Characterization of Euro-Atlantic Weather Regimes: understanding variability at different timescales

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School on Weather Regimes and Weather Types in the Tropics and Extra-tropics:
Theory and Application to Prediction of Weather and Climate
Trieste, October 2013

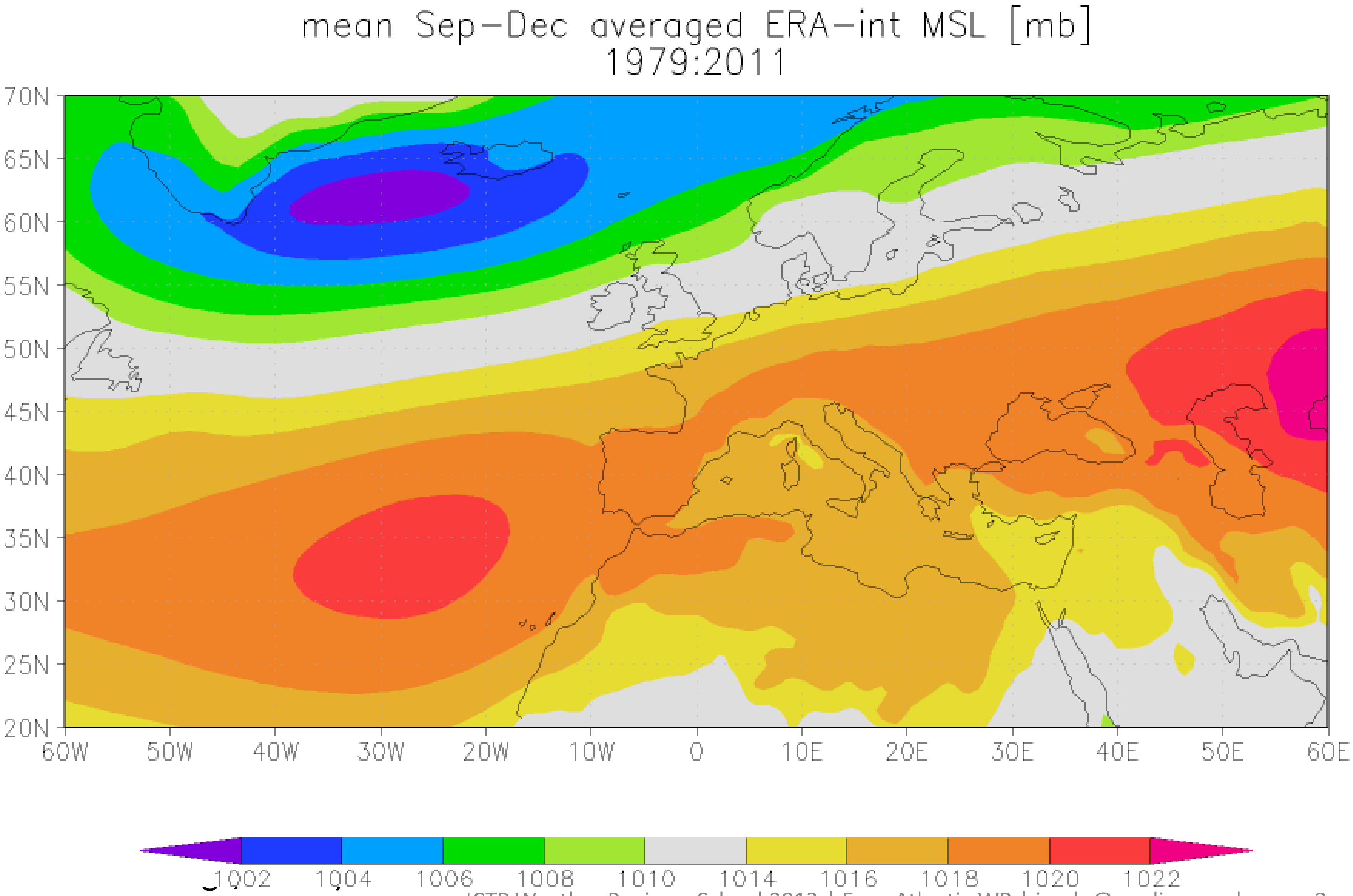
1) Climate variability

2) Atmospheric Data Classification: Weather Regimes

3) Constructing Weather Regimes for Euro-Atlantic Region in summer
   1) DATA
   2) SOM method
   3) Scientific questions

4) Interpretation/Examples:
   - Seasonal Cycle
   - Transitions
   - WR and GCM projection
   - WR and Mediterranean SST: Changes at Interannual timescales
   - WR and Changes at Interdecadal timescales: frequency & spatial pattern

North Atlantic regimes



Timescales of Climate variability

Timescales (days)

10^1

Intraseasonal variability
Madden-Julian Oscillation

10^2

10^3

Quasi-Biennal Oscillation
El Nino-Southern Oscillation

10^4

Decadal variability

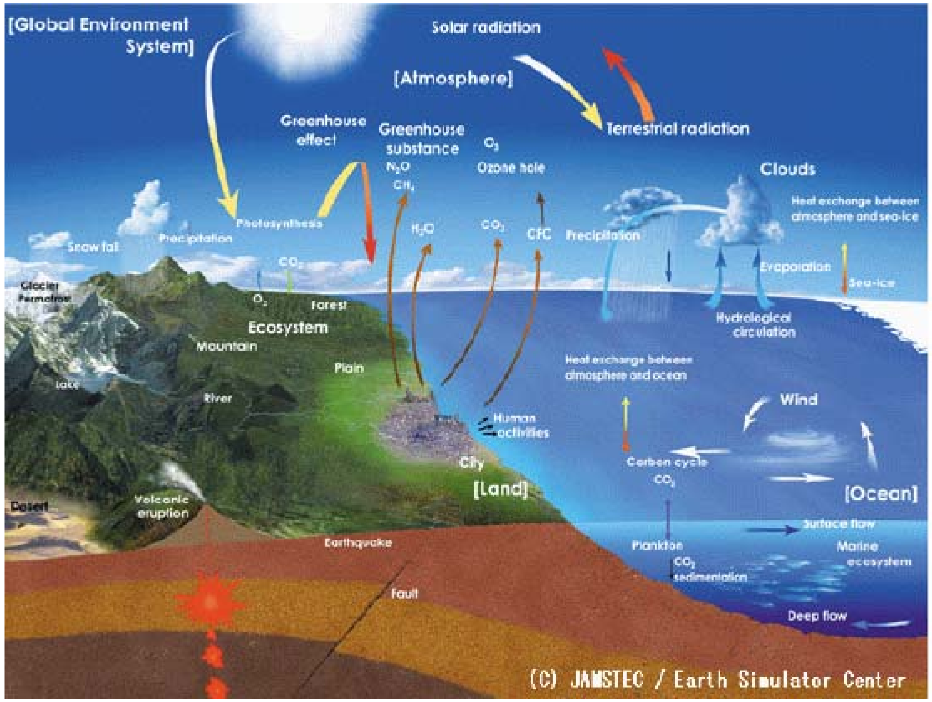
10^5

Centennial
Multicentennial and > variability

10^6

Atmosphere and land

Upper Ocean and Sea Ice



Deep Ocean

Ice Sheets

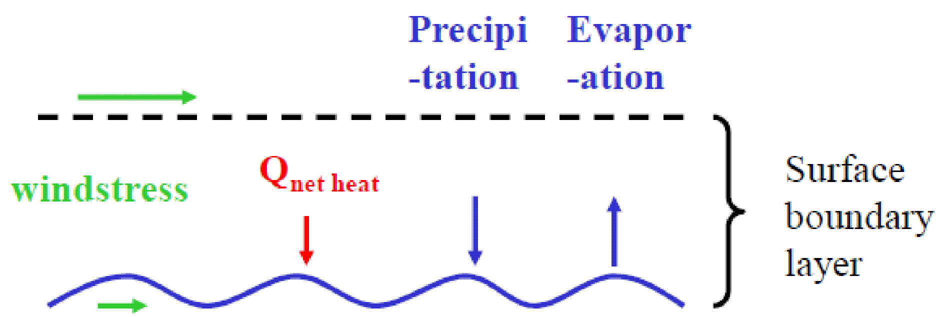
Biosphere
Carbon cycle

From R. Sutton

Ocean-Atmosphere Interaction

- The atmosphere and the ocean interact continuously
  - Fluxes of heat, fresh water and momentum
  - Surface heat flux: Radiative flux + turbulent fluxes

- Radiative flux:
  $Q_{rad} = Q_{DSW}(1\text{-}A) - \varepsilon\sigma(SST)^4 + Q_{DLW}$
- Sensible heat flux:
  $Q_{sens} \propto |u_{wind}|\ (T_{atmos}(Z_{ref}) - SST)$
- Latent heat flux:
  $Q_{lat} = -L_{evap}\, E$
  $\propto |u_{wind}|\ (q_{atmos}(Z_{ref}) - q_{sat}(SST))$



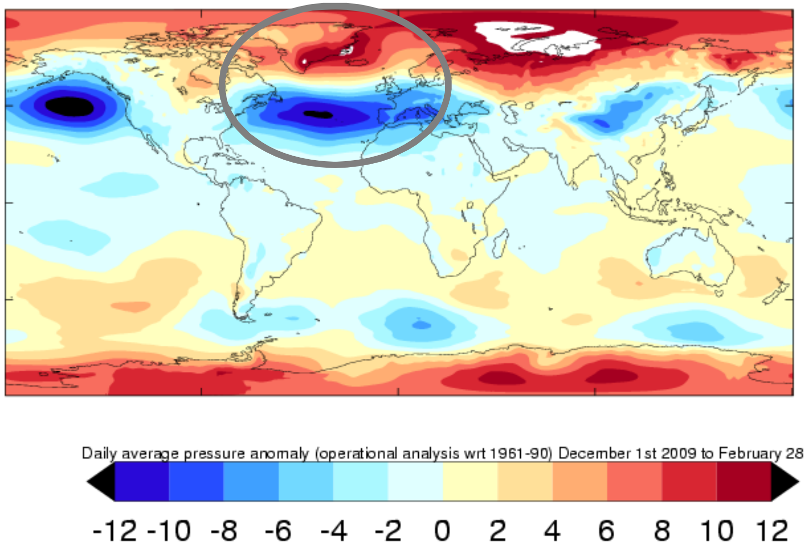
From R. Sutton

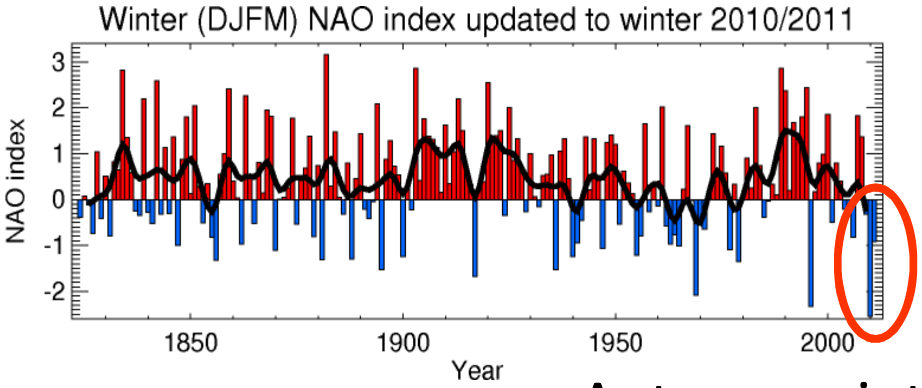
1) Climate variability

Dijon; 15Sep-30Jan
2009/2010

Dijon; 15Sep-30Jan 2009/2010

SLP Observations





IMPACTS:
Flights delays
(one night at the
Lyon airport at
Christmas time)

Autumn-winter 2009/10 ➔ –NAO

Weather Regimes to describe Dijon climate in autumn/winter 2009?

