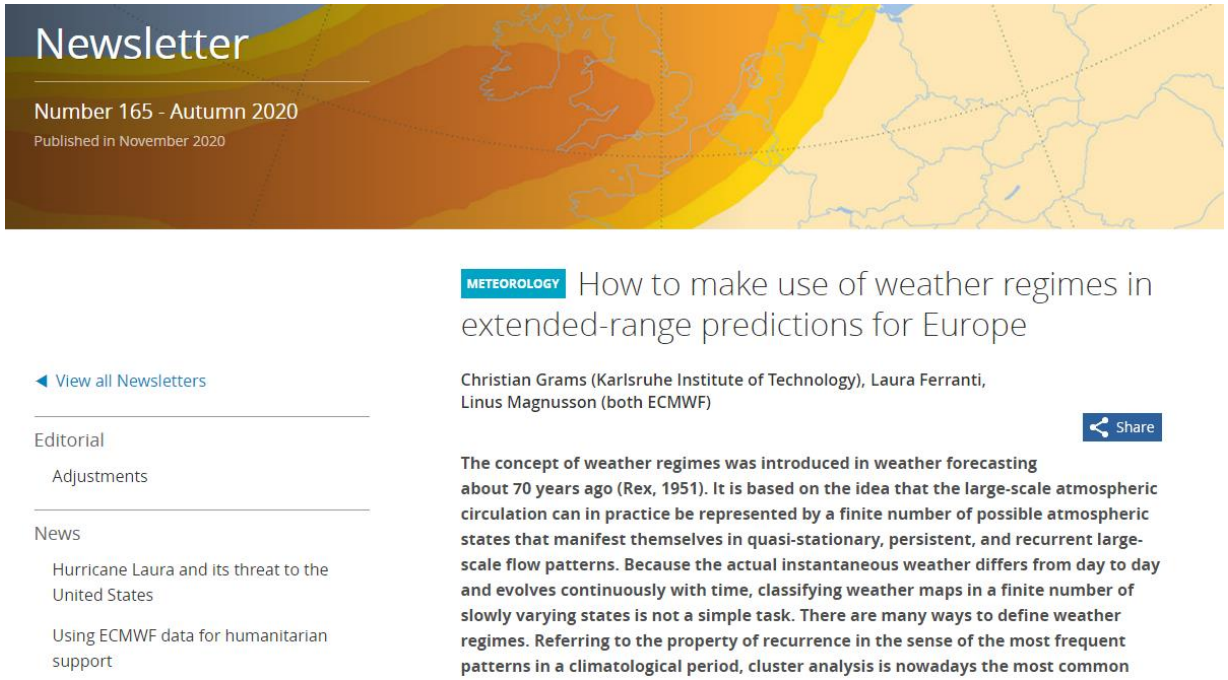
Teleconnections and weather regimes

Predictability training course 2026

Linus Magnusson

Laura Ferranti
Franco Molteni
Chris Roberts
Christian Grams (MeteoSwiss)



ECMWF

© ECMWF November 3, 2026

Motivation for use of regimes

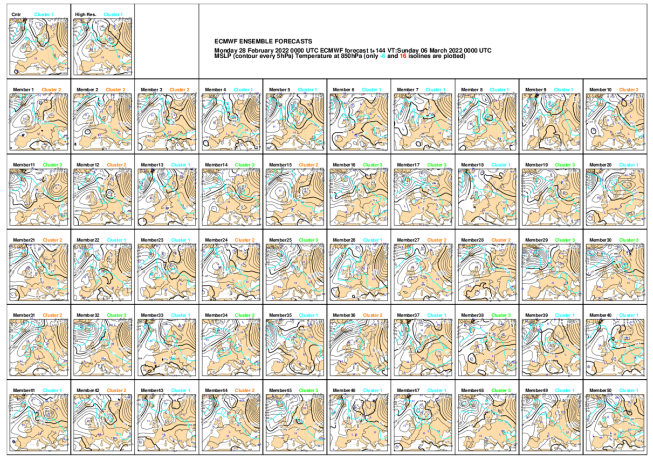
- Longer predictability in large-scale patterns
- Preferred (recurrent) states / long-lived (persistent) patterns in the atmosphere
- Dimension reduction for products – condensing informatino
- Relevance for surface weather

Overview

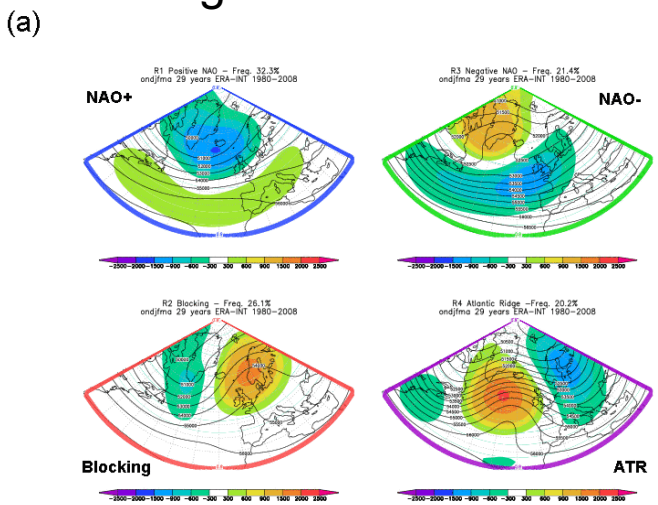
Content

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

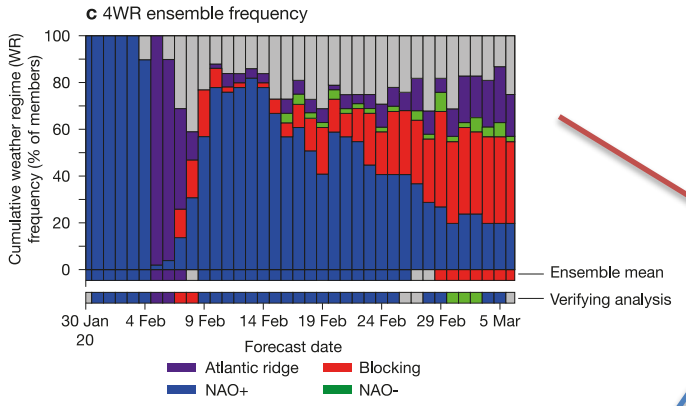
Raw forecast



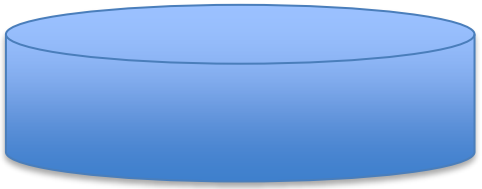
Regime definitions



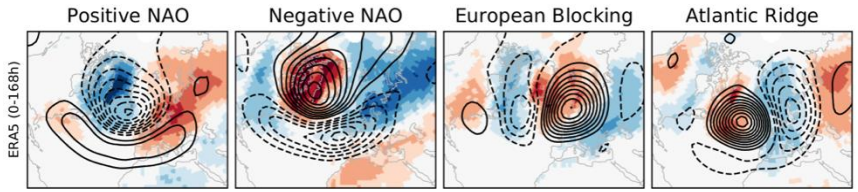
Regime products



Reanalysis



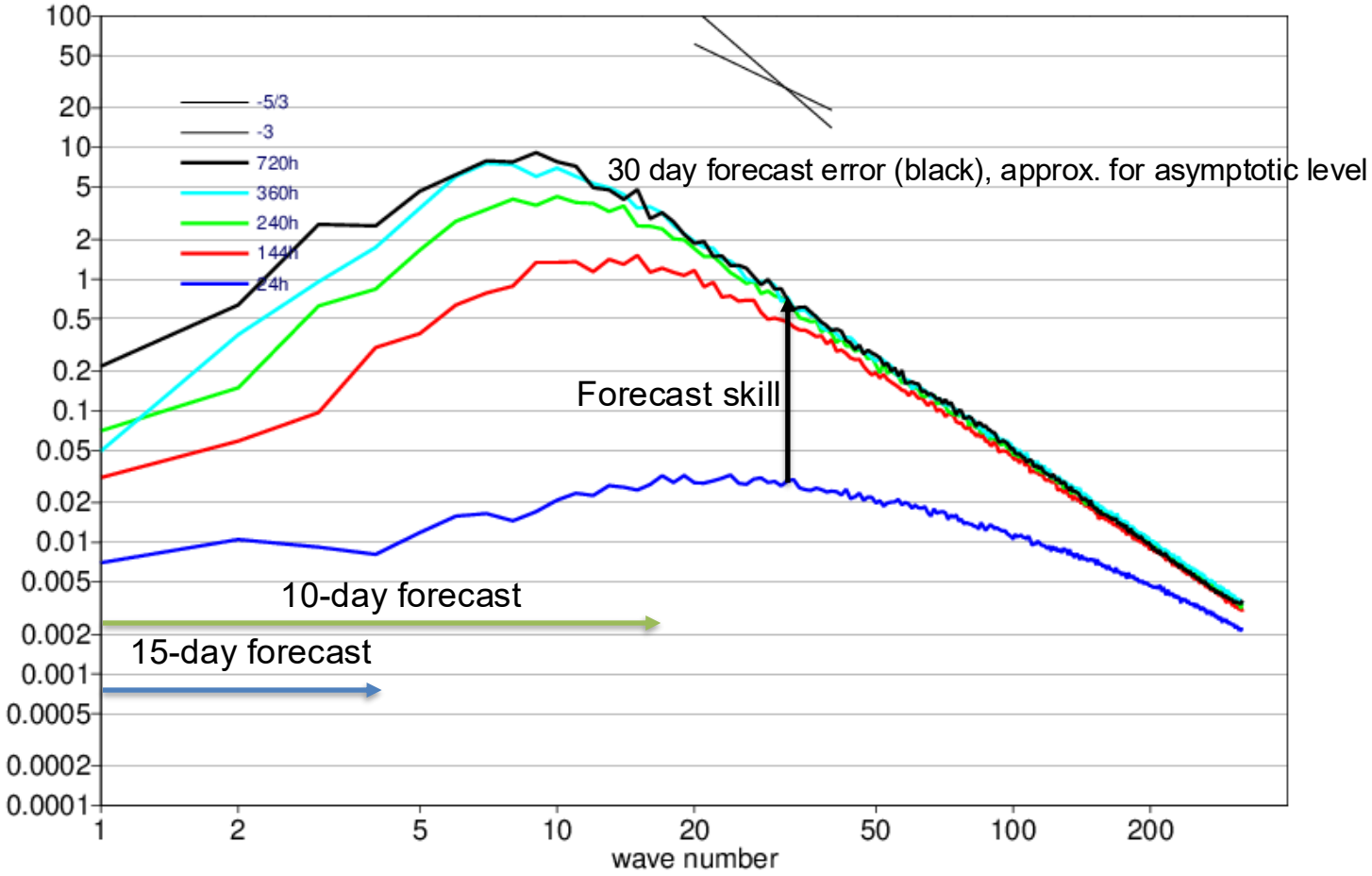
Connection to surface weather



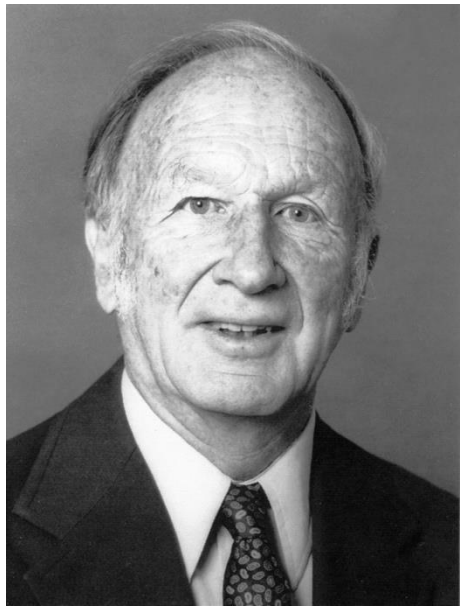
Interpretable and skilful forecast!?!



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



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



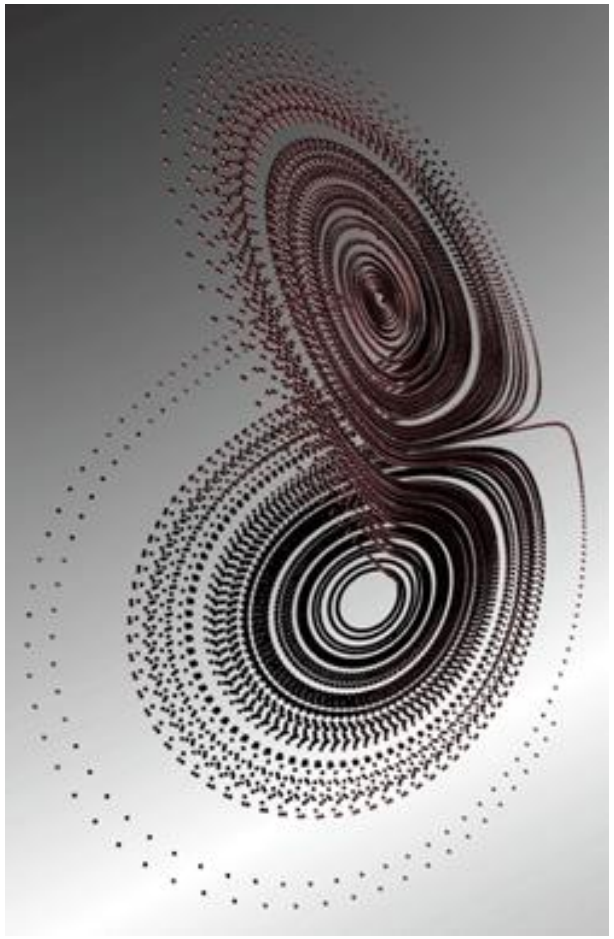
A prototype non-linear model with flow regimes

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

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

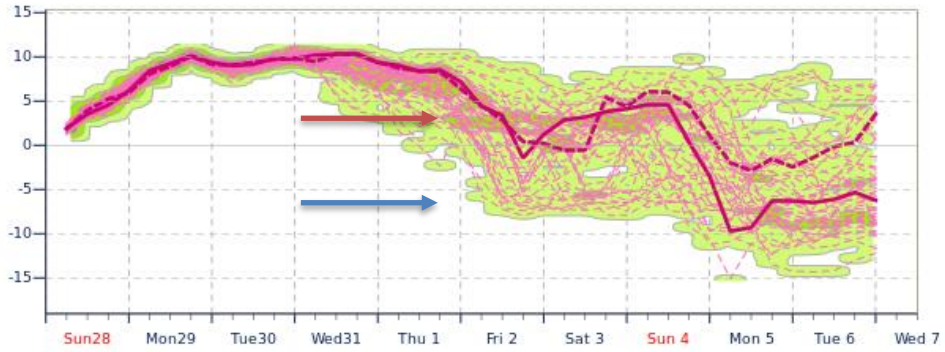
$$\dot{Z} = XY - bZ$$

Lorenz E., 1963: Deterministic non-periodic flow



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

Example of 850hPa temperature forecast



Historical notes

Early (1883) note on NAO

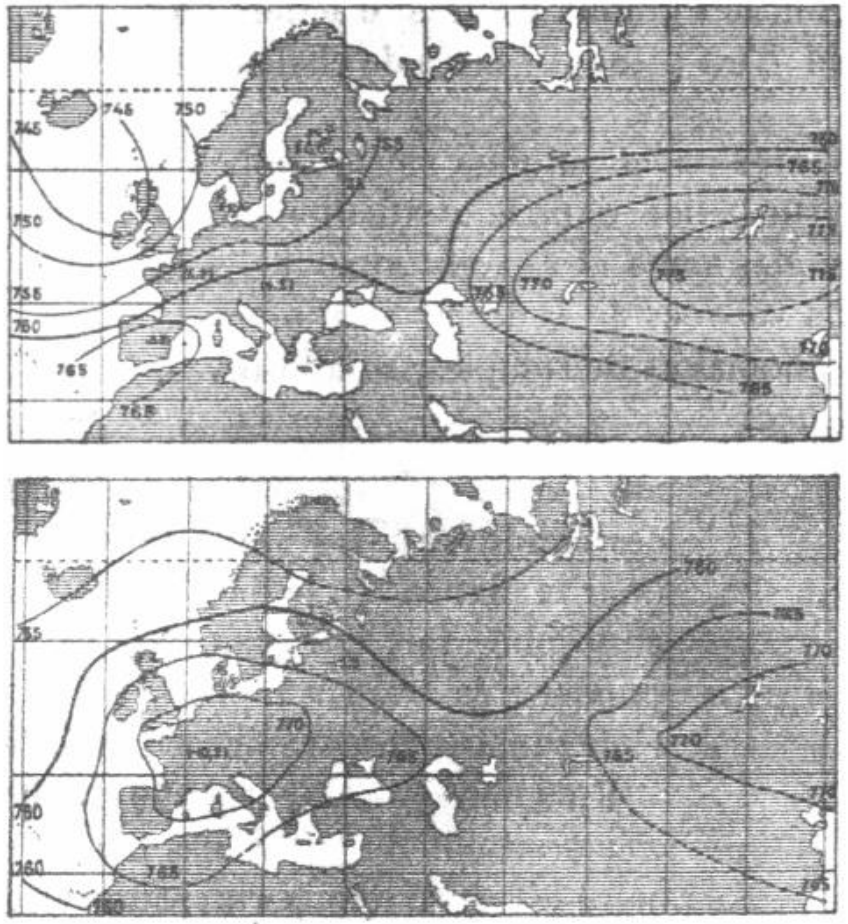


Figure 2. Vintage map showing early monthly mean sea level pressure (SLP) maps for December 1868 (top) and for December 1879 (bottom) (units in Torr; 1 Torr = 1.3332 hPa). From *Teisserenc de Bort* [1883].

