# How to identify weather patterns associated with occurrences of extreme events in models

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## About this document

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## Summary for publication

Meridional transport of heat by transient atmospheric eddies is a key component of the energy budget of the Arctic and high latitude regions. While transport in the mid-latitudes is known to be modulated by large-scale low frequency flow regimes, little is known about the link between heat flux in the polar cap and mid-latitude circulation regimes. Recent studies suggest that heat and moisture transport into polar regions happens in bursts that are associated with propagation of storms and atmospheric blocking. While the picture is evolving, a systematic assessment is still lacking.

We investigate the modulation of transient, poleward atmospheric eddy heat flux induced by the variability of the atmospheric circulation in the North Atlantic sector. Heat transport is defined by meridional advection of moist static energy, and the circulation anomalies are diagnosed with a widely used clustering technique, a jet latitude index and a blocking index. The analysis is carried out for the extra tropics in the Northern Hemisphere but special emphasis is given to heat transport crossing the 70 ◦N latitude circle. Results are based on an atmospheric reanalysis for a total of 38 extended cold seasons. Establishing quantitative relationships between circulation regimes and poleward heat transport by transient eddies can help understand linkages between mid-latitudes and the Arctic, and evaluate how they are represented in coupled GCMs. In principle, it can help exploit predictability on a sub- seasonal time scale. The relationship between extreme events of strong heat flux and circulation regimes is also assessed and the analysis indicates a fundamental role of blocking in the North Atlantic sector.

The presented empirical relationship between heat flux variability and extreme events can serve as a powerful tool for predictability analysis, but also for the evaluation of model variability.

# Work carried out

For this study, daily data from the ERA-Interim daily reanalysis (Dee et al. 2011) are obtained on a $1^{\circ}x^{\circ}1$ regular longitude-latitude grid on selected pressure levels (200, 300, 400, 500, 600, 700, 775, 850 and 925 hPa). Data used include geopotential height (Z), zonal (U) and meridional (V) components of wind, air temperature (T), specific humidity (Q).

Weather regimes have been computed following the method of Michelangeli et al. (1995) and Yiou et al. (2008). The ten leading Empirical Orthogonal Functions (EOFs) of Z at 500 hPa and the corresponding Principal Components (PCs) are computed. Then a k-means algorithm is applied, with the choice of four weather regimes over the North Atlantic region [80W - 50E; 20 - 70N] to daily data across the 1979–2017 extended cold seasons (NDJFM). Daily data classifications are obtained by determining the minimum of the Euclidean distances to the four weather regime centroids. Figure 1 shows the four weather regimes identified in NDJFM 1979-2017. In this study they are named Scandinavian blocking (Scand), Atlantic ridge (Ridge), positive NAO (NAO+) and negative NAO (NAO-).

