BLUE ACTION

Identification of key processes in bridging the Arctic warming impact and its variation on decadal timescale

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Summary for publication

Observational analysis of the Arctic warming impacts: The key driver bridging the winter Arctic warming (1980 to 2014) impact to the Northern Hemisphere has been identified, my means of an advanced multi-variable statistical analysis, to be a tropospheric pathway, linking interannual variability in Arctic warming to the Northern Hemisphere lower atmosphere variability with one month lag. Clearly, the analysis has shown, that the response to the pan-Arctic sea-ice changes does not involve the stratosphere. A covariation of sea-ice variability with Siberian snow cover may be responsible of previously proposed pathways of influences involving the stratosphere. In addition, the analysis suggests that the mechanism of the tropospheric pathway may include the intensification of the Ural anticyclone.

Coordinated experiments on Arctic warming impact and its variation on decadal timescale:
Warm Arctic Cold Eurasia in winter surface air temperature. Making use of the ensembles of atmospheric model experiment with and without Arctic sea ice forcing it has emerged that the large scale pattern of winter surface air temperature variability is an internal mode of atmospheric variability. At shorter time scales (interannual) the project models capture this internal mode of atmospheric variability. At longer time scales (multi-annual, decadal), however, the models fail to capture the variability/trend of the winter surface air temperature (over 1980-2014).

Arctic sea-ice driven variability. Within the Arctic Circle, the sea-ice driven variability explains about 3% of the total variance for sea level pressure and about 23% for surface air temperature in boreal winter at interannual and longer time scales. Regionally, the sea-ice driven variability is 1-1.5 times as large as the variability driven by the other forcings over the Arctic and northern Eurasia.

Contrasting Summer and Winter Impact of Arctic sea-ice loss. Large scale features of atmospheric circulation trends over the period 1980-2014 are not reproduced by models, both in winter and summer. While in winter internal atmospheric variability likely plays a role, the difference in summers may point to structural model deficiencies.

Multidecadal variability in sea surface temperatures and Arctic warming. The role of variations of the Pacific Ocean surface temperatures on Arctic warming and its impacts many be hard to be identified, given that preliminary results suggest sensitivity to structural model differences.

Work carried out

Observational analysis of the Arctic warming impacts (Lead: CNRS)
The key driver bridging the Arctic warming impact to the Northern Hemisphere have been analyzed in observation (Simon et al. submitted), using sea ice concentration (SIC) from the National Snow and Ice Data Center (NSIDC) from January 1979 to February 2017 (Cavalieri et al. 2003), atmospheric fields from ERA-Interim (Dee et al. 2011) and continental snow cover from NOAA/Rutgers University Global Snow Laboratory (Robinson et al. 2012). The analysis has been carried out by means of an empirical orthogonal function analysis of the sea ice concentration using separate calendar months. The main results achieved so far and the progress beyond the state of the art is reported in the following sections.

Coordinated experiments on Arctic warming impact and its variation on decadal timescale (Partners: WHOI, NCAR, CNRS, NERSC, DMI, CMCC, MPI, UoS, IAP-NZC, NLeSC)

In collaboration with D3.1 "Identification of the surface state influence in representing the Arctic warming by coordinated atmosphere-only simulations" a set of coordinated experiments have been carried out by 9 participating modelling groups (Table 1). The set of coordinated experiments aims to isolate the impacts of sea ice interannual and longer time scale variability and of Atlantic and Pacific Ocean decadal variability on the Northern midlatitudes weather and climate. The experiments have been performed with atmosphere general circulation models forced by prescribed sea surface temperatures (SSTs) and sea ice concentrations (SICs). Specifically, we used global daily ¼ degree SSTs and SICs for the 1979-2014 period from the U.K. Met Office Hadley Centre (updated from Rayner et al. 2003). This dataset was developed in the framework of the HighResMIP panel of Coupled Model Intercomparison Project phase 6 protocol (CMIP6, Haarsma et al. 2016).

The following four sensitivity experiments have been designed and carried out:

- Experiment 1 (EXP1): Daily varying SSTs and SICs from 1979-2014
- Experiment 2 (EXP2): Daily varying SSTs (1979-2014) and annually repeating daily Arctic climatological SICs. The Arctic (or Northern hemisphere) SIC climatology is constructed from the 1979-2014 period.
- Experiment 3 (EXP3): Daily varying SSTs and SICs, but with the low frequency component of the SST variability related to the Interdecadal Pacific Variation (IPV) signal removed from the daily SST field over the Pacific Ocean.
- Experiment 4 (EXP4): Daily varying SSTs and SICs, but with the low frequency component of the SST variability related to the Atlantic Multi-Decadal Variation (AMV) signal removed from the daily SST field over the Atlantic Ocean.

