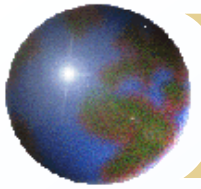


# Scientific Question-EAM

## East Asian Monsoon:

- ⊕ What are the characteristics of EAMP variation on the centennial-millennial time scale?
- ⊕ Do the variations of EAMP differ between centennial-millennial timescale and the interannual - interdecadal timescale?
- ⊕ Are the causes and mechanisms different between these two time scales?





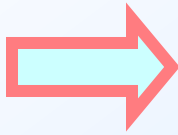
# Outline-GM and EASM



**Motivation**



**Scientific Questions**



**Model and validation**



**Results**



**Conclusion**



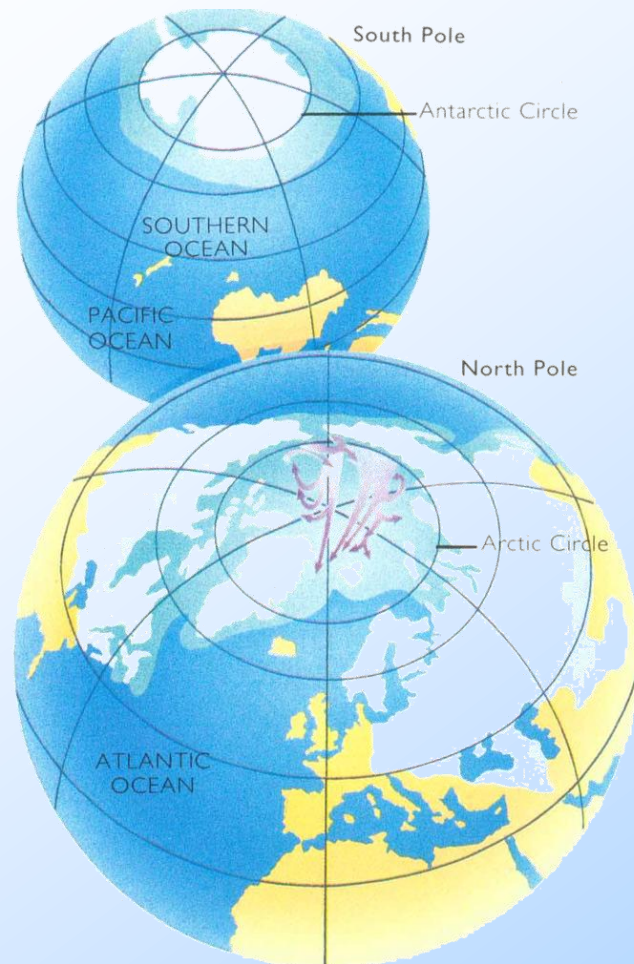
# ECHO-G Model

## *ECHAM4* & *HOPE-G* Model

***ECHAM4*** spectral atmospheric model,  
resolution T30 ( $3.75^\circ \times 3.75^\circ$ ), 19 levels

***HOPE G*** primitive equation ocean model,  
equivalent resolution  $2.8^\circ \times 2.8^\circ$  with  
equatorial grid refinement, 20 levels

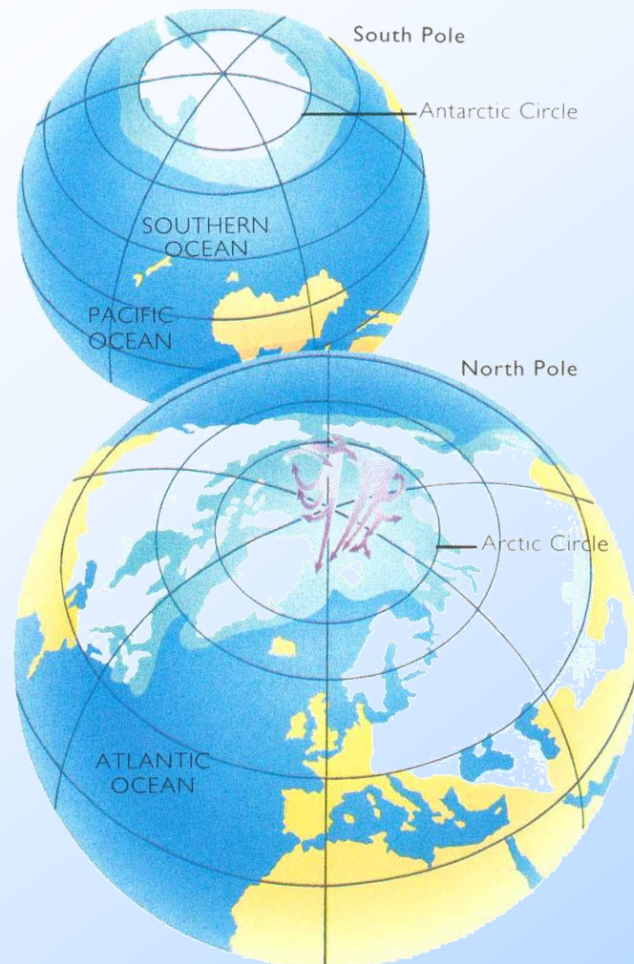
***Coupled*** through OASIS, flux correction



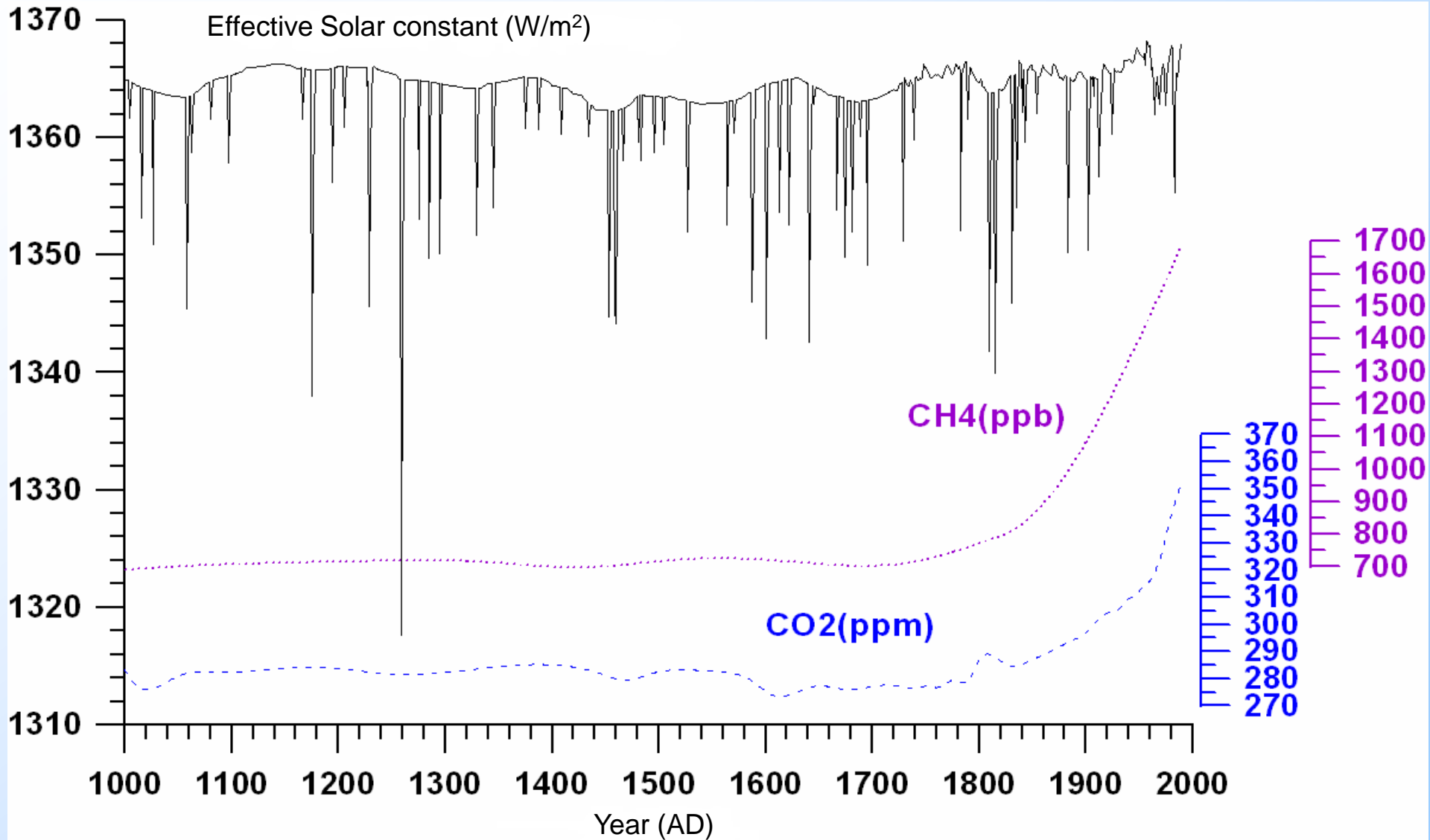
# Experiments

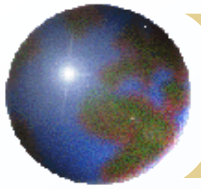
***Free (Control) run (CTL)*** driven by constant forcing of 1990 AD and integrated for 1000 years

***Forced run (ERIK)*** started in the year 900 AD with the initial conditions from the CTL. Spin up for 100 years and attain an equilibrated state around the model year 1000 AD. Then it was driven by three external forcing factors: **solar variability, volcanic aerosols and GHG concentrations (CO<sub>2</sub> and CH<sub>4</sub>)** from 1000 to 1990 AD

