

Teleconnections and weather regimes

Predictability training course 2024

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Newsletter

Number 165 - Autumn 2020

Published in November 2020

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METEOROLOGY How to make use of weather regimes in extended-range predictions for Europe

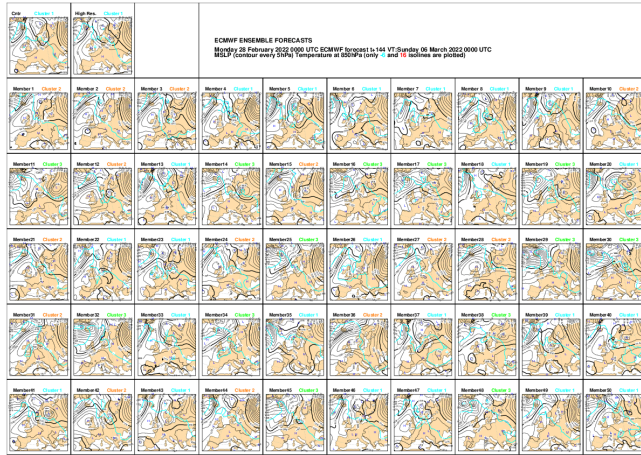
Christian Grams (Karlsruhe Institute of Technology), Laura Ferranti, Linus Magnusson (both ECMWF)

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The concept of weather regimes was introduced in weather forecasting about 70 years ago (Rex, 1951). It is based on the idea that the large-scale atmospheric circulation can in practice be represented by a finite number of possible atmospheric states that manifest themselves in quasi-stationary, persistent, and recurrent large-scale flow patterns. Because the actual instantaneous weather differs from day to day and evolves continuously with time, classifying weather maps in a finite number of slowly varying states is not a simple task. There are many ways to define weather regimes. Referring to the property of recurrence in the sense of the most frequent patterns in a climatological period, cluster analysis is nowadays the most common

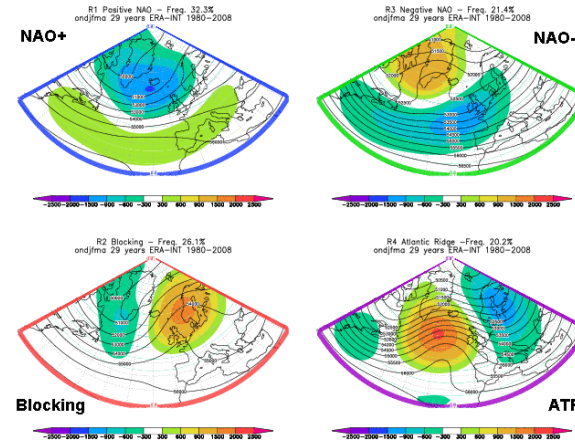
Overview

Raw forecast



Regime definitions

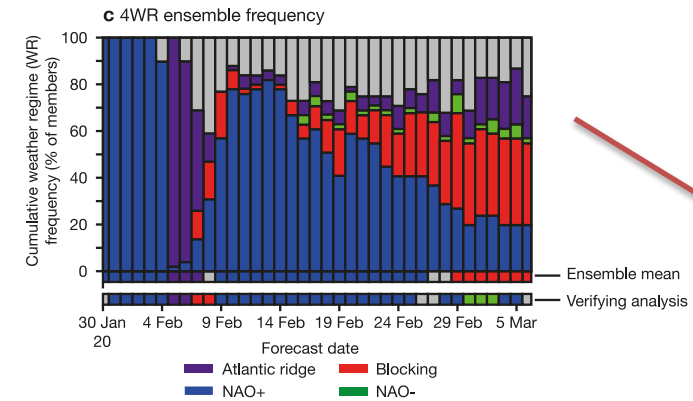
(a)




Content

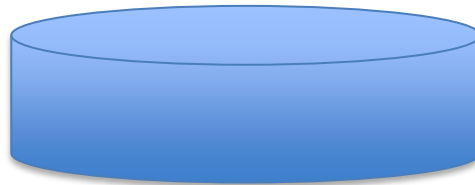
- Background/Motivation
- Regime calculation
- Products
- Connections to surface weather
- Teleconnection
- Skill

Regime products

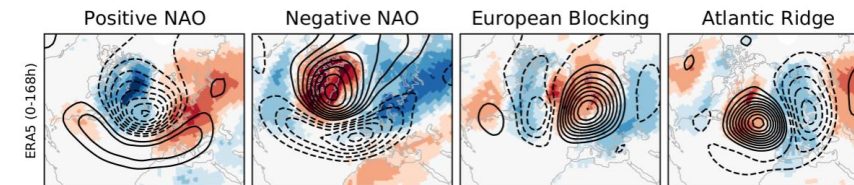


Interpretable and skilful forecast!?!


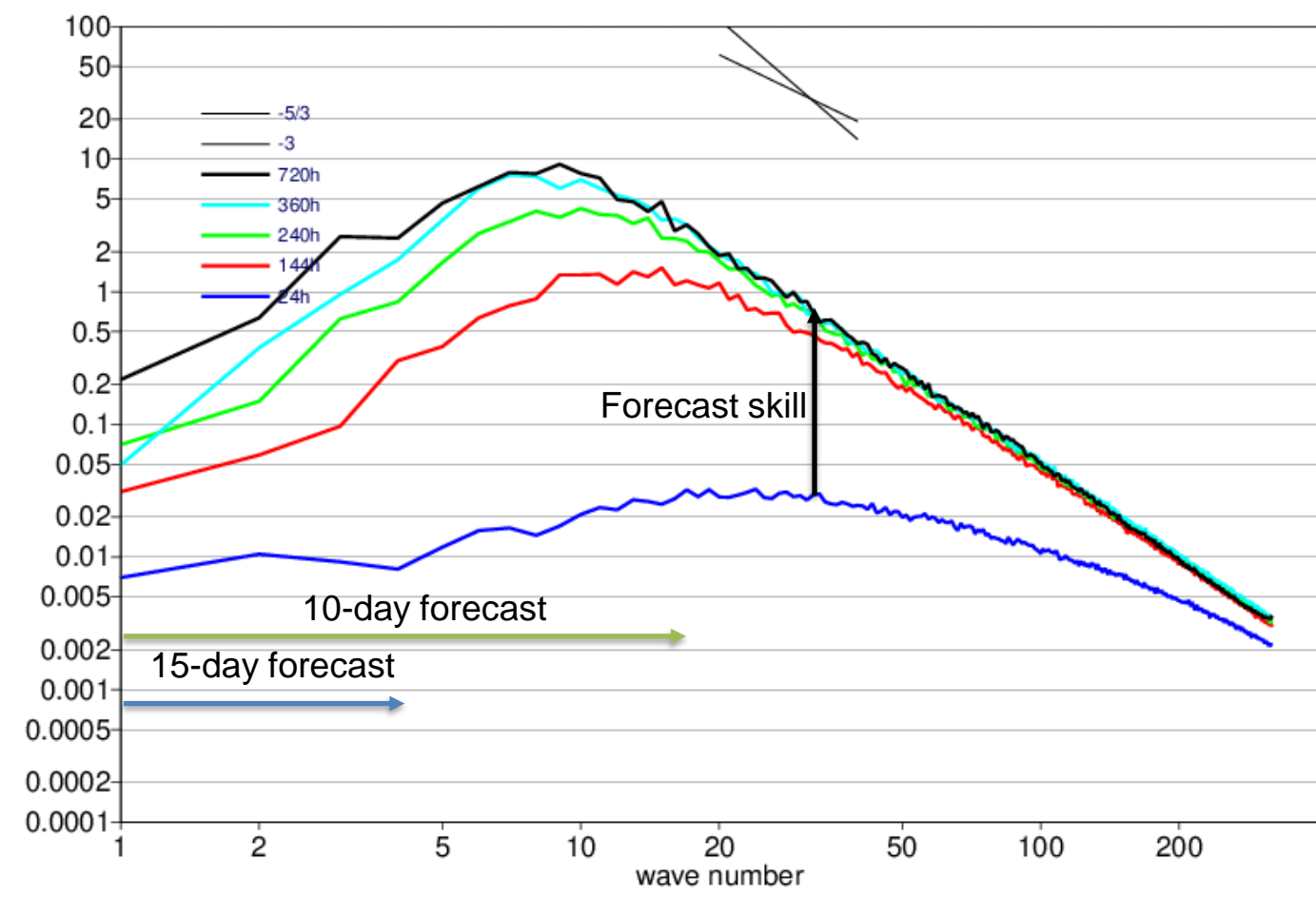
Reanalysis



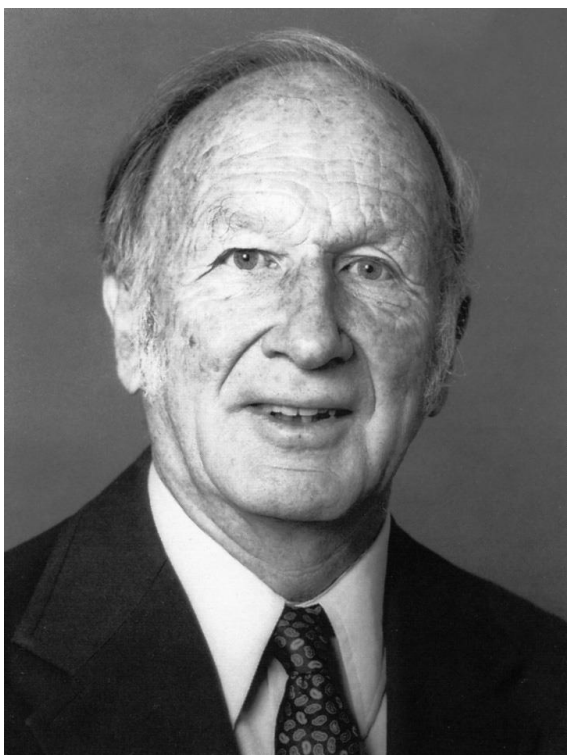
Connection to surface weather



Global error spectra for 850hPa rotational wind for Dec-Jan 2021-2022



The skilful forecast information lies in the longest waves for long forecasts



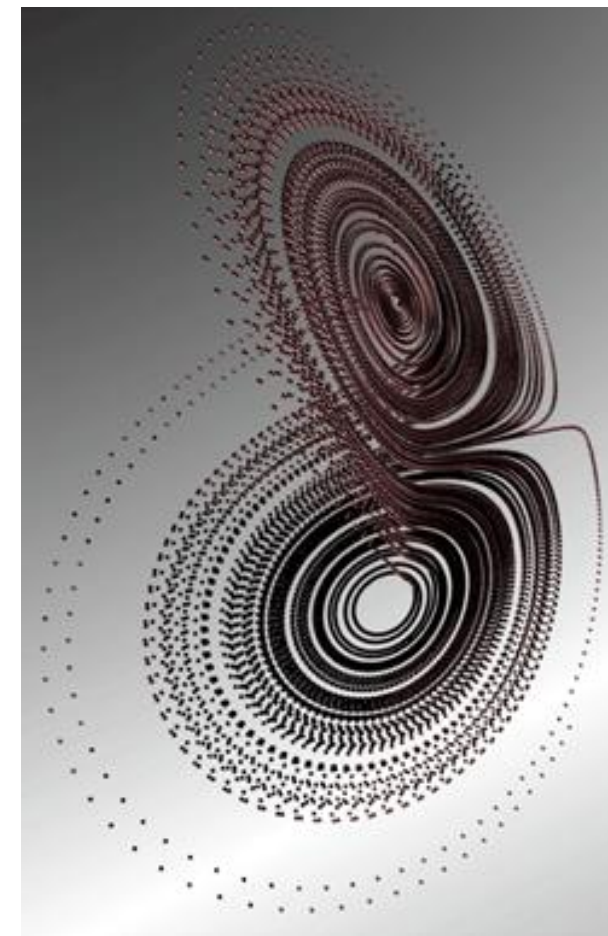
A prototype non-linear model
with flow regimes

$$\dot{X} = -\sigma X + \sigma Y$$

$$\dot{Y} = -XZ + rX - Y$$

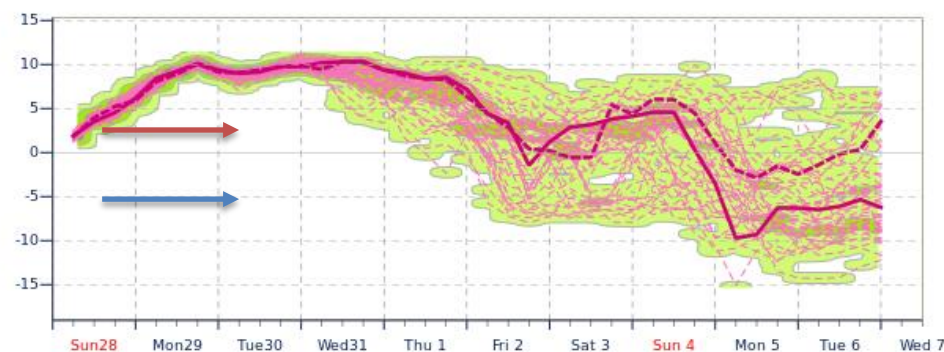
$$\dot{Z} = XY - bZ$$

Lorenz E., 1963: Deterministic non-periodic flow



- Does a finite number of recurrent and persistent weather patterns exist in the atmosphere?

Example of 850hPa temperature forecast



Early (1883) note on NAO

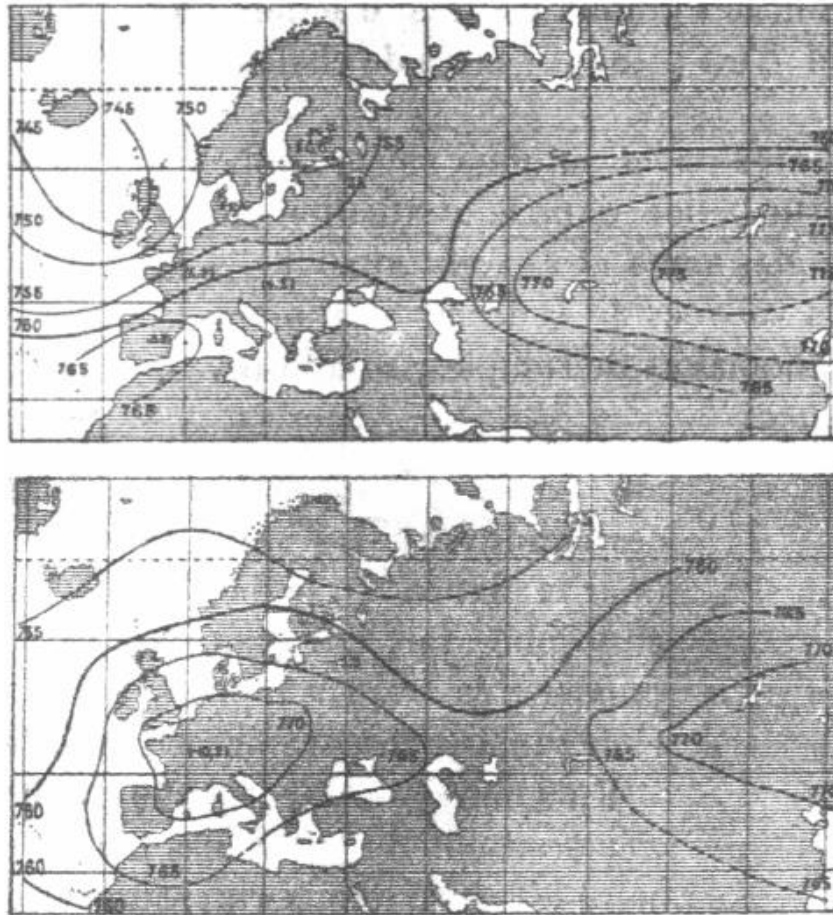


Figure 2. Vintage map showing early monthly mean sea level pressure (SLP) maps for December 1868 (top) and for December 1879 (bottom) (units in Torr; 1 Torr = 1.3332 hPa). From *Teisserenc de Bort* [1883].

From Stephenson et al. (<https://empslocal.ex.ac.uk/people/staff/dbs202/publications/2002/agu2002.pdf>)

Blockings and effect on surface weather

The Effect of Atlantic Blocking Action upon European Climate

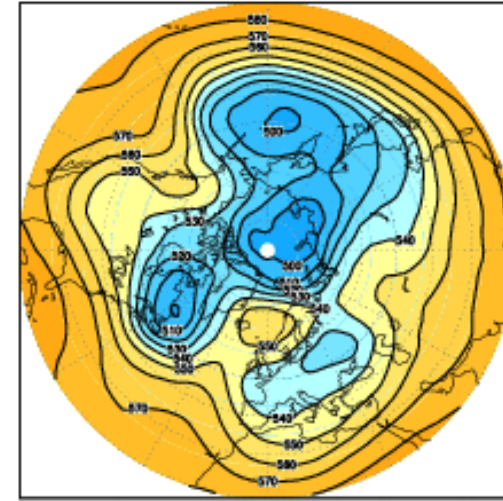
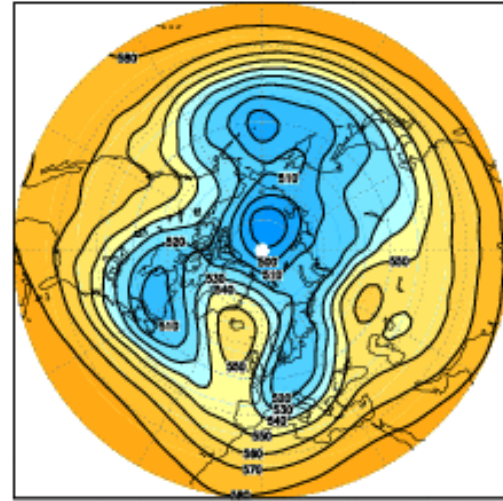
By DANIEL F. REX, University of Stockholm

(Manuscript received 28 March 1951)

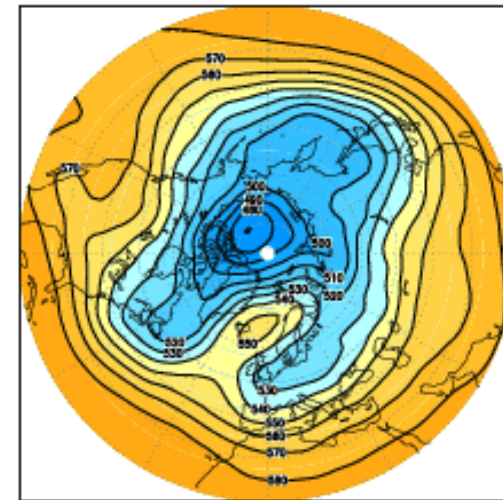
Abstract

The results of the individual analysis of six cases of Atlantic blocking action are presented in the form of mean surface and upper-level pressure distributions and of mean regional precipitation and surface-temperature isanomal patterns for winter and for summer blocked periods over the European area. A "mean" blocked sea-level pressure distribution, together with its associated isanomal pattern, are compared with similar charts constructed for a case of strong European zonal flow. A summary of the weather regime associated with European blocking is given, and variable blocking activity is discussed as a factor in the recent climatic change which has been observed over the North Atlantic-European area.

Recurrent flow patterns: examples

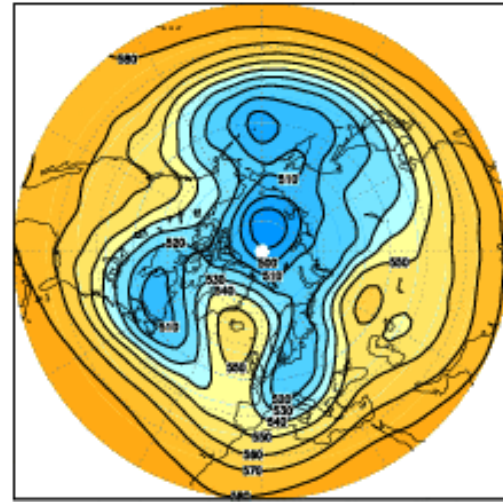


A sequence of 5-day mean
fields of 500 hPa
geopotential height
during boreal winter ...

