Seasonal weather regimes in the North Atlantic region: towards new seasonality?

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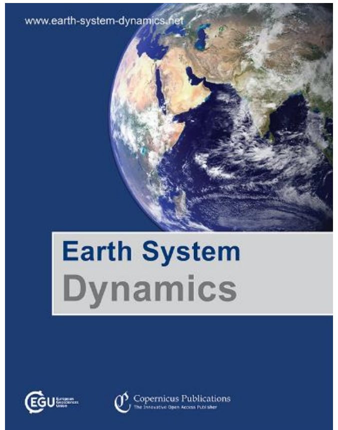
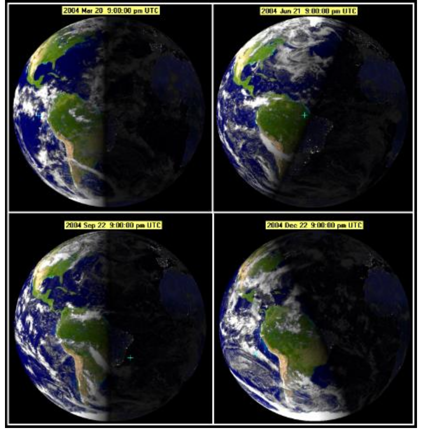
Submitted



Motivation



- Importance of seasons for the weather
  - Climate system: energy, atmospheric circulation (jet stream, ITCZ), extreme events, etc.
  - Natural systems: phenology, moonsoons, etc.
  - Human systems: health, agriculture, transportation, energy, etc.

- Role of climate change in seasonality changes (IPCC: AR5 2013, SRCCL 2019)
  - Changes of variables in climatological seasons: e.g. decreasing winter and spring frost, decreasing summer Arctic sea ice
  - Changes in seasonality of variables: e.g. longer growing season, longer fire weather season

- Meteorological seasons
  - mainly experienced by natural and human systems through the seasonality of surface weather conditions
  - **Future weather seasonality?**

State of the art (1)

- European weather conditions (Cattiaux 2010)
  - Large-scale circulation dynamics
  - Local-scale processes that reduce or amplify dynamic effects

- North Atlantic atmospheric patterns (Cassou 2008, Hurrell et al. 2003)
  - Low-frequency quasi-static structures (e.g. Icelandic Low, Azores High)
  - High-frequency propogating synoptic waves or storms
  - Role of the (fluctuating) jet stream

Preferential configurations (i.e. modes of variability) despite stochastic nature

- Weather regimes (WRs): recurring atmospheric patterns (Vrac and Yiou 2010)

State of the art (2)

- Use of WRs in meteorology since middle of XXth century (Lamb 1950, Rex 1950)
  - To understand variability of atmospheric dynamics (Vautard 1990)
  - To evaluate climate models (Sanchez-Gomez et al. 2009)

- Strong seasonal features of atmospheric dynamics and weather extremes
  - Blocking conditions facilitating cold spells in winter (Sillmann et al. 2011)

  and heatwaves in summer (Schaller et al. 2018)

- Changes in seasonality of atmospheric dynamics
  - Last decades: increasing occurrence of summer conditions, opposite for winter conditions (Vrac et al. 2014)
  - Future: earliness of summer conditions should continue to increase in the future while no trend is found for winter conditions (Cassou and Cattiaux 2016)

- Limited confidence in model representation of atmospheric circulation (Shepherd 2014)

This study

- **Questions/objectives of investigation:**
  - Representation of past seasonality in climate models vs. reanalysis (over historical period: 1979-2017)?
  - Temporal and spatial evolution of seasonal structures (over 1979-2100)?
  - Causes of seasonal evolutions?
- **Data:**
  - Variables: Z500 and surface temperature
  - One reanalysis: ERA-Interim (ERAI) over 1979-2017
  - 12 climate models: CMIP5 r1i1p1 historical + RCP8.5 over 1979-2100 (bilinearly interpolated to ERAI grid)
- **Methods:**
  - SWRs defined by Expectation-Maximization (EM) clustering on PC1 (most variance and seasonality) of Z500 fields
  - More SWRs = more freedom in the definition of seasonality (e.g. SWR7 compared to SWR4)
  - detrended-data SWRs (d-SWRs) = defined similarly to SWRs but after removing the calendar trend (smoothing spline) in regional Z500 (and temperature) average
  - Main tools of study: SWR4 1979-2017, SWR4 1979-2100, SWR7 1979-2100, d-SWR7 1979-2100

Data

Dataset	Period	Spatial resolution (lon x lat)	Institute	Reference
ERA-Interim	1979-2017	0.75° x 0.75°	ECMWF (Europe)	Dee et al. (2011)
HadGEM2-ES	1981-2005 (historical) and 2006-2099 (RCP8.5)	1.875° × 1.25°	MOHC (UK)	Jones et al. (2011)
ACCESS1-3	1979-2005 (historical) and 2006-2100 (RCP8.5)	1.875° x 1.25°	CAWCR (Australia)	Collier and Uhe (2012)
bcc-csm1-1-m	1979-2005 (historical) and 2006-2100 (RCP8.5)	1.125°	BCC (China)	Wu et al. (2014)
CanESM2	1979-2005 (historical) and 2006-2100 (RCP8.5)	2.8125° x 2.7906°	CCCma (Canada)	Chylek et al. (2011)
CNRM-CM5	1979-2005 (historical) and 2006-2100 (RCP8.5)	1.40625° x 1.4008°	CNRM (France)	Voldoire et al. (2013)
GFDL-CM3	1979-2005 (historical) and 2006-2100 (RCP8.5)	2.5° x 2°	GFDL (USA)	Griffies et al. (2011)
IPSL-CM5A-MR	1979-2005 (historical) and 2006-2100 (RCP8.5)	2.5° x 1.2676°	IPSL (France)	Dufresne et al. (2013)
IPSL-CM5B-LR	1979-2005 (historical) and 2006-2100 (RCP8.5)	3.75° x 1.8947°	IPSL (France)	Dufresne et al. (2013)
MIROC5	1979-2005 (historical) and 2006-2100 (RCP8.5)	1.40625° x 1.4008°	CCSR, NIES, JAMSTEC (Japan)	Watanabe et al. (2010)
MPI-ESM-MR	1979-2005 (historical) and 2006-2100 (RCP8.5)	1.875° x 1.8653°	MPI (Germany)	Giorgetta et al. (2013)
MRI-ESM1	1979-2005 (historical) and 2006-2100 (RCP8.5)	1.125° x 1.12148°	MRI (Japan)	Adachi et al. (2013)
NorESM1-M	1979-2005 (historical) and 2006-2100 (RCP8.5)	2.5° x 1.8947	BCCR, NMI (Norway)	Bentsen et al. (2012)

Focusing on seasonality with PC1

- Principal component (PC) analysis to reduce dimension of data while keeping most of variability and seasonality

- First PCs = capture most of the low-frequency signal
- Last PCs = capture most of the high-frequency signal

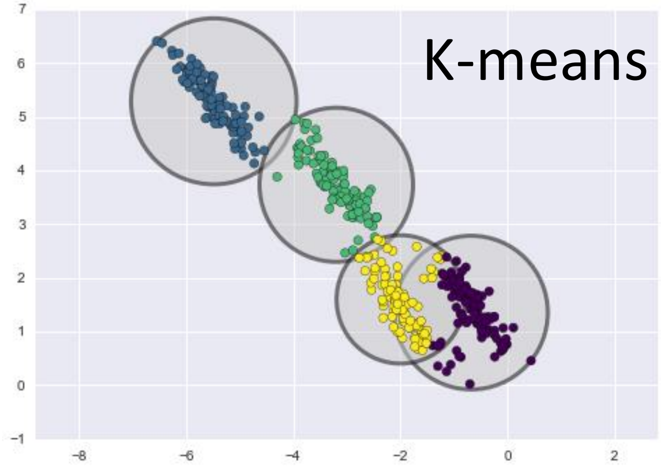
- Total spectrum = sum of all PCs over all frequencies

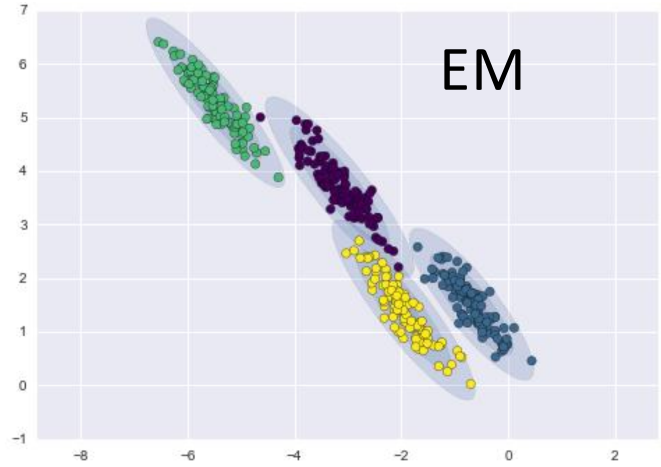
- Depending on dataset, PC1 = 49-60% of total variance

  = 95-99% of total seasonal cycle (signal at 1/365 frequency)

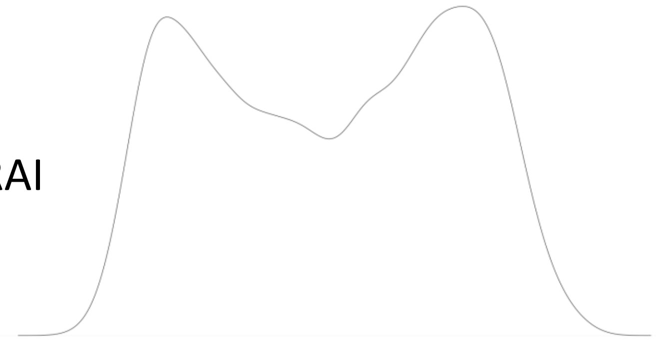
Cluster analysis

- Clustering: grouping elements together by similarity (more similar in a cluster than between clusters)
- Many ways to do it
- K-means clustering (popular): based on centroids (i.e. centers)
- EM clustering: based on distribution





pdf of PC1 ERAI



Defining SWRs with EM clustering (Vrac et al. 2014)

- EM algorithm (Dempster et al. 1977) based on a Gaussian mixture model (GMM; Peel and McLachlan 2000) estimates a multivariate pdf of PC1 values (x) as a weighted sum of K Gaussian pdfs f_k (Pearson 1894):

1

$$f(x) = \sum_{k=1}^{K} \pi_k f_k(x; \alpha_k)$$

α_k : vector of parameters of component *k* *(means μ_k and covariance matrix Σ_k)*