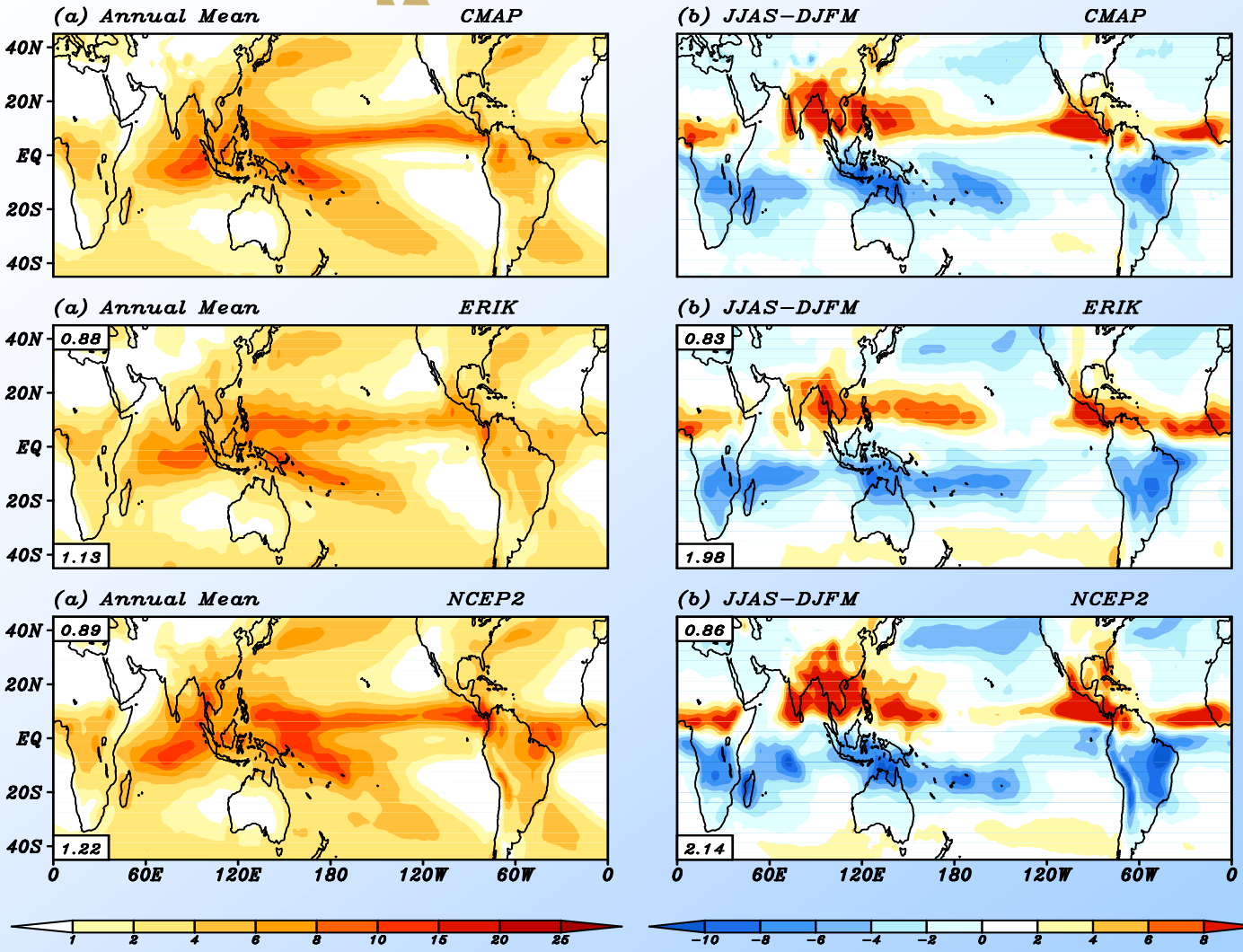


# Forcings in ERIK run





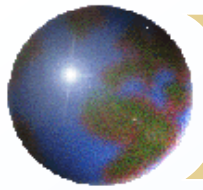
# Validation of the model



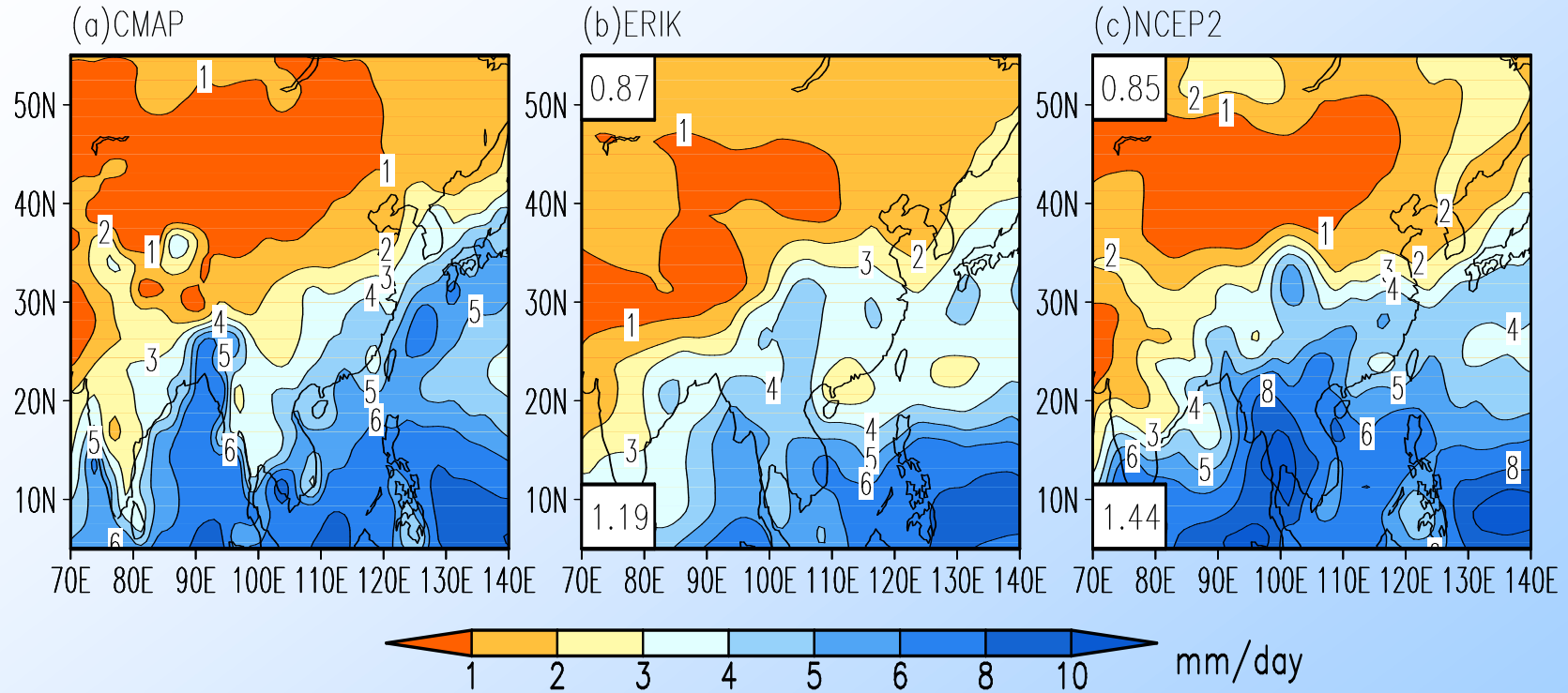
CMAP and NCEP-2 reanalysis data were derived for the period 1979-2004. ERIK was derived for the period 1965-1990 AD. The numbers shown in the upper-left corners and the lower-left corners indicate pattern correlation coefficients and root mean square errors with the CMAP data, respectively.

ERIK simulated the annual mean precipitation and GM mode comparable to those captured by reanalysis.



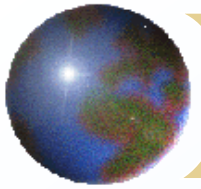


# Validation of the model

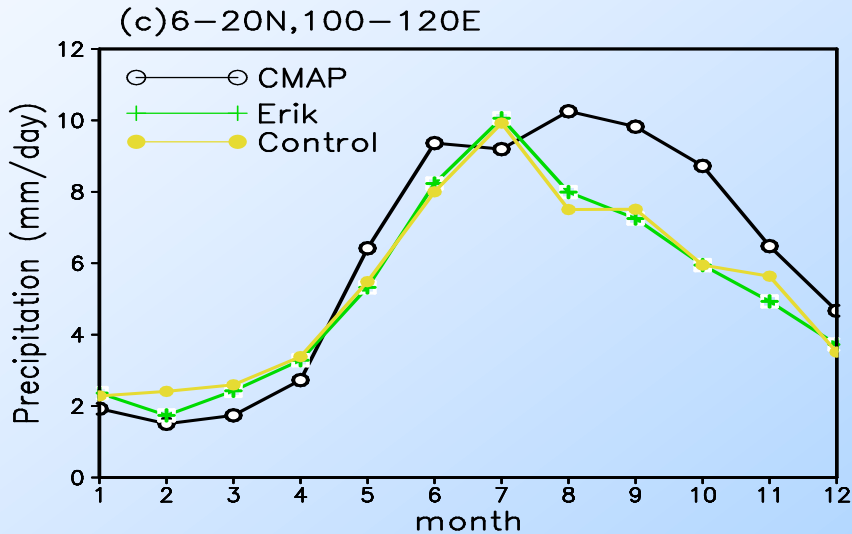
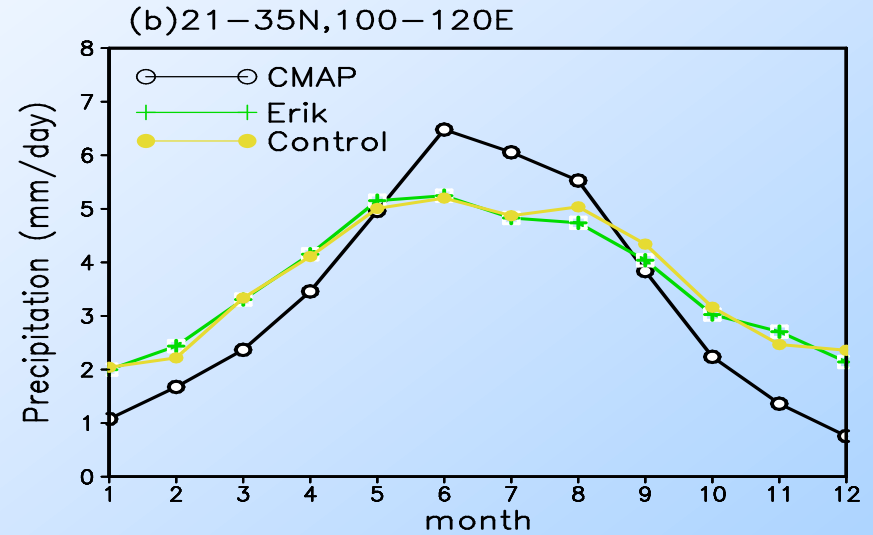
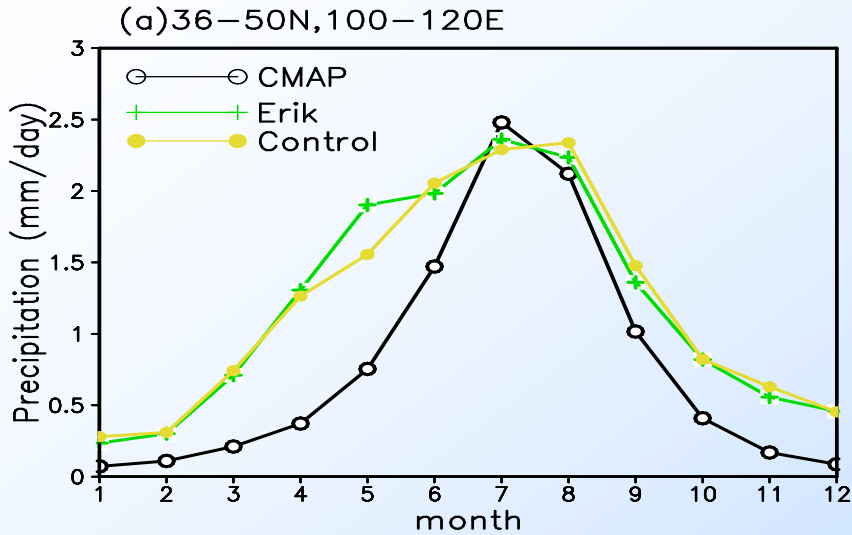