Dijon; 15Sep-30Jan 2009/2010

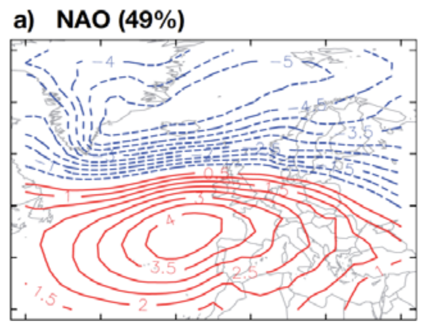
From WR we can: Discriminate important information from huge amount of data for autumn/winter 2009, But:
Can we say anything about the seasonal cycle?
Can we say anything about the interannual variability?
Can we say anything about the decadal variability?

WRs from daily data can contain all the information of the variability, from synoptic to multidecadal

Why the statistics?

- **large** datasets
  – i.e., model/reanalysis grids or observation networks, CMIP5 archive…
- **redundant** information
  – i.e., strong correlation between nearby grid-boxes
- **noisy** data
  – e.g., weather "noise" masking decadal variability or long-term trends

➢ extract "relevant" information from large datasets



Atmospheric data classification: some History

- **Weather Regime approach**
- **Climatology:** How to compose a conceptual construction of what is really observed and felt (indexes, statistical and dynamical models, etc..) in order to better understand the climate system.
  - Before XVIIth century: Empirical knowledge of climate conditions (e.g. seasonal monsoon, dry/wet season,…)
  - Between XVIIth and XIXth:
    . Thermometer, anemometer, rain gauges
    . G. Hadley (1735): relationship between trade winds and Earth rotation
    . B. Franklin (1785): first map of the « Gulf stream »
  - From XXth century:
    . G. Walker (1920): relationship between ~Azores and ~Icelandic barometric conditions = NAO
    . G. Walker (1923): relationship between eastern and western pacific barometric conditions = El Nino

Atmospheric data classification: some History

- **All the attempts to explain climate conditions / variability through gradients, oscillations, dipolar structures, etc. = first kind of statistical summary of the complex climate variability**
- From the middle of the XXth: « *meteorological conditions recorded at one station depend on geographical characteristics but also on synoptical atmospheric circulation* »
- ➔ A kind of local/regional meteorological condition is often associate with a kind of synoptical circulation that appears regularly and could stay several consecutive days
- From the 70s: The question is: ***« is there always a link between the felt and measured weather at one point and one type of synoptical circulation ? »***
- ➔ **birth of the synoptical/dynamical meaning of « weather classifications »** and concepts such as « cyclonic and rainy weather », « zonal and mild weather », etc. (also thanks to technologic development such as aviations, aerology and metorological satelites that offers new atmospheric datas)

Atmospheric data classification: some History

- Weather classification was forgotten in climatology until the 90s and then back in fashion with (I) spatialization of atmospheric data (ii) reanalysis that offers the possibility of using robust statistical/mathematical algorithms for clustering and (ii) with the study of the climate as a multiscalar dynamical system.
- E.g. first « main » papers presenting the classification of an atmospheric field:
  - **Vautard in 1990**: clustering algorithms applied on gridded (10°) daily 700 hPa geopotential heigh = 4 weather regimes for the northern hemisphere
  - **Michelangeli in 1995**: clustering algorithm used with the first reanalysis fields of the NOAA (700 hPa) = 4 weather regimes for the northern Atlantic

. Weather classification into « weather regimes » also back in fashion with the development of GCM's = a good tool to validate global climate models and to project circulation in the future

Atmospheric data classification: some History

- **And today, questions are still posed:**
  - are there links between the regional/local atmospheric conditions and some recurrent kind of atmospheric circulations ?
  - What are « multilateral » interactions between the different spatio-temporal modes of atmospheric variability that could explain « teleconnections » between scales ?
  - How the « system » works ? Is is predictable ? Well reproduced in numerical simulations ?

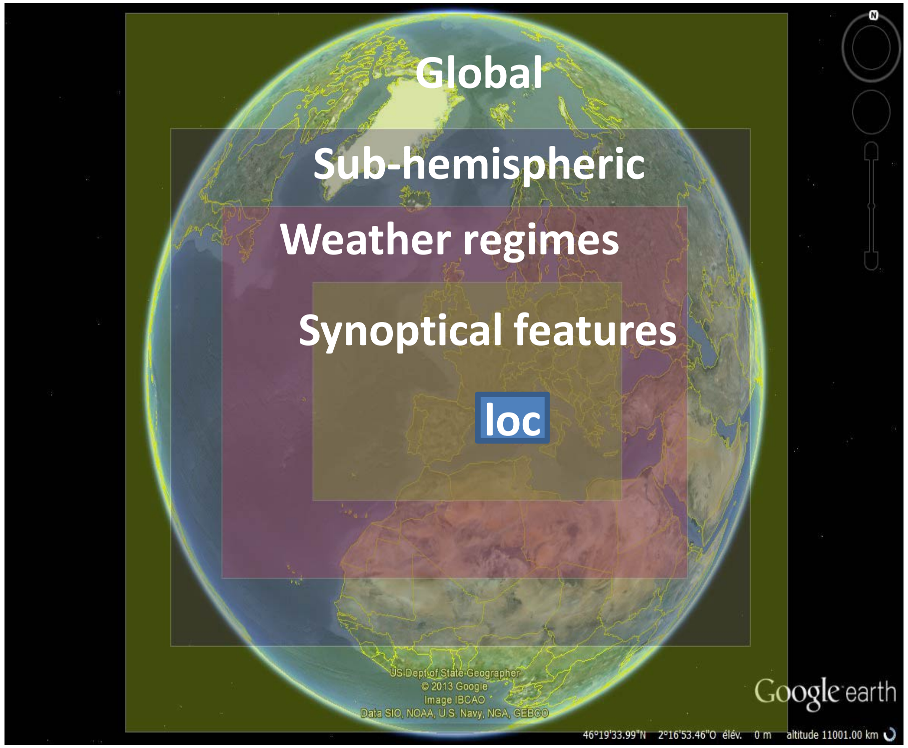


Figure courtesy of A. Ulmann

Weather regimes are one of the spatio-temporal modes of atmospheric variability (~ 30-40 millions km2, 2-10 days)

Weather Regime

Climate variability could be defined by non-linear methods extracting ‘weather regimes’

“weather regimes”: preferred atmospheric states. They are stablished by using their properties:

1) ***Recurrence*** (maximum probability of ocurrence)
2) ***Persistence*** (>= 2 days)
3) ***Quasi-stationarity*** (in the statistical sense, atmosphere states in which the large-scale movements are stationary)

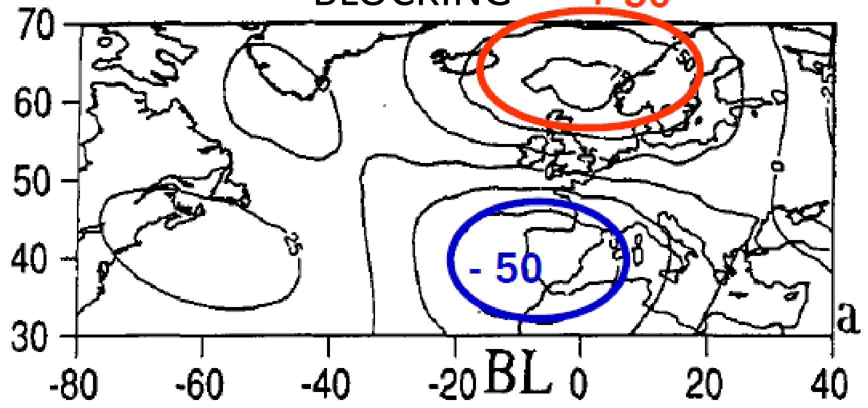
We need the probability density function of the atmospheric variables in a region and using techniques based on clusters

“The present knowledge of the atmosphere allows us to infer that low-frequency variability in the extratropics is mainly due to the alteration between several *Weather regimes*, during which the large-scale atmosphere is quasi-stationary interrupted by transitions periods” (Vautard, 1990)

Weather Types

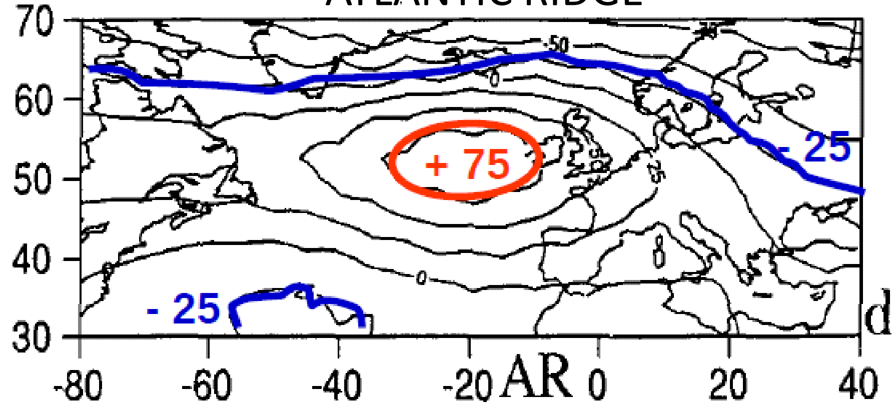
Vautard and Legrad (1988) with non-linear method and from daily Z700 data for 37 winters (1949-1985) finding 4 main types