π_k : mixture ratios (prior probability of belonging to component k)

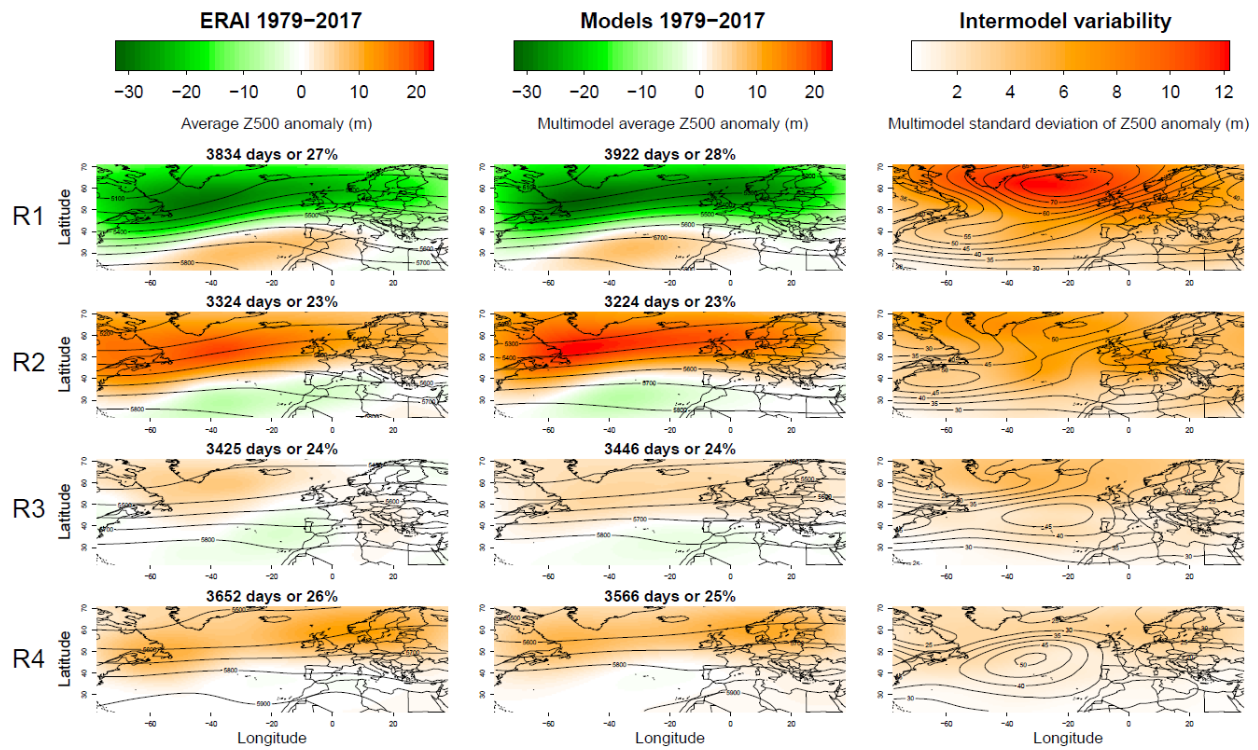
- Finally, each cluster C_k of days is defined based on the Gaussian pdfs, according to the principle of posterior maximum:

2

$$C_k = \{x; \pi_k f_x(x; \alpha_k) \geqslant \pi_j f_j(x; \alpha_j), \qquad \forall j = 1, \ldots K\}$$

- Clusters = SWRs = classification of daily Z500

SWR4 1979-2017: weather patterns

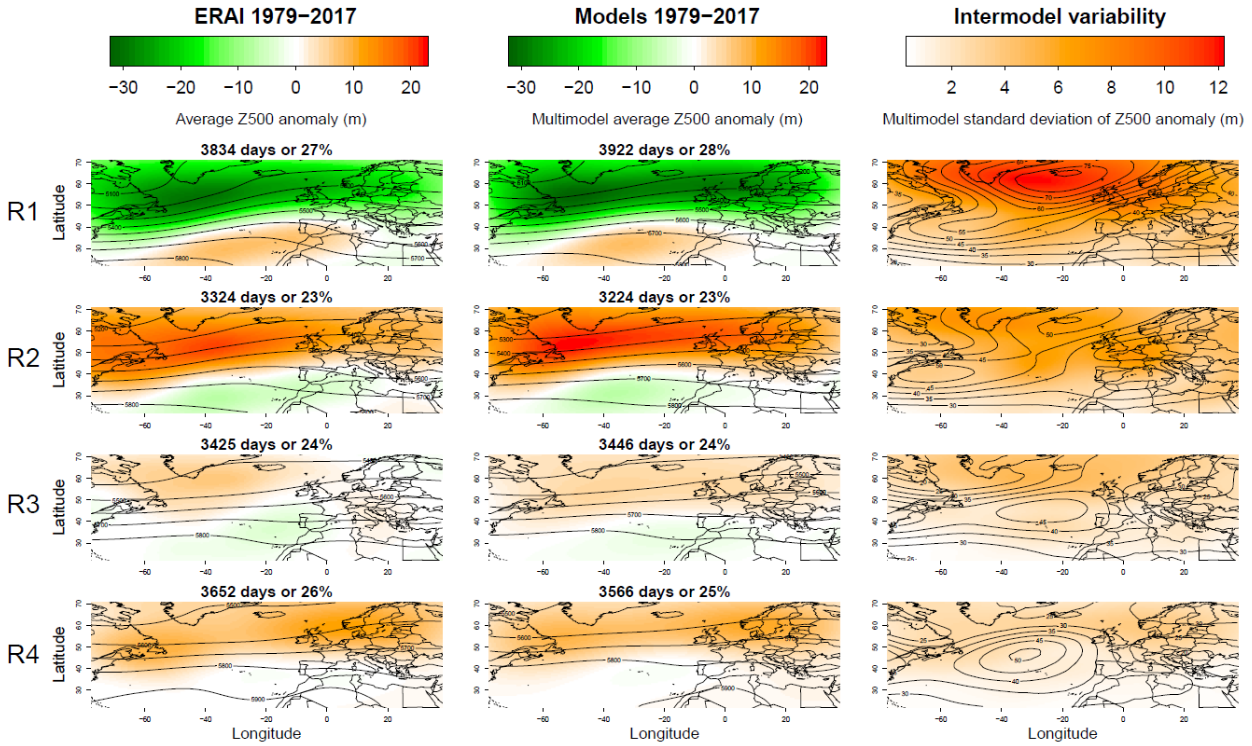


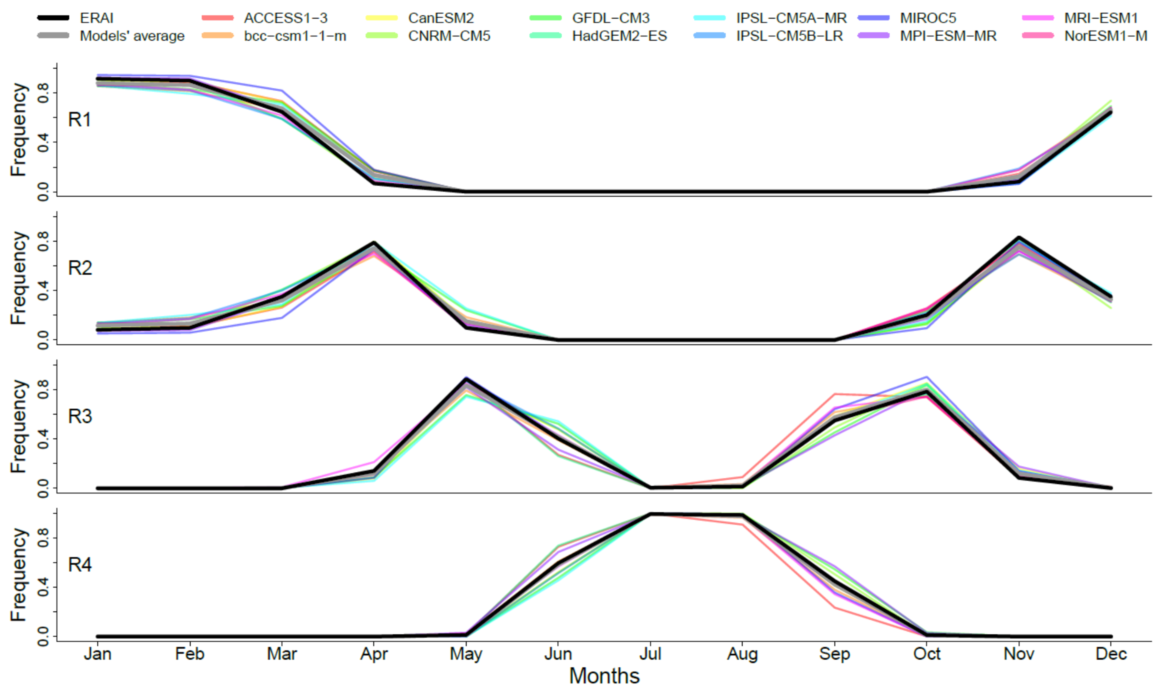
- Composite maps of regimes
- Average of seasonal anomalies (shading) and raw values (contour lines) over days belonging to regime
- Seasonal anomalies = raw values minus average seasonal cycle

- Weather patterns similar to the literature (Cassou 2008, Yiou and Nogaj 2004)
- R1 ≈ positive phase and R2 ≈ negative phase of North Atlantic Oscillation (NAO+ and NAO-, Hurrell et al. 2003)
- R3 ≈ Atlantic Ridge and R4 ≈ Scandinavian Blocking (Yiou and Nogaj 2004)
- But definition and properties different! Based on full years (Vrac et al. 2014) rather than winter (Cassou 2008, Yiou and Nogaj 2004) or summer (Guemas et al. 2010)

SWR4 1979-2017: similar structures (despite model biases)

- In space (weather patterns)
- In time (seasonal cycle)