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

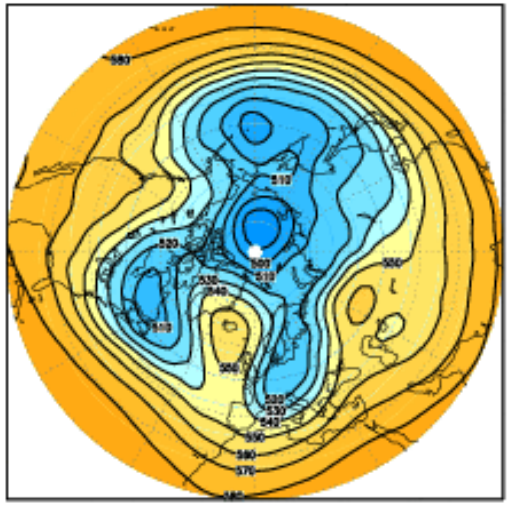
By DANIEL F. REX, University of Stockholm

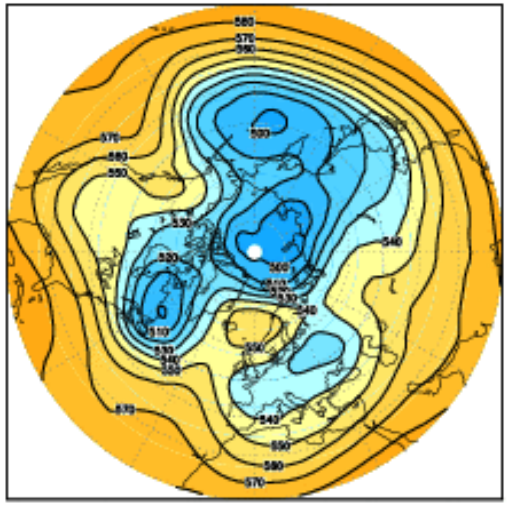
(Manuscript received 28 March 1951)

Abstract

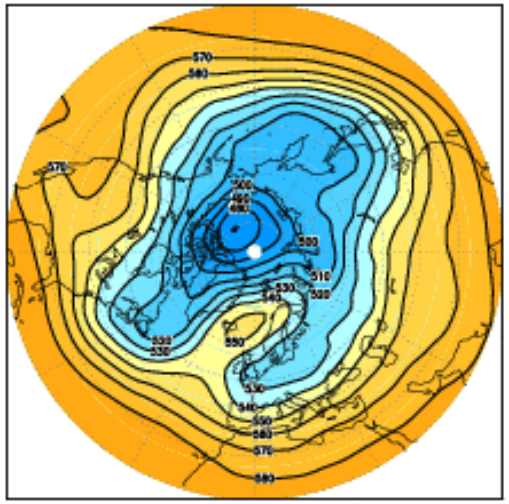
The results of the individual analysis of six cases of Atlantic blocking action are presented in the form of mean surface and upper-level pressure distributions and of mean regional precipitation and surface-temperature isanomal patterns for winter and for summer blocked periods over the European area. 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



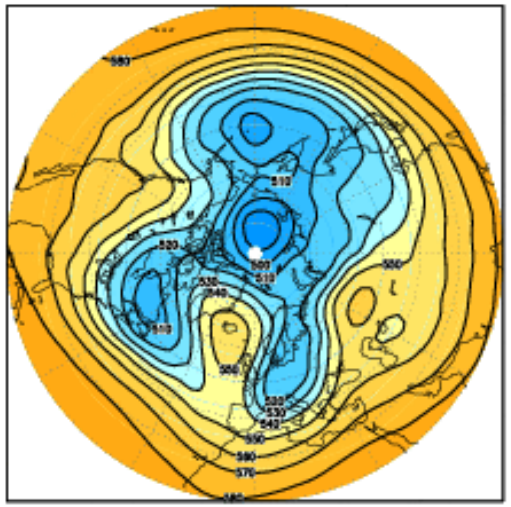


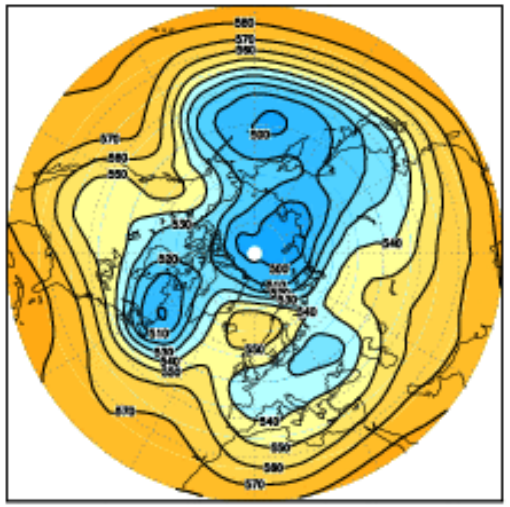
A sequence of 5-day mean fields of 500 hPa geopotential height during boreal winter …



Recurrent flow patterns: examples

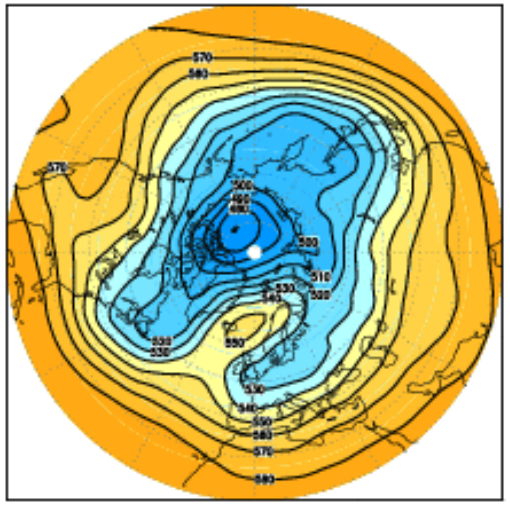
5-9 Jan 1985





4-8 Feb 1986

…but each of them occurred in a different winter



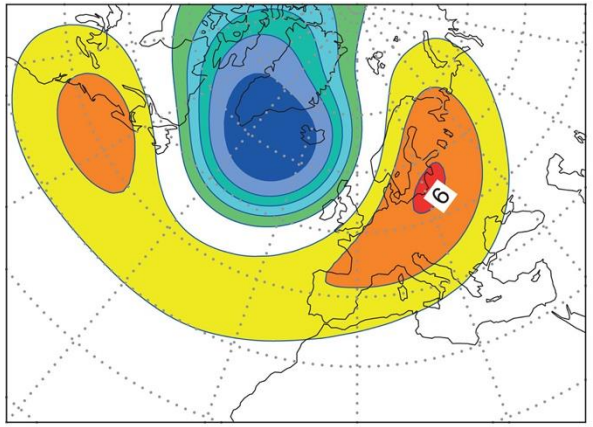
10-14 Jan 1987

EOF analysis of the Euro-Atlantic sector

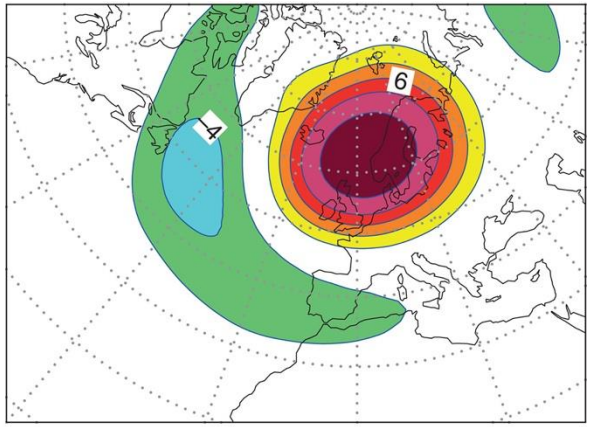
Current products at ECMWF based on:

- 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

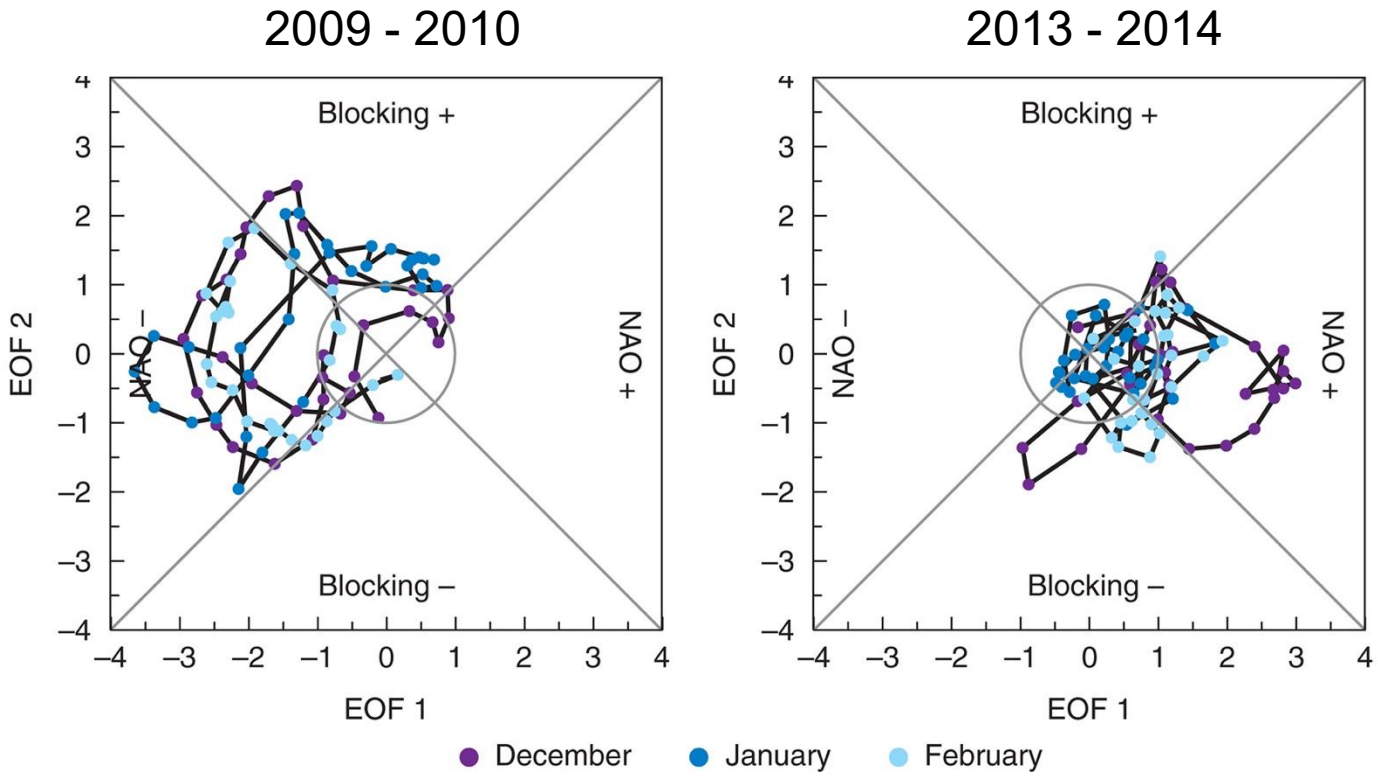
EOF1



EOF2



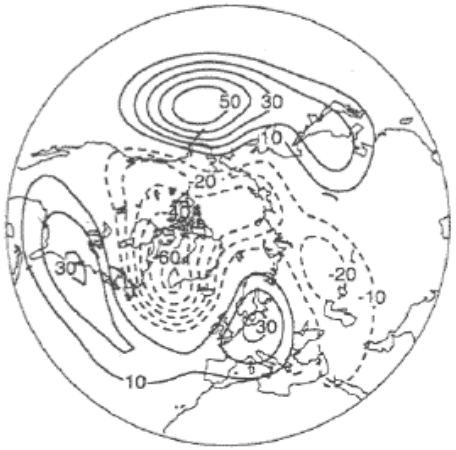
NAO and Blocking index for Winter 2009-2010 / 2013-2014

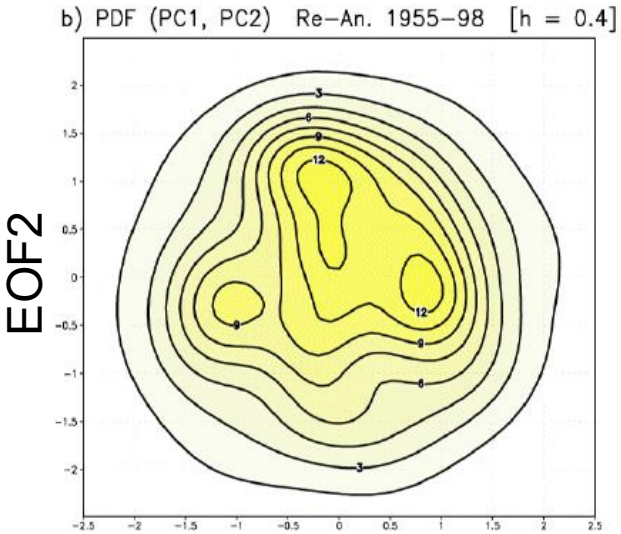


Examples of long-lived states

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

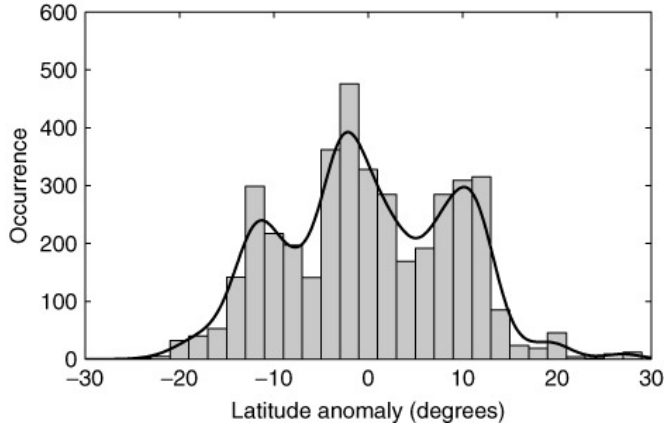








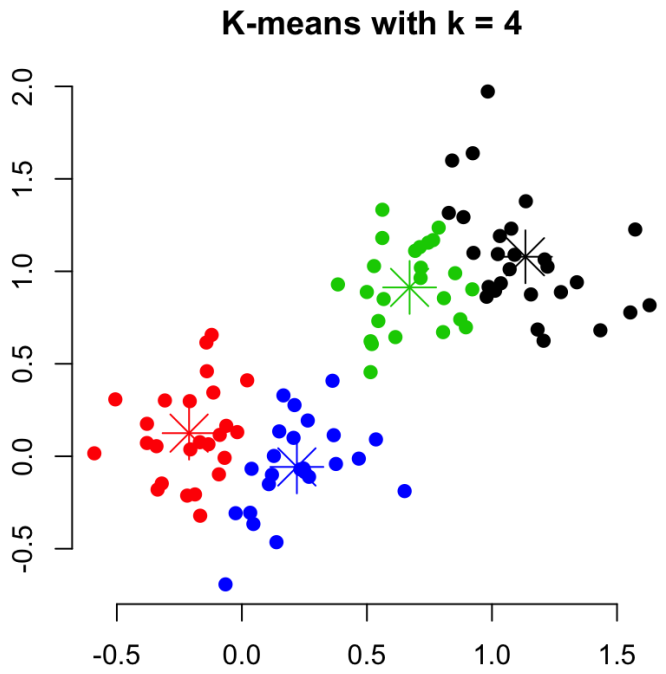
Distribution of low-level jet position over the Atlantic



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

Regimes as clusters in a multi-dimensional EOF phase space

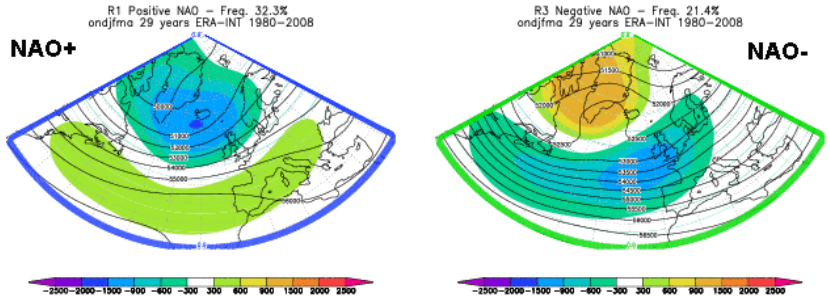
Mo and Ghil 1988 (N. Hem.)
Cheng and Wallace 1993 (N. Hem.)
Michelangeli et al. 1995 (Atl. - Europe)
Straus et al. 2007 (N. Pac. - N. America)



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

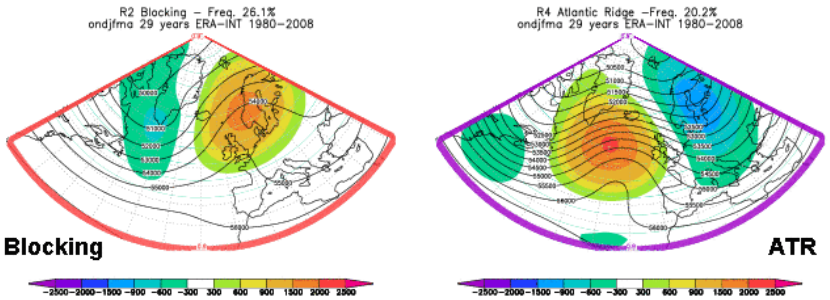
(a)

NAO + 32%



NAO- 21%

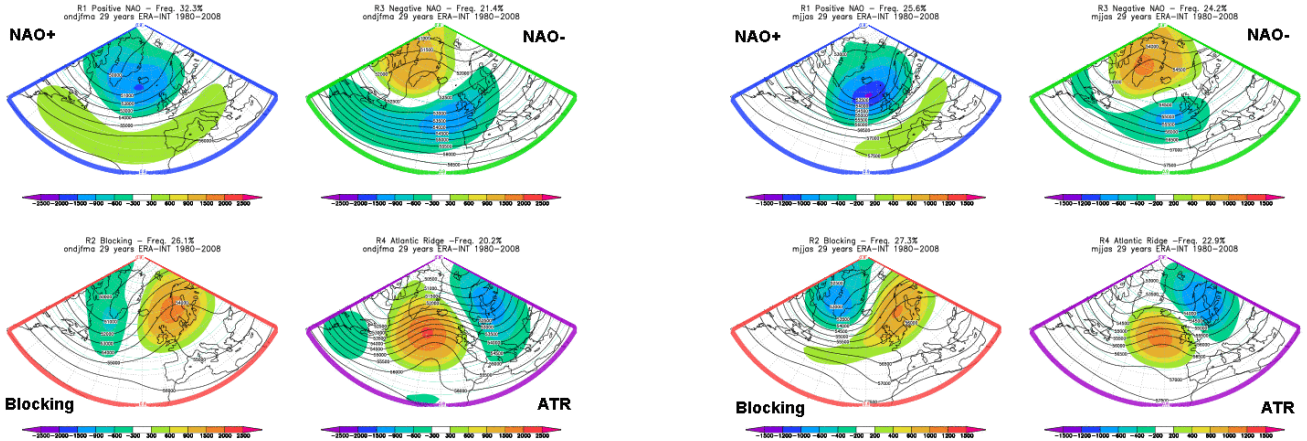
Blocking 26%



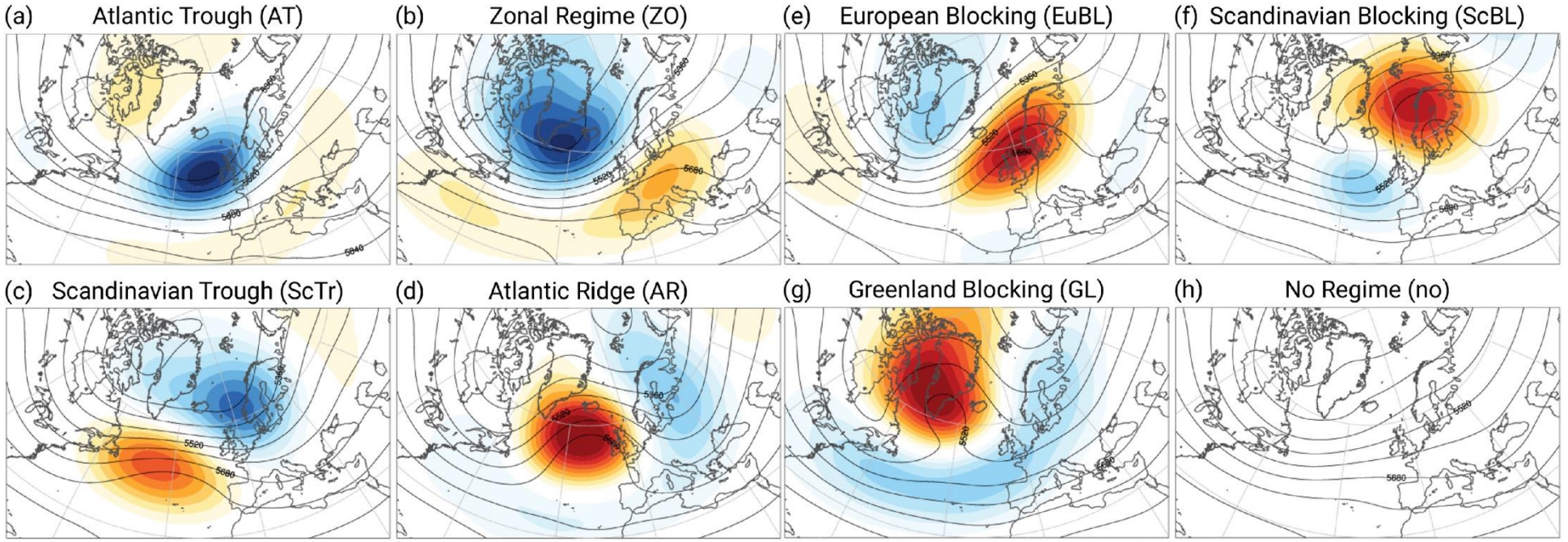
Atl. ridge 20%

Examples of weather regime definitions

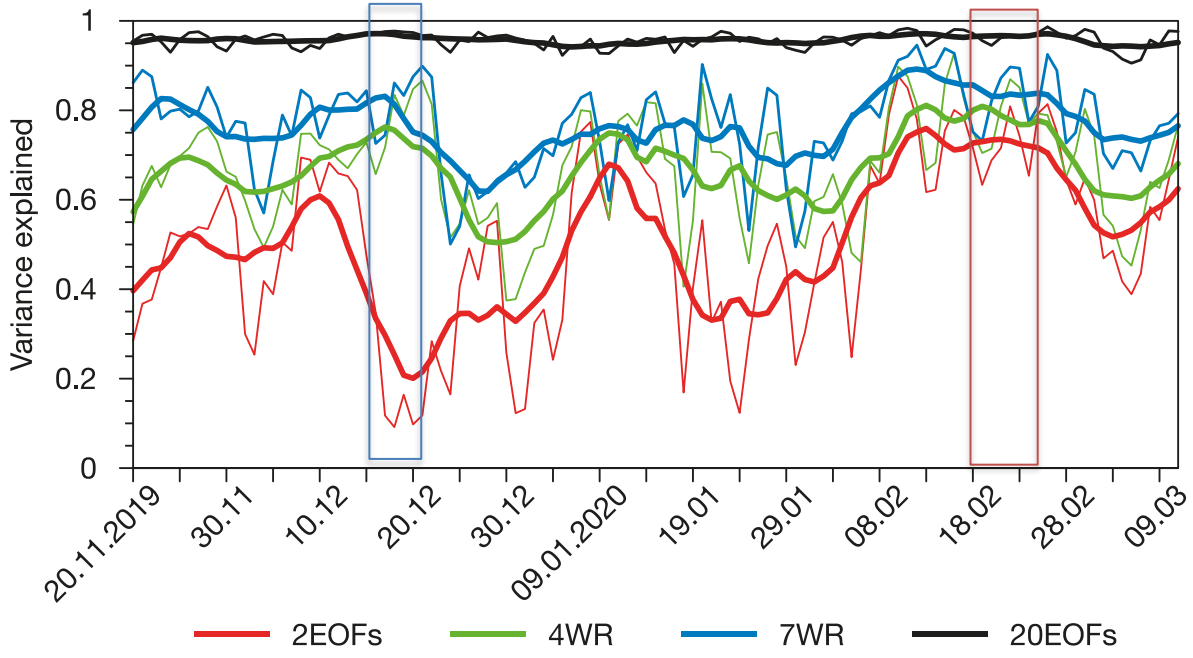
4 regimes with different patterns for winter and summer (Ferranti et al.)

