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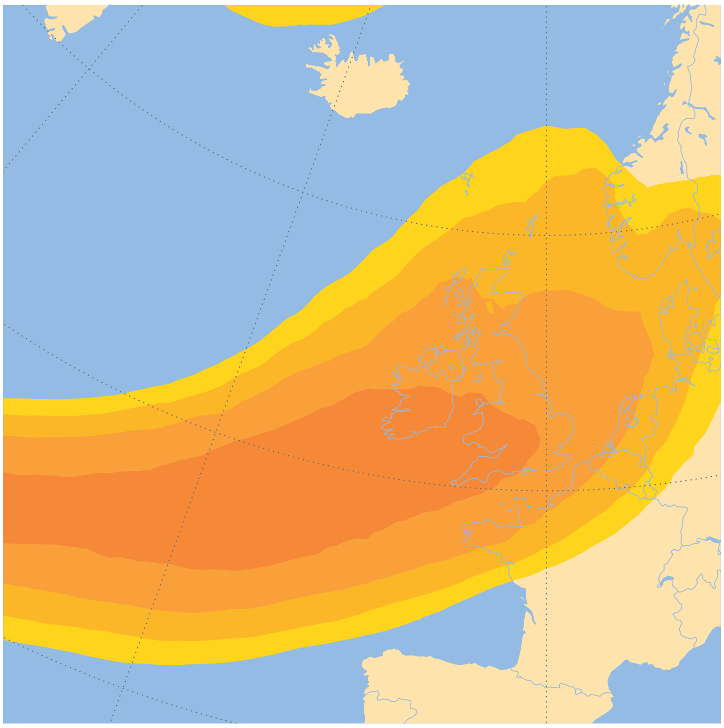

Cover image: EFI for water vapour flux on 15 February 2020

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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)

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 approach to identify regimes. Based on quasi-stationarity and persistence, weather regimes represent, in a statistical sense, the states for which the large-scale flow pattern resides for an extended period (a week to a month). This definition offers an intuitive description of the weather variability. Weather regimes then describe the long-lived, large-scale circulation pattern perturbed by individual highs and lows. In this article we will discuss a few different regime definitions for the Euro-Atlantic region with different levels of complexity and show examples of useful visualisations, using ECMWF forecasts as a basis.

Weather regimes

The real atmosphere is not discrete with its state space limited to a low number of states to reside in, but several potential stable states might exist depending on the current flow situation. There are various weather regime definitions which account for this large-scale flow variability but share common regime characteristics: their large spatial extent affecting continent-scale regions and their persistence of typically longer than 10 days. Although the existence of weather regimes over the Euro-Atlantic sector depends upon the midlatitude dynamics, the presence of external forcings, such as tropical heat anomalies or fluctuations of the stratospheric polar vortex, can modulate their frequency of occurrence.

The persistence of the weather regimes and their sensitivity to external forcings give rise to increased predictability at the extended range, when the predictability of synoptic perturbations declines. But at the same time, it raises the forecast challenge to correctly represent weather regimes and predict transitions from one regime to another in numerical models (e.g. Ferranti et al., 2015; Grams et al., 2018).

Beyond the fact that weather regimes can be regarded as physical modes with specific life cycles and transitions, another intriguing property of the regime concept is the connection of weather regimes to surface weather and weather extremes. Specific regimes particularly provide the environmental conditions conducive to large-scale cold spells in winter, heat waves in summer, and widespread heavy precipitation or thunderstorm activity. They also affect the generation of renewable energies on sub-seasonal time scales (e.g. Ferranti et al., 2019; Grams et al., 2017).

Despite the challenge of weather regime representation in numerical models, the conceptual model of regimes has proven to be a useful way to extract forecast information on the extended range, especially in ensemble forecasting. Still, with the huge amount of data from an ensemble system, it is necessary to condense the information in some way. One way to do this is to identify and visualise the dominant regime of the day in each ensemble member.

The difficulty in doing so is how to define the regimes and how to visualise them. For the regime definition there are a number of degrees of freedom: region, number of regimes, life-cycle definition, seasonality etc., and each is relevant so that there is no unique regime definition covering all use cases.