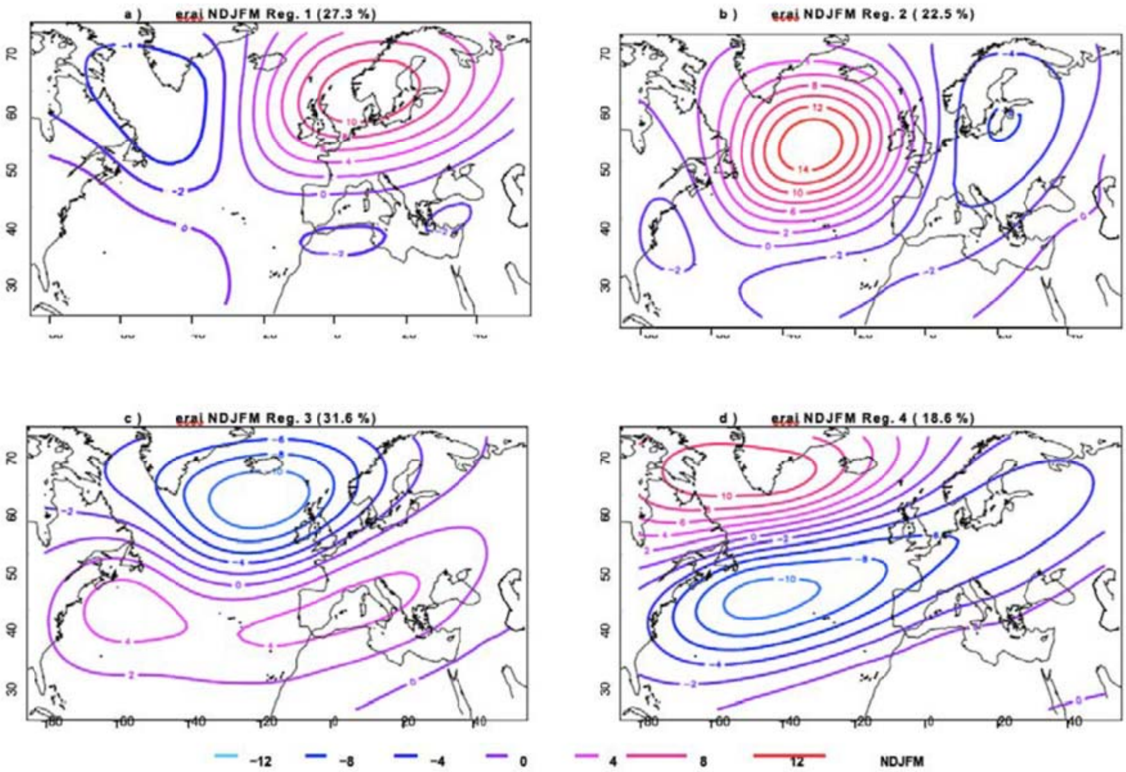


***Figure 1:** The four North Atlantic weather regimes in the extended cold season (NDJFM). Contours indicate anomalies of geopotential height at 500 hPa in meters (m). Figure taken from Ruggieri et al. (2019).*

Transient eddy quantities are computed filtering daily data with the bandpass function of the Climate Data Operators (CDO, Schulzweida et al. 2019). Synoptic frequencies have been selected between 2 and 9 days, while the intra-seasonal band is between 10-90 days. Covariances of eddy quantities have been filtered with a running mean with a window of 10 days.

A proxy of eddy kinetic energy (hereafter called "storminess" in the case of synoptic frequencies) is defined as the product V'V'. Transient eddy poleward heat flux (TEHF) is defined as V'm' where the prime denotes a bandpass filter on the appropriate frequencies and "m" is the air moist static energy. In this study the focus is on the variability of the transient eddy heat flux (or TEHF) defined. The connection with the heat budget of the Arctic polar cap is diagnosed via the zonally averaged TEHF, as done in Overland et al. (1996), Adams et al. (2000) and Serreze et al. (2007).

Statistical significance is assessed using an unpaired Student-t test with a number of effective degrees of freedom that accounts for the autocorrelation of time series, or with a bootstrap method based on sub-sampling.

# Main results achieved

The four weather regimes computed for the extended cold season (1980–2017) are shown in figure 1. Contours indicate the geopotential height at 500 hPa of the 4 centroids. The relative frequency of occurrence, displayed in brackets in the header of each panel, ranges from about 31.4% for NAO+ to 18.6% for NAO-. With the exception of the NAO+, a common feature of three weather regimes is an anticyclonic anomaly in the northern part of the domain. In particular, the NAO- can be viewed as a manifestation of Greenland blocking and the Scand regime is sometimes called "Blocking", named after blocking occurring in Scandinavia or more generally in Northern Europe. The Ridge shows a blocking-like anomaly in the central Atlantic. The NAO+ (often named 'Zonal' regime) corresponds to an intensified Icelandic low, a reinforced Atlantic jet and to absence of blocking in the domain. Hence, the four clusters can be viewed as three different locations of a blocking high (or a blocking-like anomaly), and one (NAO+) that corresponds to the lack of blocking. As discussed later in this section, weather regimes have a close but non straightforward relationship with the variability of the eddy-driven jet in the sector, with consequences for the propagation of storms that are documented hereafter.

Storminess (here defined as the square of the highpass filtered meridional wind), is typically diagnosed aloft, where it is a good proxy of eddy kinetic energy and an indicator of the presence of deep synoptic storms. In our analysis, which is focused on the transport of moist static energy in the lower troposphere by eddies, low-level storminess can be insightful to interpret presented results. As shown by figure 2, synoptic storms activity is mainly detected in the two tracks in correspondence of the Atlantic and Pacific oceans. Secondary, minor storm tracks are detectable in western Siberia, Barents Sea and in the Mediterranean Sea. The day-to-day variability largely overlaps the mean field, and one standard deviation corresponds typically to about one half of the mean value. The poleward heat flux associated with synoptic eddies is broadly coincident with the location of the storm track, but more confined in the oceanic sectors and in a mid-latitude band. There are noticeable poleward extensions of the heat flux in 3 branches, one over North America, one in GIN and Barents Seas, one in the Bering Strait. For slower eddies (labelled intra-seasonal in figure 2) the eddy kinetic energy peaks at considerably higher latitudes in the oceanic sectors and shows high values also in western Siberia. Local maxima of TEHF can be found in the mid-latitude band, in particular in the central Atlantic, in correspondence of the Auletian low and in south-east North America. There are two noticeable peaks in polar regions, one in the GIN seas, one in the Bering Strait.