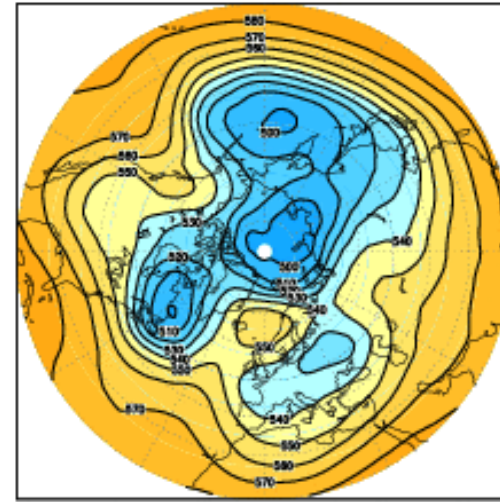


Recurrent flow patterns: examples

5-9 Jan 1985

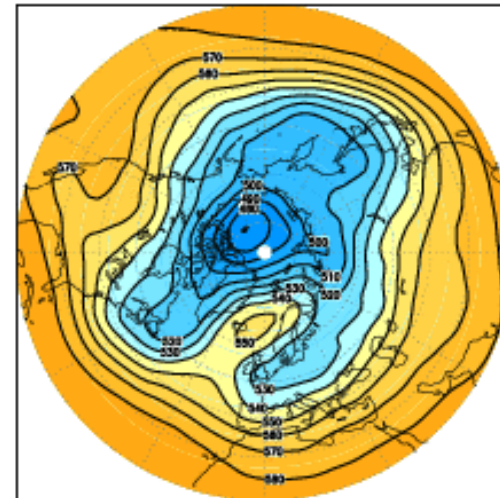


4-8 Feb 1986



...but each of them
occurred in a different
winter

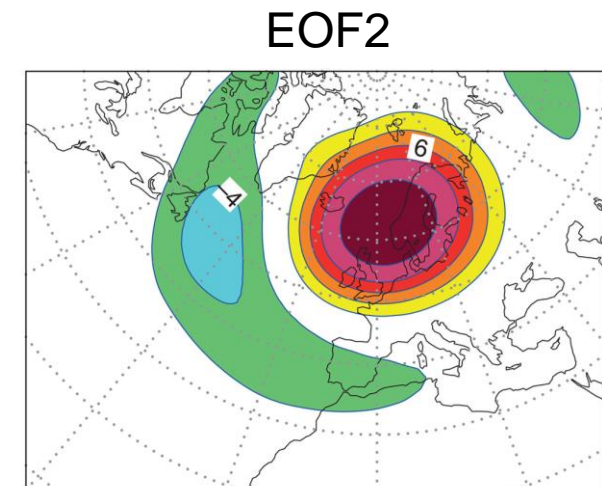
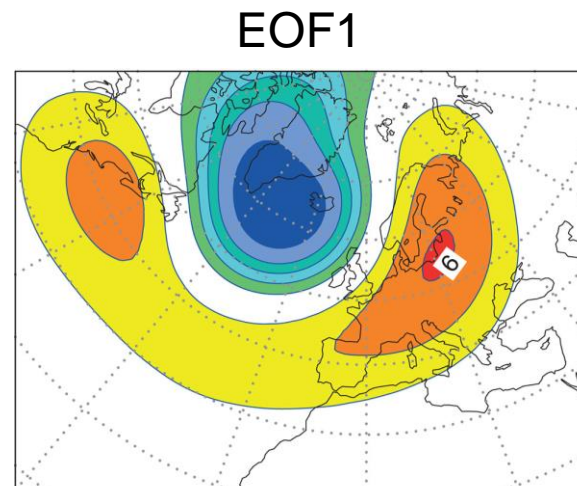
10-14 Jan 1987



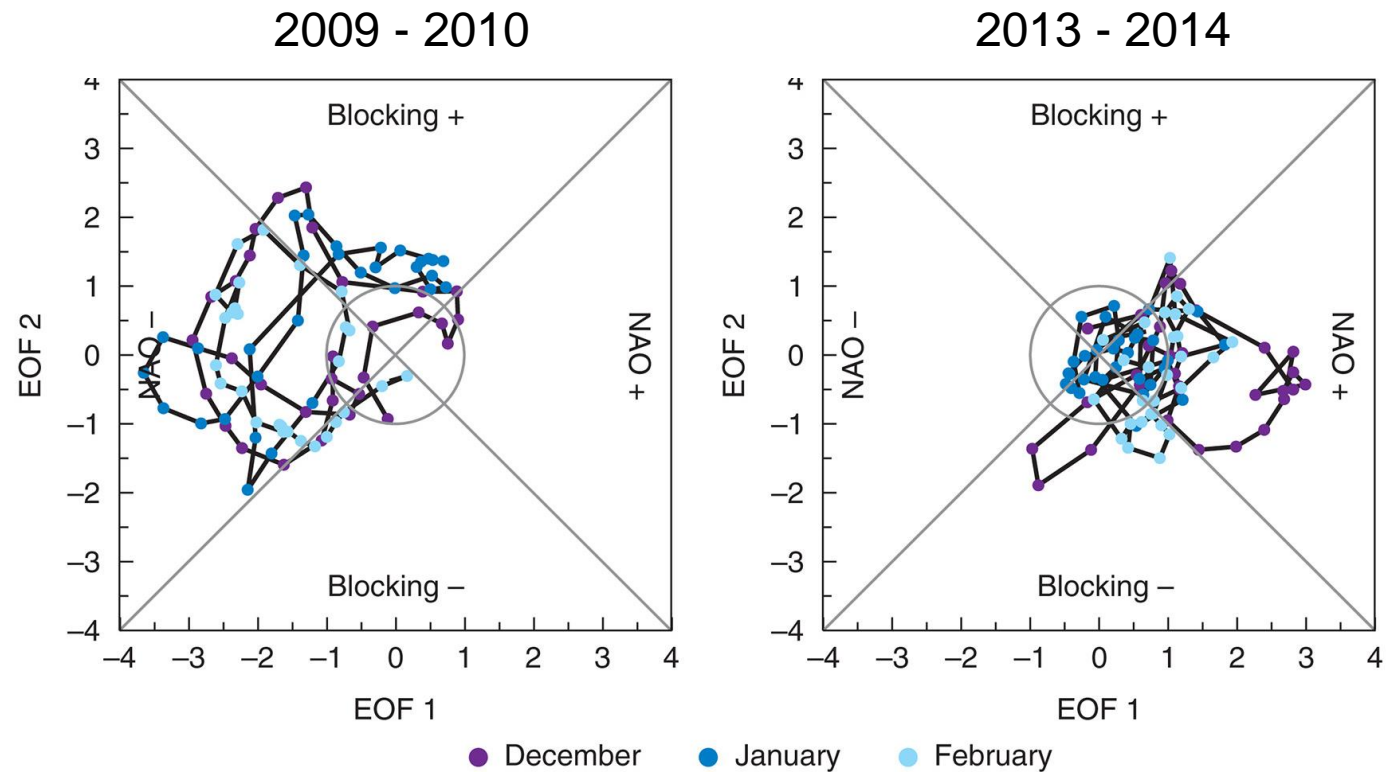
EOF analysis of the Euro-Atlantic sector

Current products at ECMWF based on:

- Daily geopotential height at 500 hPa
- Euro-Atlantic region (30°N to 88.5°N, 80°W to 40°E).
- 5-day running mean
- mean seasonal cycle was removed
- 29 years
- October to March
- ECMWF ERA-Interim data



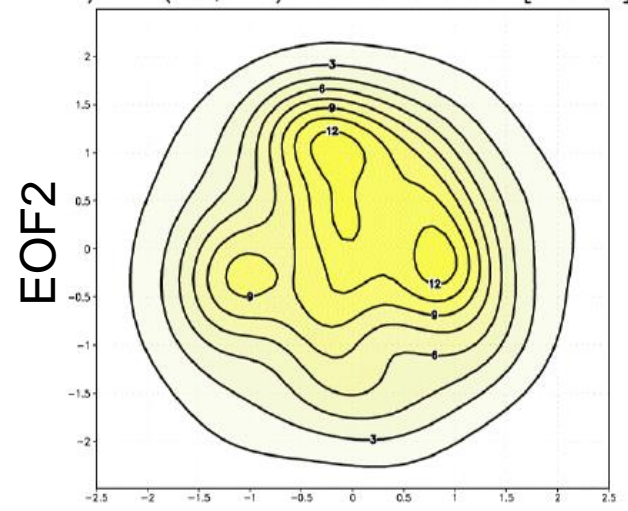
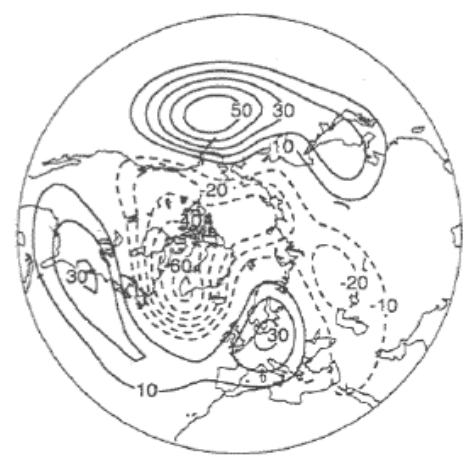
NAO and Blocking index for Winter 2009-2010 / 2013-2014



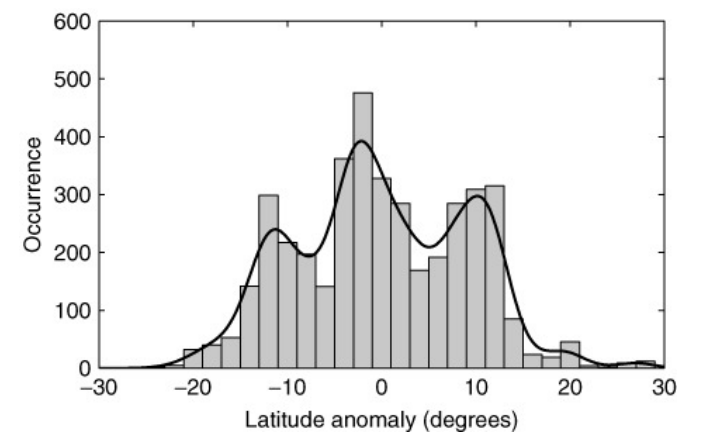
Multi-modality in two-dim. PDF from principal components: Corti et al., Nature 1999



b) PDF (PC1, PC2) Re-An. 1955-98 [h = 0.4]



Distribution of low-level jet position over the Atlantic



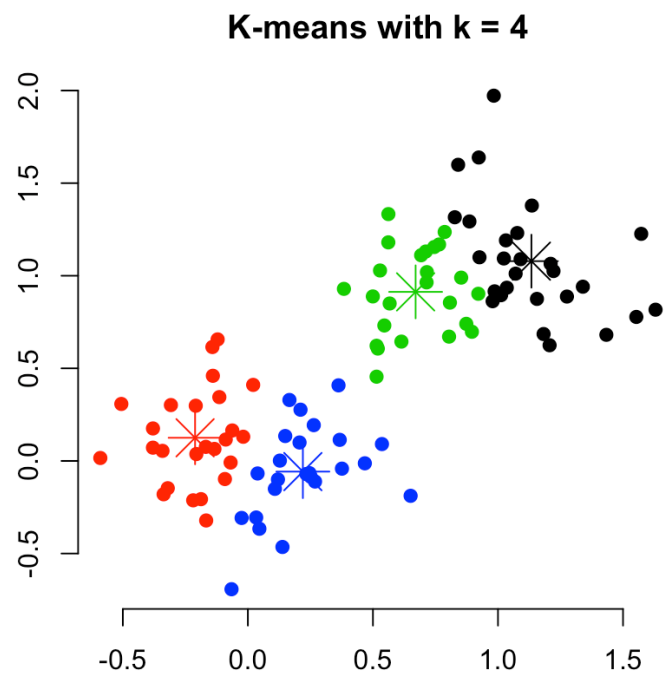
Woollings et al., 2010, 10.1002/qj.625

Regimes as clusters in a multi-dimensional EOF phase space

- Mo and Ghil 1988 (N. Hem.)
- Cheng and Wallace 1993 (N. Hem.)
- Michelangeli et al. 1995 (Atl. - Europe)
- Straus et al. 2007 (N. Pac. - N. America)

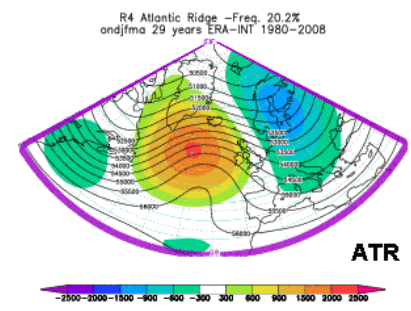
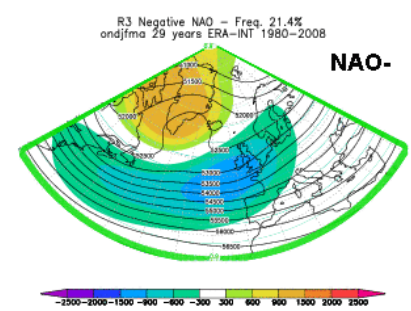
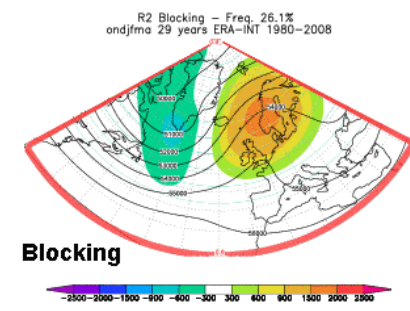
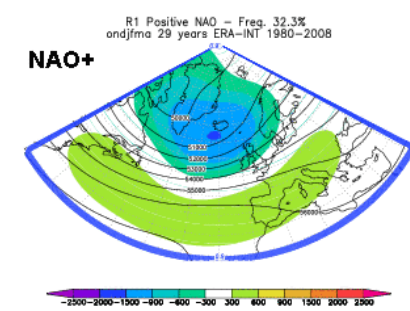
Four Euro-Atlantic regimes from K-means cluster analysis of ERA-Interim 5-day means of 500 hPa height, DJF 1980-2008

(a)



