Emergence of seasonal delay of tropical rainfall during 1979-2019

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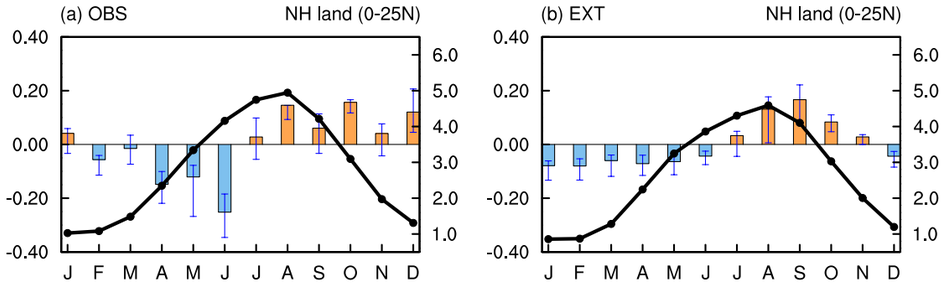
- **Motivation**

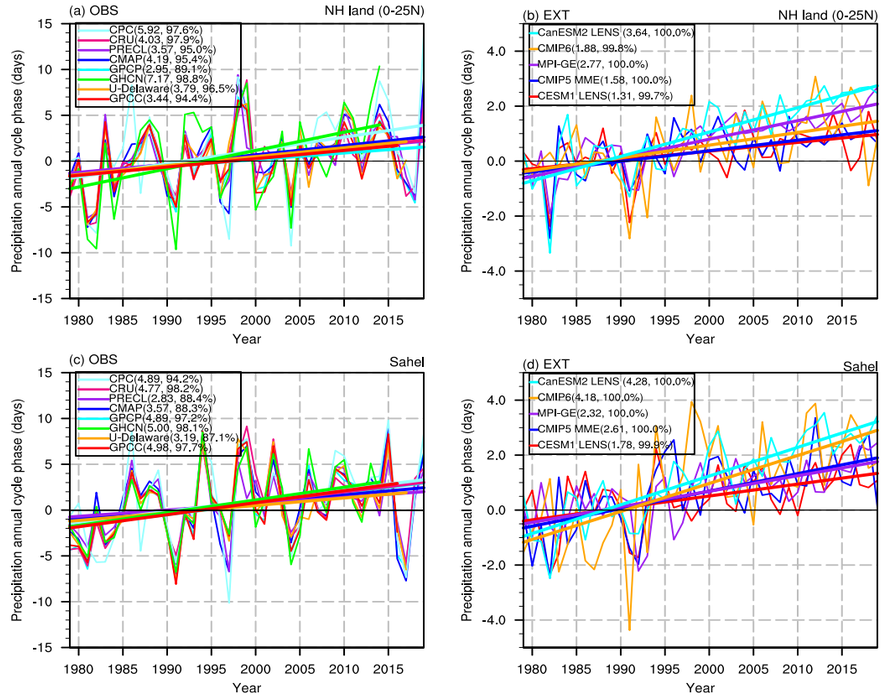
Two robust responses of tropical rainfall annual cycle under warming with simple and solid theoretical supports:

- **Enhanced amplitude over ocean:** $\Delta(\boldsymbol{P-E}) \approx \boldsymbol{\alpha \Delta T_s (P-E)}$ (Held and Soden 2006 JC)
- **Delayed phase over land:** $\Delta \frac{\partial <L_v q>}{\partial t} \approx \boldsymbol{\alpha \Delta T_s} \frac{\partial T_s}{\partial t}$ (Song et al. 2018 NCC; Song et al. 2020 GRL)

We ask: **Whether these signals have already emerged in the observation**

- Held, I. M., and B. J. Soden, 2006: Robust Responses of the Hydrological Cycle to Global Warming. *J. Climate*, 19, 5686–5699.
- Song, F., Leung, L. R., Lu, J. & Dong L. 2018: Seasonally dependent responses of subtropical highs and tropical rainfall to anthropogenic warming. *Nature Climate Change* 8, 787–792.
- Song, F., J. Lu, L.R. Leung, F. Liu, 2020: Contrasting phase changes of precipitation annual cycle between land and ocean under global warming, *Geophysical Research Letters*, in press. DOI:10.1029/2020GL090327.