In figure 3, we show the low-level storminess (850 hPa) for the four weather regimes identified in figure 1.

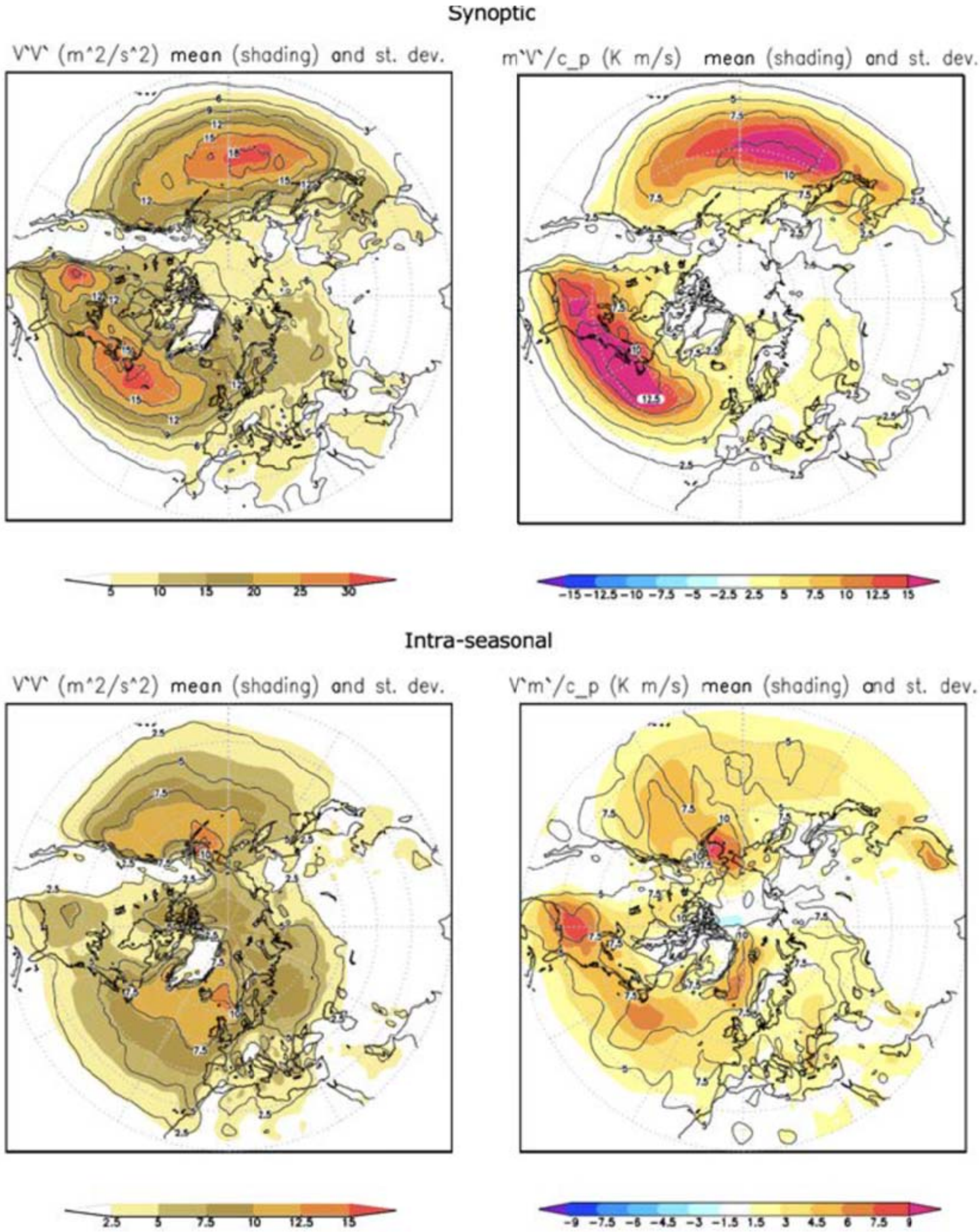


***Figure 2:*** *Top) Climatological mean (shading) and day-to-day standard deviation (contours) of variance of meridional velocity and meridional transport of moist static energy divided by $c_p$, for synoptic eddies. Bottom) As in top) but for intra-seasonal eddies. Figure taken from Ruggieri et al. (2019).*

