# Summer Heatwaves in Present and Future Climate Simulated with Global Models Participating in CMIP6

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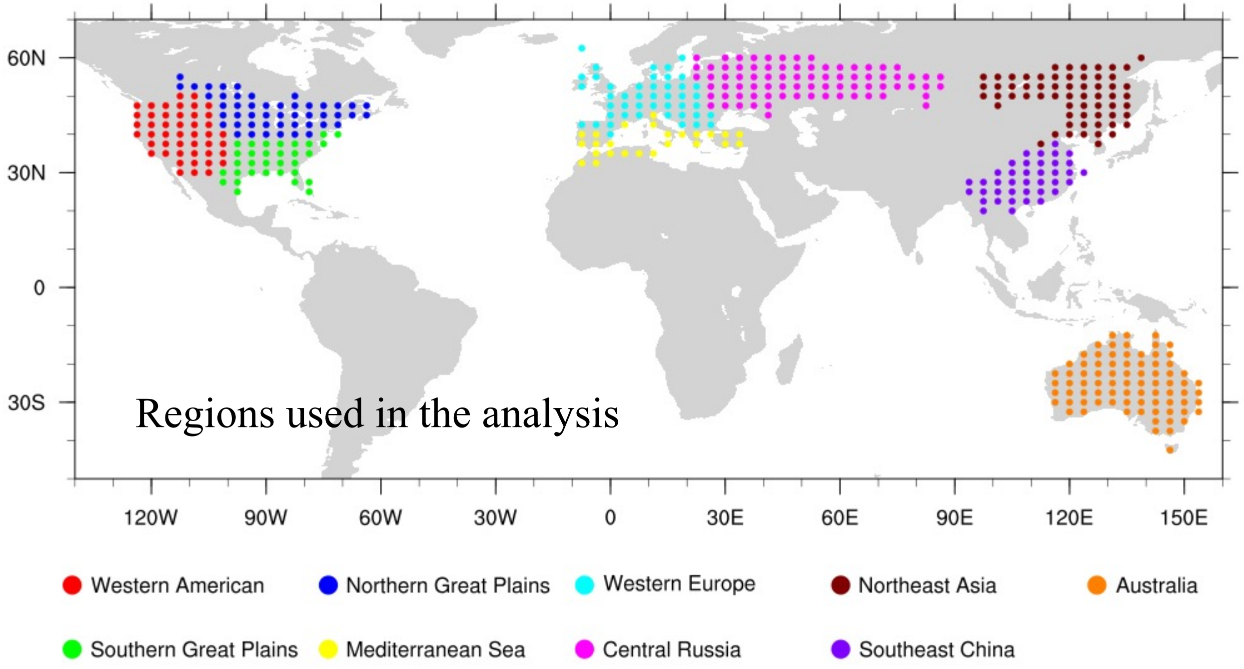
Heat waves lead to major impacts on human health, food production and ecosystems, and are projected to increase with climate change. This study evaluates global climate models participating in the Coupled Model Intercomparison Project phase 6 (CMIP6) for their performance in simulating the present climate characteristics of summer heat waves. The analysis exploits the available global datasets (reanalyses, satellite products, gridded in-situ observations) to assess the realism of variables impacting the energy and water balance at the surface during heatwave events. The role of the underlying processes affecting the occurrence and intensity of the heat waves characteristics in present and future climate is also investigated based on the multi-model analysis. A sensitivity study performed with the coupled atmospheric and land-surface modules of the IPSL climate model helps to support the multi-model analysis. A robust impact of the soil moisture on the dispersion of the heat-wave characteristics is diagnosed. For 2 models it is possible to analyse the moist heat waves whose intensity and frequency is dramatically increased with respect to the dry heat waves at the end of the 21th century.

# DATA

## Observation

| | Resolution | Variable | Period |
|---|---|---|---|
| Hadley Centre Global Historical Climatology Network–Daily data (HadGHCND) | 2.5*3.75° spatial<br>Daily temporal | T2max/T2min | 1979-2014 |
| ESA CCI Surface Soil Moisture COMBINED Product (fv04.5) | 0.25 ° spatial<br>Daily temporal | Soil Moisture (SM) | 1979-2014 |
| Global Land Evaporation Amsterdam Model (GLEAM) | 0.25 ° spatial<br>Daily temporal | Evaporation (E) | 1980-2014 |
| ERA5 | 0.25 ° spatial<br>Hourly temporal | T2m/RH | 1979-2014 |




## Models

- Near surface daily maximum temperature (T2max), minimum temperature (T2min) and related physical variables of CMIP6
- Atmospheric Model Intercomparison (AMIP) simulations are used for the evaluation of heatwave (HW) characteristics in present climate
- SSP5-8.5 simulations and historical simulations are used for HWs changes in future climate projections

# Heatwave Definition and Indices

A period of at least 3 consecutive hot days in summer, which is June, July and August in the Northern Hemisphere, whereas December, January and February in the Southern Hemisphere.

A hot day refers to the daily T2max exceeding the local 90th percentile of the control period (1979–2014). The 90th percentile is calculated for each calendar day, each model and at each grid point using a centred 15-day-long time window to account for the seasonal cycle.

