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Advanced Prediction in Polar regions and beyond: Modelling, observing system design and LInkages associated with a Changing Arctic climaTE

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Deliverable No. 1.2

Provision of process-focused, user-relevant and Arctic linkages metrics through ESMValTool

Submission of Deliverable

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Contents

Executive Summary

The APPLICATE Task 1.2.3 is dedicated to the development of diagnostics/metrics relevant to investigate climate linkages between the Arctic and the mid-latitudes. Here we report the progress made within this task and provide several lists of diagnostics/metrics that can be used by APPLICATE partners and the wider community for weather and climate model evaluation and/or climate change analyses.

There are still important gaps in our knowledge regarding the linkages between Arctic changes and mid-latitude variability and changes, both in the atmosphere and in the ocean. Substantial work has been made in Task 1.2.3 to review the literature and select the most appropriate diagnostics for documenting Arctic - mid-latitude linkages. Novel diagnostics have been developed, and several others are still under development. Partners involved in this task already use these diagnostics as metrics for the evaluation of their institutional weather and climate models. The software codes used to calculate the new diagnostics/metrics are now available for APPLICATE partners and very soon available for the wider community. Key diagnostics/metrics will become available in ESMValTool v2.0.

The upcoming release of CMIP6 and PAMIP multi-model data constitutes an ideal opportunity (Task 1.3) to sorely test these software codes and to implement well-tested diagnostics/metrics into ESMValTool. The ultimate objectives are (i) to document potential improvements in the representation of mid-latitude dynamics since CMIP5 (including linkages with the Arctic), (ii) to quantify CMIP6 projected changes in the atmospheric circulation, their uncertainties, and the contribution of the Arctic region, and (iii) to narrow model uncertainties in future projections by using the developed metrics as emergent constraints (Task 1.5).

1 Introduction

1.1 Background and objectives

There is a growing body of scientific peer-reviewed literature that suggests that long-term changes in the Arctic may impact the climate variability of the Northern mid-latitudes (see Cohen et al., 2014, for a general review and Sections 2 and 3 for more details). These linkages are thought to rely on the fact that both atmospheric and oceanic large-scale dynamics are primarily driven by the energy imbalance between equatorial and polar regions. Changes in the Arctic that may affect this equator-to-pole imbalance (e.g., the Arctic Amplification associated with the long-term sea ice loss) can therefore have consequences on the mid-latitude dynamics. Such linkages mainly occur in the ocean and the troposphere, but another potential Arctic influence is through a stratospheric pathway and the apparent stratosphere-troposphere dynamical coupling on a wide range of scales.

The aim of the Task 1.2.3 of APPLICATE (associated with the present deliverable D1.2) is to collect and/or develop diagnostics/metrics that describe such linkages in atmosphere and ocean, and to provide the code through ESMValTool (see Eyring et al., 2016, and `https://www.esmvaltool.org`). The terminology used in this document regarding the use of words like *metrics* and *diagnostics* is consistent with the Model Assessment Plan (D1.1) and the document `https://applicate.eu/images/APPLICATE_metrics_final.pdf`.

1.2 Organization of this report

This report is organized as follows: diagnostics/metrics for atmospheric linkages are detailed in Section 2, diagnostics/metrics for oceanic linkages are detailed in Section 3, and conclusions and outlook are provided in Section 4.

2 Atmospheric linkages

This work has been mainly conducted at **CNRM** (listed as CNRS-GAME in the partners). The diagnostics/metrics used to describe mid-latitude dynamics are detailed in Section 2.1 and the diagnostics/metrics used to describe Arctic linkages are detailed in Section 2.2. Section 2.3 describes additional user-relevant impact diagnostics/metrics. Information about software code used to calculate these diagnostics/metrics is provided in Section 2.4.

2.1 Mid-latitude dynamics

In order to describe Arctic - mid-latitude atmospheric linkages, a first step is to describe the mid-latitude dynamics itself. Part of the work conducted within APPLICATE has thus consisted in reviewing existing and developing new **diagnostics** in order to characterize various circulation features. They include the following: amplitude of the zonal westerly flow, trajectory and intensity of the jet stream, occurrence of anticyclonic blockings (traditionally associated with winter cold spells and summer heat waves), and behavior of main modes of intraseasonal to interannual mid-latitude variability (NAM/NAO). A selection of relevant diagnostics is provided in Table 1.

Table 1: List of diagnostics retained for describing mid-latitude atmospheric dynamics, with short description, key references, dimensions, and required CMIP-type outputs (variables and frequency) (psl = sea-level pressure; ta = air temperature; ua = zonal wind; va = meridional wind; zg = geopotential height).