Storminess is substantially different from one regime to another: Scand prevents storms from reaching Europe and the activity is intensified in the eastern Atlantic. A high-latitude signal in Barents and Greenland seas is noticeable and it forms a secondary maximum of eddy activity. The Ridge instead suppresses synoptic activity in the eastern Atlantic but positive anomalies are found in the extra-tropical regions surrounding the anticyclone, from western Atlantic to western Siberia, trough Labrador, Greenland and Norwegian seas. The positive phase of the NAO intensifies synoptic activity in Scandinavia and British isles and reduces it in the western part of the Atlantic domain. The negative phase, shown in the last panel of figure 4, is associated with a strong suppression on the poleward side of the jet and an equatorward shift. Positive anomalies are found also in the Mediterranean basin and in western Siberia. As seen in figure 4, Scandinavian blocking implies stronger transport in the central Atlantic, in the core of the jet, and weaker transport in continental Europe. Between 30W and 30E, the storm track is drastically deflected poleward, resulting in particularly strong transport in the GIN and Barents Seas. The Atlantic ridge induces a North-South dipole in the central Atlantic, with intensified transport in Labrador Sea and Denmark Strait. During the positive phase of the NAO transport is intensified in the core of the jet and weakened on the poleward and equatorward sides. This fact is consistent with a strong jet acting as a meridionally confined waveguide. Finally, the negative phase of the NAO shows a suppression of the heat flux in the upstream region of the Atlantic jet and a moderate equatorward shift, a positive signal is found over Eurasia. The analysis for intra-seasonal frequencies (10-90 days, in figures 5 and 6) suggests that there is an increase of eddy kinetic energy for the three blocked regimes (Scand, Ridge and NAO-), while NAO+ shows a suppression of the flux over a vast area of the Atlantic domain. The corresponding heat transport field shows indeed a zonally confined and meridionally elongated positive anomaly upstream with respect to the blocking, whereas NAO+ shows again a suppression at high-latitudes.