The phase changes during 1979-2019

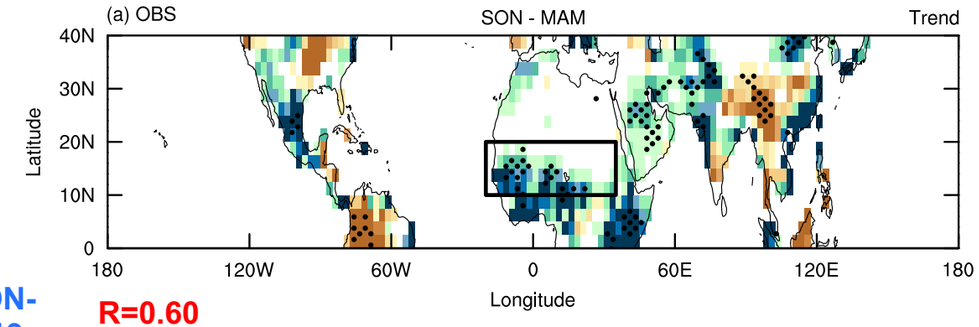
	0-25N land	Sahel
OBS	4.14±1.11	4.19±0.94
EXT	2.23	3.03
GHG	1.19 (1.47)	0.45 (0.49)
AER	1.01 (0.98)	1.45 (1.97)
NAT	0.24 (0.33)	0.39 (0.64)

OBS: GPCP, CMAP, PRECL, CPC and CRU (GHCN, GPCC and U-Delaware are also shown but not used for the calculation of trend)

EXT: 37 CMIP5 models, 16 CMIP6 models, 40 CESM1 LENS, 100 MPI-GE, 50 CanESM2 LENS

CMIP6 (46)
CMIP6 (46) + CESM1 LENS (20) + CanESM2 LENS (50)

Linear trends of pr (SON-MAM) during 1979-2019



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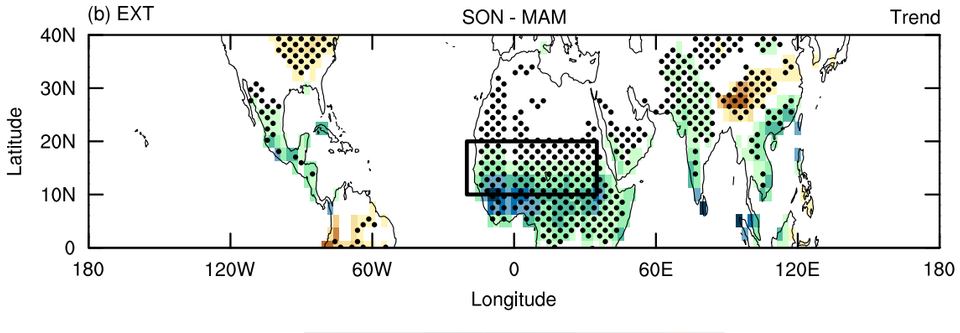
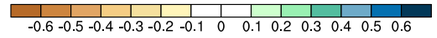
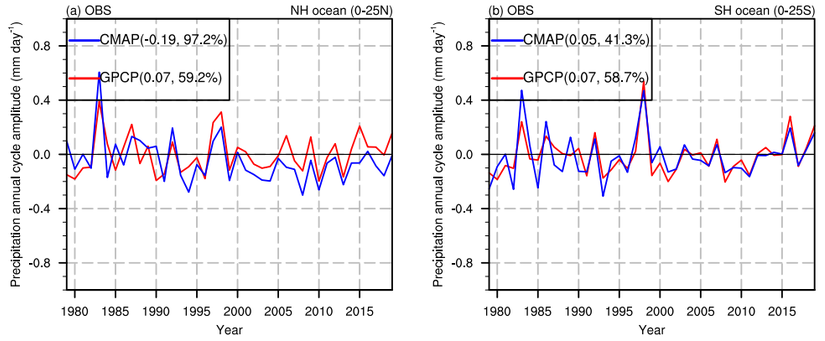
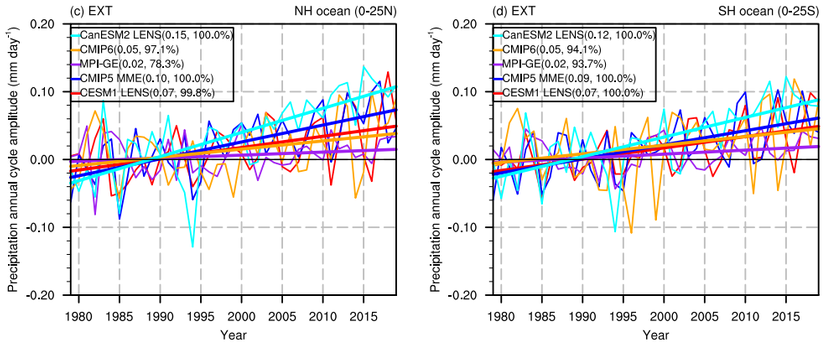