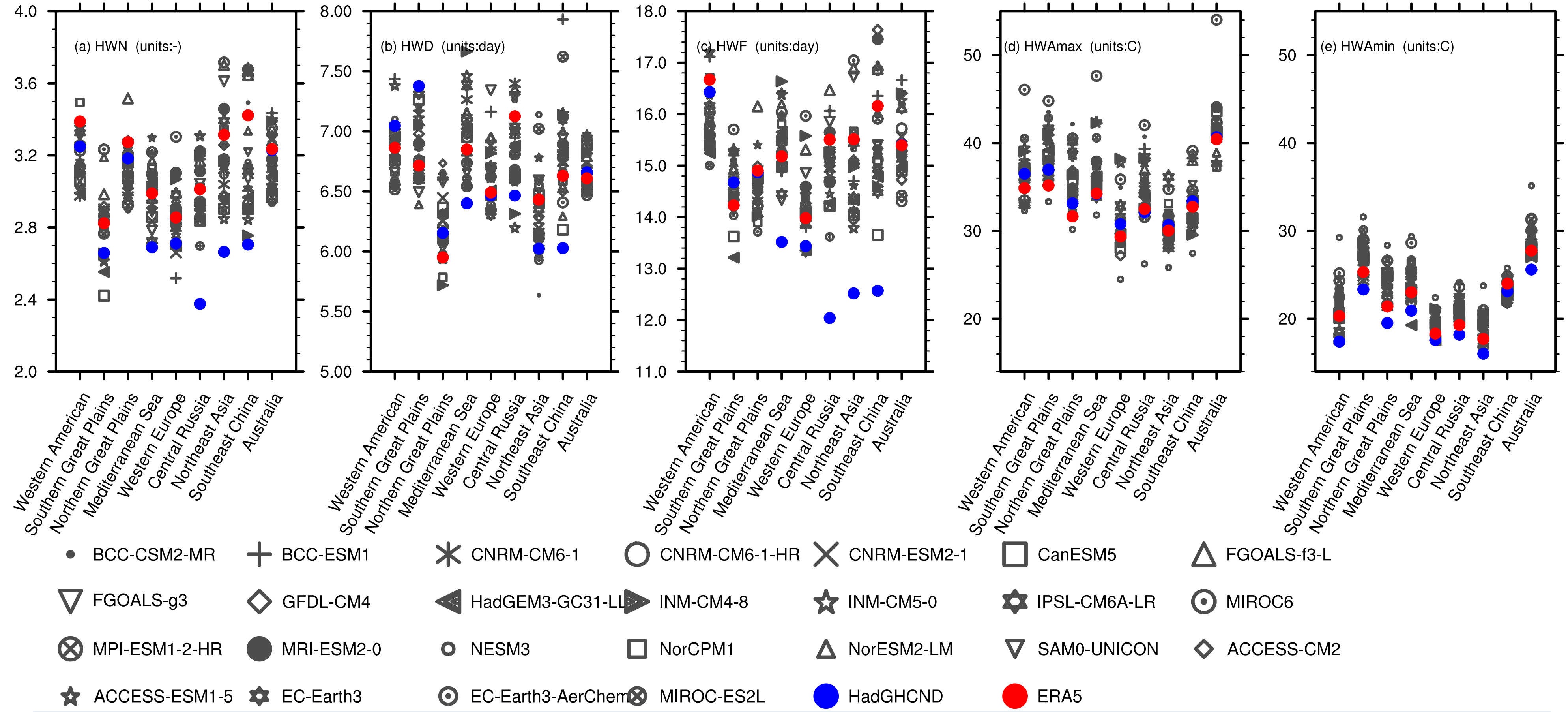
The aspect of HW is mainly represented by frequency, duration and amplitude, four indices are constructed to measure diverse aspects of HWs as following:

(1) HW number (HWN): the number of HW occurrences in one summer.
(2) HW duration (HWD): the duration of the longest event in one summer.
(3) HW day frequency (HWF): the number of participating HW days in one summer.
(4) HW amplitude (HWA): the amplitude of HW, calculated as the hottest day of the hottest summer event for T2max and T2min.

Perkins, S. E., and L. V. Alexander. 2013. "On the Measurement of Heat Waves." *Journal of Climate* 26 (13): 4500–4517.
Fischer, E. M., and C. Schär. 2010. "Consistent Geographical Patterns of Changes in High-Impact European Heatwaves." *Nature Geoscience* 3 (6): 398–403

# Realism of summer heatwaves simulated with AMIP

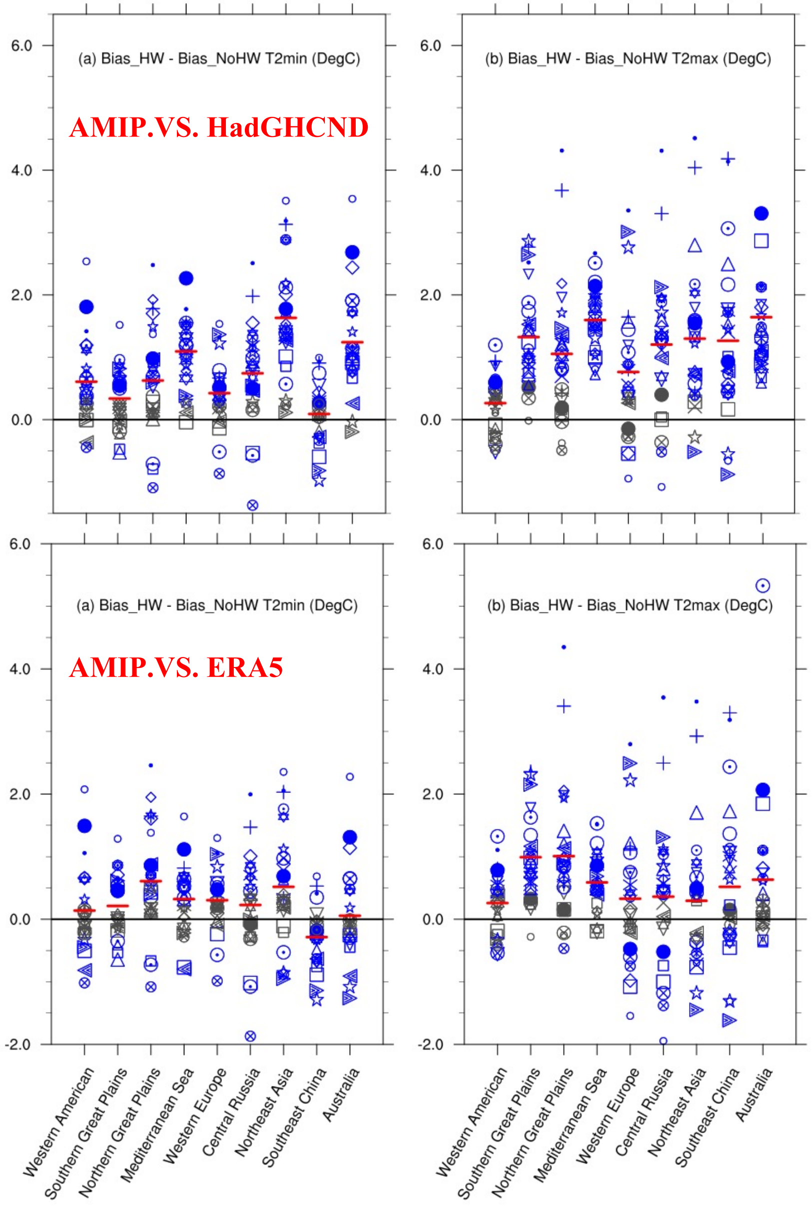
- **AMIP simulated higher HWN and HWF respect to HadGHCND observation over the Central Russia, Northeast Asia and Southeast China.**
- **Vast majority of models over-estimate significantly HWA for T2max and T2min (except over Southeast China).**
- **Relatively coarse resolution of the HadGHCND data set would lead to oversmoothed values and underestimation of extremes (Gross et al. 2018).**