Comparison of the climatological annual mean precipitation rate ( $\text{mm day}^{-1}$ ) for (a) the observed (CMAP, 1979-2007), (b) ECHO-G model simulated (in the forced ERIK run, 1961-1990), and (c) the NCEP 2 reanalysis field (1979-2007). Pattern correlation coefficients and root mean square errors (in units of  $\text{mm/day}$ ) with respect to the observation are shown in the upper-left (lower-bottom) corners of the panel (b) and (c).



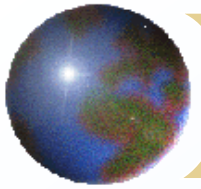


# Validation of the model

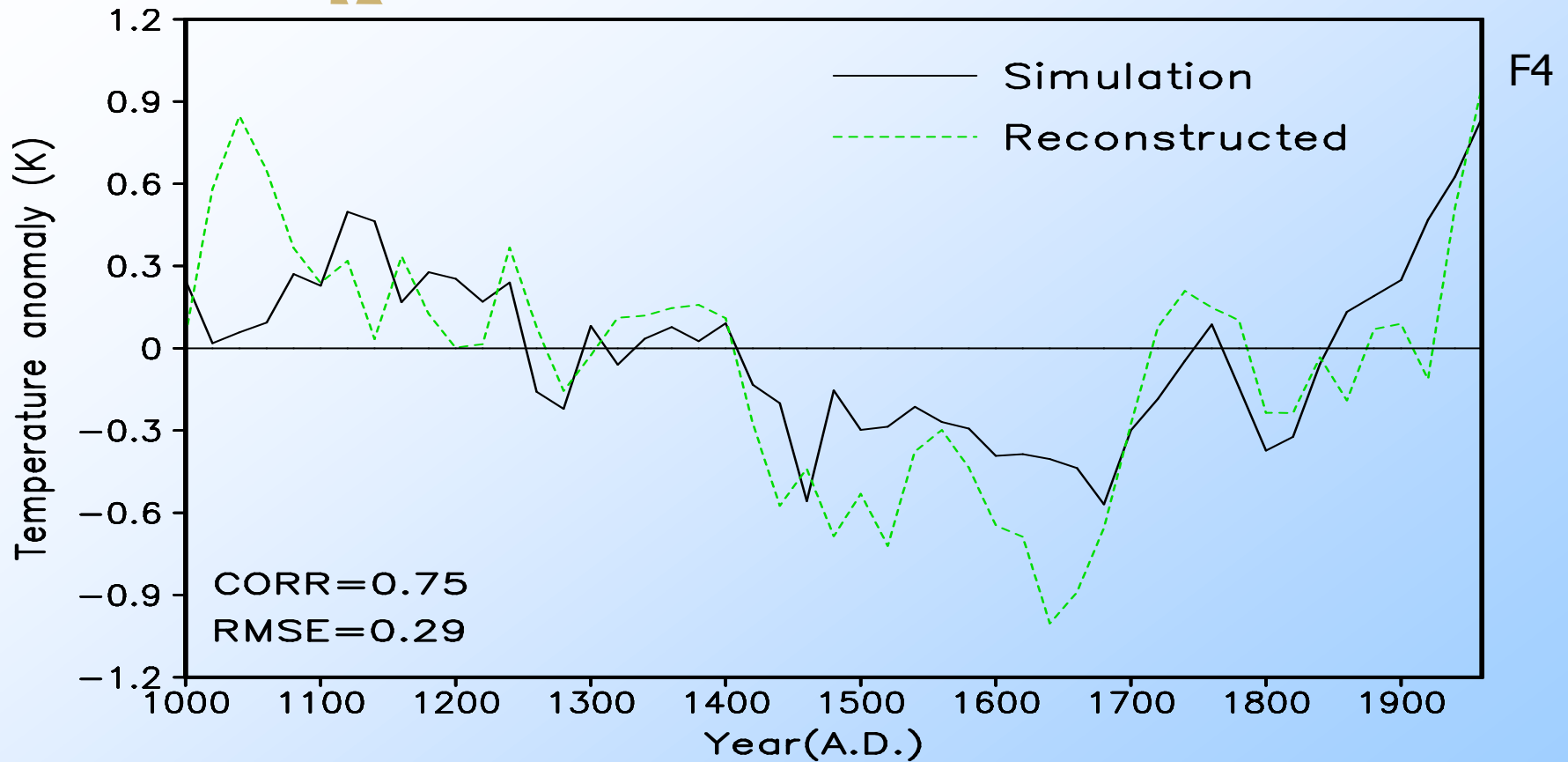


Comparison of the observed (CMAP, 1979-2007) and the simulated (ECHO-G ERİK and control runs, 1961-1990) climatological annual variation of precipitation rate ( $\text{mm day}^{-1}$ ) at (a) extratropical ( $36\text{--}50^\circ\text{N}$ ), (b) subtropical ( $21\text{--}35^\circ\text{N}$ ), and (c) tropical ( $6\text{--}20^\circ\text{N}$ ) East Asia averaged between  $100^\circ\text{E}$  and  $120^\circ\text{E}$ .