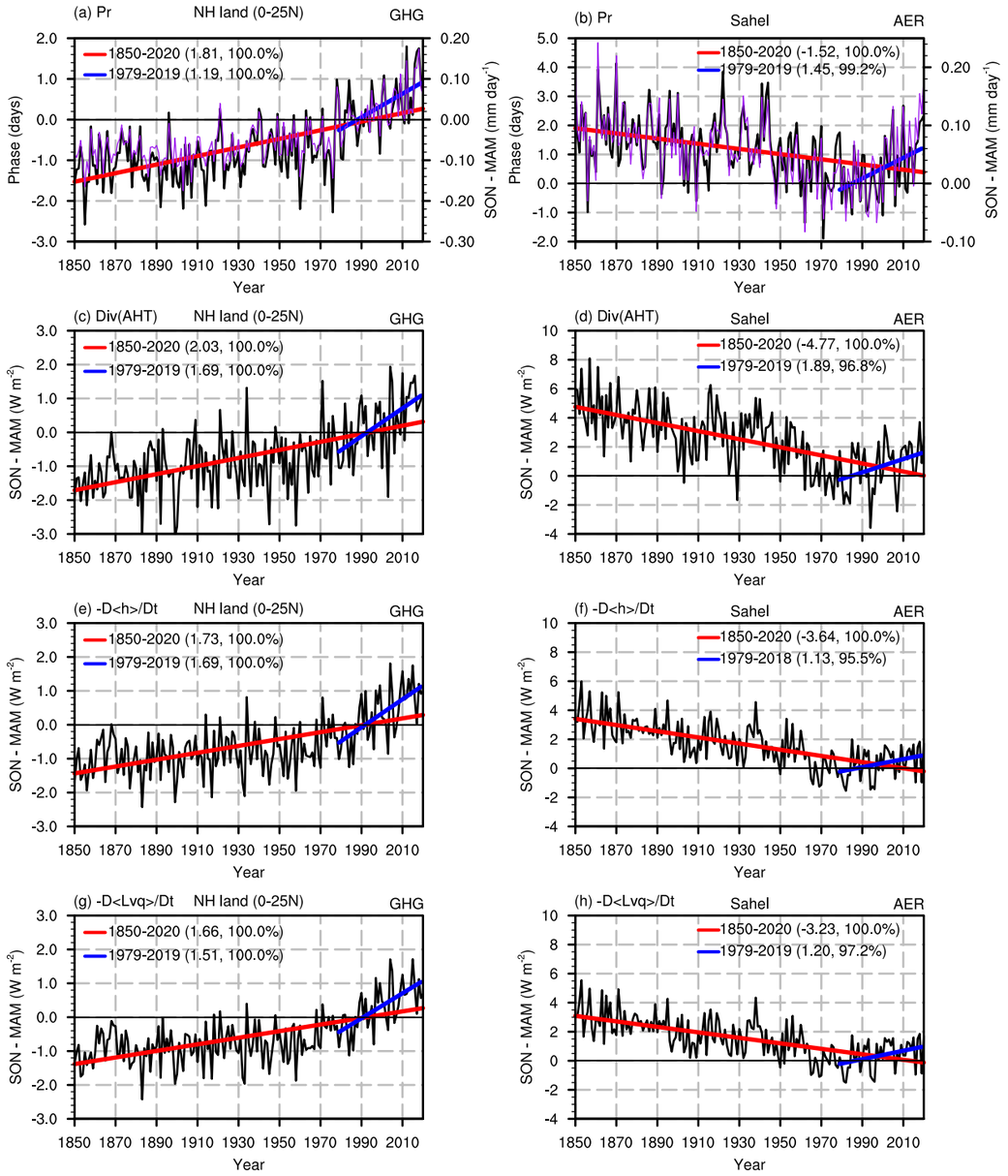
Land phase delay has emerged

Ocean amplitude enhancement has not emerged





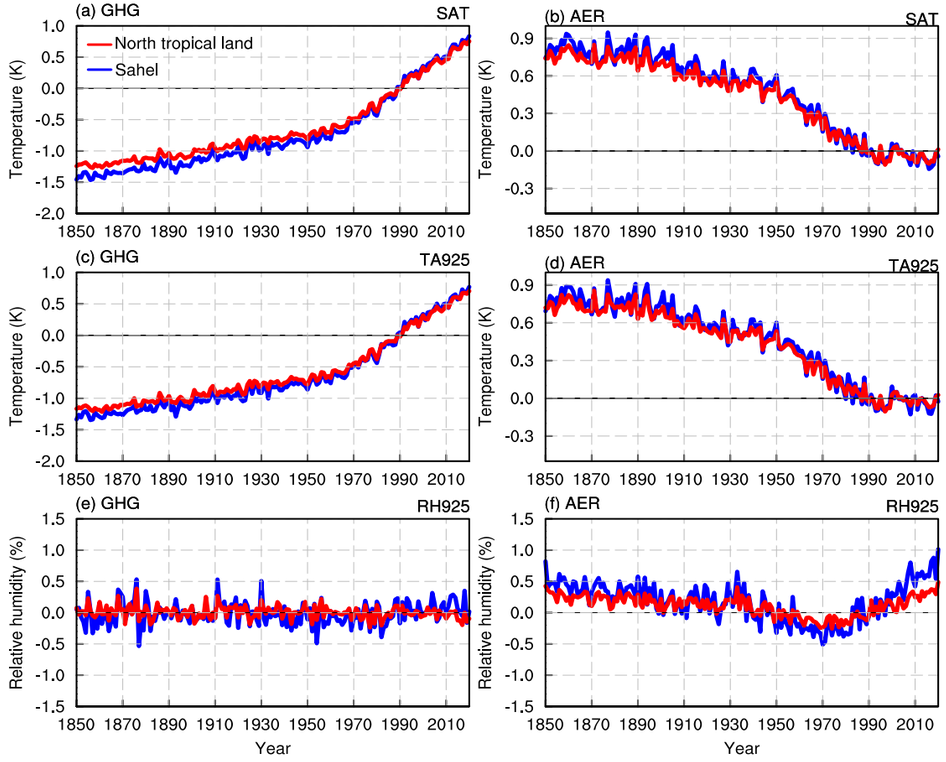
The satellite era (1979-2019) sees accelerated GHG emission and air pollution control in Europe and North America since 1980s and China since 2000s.