How to construct regimes

Weather regimes aim to describe recurrent, quasi-stationary, and persistent states of the atmospheric circulation in a specific region. Since the advent of reanalysis data, identifying the leading modes of variability and clustering has become most common (e.g. Michelangeli et al., 1995). The leading empirical orthogonal functions (EOFs) on a large-scale flow field are computed: typically anomalies of geopotential height at 500 hPa or mean sea level pressure. This is followed by a clustering of the leading EOFs which attributes each analysis time to a specific cluster in the EOF phase space and allows the computation of the pattern of the cluster mean anomaly in physical space. Prior to applying the EOF,

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analysis data is often low-pass filtered (typically 10 day cut-off) to remove synoptic-scale variability.

For the Euro-Atlantic sector, four regimes have been shown to be optimal for seasonal regime definitions. Seasonality in the amplitude of the considered large-scale flow anomaly, which is usually less in summer compared to winter, is another problem to deal with. To tackle this, regimes are often defined separately for different seasons, or consecutive 3-month periods, and blended into each other. However, summer and winter regimes differ substantially and regime behaviour in individual transition seasons often fits in either group so that there is no unique regime definition for spring and autumn. To address this problem, we here also use a novel regime definition accounting for seasonal variability by identifying an optimal number of seven year-round regimes in 500 hPa geopotential height anomalies, which are normalised to remove the seasonality in the amplitude.

Finally, even more refined regime definitions exclude days with only a weak projection into a regime by applying a persistence criterion (often at least 5 days) and further criteria to define sophisticated regime life cycles with objective life cycle stages, such as regime onset or decay. In this article we discuss the depiction of weather regimes in three such different definitions for the Atlantic-European region with increased level of complexity:

(1) The mere attribution in EOF1/2 space (see Ferranti et al., 2019). EOF1 corresponds to the two phases of the North Atlantic Oscillation (NAO), and EOF2 corresponds to the East Atlantic pattern, similar to a Scandinavian blocking in winter (BLO), so that the EOF1/2 space is also denoted as NAO±/BLO±.

(2) The classical four weather regimes based on EOF-clustering and regime attribution in EOF space, excluding weak projections into the EOFs, (denoted 4WR, see Ferranti et al., 2015). These reflect the two phases of the NAO complemented by the Atlantic Ridge and European/Scandinavian blocking regime. Two sets of 4WR are considered in operational forecasting at ECMWF, one valid for the cold period (October to April) and the other for the warm period (May to September). For the daily attribution, the 4WR spatial patterns are then adjusted to take into account the seasonal signal. A given regime is assigned only if the minimum distance between the anomalies and any of the 4WR is within an 'average value' and if the distance is significantly different from the others.

(3) A year-round definition of seven weather regimes based on EOF-clustering but with the regime attribution based on the projections of the instantaneous 10-day low-pass filtered 500 hPa geopotential height anomaly in the seven cluster mean fields in physical space and a sophisticated life-cycle definition (denoted 7WR, see Grams et al., 2017). The seven regimes reflect the 4WR patterns but allow three variants of cyclonically dominated regimes to be distinguished instead of NAO positive alone, and the four blocked regimes can distinguish blocking over Europe or Scandinavia.

Variance explained by regime definitions

In order to effectively condense forecast information, a regime definition must explain as much as possible of the variance in the atmosphere over a specific region with a few patterns. Therefore, we first discuss the variance explained by the leading 2 and 20 EOFs based on climatological variability as well as the 4WR seasonal and the 7WR year-round definition with data from 20 November 2019 until 11 March 2020 (Figure 1). The 10-day running mean removes synoptic variability in accordance with the use of 10-day low-pass filtered data for the 4WR and 7WR definitions. The computation of the variance is explained in Box 1.

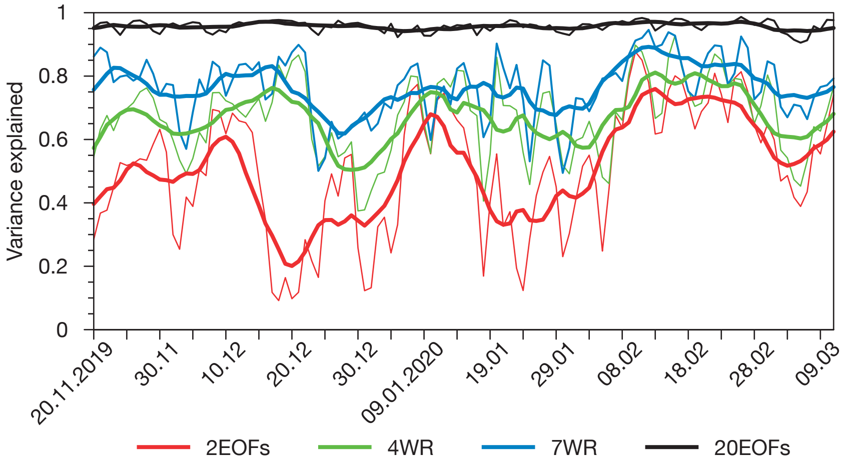


Figure 1 Variance explained by the leading 2 and 20 EOFs, and the phase space spanned by the 4WR and 7WR definitions in winter 2019/20. Thin lines show daily values, bold lines the 10-day running mean.