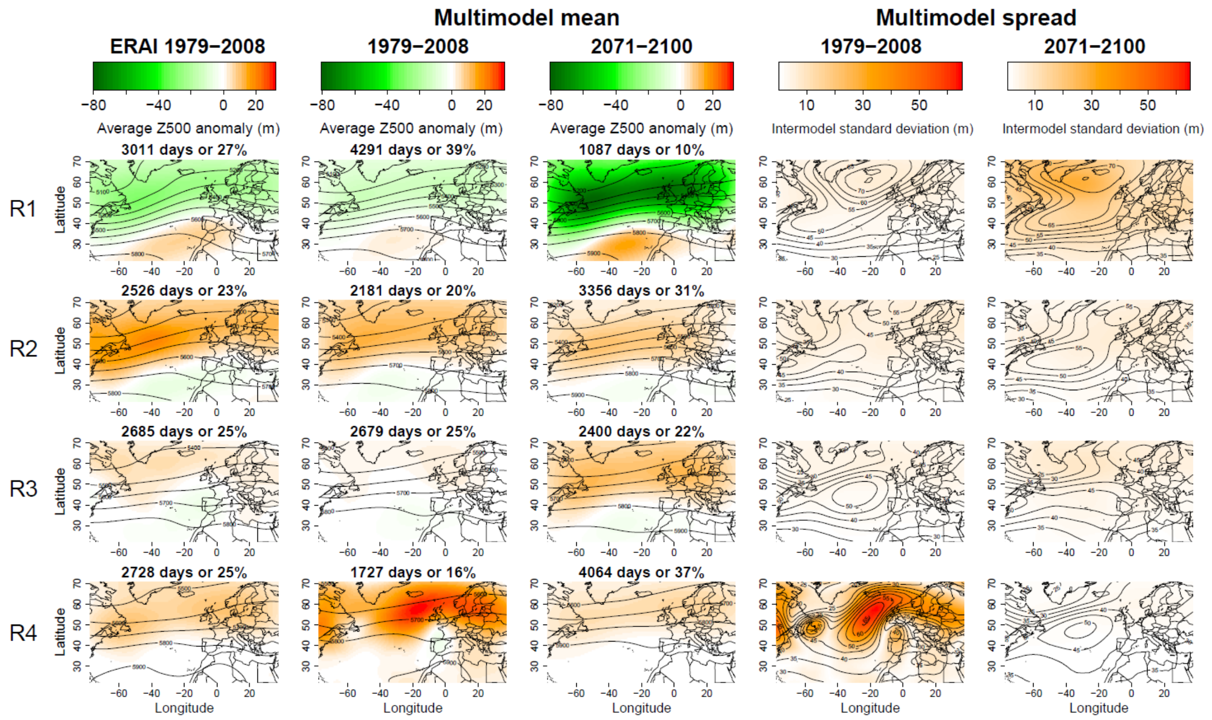


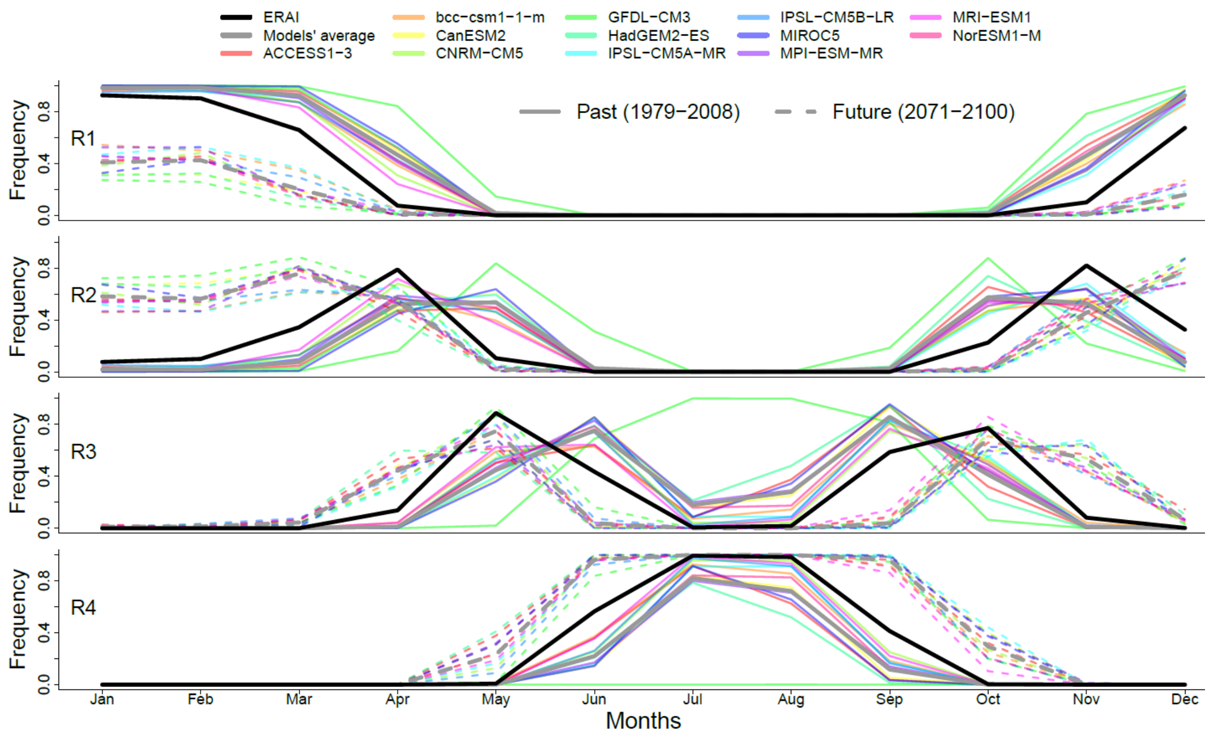
- Composite maps of regimes
- Average of seasonal anomalies (shading) and raw values (contour lines) over days belonging to regime
- Seasonal anomalies = raw values minus average seasonal cycle

- Frequency = regime days / days in month
- Average seasonal cycle over 1979-2017

SWR4 1979-2100:
changes between 1979-2008 and 2071-2100

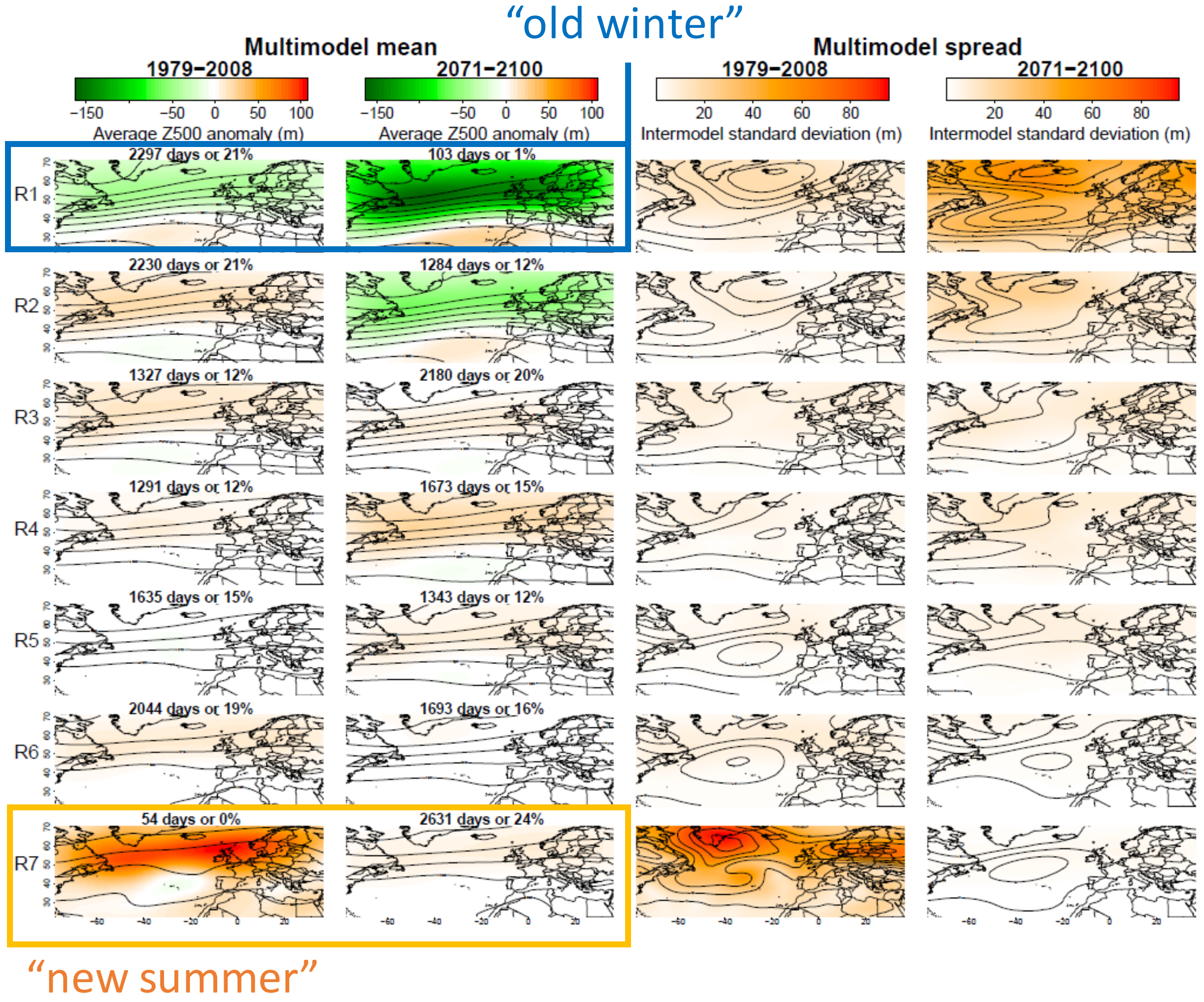
- Winter conditions decreasing in frequency and pattern strengthening
- Summer conditions increasing in frequency and pattern weakening