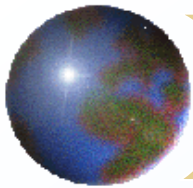


# Validation of the model

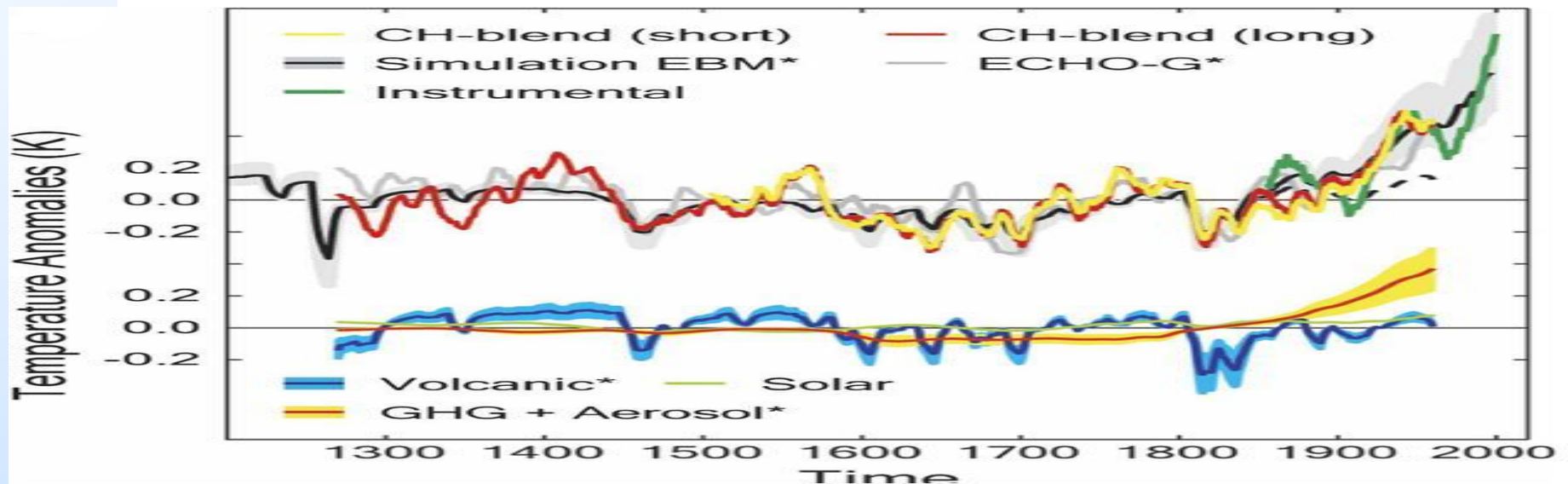
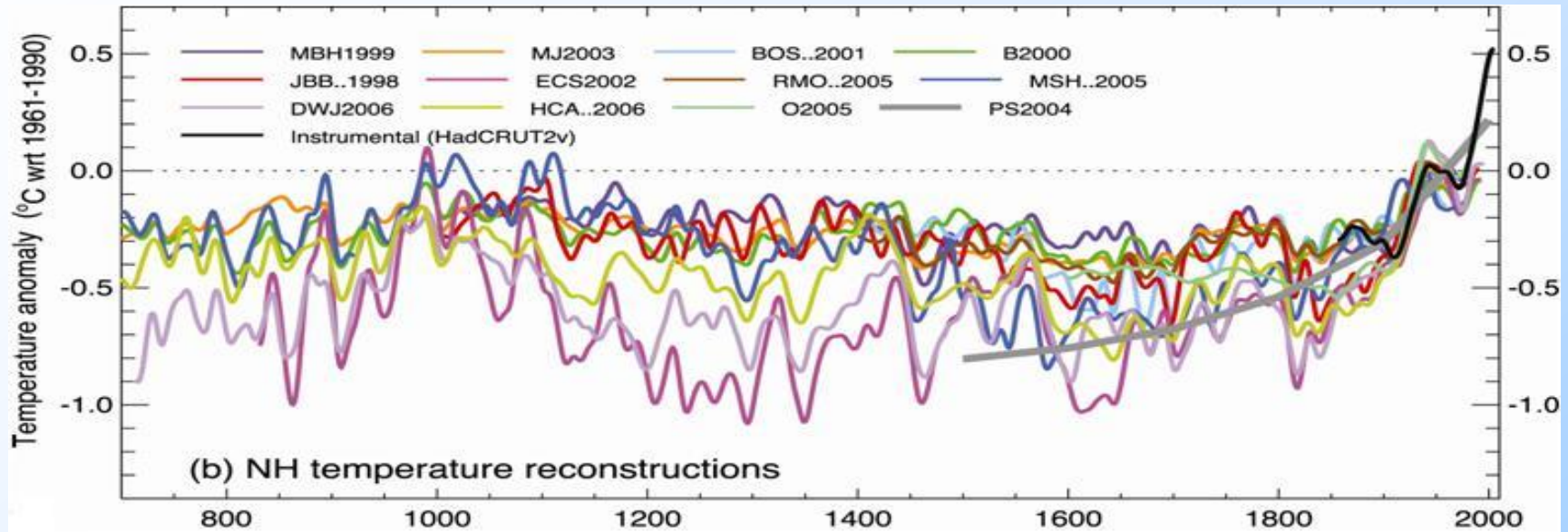


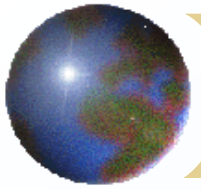
Comparison of the surface temperature variation of the proxy data (Yang et al. GRL, 2002) with ERIK simulated results. A 20-year average was applied to the time series.