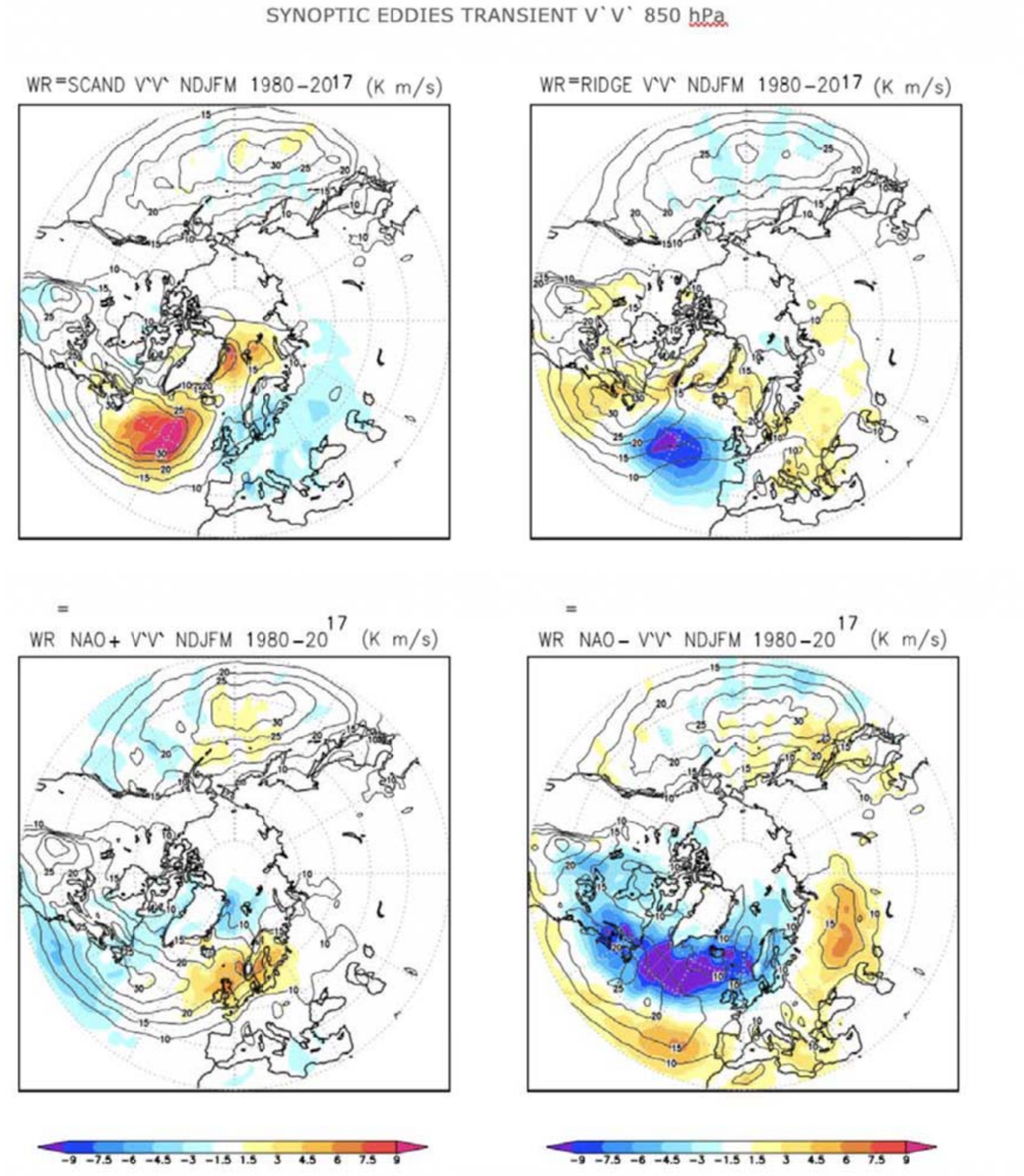


***Figure 3:*** *Composites of mean anomalies (shading) of variance of meridional velocity for synoptic eddies for the four weather regimes. Anomalies are computed from a daily climatology. Contours indicate the mean field associated with the weather regime, obtained adding the anomalies and the mean NDFJM value. Figure taken from Ruggieri et al. (2019).*