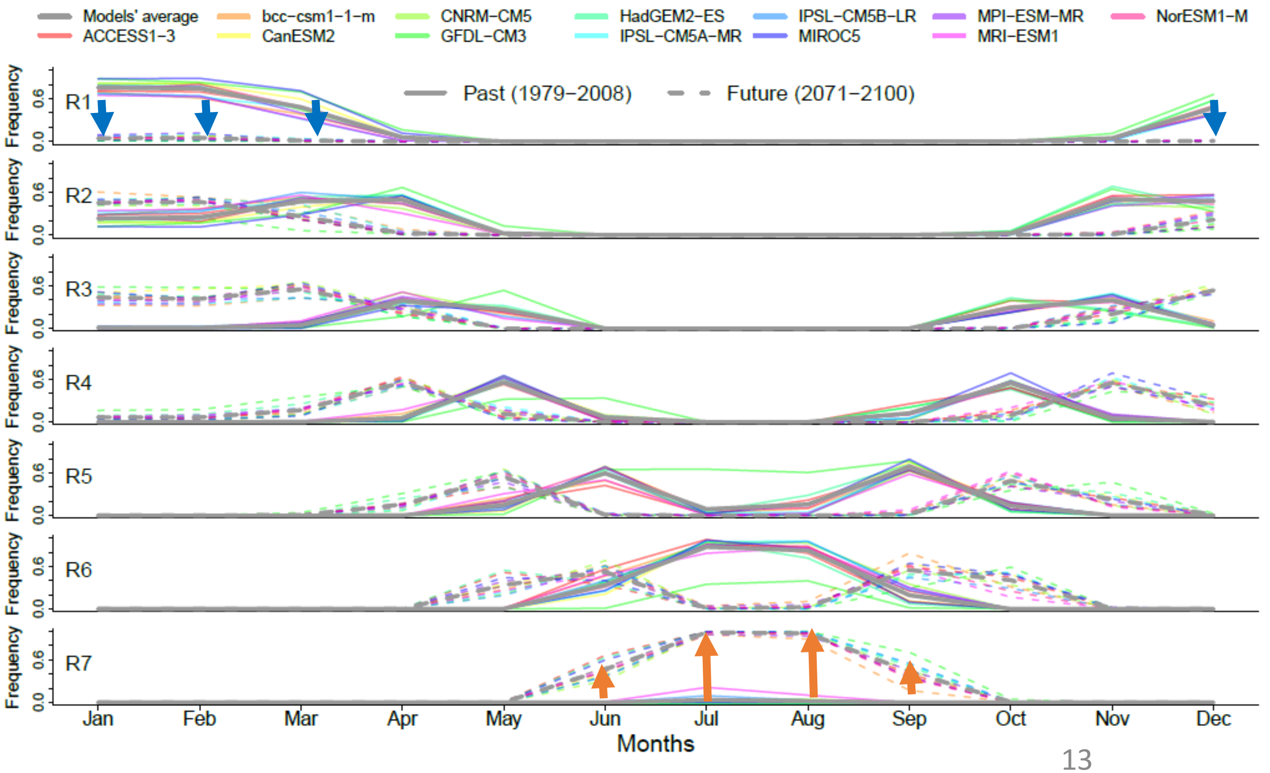
SWR7 1979-2100: disappearance and appearance of structures

- Disappearance of past winter conditions



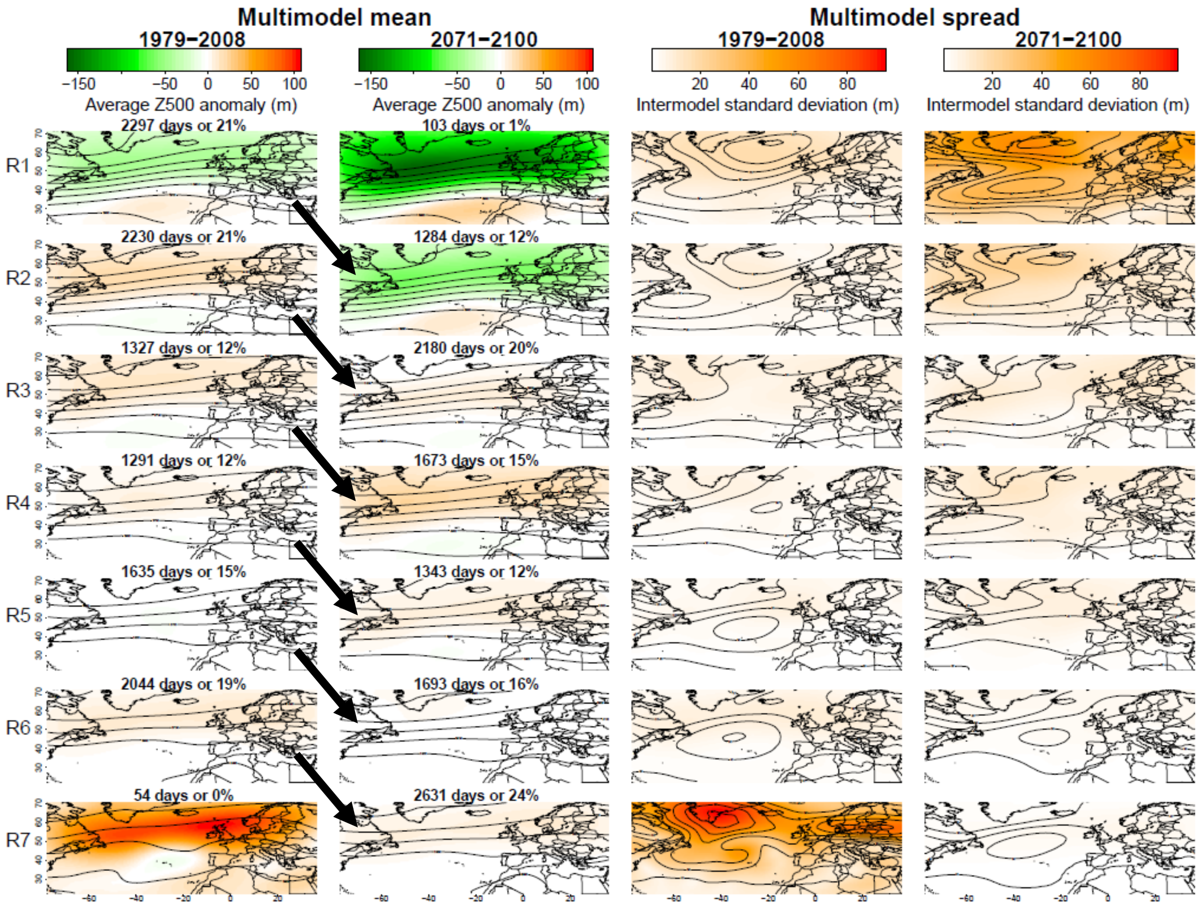
- Appearance of new summer conditions

- Yes but evolution of raw Z500 seasonal cycle! (averaging +90hPa between 1979-2008 and 2071-2100)

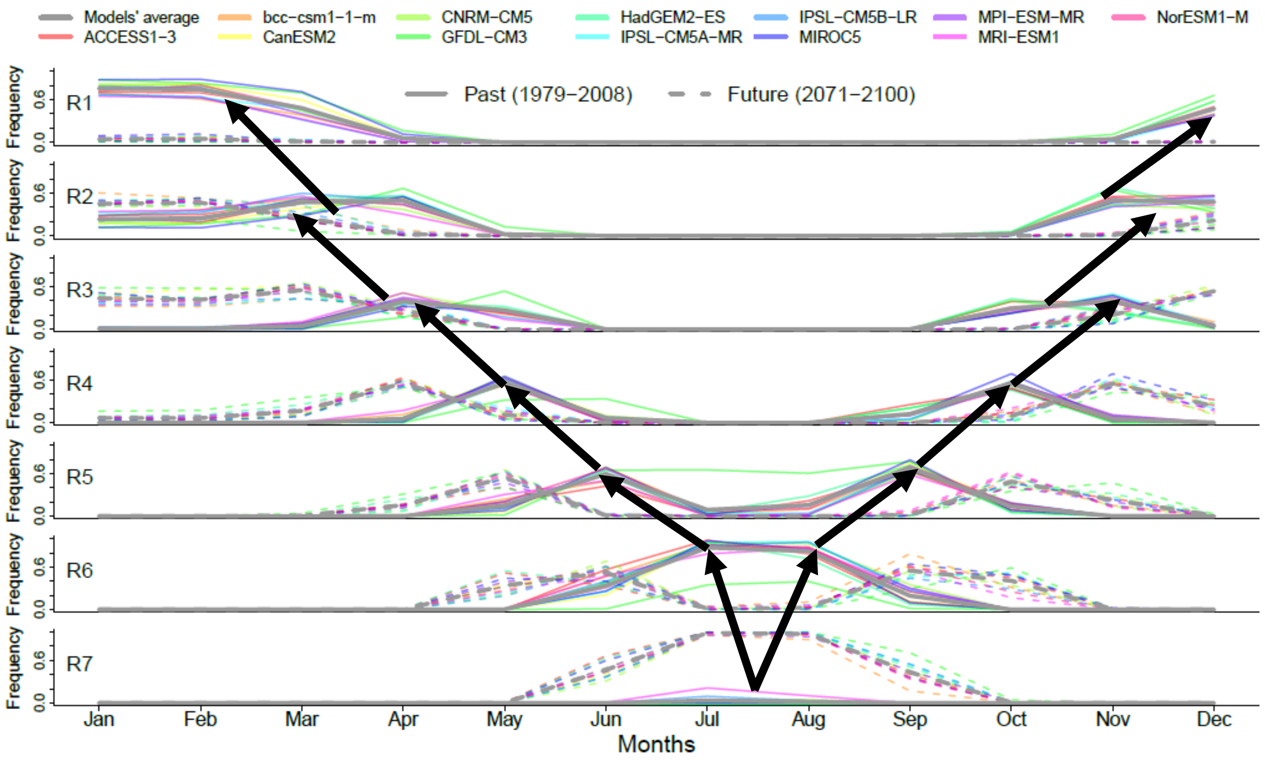


SWR7 1979-2100: disappearance and appearance of structures

- Long-term swap of regimes (R1 to R2, R2 to R3, etc.)