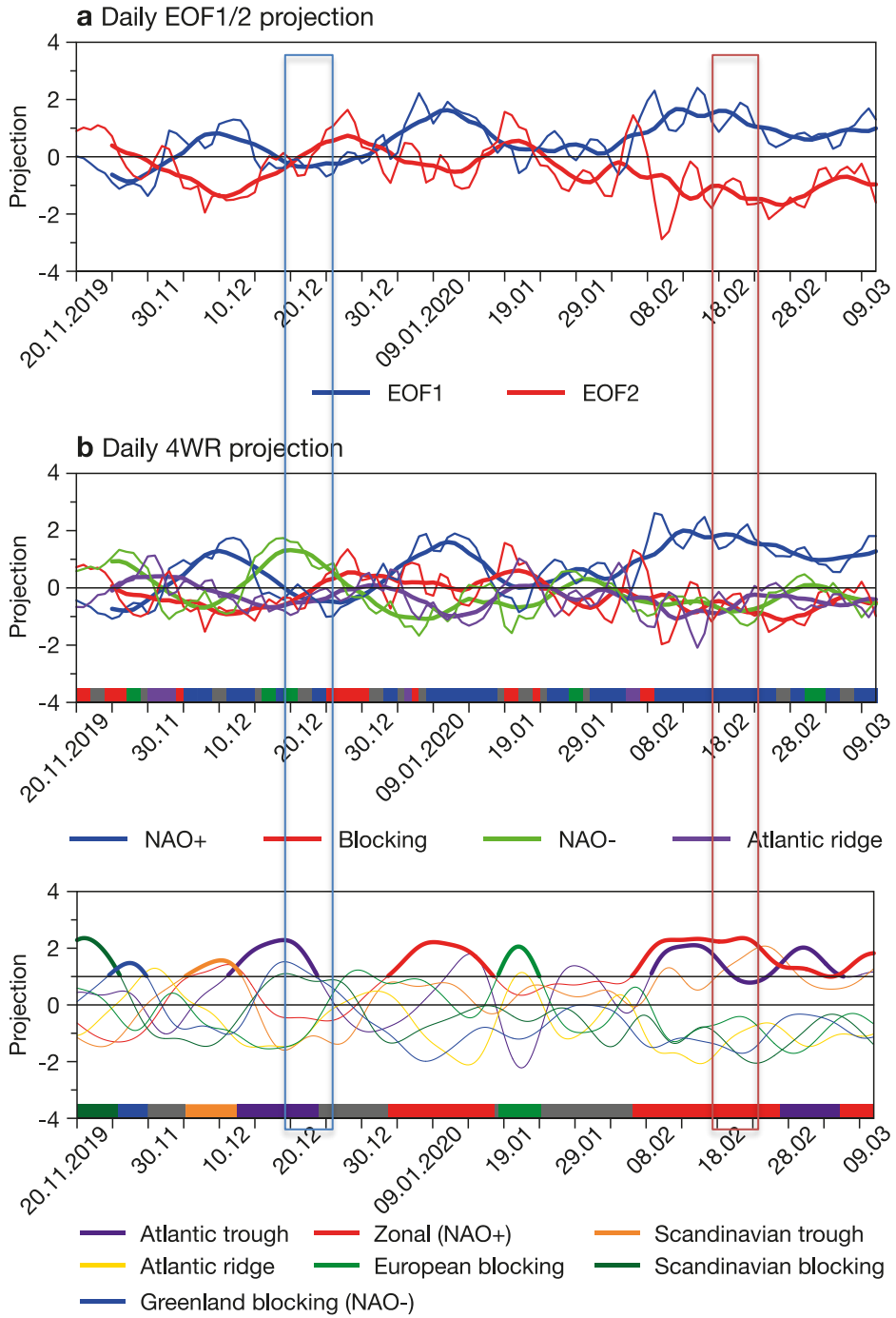


7 year-around regimes (Grams et al. 2017, 10.1038/nclimate3338, Grams et al., 2026)