BLOCKING



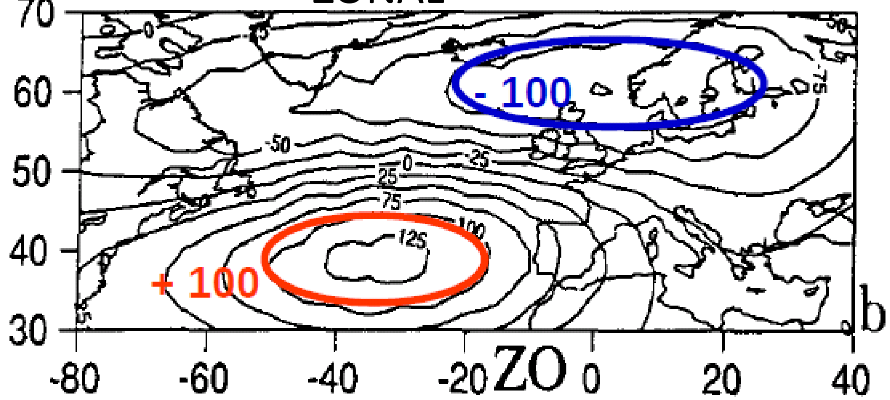
Dipolar pattern: Easterly winds

ATLANTIC RIDGE



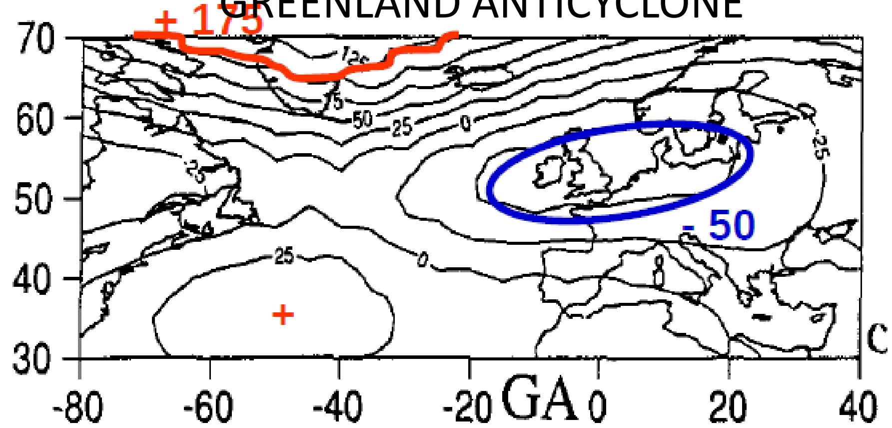
Anticyclone over Atlantic

ZONAL



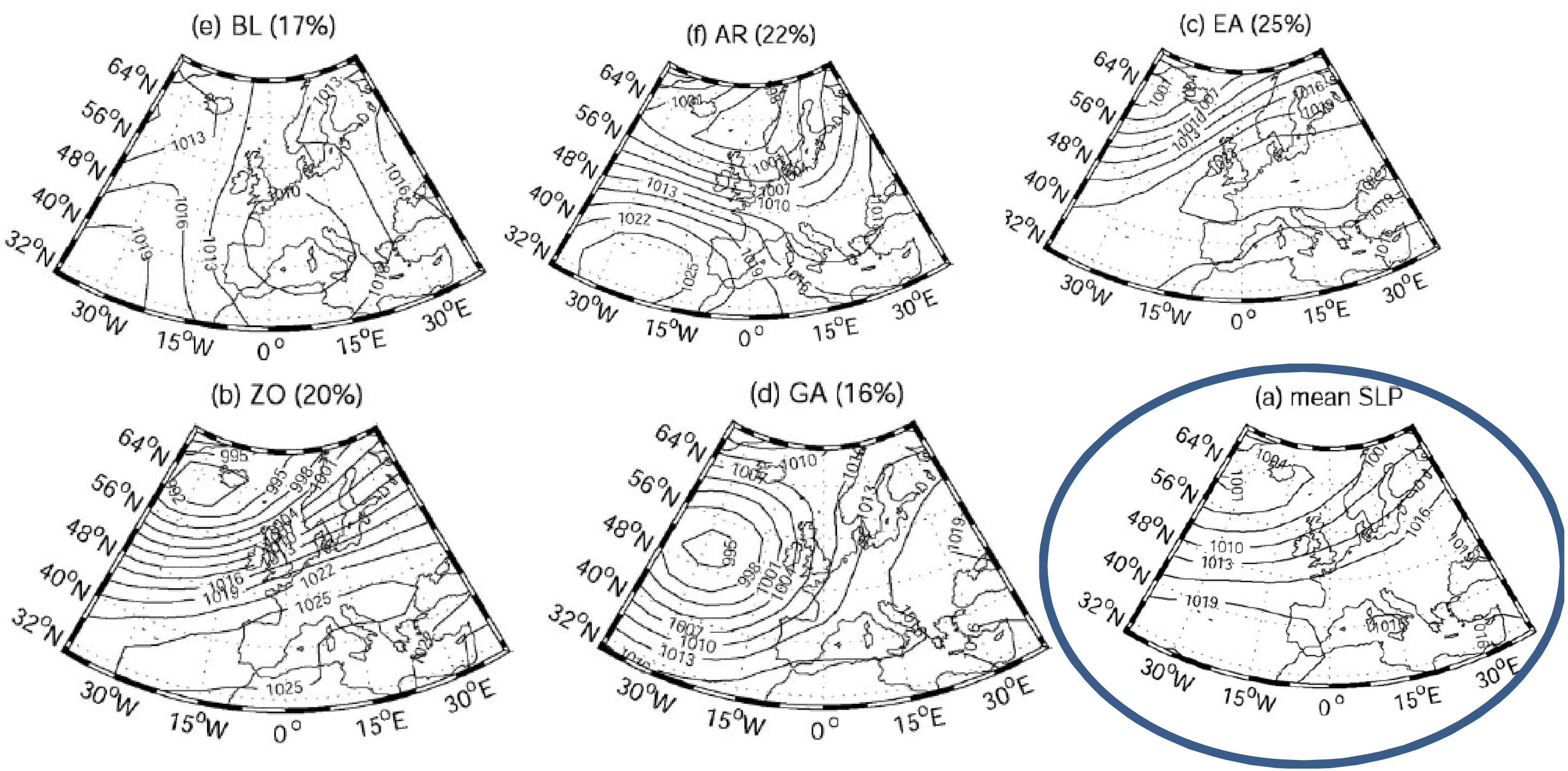
strengthening of the western Atlantic jet

GREENLAND ANTICYCLONE



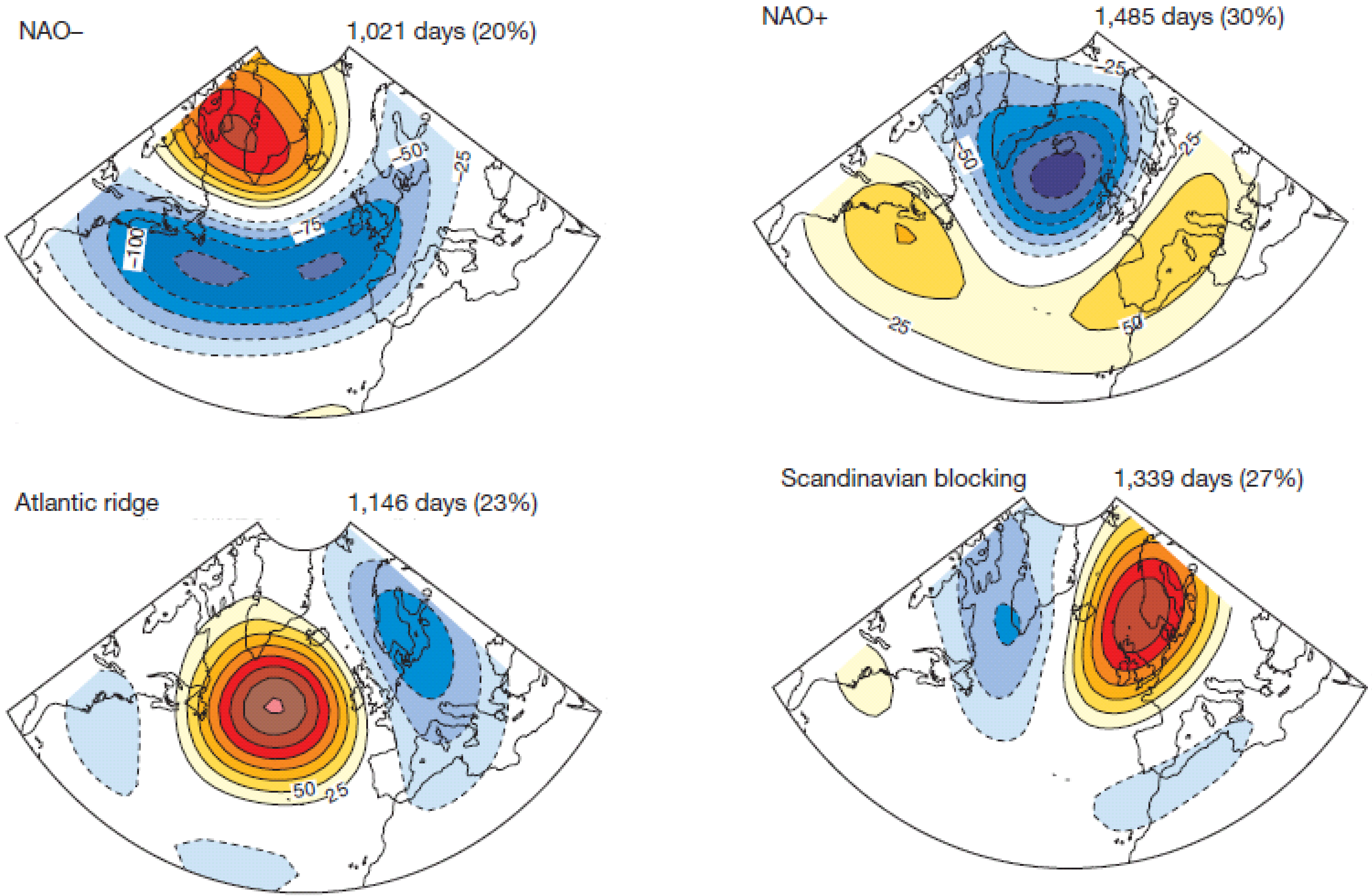
Synoptic perturbation can crossed Europe

Weather Types

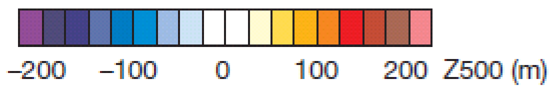


from Oct-March SLP daily ERA40, Ullmann and Moron (2006)

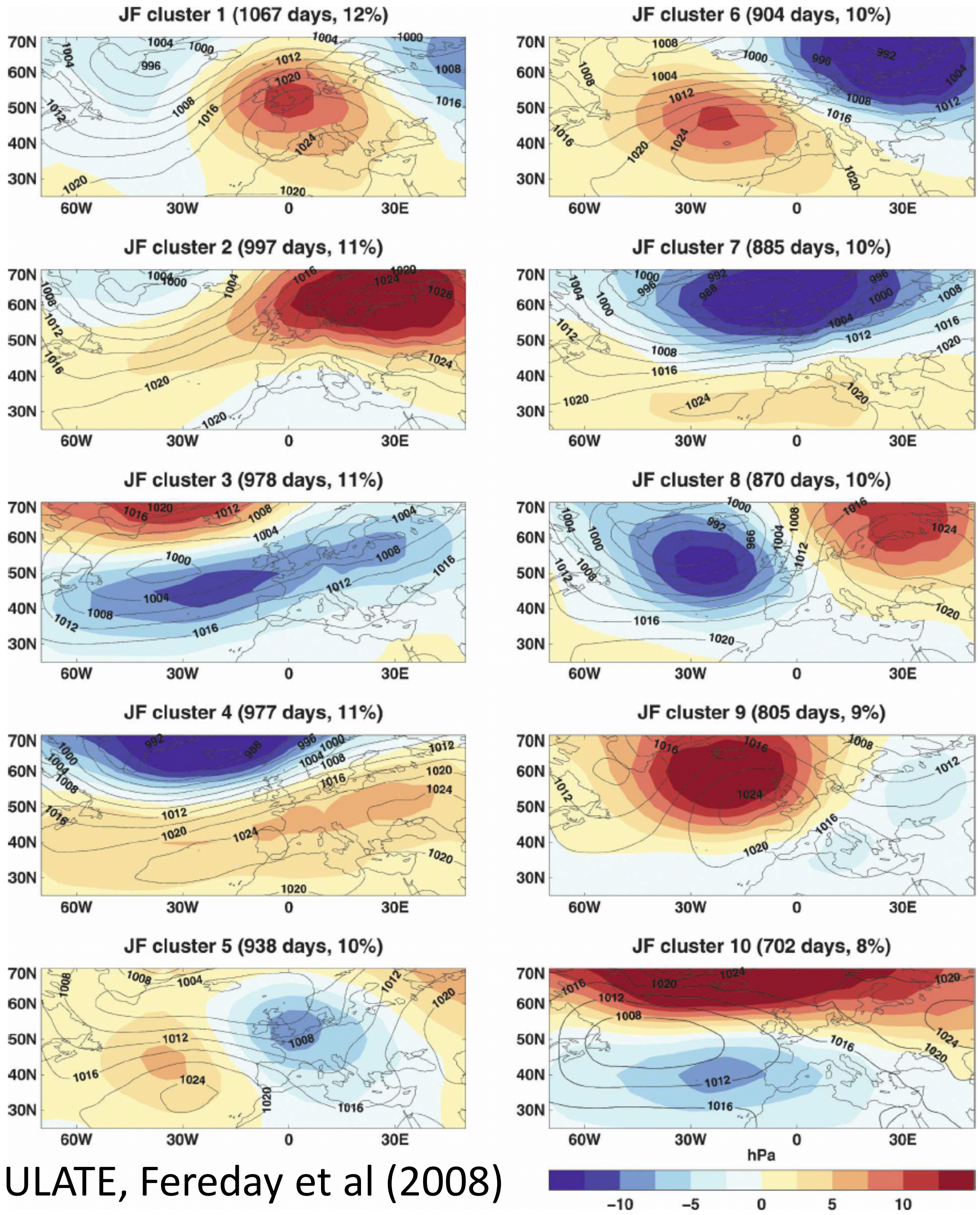
Weather Types



From winter z500 daily ERA40, Cassou (2008)