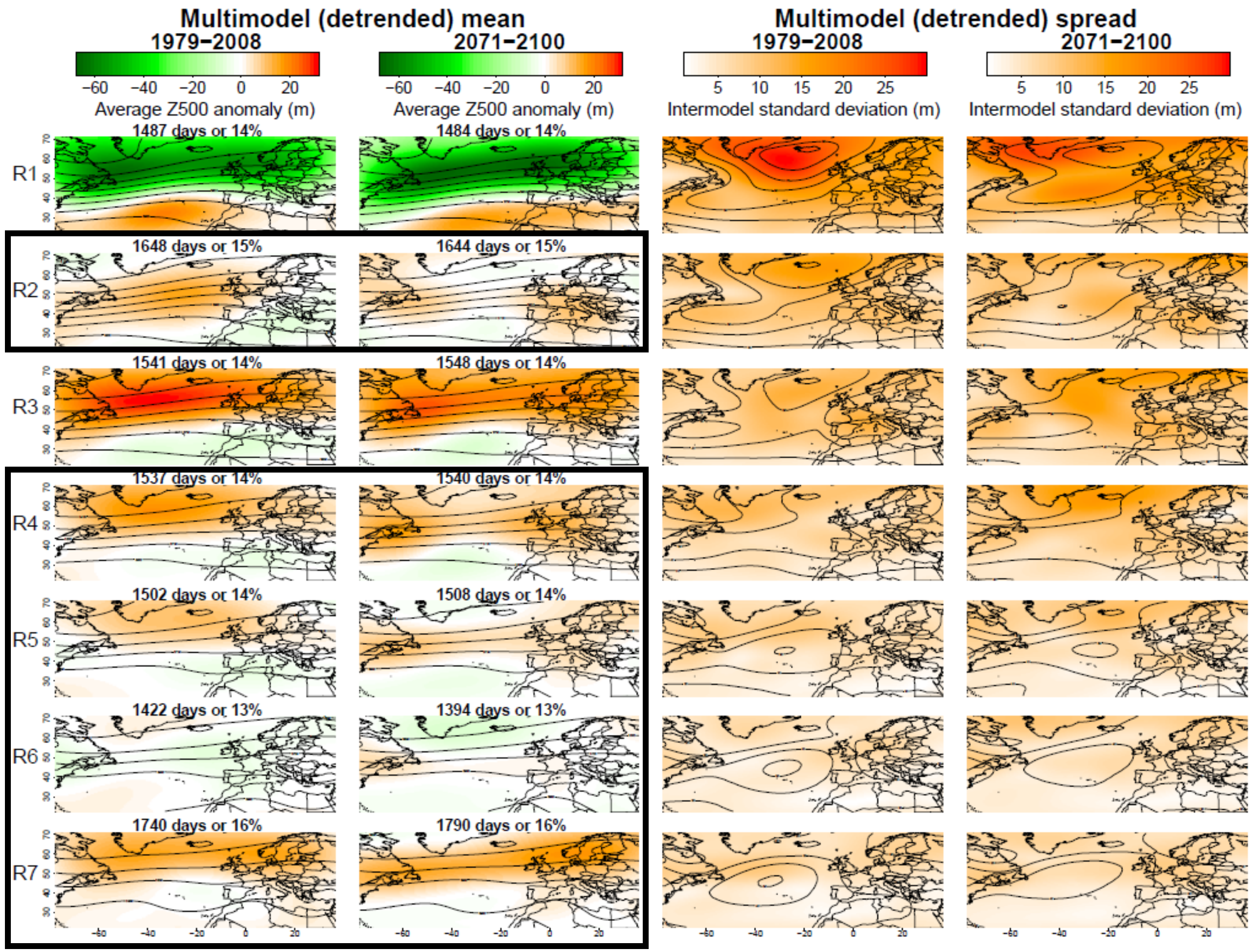


- Very similar seasonality! According to evolution of raw Z500 seasonal cycle

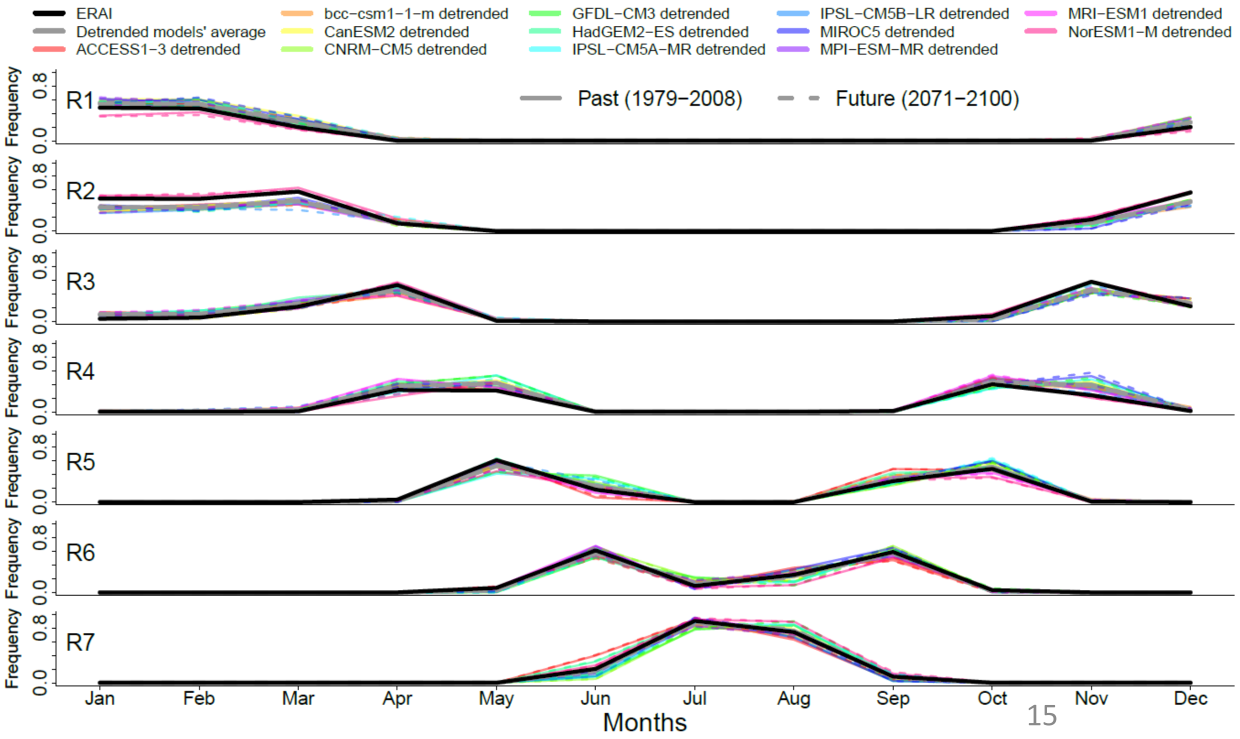


d-SWR7 1979-2100:
almost constant in time, small changes in space

- defined similarly to SWRs but after removing the calendar trend (smoothing spline) in regional Z500



- d-SWR7: indicates that calendar Z500 regional trend drives evolution of SWR4 and SWR7
- Changing d-SWR7 weather patterns: due to heterogeneity of regional calendar trend



Main conclusions

- **Historical period**: in general climate models able to reproduce similar structures (weather patterns, seasonal cycle) as in climate reanalysis (despite individual model biases)

- **SWR4 and SWR7 1979-2100:** historical winter conditions continue to decrease in the future while historical summer conditions continue to increase. Strengthening of winter pattern and weakening of summer pattern (wrt. increase of Z500 seasonal cycle!)

- **SWR7 1979-2100**: future seasonality of weather regimes similar to past (wrt. increase of Z500 seasonal cycle!)

- **d-SWR7 1979-2100:** the calendar Z500 regional trend drives the evolution of SWRs and changing spatial patterns correspond to the heterogeneity of that trend

Limitations and perspectives

- **Limitations:**

- Uncertainties and errors in the climate representation of ERAI and models, especially atmospheric dynamics (Shepherd 2014) and surface temperature in models (Jones et al. 2013)

- Bias correction methods could lead to more realistic SWRs but imply other issues e.g. modifications of spatial and temporal structures (and trends) possibly generating physical inconsistencies (Vrac 2018; François et al. 2020)

- Apparent consistency between climate models on future evolution of seasonal dynamics seems at odds with other studies where projected circulation response differs strongly between models (e.g. Barnes and Polvani 2015)

- **Perspectives:**

- Apply similar methods to explore changes in weather seasonality at a more local scale by downscaling meteorological variables (e.g. humidity, wind speed, temperature) based on large-scale weather regimes (Vrac and Yiou 2010) in order to bring more locally-relevant insights for social matters related to the weather

Supplementary information

Density estimation via GMM (1)

- The parameters α_k and π_k (*k = 1, … K*) of the GMM are unknown and must be estimated
- Estimation done iteratively in EM by maximizing the likelihood that the current statistical model represents the observed data (Fraley and Raftery 2002)
- GMM initialization by separation in quantiles
- Basis of EM: possibility to calculate π when knowing α (μ and Σ) and vice-versa, enabling the optimization of both

Density estimation via GMM (2)

- Expectation step estimates the posterior probability p_{ik} (update of π_{ik}) that the observation x_i belongs to f_k with the current parameter estimates (at stage t):

$$p_{ik}^t = \frac{\pi_k^t f_k(x_i, \alpha_k^t)}{\sum_{k=1}^{K} \pi_k^t f_k(x_i, \alpha_k^t)}$$

- Maximization step uses the posterior probabilities to improve the estimates of GMM parameters (stage $t+1$):

$$\pi_k^{t+1} = \frac{1}{n} \sum_{i=1}^{n} p_{ik}^t \qquad \mu_k^{t+1} = \frac{1}{n\,\pi_k^{t+1}} \sum_{i=1}^{n} x_i\, p_{ik}^t \qquad \sum_k^{t+1} = \frac{1}{n\,\pi_k^{t+1}} p_{ik}^t (x_i - u_k^{t+1})' (x_i - \mu_k^{t+1})$$

where n : number of observations

- Repetition of steps E and M iteratively
- Termination when convergence of model parameter (or after a maximum number of iterations)

Selection of statistical model

- Gaussian distributions are ellipsoids in space determined by:
  - The mean (location)
  - The covariance matrix $\sum$ (geometric features: volume, shape, orientation)

- Freedom of EM in SWR definition depends on:
  - **Number *K* of clusters** → evaluated through Bayesian Information Criterion (BIC; Schwartz et al. 1978)
  - **Constraints on covariance matrix** $\sum$ → univariate (PC1) → variance can be equal or different between clusters (constraint on volume of clusters)

- Minimizing the BIC = compromise between simple model and good data representation:

$$BIC(K) = p\,log(n) - 2\,log(L)$$

L : likelihood of parametrized mixture model

p : number of parameters to estimate

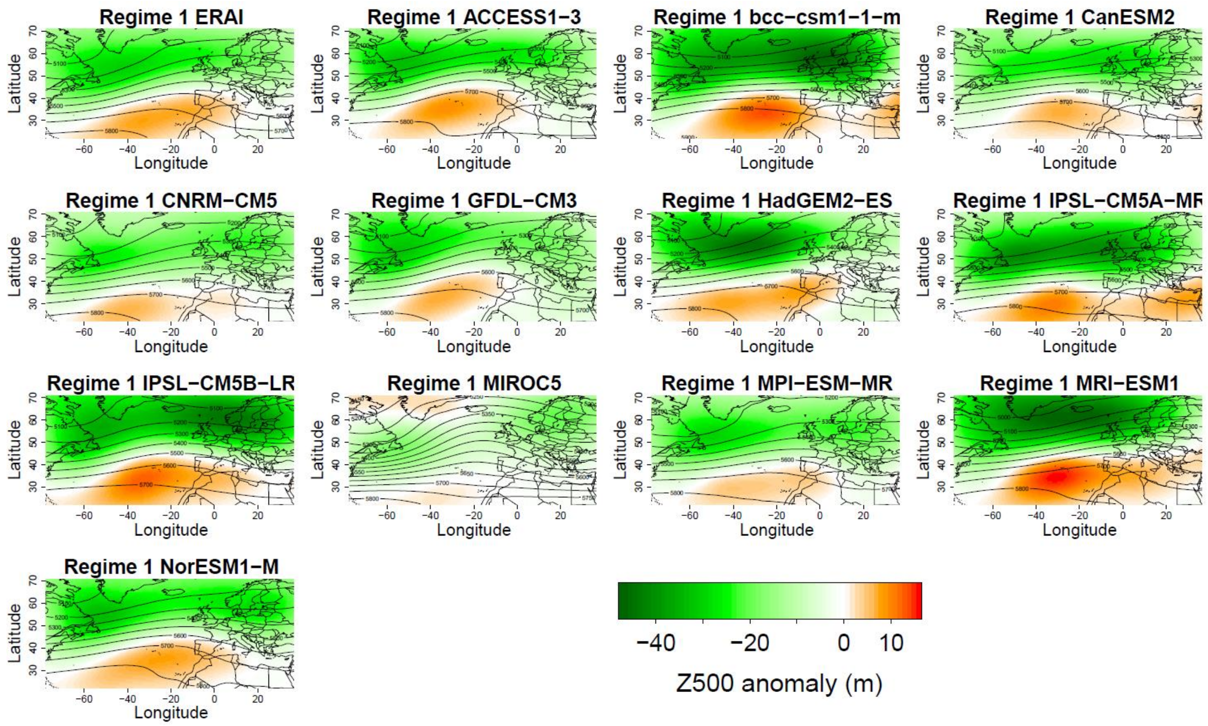
n : sample size (i.e. number of days)