**NAO +
32%**

**Blocking
26%**

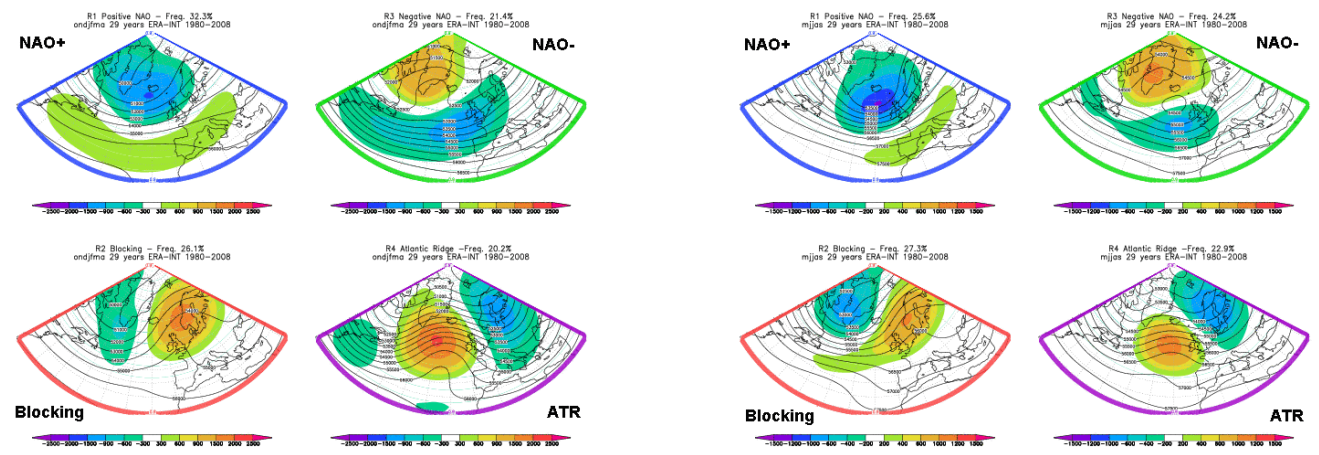


**NAO-
21%**

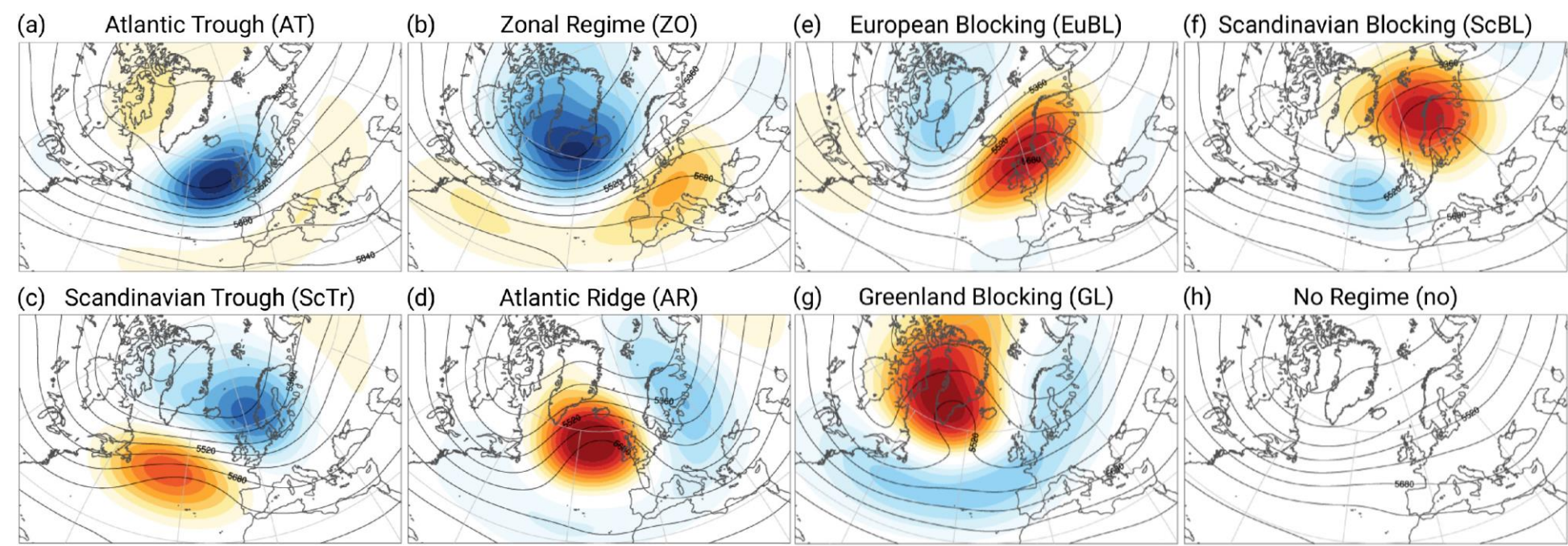
**Atl. ridge
20%**

Examples of weather regime definitions

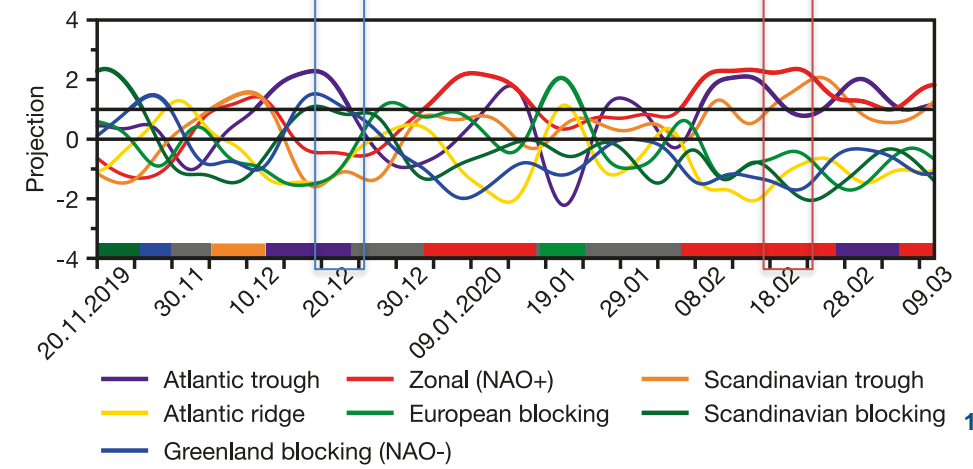
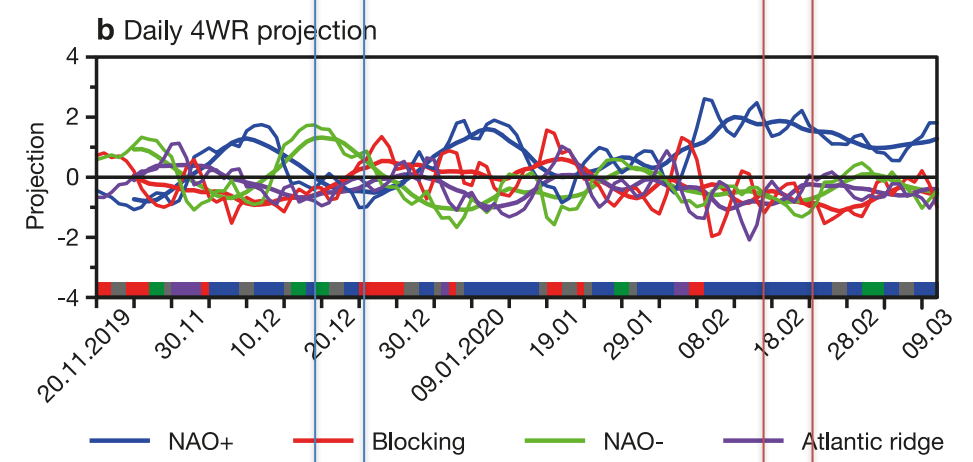
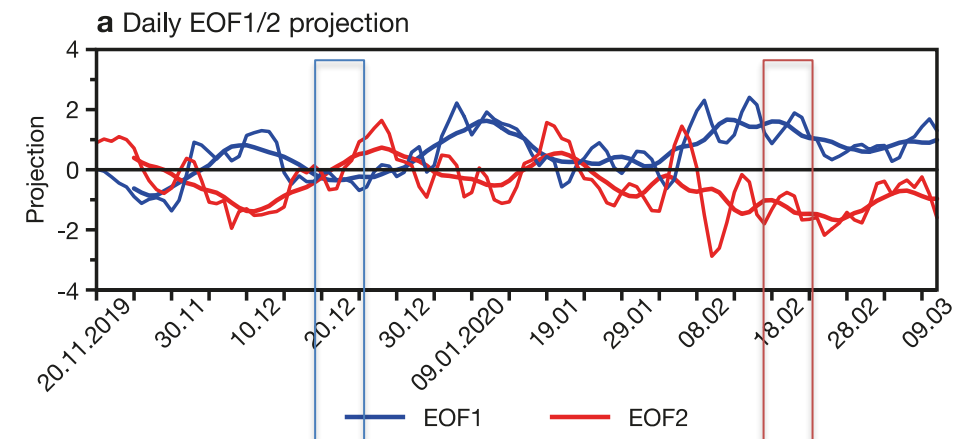
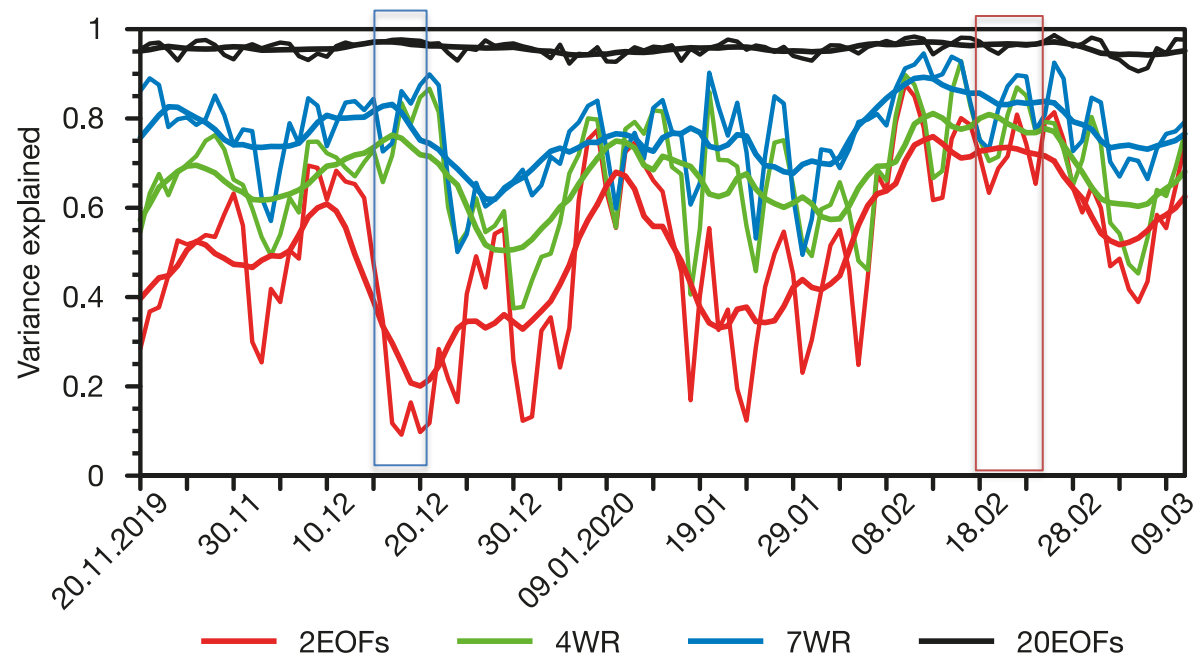
4 regimes with different patterns for winter and summer (Ferranti et al.)



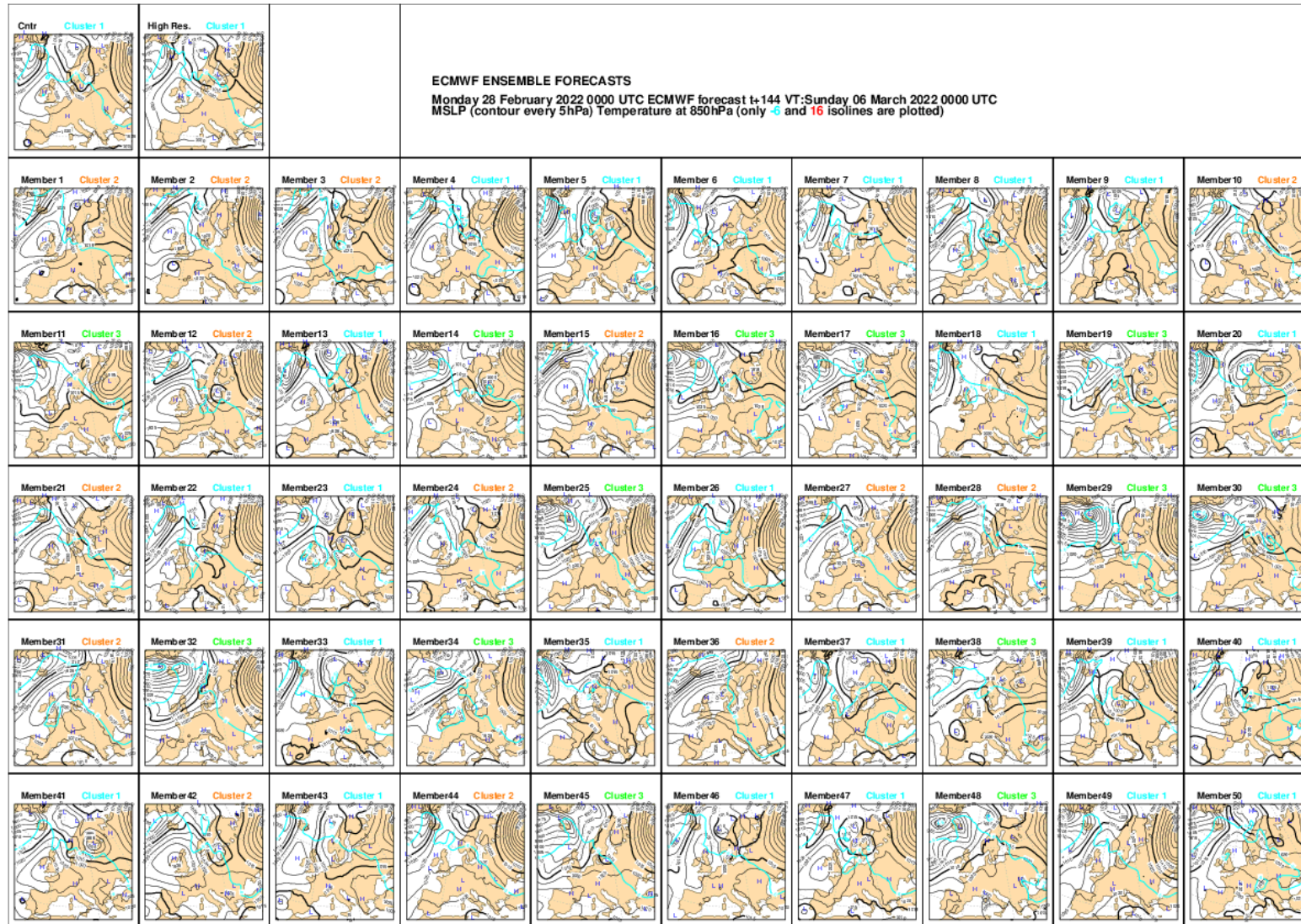
7 year-around regimes (Grams et al. 2017, 10.1038/nclimate3338)



Daily projections onto each regime and variance explained by each set

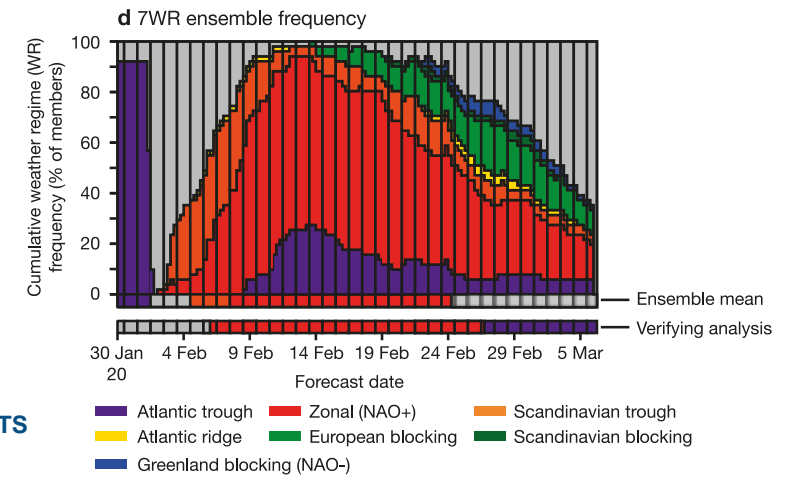
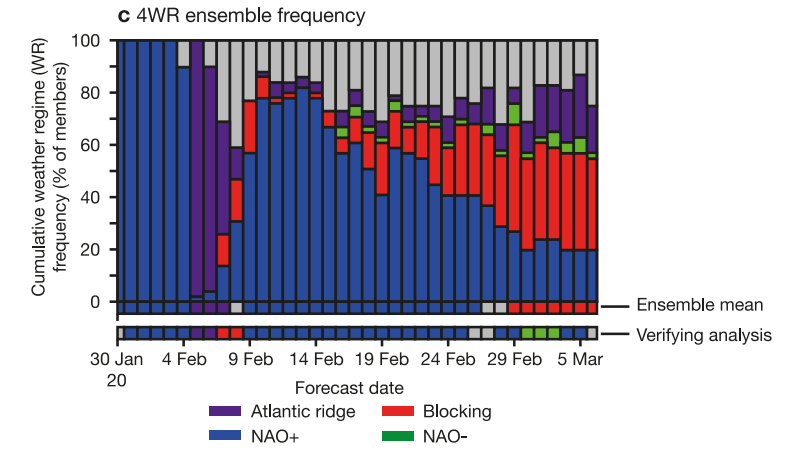
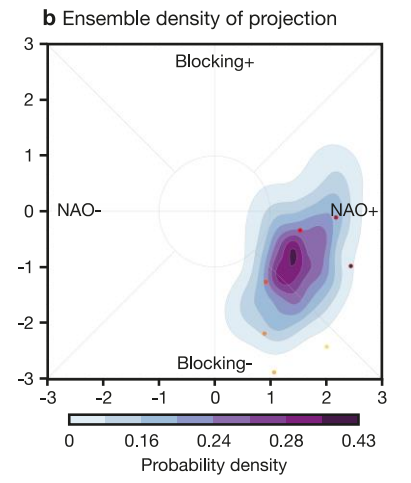
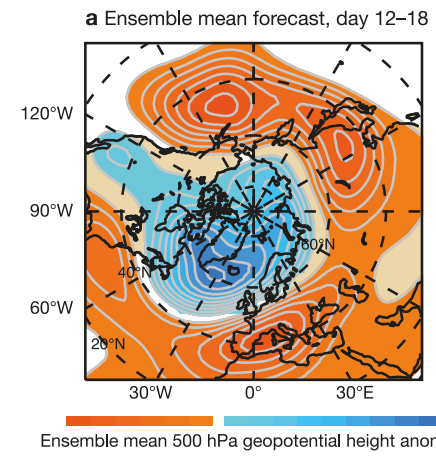
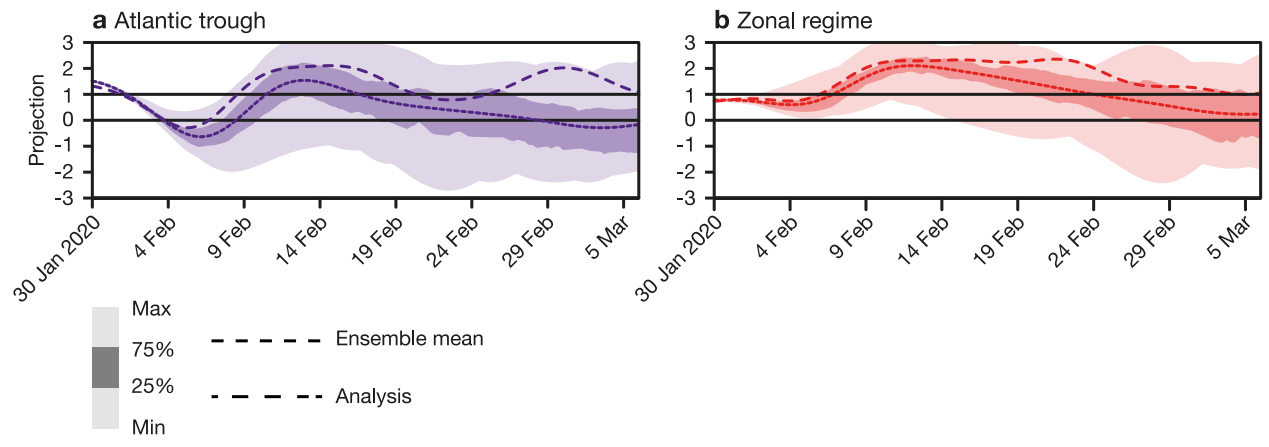


Need to condense ensemble information



Example of products

- Life-cycle (persistence of regime)
- Continuous or categorical attribution
- Orthogonality make it possible for 2-d visualisation



Regime composites: Z500 (20 m contour spacing) and T2m (shading)

Composites lag regimes by 0 day(s)

euroatlwinter_4wr_z500_10eofs

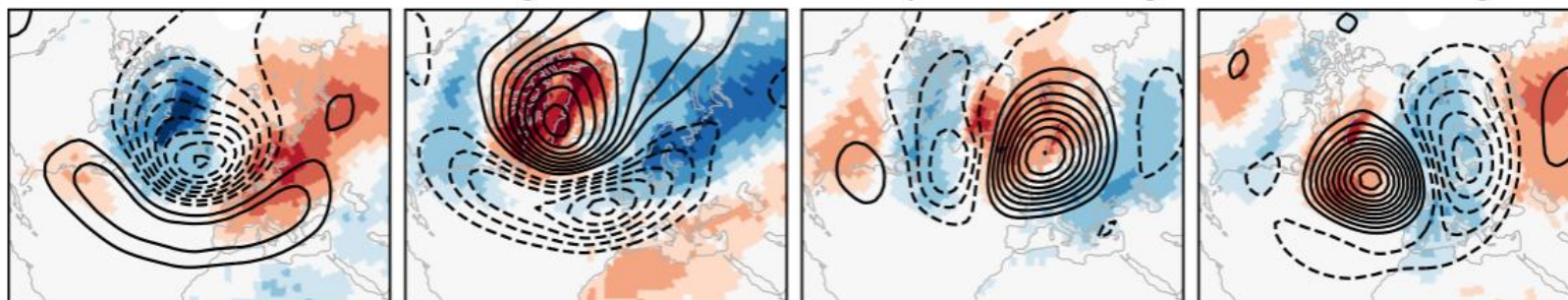
Positive NAO

Negative NAO

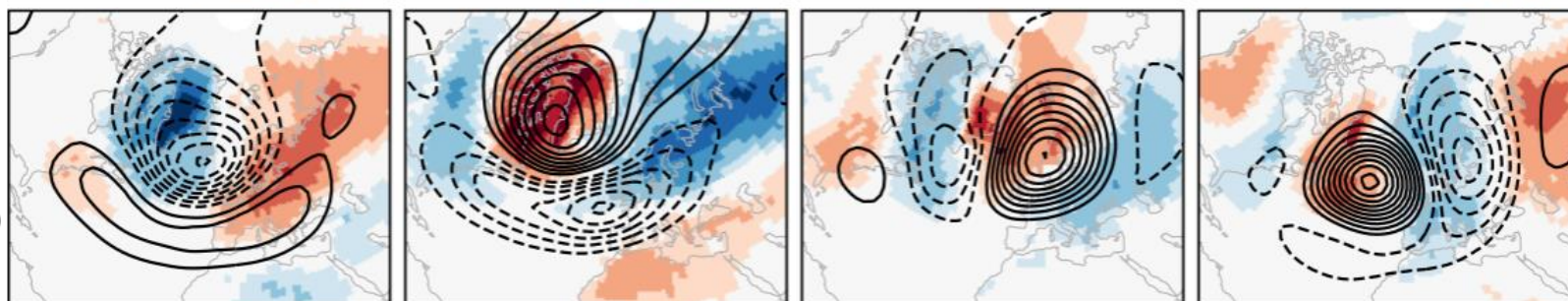
European Blocking

Atlantic Ridge

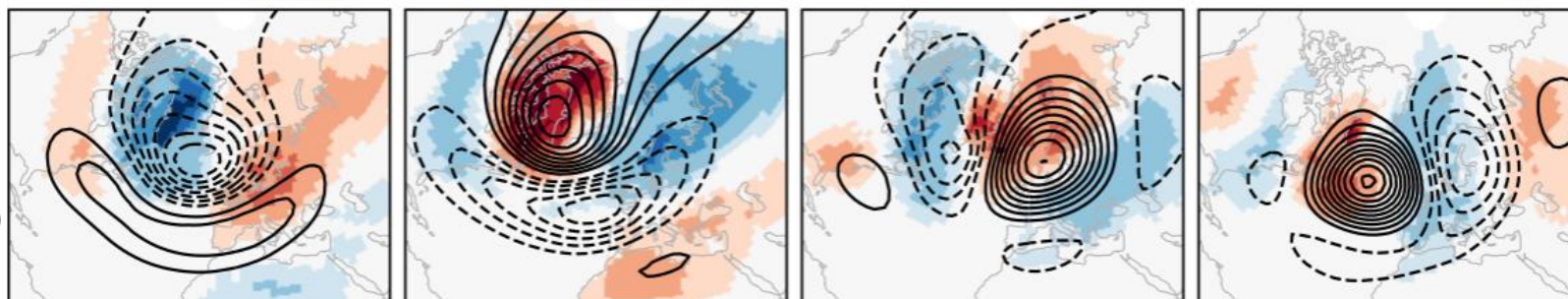
ERA5



Oper.
CY47R1
(week 1)



Oper.
CY47R1
(week 6)



Regime structures and surface impacts are well-represented in operational reforecasts (CY47R1) and stable across S2S lead times (week 1 to week 6).