HW indices in AMIP simulations, HadGHCND observation and ERA5 reanalysis data during 1979-2014 (36 years average) for 9 regions (x axis).

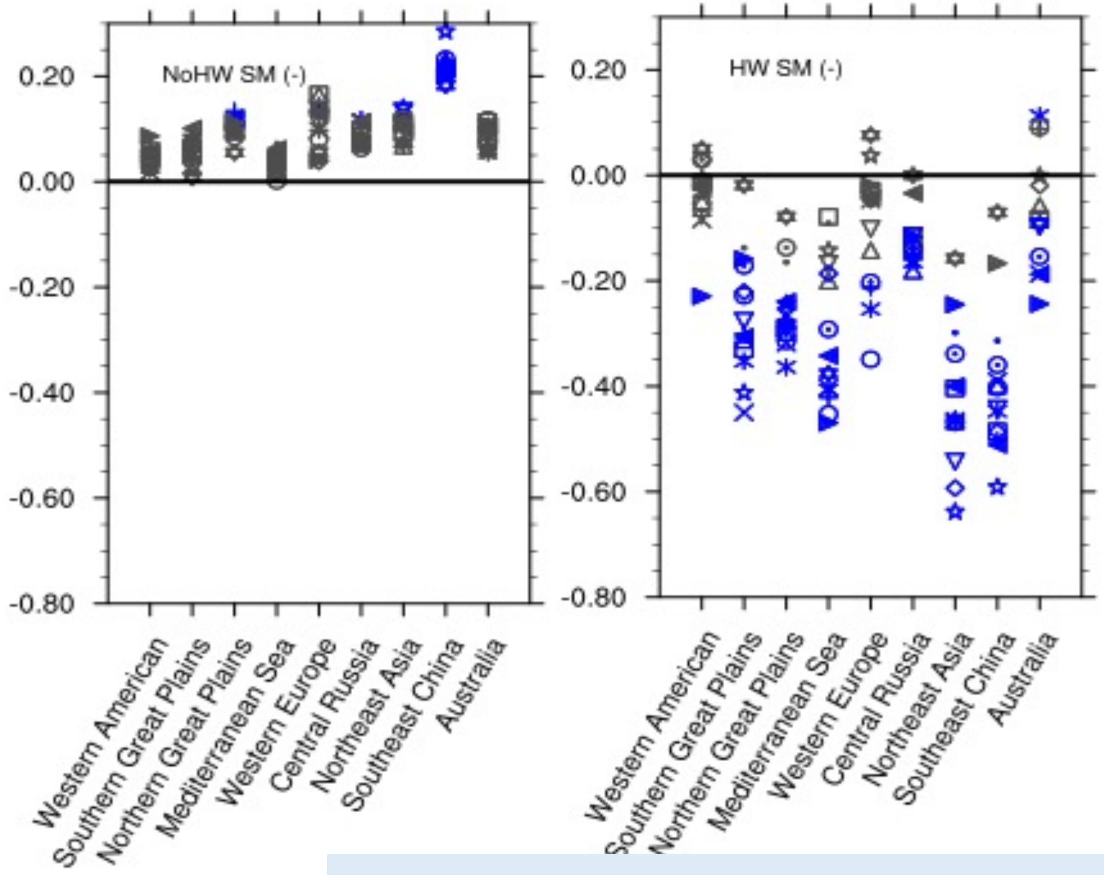

Gross, Mia H., Markus G. Donat, Lisa V. Alexander, and Scott A. Sisson. 2018. “The Sensitivity of Daily Temperature Variability and Extremes to Dataset Choice.” *Journal of Climate* 31 (4): 1337–59.

# Realism of summer heatwaves simulated with AMIP




Bias difference between HW days and not HW days

**The stronger warm (or weaker cold) biases of T2max during the HW days in present climate can be explained by stronger under-estimated SM.**