Diagnostic	Short description	References	Dim.	Var.	Freq.
Zonal wind index	Zonal average of zonal wind	Francis and Vavrus (2012), Barnes and Polvani (2015), Zappa and Shepherd (2017)	lat×plev	ua	mon
Zonal geopotential index	Difference of zonal averages of geopotential height between 40–60° and 60–80° latitude	Woollings (2008)	plev	zg	mon
Zonal SLP index	Difference of zonal averages of SLP at 35° and 65° latitude	Li and Wang (2003)	scalar	psl	mon

Jet speed, position, width	Identification of the eddy-driven jet stream by averaging daily lower tropospheric zonal wind (e.g. 700 or 850 hPa) and fitting a parabola around the maximum; position = latitude of the max wind, speed = value of the max wind, width = latitude width at half of the max wind	Woollings et al. (2010), Barnes and Polvani (2013), Barnes and Polvani (2015)	scalar	ua	day
Jet sinuosity	Identification of the daily jet trajectory by an iso-contour of Z500; sinuosity = length of the trajectory divided by length of the straight line	Cattiaux et al. (2016), Martin et al. (2016), Peings et al. (2017), Vavrus et al. (2017)	scalar	zg	day
Jet amplitude	Monthly range of latitudes encompassing daily jet trajectories	Peings et al. (2018)	scalar	ua zg	day
1D blocking index	Identifies reversals in the daily Z500 meridional gradient from differences between 40, 60 and 80 °N	Tibaldi and Molteni (1990), Barnes and Polvani (2015)	lon	zg	day
2D blocking index	Same as 1D but with latitude dependence	Scherrer et al. (2006)	lon×lat	zg	day
Blocking tracking algorithm	Detects and identifies tracks of anomalies of high-tropospheric potential vorticity	Schwierz et al. (2004), Croci-Maspoli et al. (2007b), Croci-Maspoli et al. (2007a)	lon×lat	ua va ta	6hourly
NAO station-based index	Difference of SLP between grid points corresponding to Lisbon and Reykjavik	Hurrell et al. (2003)	scalar	psl	mon
NAO/NAM PC-based index	Principal component associated with the first EOF of winter monthly SLP or Z500 anomalies	Miller et al. (2006), Cattiaux and Cassou (2013)	scalar	psl zg	mon

NAO/NAM pattern	First EOF of winter monthly SLP or Z500 anomalies	Miller et al. (2006), Cattiaux and Cassou (2013)	lon×lat	psl zg	mon

As all these diagnostics use variables for which observational references are generally available (often through atmospheric reanalyses), they can easily be turned into **metrics** for model evaluation purposes. Figure 1 illustrates how the NAO/NAM pattern and the Tibaldi-Molteni 1D blocking index have been used to evaluate several intermediate development versions of the CNRM-CM model (see caption for details). Overall, it shows that climate models represent the NAM/NAO pattern fairly well but still have difficulties to simulate the observed longitudinal location and/or seasonal timing of atmospheric blockings. The CNRM-CM model has been slightly improved on these aspects since the CNRM-CM5 version, and these results will be incorporated into an evaluation paper in preparation (Voldoire et al., in prep.).