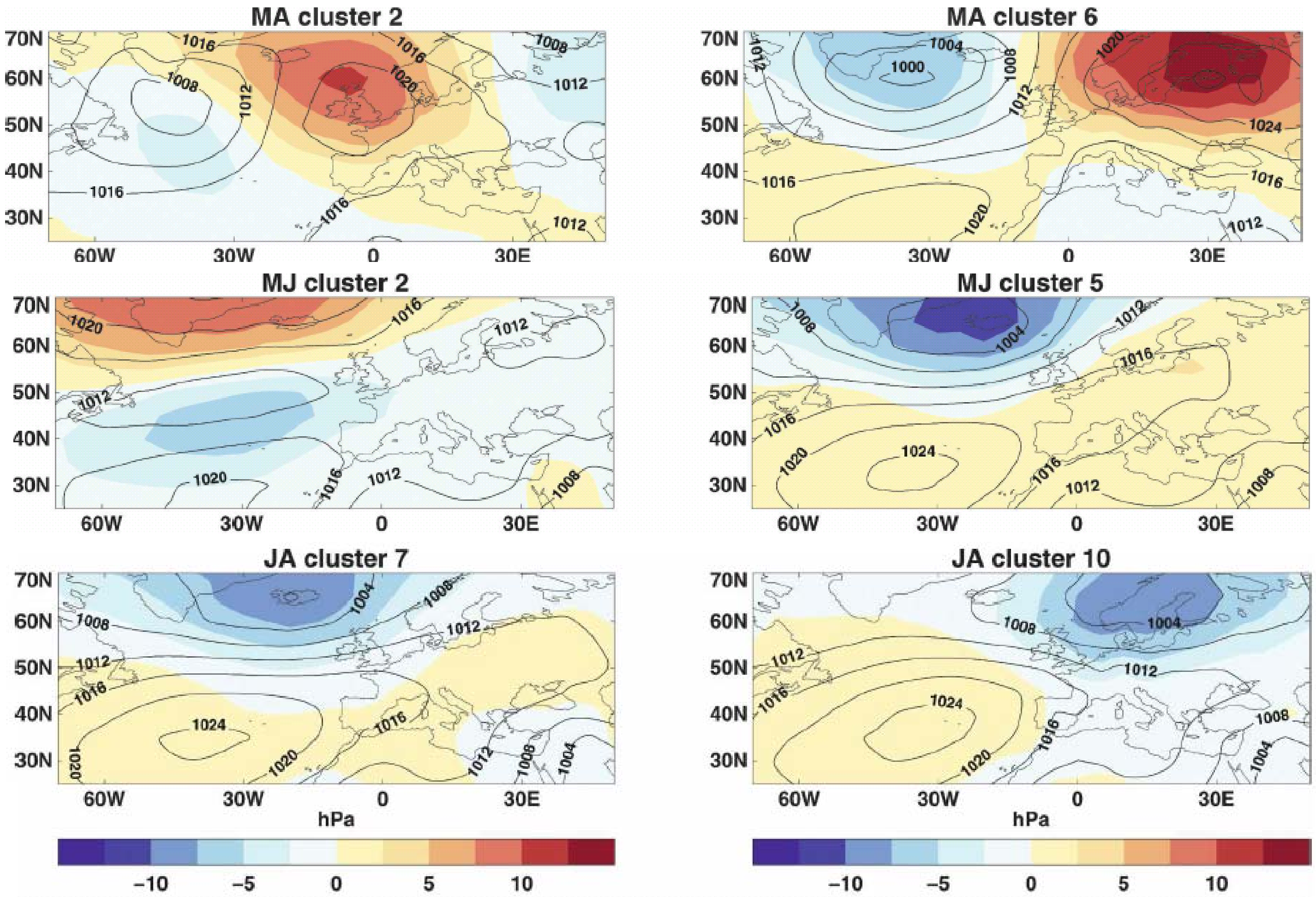


Weather Types



From JF SLP daily EMULATE, Fereday et al (2008)

Weather Types
What about the summer?



March-April

May-June

July-August

From SLP daily EMULATE, Fereday et al (2008)

Weather Types
What about the summer?

- For weather classification we need:

  -DATA: Summer variables over Euro-Atlantic

  -METHOD: SOM

  -SCIENTIFIC QUESTIONS:

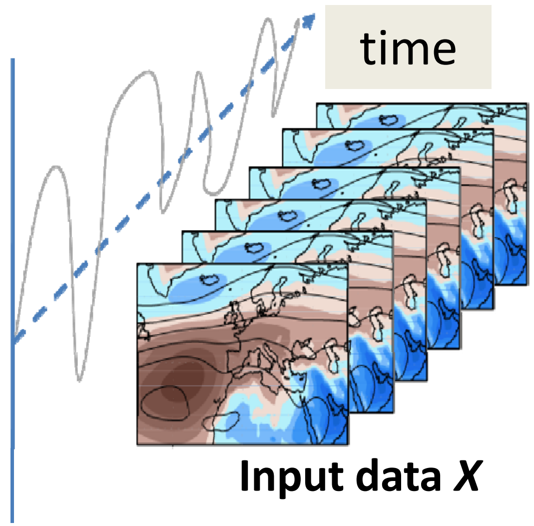
    * Characterization of summer WR?

    * Do the GCMs project onto WR? (i.e. Models reproduce natural variability?)

    * Do changes in boundary conditions change WR features? (i.e. if North Atlantic is warm do I get more –NAO??. If the Mediterranean Sea is warm do the WR frequency change?

Multivariate data

- Variables: INPUT data ERA-int
  - -Sea Level Pressure
  - -700hPa geopotential height
  - -specific humidity at 700hPa



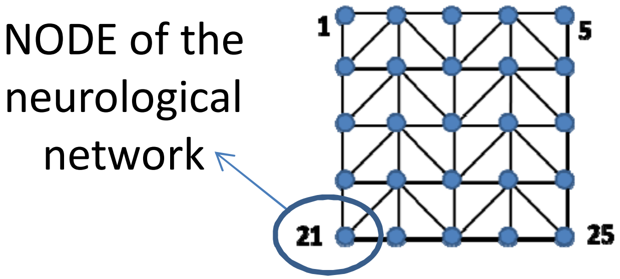
- Time-step: Daily
  - Daily
  - May-June-July-August-September-October
  - and period 1989-2008
- Each grid point characterized by 3 dimensions: longitude, latitude and variables (SLP*700hPa)
- Standardized units for more than 1 variable

Self Organizing Maps

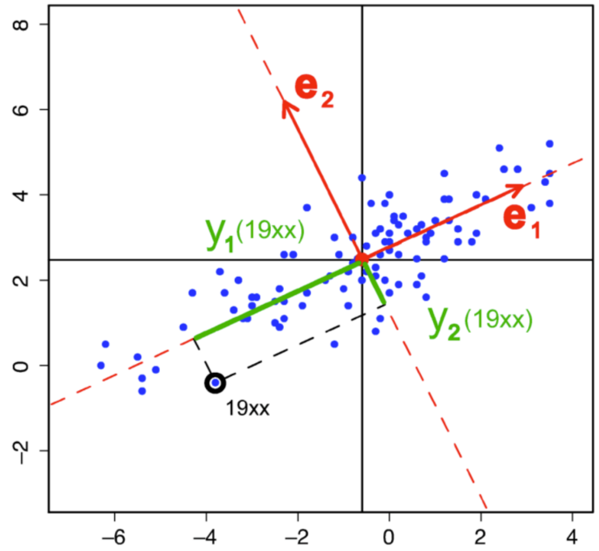
- SOMs is an unsupervised neuronal network method used to visualize and interpret large high-dimensional data sets. It has been invented in the 80's by Teuvo Kohonen
- Map of a regular grid of "NEURONS". The map attempts to represent all the available observations with optimal accuracy using a restricted set of patterns. At the same time the patterns become ordered on the grid so that similar patterns are close to each other and dissimilar patterns far from each other
- The algorithm exposes the input data X to a layer of neurons which have a weight verctor of Ndimension

Self Organizing Maps

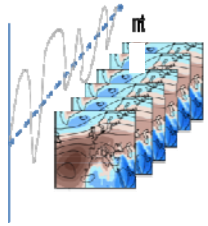
- Phase 0): Initialization of (a priori)
  - Number neurons: 25
  - Neighbourhood function => Gaussian
  - Learning rate coefficient (determine the velocity of system to adjust in time) => 0< α <1
  - Lattice (how the neurons are connected, i.e. topological map) => hexagonal grid



Initialization linear: Weight vectors are spanned in subspace of 2 leading Eigvectors



Self Organizing Maps



- INPUT LAYER N-dimension $X_i \Rightarrow \quad i = 1 \cdots m$
- NEURONS N-dimension $j = 1 \cdots n$
- WEIGHT VECTOR W_j
- Phase 1) At each X new input is exposed to the Neurons in an iterative process, where:
    - Neurons compete for being the "winner" Wc or Best Matching Unit (BMU)

$$d = \left| X - Wc \right| = \min_j \left| X - W_j \right| \quad \forall j$$

Self Organizing Maps

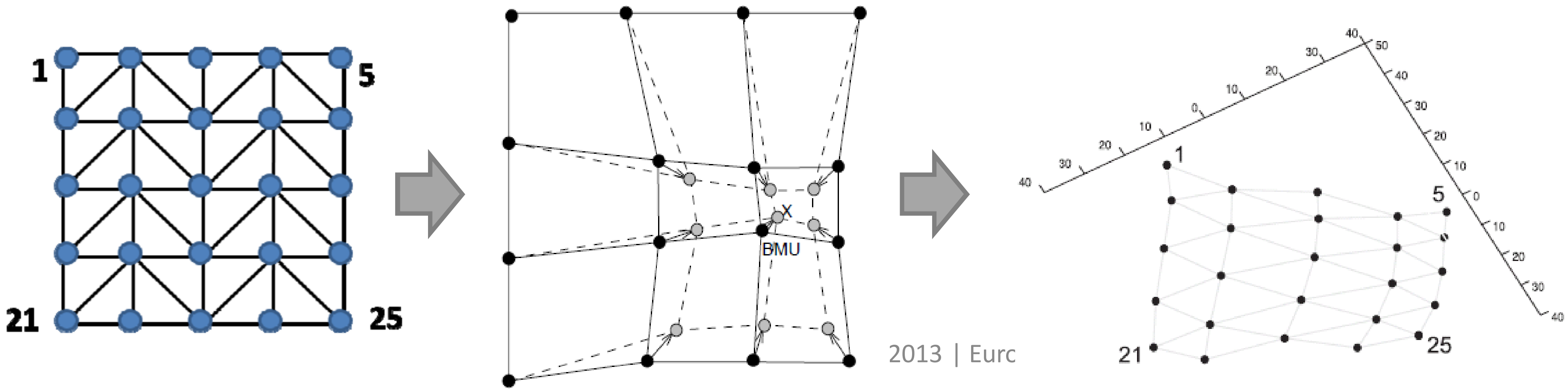
- <u>Phase 2)</u>: BMU and its neighbours are updated onto direction of *X*