Computing explained variance

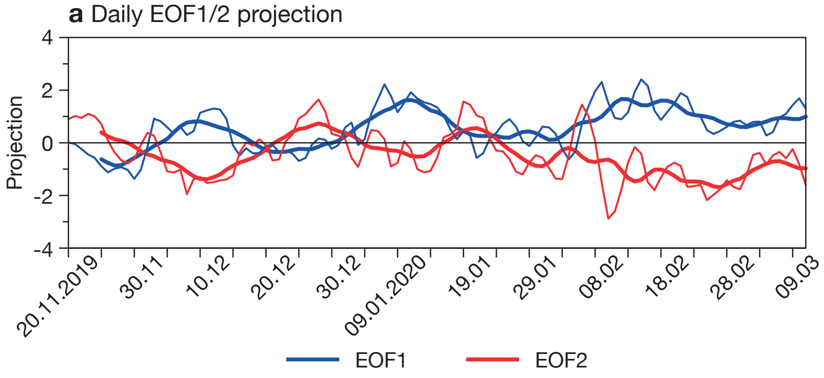
A

The variance is computed with the following procedure: (1) use the Gram-Schmidt method to create an orthogonal base for each set of regimes, and (2) calculate the sum of the variance explained by the projection of the daily anomaly onto each orthogonal field. The sum of the variance is divided by the total variance of the daily field. The variance explained by the leading 20 EOFs (black in Figure 1) serves as a benchmark and is above 0.95 for almost the entire period.

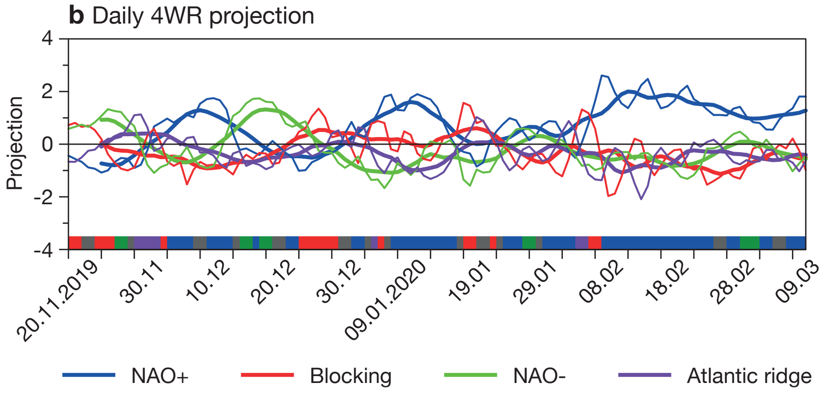
Much of the variance is explained already by the leading 2 EOFs (red), with on average 50% during the plotted period. Increasing the number of EOFs to 3 and 7 would increase the explained variance to around 65% and 80% respectively (not shown), while gradually reducing the temporal variability in explained variance. Likewise, the more complex 4WR and 7WR definitions explain on average 67% and 77% of the variance, respectively, both with similar temporal variability. The temporal variability in the explained variance is less for the more complex regime definitions with additional clustering compared to the raw EOFs. In particular during a period in the middle of December 2019, 2 EOFs explained only 20–30% of the variance compared to 60–80% by the other definitions. On the other hand, during the second half of February 2 EOFs explained more than 70% of the variance while 7WR explained more than 90%. Thus, while the 2 leading EOFs already explain a substantial fraction of variance, adding more complexity helps explain the bulk of variance during different flow situations. 7WR seems to be a good compromise to explain about 80% of the variance during most times, while the 7 possible states remain manageable.