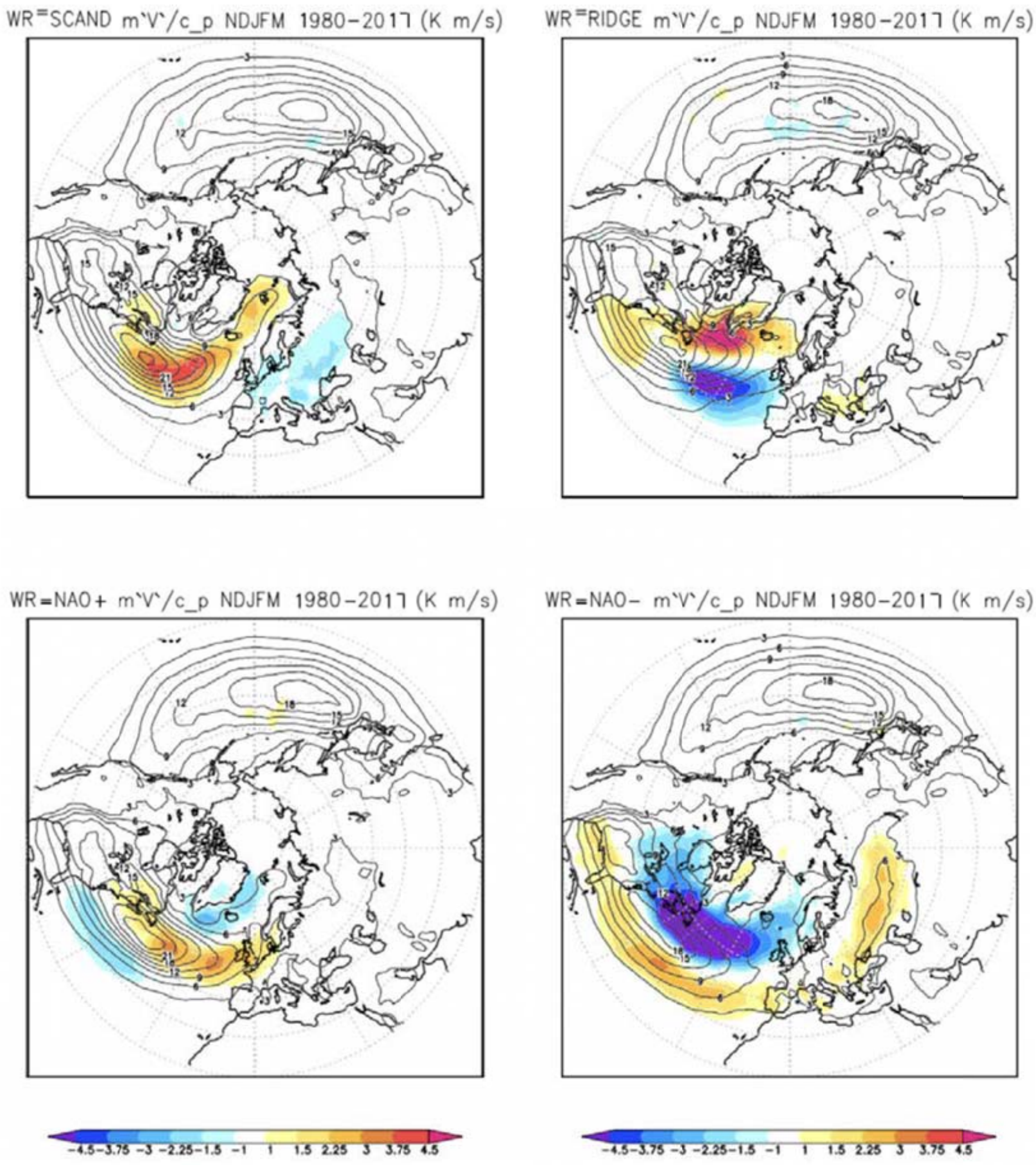


***Figure 4:*** *As in figure 3 but for meridional moist static energy flux by transient synoptic eddies. Figure taken from Ruggieri et al. (2019).*

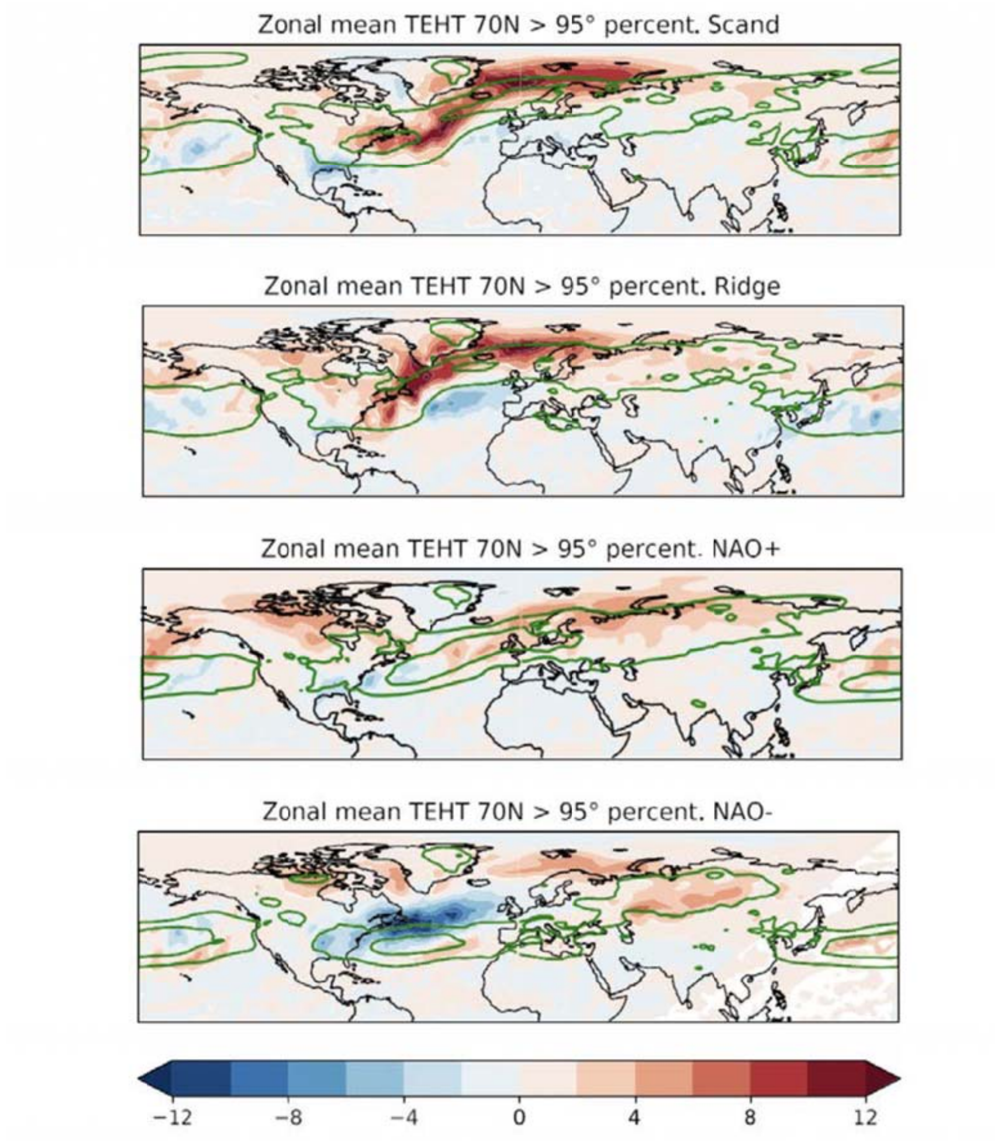


***Figure 5:*** *Composites of anomalous meridional heat transport for days with extremely positive zonal mean heat flux at 70 ◦N (95th percentile), conditional to the occurrence of a weather regime. The threshold of the 95th is defined for each regime separately and days above the threshold all belong to the same weather regime. Figure taken from Ruggieri et al. (2019).*