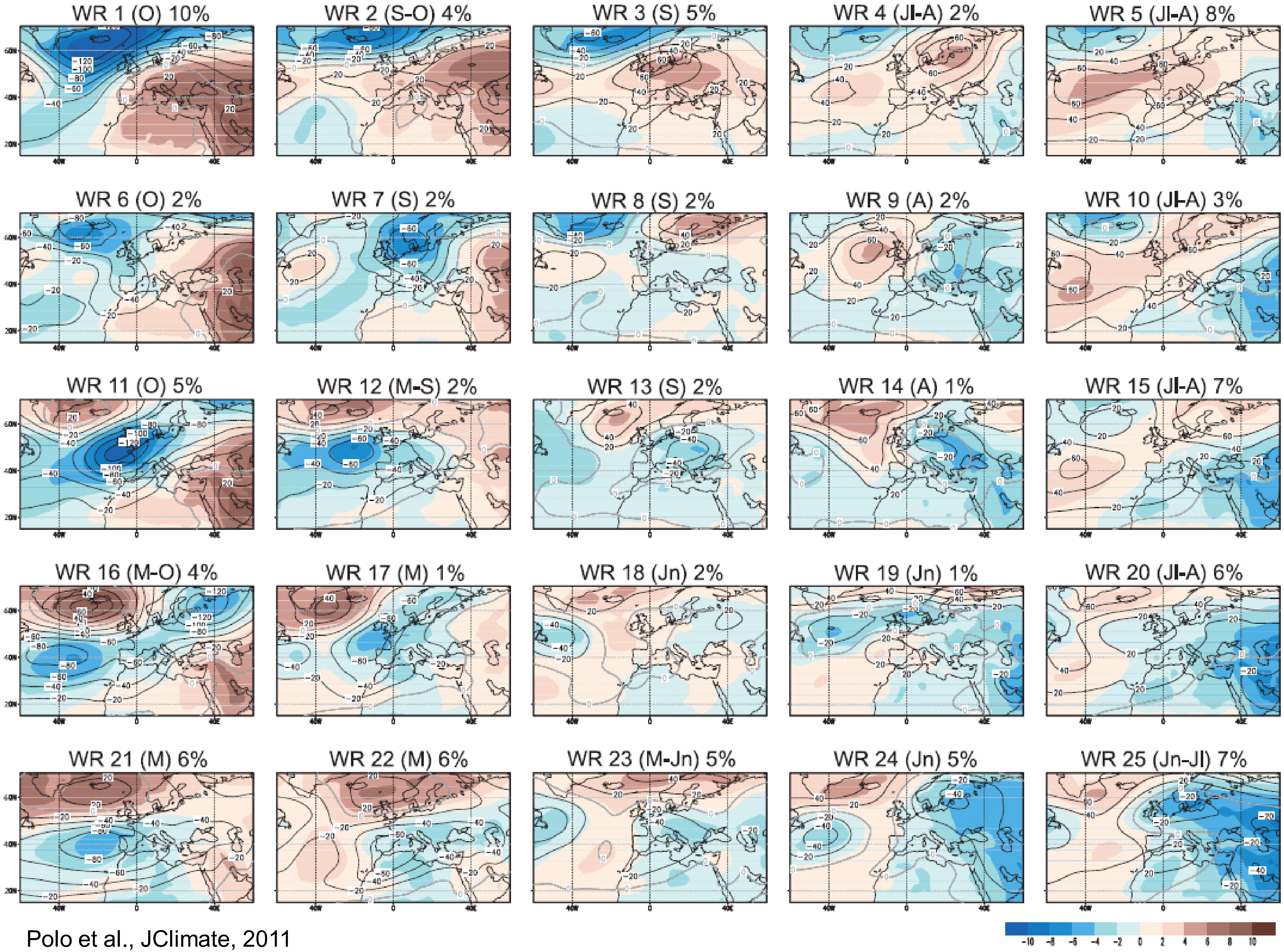
$$\begin{cases} \dfrac{dW_j}{dt} = \alpha(t)(X - Wc) & j \in N_c \\ \dfrac{dW_j}{dt} = 0 & j \notin N_c \end{cases}$$

Learning coefficient $0 < \alpha < 1$

-The process continues in random order until Wj are stabilized (convergence)

- ➔ Finally each daily field is classified into **one and only one** of the BMUs (criterion of minimum Euclidean distance)
Composite map = SOM; SOM+ Persistence(>2days) = WR