# Validation of the model





# Outline-GM and EASM



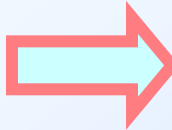
**Motivation**



**Scientific Questions**



**Model and validation**

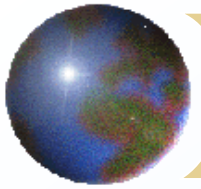


**Results**



**Conclusion**

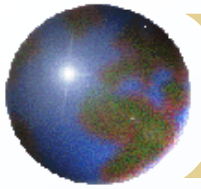




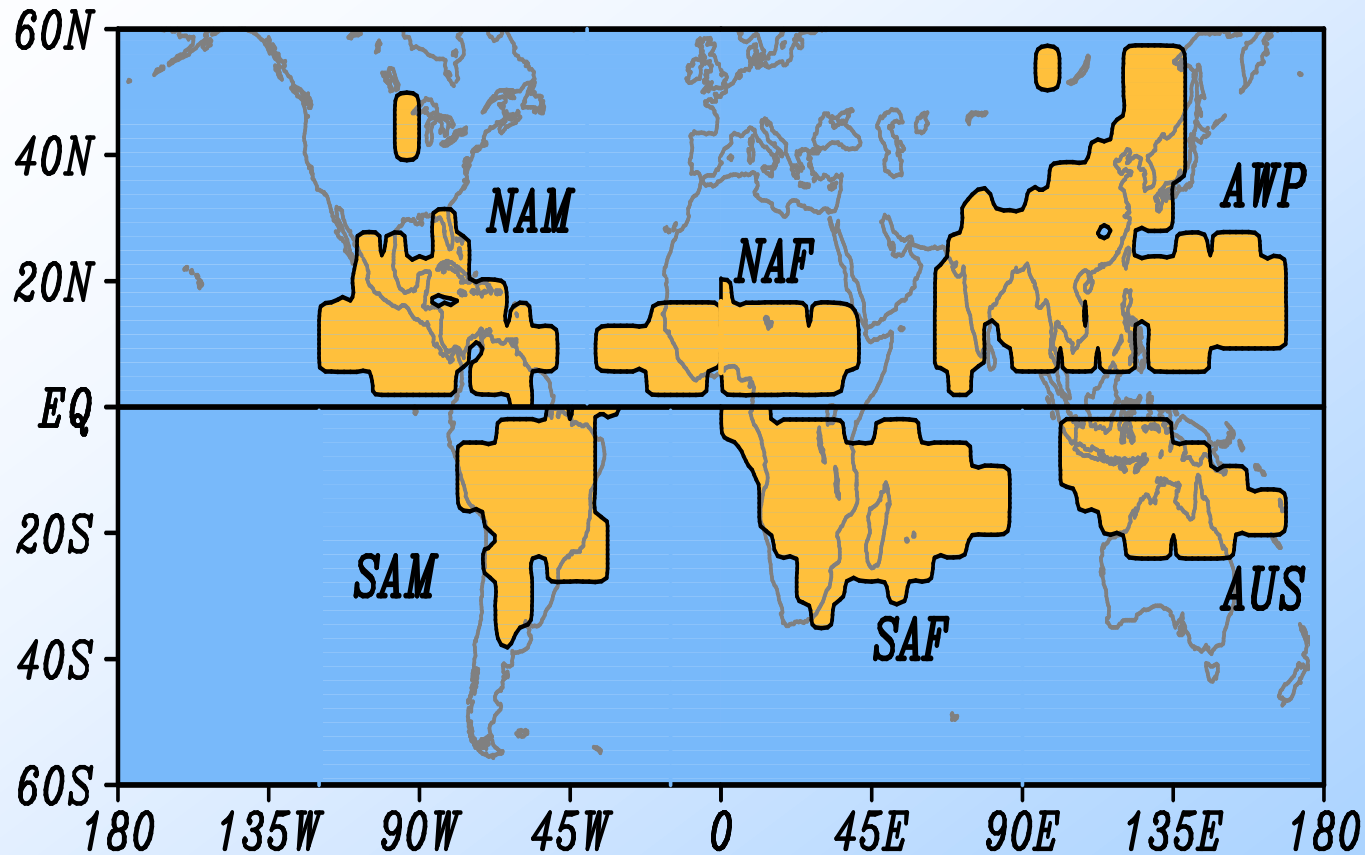
# Results

- ✦ **Part 1: Global Monsoon (GM)**
- ✦ **Part 2: East Asian Monsoon (EAM)**





# Definition of Global Domain and Indices

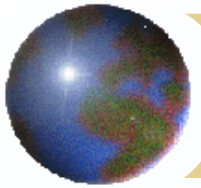


1. AR of precipitation exceeds 2 mm/day
2. Local summer precipitation exceeds 55% of annual rainfall

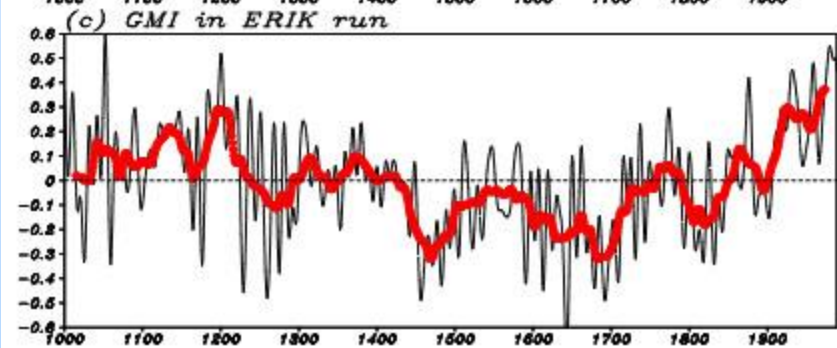
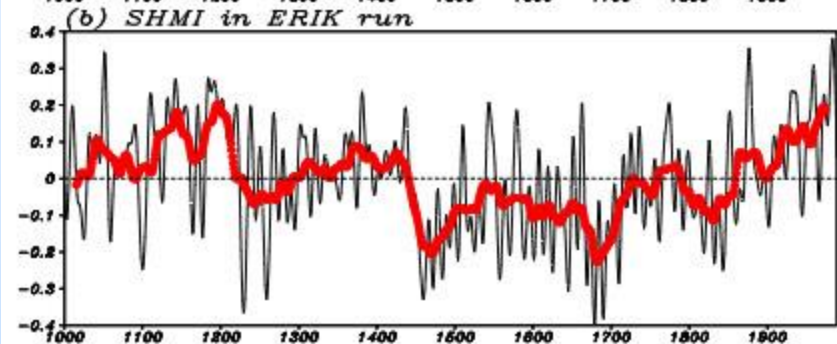
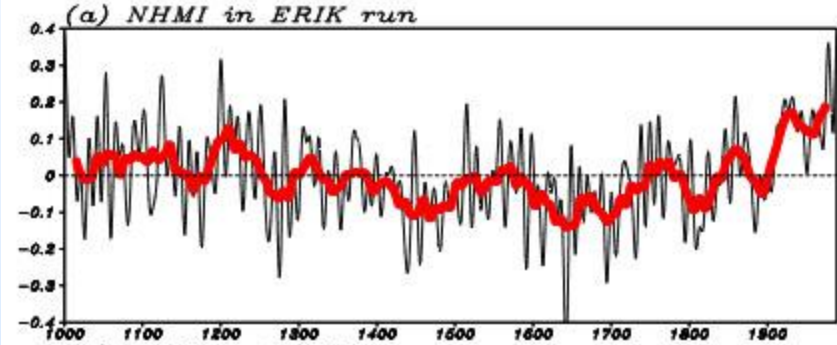
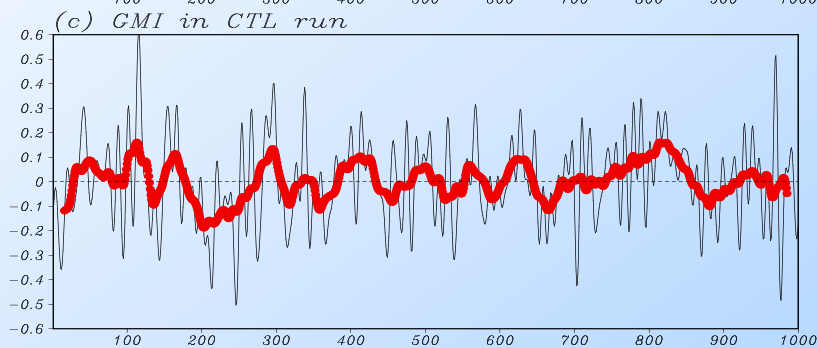
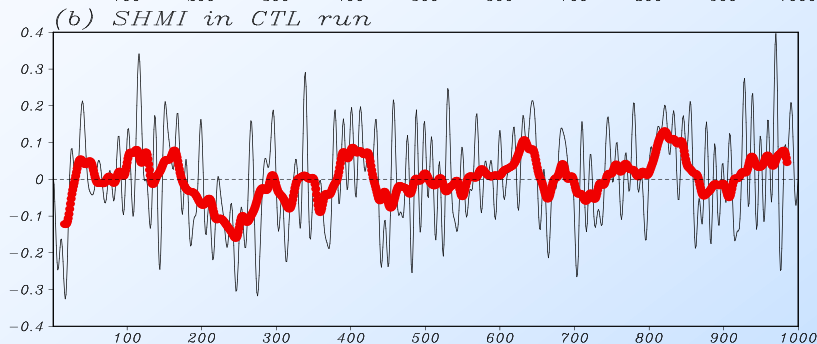
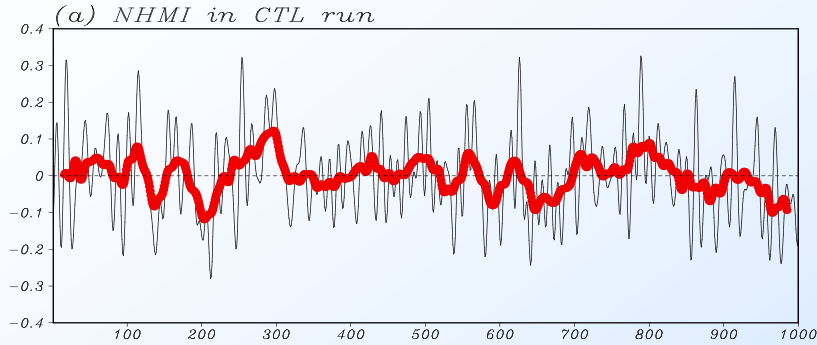
AR: MJJAS precipitation minus NDJFM precipitation in the Northern Hemisphere (NH) and NDJFM minus MJJAS precipitation in the Southern Hemisphere (SH).

NHMI : JJA rainfall falling in NH monsoon domain.  
 SHMI: DJF rainfall falling in SH monsoon domain.  
 GMI=NHMI+SHMI



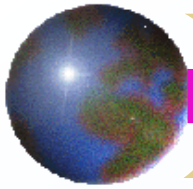


# Variation of Monsoon Indices

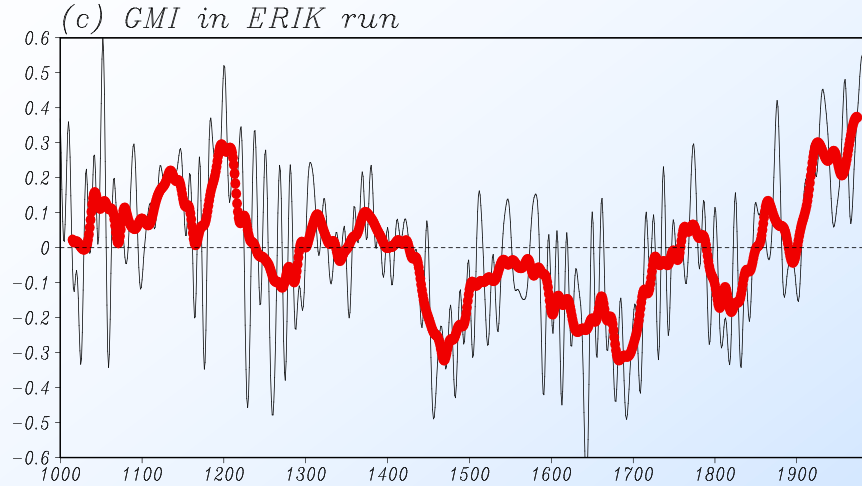


- ⊕ Time series of 7-year running mean GM indices (black lines).
- ⊕ 31-year running means (red lines) highlight centennial-millennial variations



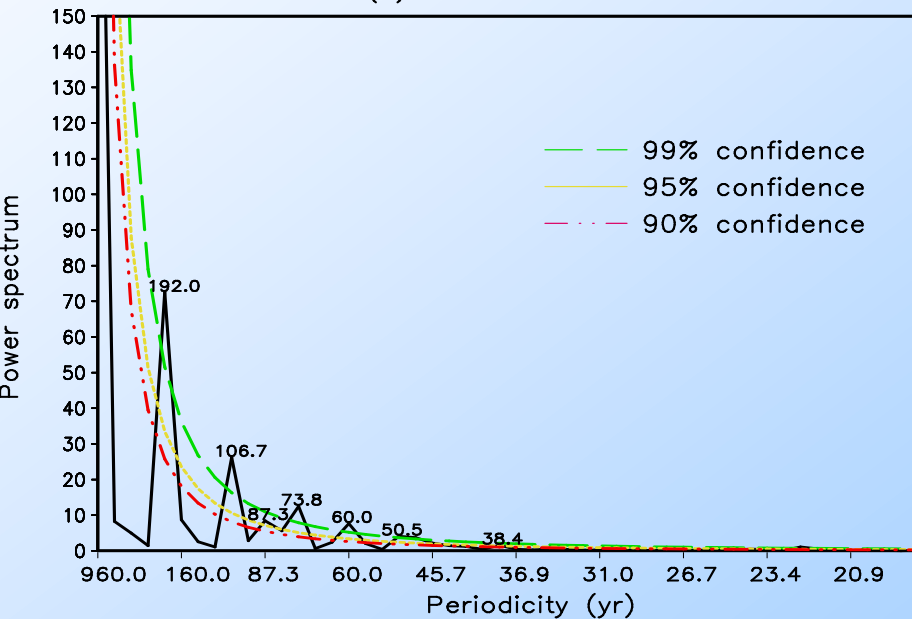


# Periodicity of the GMI in the last millennium



LIA (1450-1850) : **Weak GM**  
 Spörer Minimum (1460)  
 Maunder Minimum (1685)  
 Dalton Minimum (1800)  
 MWP (1030-1240) : **Strong GM**  
 1060 ; 1150 ; 1210