## Progress beyond the state of the art

Messori and Czaja (2013) found that extreme events are crucial for extratropical heat transport by transient eddies and noted that the probability density function for local heat transport is strongly skewed towards positive values. They conclude that a large fraction of the total heat transport is attributable to few, extreme events. These findings have implications for results presented and suggest that potentially the property of the mean of the distribution is poorly informative of the variability of the heat budget of the polar cap. While a thorough analysis of heat transport extremes variability and its link with weather regimes is beyond the scope of this study, investigating the role of extremes is crucial for a sound interpretation of presented results.

Synoptic eddies have a strongly positively skewed distribution, with individual regimes showing a local peak in the polar cap. On the other hand, the intra-seasonal band shows a symmetrical distribution poleward of 60 °N. This finding suggests that extremely positive values of synoptic TEHF may reveal links with the atmospheric circulation that are not outlined by previously presented results.

A simple analysis presented in figure 5 reveals the peculiar role of Scand and Ridge also for extreme zonal mean heat transport. In this figure, the 95th percentile of zonal mean synoptic TEHF is computed for the 4 PDFs associated with individual weather regimes (i.e. the distribution obtained if only days with the selected regime are retained). The TEHF is then averaged for all days above the 95th percentile belonging to the selected weather regimes. The associated 850 hPa zonal wind field is shown with green contours. In presence of Scand or Ridge, extremely strong TEHF is produced by a confined band of intensified meridional flux extending from the Gulf Stream region up to Eurasian polar regions, touching the Kara Sea. Values can reach 12 K $ms^{-1}$ in the Labrador Sea and in the Nordic seas. This pattern of extreme transport is associated with a poleward shifted and strongly tilted low-level jet. This l-shaped, tilted and elongated pattern is slightly shifted poleward and eastward in the case of Scand, and more contracted around the Atlantic ocean in the case of the Ridge, but essentially it can be viewed as a common mode of extreme zonal mean TEHF into the polar cap that can occur in presence of both weather regimes. Noticeable in these respects is the lack of similar zonally confined patterns for the NAO ±. In this case, positive values of moderate intensity (up to 6 K $ms^{-1}$) are scattered over multiple sectors, from North America, to Bering Strait, to the Barents and Kara seas.

The qualitative difference between the pairs Scand-Ridge and NAO± is more evident in figure 6: the first panel (top) shows the longitudinal profile at 70 °N of the TEHF fields shown in figure 5. In the case of Scand-Ridge extreme transport in a zonal mean sense is the signature of strong and localised anomalies confined in the Euro-Atlantic sector, with a peak around 0 °E. During NAO± the anomalous heat flux is positive over a wide areas of the Northern Hemisphere, but the magnitude of anomalies over the North Atlantic is small if compared to other longitudes and values reached are locally smaller than Scand-Ridge. The bottom panel of figure 14 also shows that intense zonal mean heat flux during Scand/Ridge is always found with a positive anomaly in the Euro-Atlantic sector, while if the extreme flux event happens during NAO± it is unlikely to find positive anomalies in the Atlantic area.

Overall, the results show that transient eddy heat flux is substantially modulated by mid-latitude weather regimes on a regional scale also in polar regions. On a zonal mean sense, the phases of the North Atlantic Oscillation do not change significantly the synoptic heat flux, whereas Scandinavian blocking and Atlantic Ridge are associated with an intensification. The relationship between extreme events of strong heat flux and circulation regimes is also assessed and the analysis indicates a fundamental role of blocking in the North Atlantic sector.

# Impact

**How has this work contributed to the expected impacts of Blue-Action?**

This work is immediately linked to the key objective of WP1 to improve sub-seasonal predictability by a process-based evaluation that identifies the conditions in which extremes are likely to form. As outlined in the work program of WP1, in a next step, predictability itself might be improved by basing the analysis on the conditions suggested in the present work.

On a broader level, the presented empirical relationship between heat flux variability and extreme events will be a valuable tool for the evaluation of model variability, in particular with respect to the model's ability to represent the conditions for extreme events.