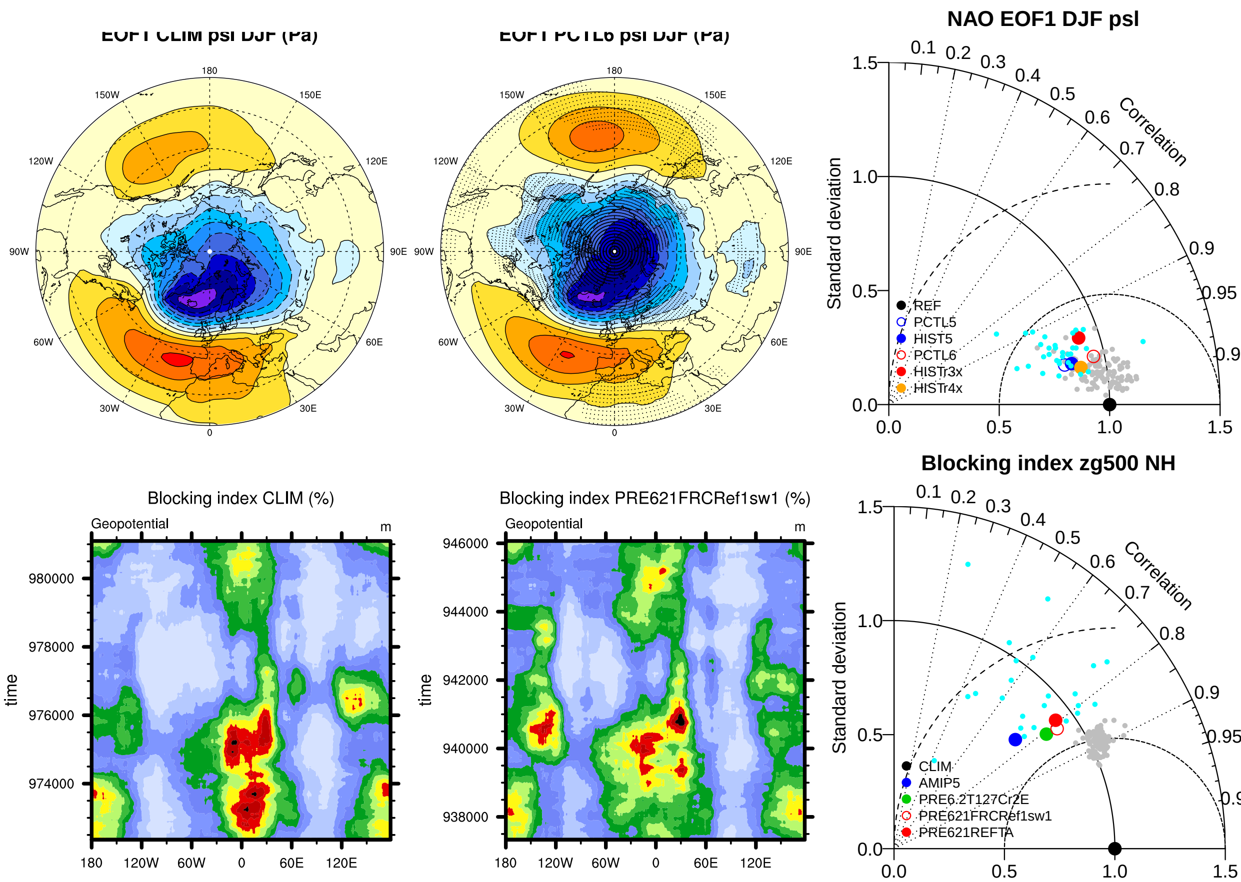

Figure 1: *Top:* NAO/NAM pattern for the ERA-Interim reanalysis (left) and a CNRM-CM development model version (middle), together with a Taylor diagram (right) illustrating spatial correlations and ratios of standard deviation between the reanalysis and several model versions (colors: blue for CNRM-CM5, red, orange and green for newer versions), state-of-the-art CMIP5 models (cyan), and bootstrapped reanalysis (gray, for statistical significance). *Bottom:* Same for the climatology of the Tibaldi-Molteni blocking index (x-axis: longitude, y-axis: days from January 1st to December 31st). The goal in Taylor diagrams is to get as close as the (1,0) point as possible; to this aim, newer versions of the CNRM-CM model performs better than CNRM-CM5.

2.2 Linkages with the Arctic and other drivers

In this section we present the diagnostics retained for characterizing the main drivers of the mid-latitude dynamics at intra-seasonal, inter-annual and multi-decadal time scales. First, a selection of **Arctic diagnostics** linked to surface processes (e.g. changes in sea ice and/or snow cover) or stratospheric processes (e.g. strength of the polar vortex) is provided in Table 2.

Table 2: Same as Table 1 but for linkages with Arctic (all diagnostics are scalar and computed on a monthly basis) (sic = sea-ice concentration; sit = sea-ice thickness; snc = snow cover; tas = surface air temperature).

Diagnostic	Short description	References	Variables
Arctic Amplification index	Surface or near-surface (850 hPa) warming averaged over 60°N–90°N divided by global mean surface warming	Manzini et al. (2014), Zappa and Shepherd (2017)	ta tas
Arctic sea ice extent + volume	Sea ice fraction summed over the Northern Hemisphere or per Arctic region (Central Arctic, Barents-Kara as the 70°N–82°N/15°E–103°E domain, etc.), possibly multiplied by sea ice thickness (for volume)	Cohen et al. (2014), Oudar et al. (2017) (among many others)	sic sit
Eurasian / Siberian snow cover	Snow fraction summed over Eurasia / Siberia as the 35°N–60°N/40°E–180°E domain	Cohen and Entekhabi (1999), Douville et al. (2017)	snc
Polar vortex strength	Zonal average of the zonal wind at 20 or 50 hPa and between 70°S and 80°N	Hardiman et al. (2012), Karpechko and Manzini (2017), Zappa and Shepherd (2017)	ua

Linkages between the Arctic and the mid-latitudes can then be assessed by investigating relationships between diagnostics of Table 1 and Table 2. Depending on the application, this can be done at several time scales (intra-seasonal to multi-decadal). For example, Figure 2 illustrates how the inter-annual linkage between the NAO and the Barents-Kara sea ice extent has been evaluated in successive versions of the CNRM-CM model: again CNRM-CM6 performs slightly better than CNRM-CM5.