-4.0

-2.4

-0.8

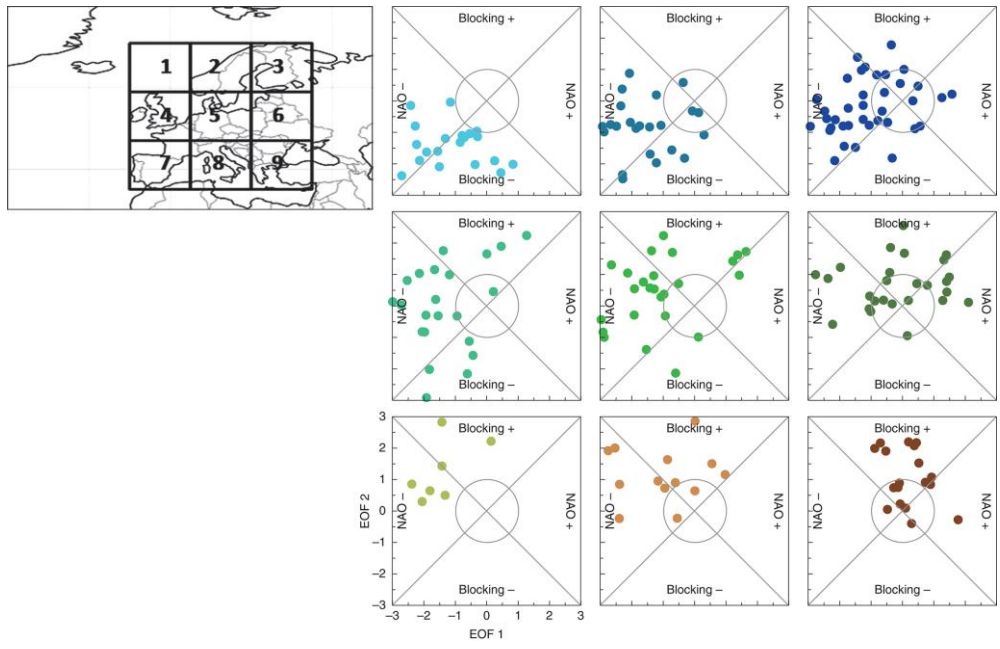
0.4

1.6

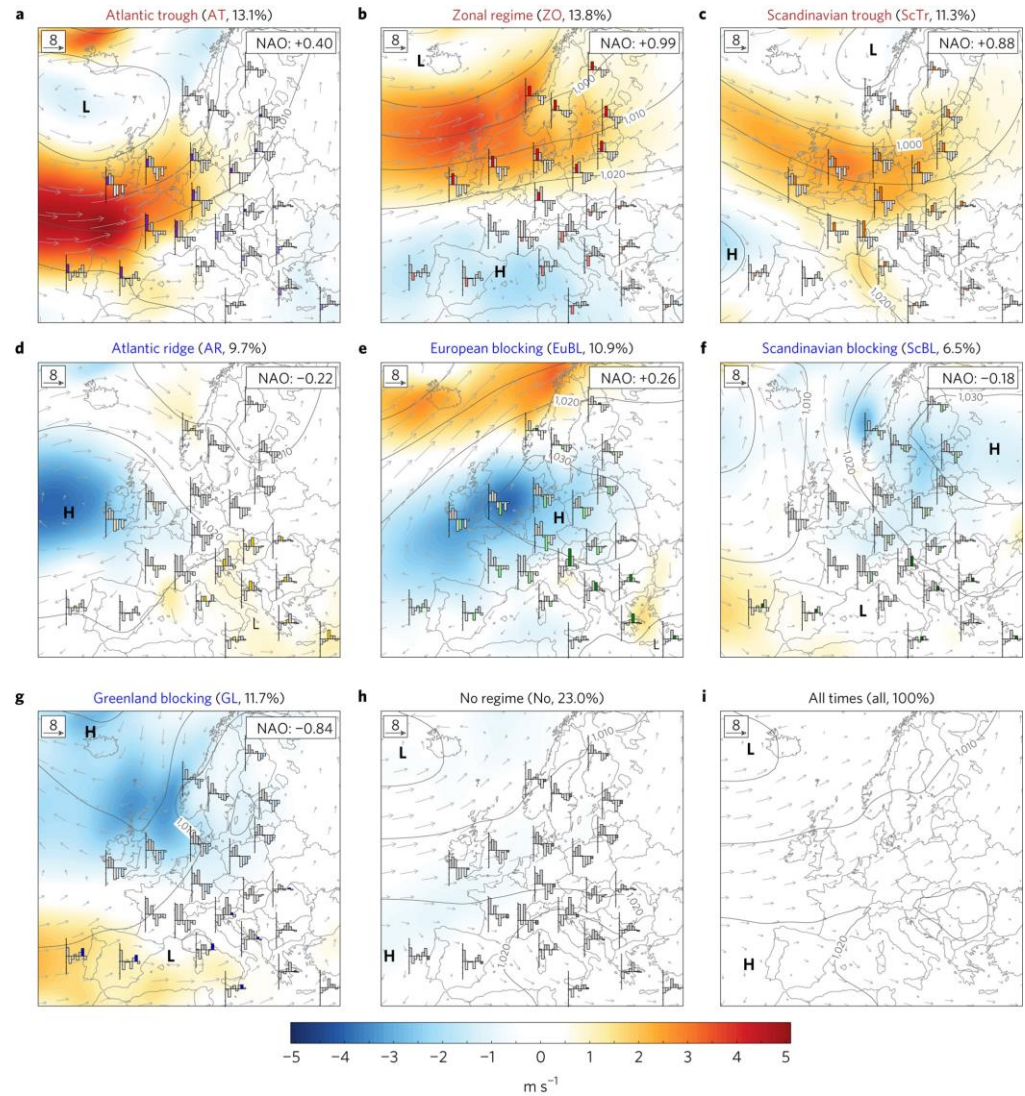
3.2

K

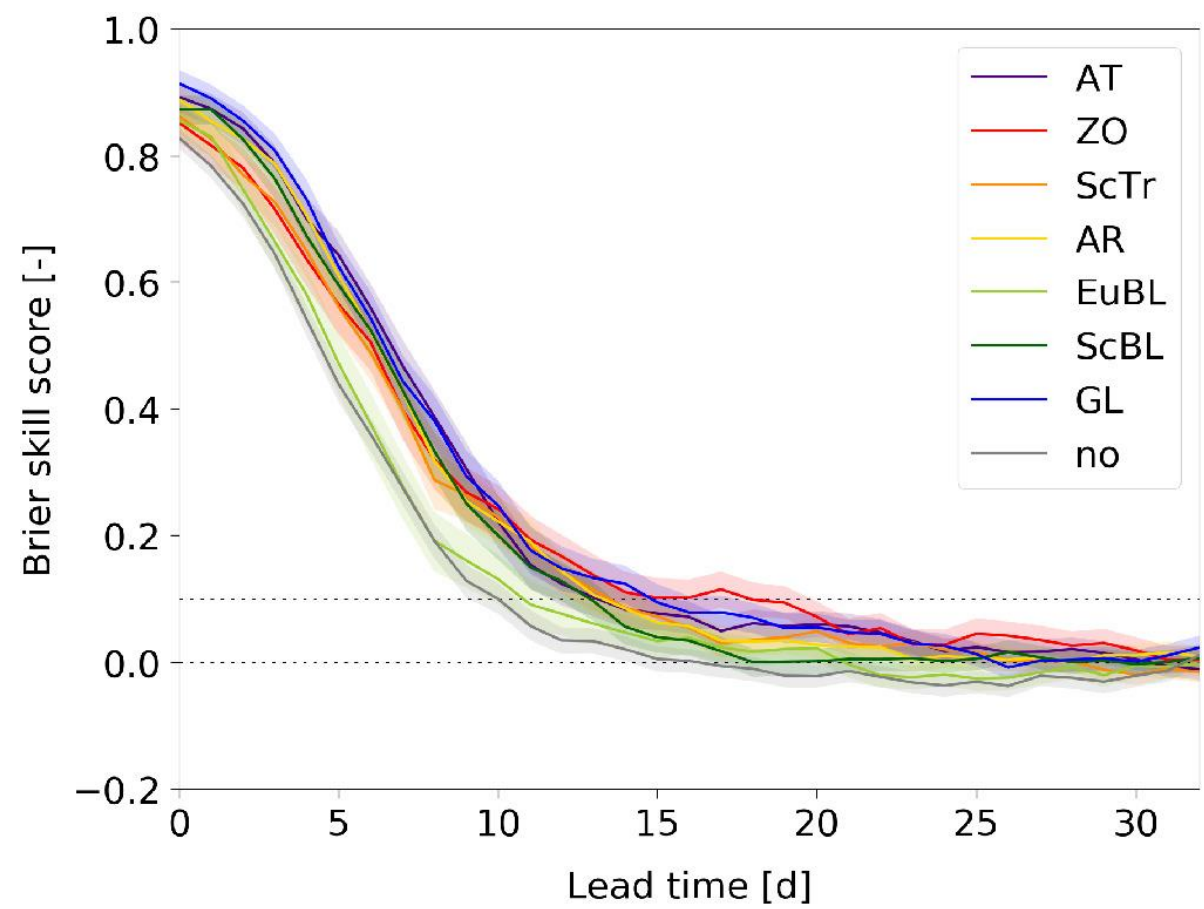
Temperature extremes and connection to EOF2
Ferranti et al. (2018, 10.1002/qj.3341)



Wind anomalies and connection to wind power generation (7WR)
Grams et al. (2017, 10.1038/nclimate3338)



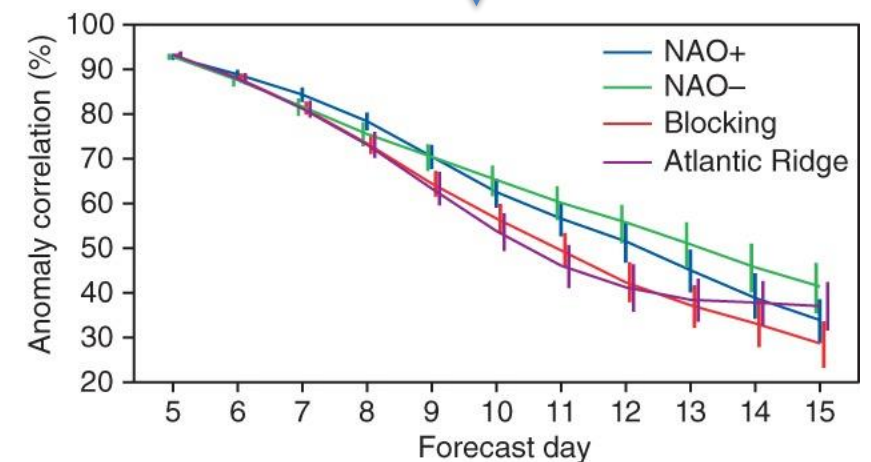
Verification of regime forecasts



From Bueler et al. (2021, <https://doi.org/10.1002/qj.4178>)

How to verify:

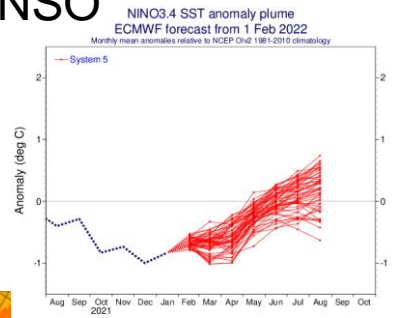
- Discrete verification of one regime (Brier)
- Continuous verification (CRPS) of projections
- Combined Brier skill score of all regimes
- Anomaly correction of ensemble mean of projections
- Conditional verification on the initial regime



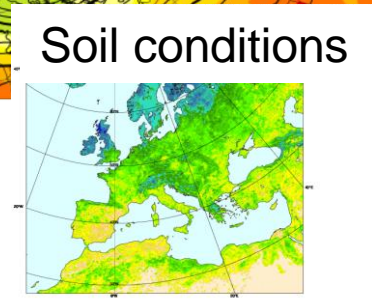
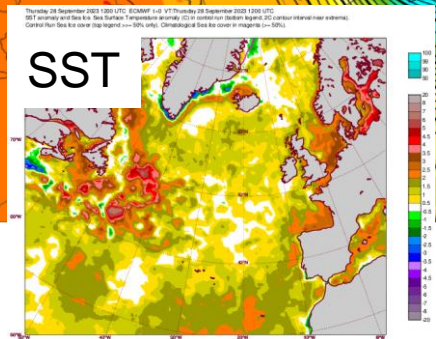
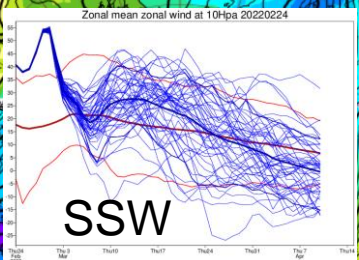
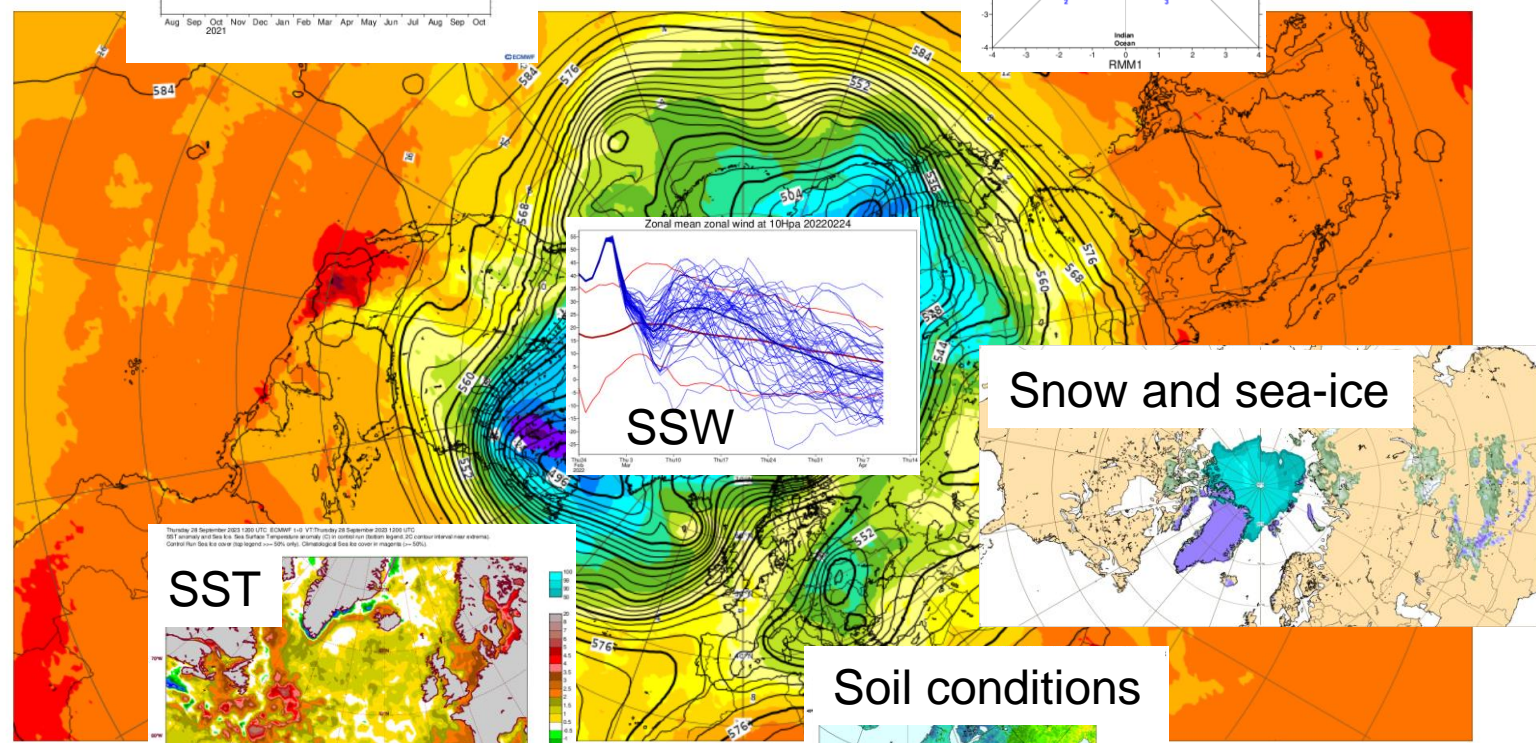
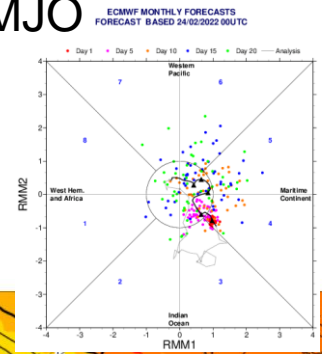
From Ferranti et al. (2015, <https://doi.org/10.1002/qj.2411>)

Windows of opportunities: External forcing on mid-latitude wave guide

ENSO



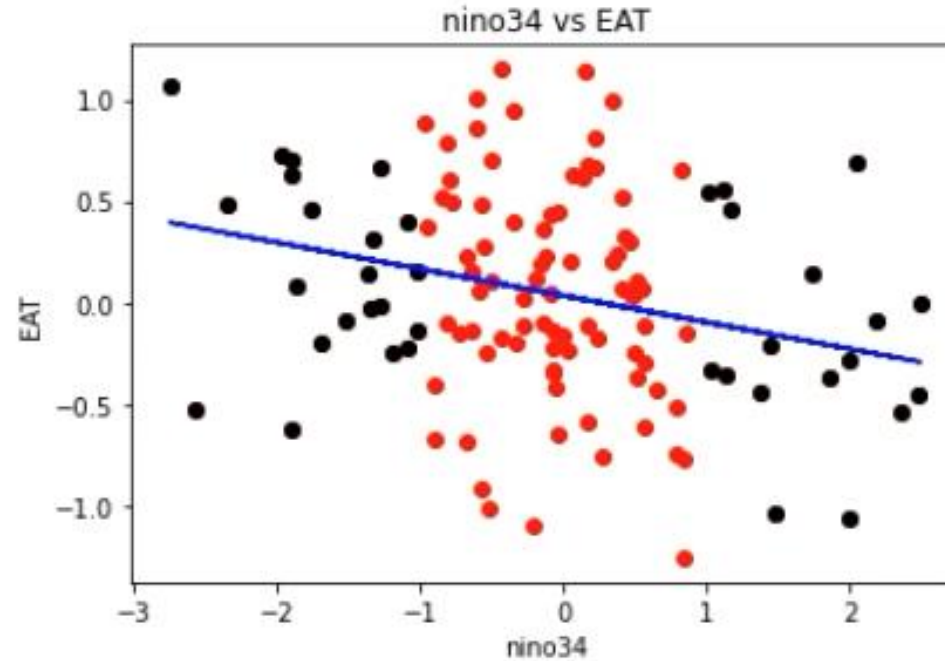
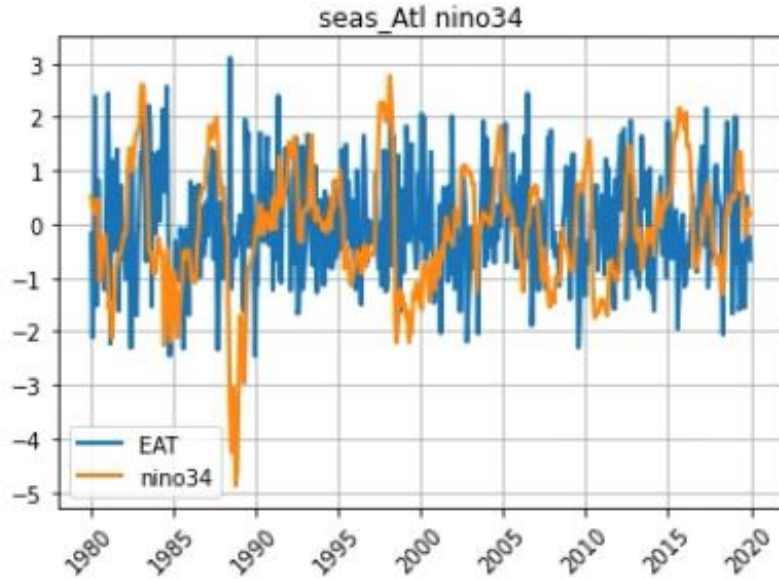
MJO



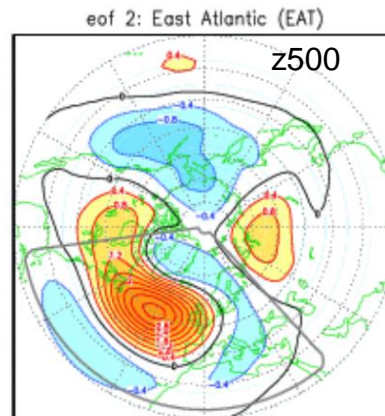
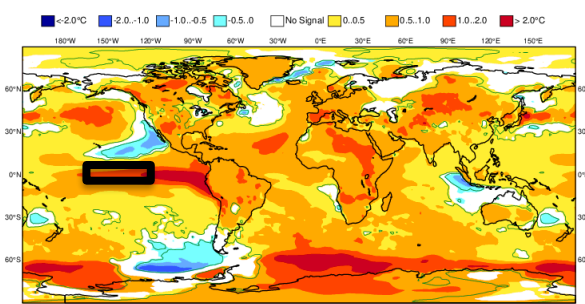
Teleconnections - example: Does El Nino influence European summers?