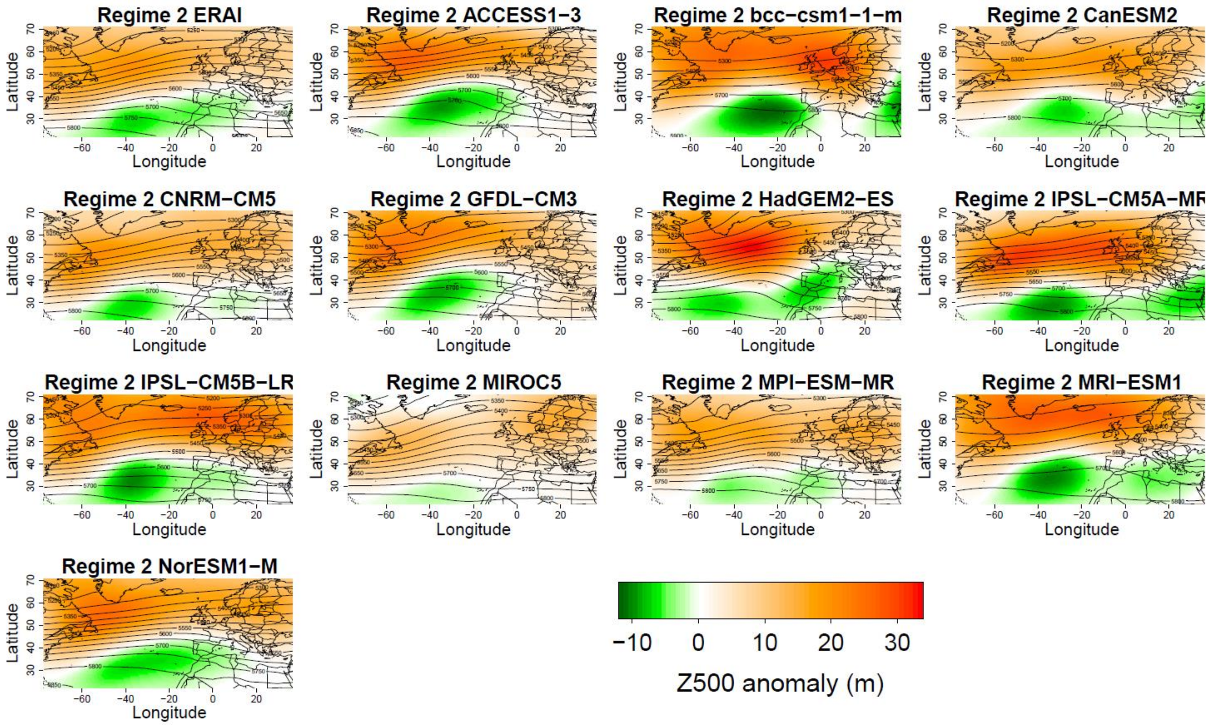
- Four SWRs: plateau of BIC and traditional (astronomical) number of seasons
- The GMM with the best BIC is selected (between equal and different variance)

Defining d-SWRs (based on detrended data)

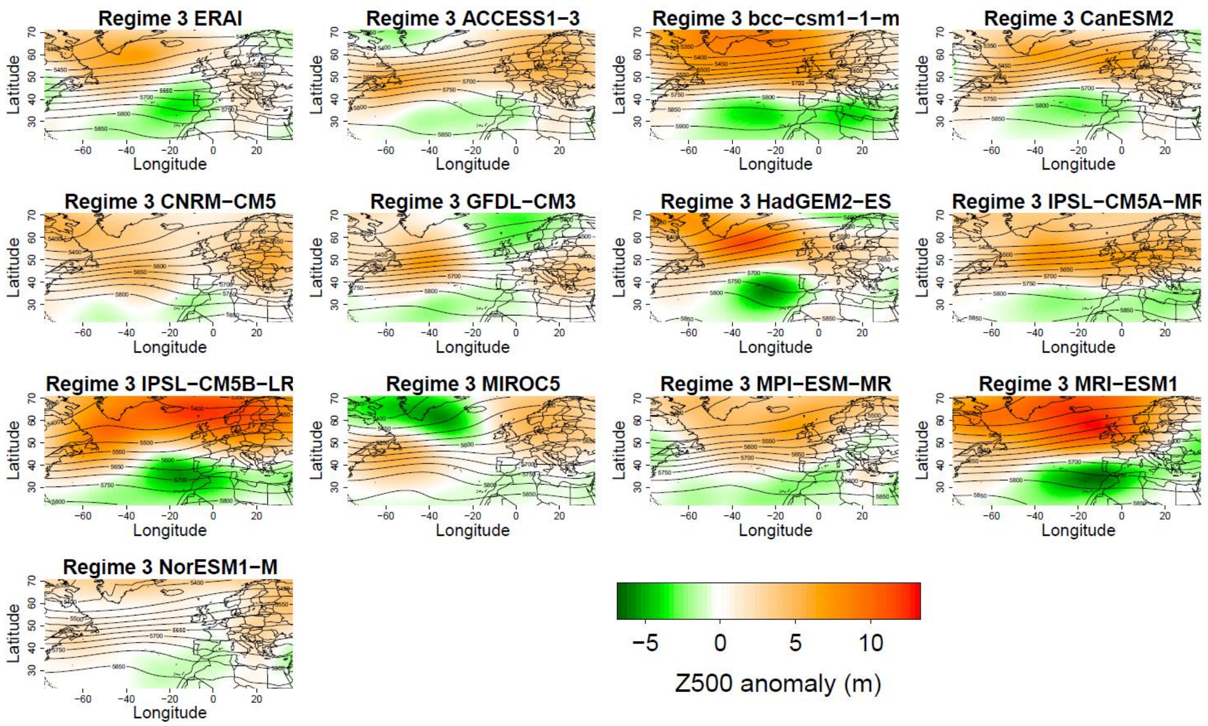
- The large-scale increase in Z500 due to human influence (Christidis and Stott 2015) is expected to drive SWR evolutions
- SWRs based on detrended data (d-SWRs) are obtained through the same method as previously but after removing the large-scale spatial Z500 trend from the original data while keeping the seasons and spatial patterns
- Detrending done by estimating (nonlinear cubic smoothing spline) and removing the calendar trend (1 trend per day of the year) in the Z500 (and TAS) spatial mean over the whole region, and adding the estimated seasonal cycle of 2017 (stationary seasonality)
- The resulting local trend of the detrended data is the residual of the regional trend
- A negative residual trend at a given gridpoint means that its Z500 values are increasing less than the regional average, or even are decreasing, whereas a positive residual trend means that the local trend is higher than that of the regional average

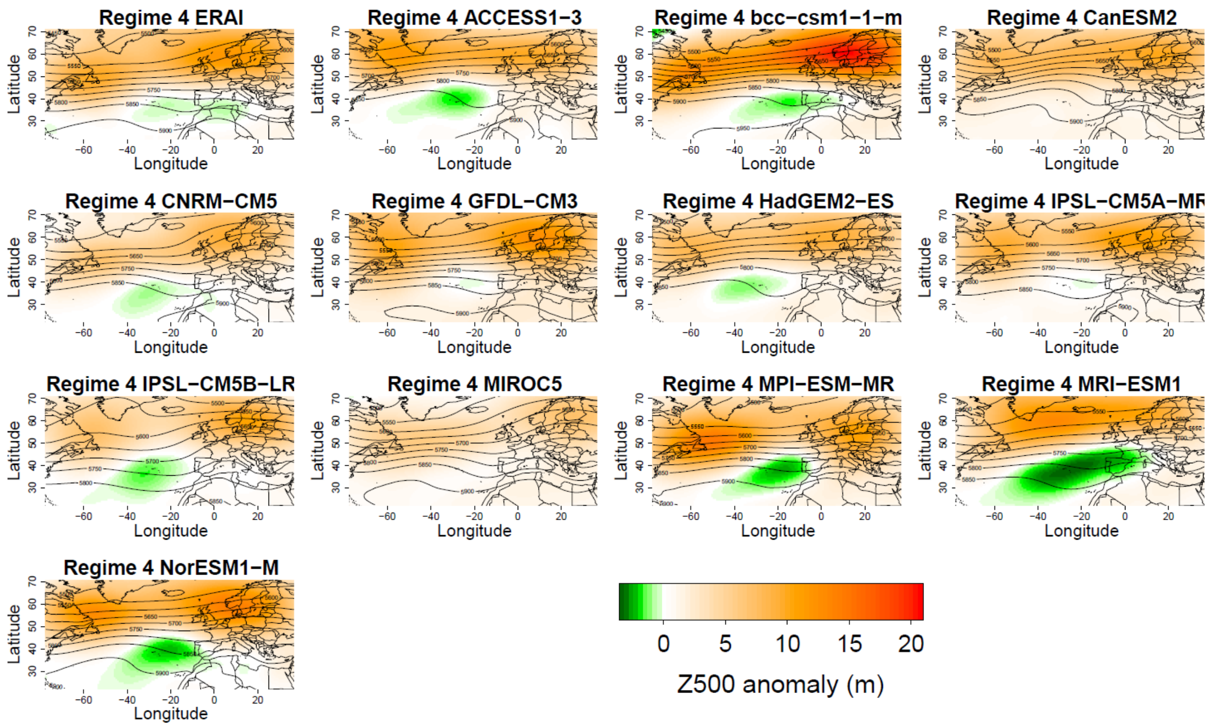
SWR4 1979-2017:
individual model biases (R1 and R2)