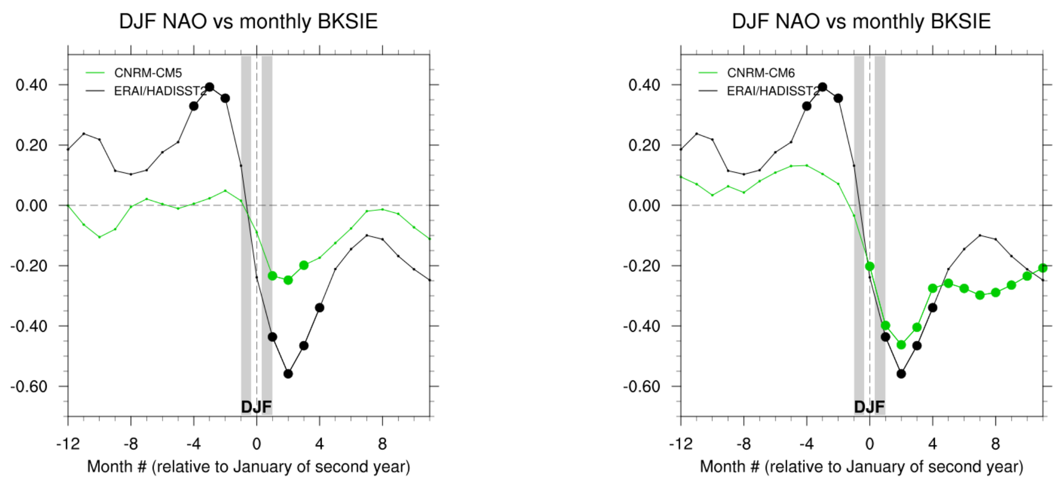

Figure 2: Lead-lag correlation between the winter NAO (SLP station-based index) and the Barents-Kara sea ice extent (sic summed over 70–80 °N and 15–103 °E) in the observations (black) and the model (green), versions CNRM-CM5 (left) and CNRM-CM6 (right). Significant correlations are pointed; positive (negative) values for negative (positive) lags indicate that autumn (spring) sea ice is (anti-)correlated with winter NAO.

The Arctic is not the only region able to affect the mid-latitude atmospheric dynamics. In particular, long-term changes in the tropics are likely to modify the equator-to-pole energy imbalance, and the poleward extension of Hadley cells is likely to affect the position of mid-latitude jets. At shorter time scales, localized sea-surface temperature or precipitation anomalies in the tropics can also generate Rossby waves that propagate through the extra-tropics, impacting the atmospheric circulation. The position of the strong surface oceanic currents, such as the Gulf Stream, also interacts with the atmospheric circulation features. Table 3 provides a selection of diagnostics concerning such **other potential drivers** of the mid-latitude dynamics at inter-annual to centennial time scales.

Table 3: Same as Table 1 but for other potential drivers of mid-latitude dynamics (all diagnostics are scalar and computed on a monthly basis) (pr = precipitation amount; ts = sea-surface temperature).

Diagnostic	Short description	References	Variables
Global mean surface temperature	Global mean surface temperature	-	tas
Tropical high-tropospheric warming	Atmospheric warming averaged at 250 hPa and 30°S–30°N	Manzini et al. (2014) ,Zappa and Shepherd (2017)	ta
Equator-to-pole temperature gradient	Difference or ratio of warming between 30°S–30°N (possibly restricted to high-troposphere, e.g. 250 hPa) and 60°N–90°N (possibly restricted to the surface or 850 hPa)	Cattiaux et al. (2016), Peings et al. (2017), Peings et al. (2018)	ta
Localized tropical SST anomalies	Sea-surface temperature averaged over tropical sub-regions, such as the Niño 3.4 region (5°S–5°N, 170°–120°W)	Cattiaux and Cassou (2013)	ts
Localized tropical precipitation anomalies	Precipitation averaged over tropical sub-basins, e.g. central Pacific (180°–120°W) and western and central Indian (30°–90°E)	Branstator (2002), Molteni et al. (2015), Douville et al. (2018)	pr
Mid-latitude SST gradients	Averaged meridional sea-surface temperature gradient in regions of strong surface currents, e.g. over 80°–30°W, 45°–55°N for the Gulf Stream	Peings et al. (2018)	ts

Hadley cell width index	Distance (in degree-latitude) between the latitudes where the 700–400 hPa average value of the meridional streamfunction first equals zero in each hemisphere (possibly per basin)	Peings et al. (2018)	ua va

Figure 3 illustrates how these diagnostics can be used in order to describe the influence of Arctic vs. other processes in modulating the mid-latitude atmospheric dynamics: in CMIP5 models, projected changes in zonal geopotential index and jet stream amplitude have been found to be highly correlated with the ratio of warming between the tropics and the pole (Peings et al., 2018).