Teleconnections during JJA

Time-series of two indices



ECMWF Seasonal Forecast System 5
 Mean 2m temperature anomaly JJA 2023
 Forecast start is 01/05/23, climate period is 1993-2016
 Ensemble size = 51, climate size = 600



Composites +/- 1 stdev (black points):

Positive: -0.16 (17 of 120)

Negative: 0.17 (21 of 120)

Correlation: 0.29

See also:

Wulff et al., (2017): <https://doi.org/10.1002/2017GL075493>

O'Reilly et al., (2018): <https://doi.org/10.1175/JCLI-D-17-0451.1>

Impact from ENSO during DJF in reanalysis

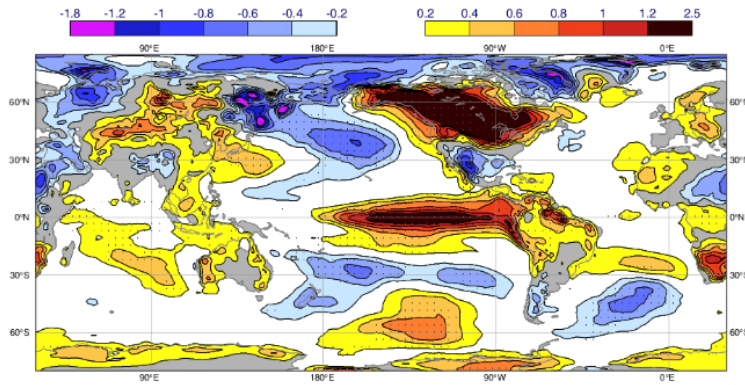
Composites on El Nino

2-metre temperature

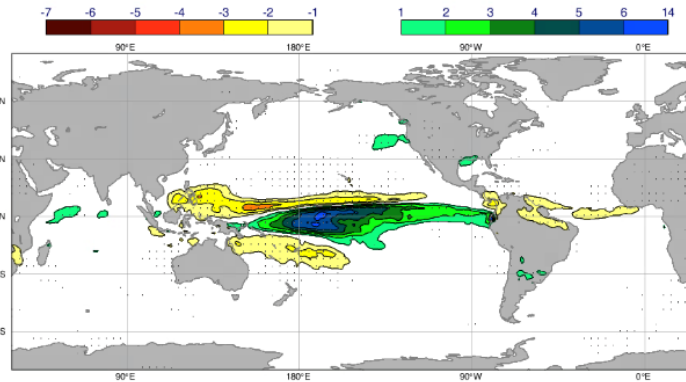
Precipitation

Z500

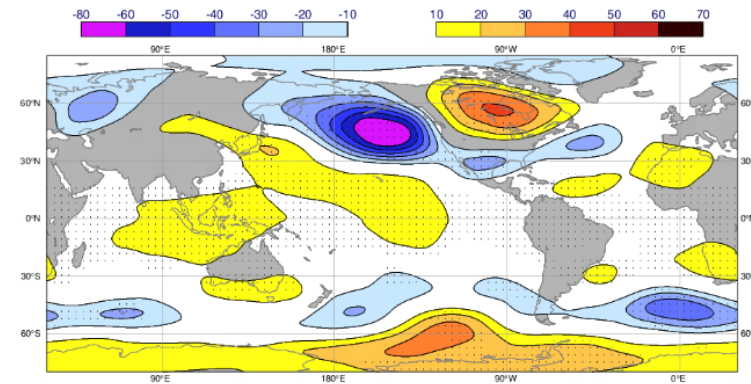
Teleconnection composite positive ERA Interim Nino34 SST DJF 2T, 26 cases
Dotted: 5 % significance



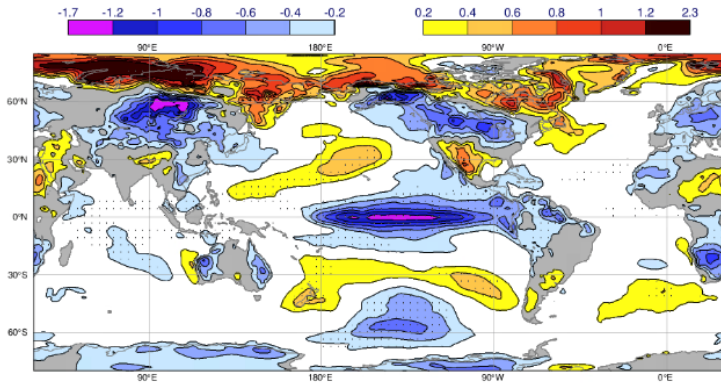
Teleconnection composite positive ERA Interim Nino34 SST DJF TP, 26 cases
Dotted: 5 % significance



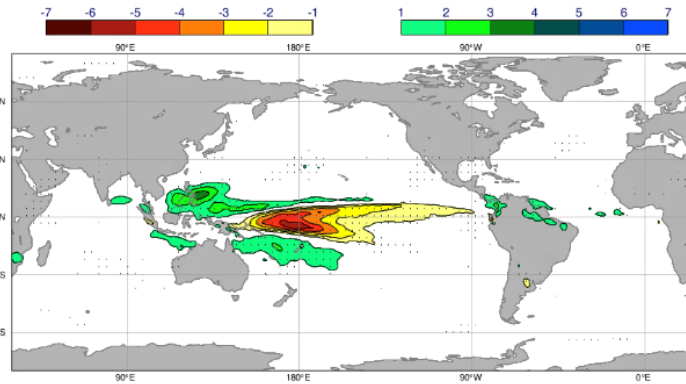
Teleconnection composite positive ERA Interim Nino34 SST DJF Z500, 26 cases
Dotted: 5 % significance



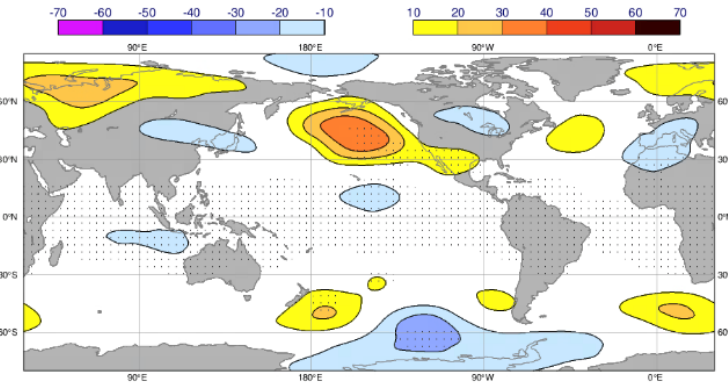
Teleconnection composite negative ERA Interim Nino34 SST DJF 2T, 33 cases, Dotted: 5 % significance



Teleconnection composite negative ERA Interim Nino34 SST DJF TP, 33 cases, Dotted: 5 % significance



Teleconnection composite negative ERA Interim Nino34 SST DJF Z500, 33 cases, Dotted: 5 % significance

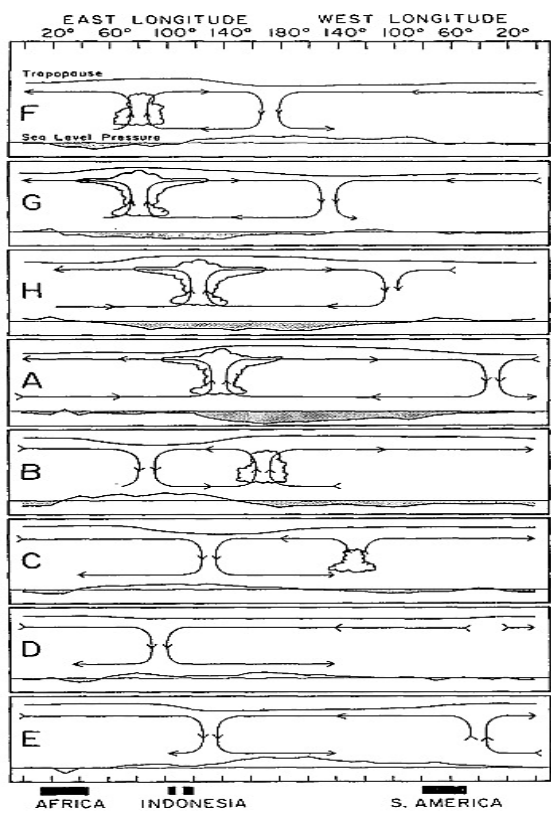


Composites on La Nina

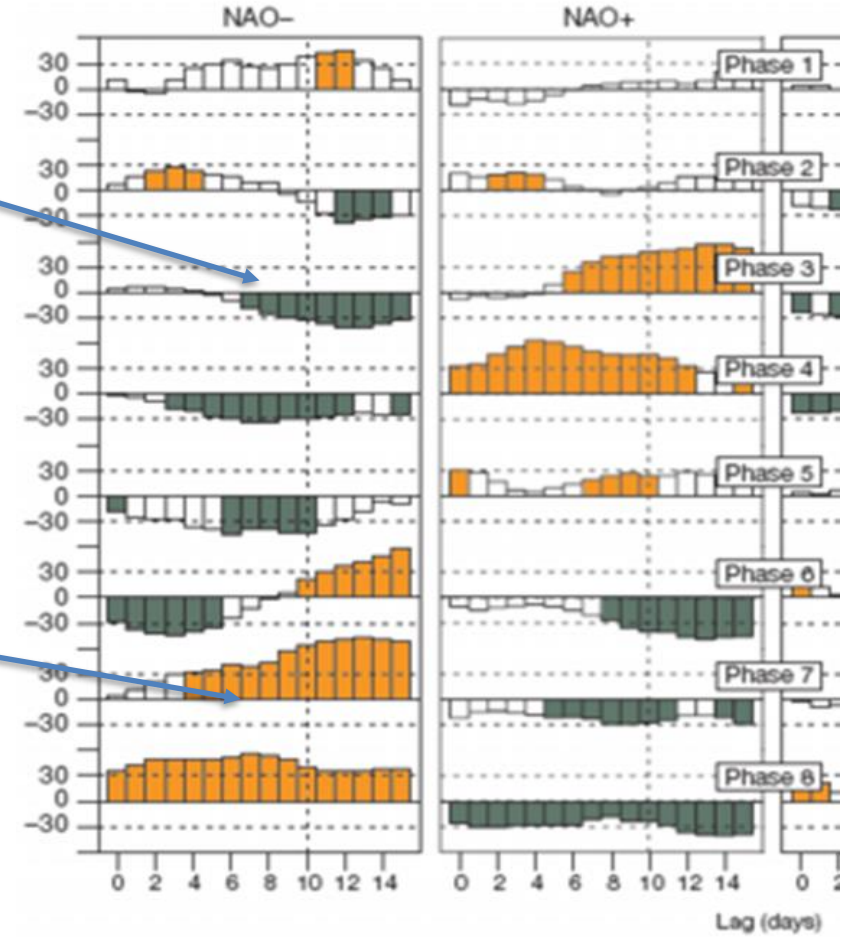
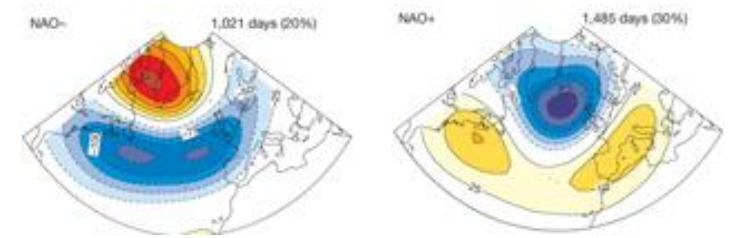
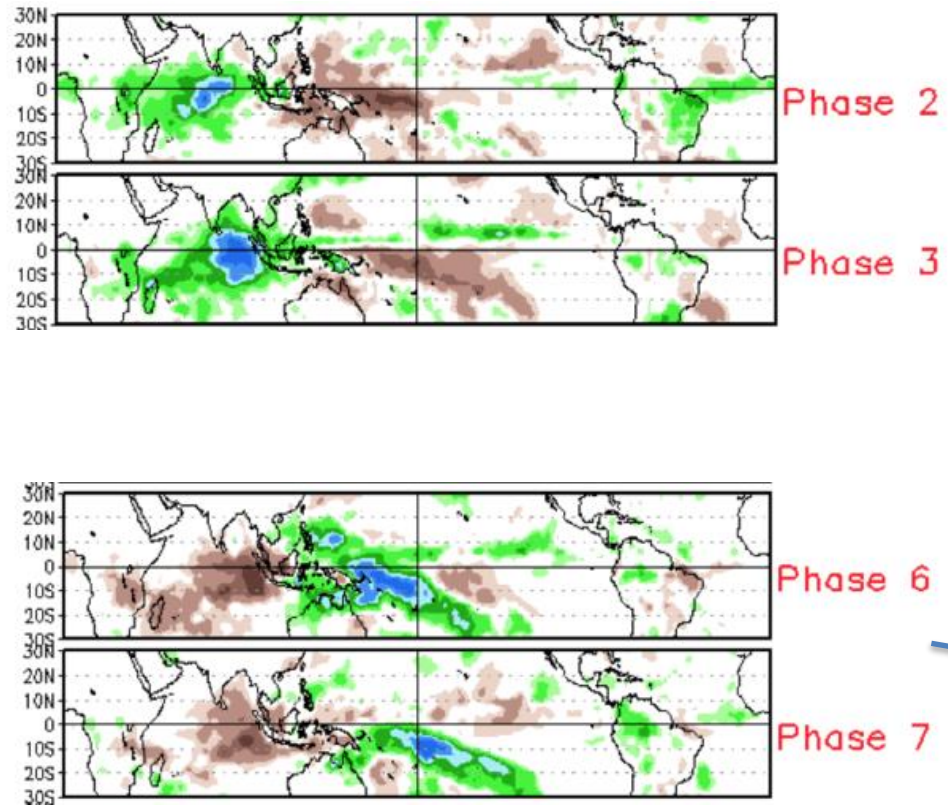
Regime frequencies are affected by MJO phase (Cassou, Nature 2008)

Lagged correlations for NAO

Madden-Julian Oscillation

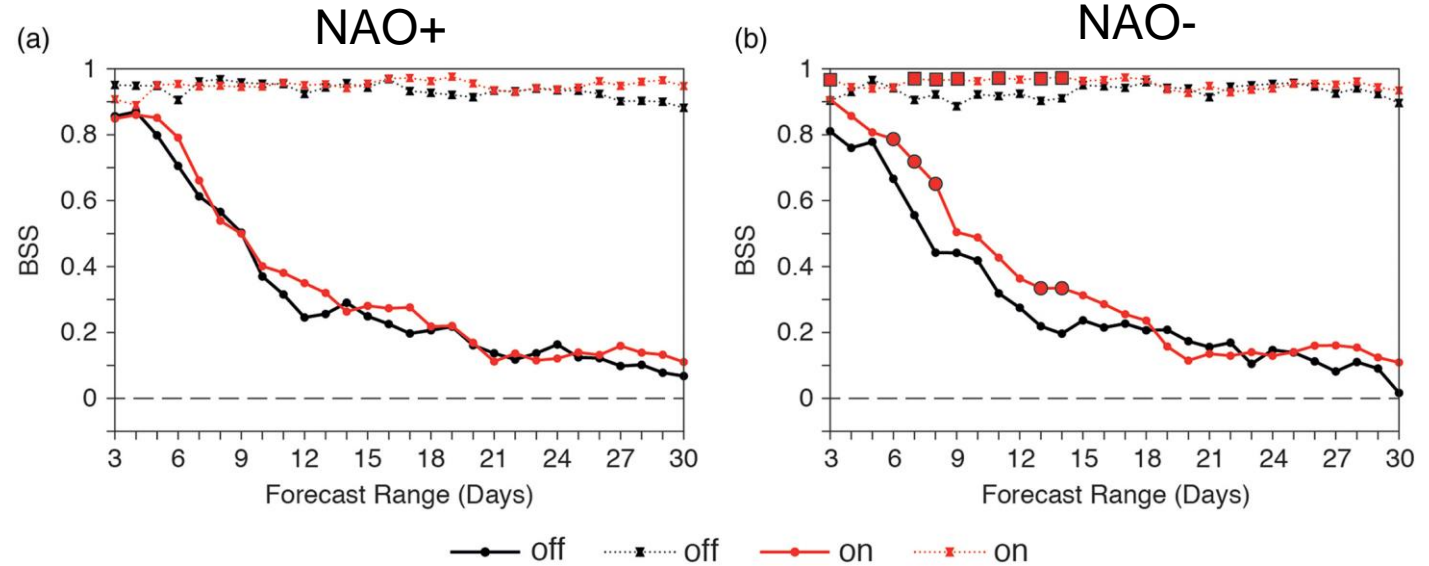
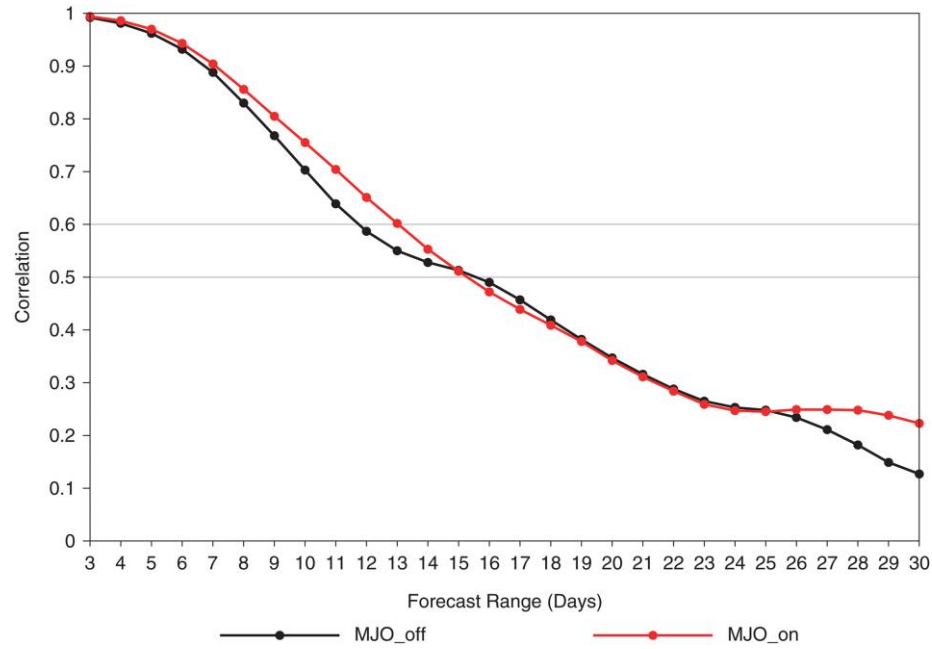


Precipitation anomaly



Conditional verification (on active MJO)

Ensemble mean correction for NAO

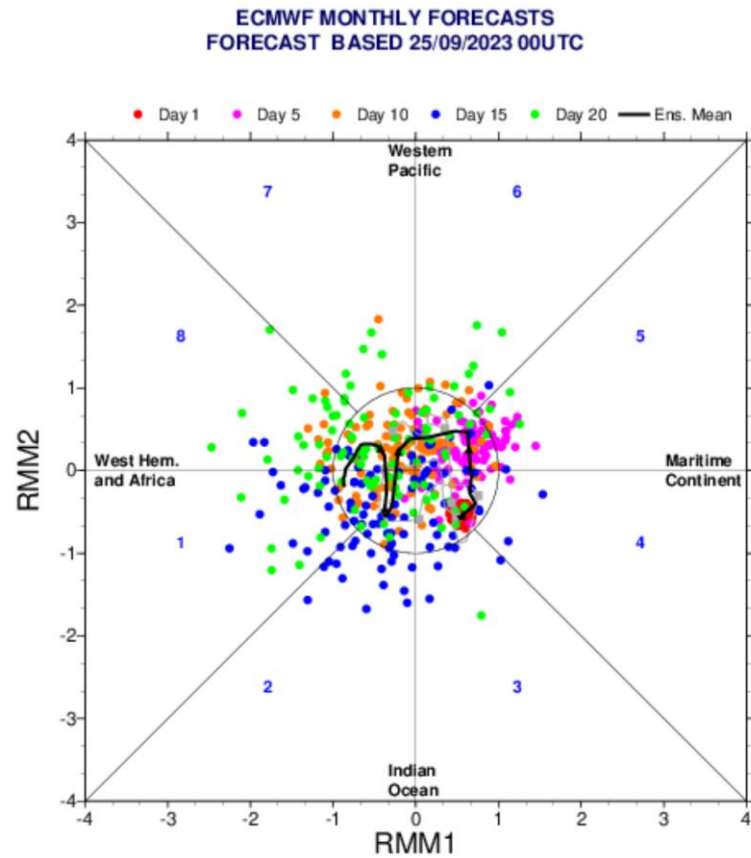


More skilful NAO- forecasts if MJO active in initial conditions

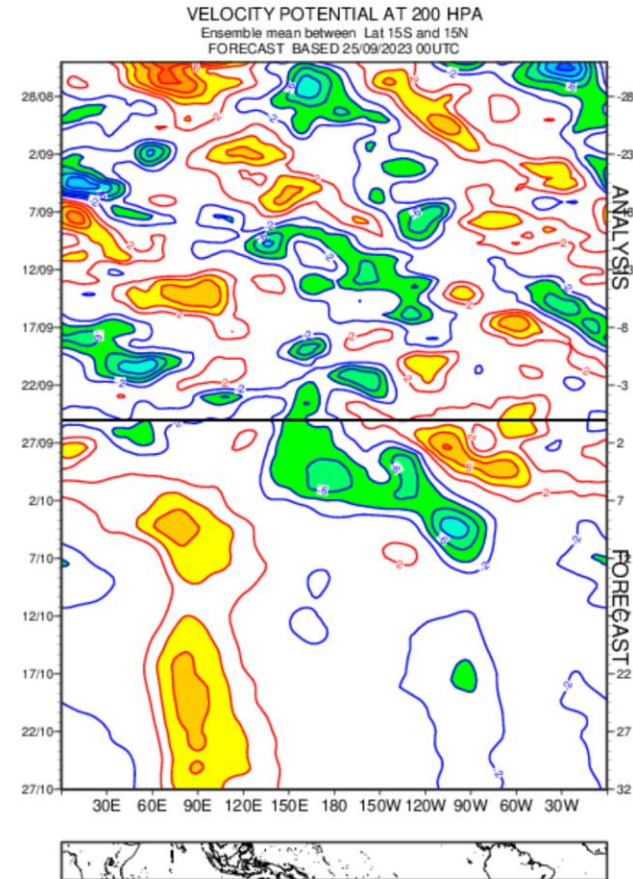
From Ferranti et al. (2018, <https://doi.org/10.1002/qj.3341>)

Forecast products for predictability drivers – MJO

Madden-Julian Oscillation (MJO) index - Extended range forecast



Time-longitudes sections - Extended range forecast



To capture a window of opportunity it takes

- That a teleconnection exists
- That the driver of the teleconnection is predictable
- That the forecast system can capture the teleconnection
- Reliable spread from the ensemble

- If building a statistical model or manual interpretation:
 - (Non-linear) interactions between drivers
 - Small sample from reanalysis (risk for overfitting)