(c) GMI in ERIK run



**Periodicity :**

**192 a**

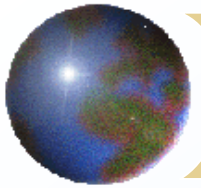
**107 a**

**74 a**

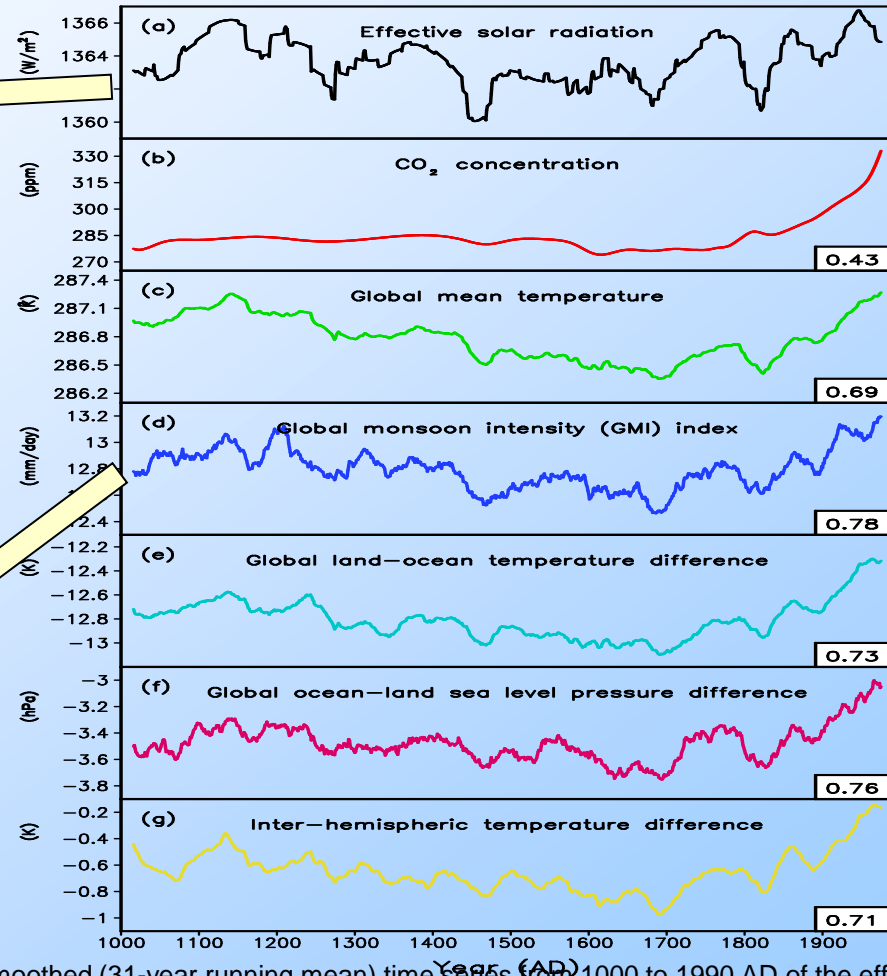
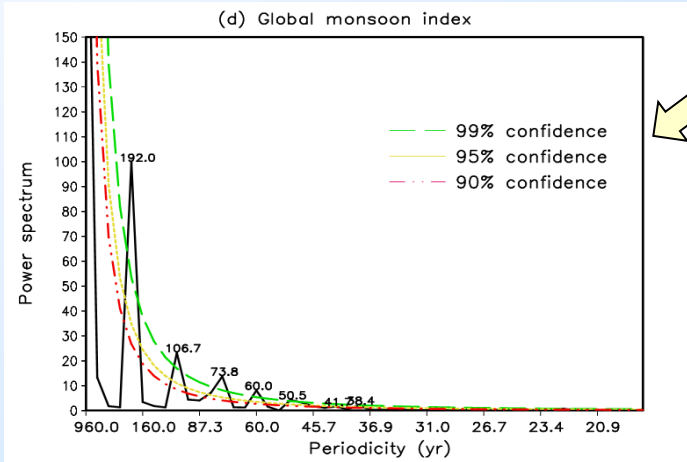
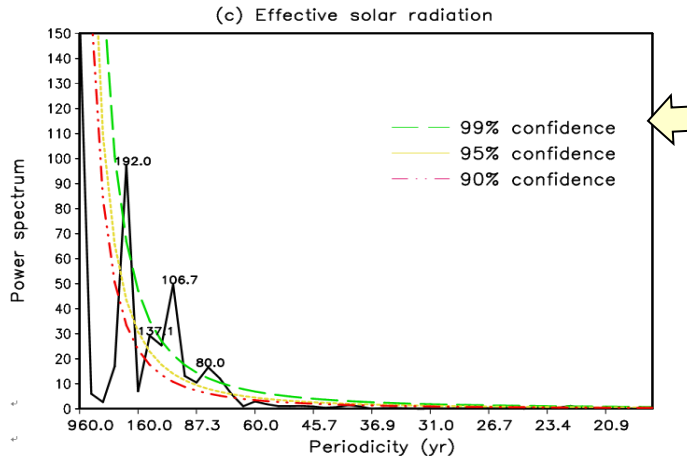
**Confidence :**

**99%**



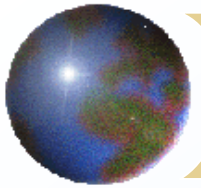


## Attribution



The spectrum of the GMI has pronounced peaks on 192, 107, and 74 years, which corresponds well to the significant spectral peaks from effective radiative forcing at around 192, 107, and 80 years.

Smoothed (31-year running mean) time series from 1000 to 1990 AD of the effective solar radiation (a,  $W/m^2$ ),  $CO_2$  concentration (b, ppm), global mean temperature (c, K), global monsoon intensity (GMI) index (d, mm/day), global land-ocean temperature difference (e, K), global land-ocean sea-level pressure difference (f, hPa) and inter-hemispheric temperature difference (g, K). The numbers shown in the lower-right corners indicate the correlation coefficients of these factors with effective radiation forcing

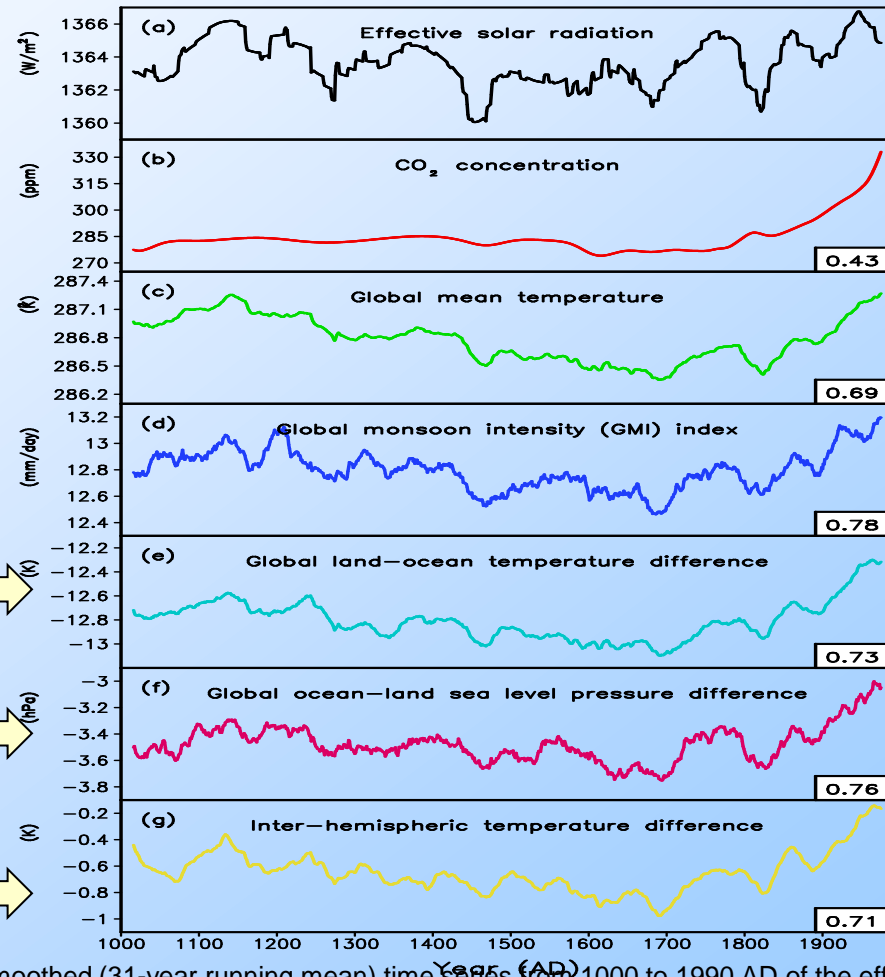


# Mechanism

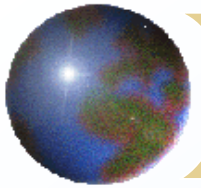
When effective radiative flux increases, the land warms more than the ocean, thus the **thermal contrast between continent and ocean gets reinforced**.

The **inter-hemispheric temperature difference** varies in consistent with the effective radiative forcing.

The reinforced thermal contrast further enhances the **pressure differences between the land and ocean**, thus strengthens the monsoon circulation and associated rainfall



Smoothed (31-year running mean) time series from 1000 to 1990 AD of the effective solar radiation (a,  $W/m^2$ ),  $CO_2$  concentration (b, ppm), global mean temperature (c, K), global monsoon intensity (GMI) index (d, mm/day), global land-ocean temperature difference (e, K), global land-ocean sea-level pressure difference (f, hPa) and inter-hemispheric temperature difference (g, K). The numbers shown in the lower-right corners indicate the correlation coefficients of these factors with effective radiation forcing

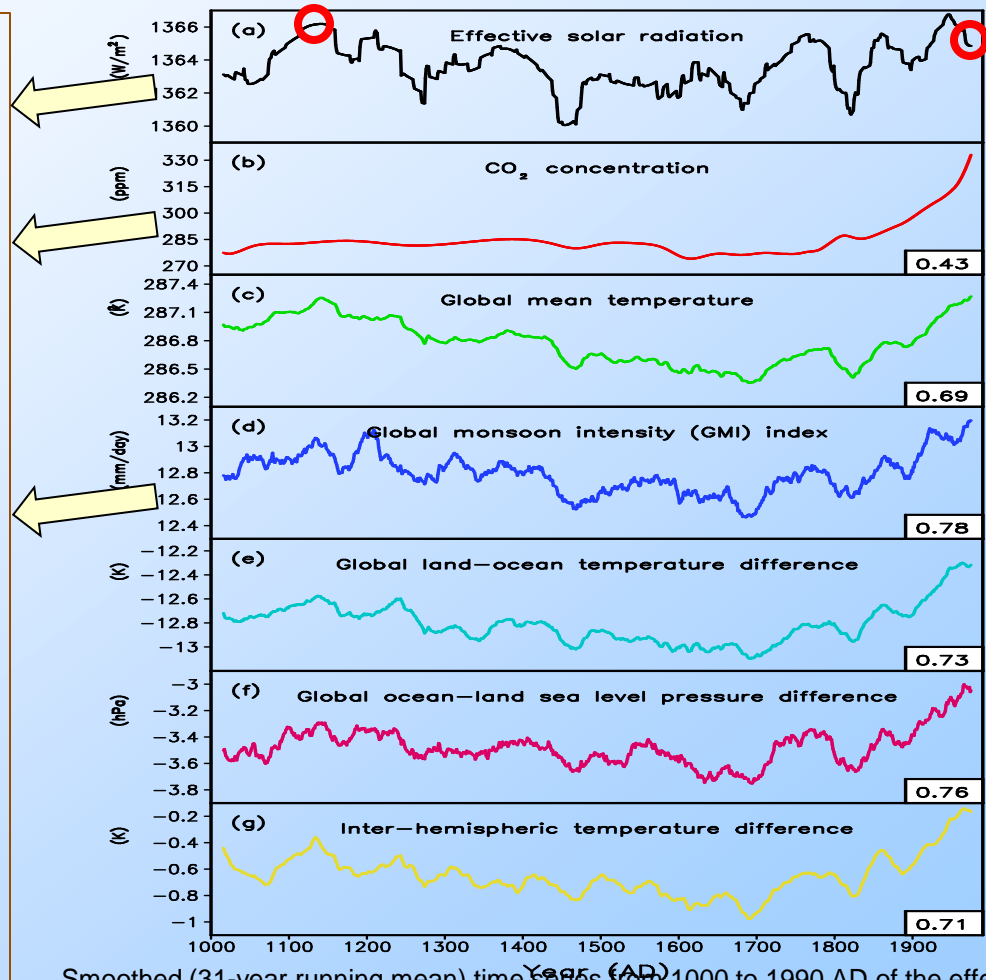


# Attribution

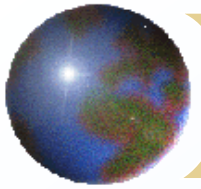
The effective solar irradiance in the late 20<sup>th</sup> century is 0.52 W/m<sup>2</sup> lower than that during MWP, but the GM rainfall rate in the PWP is higher.