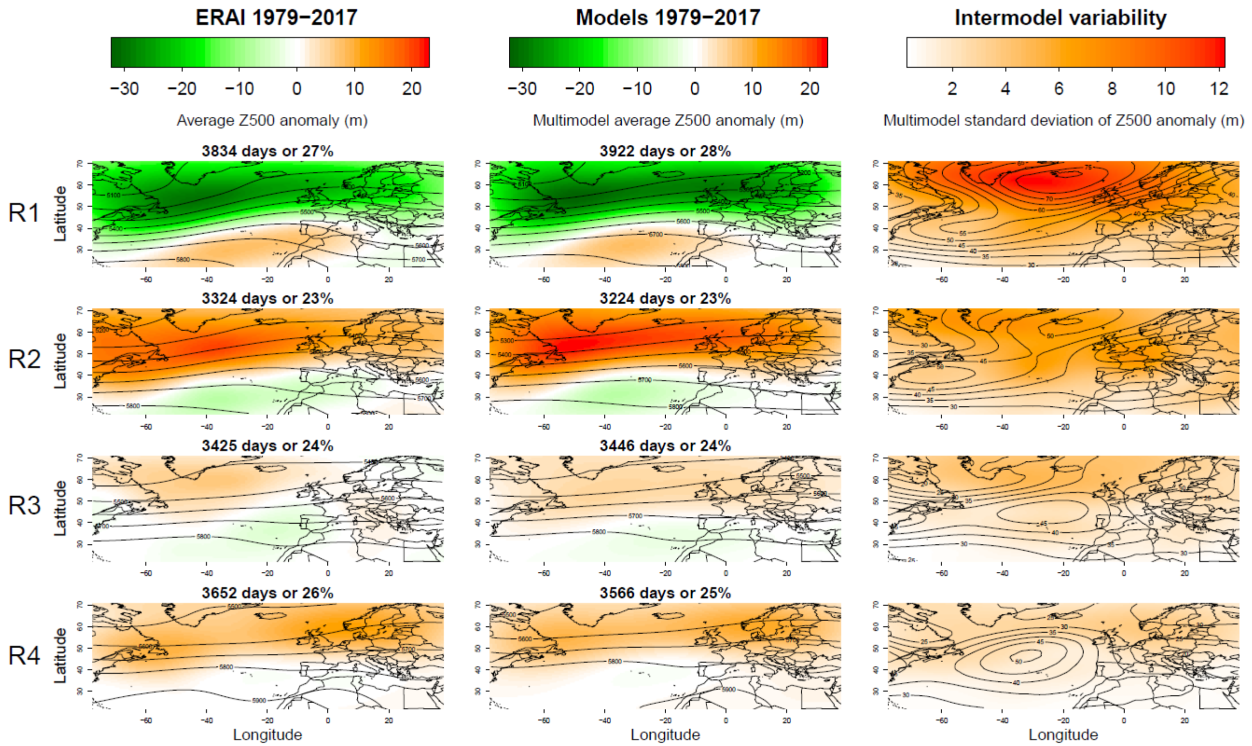
SWR4 1979-2017: individual model biases (R3 and R4)



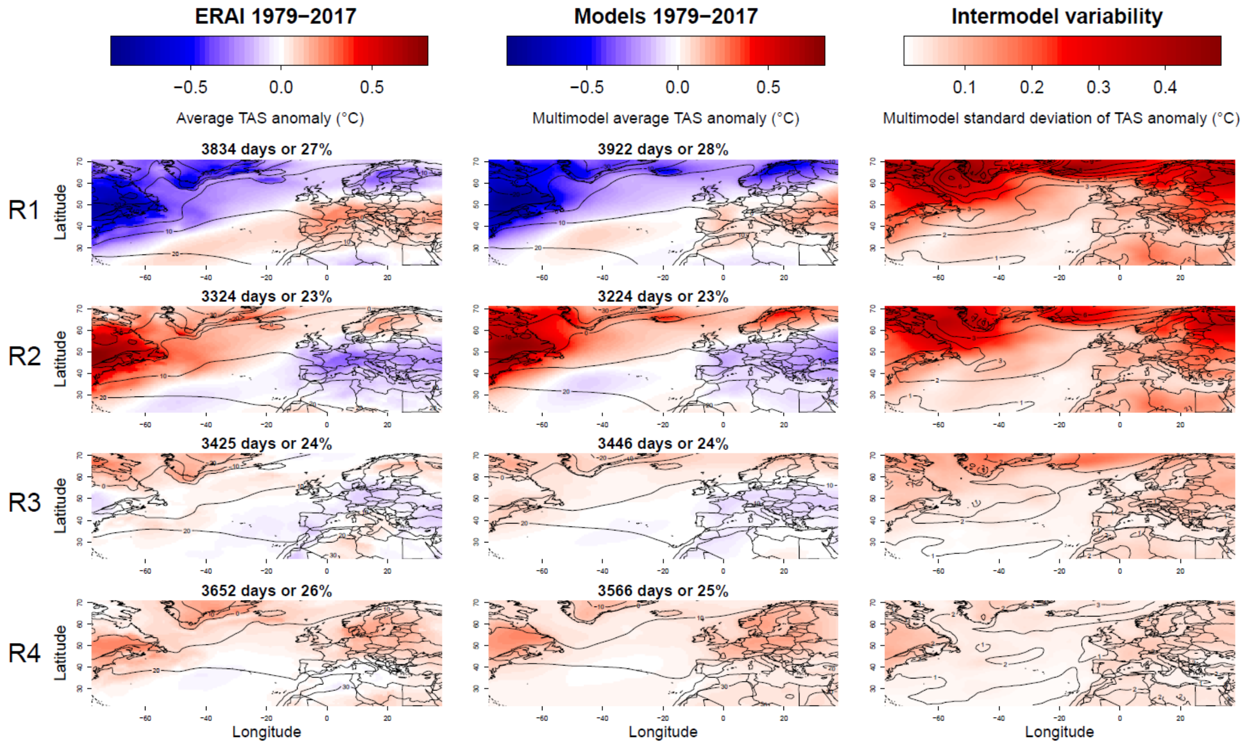


SWR4 1979-2017: similar surface temperature patterns

- Z500 patterns

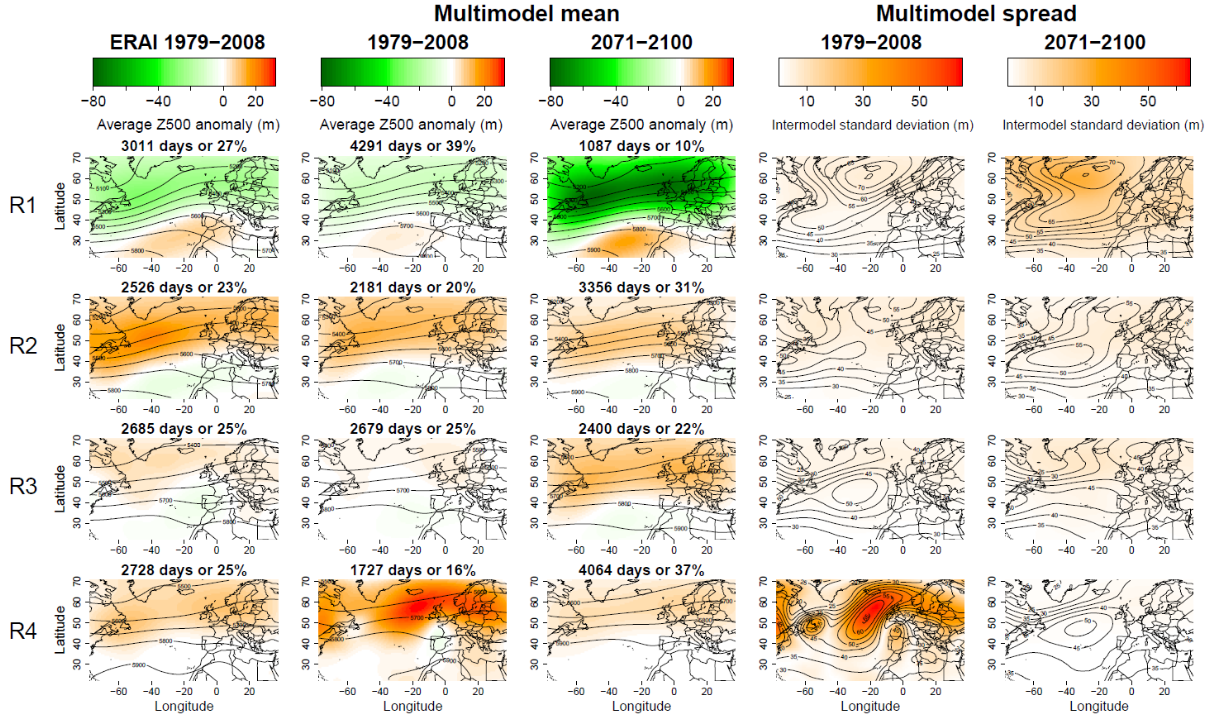


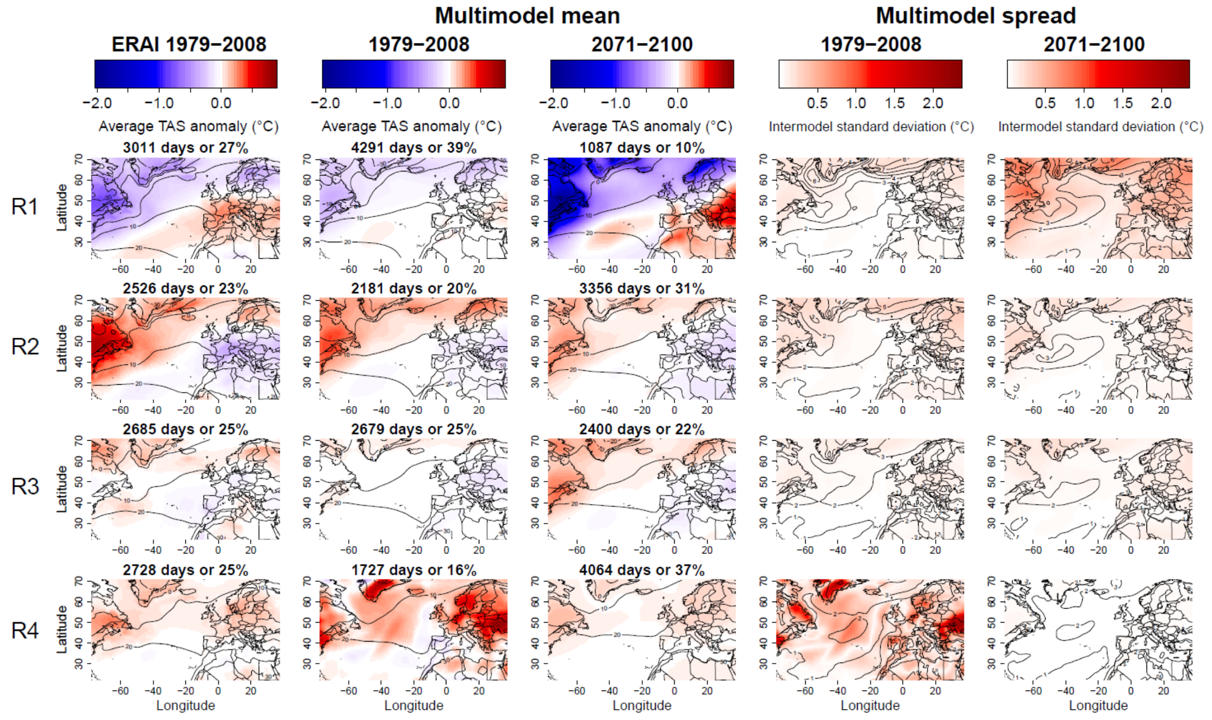
- Surface temperature patterns (conditionally to regimes)