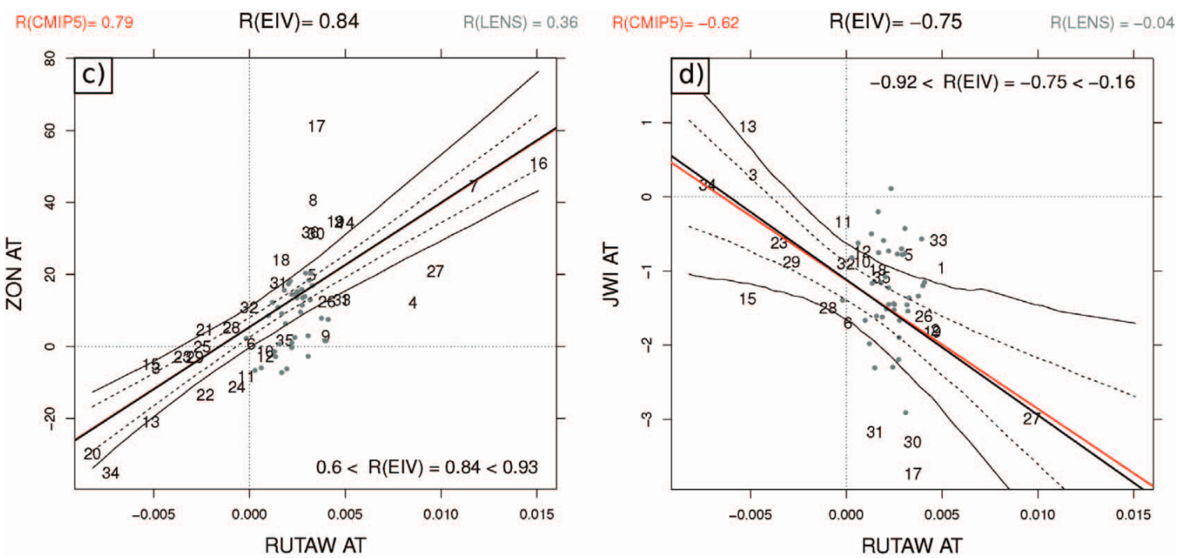

Figure 3: Projected changes in CMIP5 (numbers) and CESM-LENS (grey dots) for zonal index (left) and jet amplitude (right) as functions of projected changes in the ratio of warming between the tropical high-troposphere and the Arctic surface. Details in Peings et al. (2018).

2.3 User-relevant and impacts-oriented diagnostics

In the mid-latitudes, the atmospheric dynamics is the main driver of surface weather. In particular, in winter, situations of sinuous jet stream and/or blocking episodes are associated with cold spells and snowfall episodes that can have strong socio-environmental impacts, especially on the transport and energy sectors. Changes in the atmospheric circulation, associated with the Arctic Amplification or other remote processes, can therefore modify the odds of occurrence of such impacting events.

Many impact- or user-relevant diagnostics already exist in the literature (e.g., Table 1 of Sillmann et al., 2014). In Task 1.2.2 (Deliverable 2.1), a series of user-relevant diagnostics/metrics were developed by APPLICATE partners for use in a range of applications. In Task 1.2.3, a short selection of diagnostics specifically related to Arctic - mid-latitude atmospheric linkages and their influence on winter impacting events has been made and is provided in Table 4. The number of cold days has been used in Peings et al. (2018): one important result is that the projected future decrease in cold spells is modulated by the ratio of warming between the tropical high-troposphere and the Arctic surface.

Table 4: Same as Table 1 but for user-relevant diagnostics, i.e. for assessing impacts of Arctic linkages on surface weather.

Diagnostic	Short description	References	Dim.	Var.	Freq.
Number of cold days	Annual (or seasonal) number of days with mean (or min.) temperature below the 10th percentile of the climatology)	-	lon×lat	tas(min)	day
Number of freezing days	Annual (or seasonal) number of days with mean (or min.) temperature below 0 °C	-	lon×lat	tas(min)	day
Number of snow-covered days	Annual (or seasonal) number of days with snow on ground	-	lon×lat	snc	day