**Impact on the business sector**

This work contributes to setting up a robust and reliable forecasting framework that can help meteorological and climate services to deliver better predictions, including at sub-seasonal and seasonal time scales and to better servicing the economic sectors that rely on improved forecasting capacity (e.g. shipping) with specific ties with WP5.

# Lessons learned and Links built

The work showed that an analysis of weather patterns associated with the occurrence of extreme events in the Arctic is possible at the temporal and spatial resolution provided by the ERAinterim reanalysis, which is in turn a resolution that most coupled climate models and climate forecast systems can provide. This proof-of-concept study is taken up especially by WP1 in **Task 1.4** in the course of the project, but likely also by several other groups in the community. In particular, we are in contact with **APPLICATE** and **PRIMAVERA** to compare our results to their systems.

The present proof-of-concept works also links nicely to the Milestone 4 “Guidelines how to quantify extremes in models using EVT” and to the the paper by Tamas Bodai and Torben Schmith (2019) “Does the AO index have predictive power regarding extreme cold temperatures in Europe?” (submitted to Extremes), which takes a view to seasonal forecasting via extreme value statistics, and apples the method of Nonstationary extreme value statistics to determine the predictive power of large scale quantities. As they find that for winter cold extremes over Europe, the monthly mean daily minimum local temperature has a much larger predictive power than the nonlocal monthly mean Arctic Oscillation index, it will be highly valuable to combine this view and the view presented here in the upcoming analysis. In addition, this work will be combined with the work by Dobrynin et al., 2018, which itself has a strong link to the Copernicus Climate Change Service for seasonal predictions.

# Contribution to the top level objectives of Blue-Action

The work contributes to Objective 1 Improving long range forecast skill for hazardous weather and climate events laying the fundamentals for the identification of large-scale viability on which extreme events are likely to form.
The work presented in the deliverable shows the link large-scale and low-frequency regimes of atmospheric circulation are linked with heat transport in polar regions. It has been found that heat

transport extremes in the Euro-Atlantic sector of the polar cap are conditional to the occurrence of blocking in the Atlantic Ocean and in Europe (see figures 4 and 5). The identification of this link indicates potential predictability for the Arctic environment enslaved to skill in predicting mid-latitude regimes and paves the way for further analysis in a multi-model framework.

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# Dissemination and exploitation of Blue-Action results

## Dissemination activities

| Type of dissemination activity | Name of the scientist (institution), title of the presentation, event | Place and date of the event | Type of Audience | Estimated number of persons reached | Link to Zenodo upload |
|---|---|---|---|---|---|
| Participation to a conference | Paolo Ruggieri (CMCC) Talk "Atlantic weather regimes and poleward heat transport by transient eddies , at EGU 2019 | Vienna (AT), 8-13 April 2018 | Scientific Community (higher education, Research) | 100 | [https://zenodo.org/record/2641773#.XQodydMzafU](https://zenodo.org/record/2641773#.XQodydMzafU) |
| Participation to a conference | Paolo Ruggieri (CMCC), Atlantic weather regimes and poleward heat transport by transient eddies in polar regions , EMS (abstract accepted for an oral presentation) | Copenhagen (DK), September 2019 | Scientific Community (higher education, Research) | 50 | [https://www.zenodo.org/communities/blue-actionh2020/](https://www.zenodo.org/communities/blue-actionh2020/) |
| Participation to an event other than a conference or workshop | Paolo Ruggieri (CMCC) Talk "Atlantic weather regimes and poleward heat transport by transient eddies | L'Aquila (IT), 9 May 2019 | Scientific Community (higher education, Research) | 30 | [https://zenodo.org/record/3060542#.XQod2NMzafU](https://zenodo.org/record/3060542#.XQod2NMzafU) |

## Peer reviewed articles

- Tamas Bodai and Torben Schmith (2019), “Does the AO index have predictive power regarding extreme cold temperatures in Europe?” submitted to Extremes.
- Paolo Ruggieri, M. Carmen Alvarez-Castro, Panos Athanasiadis, Alessio Bellucci, Stefano Materia, Silvio Gualdi (2019), “North Atlantic circulation regimes and heat transport by transient eddies”, Journal of Climate, in review.

## Uptake by the targeted audiences

As indicated in the Description of the Action, the audience for this deliverable is the general public (PU) and thus this deliverable is made available to the world via [CORDIS.](CORDIS.)

**This is how we are going to ensure the uptake of the deliverables by the targeted audiences:**

Apart the submission of the paper of Ruggieri et al., the team of authors has already planned some further dissemination at the scientific events in the second half of 2019 (September event reported above and annual meeting Blue-Action in October 2019).