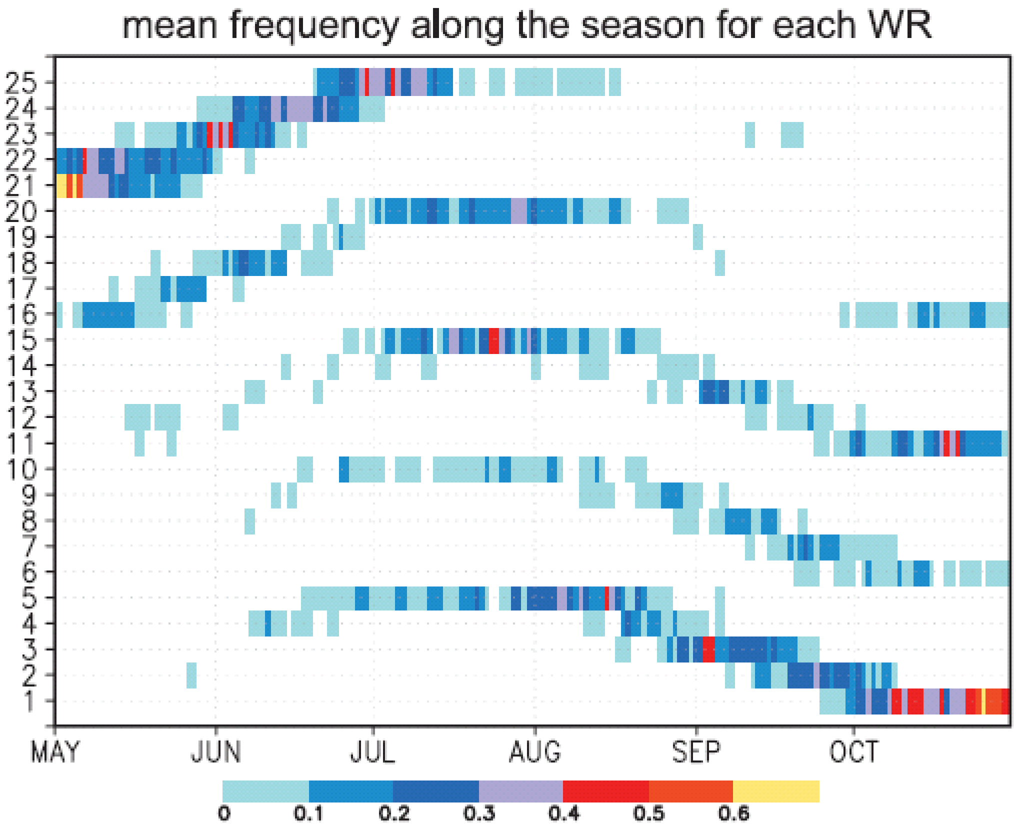


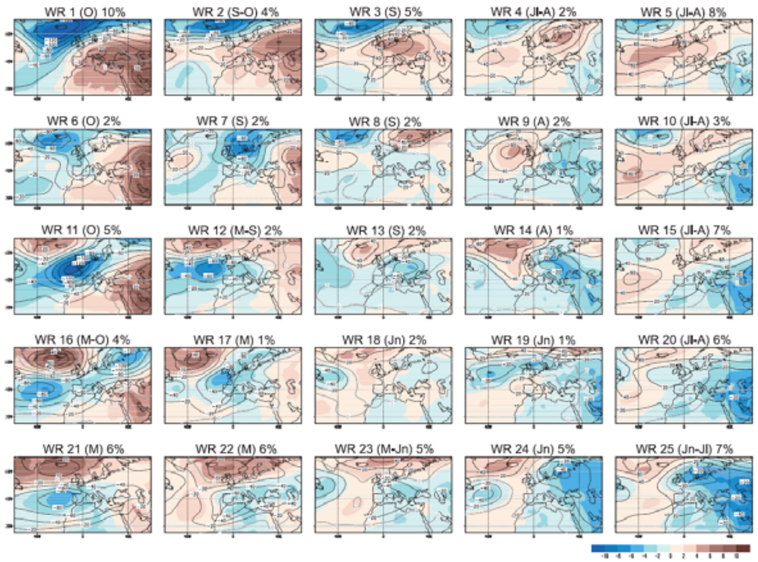


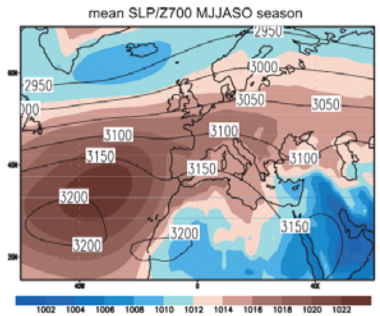
Polo et al., JClimate, 2011

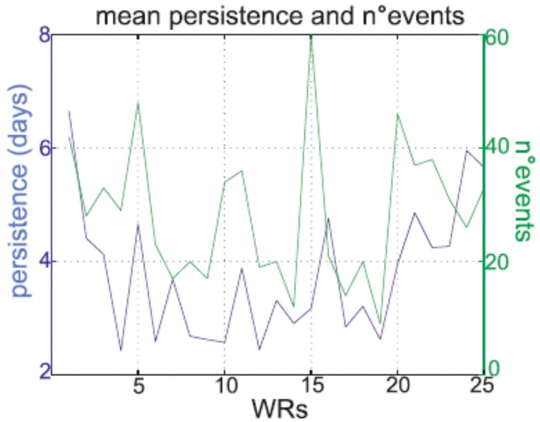
3) Summer WR

Character: Seasonal cycle





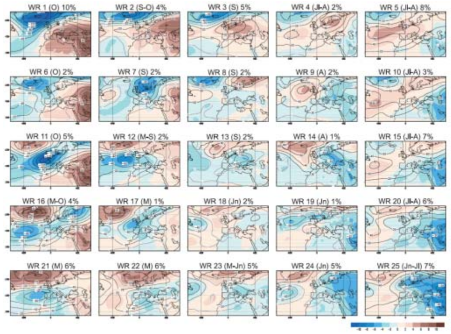


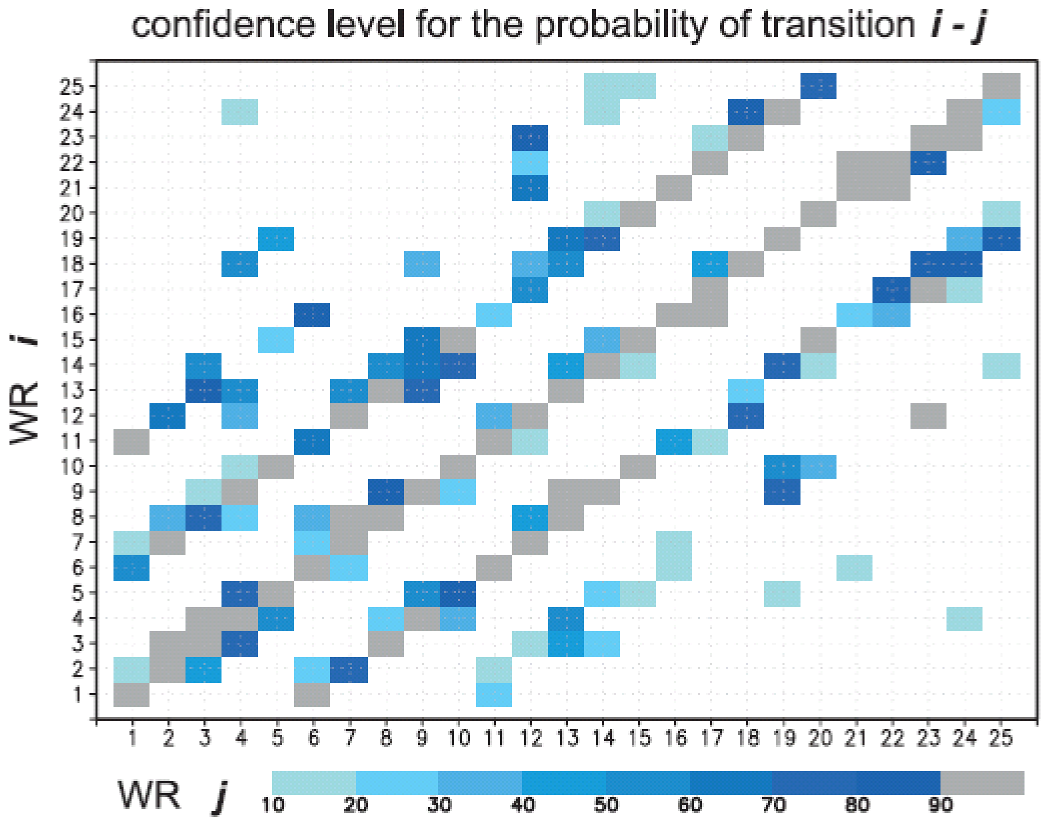


Polo et al., JClimate, 2011

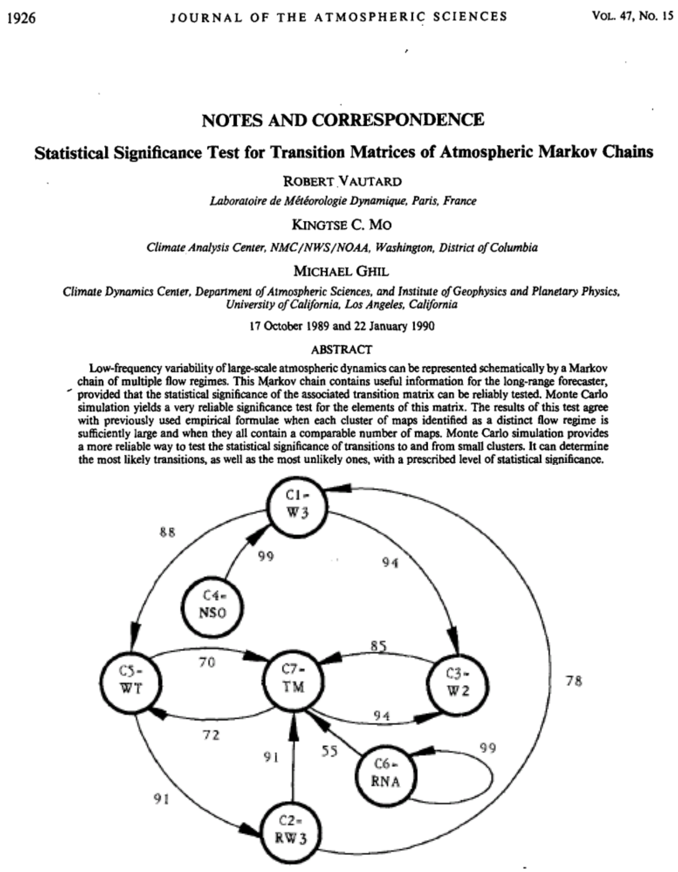
Character: Transitions

3) Summer WR





Polo et al., JClimate, 2011



1926 JOURNAL OF THE ATMOSPHERIC SCIENCES VOL. 47, NO. 15

NOTES AND CORRESPONDENCE

Statistical Significance Test for Transition Matrices of Atmospheric Markov Chains

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17 October 1989 and 22 January 1990

ABSTRACT

Low-frequency variability of large-scale atmospheric dynamics can be represented schematically by a Markov chain of multiple flow regimes. This Markov chain contains useful information for the long-range forecaster, provided that the statistical significance of the associated transition matrix can be reliably tested. Monte Carlo simulation yields a very reliable significance test for the elements of this matrix. The results of this test agree with previously used empirical formulae when each cluster of maps identified as a distinct flow regime is sufficiently large and when they all contain a comparable number of maps. Monte Carlo simulation provides a more reliable way to test the statistical significance of transitions to and from small clusters. It can determine the most likely transitions, as well as the most unlikely ones, with a prescribed level of statistical significance.

- For each WR (t) compute frequency (t+1) ➔ Transition Matrix
- Significance for transitions with MonteCarlo test

Example: Model projection

- Are the AGCM reproducing variability (WR)? How different is from observations?
  - The reproduce some part of the variability of the real world BUT with a bias

Table 2. Weather Regime Frequency of Occurrence in the ERA40 Reanalysis and in the CNTL Experiment for the Five AGCMs, Shown as a Difference to ERA40[a]

	Weather Regimes (%)			
	BL	ZO	AR	GA
ERA40	24	30	24	22
ARP	+2	0	**−9**	**+7**
HAD	0	+1	**−6**	**+5**
ECH	+1	−3	**−3**	**+5**
IAP	−2	**−4**	**−4**	**+10**
CAM	−1	**−4**	−1	**+6**

[a]The significant differences at 95% significance level are indicated in bold.

Sanchez-Gomez et al., GRL, 2008

Example: Model projection

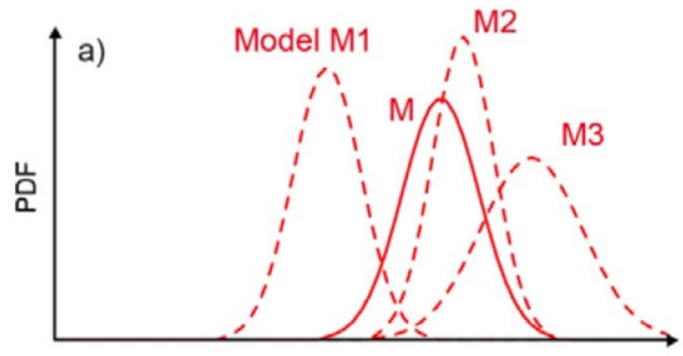
- Projection consists in classifying each X input model data according with the observed SOM

$$\Pr oj\,[m,nt] = SOM\,[ns,m] * Ens\,[nt,ns] \quad / \max \,\&\, > 0$$

$$Dist = \sqrt{\sum_j SOM - Ens} \quad / \min$$

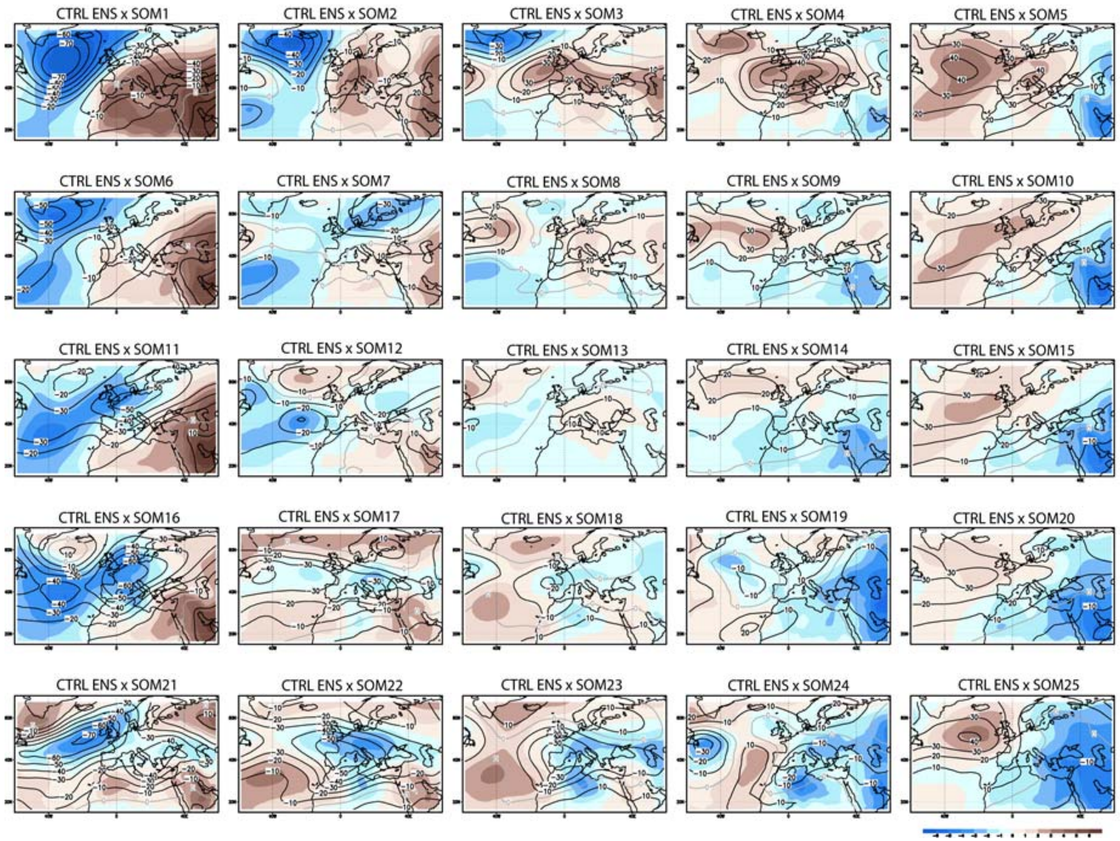
+ Persistence

Significance: Permute Ens
if Proj>ProjPerm ➔ c=c+1
➔ Sig=(1-c/nperm)100



Example: Model projection

- 2 AGCMs: UCM (UCLA) and CNRM (ARPEGE)
- ➔ Ensemble Mean of 10 runs each CTRL (forced with global SST climatology)