2.4 Software codes and ESMValTool

All the atmospheric diagnostics listed in previous subsections have been coded at CNRM using common languages (R, NCL, CDO) and **can now be shared on demand**. However, they have not been implemented into ESMValTool so far. One reason is that they do not necessarily represent standard or widely used metrics since they involve a number of arbitrary choices: selection of a geographical domain (e.g., a basin, the whole hemisphere), selection of a calendar period (e.g. a month, a season), choice of the variable of interest (sea-level pressure vs. geopotential height), etc. We feel that it might be therefore preferable for a user to adapt our codes rather than use a hard-coded version from a shared tool. Another reason is that some diagnostics are so simple to code (see examples below) that their implementation into such shared tools does not seem to be crucial. Furthermore, it will be critical to thoroughly test diagnostics and metrics before incorporation in ESMValTool. The upcoming analysis in WP1 of CMIP5 and CMIP6 models will provide the basis for identifying selected metrics and diagnostics for incorporation in ESMValTool (Tasks 1.3 and 1.5). Alternatively, some of the code could be shared with the wider community by other means (e.g., GitHub). A thorough discussion of on how to best disseminate linkages metrics and diagnostics will carried out at the upcoming APPLICATE General Assembly, which will be held from 28–30 January 2019.

a) Example of code for the zonal index defined in Table 1 and used in Figure 3:

```
cdo sellevel,50000 <zgfile> tmp
cdo fldmean -sellonlatbox,0,360,20,50 tmp tmpS
cdo fldmean -sellonlatbox,0,360,60,90 tmp tmpN
cdo sub tmpS tmpN <ofile>
rm tmp*
```

where `zgfile` is a monthly file of geopotential height.

b) Example of code for the ratio of warming between the tropical high-troposphere and the Arctic surface defined in Table 3:

```
cdo timmean -selyear,<period1> <tafile> tmp1
cdo timmean -selyear,<period2> <tafile> tmp2
cdo sub tmp2 tmp1 tmp
cdo sellevel,25000 tmp tmpH
cdo sellevel,85000 tmp tmpL
cdo fldmean -sellonlatbox,0,360,-30,30 tmpH tmpHT
cdo fldmean -sellonlatbox,0,360,60,90 tmpL tmpLA
cdo div tmpHT tmpLA <ofile>
rm tmp*
```

where `tafile` is a monthly file of atmospheric temperature and `period1` and `period2` are the time periods chosen to assess changes (typically 1971–2000 and 2071–2100).

3 Oceanic linkages

Section 2 has outlined the work that APPLICATE has done in terms of evaluating atmospheric linkages between the Arctic and the mid-latitudes. In addition to the atmosphere, linkages between the Arctic and the mid-latitudes may be mediated by ocean. In a similar manner to the atmosphere, large-scale ocean dynamics are primarily driven by the energy imbalance between equatorial and polar regions. Therefore, assessing how energy is transported into and out of the Arctic Ocean through the major Arctic Gateways (Davies Straits, Fram Strait, Barents Sea Opening, Berings Straits) is essential to understanding potential Arctic to mid-latitude oceanic linkages.

However, substantially less research has been performed in understanding ocean linkages than for the atmosphere. In particular, less data/variables are available, either in observations, reanalyses or in model outputs. The work performed for oceanic linkages in APPLICATE and reported in this section is therefore more exploratory in nature in comparison to the work performed in Section 2.

The following paragraphs report the progress that has been made by the different partners involved in this task.

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At **AWI**, a series of diagnostics have been developed that quantify fluxes of volume, heat, freshwater (solid and liquid). These were augmented by diagnostics addressing ocean deep convection and the strength of the Atlantic meridional overturning circulation (AMOC). These diagnostics have been applied to various control and climate change simulations carried out with the AWI climate model, using the HiResMIP protocol (Sein et al., 2018). Experiments include configurations with low and high resolutions, both in the atmosphere and ocean, as well as mixed-configurations in which resolution is increased in either the atmosphere or ocean, while keep coarse resolution in the respective other component. In general, a surprisingly strong sensitivity of the simulated fluxes to horizontal resolution has been found for different Arctic gateways. This is illustrated in Figure 4 for Fram Strait.

Further plans include applying the new diagnostics to the APPLICATE simulations in WP2 and WP5, thereby also linking the time series to two-dimensional fields, allowing for time lags. Furthermore, a critical assessment will be needed to establish whether/how to incorporate the diagnostics into ESMValTool, given that model data on native meshes, that are needed to thoroughly compute flux time series, are not readily available from CMIP data archives.