Examples of regime depiction in analysis

Figures 2 and 3 show the projections into each regime from the three different regime definitions in extended winter 2019/2020 (20 November 2019 to 10 March 2020) based on operational analysis data. As mentioned above, a 10-day low-pass filter has been applied to the projection time-series. For the 4WR regime definition, the present regime is determined by the regime with the highest positive projection coefficient in EOF space and weak projections are assigned to no regime. For the 7WR, the present regime is determined based on a life-cycle definition in physical space and requiring at least 5-day persistence.



a Daily EOF1/2 projection



b Daily 4WR projection

Figure 2 Normalised projection of unfiltered 500 hPa geopotential height from operational analysis into (a) the first and second EOF and (b) the 4WR definition in winter 2019/2020. For 4WR we additionally show the daily attribution based on the distance to the cluster mean in EOF phase space with grey attributed to no regime.

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Before discussing the results, the reader should be reminded that the end of winter 2019/2020 was very mild in north-western Europe with prevalent positive NAO conditions (see also Magnusson et al., 2020). This is apparent in all regime definitions, with a dominance of EOF1 in the NAO±/BLO± definition (Figure 2a), NAO+ in the 4WR (Figure 2b), and the cyclonic-type regimes (Atlantic trough, zonal, Scandinavian trough) in the 7WR (Figure 3).

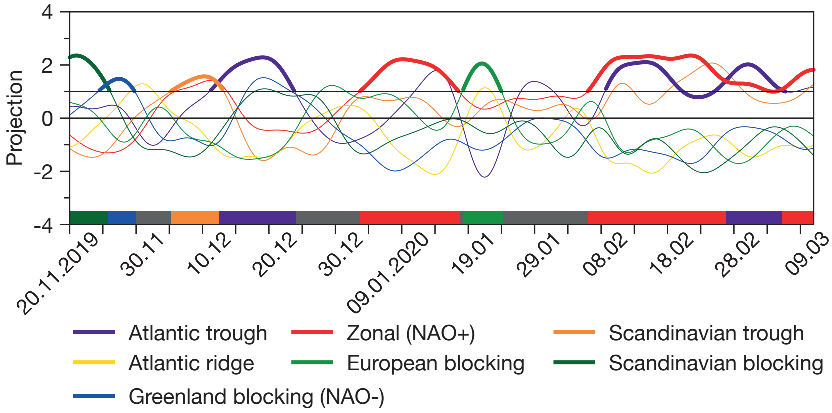

Figure 3 Normalised projection of 10-day low-pass filtered normalised 500 hPa geopotential height into the 7 year-round regime life-cycle definition (7WR) in winter 2019/2020. Coloured lines show projection, bold lines indicate active regime life cycle with at least 5-day persistence. The bottom coloured bar shows the attributed regime (active life cycle and maximum projection) with grey attributed to no regime. Note that the attributed regime might not be dominant for 5 days as simultaneous life cycles are possible.

The most persistent period took place through February into March, during which all regime definitions explained more than 70% of the variance (see discussion of Figure 1 above). During this period, the leading 2 EOFs were sufficient to explain most of the variance over the Euro-Atlantic area. However, 7WR gave the additional information of a slightly southward shifted storm track with the detection of a concomitant Atlantic trough regime in early March.

In contrast to the good agreement between the different definitions in February, there is a difference in the conveyed message in December. During this period a trough was present west of the British Isles, resulting in stormy conditions. Here the NAO±/BLO± definition failed to explain the variance as the projections onto the leading 2 EOFs were low. At the same time 4WR switched from NAO+ to NAO-, as it could not resolve the slight southward shift of the cyclonic pattern. However, the 7WR definition was able to identify this shift indicating Atlantic trough. In that case merely thinking of NAO- as a cold, calm regime in Europe is misleading, as the actual Atlantic trough indicates a stormy period with a strong southward shifted storm track. Moreover, in early December prior to the southward shift of the storm track and transition into NAO-/Atlantic trough in the 4WR/7WR definitions, the dominant projection into the Scandinavian trough for 7WR indicates that the cyclonic activity was further East than in the classical NAO+/zonal regime.