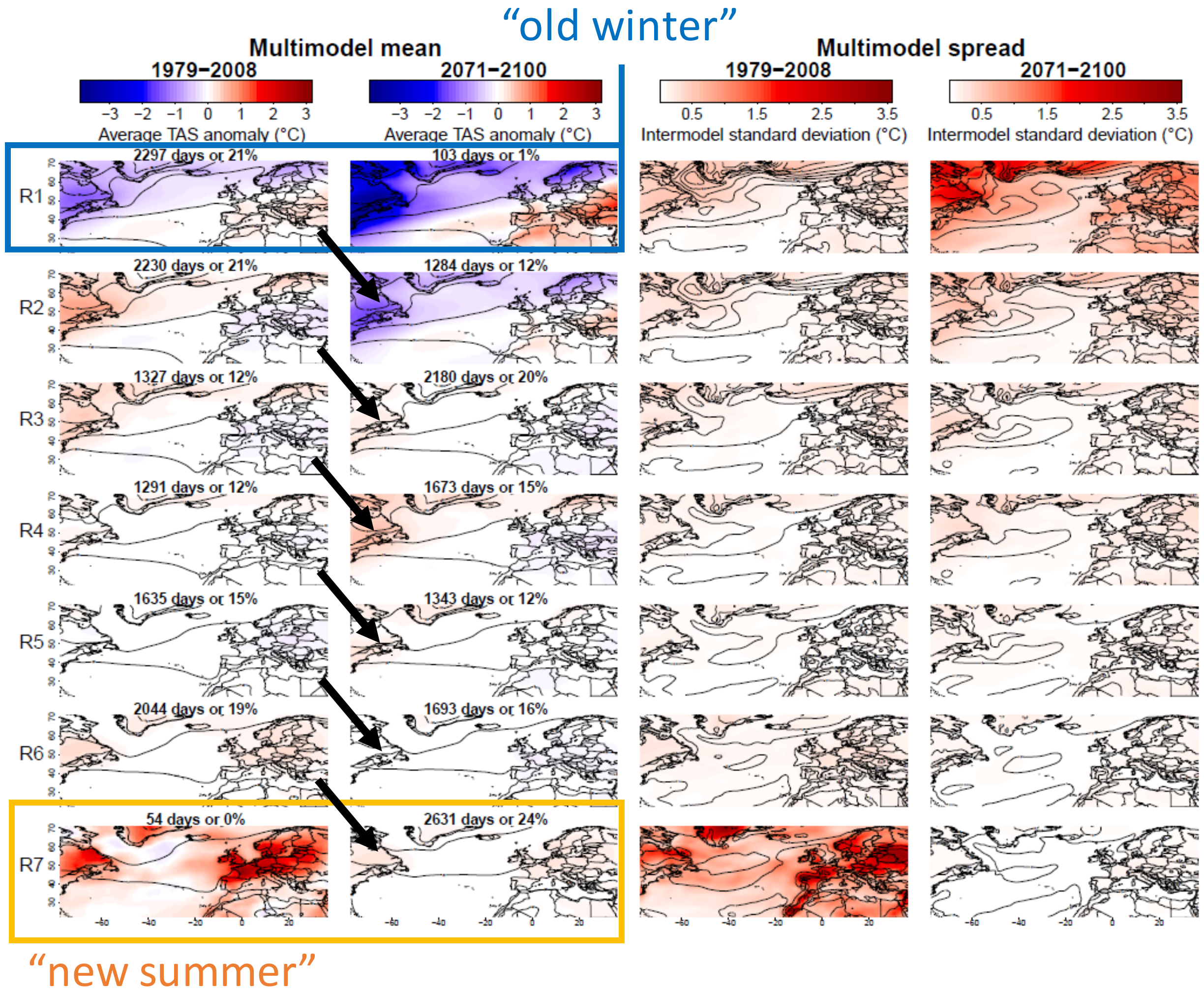
SWR4 1979-2100: associated surface temperature patterns

- Similar to Z500: - Winter pattern strengthening
  - Summer pattern weakening



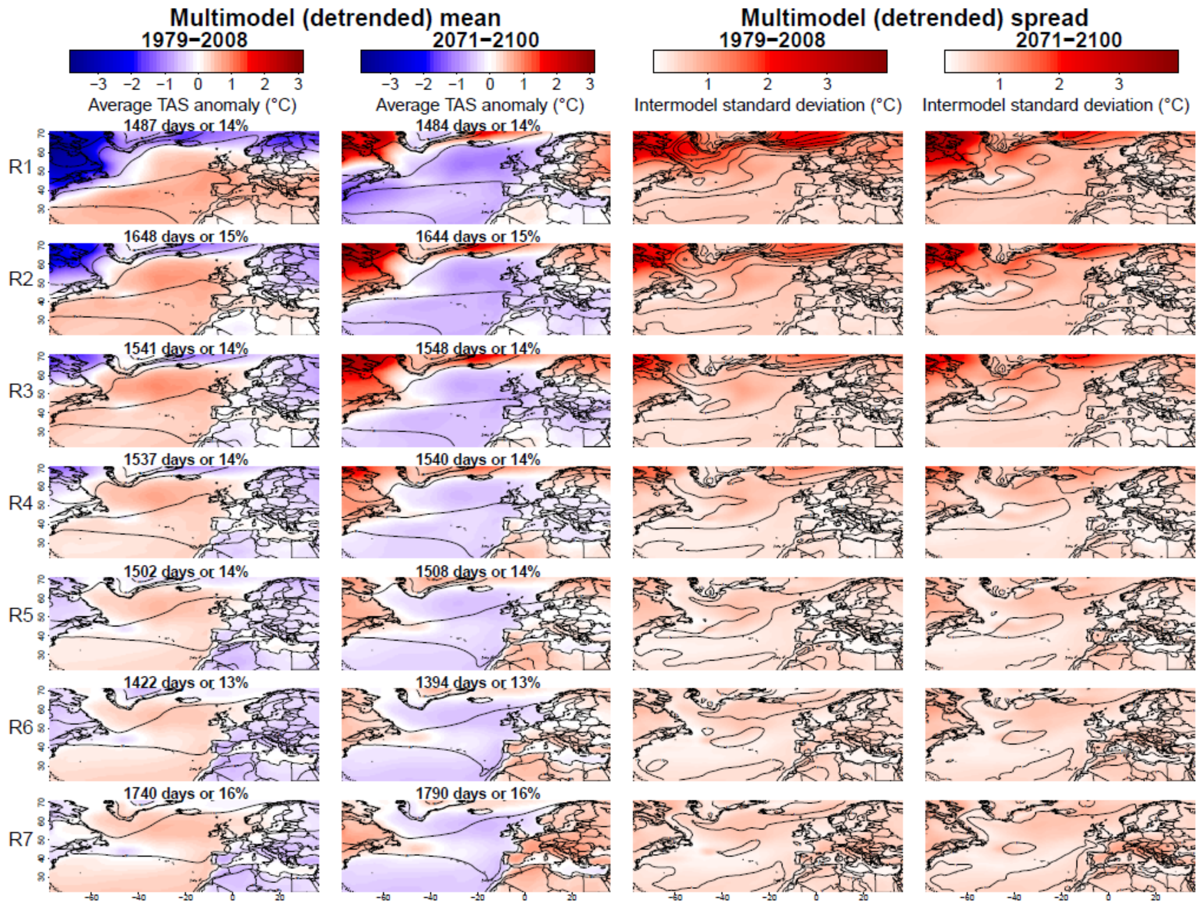


SWR7 1979-2100:
associated surface temperature patterns



- Very similar surface temperature seasonality! According to evolution of raw surface temperature seasonal cycle

d-SWR7 1979-2100:
associated surface temperature patterns



- Change relative to regional average calendar trend
  - Warming over continents (low heat capacity)
  - Cooling over oceans (high heat capacity)
  - Arctic amplification in winter (R1 to R3)

Discussion (1)

- **Past seasonal variability:** agreement with results of Vrac et al. (2014) but more pronounced winter evolution (more recent detaset better capturing global warming; Stocker et al. 2013).

- **Weather patterns at end of 21st century vs. end of 20th century:**

-75% days of NAO+, -10% days of Atlantic Ridge, +54% days of NAO-

+135% days of Scandinavian Blocking (May to October)

Weakening of NAO- and Scandinavian Blocking patterns

Strengthening of NAO+ and Atlantic Ridge patterns

facilitating the persistence of hot and dry spells over Europe (Röthlisberger and Martius 2019)?

summer weather more persistent in a warmer world (Pfleiderer et al. 2019)?

consistent with a decrease of cold spells over Europe (Peings et al. 2013) as they are facilitated by Scandinavian Blocking conditions in winter (Buehler et al. 2011)

Discussion (2)

- **Drivers of evolutions:**

- Large-scale Z500 increase during 1979-2012 mostly due to human forcings (Christidis and Stott 2015)

- Strong link between human forcings and SWR evolutions detected here, although climate models overestimate the surface warming and Z500 increase over the past period (Christidis and Stott 2015, Jones et al. 2013)

- Spatial trends of increasing and decreasing Z500 within regimes = large-scale increase of Z500 vs. seasonal shift of regimes towards winter period (lower Z500 than during the rest of the year)

- Cooling trends reported by Vrac et al. (2014) understood here as the temporal shift of regimes towards the winter period

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