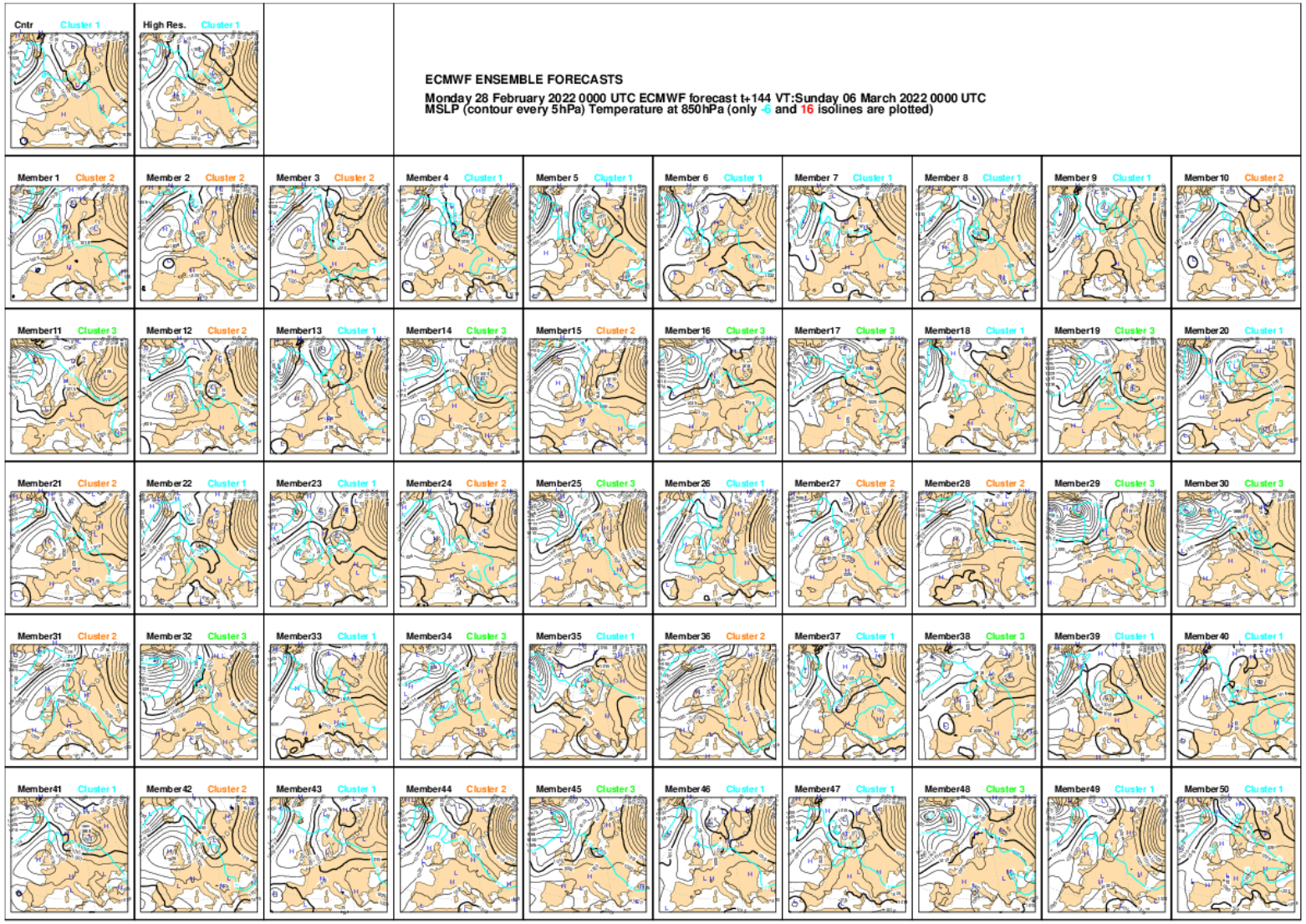


Daily projections onto each regime and variance explained by each set



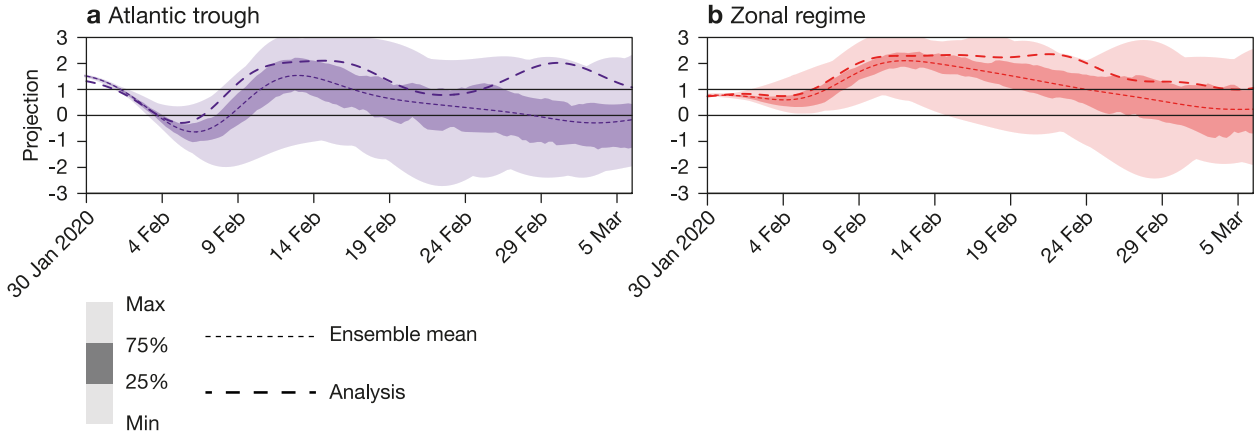


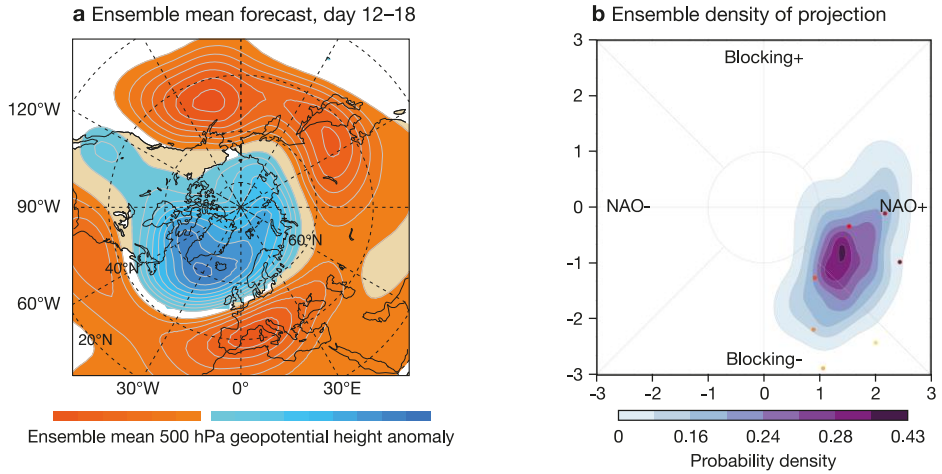
Need to condense ensemble information

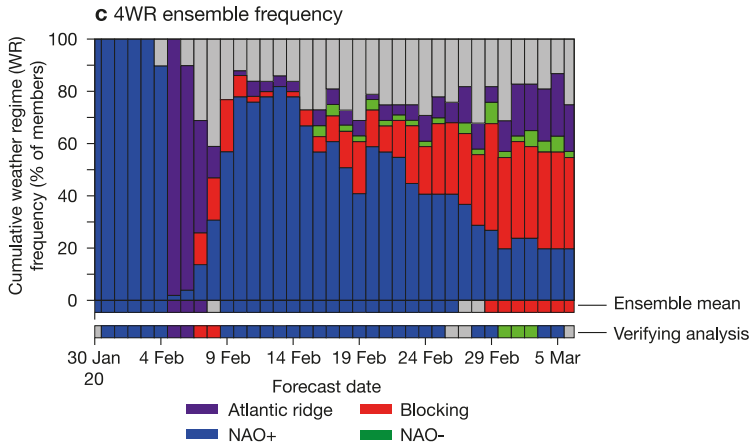


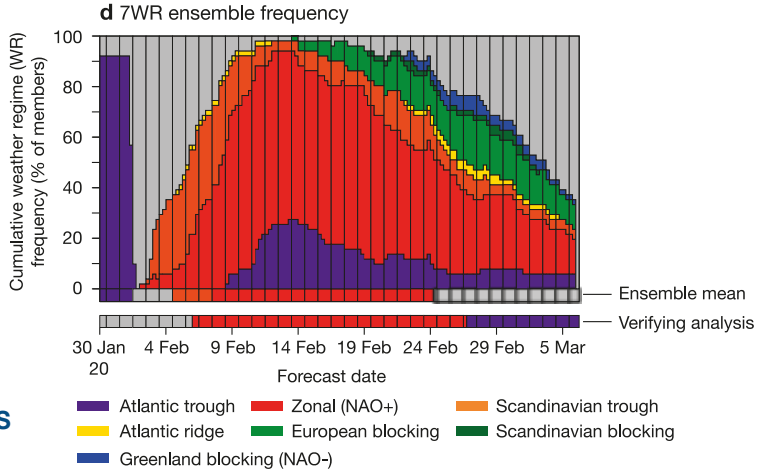
Example of products

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



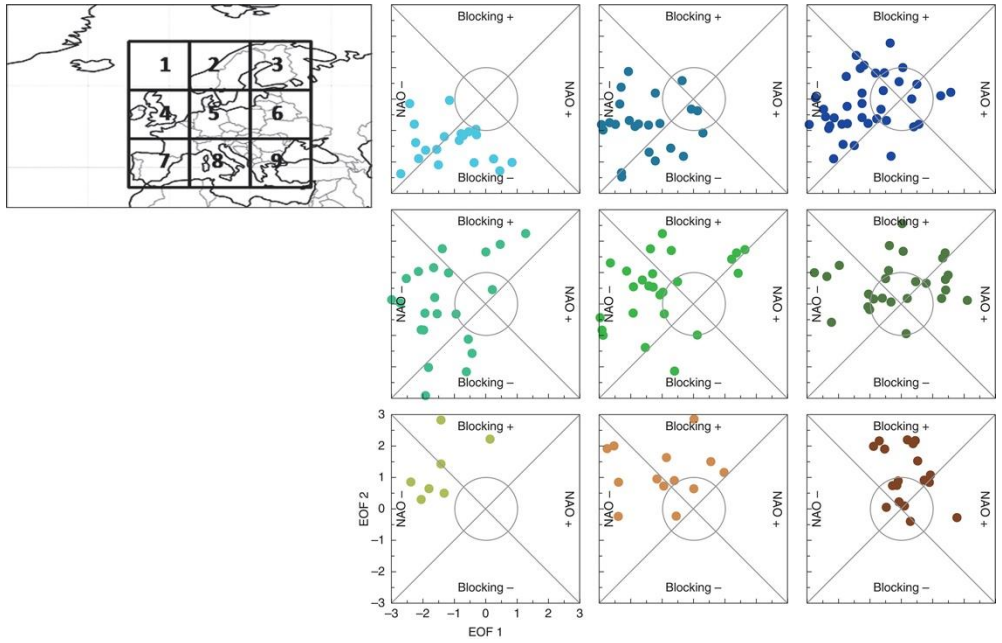




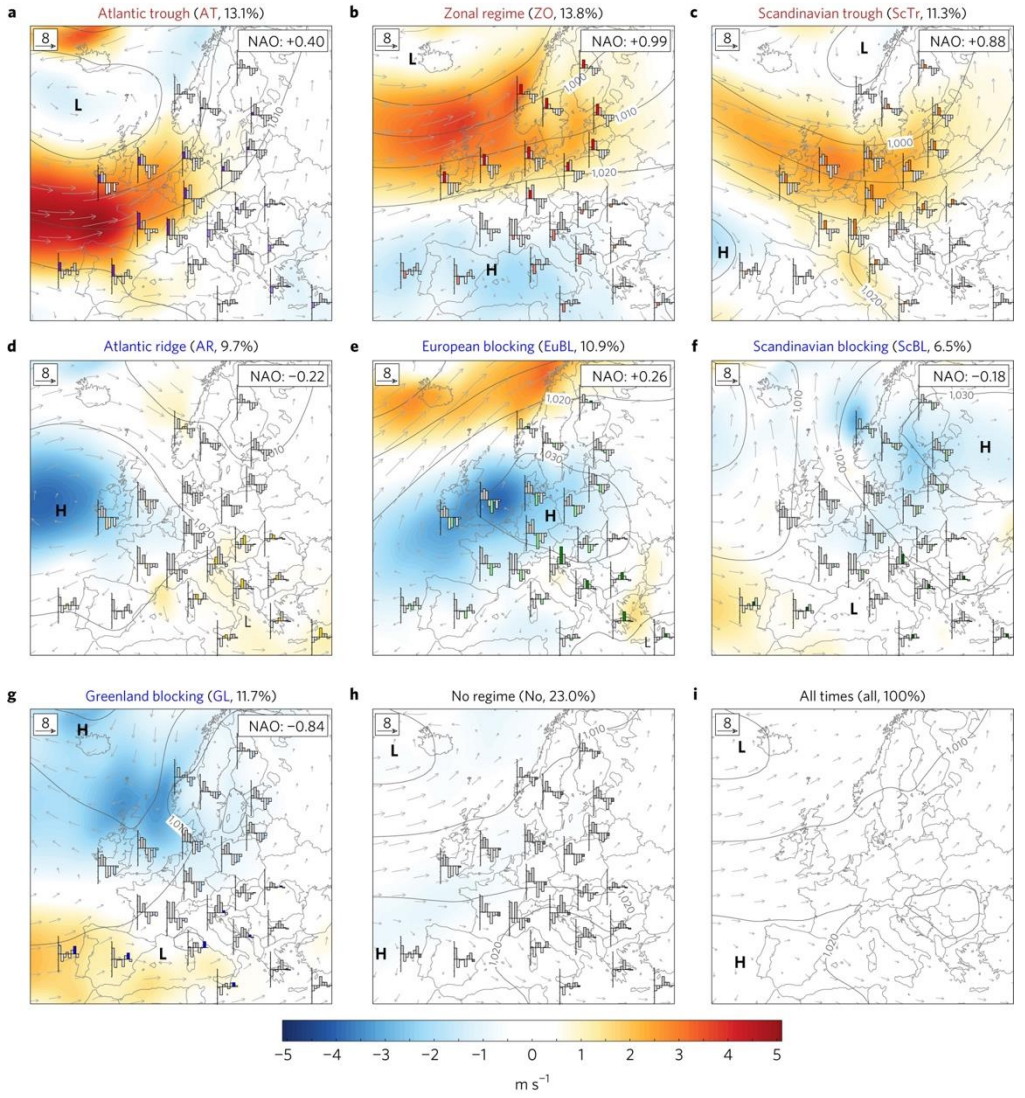


Connection to surface weather

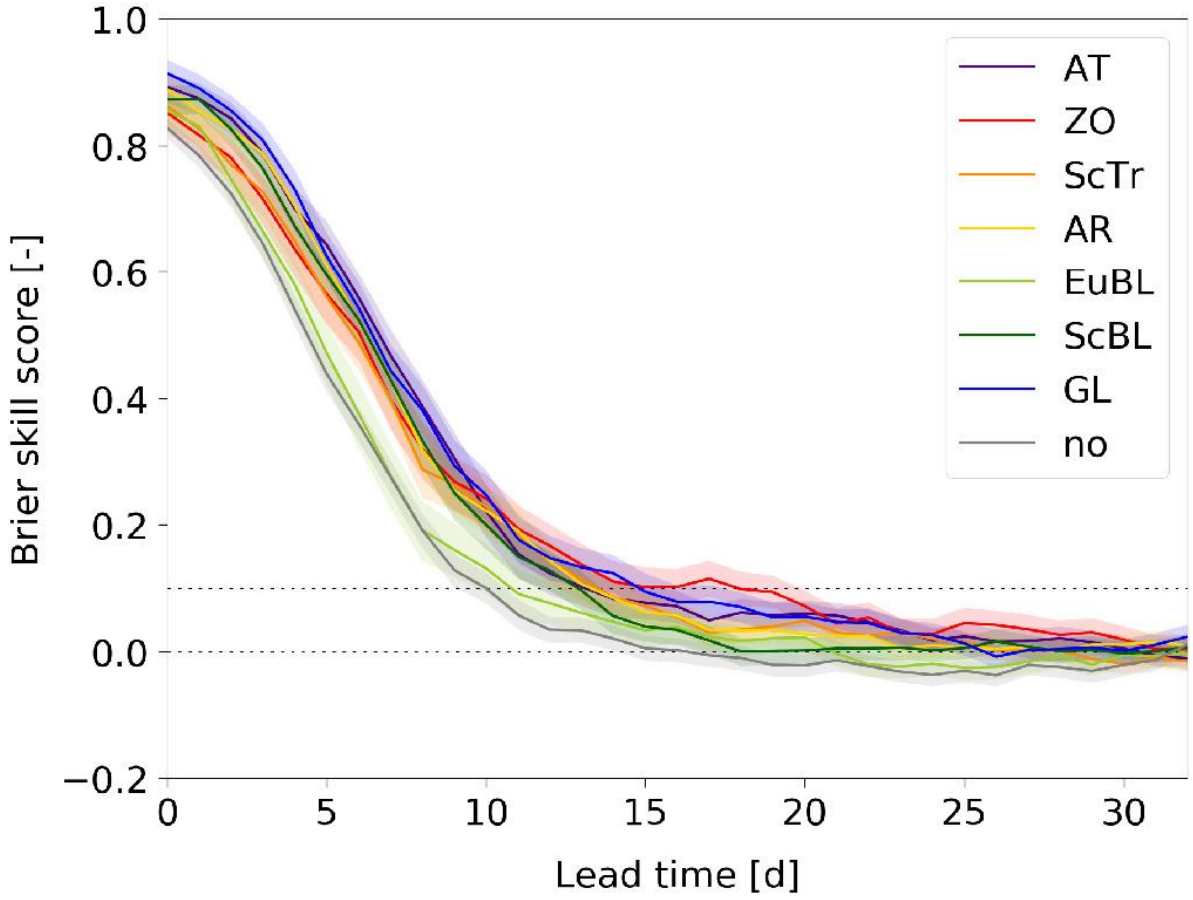
Cold extremes and connection to EOF1/2
Ferranti et al. (2018, 10.1002/qj.3341)



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



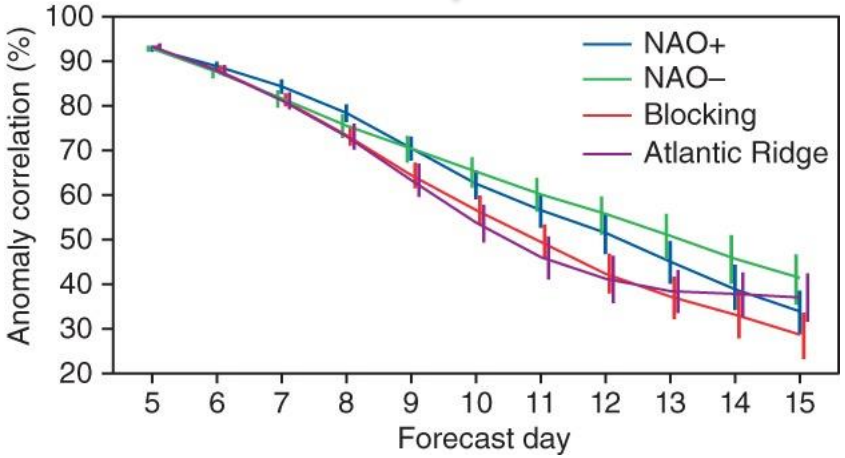
Verification of regime forecasts



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

How to verify:

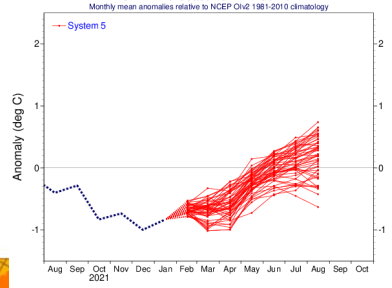
- Discrete verification of one regime (Brier)
- Continuous verification (CRPS) of projections
- Combined Brier skill score of all regimes
- Anomaly correction of ensemble mean of projections
- Conditional verification on the initial regime



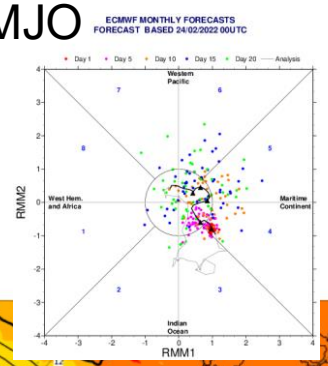
From Ferranti et al. (2015, https://doi.org/10.1002/qj.2411)

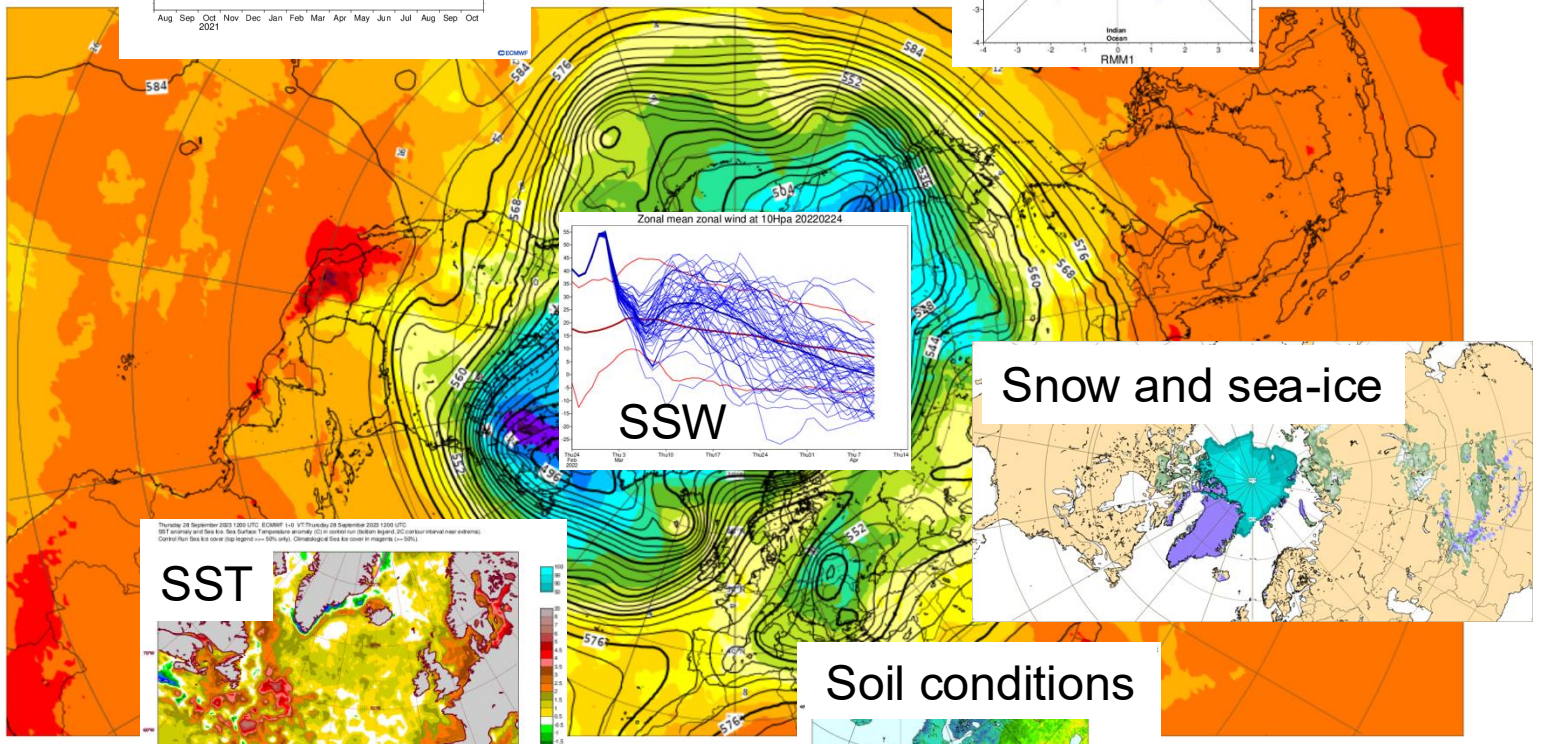
Windows of opportunities: External forcing on mid-latitude wave guide

ENSO



MJO



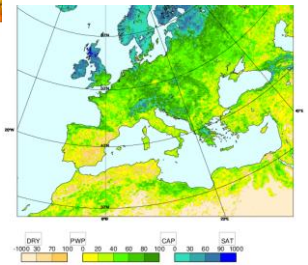


SSW

Snow and sea-ice

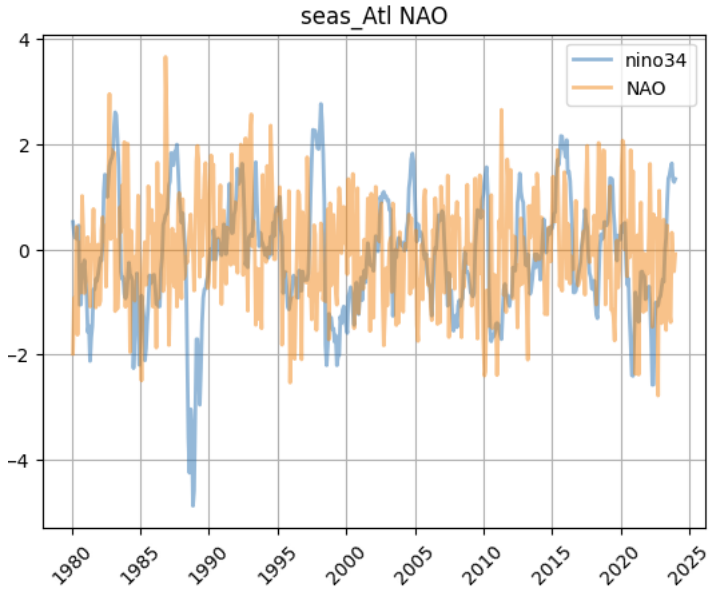
SST

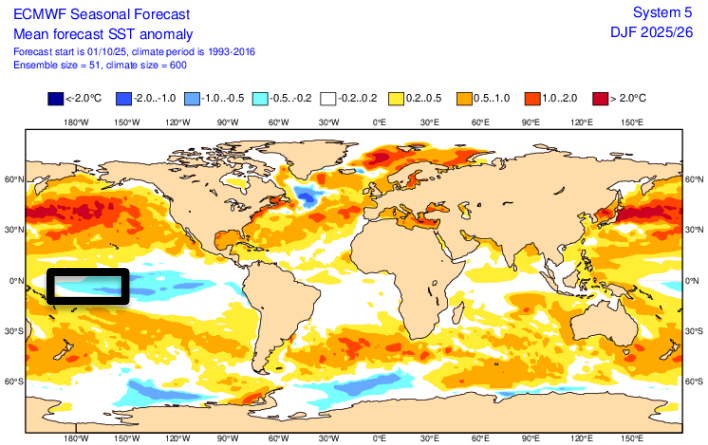
Soil conditions



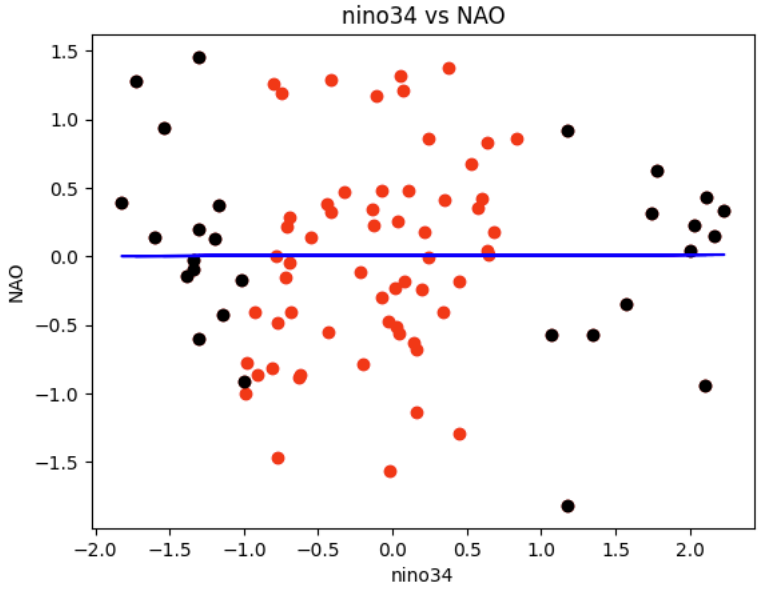
Teleconnections - example: Does El Nino influence European winters?

Time-series of two indices (monthly means)





Teleconnections during Feb-March



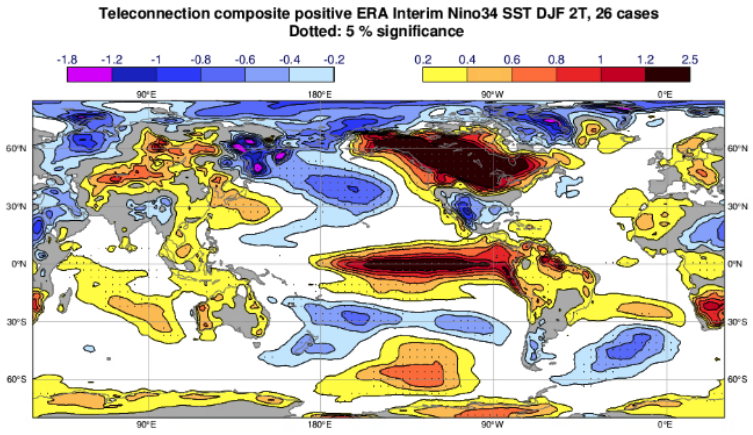
Composites +/- 1 stdev (black points):
Positive: -0.09 (13 of 88 months)
Negative: 0.15 (25 of 88 months)
Correlation: 0.0

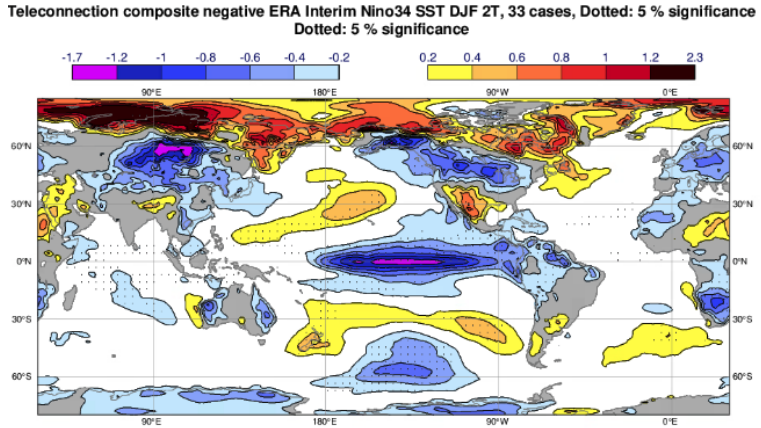
Impact from ENSO during DJF in reanalysis

