Subtropical Stationary Waves connecting Hydrological Extremes to Climate Warming in Boreal Summer

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Abstract

Inland hydrological extremes (droughts and extreme rainfall events) can cause enormous economic loss and threaten lives. Subtropical stationary waves may act as an important bridge connecting regional hydrological extremes with global warming. Here, we investigate the past and future responses of SWA to increasing climate forcing using 31 CMIP5 GCMs. Twenty-three out of 31 models display a consistent increase in climatological-mean SWA in response to warming. The comparison of half-century trends between preindustrial control (PiControl), historical, and RCP8.5 simulations indicates that the amplitude of stationary waves is likely to intensify in a warming climate, and a positive SWA trend is at least partially driven by increasing external forcing. Then we investigate the interannual relationship between SWA and hydrological-extreme frequency. Regression of interannual variability in hydrological-extreme frequency on SWA suggest that high SWA is related to increased heavy-rainfall day frequency over south Asia, the Indochinese Peninsula, and southern China (SA-EA), and to increased dry-spell-day frequency over the northwestern and central United States (NUS) and southern United States and Mexico (SUS-MEX). These relationships are intensified from historical to RCP8.5. The projected amplification of SWA, combined with intensification of the relationships between SWA and frequency of hydrological extremes, may partially explain projected increases in number of dry-spells over NUS and SUSMEX and in frequency of heavy-rainfall days over SA-EA.

Motivation

In the Northern Hemisphere summer, the subtropical stationary waves are portrayed by subtropical highs over North Pacific and North Atlantic, and monsoon lows over Eurasia and North America (Fig.1(a)). Using observational data, Yuan et al (2015) found that the subtropical stationary waves have amplified by 0.4/decade in the period 1979-2013 (Fig.1b). Our key questions are:

1. In comprehensive GCMs, by how much does the amplitude of summer subtropical stationary waves increase in response to forcing?
2. How do hydrological extremes relate to stationary waves, and how does this relationship change in response to forcing?
3. How do changes in stationary waves and the relationship between stationary waves and hydrological extremes contribute to projected changes in the number of hydrological extremes in a warming climate?