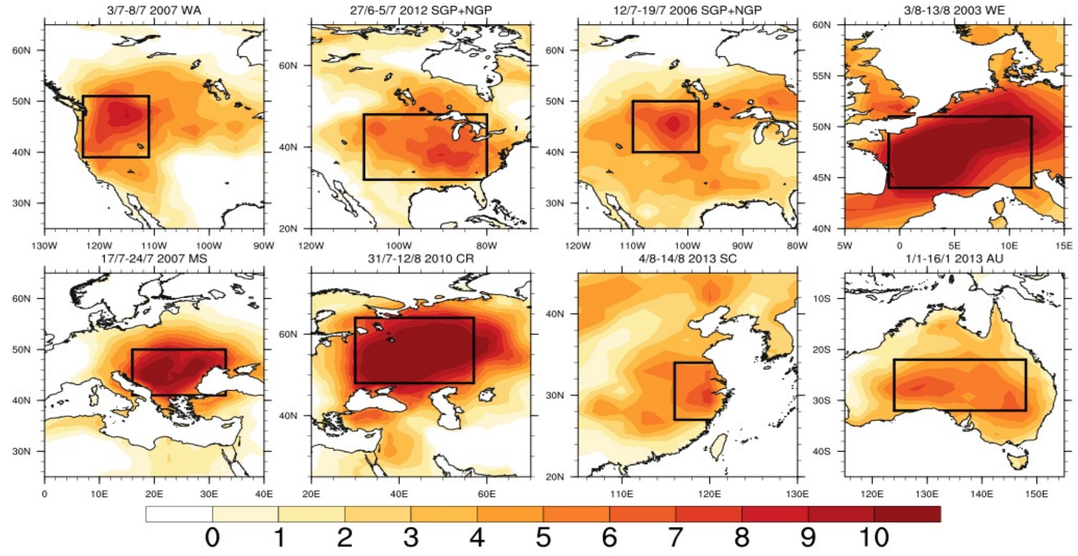

Biases of standard SM(-) for HW days and not HW days

OBS: ESA CCI Surface Soil Moisture COMBINED Product

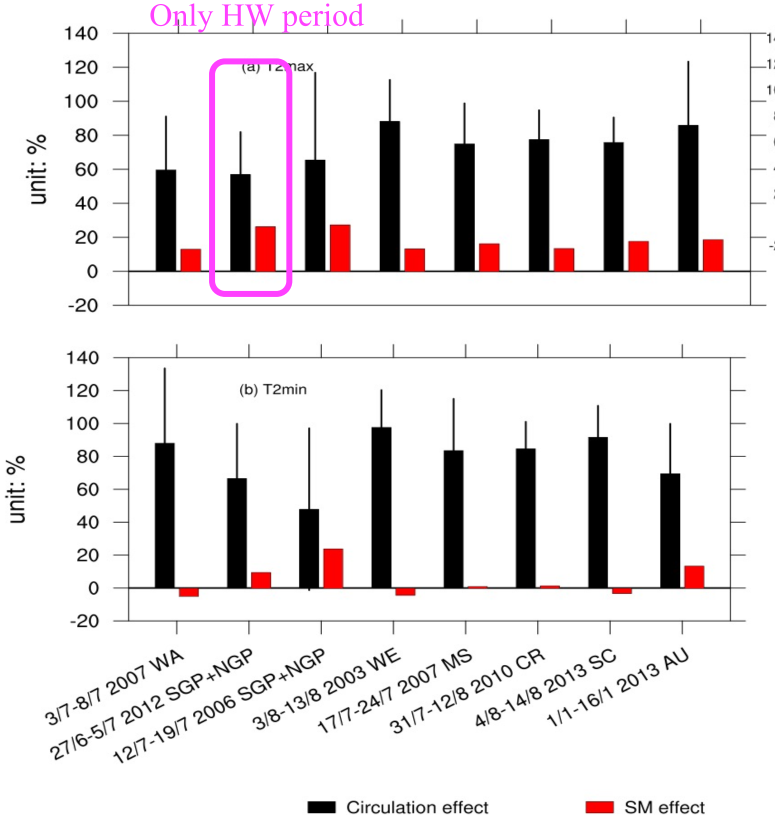
# Sensitivity experiments to the atmosphere circulation and to the superficial soil moisture

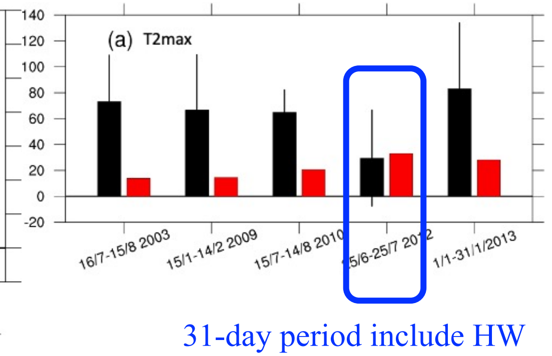
- **The circulation is always the major driver for the HW's analyzed.**
- **HW characteristics are modulated by the level of dryness of the soil during the HW.**

| | Ensemble | Atmosphere | Soil moisture |
|---|---|---|---|
| **atmF_smF** | 21 | Free | Free |
| **atmN_smNclm** | 1 | Nudging | Nudging by climatology of the daily pseudo-observations |
| **atmN_smN** | 1 | Nudging | Nudging by the daily pseudo-observations |




Spatial distribution of 8 HW events period averaged T2max anomaly (°C) in ERA5. The anomaly is respect to the 1983-2002 climatology



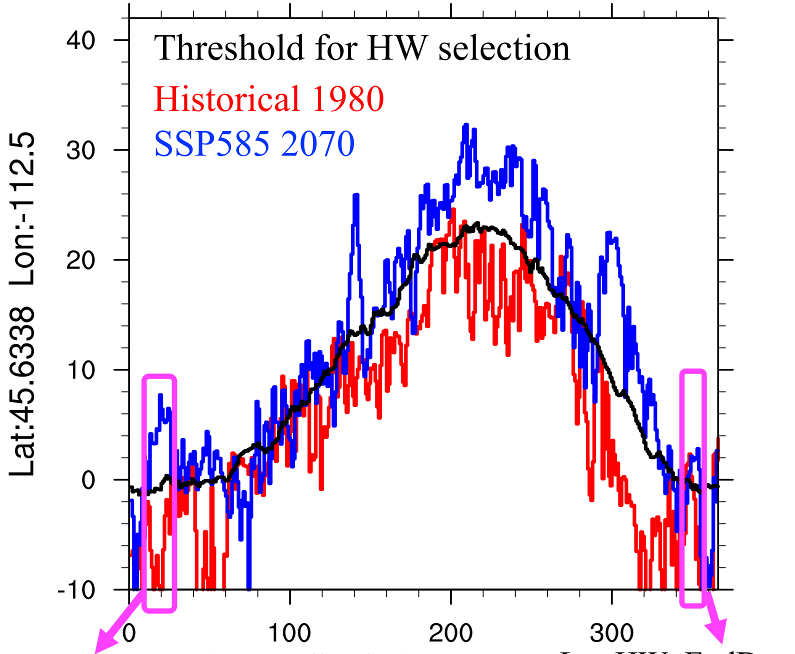

Wehrli, Kathrin, Benoit P. Guillod, Mathias Hauser, Matthieu Leclair, and Sonia I Seneviratne. 2019. "Identifying Key Driving Processes of Major Recent Heat Waves." *Journal of Geophysical Research: Atmospheres*.