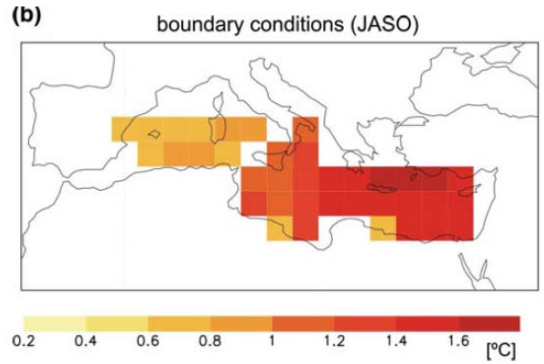


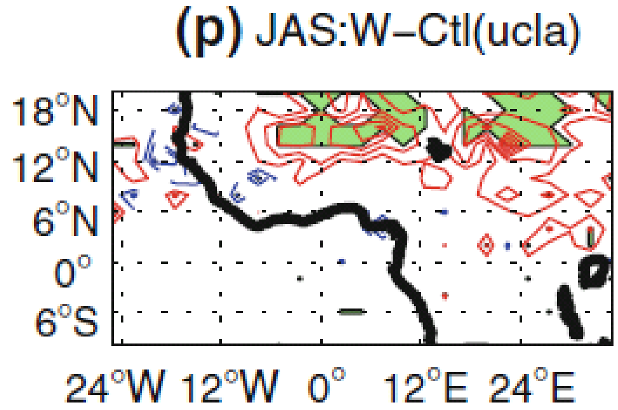
Example: Air-sea interaction

- Changes in WR frequency due to SST forcing
  – Interannual change in the WR frequency due to Temperature anomalies over the Mediterranean Sea

AMMA: Multi-model study of the atmospheric response to anomalous Mediterranean SST and West African Monsoon

– ARPEGE-Climat Version 3 IPCC-AR4 in truncature 42 with 45 levels run at CNRM (Centre National de Recherches Météorologiques, Météo-France)
– ECHAM Version 4 in truncature 30 with 32 levels run at ENEA (Italian National Agency for New Technologies, Energy and Environment)
– LMDZ Version 4 (96 long, 71 lat and 19 levels) run at IPSL (Institut Paul-Simon Laplace)
– UCLA Version 7.3 (2° long × 2.5°lat, 29 levels) run at UCM (Universidad Complutense de Madrid)

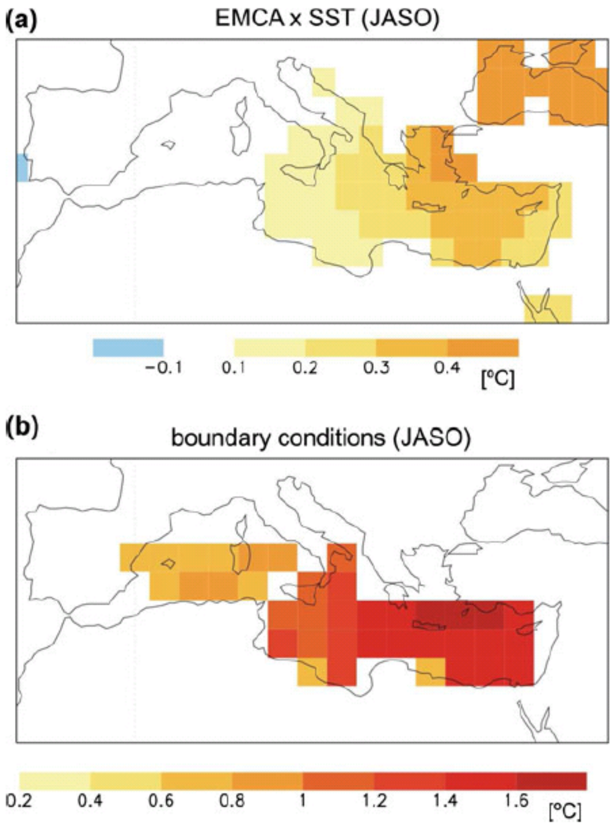


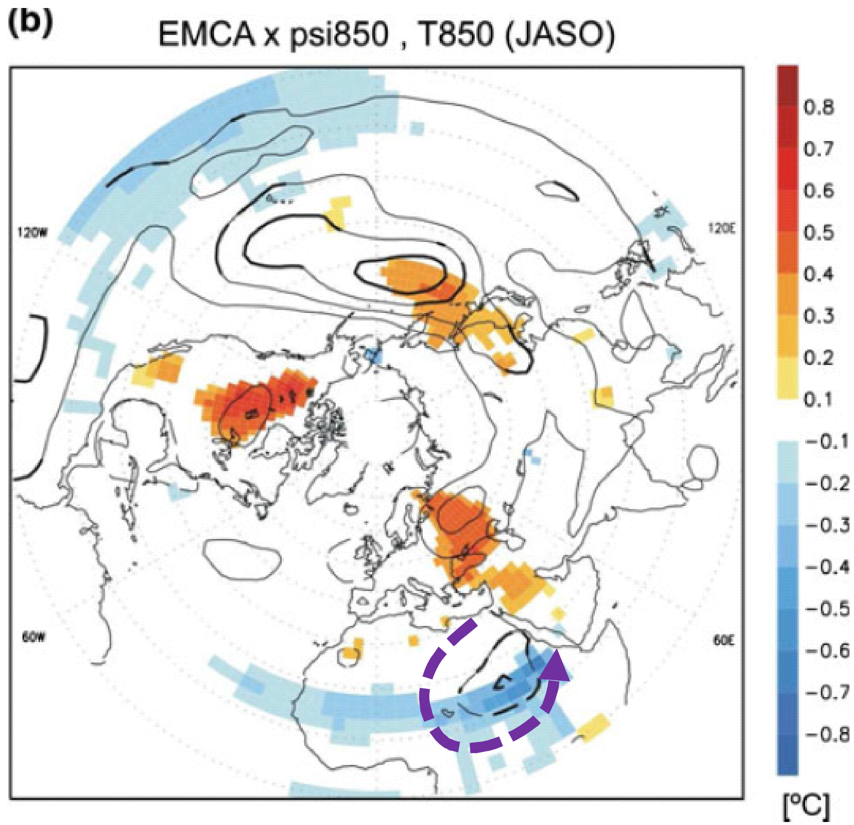


Fontaine et al., ClimDyn, 2010

Example: Air-sea interaction

- Changes in WR frequency due to SST forcing
  - Forced experiment: Med Positive, Med Negative and climatology elsewhere

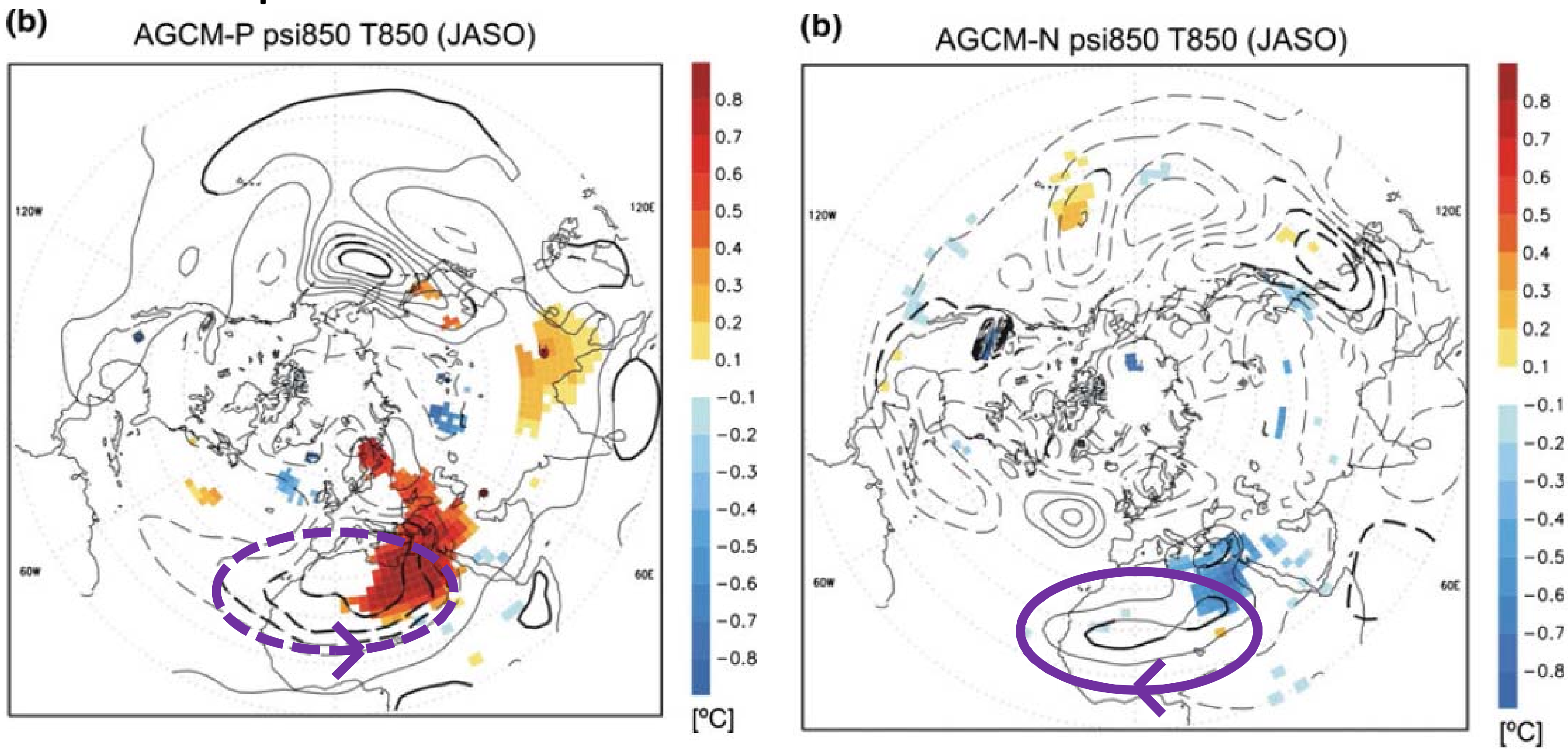




Garcia-Serrano et al., ClimDyn, 2013

Example: Air-sea interaction

- Changes in WR frequency due to SST forcing
  - Interannual change in the atmosphere due to Temperature anomalies over the Mediterranean Sea

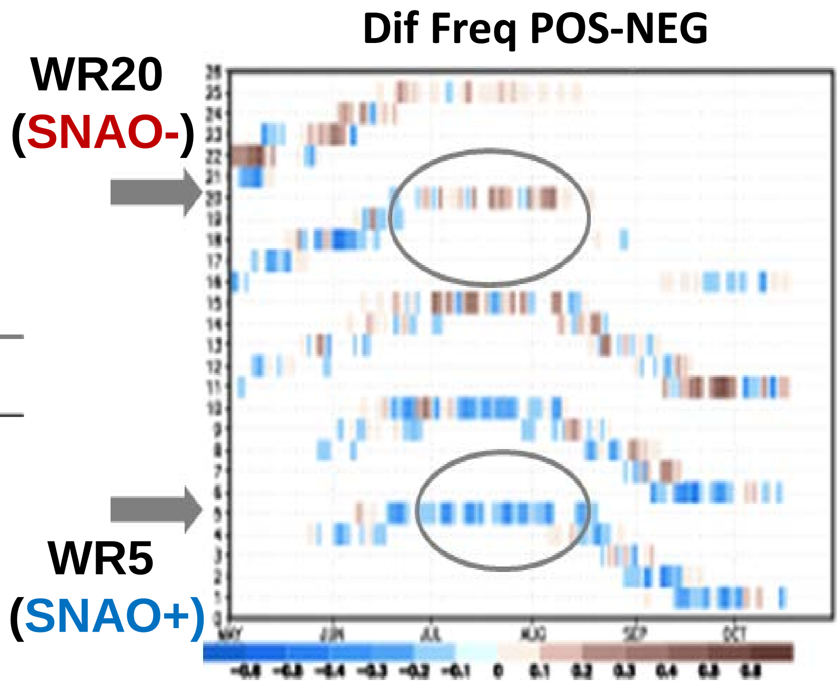


Garcia-Serrano et al., ClimDyn, 2013

Example: Air-sea interaction

- Changes in WR frequency due to SST forcing
  - Interannual change in the WR frequency due to Temperature anomalies over the Mediterranean Sea?