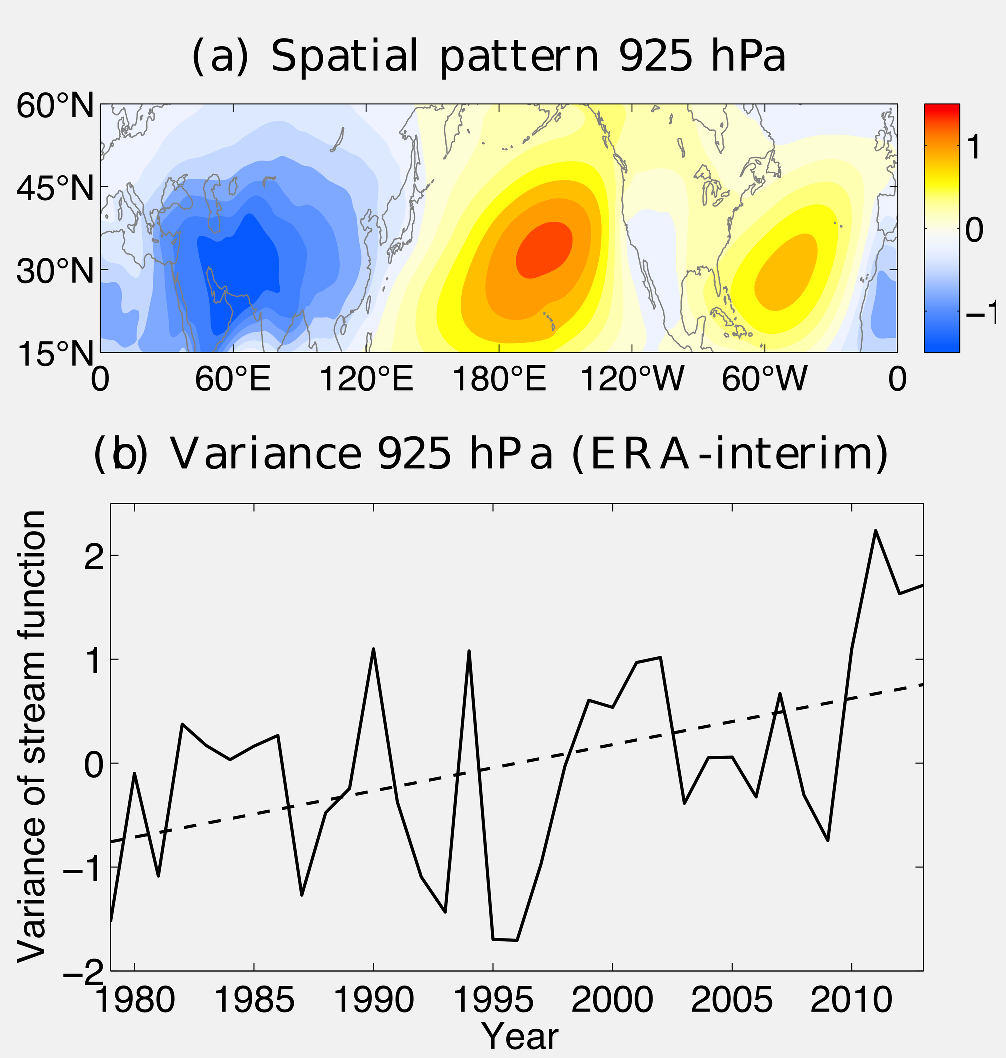

Fig. 1: (a) Climatology of eddy stream function at 925 hPa in JJA during 1979-2013 (units: $10^7 m^2 s^{-1}$) in ERA-interim reanalysis data. (b) Normalized variance of eddy stream function at 30°N in JJA at 925 hPa (Yuan et al. 2015)

Stationary wave amplitude (SWA)

$$SWA = \frac{1}{n}\sum_{i=1}^{n}(\psi_i - \bar{\psi})^2 \quad (1)$$

where ψ_i is the streamfunction along the latitude 30N at 925 hPa, $\bar{\psi}$ is the zonal mean streamfunction.

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Response of SWA to anthropogenic forcing

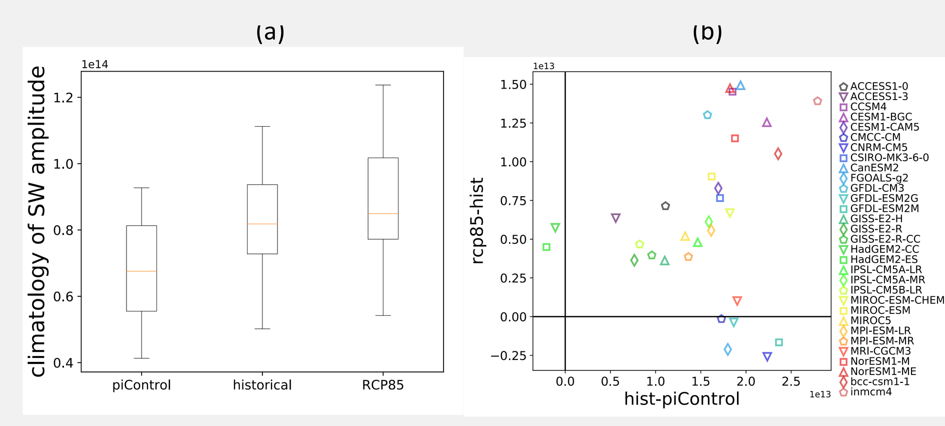

Fig. 2: (a) 31-model ensemble of 50-year climatological SWA in piControl, historical and RCP8.5 scenarios. Red lines 50%, boxes 25%-75%, caps 5%-95%. (b) Difference of climatological SWA between RCP8.5 and historical against that between historical and piControl.