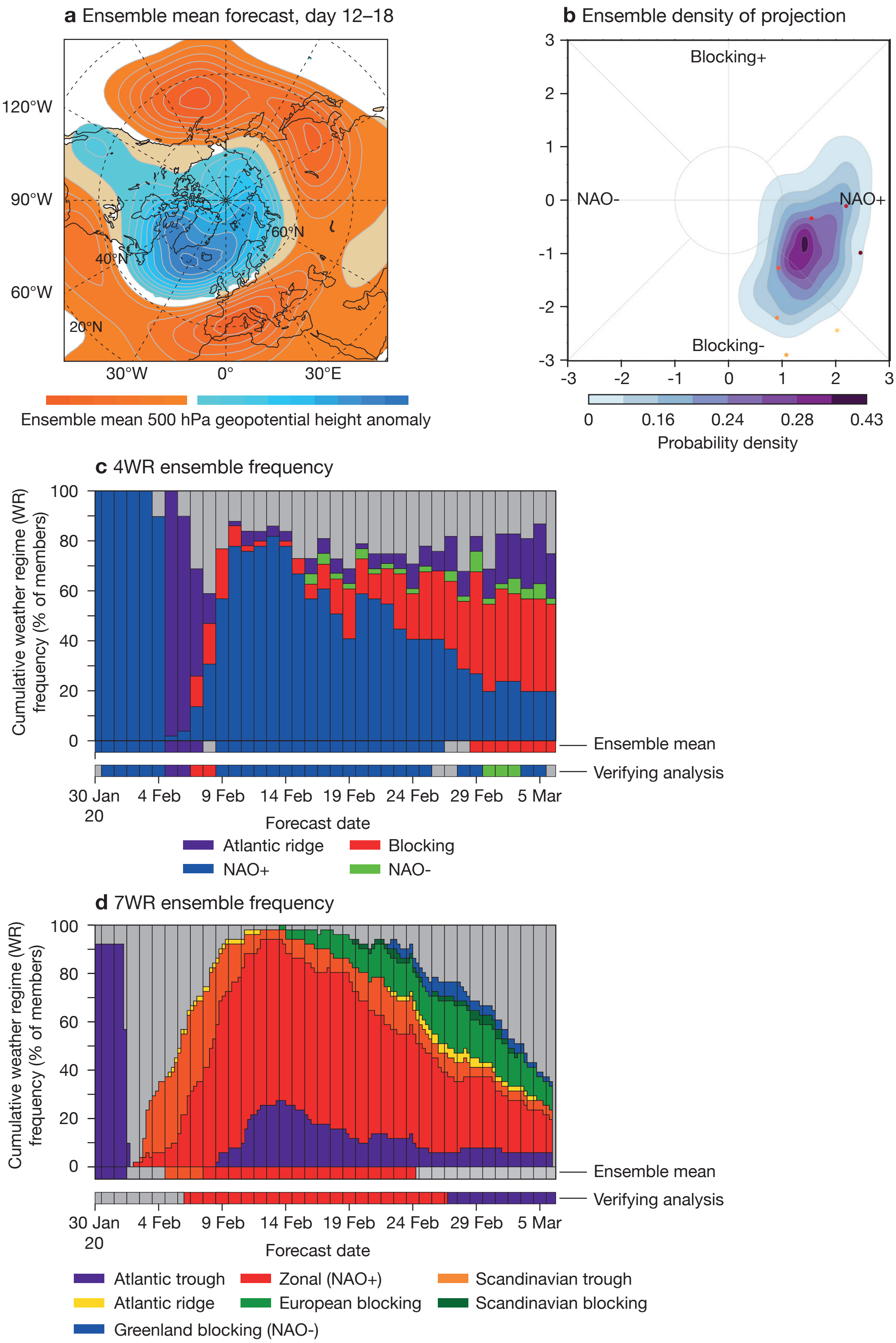

Figure 4 Different visualisations of extended-range forecast initialised on 30 January 2020, showing (a) ensemble mean 500 hPa geopotential height anomaly for week 3 (valid 12–18 days after initialisation), (b) ensemble density of projection in NAO±/BLO± space for week 3, with the dots marking the daily values of the verifying analysis (yellow = first day to brown = last day), (c) categorical weather regime probability in ensemble for 4WR definition (daily data) and (d) categorical weather regime probability in ensemble for 7WR definition (6-hourly data). Additionally, the ensemble-mean attribution and the verifying analysis are shown.

Examples of forecast products

An important aspect of how to get the most information from the forecasts is how to visualise the products. Regime forecasts are a way to condense the amount of information. In this section we are illustrating different ways to visualise regime forecasts. In Figure 4 we show examples of products from the same ECMWF extended-range forecast, initialised on 30 January 2020, which was a week before the onset of the positive NAO regime in all definitions that lasted for the rest of February. This forecast was also discussed in ECMWF Newsletter 163 (Magnusson et al., 2020). The first panel shows the ensemble mean anomaly of 500 hPa valid for 10–16 February (Figure 4a). The forecast had a strong negative anomaly over the north-eastern Atlantic and a positive anomaly to the south, which is the signature for a positive NAO. The next panel visualises the NAO±/BLO± definition showing the 2-dimensional distribution of daily projections of all ensemble members in the space spanned by the two leading EOFs (Figure 4b). The advantage of having two orthogonal regimes is that the forecasts can be visualised in such a phase diagram. Here we see that the product clearly indicates the state of a combination of the positive phase of EOF1 (NAO positive) and a negative phase of EOF2 (trough over Scandinavia). This very simple description of the forecast atmospheric evolution can be very effective in situations like this, in which the two leading EOFs already explain most of the variance, while other situations require a higher level of complexity (cf. discussion of Figure 1 above).