Therefore, the solar and volcanic forcing can not account for most of the observed increase of GM precipitation in the 1961-1990.

Rapid increase of atmospheric CO<sub>2</sub> and CH<sub>4</sub> might have a positive contribution to the recent increase in the GM precipitation.



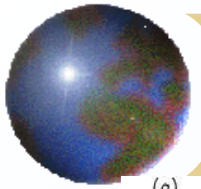
Smoothed (31-year running mean) time series from 1000 to 1990 AD of the effective solar radiation (a, W/m<sup>2</sup>), CO<sub>2</sub> concentration (b, ppm), global mean temperature (c, K), global monsoon intensity (GMI) index (d, mm/day), global land-ocean temperature difference (e, K), global land-ocean sea-level pressure difference (f, hPa) and inter-hemispheric temperature difference (g, K). The numbers shown in the lower-right corners indicate the correlation coefficients of these factors with effective radiation forcing



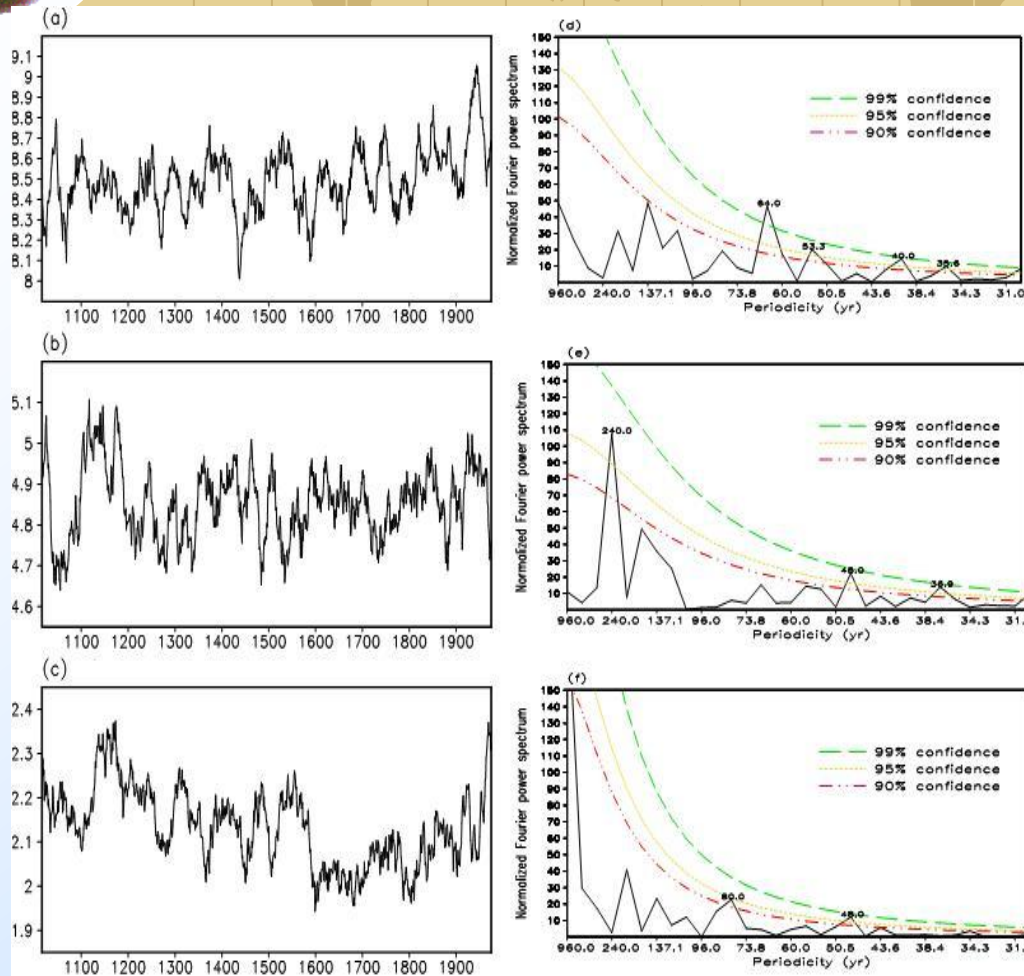
# Results

- ✦ Part 1: Global Monsoon (GM)
- ✦ Part 2: East Asian Monsoon (EAM)





# Variation of EAM Precipitation Rate

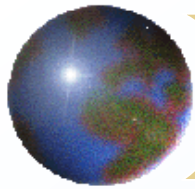


Centennial-millennial variation of the EASM is essentially a forced response.

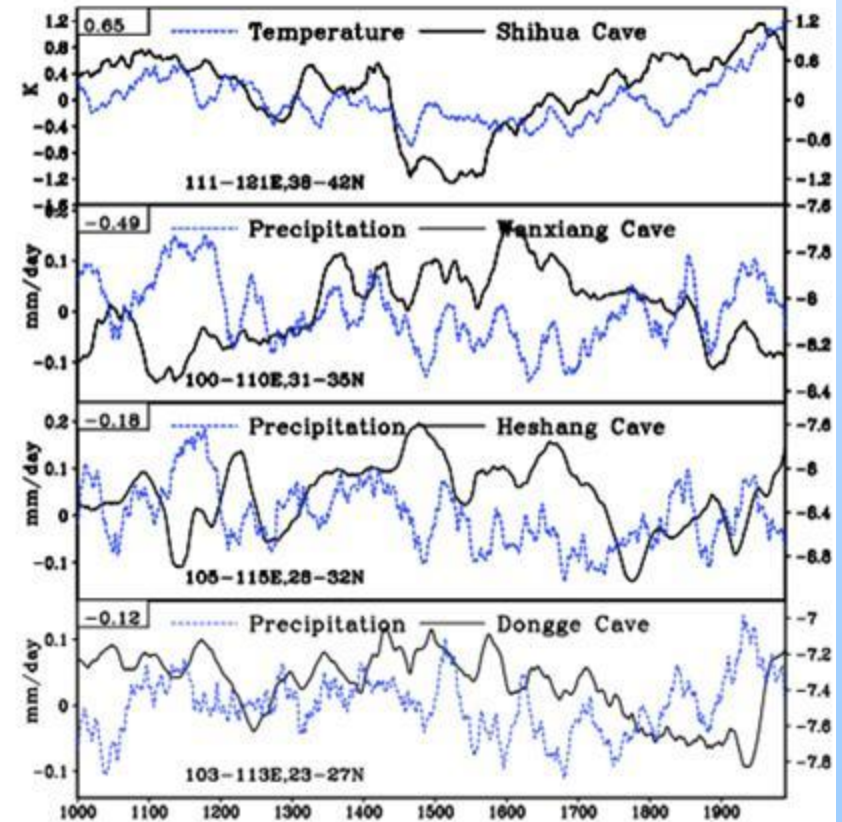
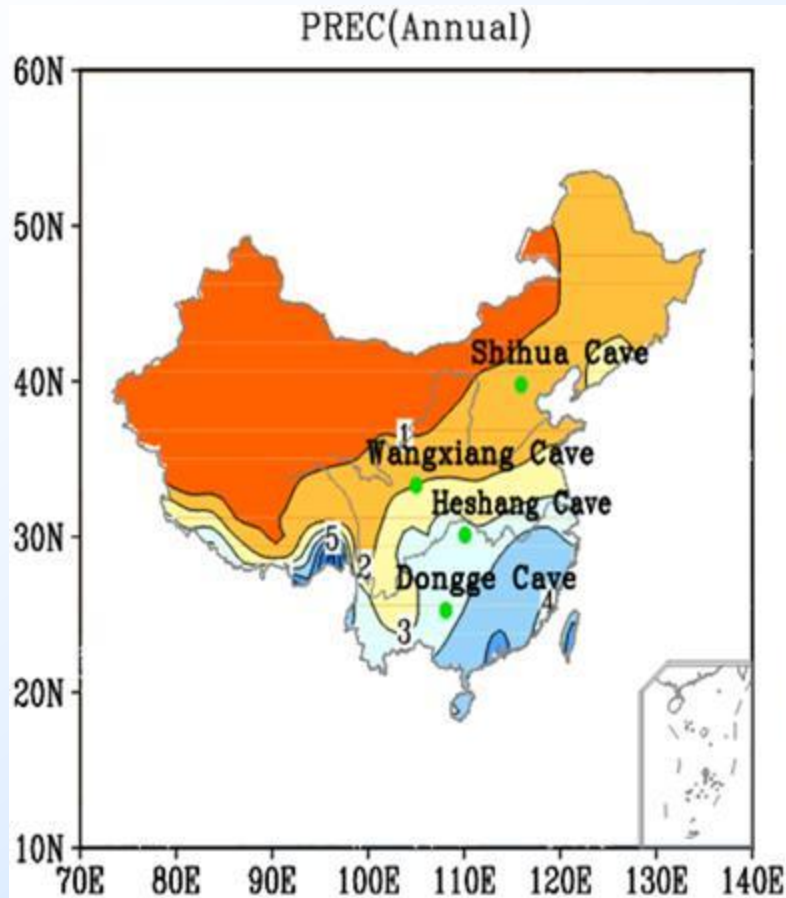
The strength of the response depends on latitude: The variation of the extratropical and subtropical rainfall also tends to follow the effective solar radiation forcing closely, but the tropical rainfall is insensitive to the effective solar radiation forcing.