[< Previous Article](#) [Next Article >](#)



Monthly Weather Review

Article Type: **Research Article**

Euro-Atlantic weather regimes and their modulation by tropospheric and stratospheric teleconnection pathways in ECMWF reforecasts

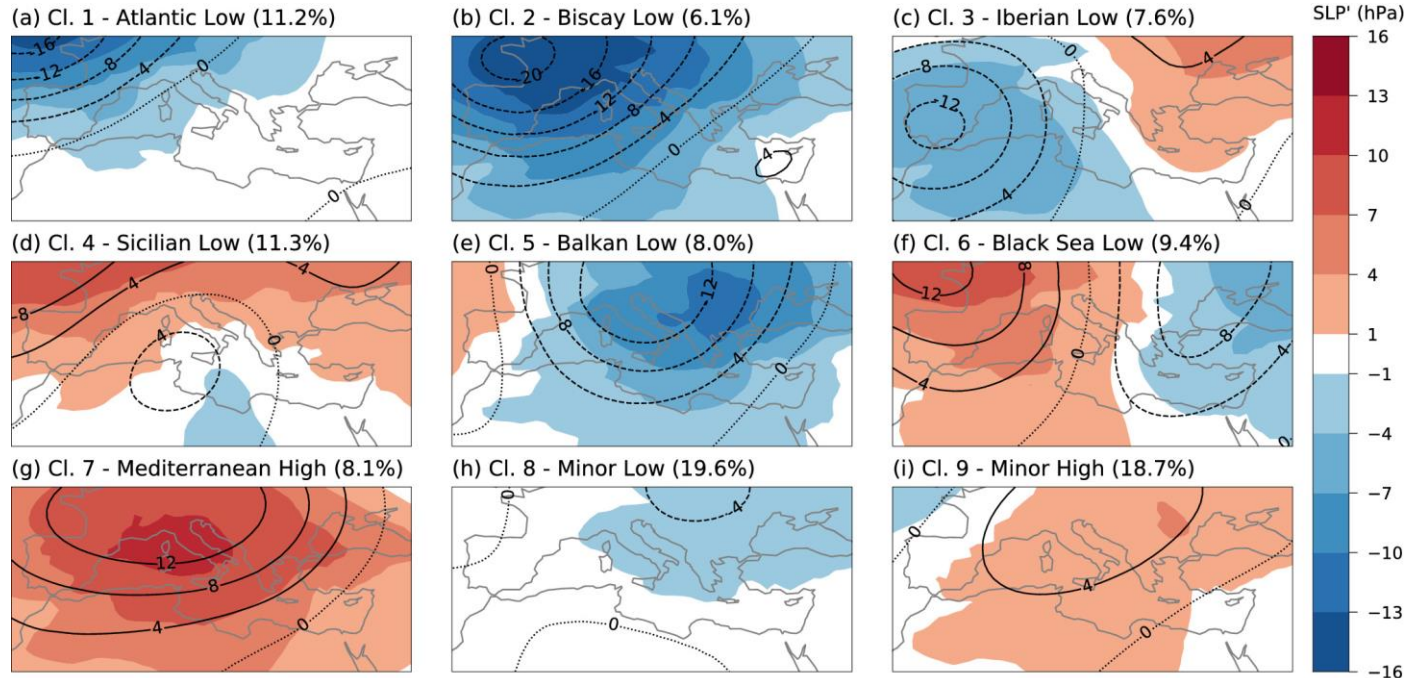
Christopher D. Roberts, Magdalena A. Balmaseda, Laura Ferranti, and Frederic Vitart

Online Publication: **23 Aug 2023**

DOI: <https://doi.org/10.1175/MWR-D-22-0346.1>

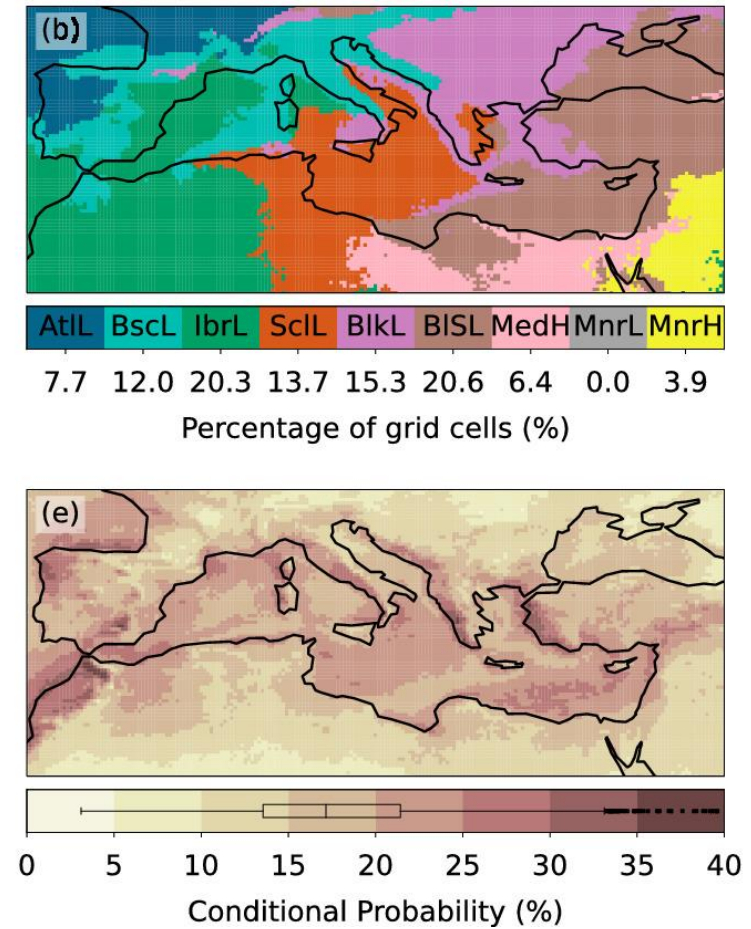
Regimes for other regions – Mediterranean example

Mastrantonas et al., 2021, 10.1002/qj.4236



Connections to extreme rainfall

WinterHalf statistics

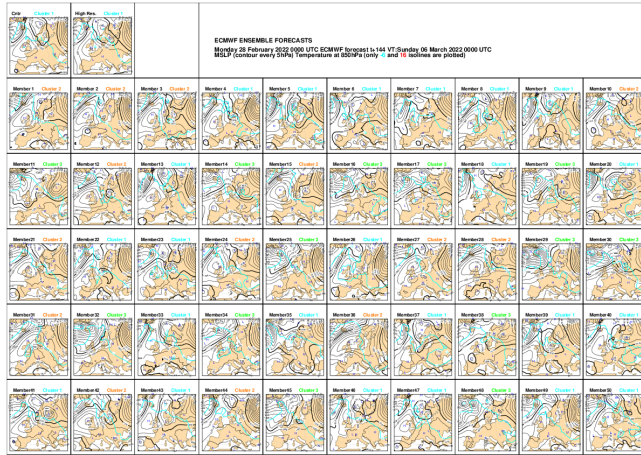


Summary

Content

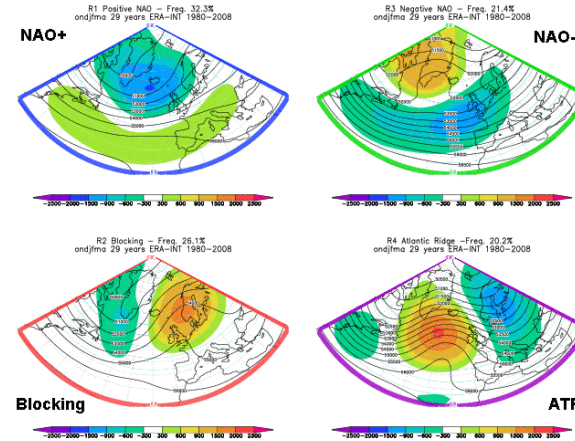
- Background/Motivation
- Regime calculation
- Products
- Connections to surface weather
- Teleconnections
- Skill

Raw forecast

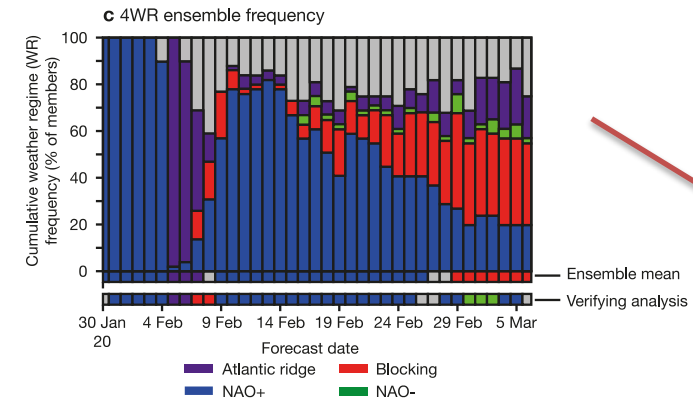


Regime definitions

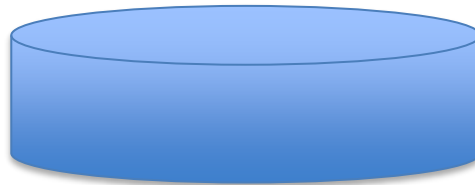
(a)



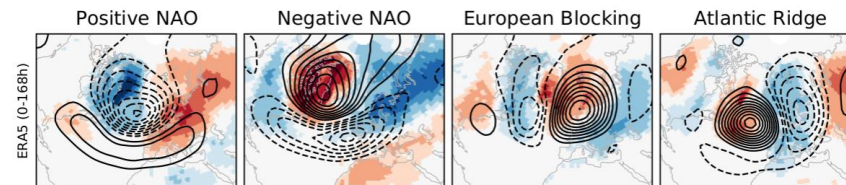
Regime products



Reanalysis



Connection to surface weather



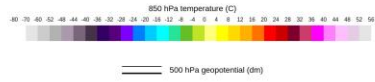
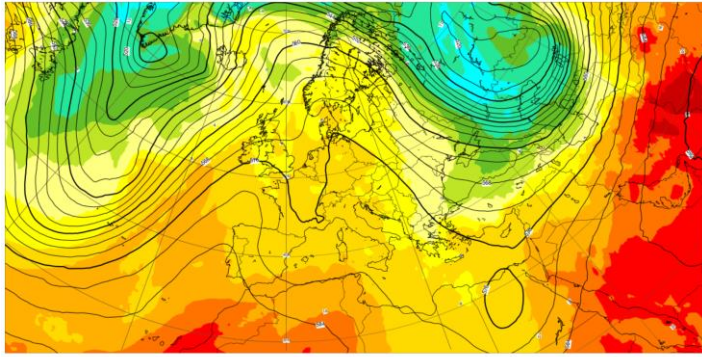
Skilful and interpretable forecast!?!

Products from yesterday

Analysis

500 hPa geopotential height and 850 hPa temperature

Base time: Wed 06 Nov 2024 00 UTC Valid time: Wed 06 Nov 2024 00 UTC (+0h) Area : Europe

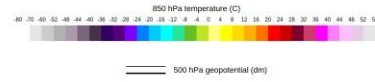
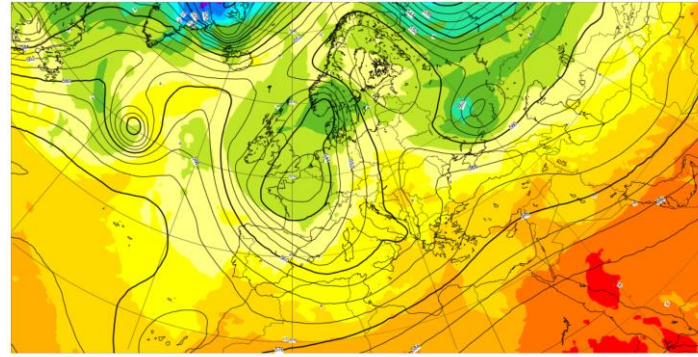


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Source: reanalysis data
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Created at 2024-11-07T00:31:36Z

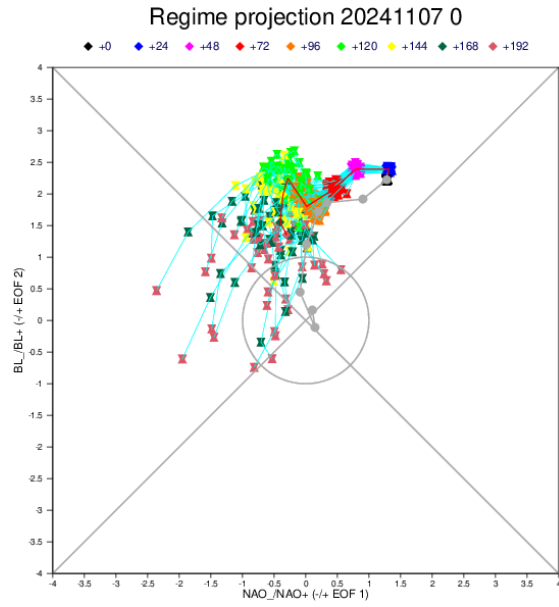
10 day forecast

500 hPa geopotential height and 850 hPa temperature

Base time: Wed 06 Nov 2024 00 UTC Valid time: Sat 16 Nov 2024 00 UTC (+240h) Area : Europe



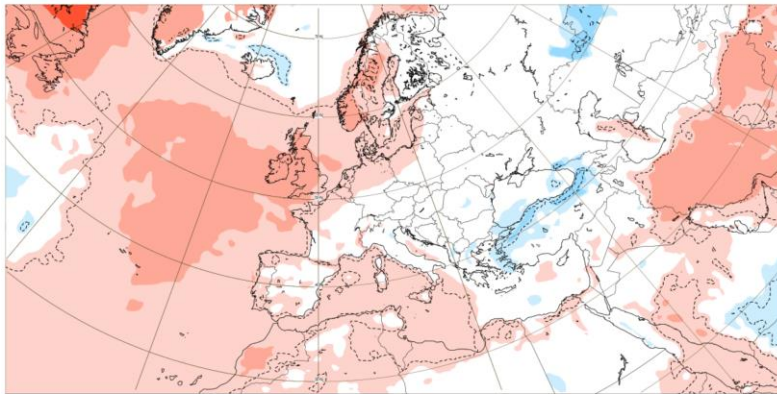
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Created at 2024-11-07T00:31:36Z

2 m temperature: Weekly mean anomalies

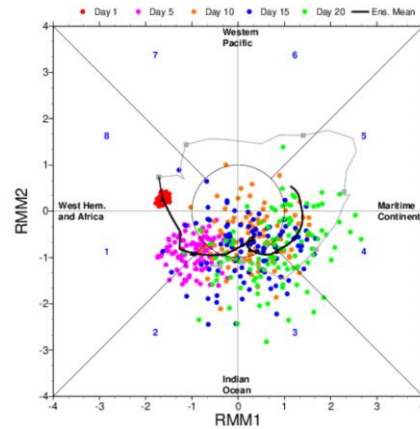
Base time: Wed 06 Nov 2024 Valid time: Mon 25 Nov 2024 - Mon 02 Dec 2024 (+624h) Area : Europe



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Madden-Julian Oscillation (MJO) index - Extended range forecast

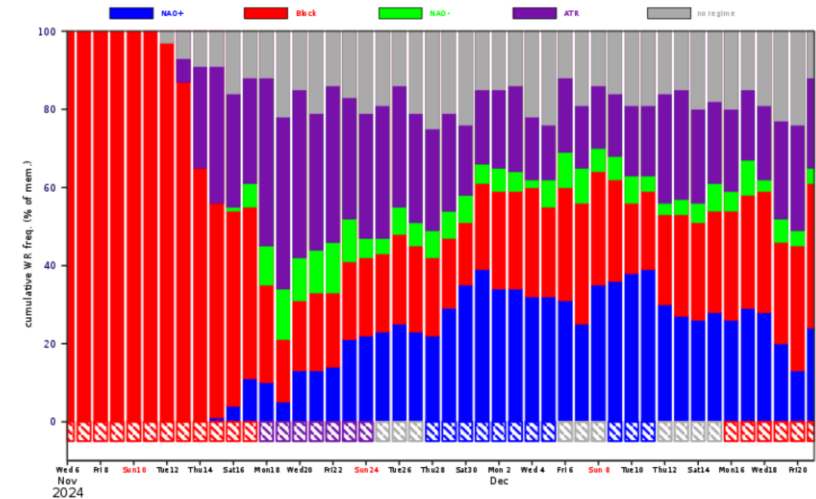
ECMWF MONTHLY FORECASTS
FORECAST BASED 06/11/2024 00UTC



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Weather regimes probabilities - Extended range forecast

Weather Regime frequency
Ensemble Forecast: 20241106



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Created at 2024-11-07T00:31:36Z

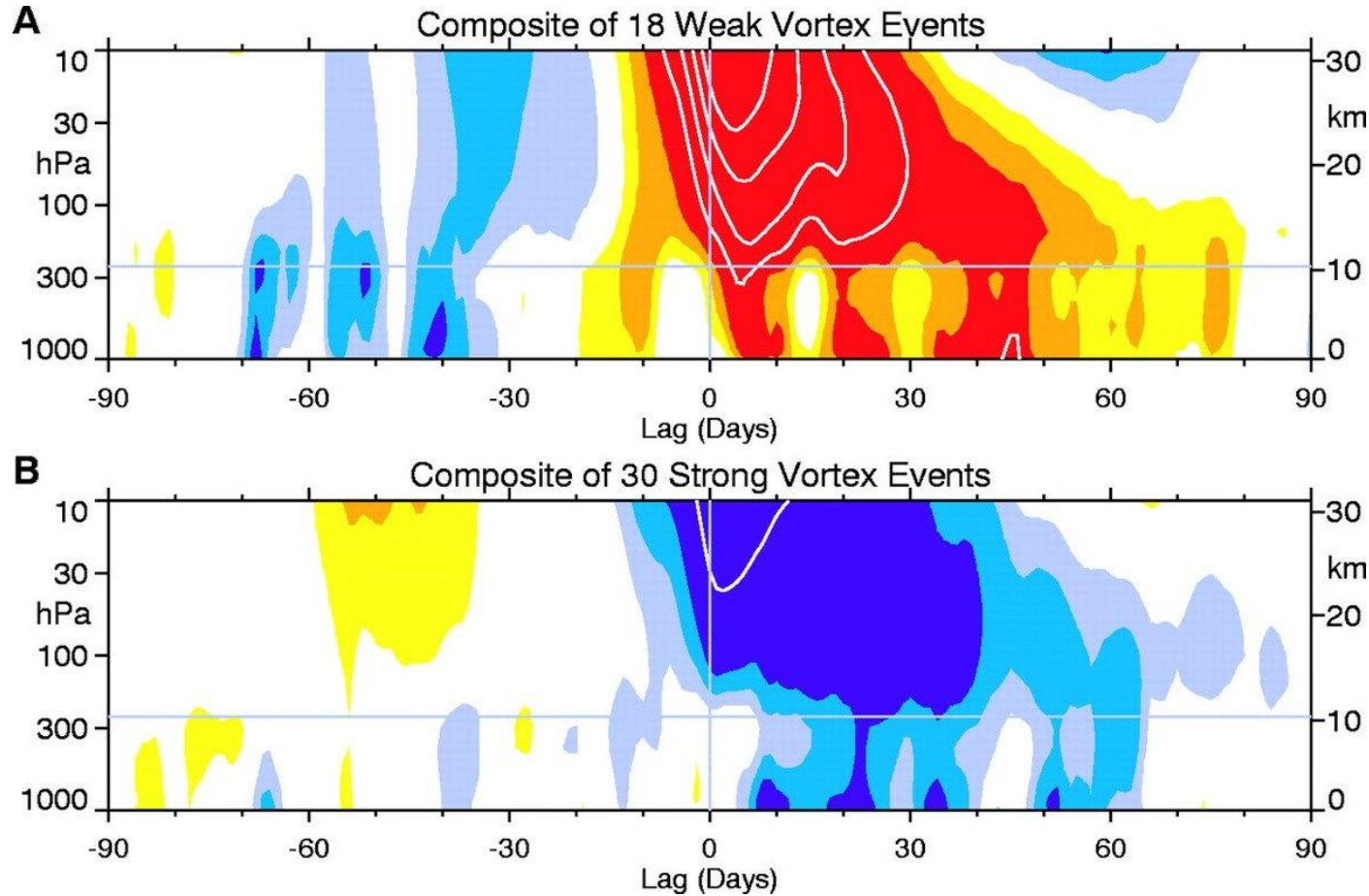
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Created at 2024-11-07T00:31:36Z

Key references

- <https://www.ecmwf.int/en/newsletter/158/meteorology/new-product-flag-risk-cold-spells-europe-weeks-ahead>
- <https://www.ecmwf.int/en/newsletter/165/meteorology/how-make-use-weather-regimes-extended-range-predictions-europe>

Sudden stratospheric warming (SSW)

Composites of weak and strong Polar Vortex (from Baldwin and Dunkerton, 2001)

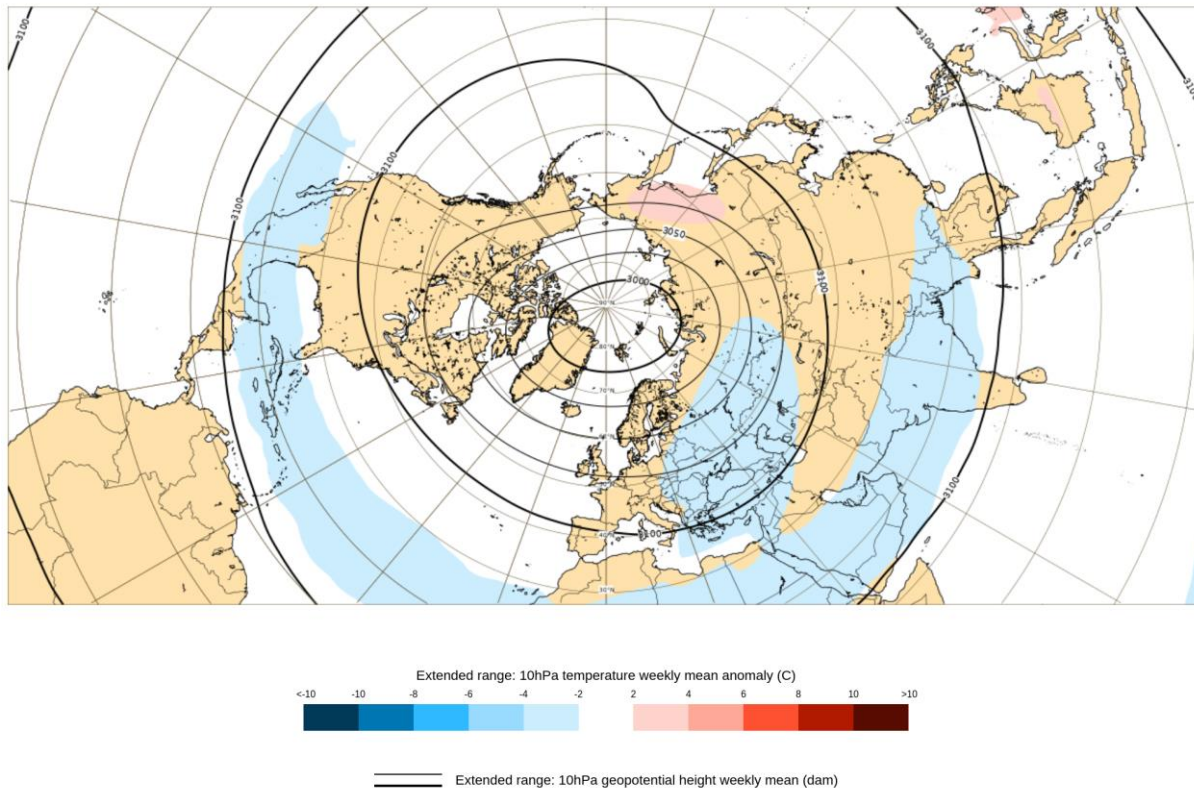


Decrease polar vortex in the troposphere after a stratospheric warming, which could lead to negative NAO during the following month.