Composites on El Nino

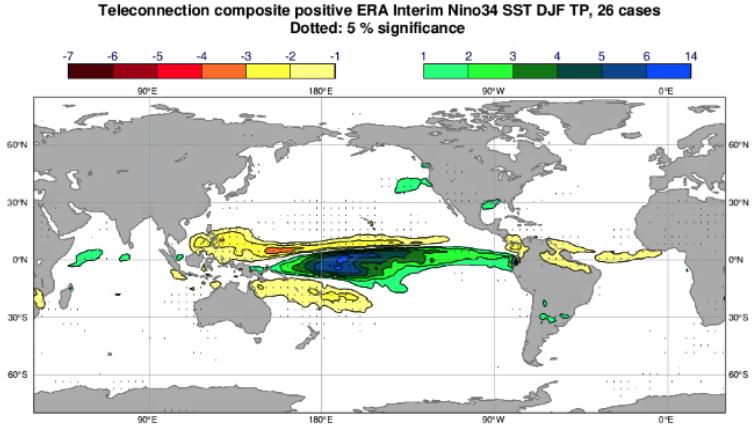
Composites on La Nina

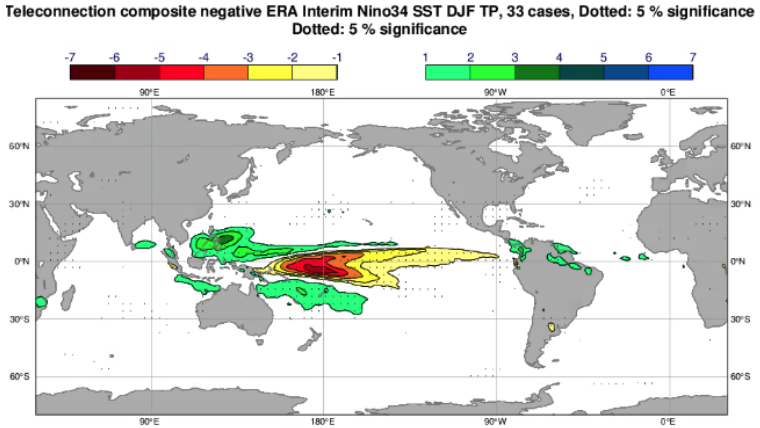
2-metre temperature



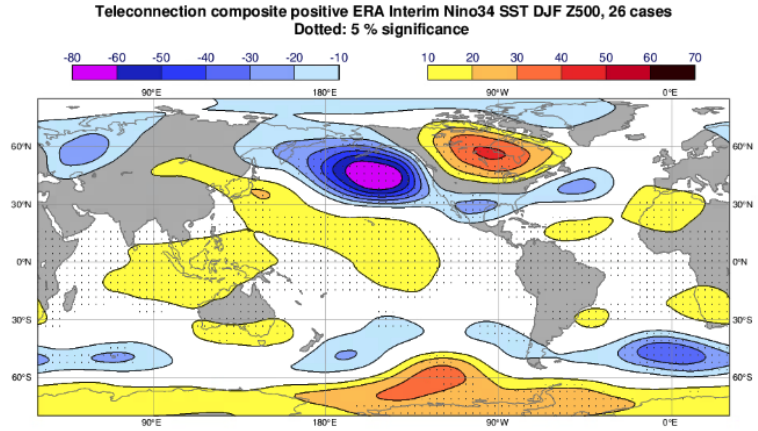


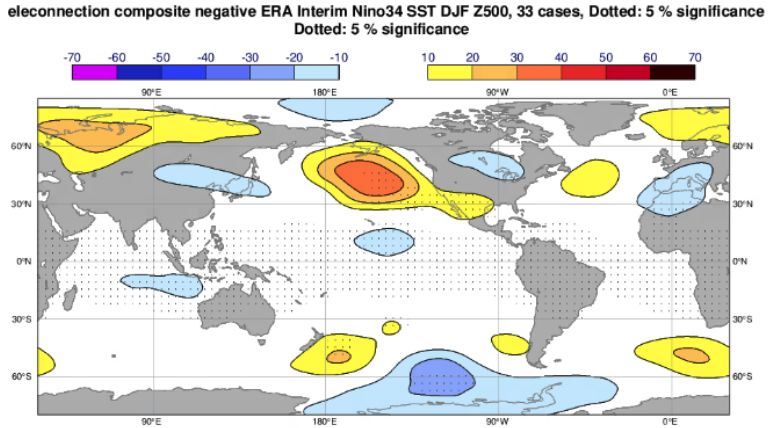
Precipitation





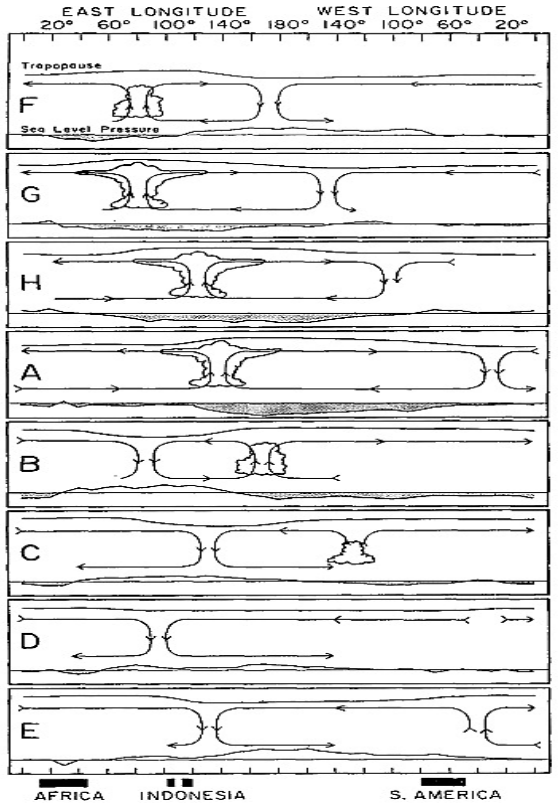
Z500



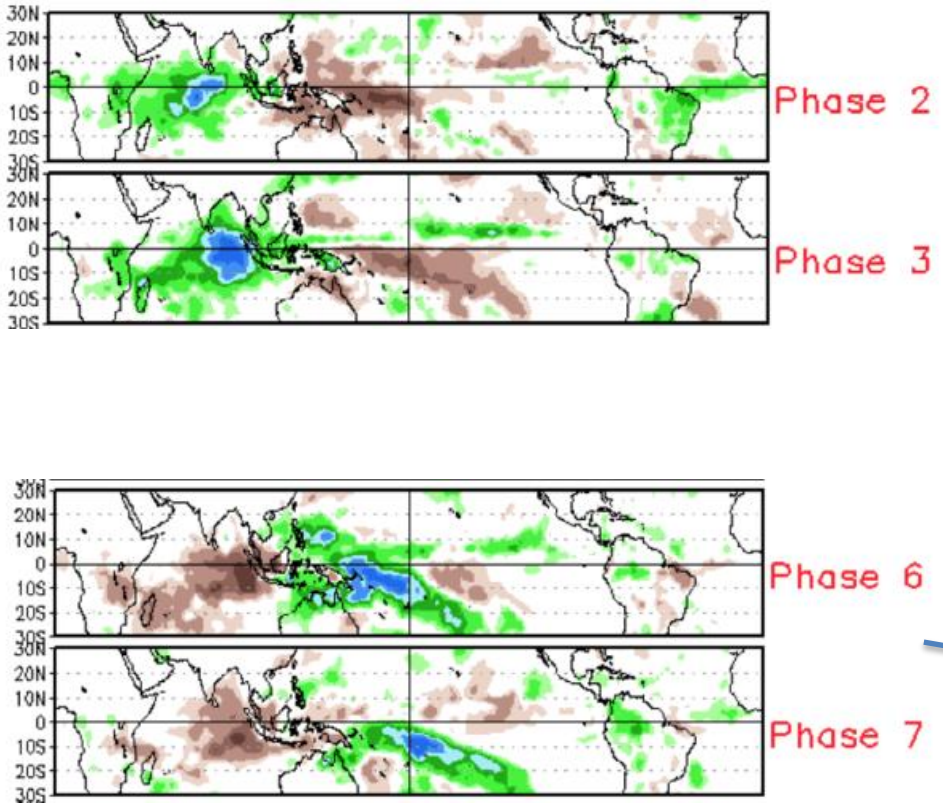


Regime frequencies are affected by MJO phase (Cassou, Nature 2008)

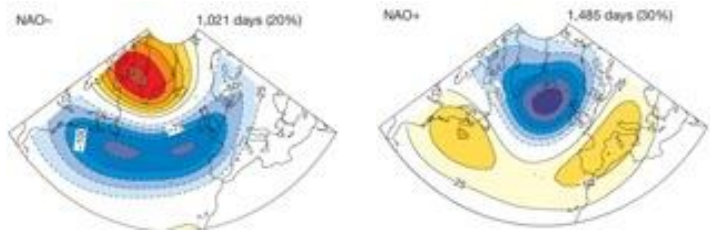
Madden-Julian Oscillation

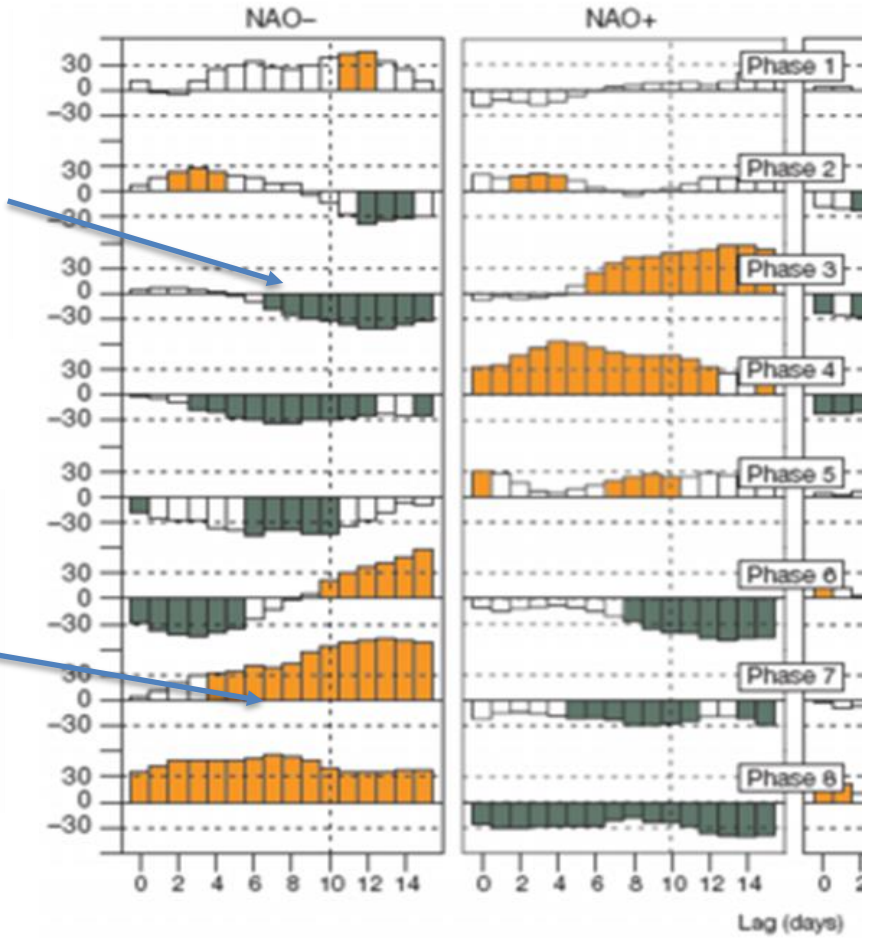


Precipitation anomaly



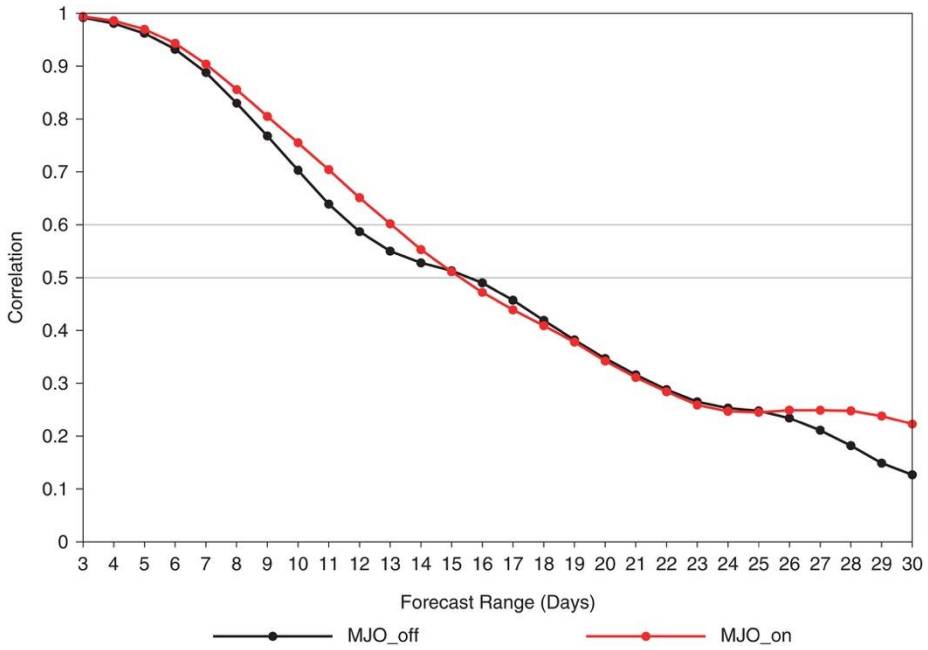
Lagged correlations for NAO

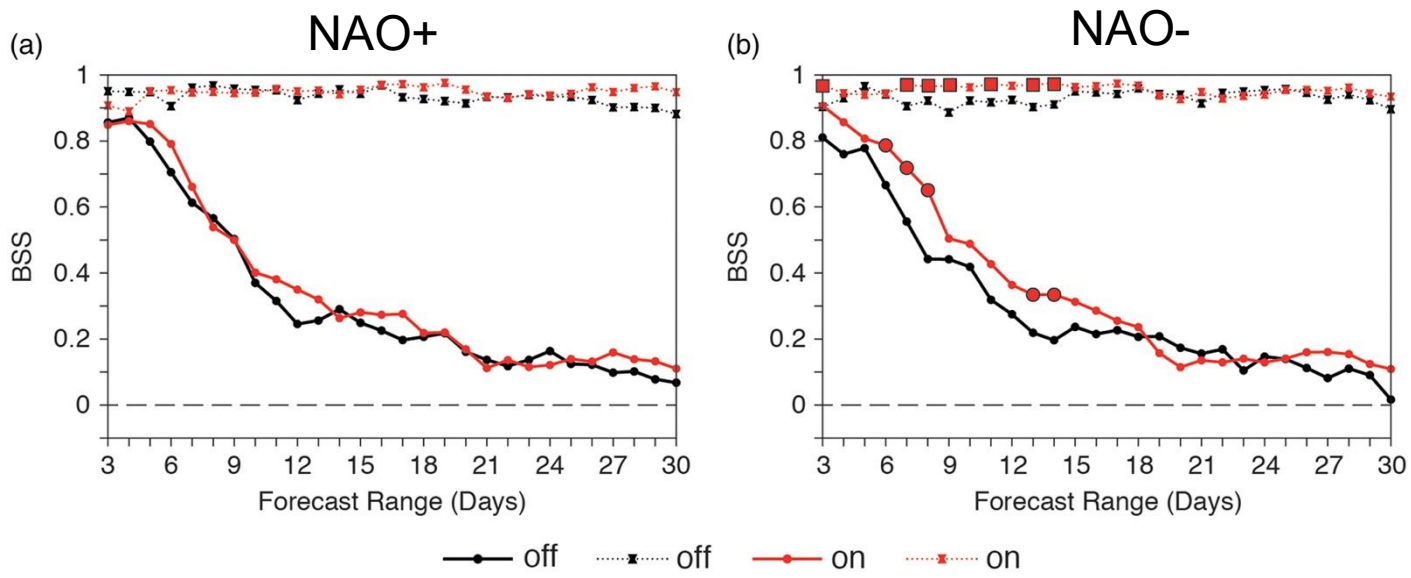




Conditional verification (on active MJO)

Ensemble mean correction for NAO



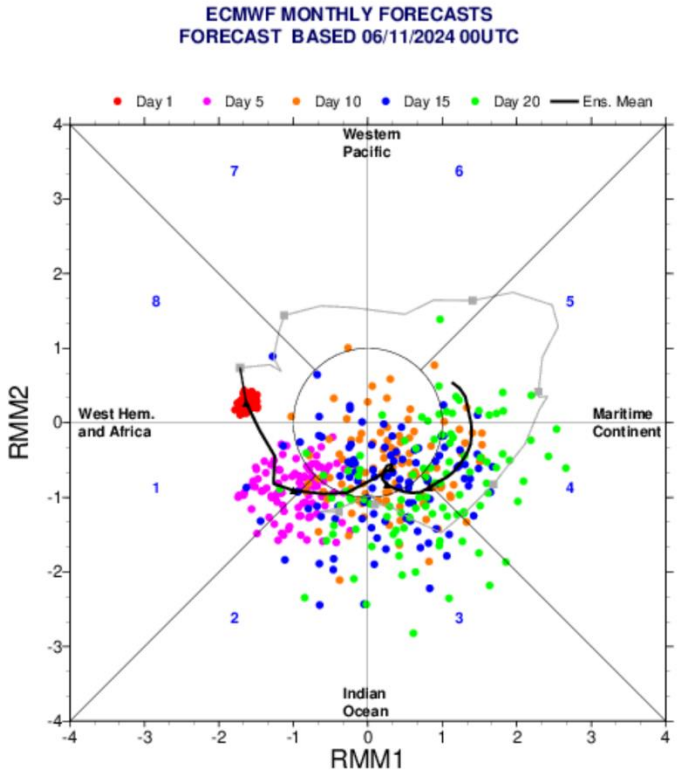


More skilful NAO- forecasts if MJO active in initial conditions

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

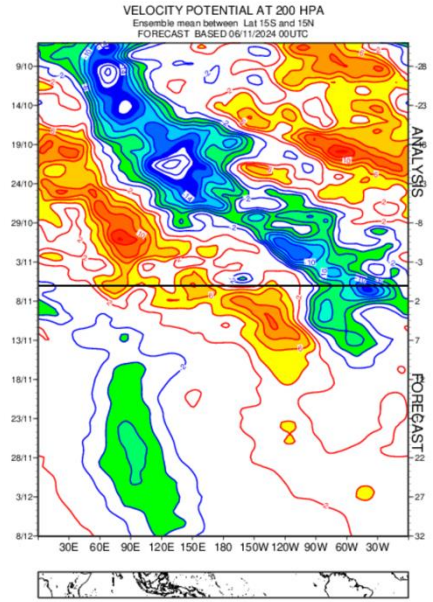
Forecast products for predictability drivers – MJO

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



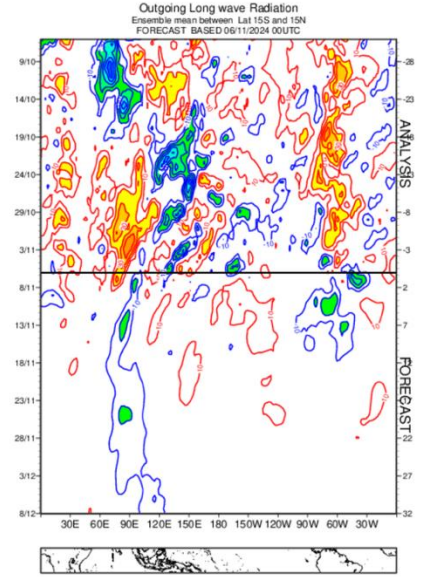
© 2024 European Centre for Medium-Range Weather Forecasts (ECMWF)
Source: www.ecmwf.int
Licence: CC BY 4.0 and ECMWF Terms of Use (https://apps.ecmwf.int/datasets/licences/general/)
Created at 2024-11-06T20:49:47.437Z

Time-longitudes sections - Extended range forecas



© 2024 European Centre for Medium-Range Weather Forecasts (ECMWF)
Source: www.ecmwf.int
Licence: CC BY 4.0 and ECMWF Terms of Use (https://apps.ecmwf.int/datasets/licences/general/)
Created at 2024-11-06T20:49:54.092Z

Time-longitudes sections - Extended range forecast



© 2024 European Centre for Medium-Range Weather Forecasts (ECMWF)
Source: www.ecmwf.int
Licence: CC BY 4.0 and ECMWF Terms of Use (https://apps.ecmwf.int/datasets/licences/general/)
Created at 2024-11-07T11:26:35.773Z

To capture a window of opportunity it takes

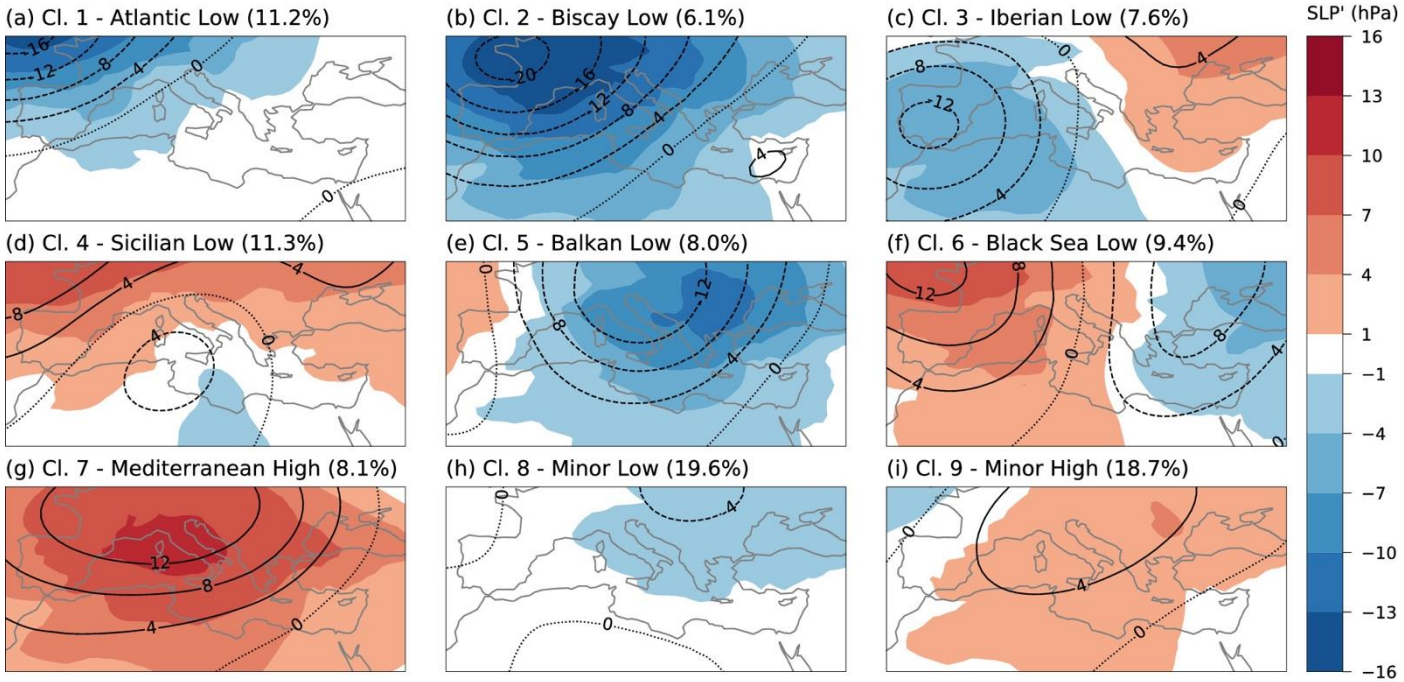
- That a teleconnection exists
- That the driver of the teleconnection is predictable
- That the forecast system can capture the teleconnection
- Reliable spread from the ensemble