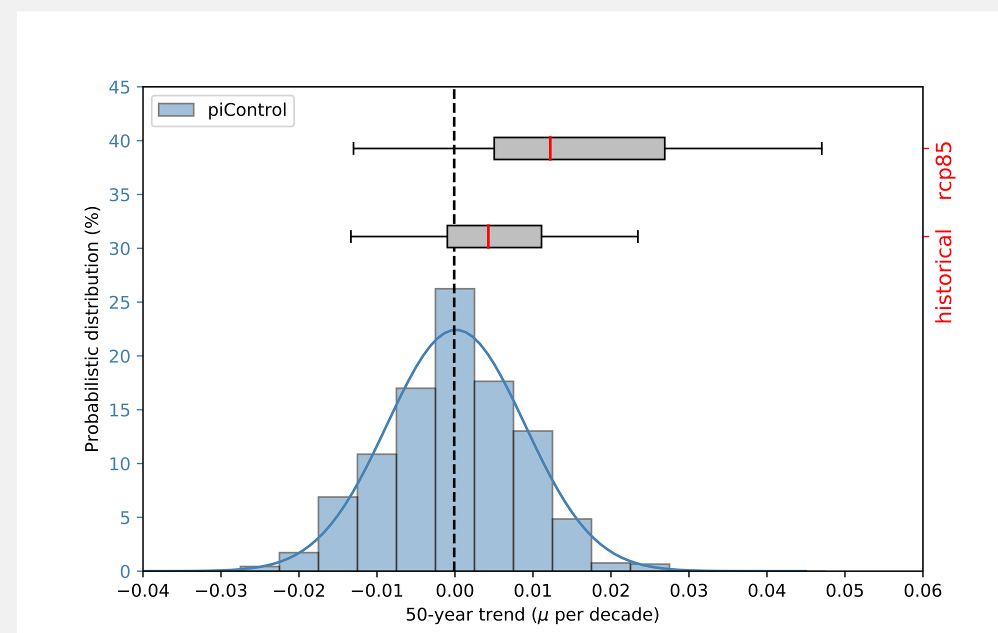

Fig. 3: Probabilistic distribution of the 50-yr trend of stationary wave amplitudes in the PiControl scenario obtained by the bootstrapping method (blue histogram).Boxplots show the intermodel spread of the linear trend of stationary wave amplitudes during the last 50 years of the historical and RCP8.5 scenarios.

Circulation changes related to SWA

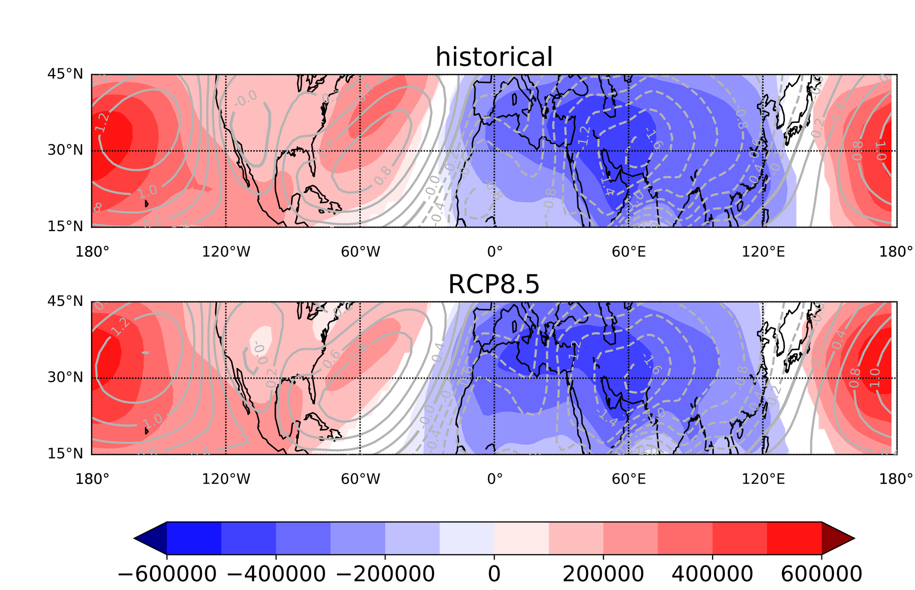

Fig. 4: The 20-model ensemble mean of climatological eddy streamfunction (contours) and regression coefficient of eddy streamfunction on SWA (shadings) in the last 50 years of (top) historical and (bottom) RCP8.5 simulations ($10^7 m^2 s^{-1}$).