Forecast products for predictability drivers – Stratospheric polar vortex

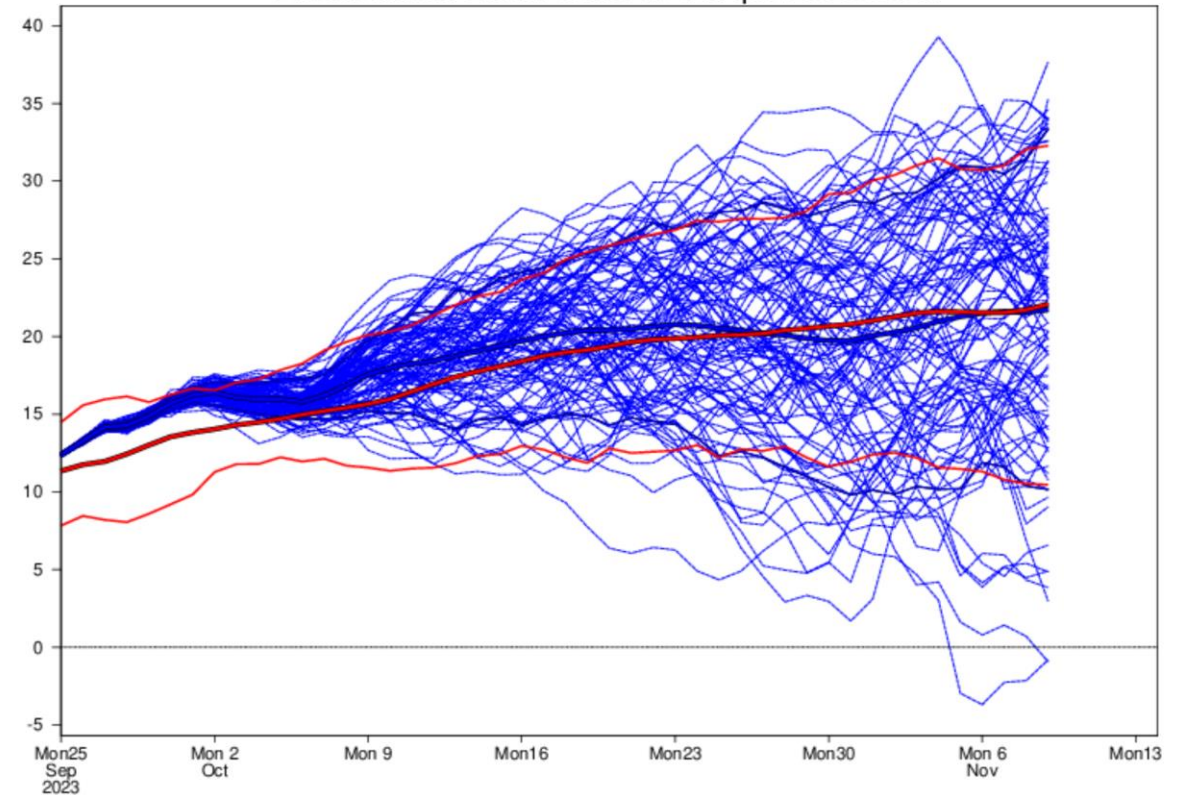
10hPa temperature: Weekly mean anomalies

Base time: Mon 25 Sep 2023 00 UTC Valid time: Mon 09 Oct 2023 00 UTC - Mon 16 Oct 2023 00 UTC (+504h) Area : North Pole



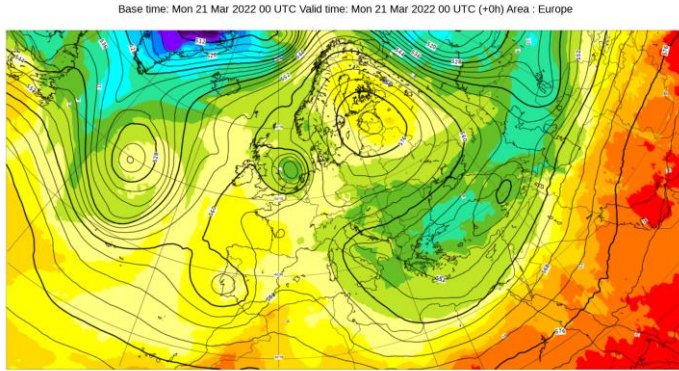
Mean zonal wind at 10 hPa - Extended range forecast

Zonal mean zonal wind at 10Hpa 20230925

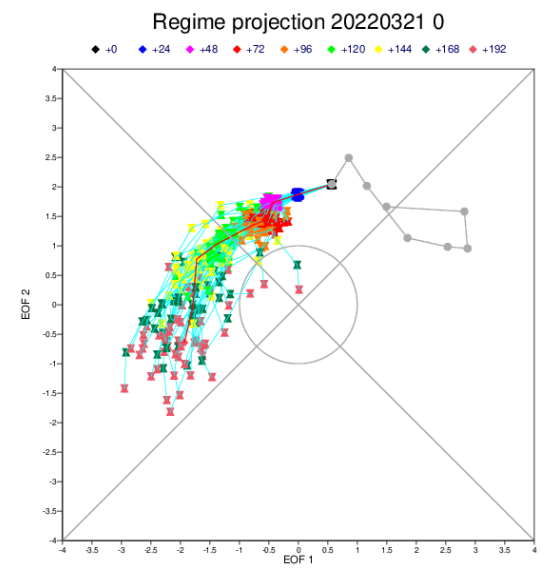
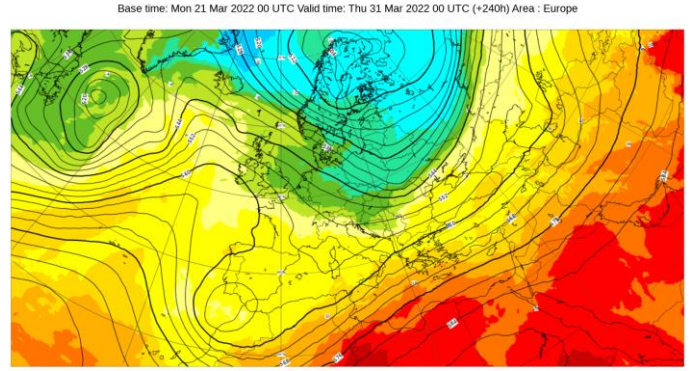


Products from today

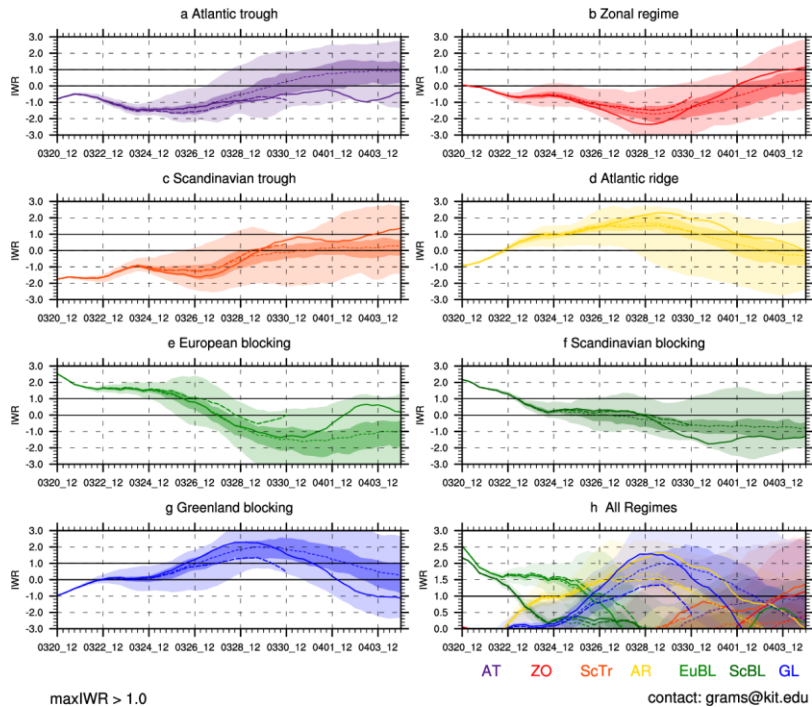
Geopotential 500 hPa and temperature at 850 hPa Analysis



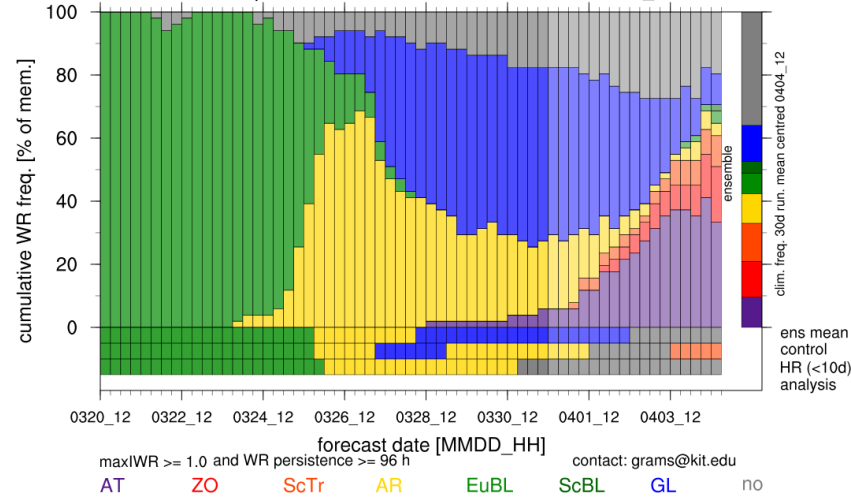
Geopotential 500 hPa and temperature at 850 hPa 10 day forecast



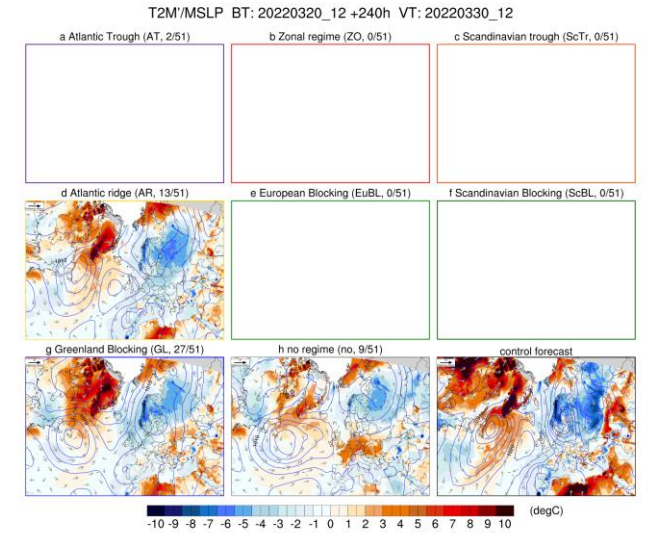
WR index ensemble BT: 20220320_12



WR freq in ensemble forecast initialised at 20220320_12



Temperature anomalies +10 days



Courtesy C. Grams (KIT)

Weather regimes and related dynamical concepts

Weather regime:

A persistent and/or recurrent large-scale atmospheric circulation pattern which is associated with specific weather conditions on a regional scale

Flow regime:

A persistent and/or recurrent large-scale flow pattern in a (geophysical) fluid-dynamical system

Multiple equilibria:

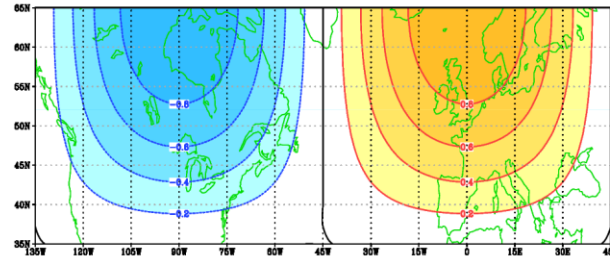
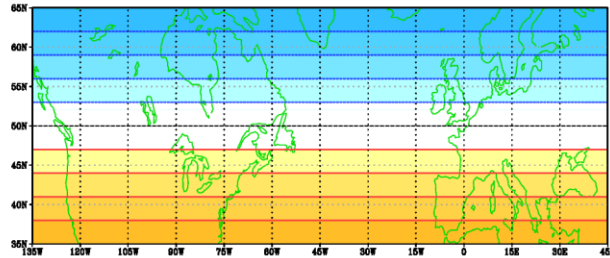
Multiple stationary solutions of a non-linear dynamical system

3-variable NAO model: basic functions and equations

(Molteni and Kucharski, Climate Dyn. 2019, doi:10.1007/s00382-018-4509-4)

$$\psi = - (U' + U_0) y + A \psi^*_1 + B \psi^*_2 + \psi^*_0$$

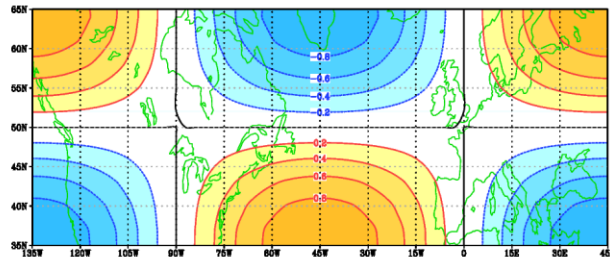
U'



ψ^*_0

North America / Atlantic / Europe (NAE) channel:
135W-45E, 35N-65N

A
~ NAO
index

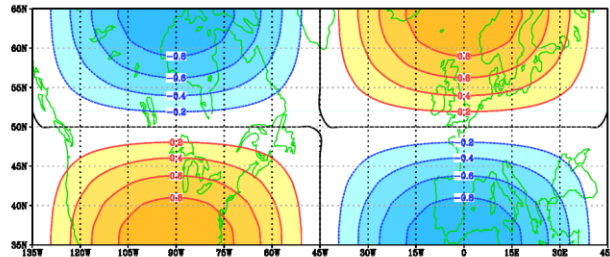


$$dU'/dt = \gamma A - \sigma U' - k (U' - U^*)$$

$$dA /dt = U' B - \sigma U' - k A$$

$$dB /dt = -U' A - k (B - B^*)$$

B



Vorticity advection by zonal wind

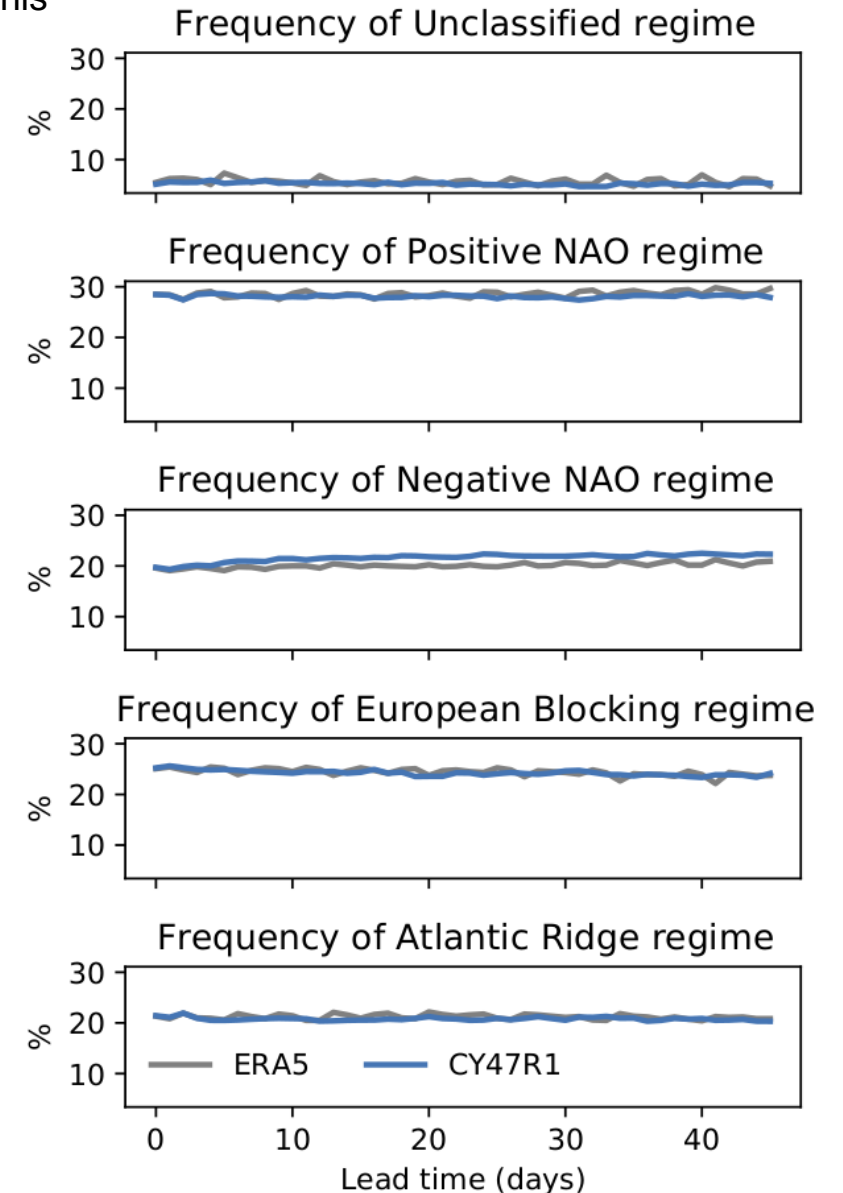
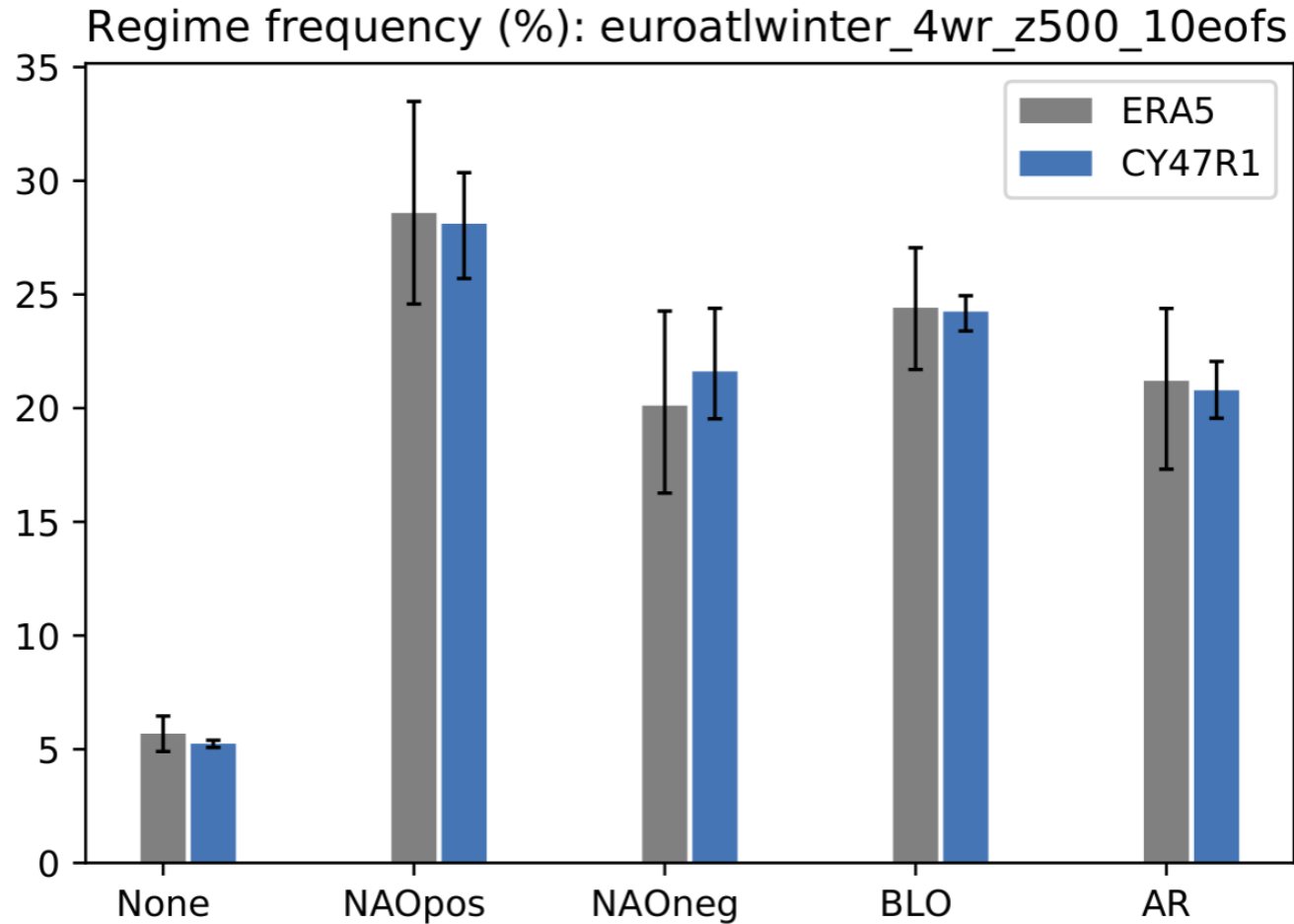
Convergence of meridional heat transport by pl. waves