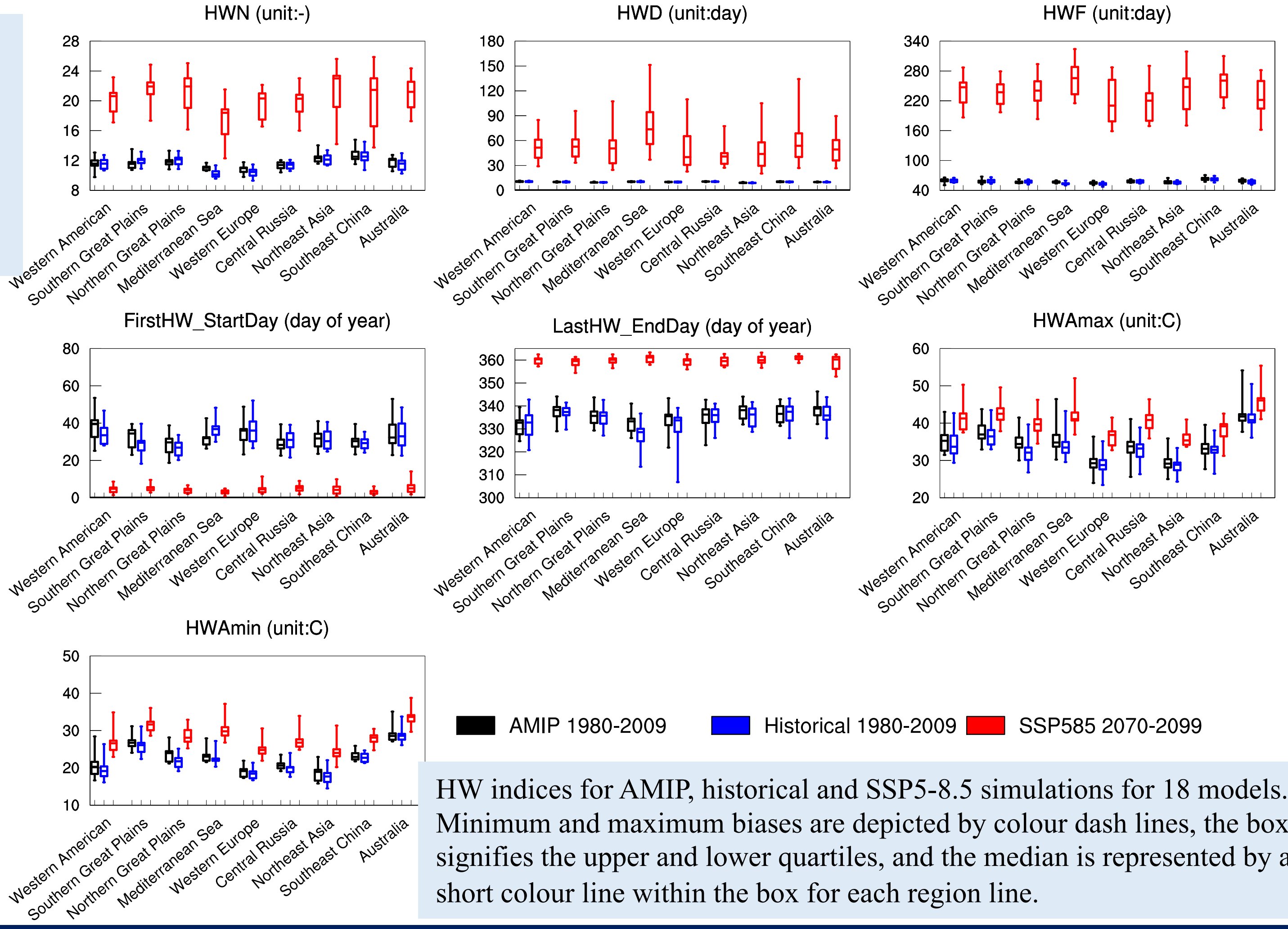
The black bar is the atmospheric circulation effect without induced SM effects ((atmN_smNclm - atmF_smF)/ atmN_smN)with the standard deviation of 21 ensemble atmF_smF simulations.
The red bar is the SM effect given the observed circulation ((atmN_smN - atmN_smNclm)/ atmN_smN)