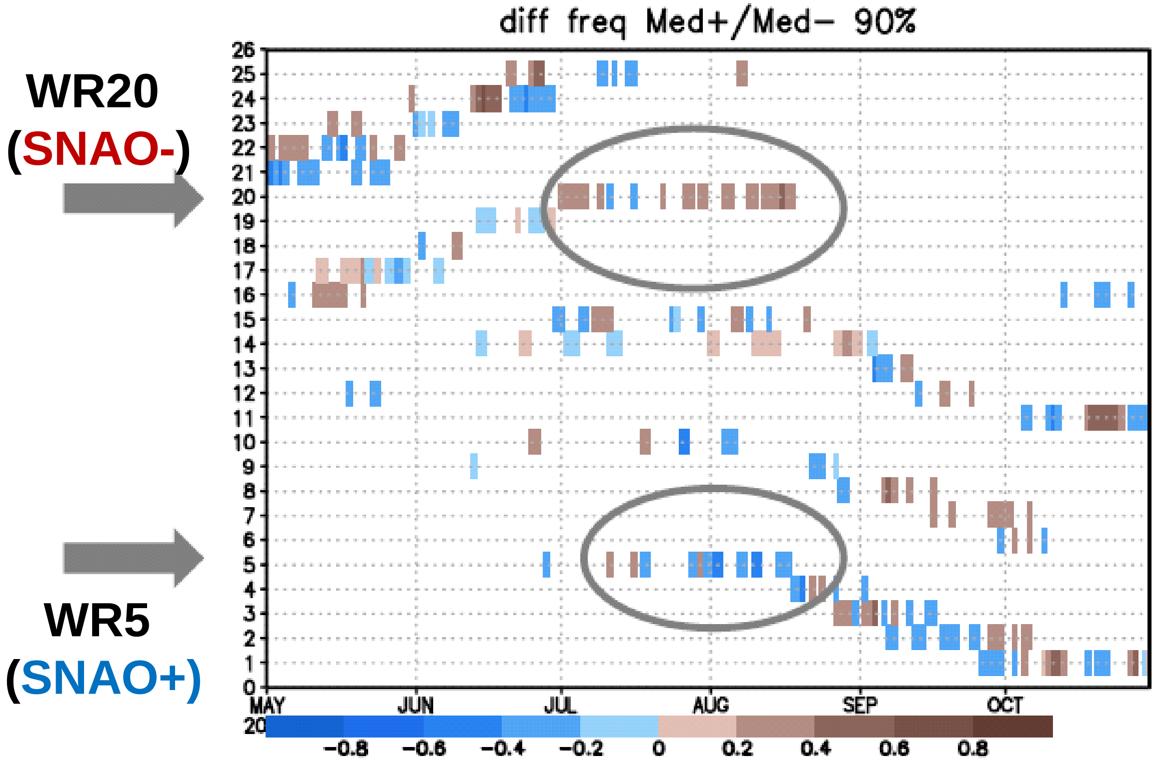
Frequency JJA (%)	CTRL-ENS UCM-CNRM	ENS MED-POS	ENS MED-NEG	OBS
WR20 SNAO-	16.2	17.3	10.3	10.2
WR5 SNAO+	11.9	4.2	16.3	18.5



Polo et al., EGUp 2010

Example: Air-sea interaction

- Changes in WR frequency due to SST forcing
  - These changes are also true for the observations



Example: Inter-decadal variability

- Changes in WR frequency due to SST forcing
  - AGCM have their own internal variability: noise
  - Atmosphere will respond to the boundary conditions (SST) forced variability: signal

- Changes in WR frequency/spatial pattern
  - Changes between periods

P2=[1979:2008]

P1=[1957:1978]

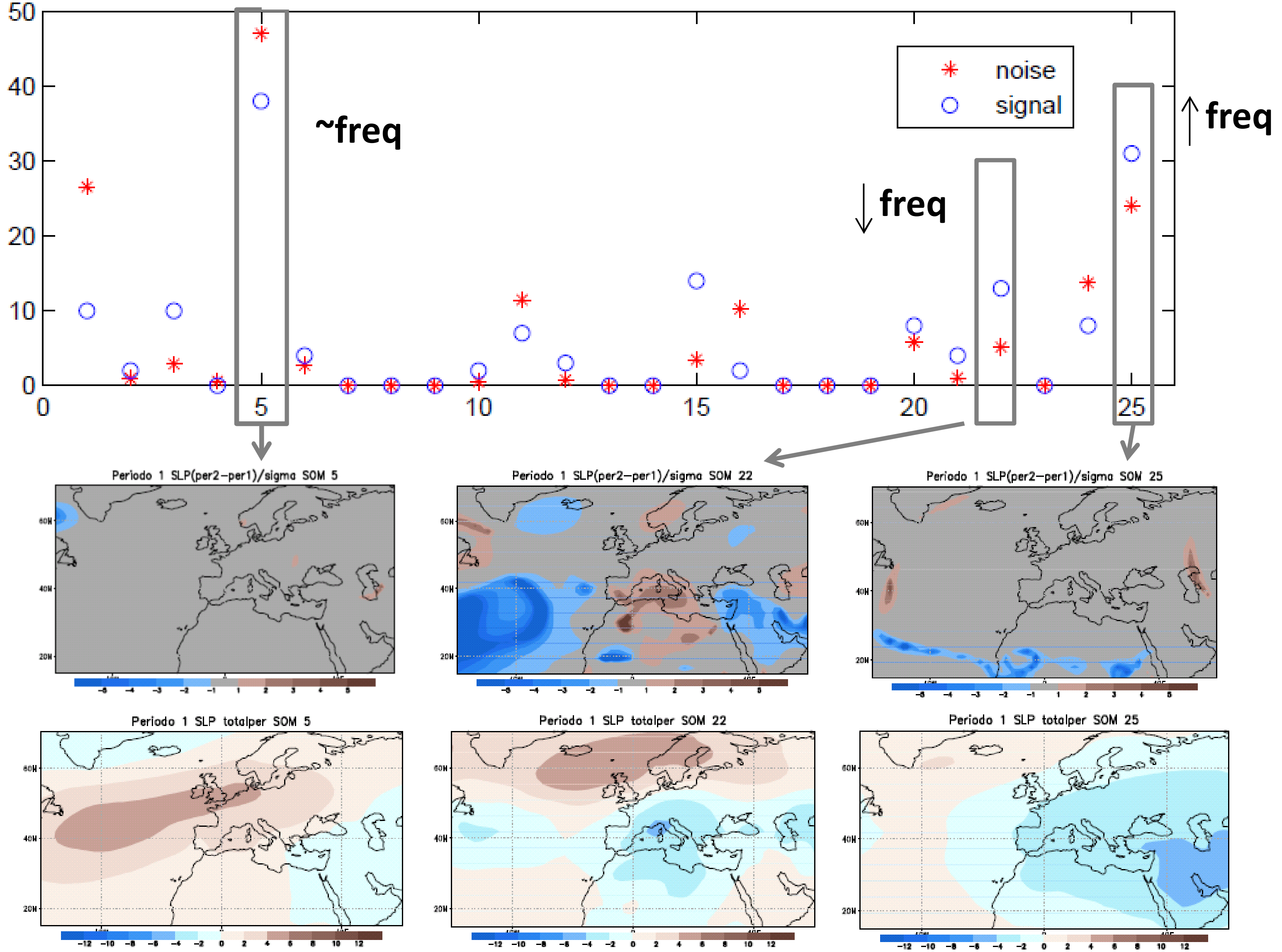
  - Projection WR onto GCMs outputs:

1 member of UCM- AMIP simulation

3 members of IPSL- AMIP simulation

Example: Inter-decadal variability

Number of days [Period2-Period1] & Sigma



NO change Freq/Spat	**Change Freq/Spat**	**Change Freq No change Spat**

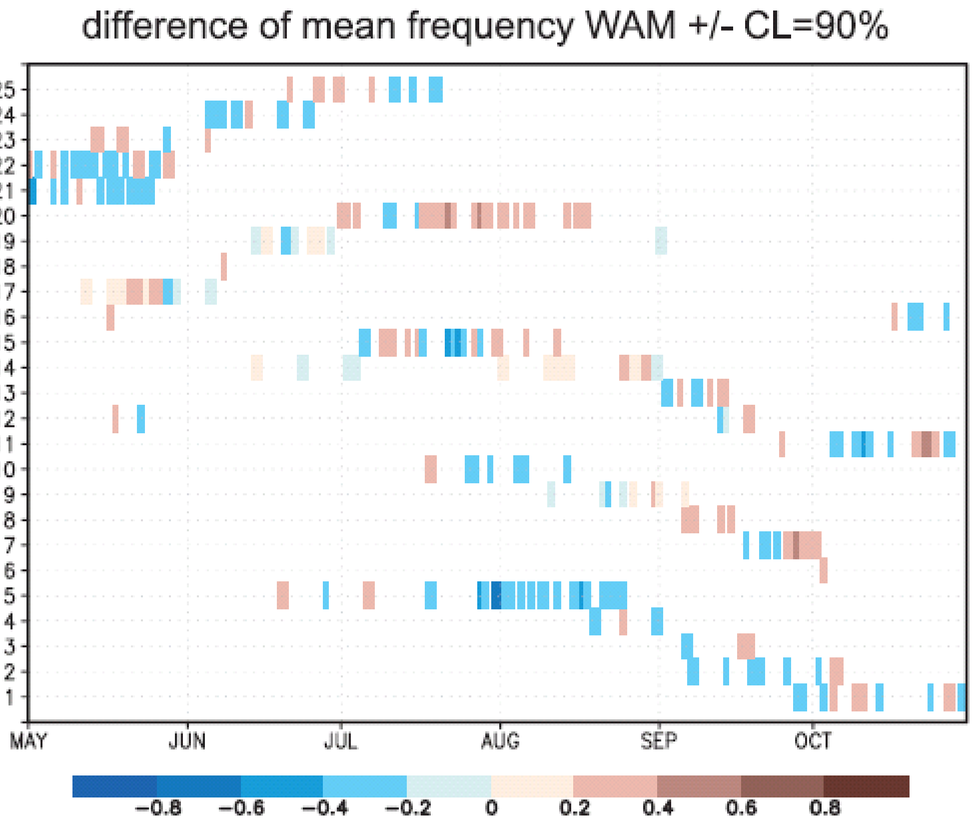
Example: impact on the tropical climate?

Wet years

-

Dry years

=



WEST AFRICA

TO BE ANSWERED ON MONDAY…

Summary

- **In the Euro-Atlantic sector, Weather Regimes are linked to perturbations of the Jet Streams**
- **Weather Regime approach is useful to find preferred states of the atmosphere that define from synoptic to low-frequency atmospheric variability**
- **Low frequency can be interpreted as a change in the amplitude/frequency of the WR or in the preferred transitions between them**
- **Ocean-Atmosphere interaction brings variability to the climate system at many timescales**
- **Mediterranean SST positive (negative) anomalies could be a precursor of more frequency of particular WR related to summer negative (positive) NAO.**