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

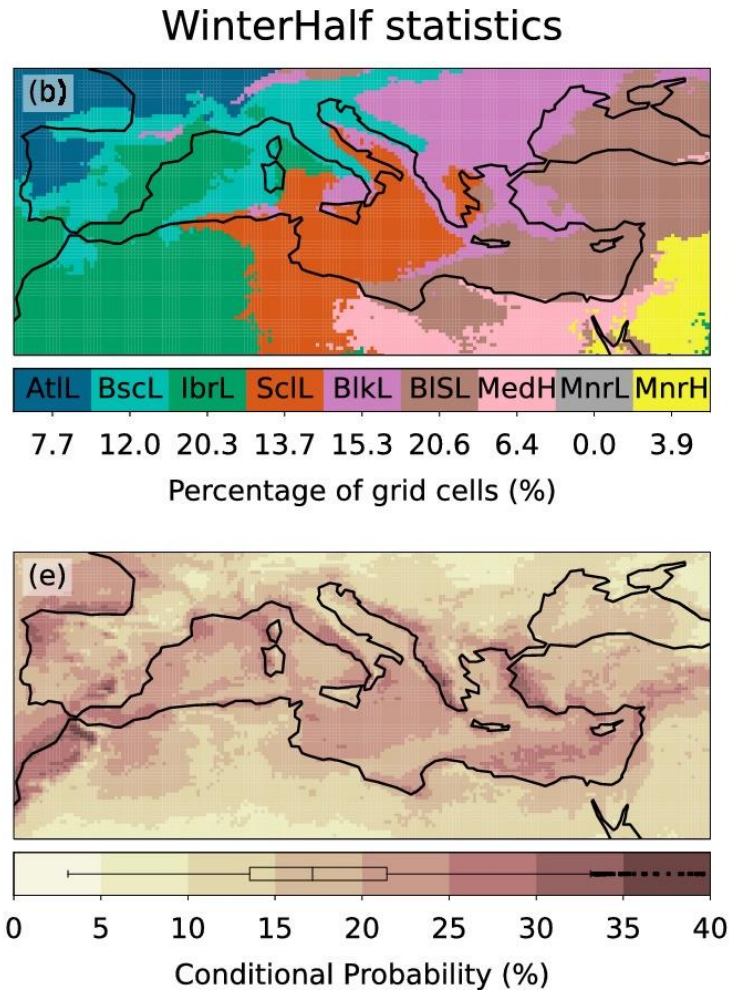


Regimes for other regions – Mediterranean example

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



Connections to extreme rainfall

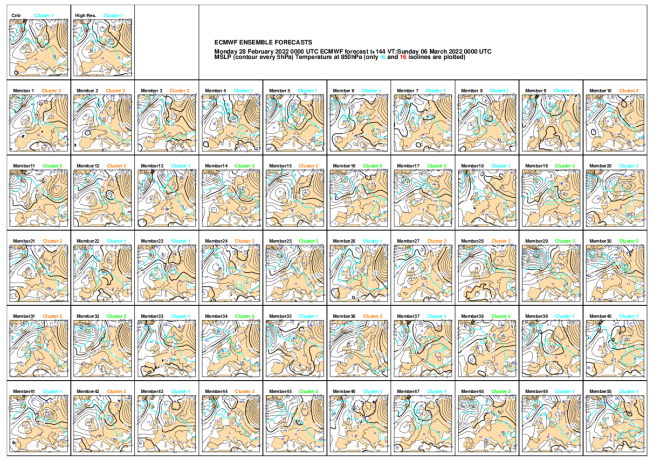


Summary

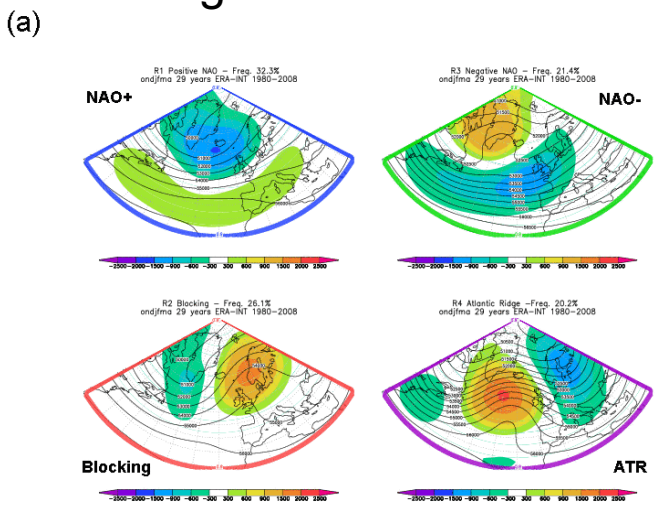
Content

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

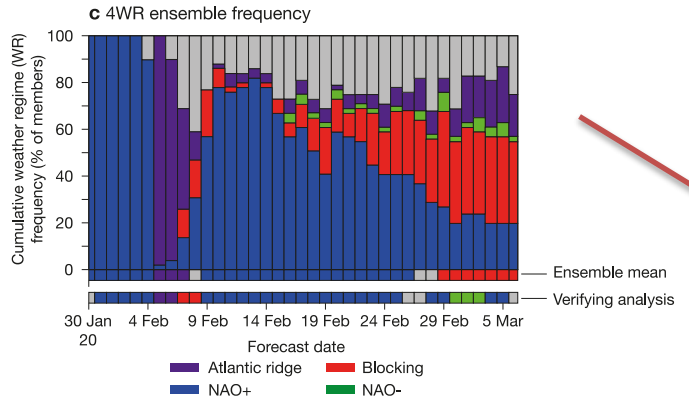
Raw forecast



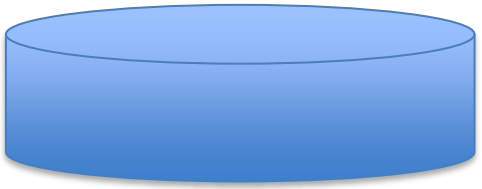
Regime definitions



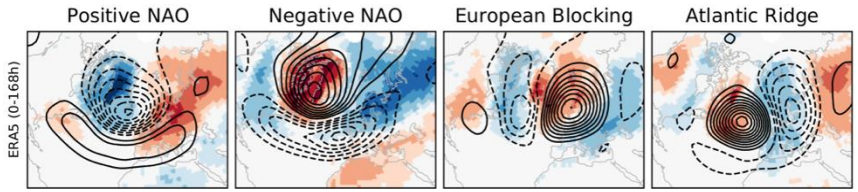
Regime products



Reanalysis



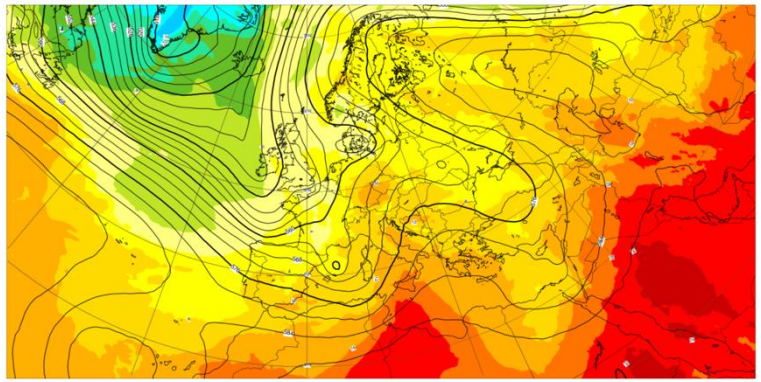
Connection to surface weather



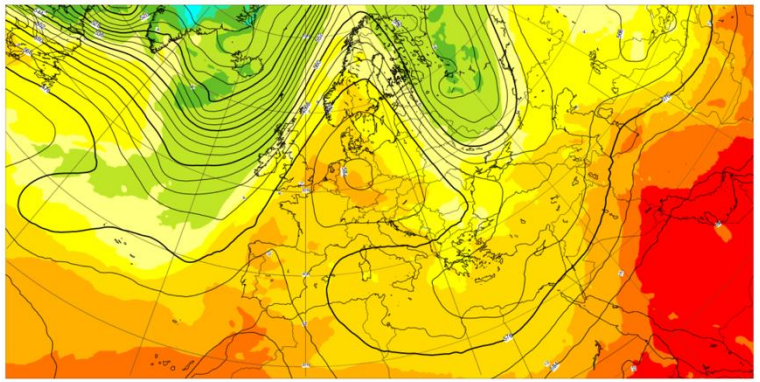
Skilful and interpretable forecast!?!

Products from yesterday

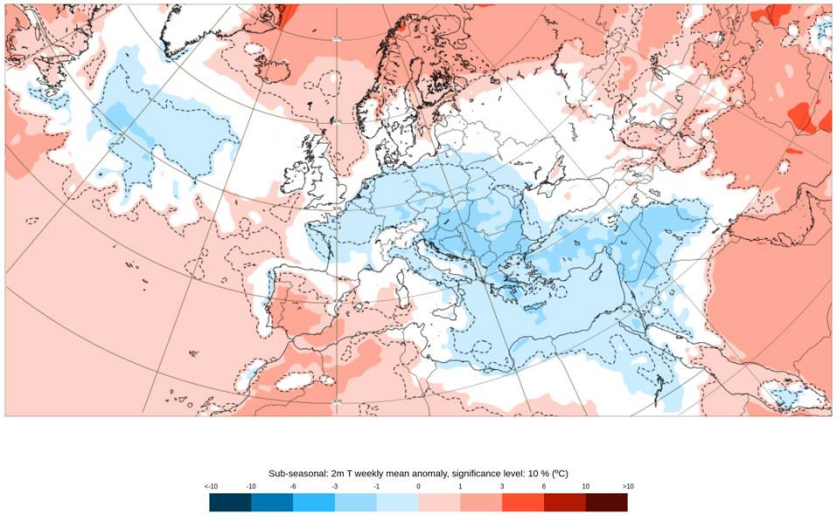
Analysis

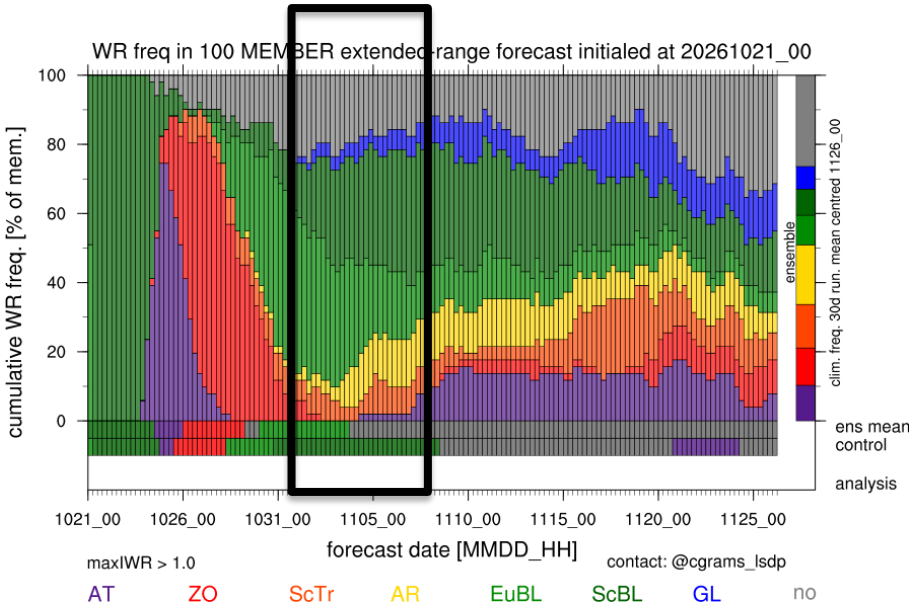


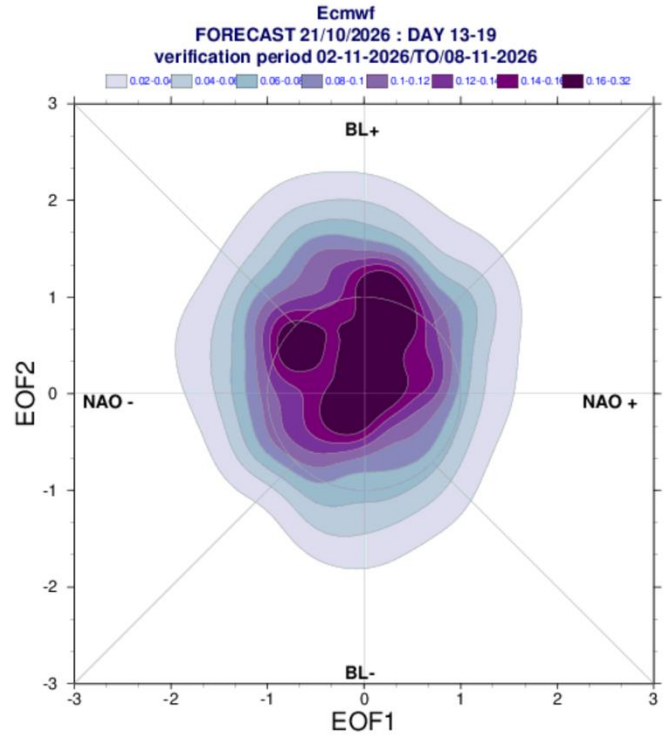
10 day forecast



2-metre temperature anomaly
2-11 November





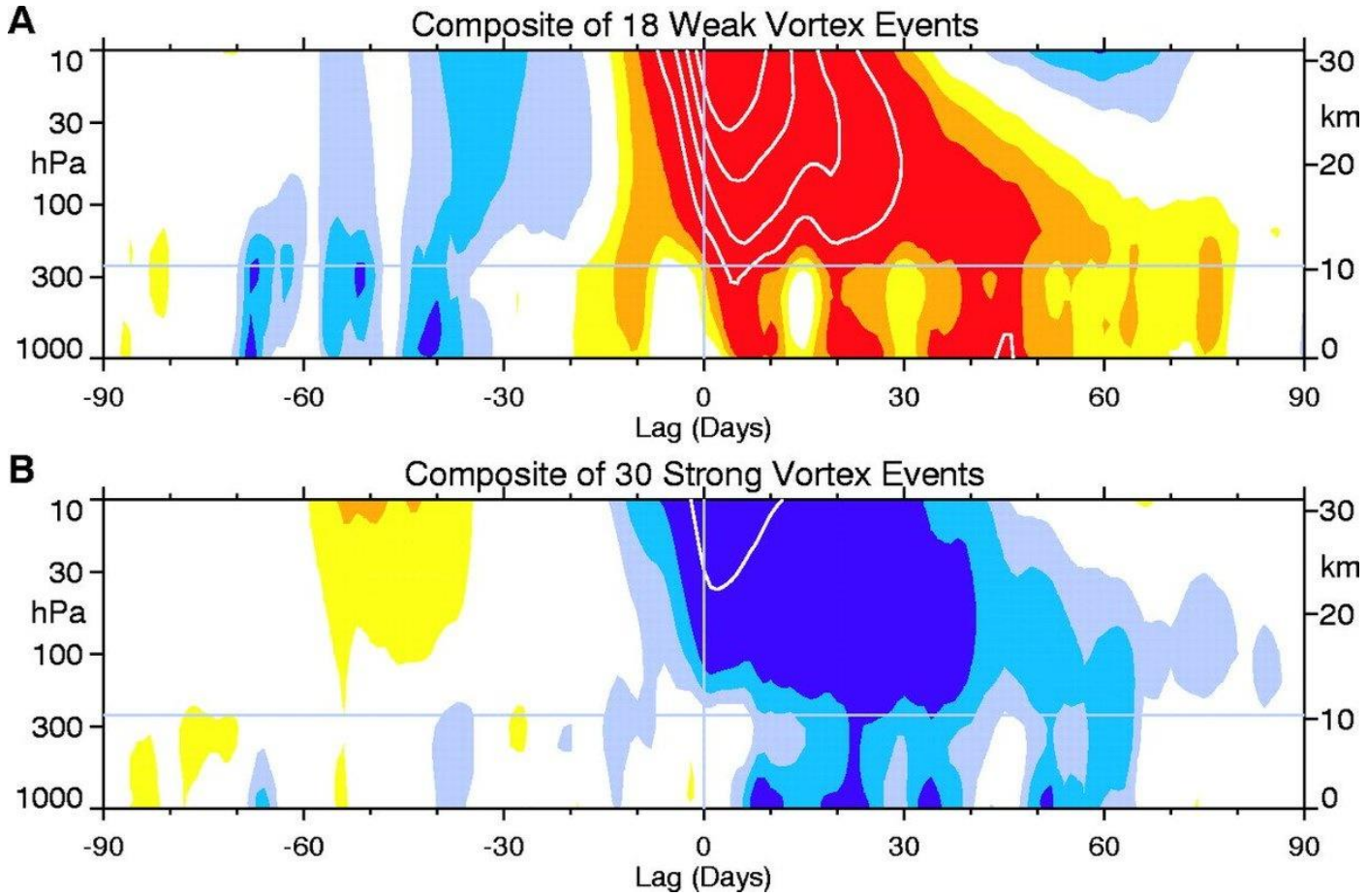


Key references

- 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)

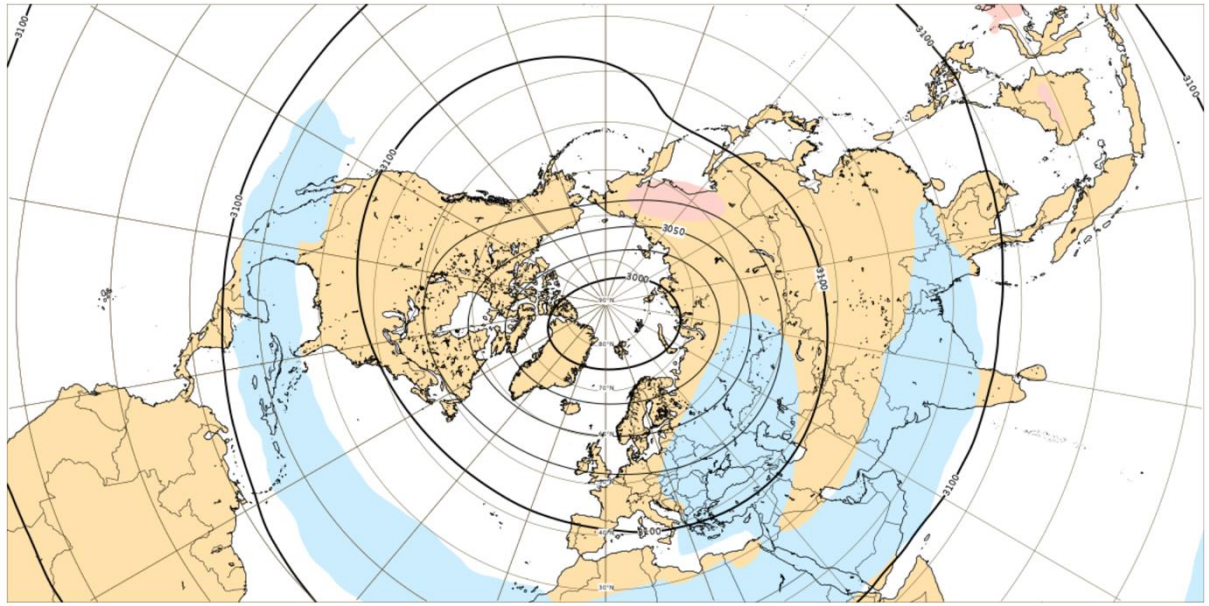


Decrease polar vortex in the troposphere after a stratospheric warming, which could lead to negative NAO during the following month.