The two bottom panels (Figure 4c,d) show the regime forecasts where the dominating regime is detected for each ensemble member, with the size of each colour bar representing the probability for each regime and the x-axis representing the forecast length. The top plot is for 4WR and the bottom one for 7WR. This type of plot gives an overview of the ensemble distributions among the regimes and also the time evolution, but the drawback is that the categorical selection of regimes can hide information. Both regime forecasts correctly predict the final onset of an NAO+/zonal regime around 8 February. The visualisations shown in Figure 4a-c are freely accessible as official forecast products in the ECMWF charts catalogue (*https://www.ecmwf.int/en/forecasts/charts*). To complement the categorical product with continuous information about the actual strength of the regime projection in the forecast, Figure 5 shows the time evolution of the ensemble distribution of the normalized projection for two of the regimes in 7WR. In the example situation it reveals that after the onset of the zonal regime, the projection into Atlantic trough remains concomitantly high, which reflects a slight southward shift of the storm track compared to a classical positive NAO.

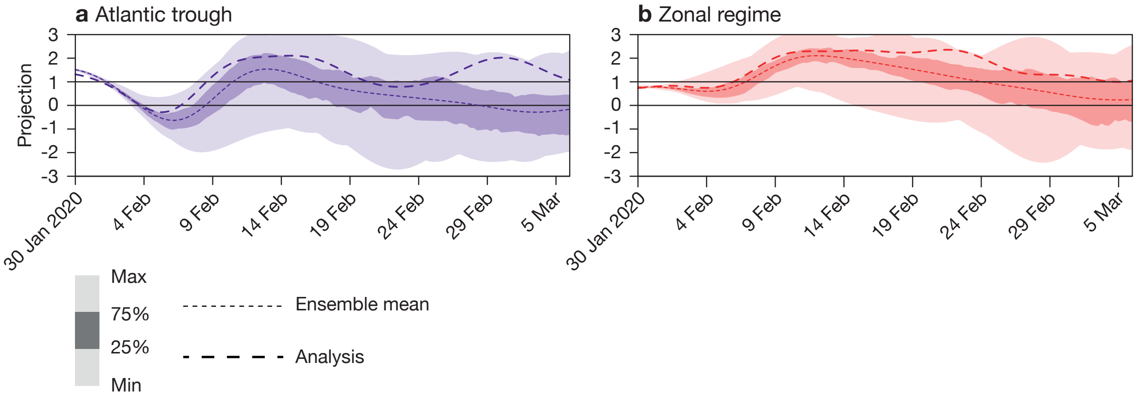

Figure 5 Ensemble distribution of continuous weather regime index (normalized projection) in (a) the Atlantic trough of the 7WR definition and (b) the zonal regime of the 7WR definition. Light colours indicate the range of min/max projection, darker colours the interquartile range, short dashed line the ensemble mean projection and long dashed line the projection of the verifying analysis.

Summary

This article illustrated different ways to condense forecast information for the extended range with the help of weather regimes. We argue that using different regime definitions is a way to deal with flow-dependent predictability and better assess the current forecast skill horizon. We discuss a range of forecast products all based on weather regimes but each with a different level of complexity. While simple forecast products based on NAO±/BLO± projections or categorical attribution of ensemble members provide a quick overview, complementing this with continuous forecast information in terms of regime projections is a way to avoid misinterpretations in suspicious situations (e.g. the slight southward shift of the storm track in February 2020 or the putative transition from NAO+ into NAO- in December 2019). ECMWF has today operational products based on NAO±/BLO± and 4WR accessible via the charts catalogue (Figure 4b and 4c). The 7WR products are for now available as test products at the Karlsruhe Institute of Technology (KIT). Using such products in a routine way would help forecasters gain experience in regime behaviour and their impact on surface weather (e.g. cold spells, see Ferranti et al., 2019) on sub-seasonal time scales.

Further reading

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European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading, RG2 9AX, England

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