Diabatic heating induced by surface heat flux

Radiative damping towards equilibrium state

Climatological regime frequencies (SONDJFM, 2000-2020)

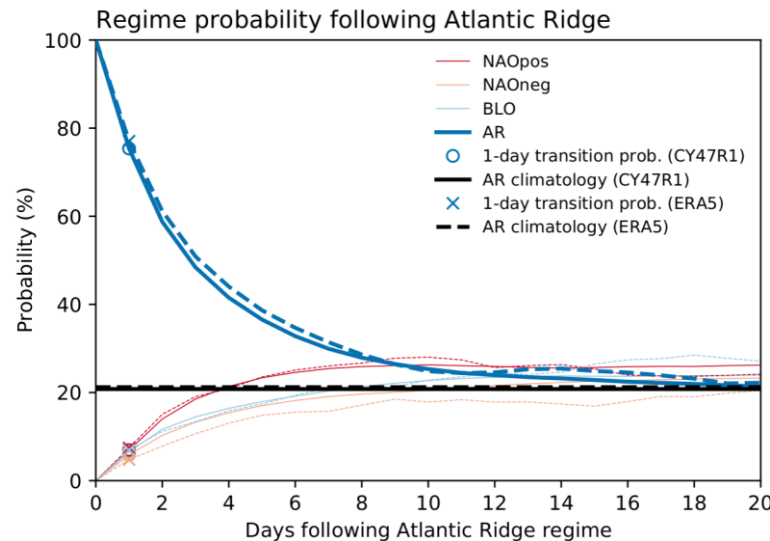
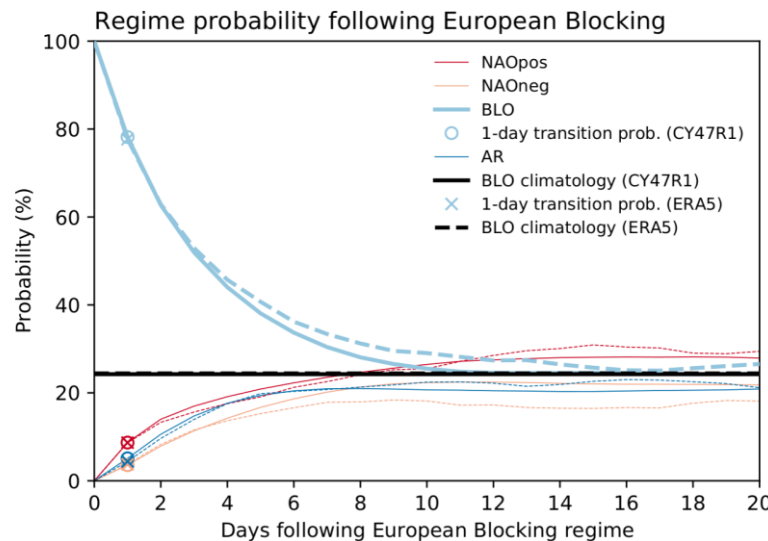
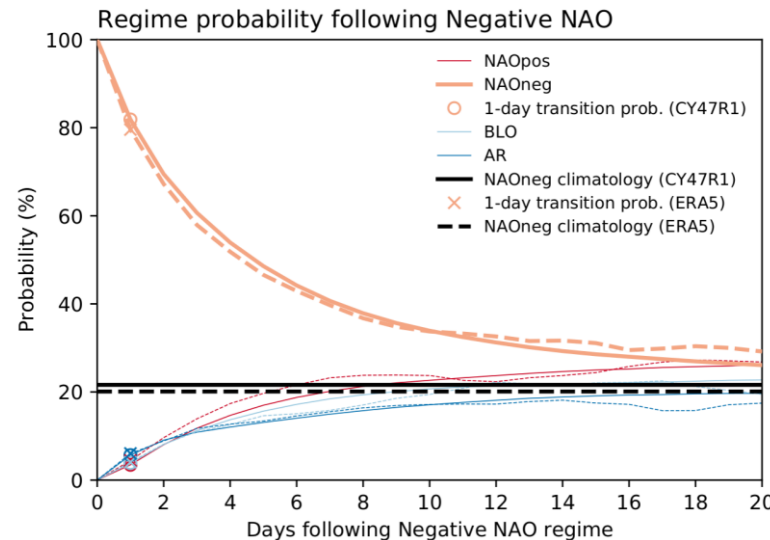
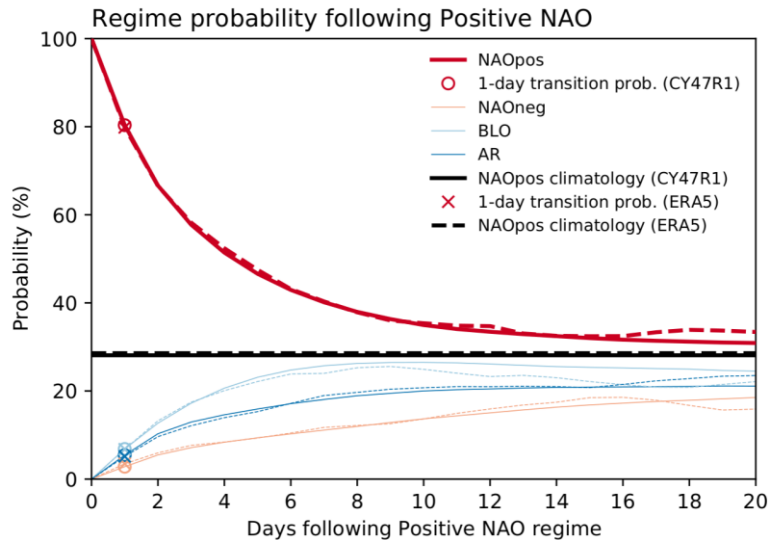
CY47R1 reforecasts accurately represent the climatological distribution of regimes. This distribution is also relatively stable for S2S lead times.



N.B. Regimes are assigned if the closest cluster centroid is also the cluster centroid with maximum projection onto forecast anomalies. If different clusters have minimum distance/maximum projection, then no regime is assigned.

Conditional regime probabilities (SONDJFM, 2000-2020)

The transition between regimes can be described as discrete-time Markov chain where the probability of a regime on day n depends only on the initial regime. The transition from regime i to regime j is described by the conditional probability $p_{ij}^{(n)} = Pr(X_n = j | X_0 = i)$, where X_n is the random variable corresponding to the regime state on day n .



CY47R1 reforecasts accurately reproduce regime probabilities when conditioned on the initial regime.

1-day transition and persistence probabilities are indicated by 'x' and 'o' markers.

Interesting points:

- Initializing with positive/negative NAO regime increases probability of this regime above climatological frequency for > 20 days.
- Probability of a blocking regime ~10 days after initial blocking regime (i.e. $Pr(X_{10} = blocking | X_0 = blocking)$) is lower in CY47R1 than ERA5.

Regime structures and surface impacts (SONDJFM, 2000-2020)

Regime composites: Z500 (20 m contour spacing) and precipitation (shading)

Composites lag regimes by 0 day(s)

euroatlwinter_4wr_z500_10eofs

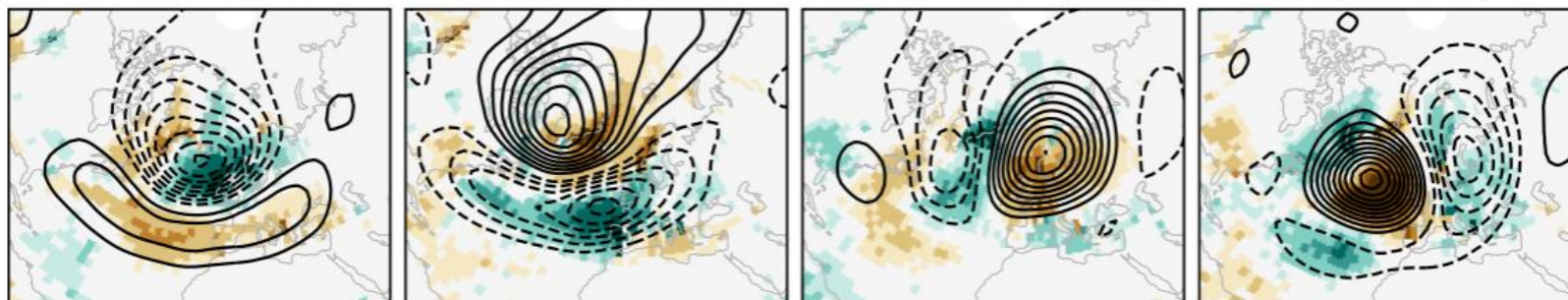
Positive NAO

Negative NAO

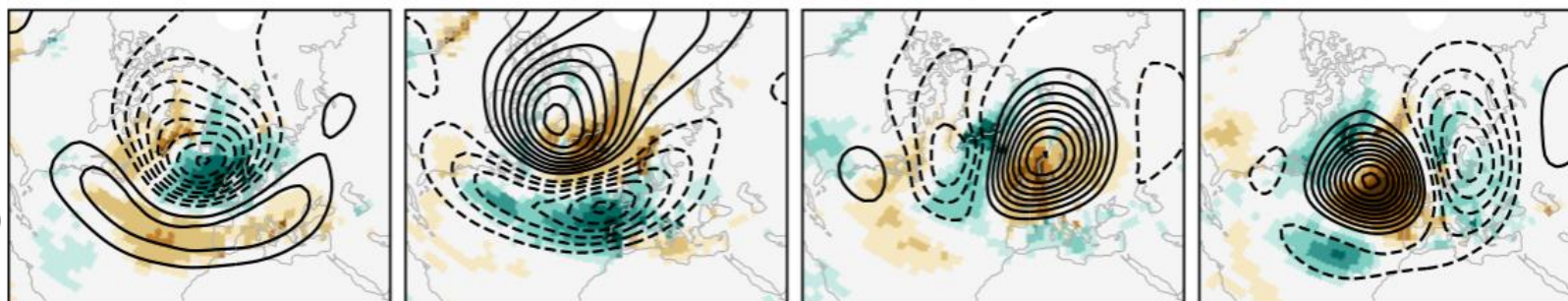
European Blocking

Atlantic Ridge

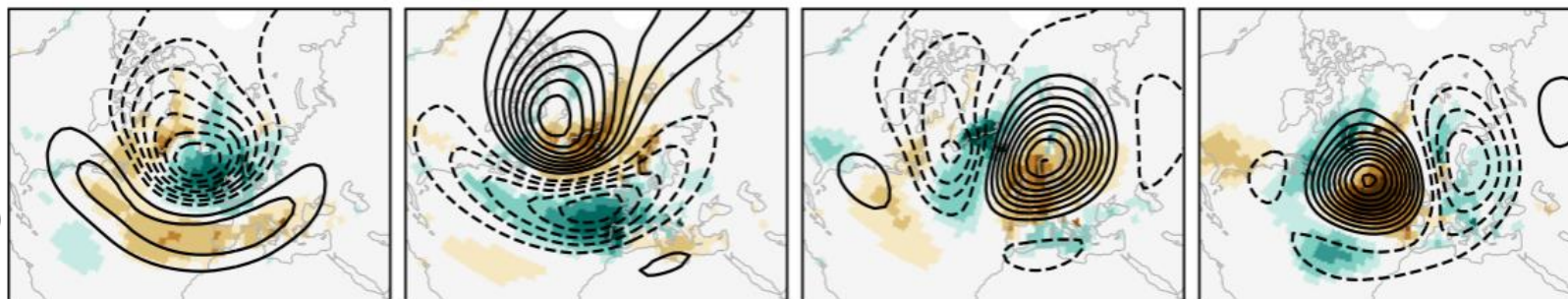
ERA5



Oper.
CY47R1
(week 1)



Oper.
CY47R1
(week 6)



-2.50

-1.50

-0.50

0.25

1.00

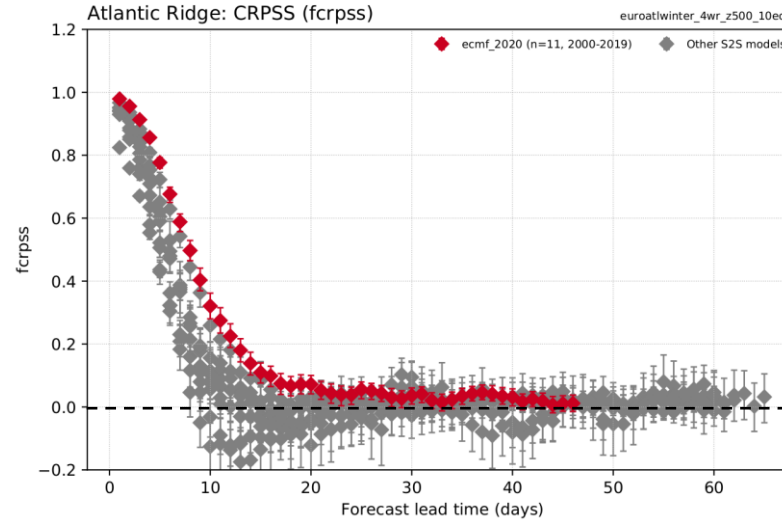
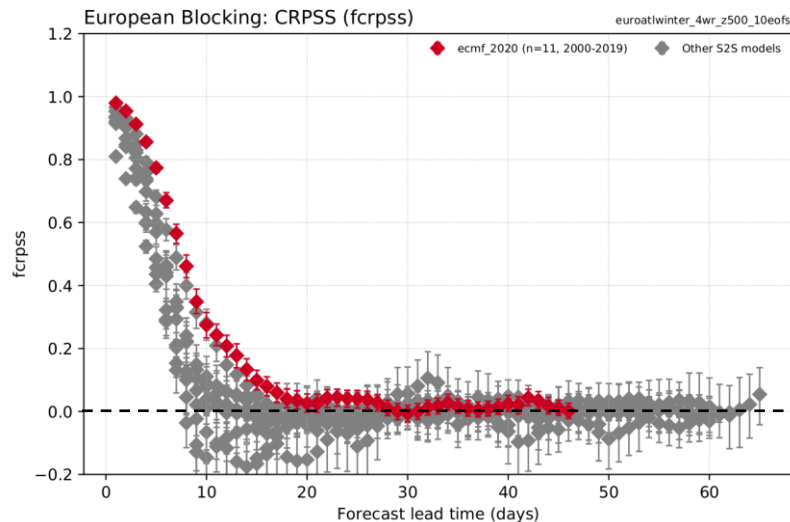
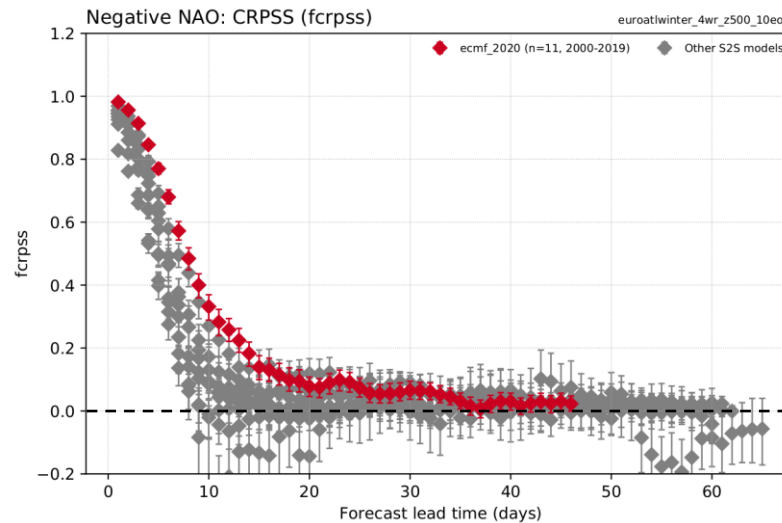
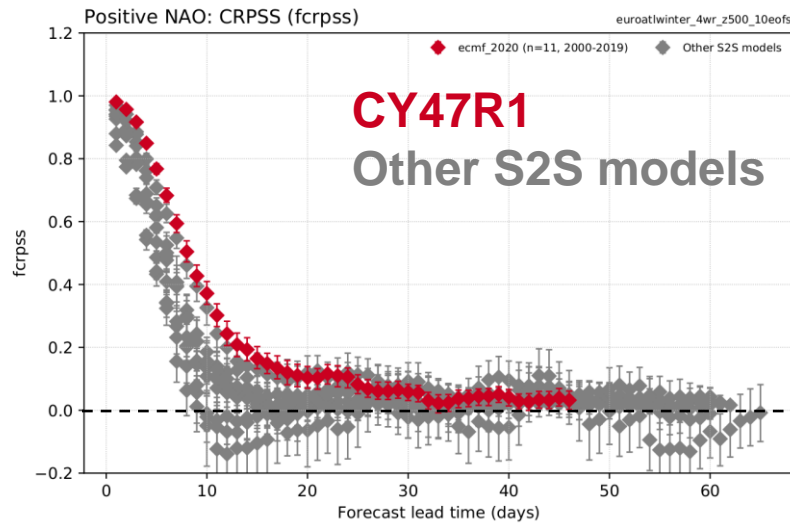
2.00

mm/day

Regime structures and surface impacts are well-represented in operational reforecasts (CY47R1) and stable across S2S lead times (week 1 to week 6).

Skill in operational S2S reforecasts (all year)

Regime skill is shown below for the fair CRPSS derived by projecting anomalies (in EOF space) onto regime centroids. The results are qualitatively similar for other scores derived from either continuous or categorical data (e.g.BSS).



ECMWF skill compares favourably to other S2S models (**caveat:** different reforecast periods, start dates, and ensemble sizes makes direct comparisons difficult).

Skill is limited at extended-range lead times (i.e., beyond week 2).

Days until CORR < 0.5

- 14 days for NAO+
- 14 days for NAO-
- 12 days for European Blocking
- 11 days for Atlantic Ridge

Days until BSS < 0

- 7 days for NAO+
- 7 days for NAO-
- 7 days for European Blocking
- 6 days for Atlantic Ridge