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



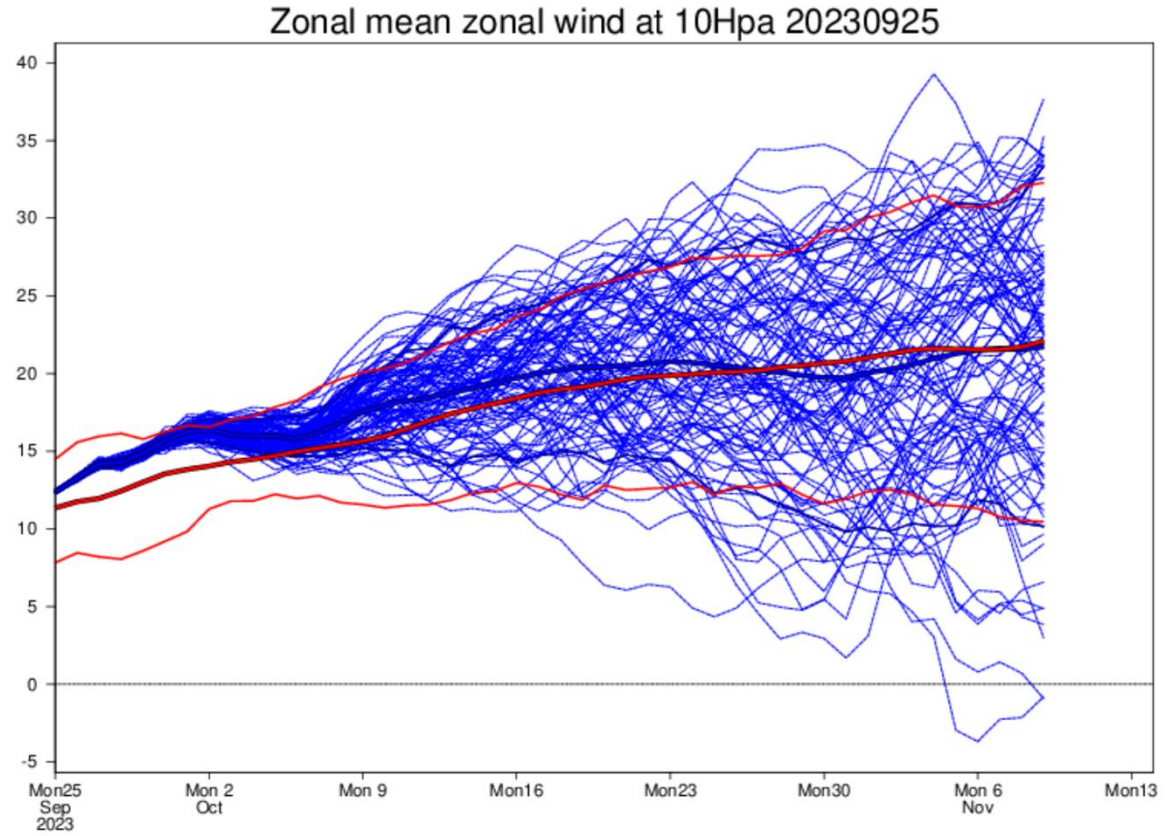
Extended range: 10hPa temperature weekly mean anomaly (C)



Extended range: 10hPa geopotential height weekly mean (dam)

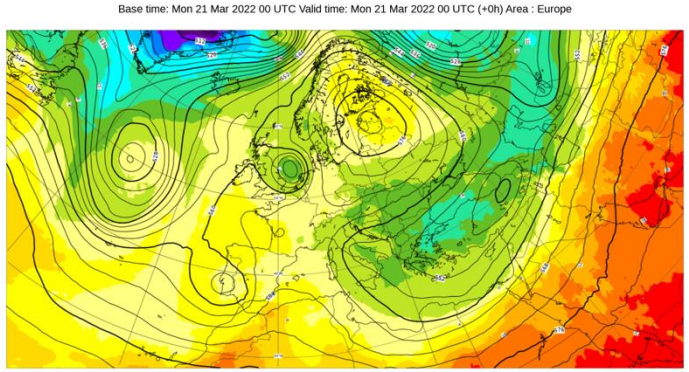
© 2023 European Centre for Medium-Range Weather Forecasts (ECMWF)
Source: www.ecmwf.int
Licence: CC BY 4.0 and ECMWF Terms of Use (https://apps.ecmwf.int/datasets/licences/general/)
Created at 2023-09-26T11:54:46.109Z

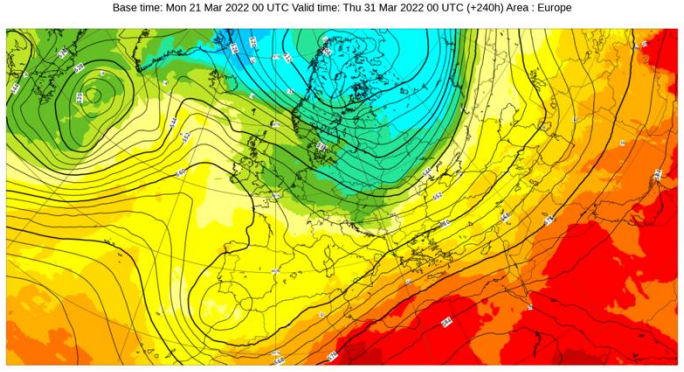
Mean zonal wind at 10 hPa - Extended range forecast

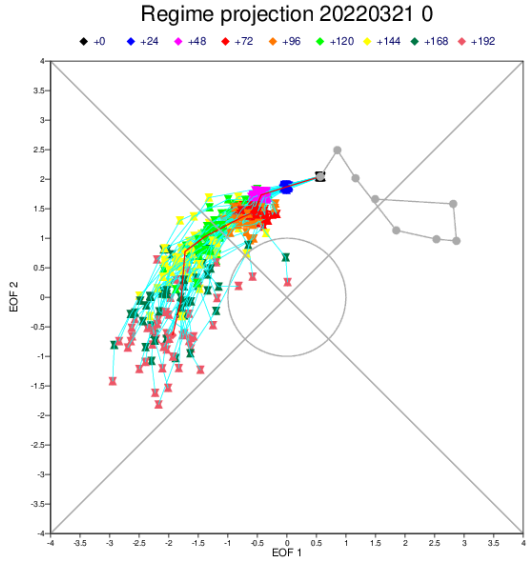


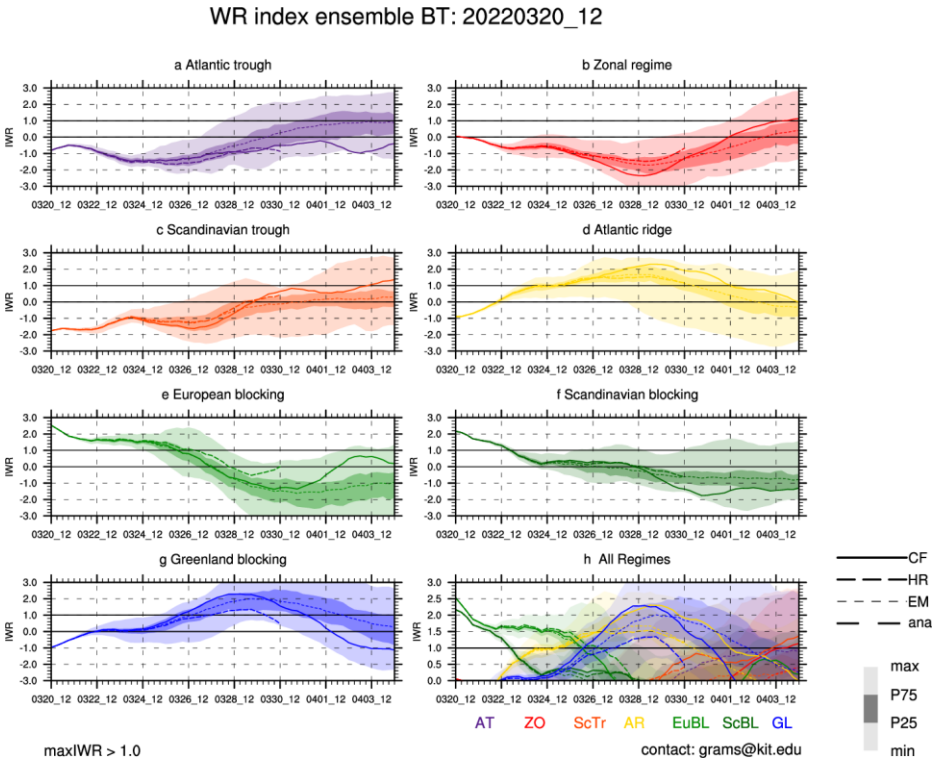
© 2023 European Centre for Medium-Range Weather Forecasts (ECMWF)
Source: www.ecmwf.int
Licence: CC BY 4.0 and ECMWF Terms of Use (https://apps.ecmwf.int/datasets/licences/general/)
Created at 2023-09-26T11:44:40.206Z

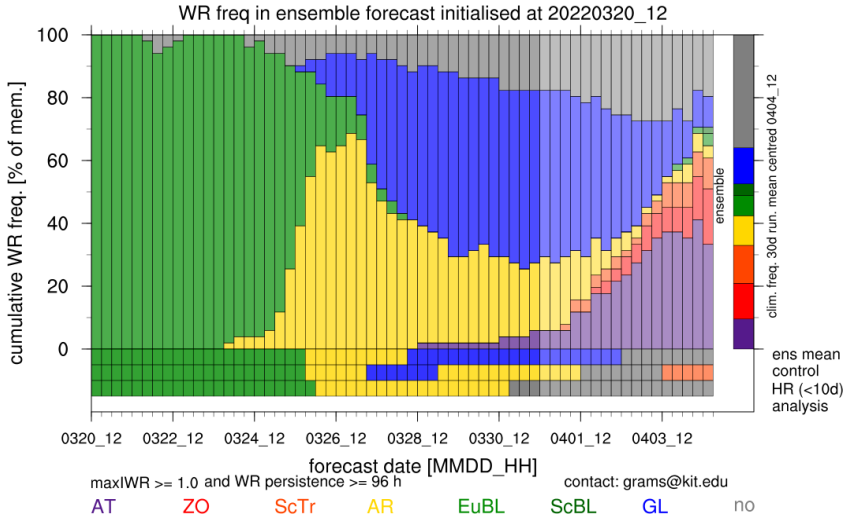
Products from today



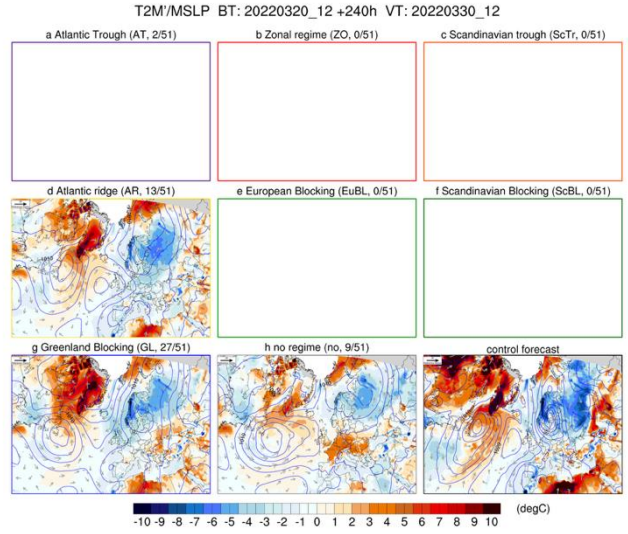








Temperature anomalies +10 days



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:

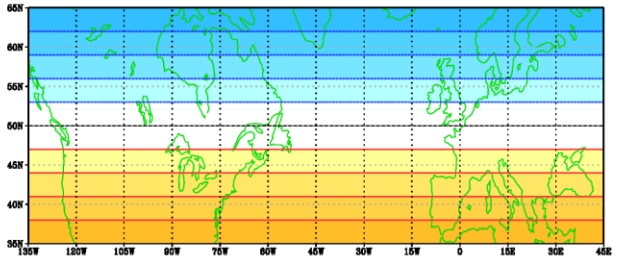
Multiple stationary solutions of a non-linear dynamical system

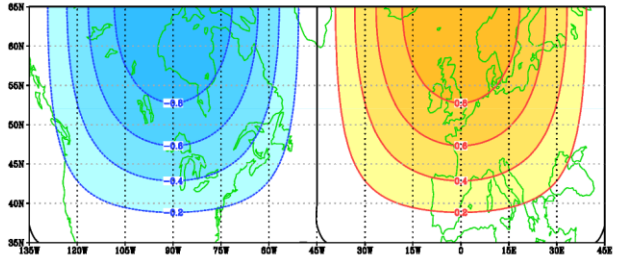
3-variable NAO model: basic functions and equations

(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'



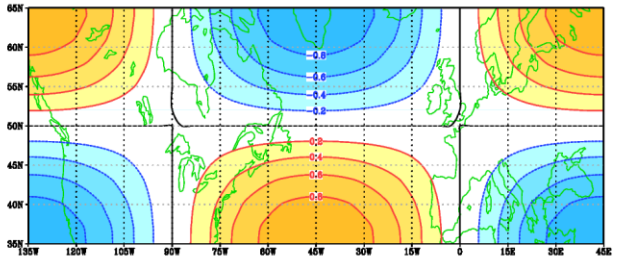


ψ^*_0

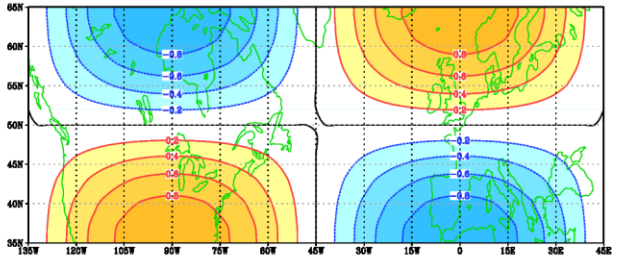
North America / Atlantic / Europe (NAE) channel:

135W-45E, 35N-65N

A
~ NAO index



B



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

$$\frac{dA}{dt} = U' B - \sigma U' - k A$$

$$\frac{dB}{dt} = -U' A - k(B - B^*)$$

Vorticity advection by zonal wind

Convergence of meridional heat transport by pl. waves

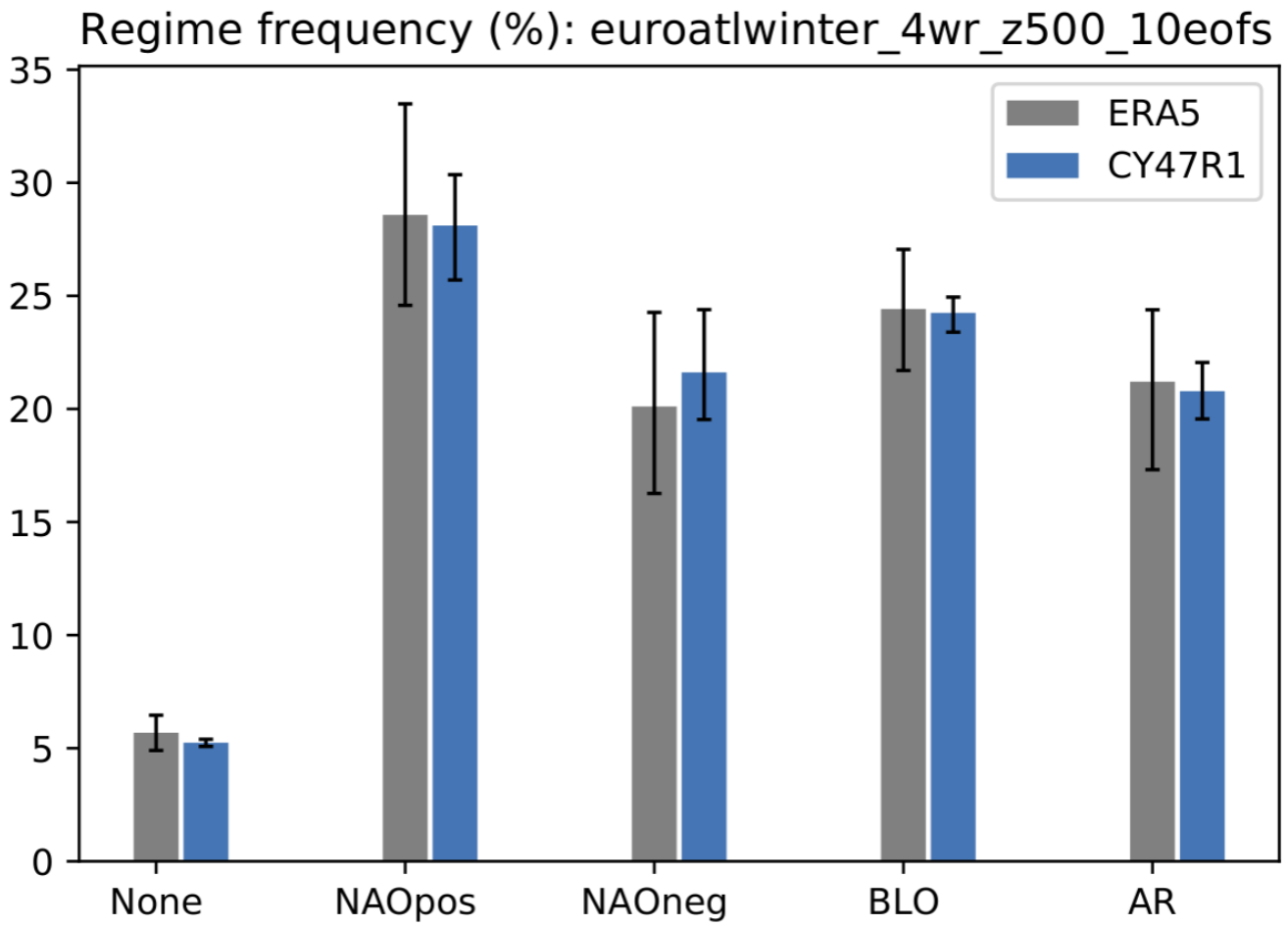
Diabatic heating induced by surface heat flux

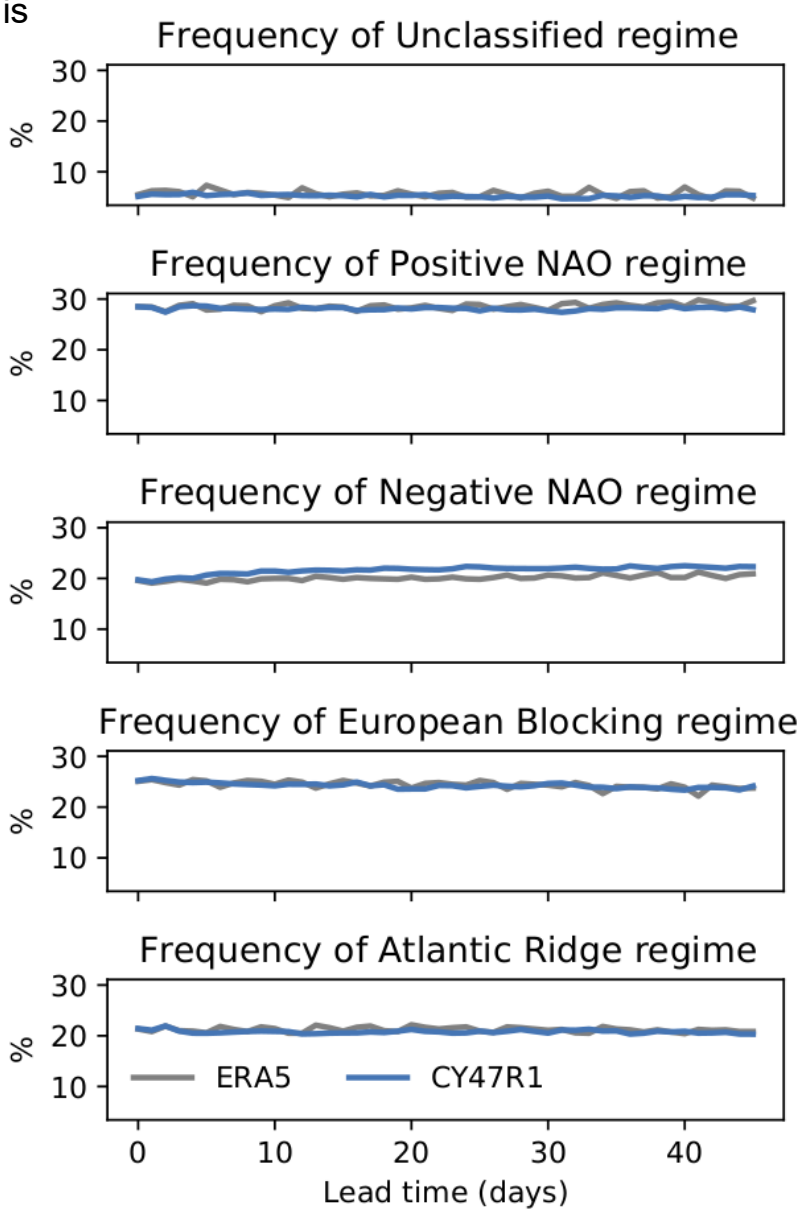
Radiative damping towards equilibrium state

ECMWF

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.