Definition of hydrological extremes

- Heavy rainfall day: a day when the precipitation exceeds the 99th percentile of daily precipitation in JJA during the period 19552005.
- Dry-spell: an event of at least 3 consecutive days when daily precipitation is less than 1mm.

Relationship between SWA and hydrological extremes

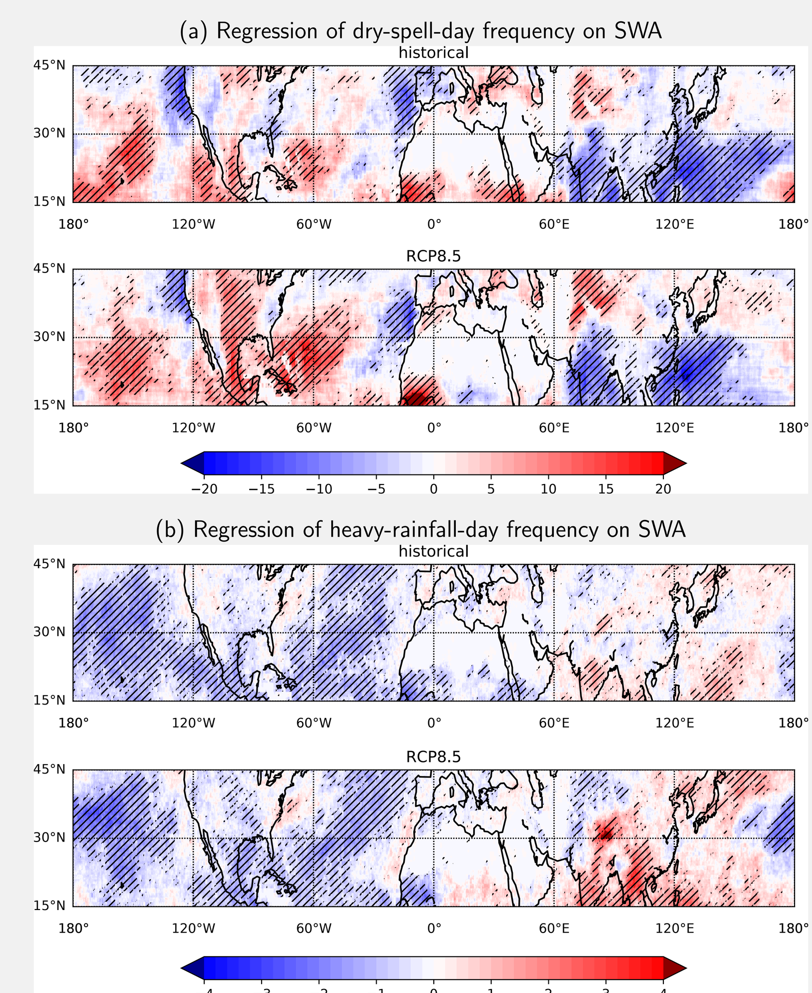

Fig. 5: Mean of multimodel ensemble regression coefficient (day μ^{-1}) between SWA and interannual variability in the number of (a) dry-spell days and (b) heavy-rainfall days in historical simulations in the upper panels and RCP8.5 simulations in the lower panels. Hatched areas denote values are significant at the $p < 0.1$ level by the StudentâĂŹs t test

Contribution on changes in hydrological extremes

Multiple linear regression of number of hydrological extremes on both the normalized SWA and global mean surface temperature (GMST) in JJA:

$$n_i(x,y) = R_{SWA}(x,y)NSWA_i + R_{GMST}(x,y)NGMST_i + \alpha + \epsilon_i \quad (2)$$

Changes in number of hydrological extremes predicted by changing SWA from historical to RCP8.5 but holding GMT unchanged:

$$\delta_{SWA}(x,y) = R_{SWA_RCP85}(x,y) \times (\overline{NSWA_{RCP85}} - \overline{NSWA_{hist}}) \quad (3)$$