# Heatwaves in Future Climate Projections (SSP5-85)

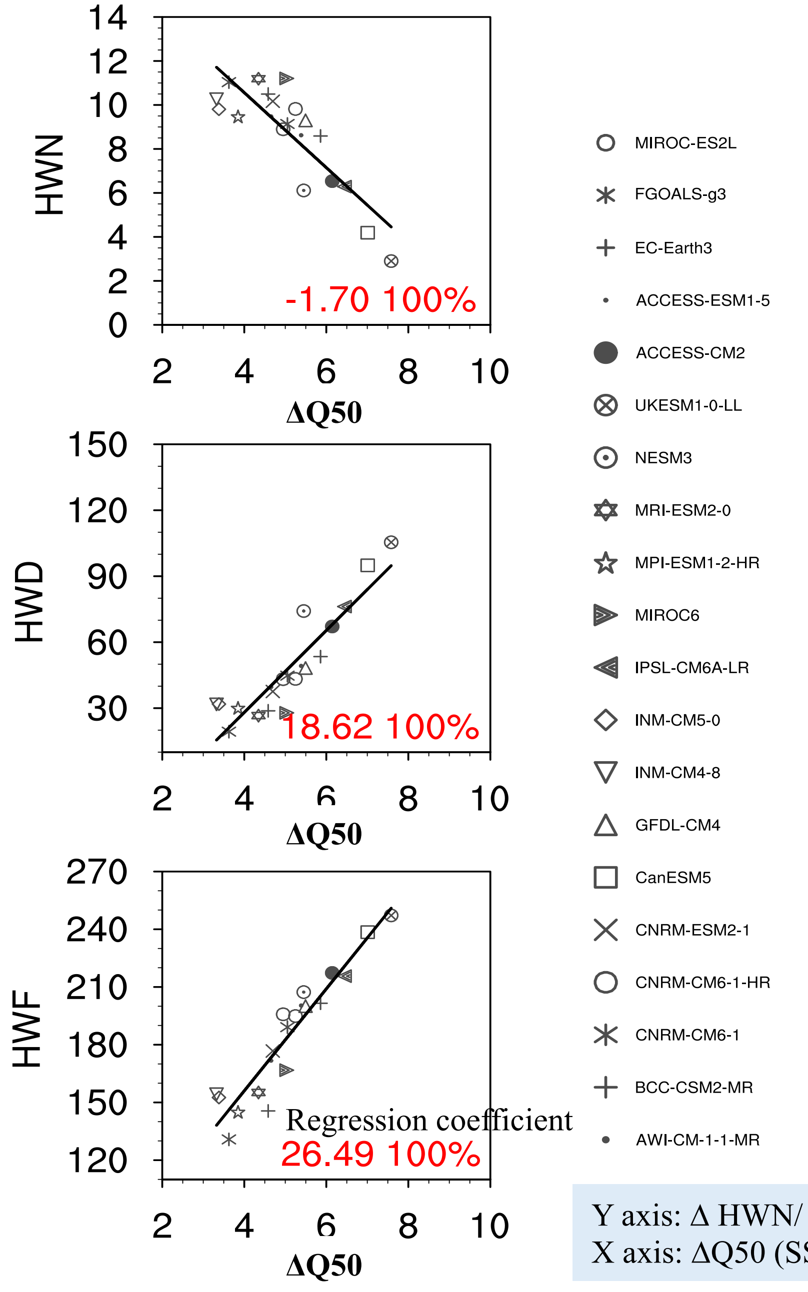
- **HWN, HWD and HWF will increase in the future climate (slight regional differences).**
- **HW can start earlier ( up to in January) and end later (up to December) (these dates probably depends on the natural variability, to be explored).**
- **All models show more than 2C increase for both HWA_t2max and HWA_t2min.**
- **The spread of the HW characteristics amongst 20 models is larger in the projections than in the historical simulations (HWN, HWD and HWF ).**

HW: at least 3 consecutive hot days. A hot day refers to the daily T2max exceeding the local 90th percentile of the control period (1979–2014).
Since the longest heatwave duration of SSP5-8.5 simulations could larger than 90 days, so heat waves are diagnosed at the yearly scale for future climate projections.

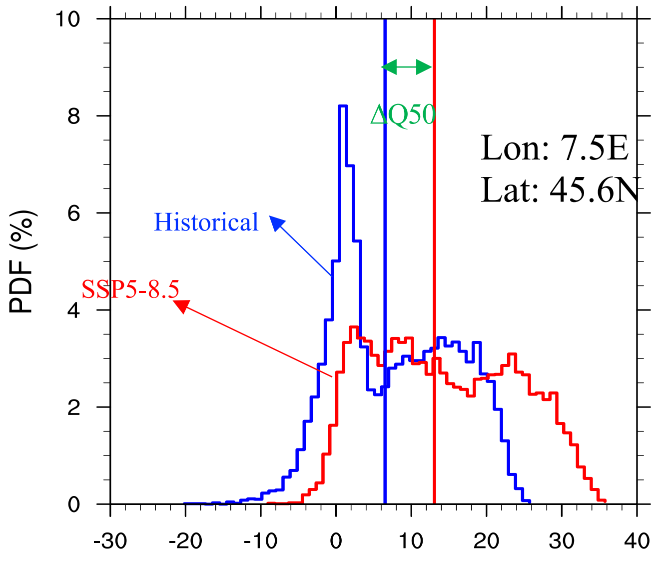



HW indices for AMIP, historical and SSP5-8.5 simulations for 18 models. Minimum and maximum biases are depicted by colour dash lines, the box signifies the upper and lower quartiles, and the median is represented by a short colour line within the box for each region line.




- **As the mean annual temperature increases (ΔQ50), HWD and HWF increases but HWN increases less rapidly.**
- **ΔQ50 is used as an indicator for the shift of the pdf, which is related to the climate sensitivity. Uncertainties of the climate sensitivity can be responsible for the larger models' dispersion for HWN, HWD and HWF in SSP5-8.5 simulations.**