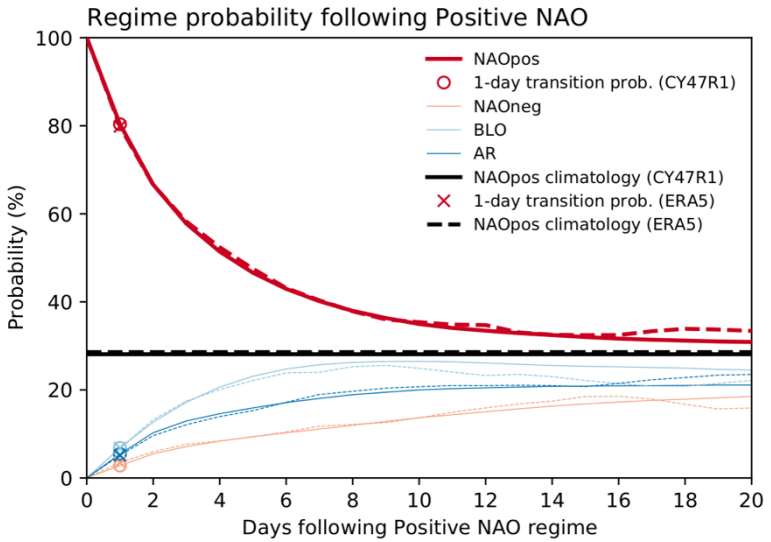


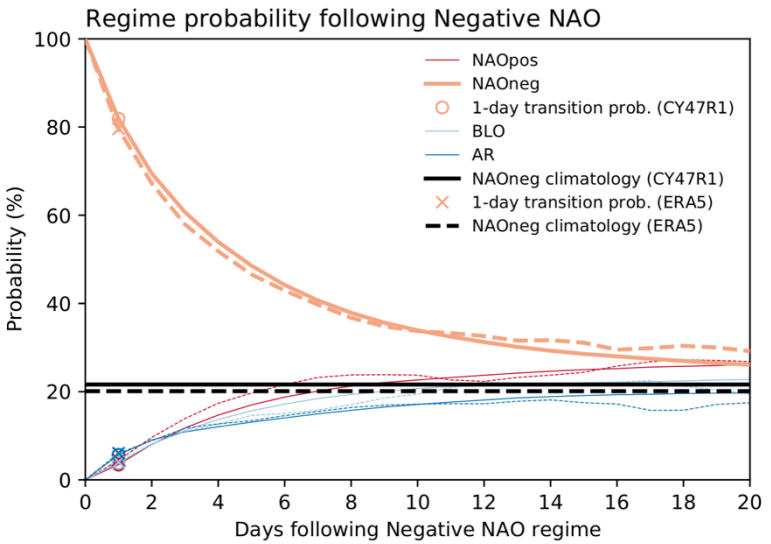


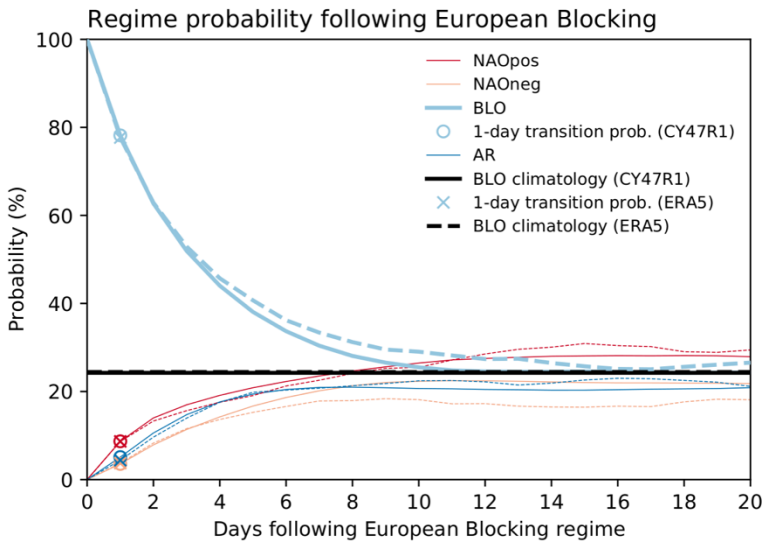
N.B. Regimes are assigned if the closest cluster centroid is also the cluster centroid with maximum projection onto forecast anomalies. If different clusters have minimum distance/maximum projection, then no regime is assigned.

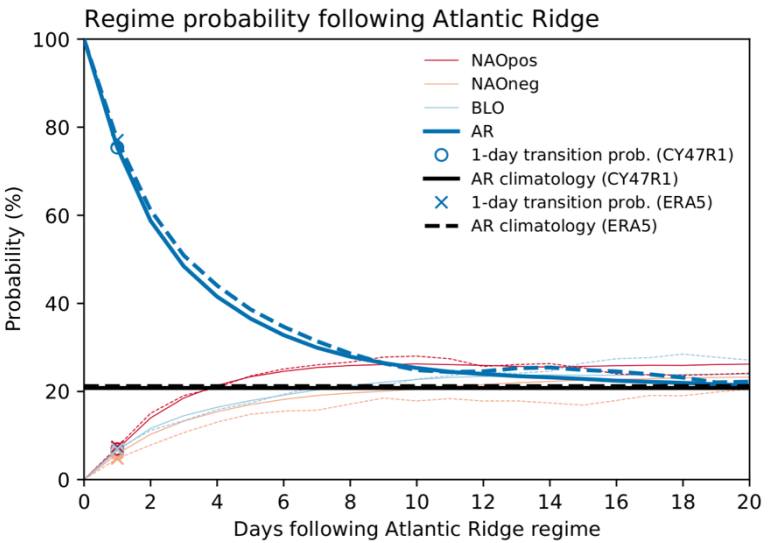
Conditional regime probabilities (SONDJFM, 2000-2020)

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 $p_{ij}^{(n)} = Pr(X_n = j \mid X_0 = i)$, where X_n is the random variable corresponding to the regime state on day *n*.).









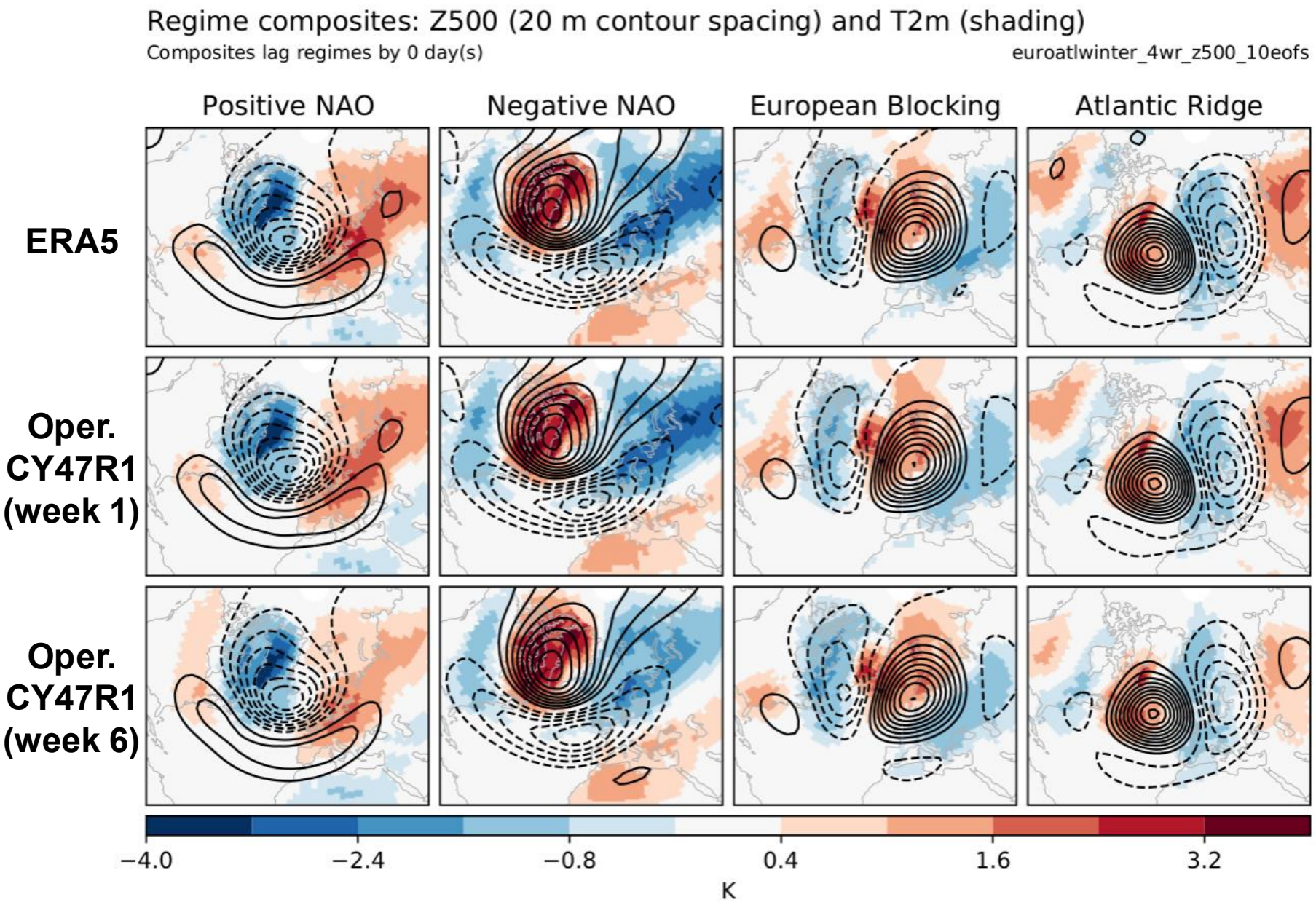
CY47R1 reforecasts accurately reproduce regime probabilities when conditioned on the initial regime.

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

Interesting points:

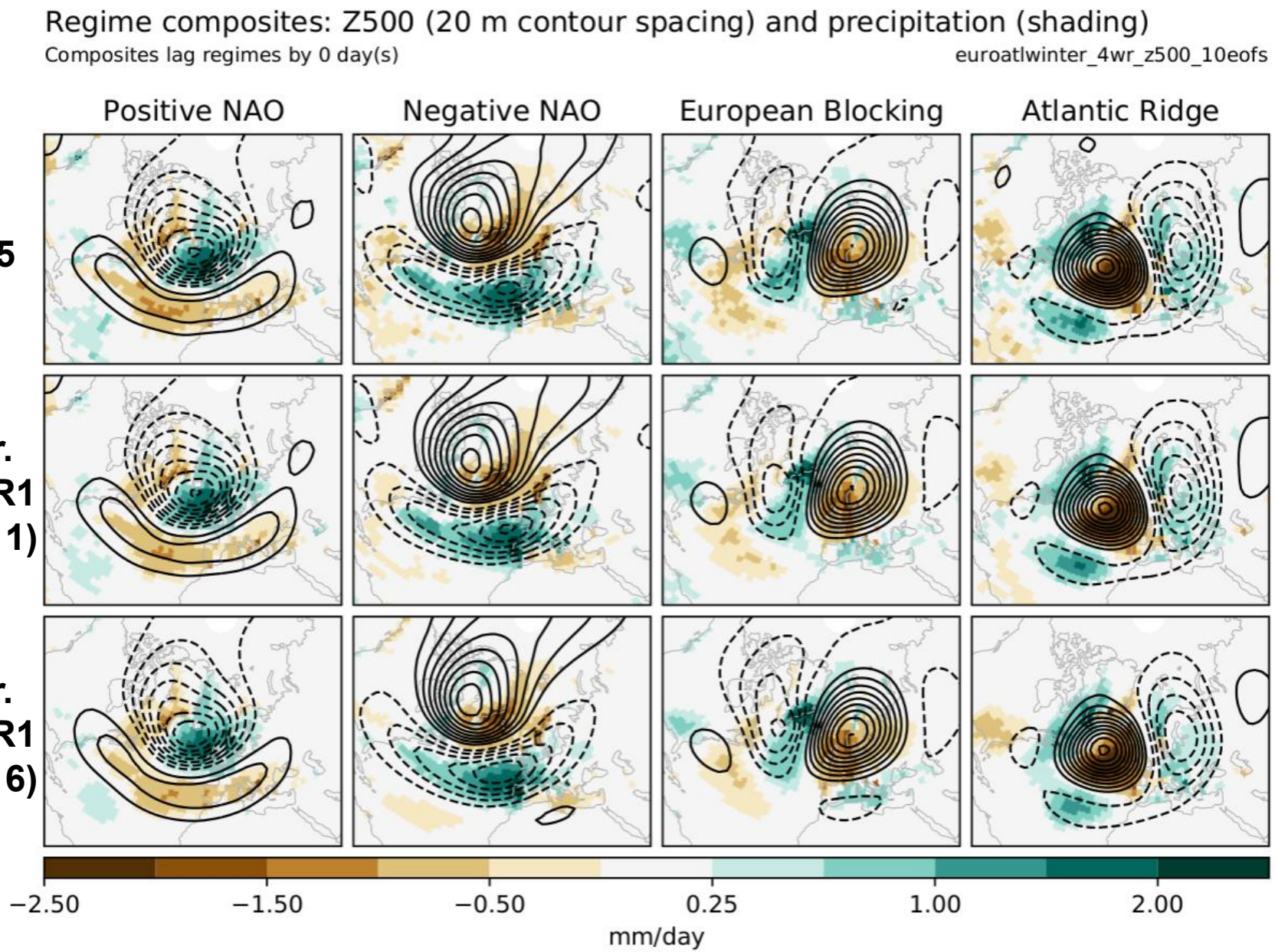
- Initializing with positive/negative NAO regime increases probability of this regime above climatological frequency for > 20 days.
- Probability of a blocking regime ~10 days after initial blocking regime (i.e. $Pr(X_{10} = blocking \mid X_0 = blocking)$) is lower in CY47R1 than ERA5.

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



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

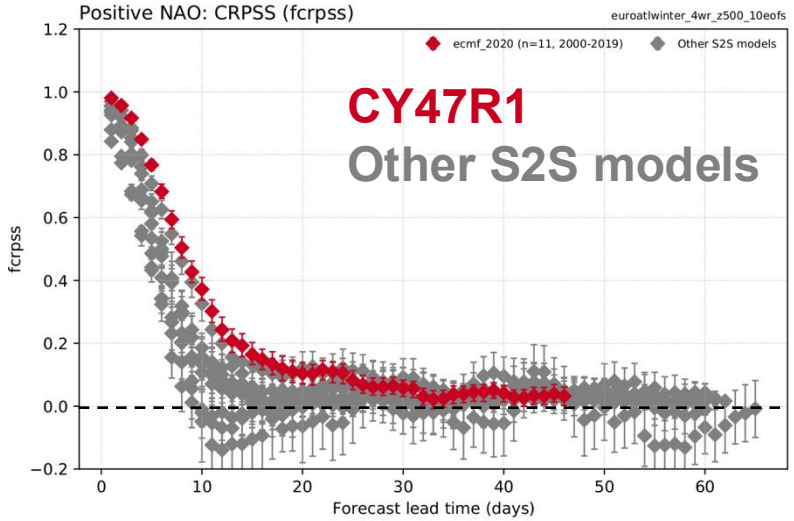
Regime structures and surface impacts (SONDJFM, 2000-2020)

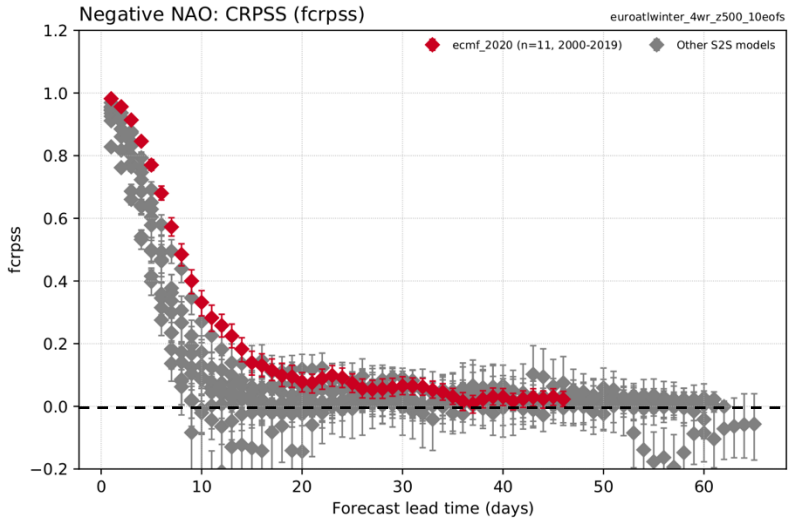


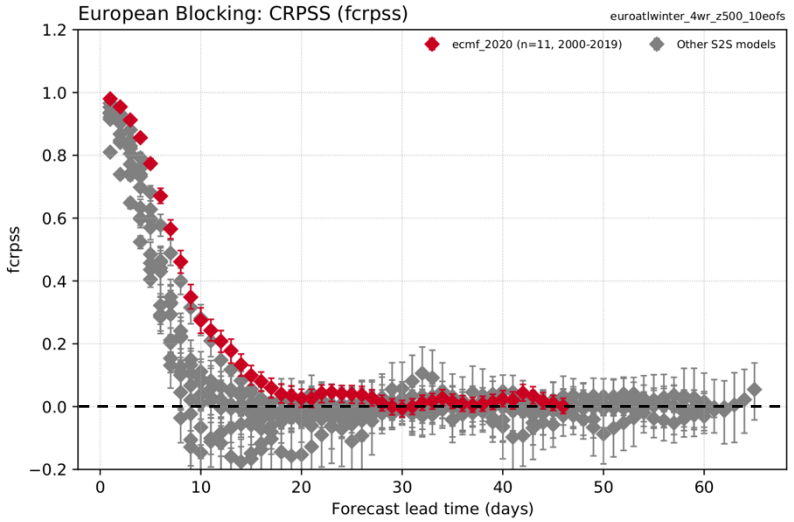
Regime structures and surface impacts are well-represented in operational reforecasts (CY47R1) and stable across S2S lead times (week 1 to week 6).

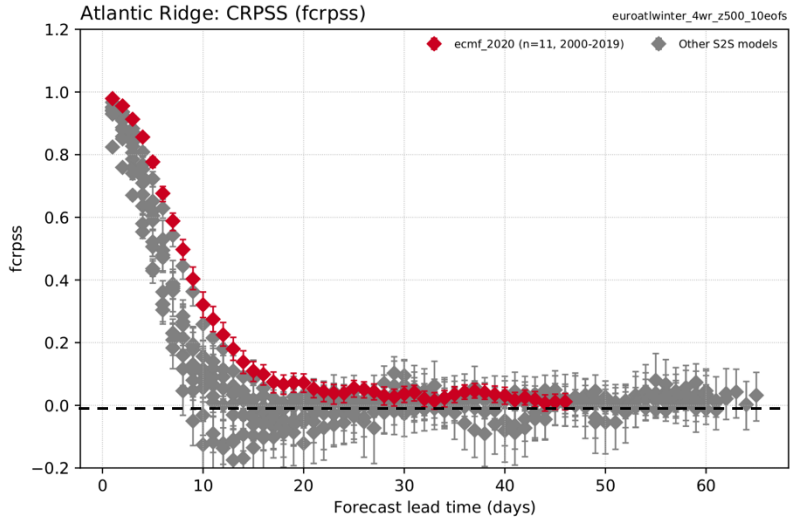
Skill in operational S2S reforecasts (all year)

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