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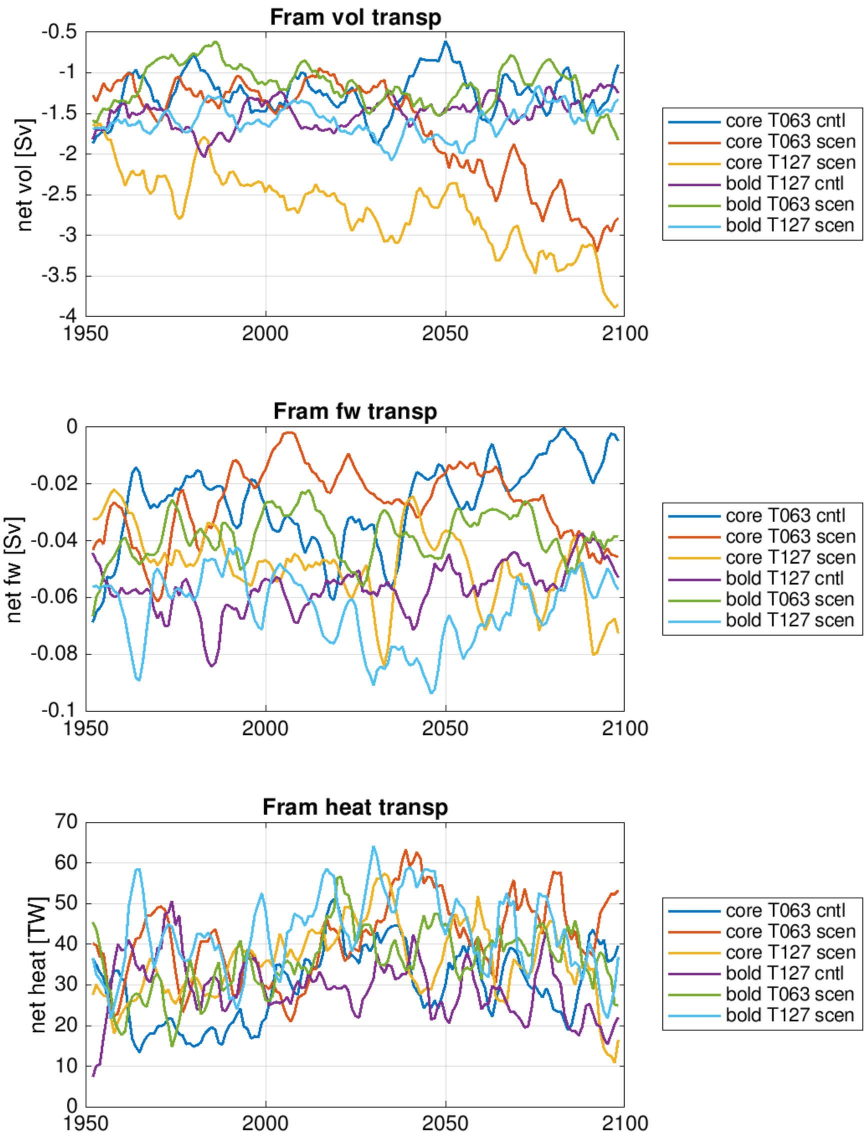

Figure 4: Annual mean transports of volume (Sv), freshwater (Sv) and heat (TW) through Fram Strait for control simulations and climate change scenarios (RCP8.5) with the AWI climate model at low and high resolution, as well as for mixed-resolution experiments. The high-resolution (low-resolution) atmosphere is indicate by T127 (T63) and the high-resolution (low-resolution) ocean by bold (core). Data have been smoothed with a five-year running mean filter.

At **CERFACS**, a series of metrics have been defined focused on water masses, circulation features and fluxes into and out of the Arctic Ocean. A simplified view of these fluxes is provided in Figure 5.

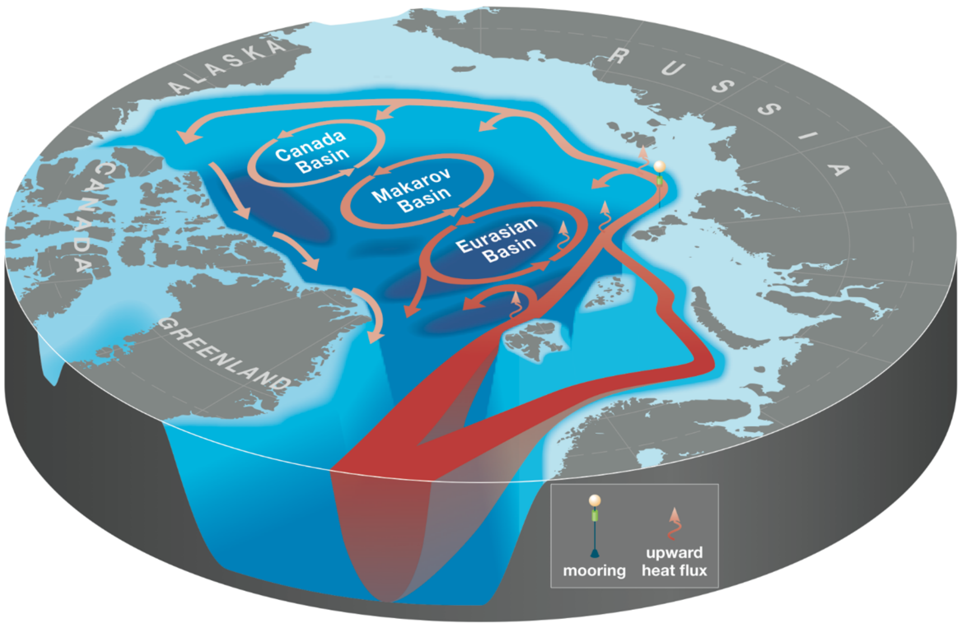

Figure 5: Schematical view of various fluxes involved in oceanic Arctic - mid-latitude linkages. Reproduced from Polyakov et al. (2010).