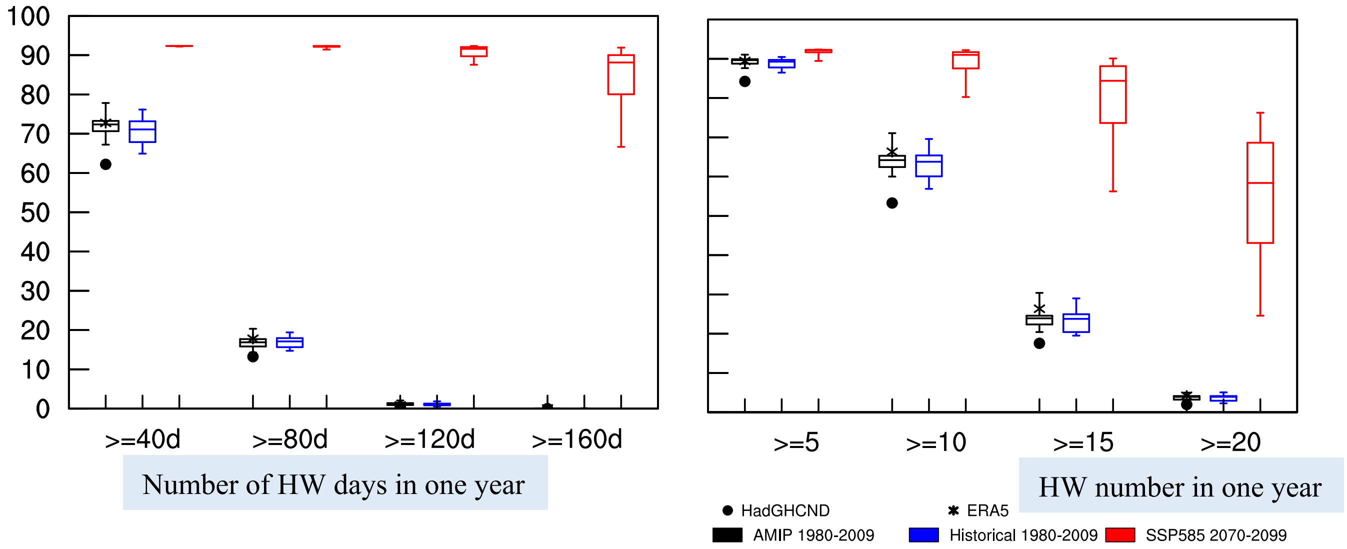



Schoetter, Robert, Julien Cattiaux, and Hervé Douville. 2015. "Changes of Western European Heat Wave Characteristics Projected by the CMIP5 Ensemble." Climate Dynamics 45 (5–6): 1601–16. https://doi.org/10.1007/s00382-014-2434-8.
Argüeso, Daniel, Alejandro Di Luca, Sarah E. Perkins-Kirkpatrick, and Jason P. Evans. 2016. "Seasonal Mean Temperature Changes Control Future Heat Waves." *Geophysical Research Letters*.

Y axis: Δ HWN/ Δ HWD/ Δ HWF (SSP585-Historical)
X axis: ΔQ50 (SSP585-Historical)

# Heatwaves in Future Climate Projections (SSP5-85)

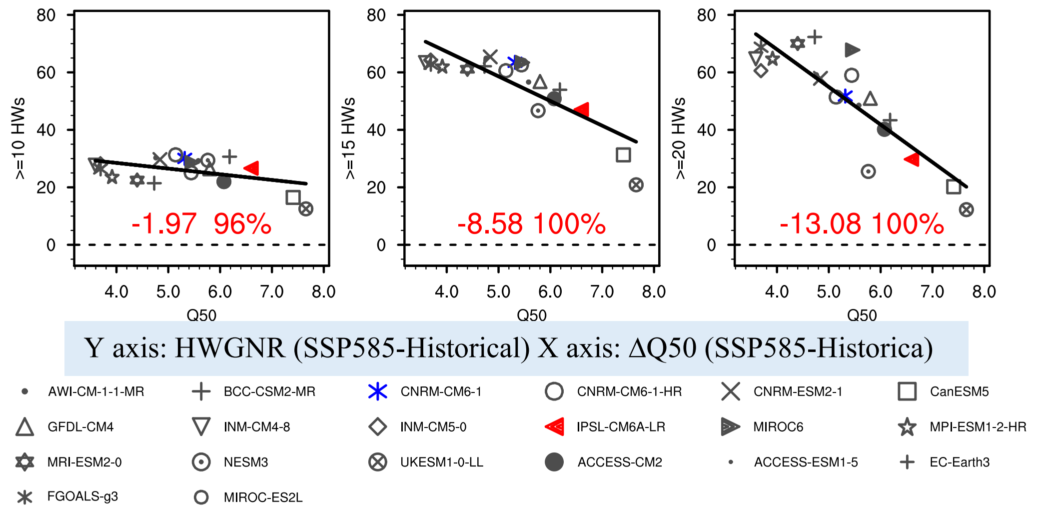
- **On the continental scale : larger areas will be exposed to more frequent HW in future.**
- **The spread amongst of the model is large and is related to the climate sensitivity.**

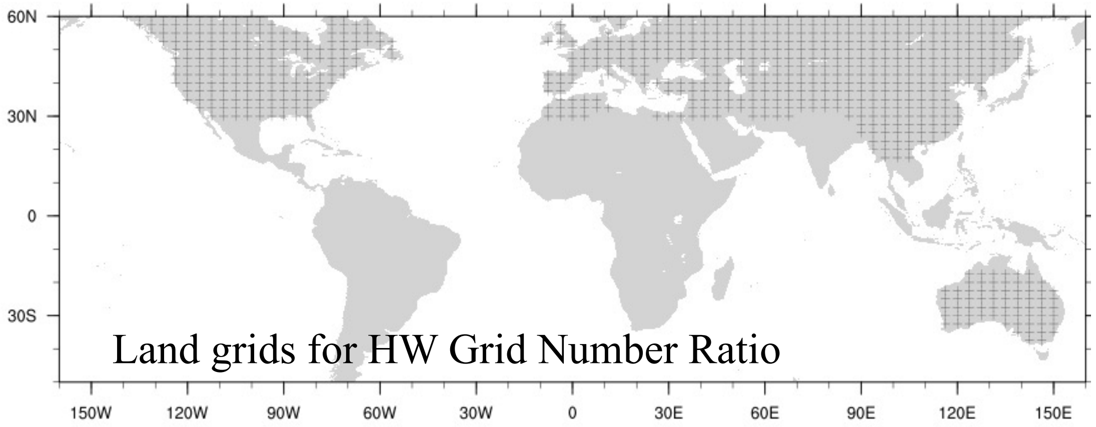



HW Grid Number Ratio (Y axis) for different HWN and HWF levels (X axis)

$$“>=5” : \frac{\textit{Number of grid points with at least 5 HWs}}{\textit{All grids number}} * 100\%$$

HW: A period of at least 3 consecutive hot days. A hot day refers to the daily T2max exceeding the local 90th percentile of the control period (1979–2014). The 90th percentile is calculated for each calendar day, each model and at each grid point.