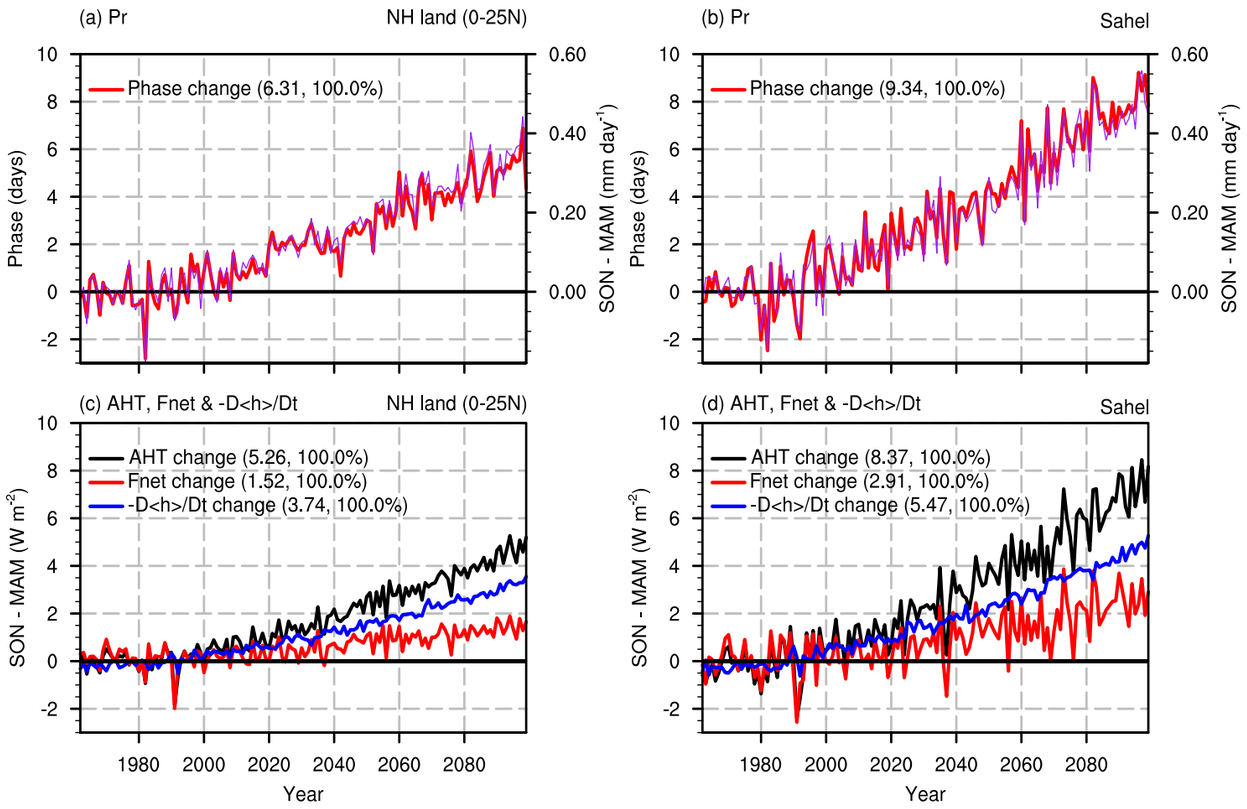
$$\Pr \sim \nabla \cdot AHT = F_{net} - \frac{\partial <h>}{\partial t}$$

When relative humidity is fixed, $\Delta \frac{\partial q}{\partial t} \approx a \Delta T \frac{\partial T}{\partial t}$ GHG

When temperature is fixed, $\Delta \frac{\partial q}{\partial t} = b \Delta r \frac{\partial T}{\partial t}$ AER



What we expect in the future and what we need to do



- **3-5 years:** Understand why GHG changes the effective atmospheric heat capacity C_A through changing the temperature while AER changes the C_A mainly through the relative humidity in the recent decades.

- **5-10 years:** Understand the seasonal delay asymmetry between northern and southern tropical land