The 21-year running mean time series of MJJA precipitation rate derived from the ERIK run (a, b, c) and the corresponding spectra (d, e, f) for the three sub-regions of the EAM: tropical (6-20°N, 100-120°E) (upper panels), subtropical (21-35°N, 100-120°E) (middle panels), and extratropical (36-50°N, 100-120°E) (lower panels). The statistical significance of the spectral peaks was tested against the red noise spectrum at 99%, 95% and 90% confidence level.



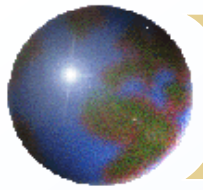


# Model-proxy comparison

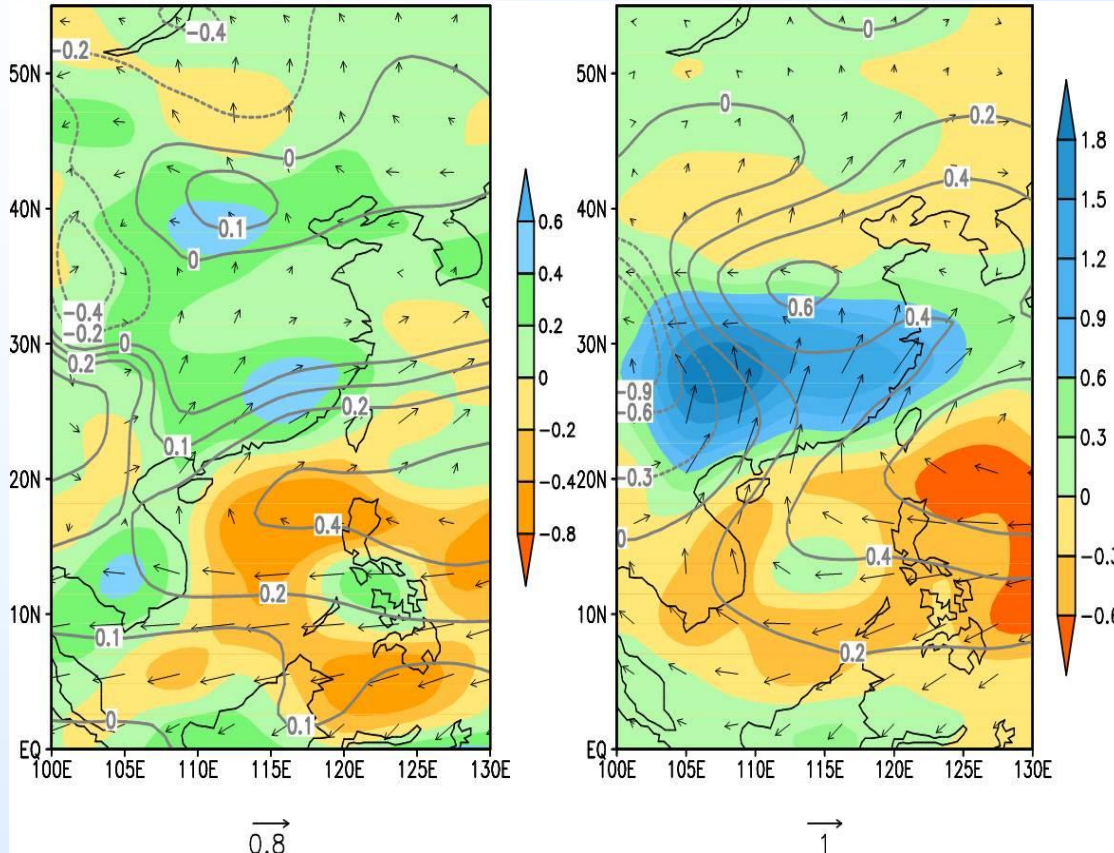


The proxy data in the extratropical EA reflect the EASM rainfall variations more sensitively.





# Variation of spatial structure

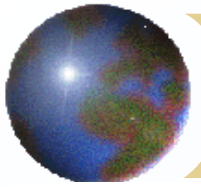


The subtropical and extratropical rainfall increases simultaneously on centennial-millennial timescale.

The centennial-millennial variation differs from the interannual variability that arises primarily from the internal feedback processes.

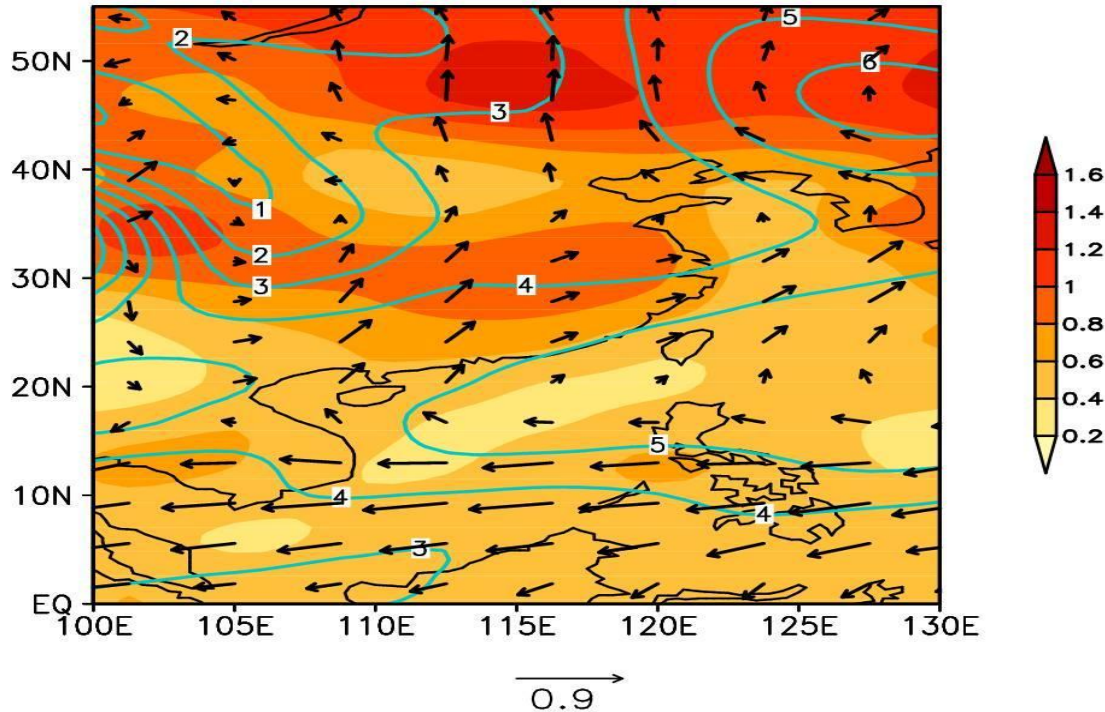
Comparison of the spatial structures of the forced and internal mode. The color shading represents the MJJA mean precipitation rate (mm day<sup>-1</sup>), contours denote the sea-level pressure (hPa), and arrows represent the 850 hPa winds (m/s).





# Mechanism

t2m & 850hPa ght & 850hPa wind



The differences between MWP and LIA (MWP minus LIA) in the MJJA mean surface air temperature (shading in unit of K), 850hPa geopotential height (solid contours in unit of m) and 850 hPa wind (vector in unit of m/s).

The effective solar radiation forcing increases



The surface air temperature in the mid-latitude continent increases more rapidly than over the adjacent ocean

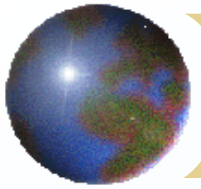


The land-ocean differential warming amplifies the pressure gradient between the land and ocean



Southwesterly is enhanced and EASM is intensified





# Outline-GM and EASM



**Motivation**



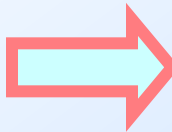
**Scientific Questions**



**Model and validation**

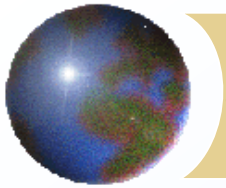


**Results**



**Conclusion**

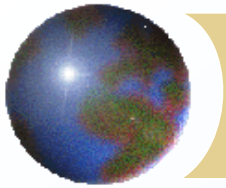




# Conclusion-GM

- ✦ The model results indicate that the centennial-millennial variation of the GM and EASM is essentially a forced response to the external radiative forcings
- ✦ Weak GM precipitation was simulated during the LIA (1450-1850) with three minima around the Spörer Minimum (1460), Maunder Minimum (1685), and Dalton Minimum (1800) periods of solar activity. Strong GM during the MWP (ca. 1030-1240).
- ✦ The GMI has pronounced bi-centennial and centennial variations. There is also a 70-80 year spectral peak.
- ✦ Before the industrial period, the effective solar radiative forcing reinforce the thermal contrasts between the ocean and continent resulting in the centennial- millennium variation in the GM.
- ✦ The prominent upward trend in GM precipitation occurring in the last 30 years (1961-1990) appear unprecedented and owed possibly in part to the increase of atmospheric carbon dioxide concentration.





# Conclusion-EAM

- ❖ **The centennial-millennial variation of the EAM is essentially a forced response to the external radiative forcing. The strength of the response depends on latitude.**
- ❖ **The spatial structure of the centennial-millennial variation differs from the interannual variability that arises primarily from the internal feedback processes within the climate system.**
- ❖ **When the effective solar radiation forcing increases, the surface air temperature in the mid-latitude continent increases more rapidly than over the adjacent ocean. The land-ocean differential warming amplifies the pressure gradient between the land and ocean, enhancing southwesterly and increasing monsoon.**
- ❖ **The proxy data in the extratropical EA reflect the EAM rainfall variations more sensitively.**



***Thank you!***