Changes in number of hydrological extremes that are predicted by concurrent changes in R_{SWA} and SWA:

$$\begin{aligned}\delta n_{SWA\times R}(x,y) = R_{SWA_RCP85}(x,y) \times \overline{NSWA_{RCP85}} \\ - R_{SWA_hist}(x,y) \times \overline{NSWA_{hist}}\end{aligned} \quad (4)$$

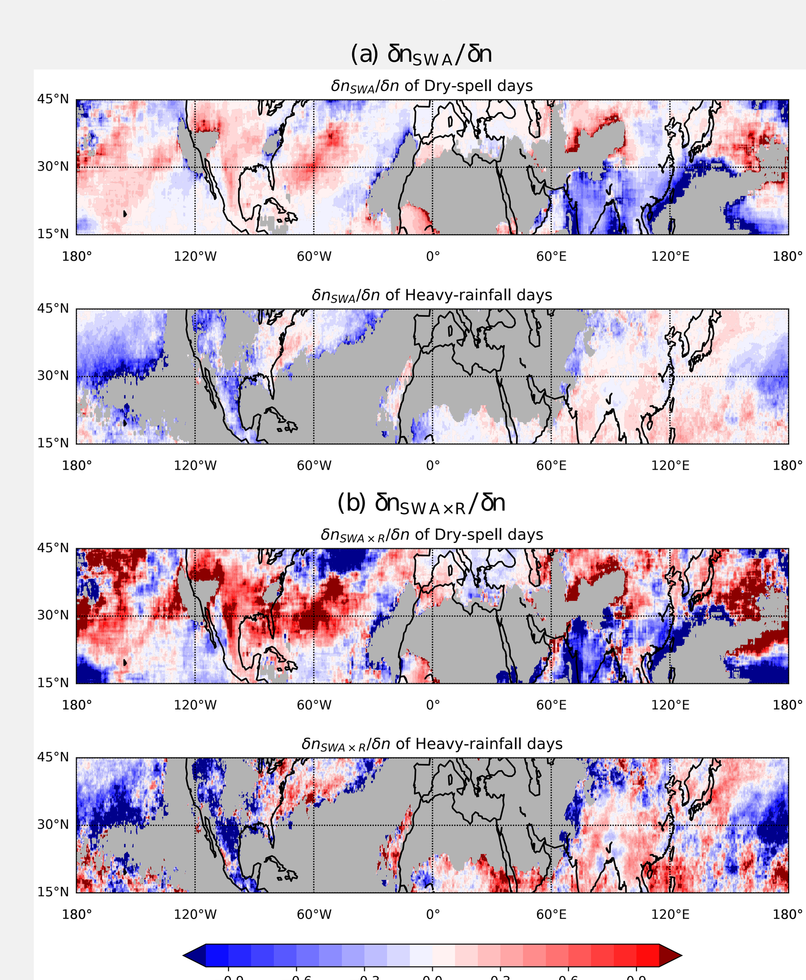

Fig. 6: Mean of multimodel ensemble regression coefficient (day μ^{-1}) between SWA and interannual variability in the number of (a) dry-spell days and (b) heavy-rainfall days in historical simulations in the upper panels and RCP8.5 simulations in the lower panels.