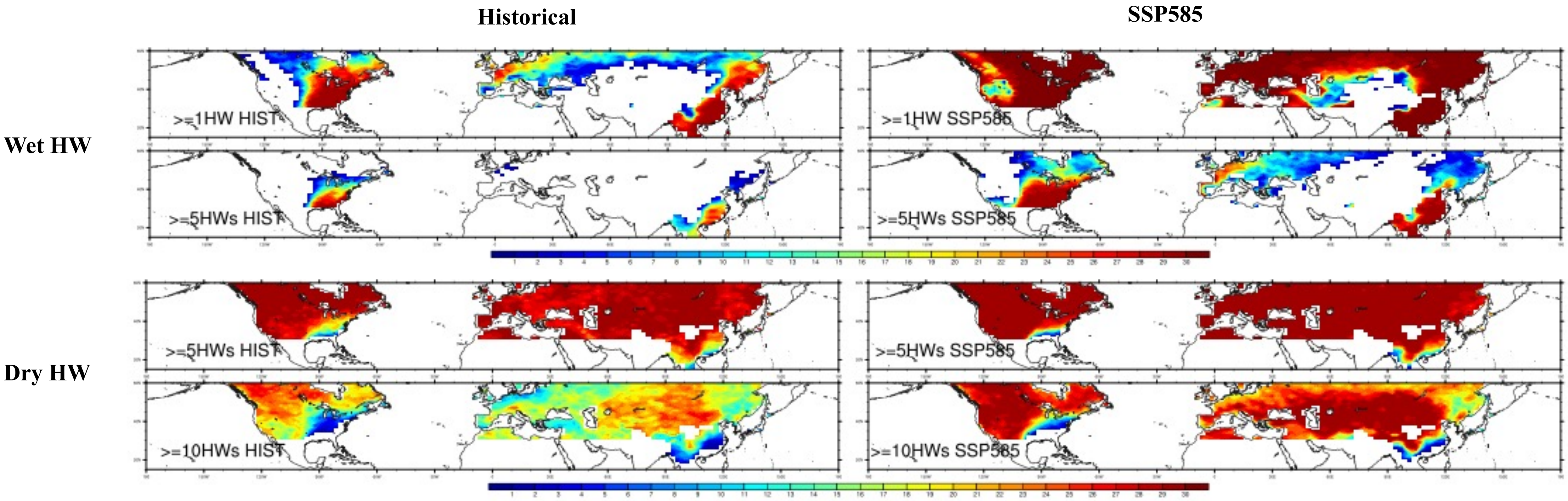


# Heatwaves in Future Climate Projections (SSP5-85)

## Continental change in the annual occurrence of HW

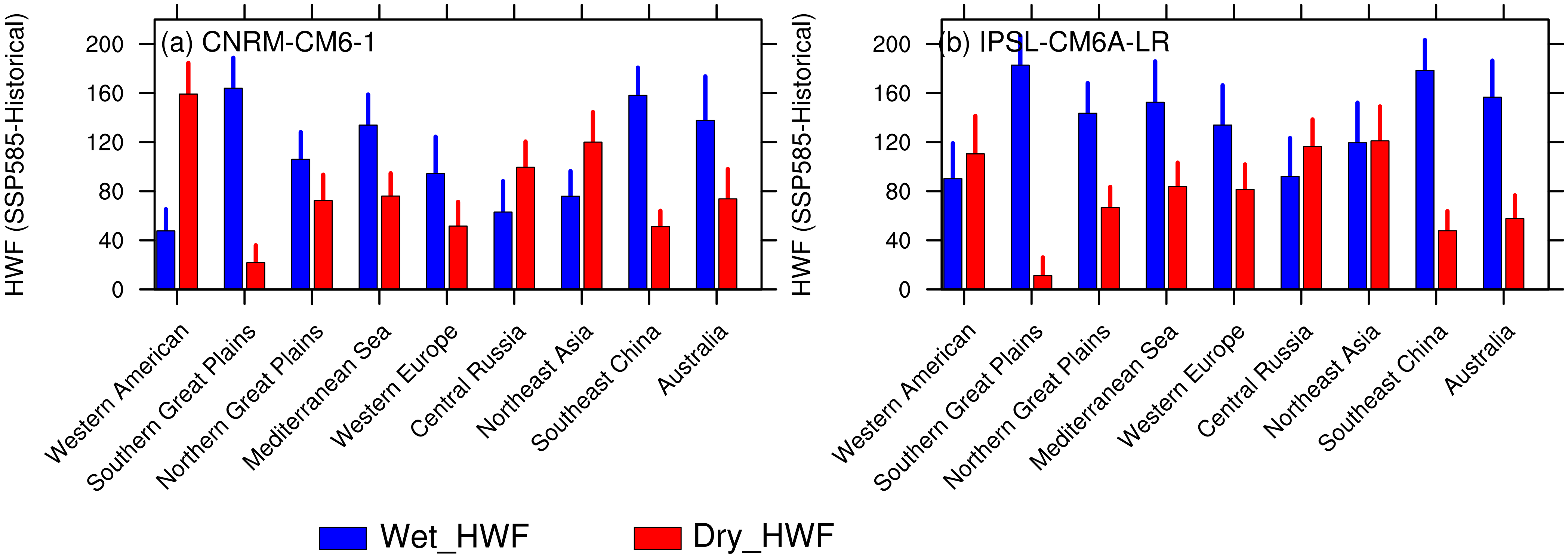
- Total HW are split into wet and dry HW. For one selected HW case, if apparent temperature (http://www.wpc.ncep.noaa.gov/html/heatindex_equation.shtml) higher than T2max more than one day, this case is the wet HW, otherwise is the dry HW.
- Wider areas will be affected by wet HWs in the end of the century (including areas dry in the present climate)




Spatial distribution of total year numbers for the target HW numbers, for historical simulation (1980-2009, left) and SSP5-8.5 simulation (2070-2099, right) of IPSL-CM6A-LR. “>=1HW” means there is at least 1 HW detected for one year.

# Heatwaves in Future Climate Projections (SSP5-85)

- **For most of the selected regions, the wet HW frequency increases more than dry HW frequency (except Western American, Central Russia and Northeast China).**
- **Only two models in CMIP6 database  give enough information to diagnose wet HW.**




HW frequency change from historical simulation (1980-2009) to SSP5-8.5 simulation (2070-2099) for wet HW(blue) and dry HW(red) with the standard deviation of 30 years.