In order to quantify the oceanic linkages between the North Atlantic ocean and the Arctic, the volume transports as well as the transports of heat and freshwater through Arctic major gateways have been evaluated in a preindustrial control and in historical simulations done with the CNRM-CM6 model. This analysis will be expanded to a larger set of models that contribute to APPLICATE, e.g. in Task 1.3. We will compare the models results among them and to available estimates from observations. Most of the models based on the NEMO oceanic code have these transports computed online and therefore the comparison of the outputs between the models based on NEMO should be relatively straightforward, either through ESMValTool or through other available mapping software.

Other ways to quantify the changes of water masses as they enter the Arctic is to look at vertical sections and profiles of temperature and salinity in specific basins of the Arctic like the Eurasian Basin or the Canadian Basin, as done by Ilicak et al. (2016). This allows to analyze the path of the warm flow coming from the Atlantic (Polyakov et al., 2010). Models usually have large biases in the simulated properties of Atlantic water, which is mixed too fast as it enters the Arctic (Jahn et al., 2012; Koenigk and Brodeau, 2014). This analysis has been performed on a preliminary set of simulations based on the CNRM-CM6 model and have not compared yet the results to the other APPLICATE models. Future analysis will allow to determine whether the model developments made in APPLICATE improve such biases and hence the oceanic linkages.

In order the characterize the possible impacts of changes in these oceanic transports on sea ice, we have defined a diagnostic based on the correlation between these transports and sea ice area and volume for the different basins of the Arctic that can be applied to all models once these quantities are derived.

In addition a diagnostic has been defined to characterize the influence of Arctic freshwater export on the mid-latitude oceanic circulation that is simply the correlation between indices of freshwater transports through major gateways and the AMOC at different latitudes.

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At **UCL**, a diagnostic has been developed to quantify the linkages between Arctic sea ice area/volume (ASIA/ASIV) and poleward Atlantic Ocean heat transport (AOHT) computed at 3 different latitudes (50, 60 and 70 °N). This diagnostic is simply the regression slope between both quantities. Across the PRIMAVERA Stream 1 models that were analyzed, regression slopes were found that they were overall negative, meaning that ASIA and ASIV decrease with increasing AOHT. Furthermore, the higher the latitude that AOHT was computed, the stronger the anti-correlation between ASIA/ASIV and AOHT. The specific Arctic regions that are more directly influenced by Atlantic OHT are in the Atlantic sector of the Arctic Ocean, i.e. Barents/Kara Seas and GIN Seas, which first receive the warm Atlantic water inflow. No clear impact of resolution on the strength of these relationships was found. The paper is nearly submitted (Docquier et al., in prep.) and the plan is to incorporate the diagnostic into ESMValTool.

Further plans include the development of diagnostics for assessing:

- sea-ice volumetric export at Fram Strait;
- strength of the Atlantic Meridional Overturning Circulation (AMOC);
- poleward oceanic heat transport per latitude (integrated over longitudes in the Atlantic basin and over vertical levels).

4 Conclusions and outlook

At this stage, the main outcomes / conclusions of Task 1.2.3 are:

- existing diagnostics for atmospheric and oceanic Arctic - mid-latitude linkages have been reviewed from the literature, and a selection has been made;
- a few novel diagnostics have been developed, either for atmospheric linkages (Peings et al., 2018) or for oceanic linkages (Docquier et al., in prep.);
- work is still in progress, especially for oceanic linkages for which relevant variables are not systematically available (the upcoming release of CMIP6 / PAMIP simulations will help);
- most diagnostics can easily be turned into metrics when reference products are available, and are already used by APPLICATE partners for the evaluation of their climate model (e.g., Voldoire et al., in prep.);
- most diagnostics have been coded in common programming languages and can be easily shared on demand;
- most diagnostics have not been implemented in ESMValTool yet.

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Next steps include:

- continue to develop/collect diagnostics, especially for oceanic linkages and/or the users community;
- further evaluate climate models, including multi-model ensembles from the upcoming CMIP6 (Task 1.3) and PAMIP (WP3) experiments;
- investigate how these diagnostics/metrics can be used as emergent constraints to reduce future uncertainties in climate projections (Task 1.5);
- implement selected diagnostics into ESMValTool and/or think about alternative and more efficient ways to share codes.

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