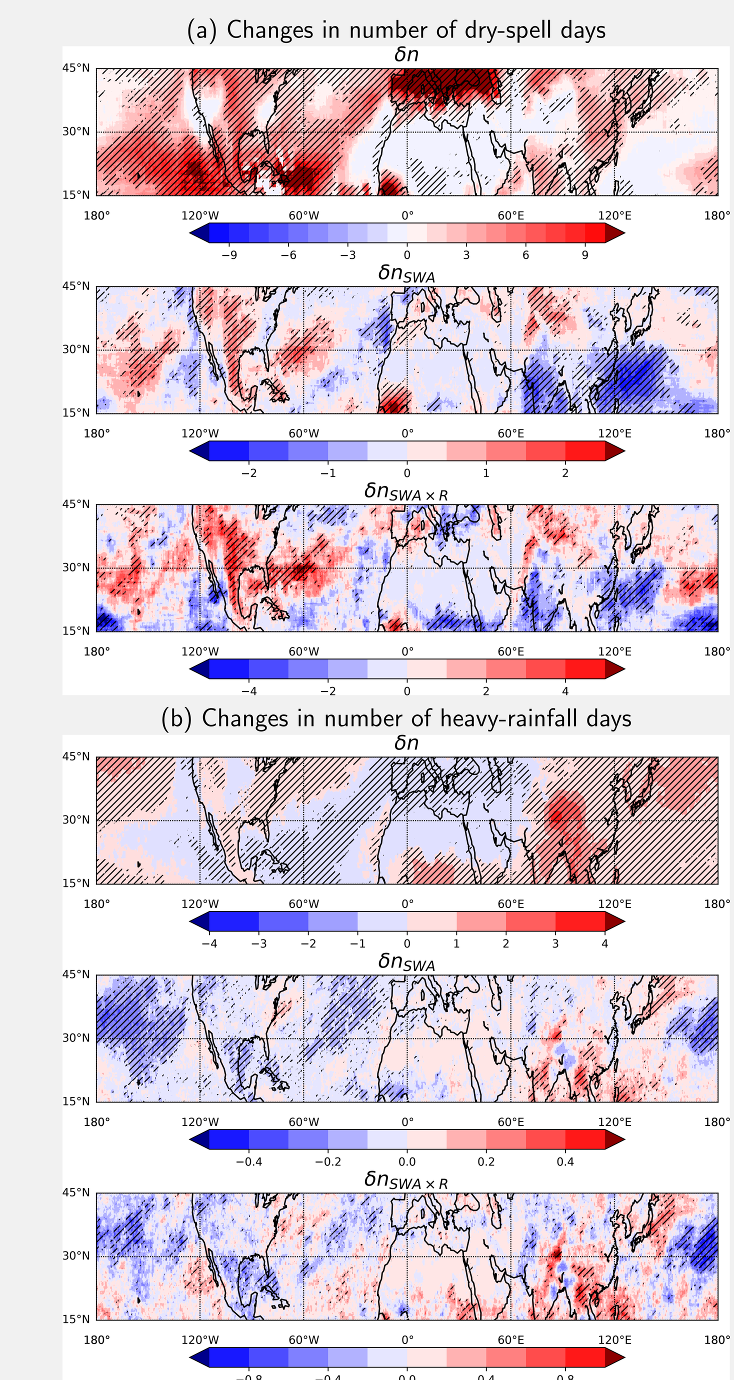

Fig. 7: Multimodel mean of changes in projected number of hydrological extremes (δn), changes in predicted number of hydrological extremes explained by changes in SWA alone (δn_{SWA}), and changes in predicted number of hydrological extremes explained by changes in both SWA and regression coefficient between SWA and hydrological extremes ($\delta n_{SWA\times R}$) from historical to RCP8.5 for (a) dry-spell days and (b) heavy-rainfall days (unit is days).

Conclusion

In conclusion, Our results suggest that

- The observed positive trend of SWA has been made more likely as a result of positive anthropogenic forcing.
- Positive SWA anomalies are related to the increased number of heavyrain-fall days and decreased frequency of dry-spell days over SA-EA, as well as the increased number of dryspell days over the NUS and SUSMEX.
- Positive amplitude anomalies of stationary waves relate to deepening of the Eurasian low and strengthening of the North Pacific high and the North Atlantic high, which could provide persistent local conditions that favor hydrological extremes over the aforementioned regions.
- The subtropical stationary waves can play an important role in explaining the projected increase in the number of heavy-rainfall days over SA-EA, and number of dry-spells over NUS and SUSMEX.

Reference

J. Yuan, W. Li and Y. Deng (2015): Amplified subtropical stationary waves in boreal summer and their implications on water extremes. Environ. Res. Lett., 10, 104009

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