The methods used to remove the Pacific or Atlantic low frequency component of the SST variability is described in Deliverable D3.1 and in the last project report.

Analysis of experiments (WHOI-NCAR, CNRS, NERSC, DMI, CMCC, MPI, UoS, IAP-NZC, NLeSC)

The analysis of the experiments makes use of statistical methods tailored to extract the key processes in bridging the Arctic warming impact and its variation on decadal timescale to the Northern hemisphere circulation, and it is in progress. Hereafter we report the main results achieved so far and the progress beyond the state of the art.

Table 1. Models and institutions providing coordinated experiments. *Number of members in EXP1 and EXP2 given, and number of members in EXP3 and EXP4, if different.

Models	CESM2-WACCM6	LMDZOR6	NorESM2-CAM6	EC-Earth3	CMCC-CM2-HR4	ECHAM6.3	HadGEM3	IAP-AGCM	EC-Earth3
Institution	WHOI-NCAR	CNRS	NERSC	DMI	CMCC	MPI	UoS	IAP-NZC	NLeSC

Horizontal resolution (km)	~100	~150	~100	~80	~100	~100	~60	~100	~40
Ensemble members	30	30/20	20	20	10	10	10	15	10/1
Reference	Gettelman et al. (2019)	Hourdin et al. (2019)	Bentsen et al. (2013)	Döscher et al. (2019)	Cherchi et al. (2019)	Müller et al. (2018)	Walters et al. (2017)		Döscher et al. (2019)

Main results achieved

1. Observational analysis of the Arctic warming impacts (Lead: CNRS)

The first EOF captures the long-term decrease of the sea-ice extent, as shown by Fig. 1.1 (in the November case). On top of the long term trend, there are interannual fluctuations. In order to characterize the short-term response of the climate to a warming Arctic, we investigate the links between the observed climate and these interannual SIC variations. We consider the atmospheric variations lagging these fluctuations by one to three month. This short-term response excludes the potential role of ocean-atmosphere feedbacks (Deser et al. 2015). In the following, the detrended first principal component, called dPC1, is used as an index of the sea ice.

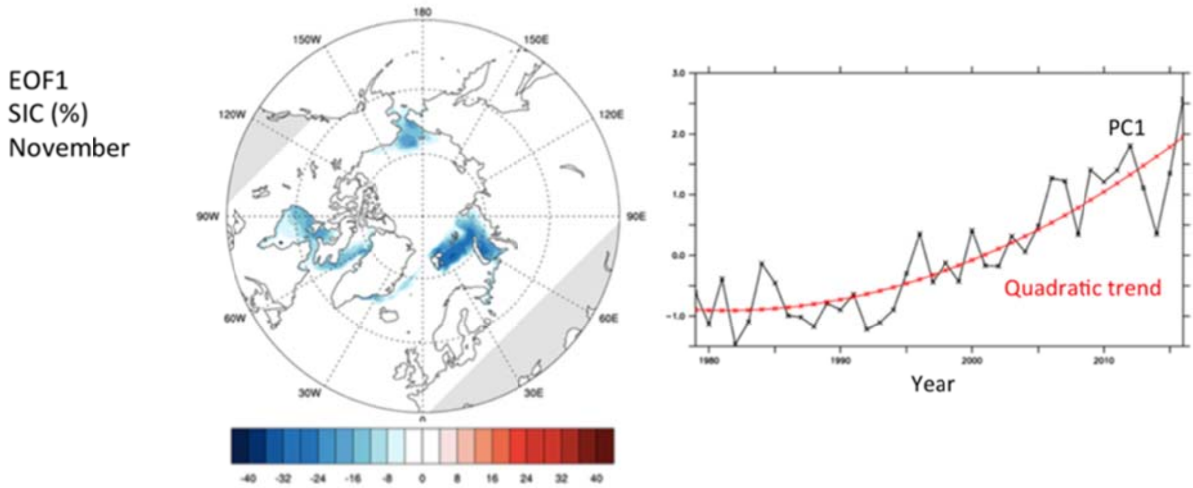

Fig. 1.1 *First EOF (left, color, in %) and associated normalized PC (right, black line) for the November sea ice concentration. The red line on the right panel shows the quadratic trend of the PC1.*

To investigate the causality between the SIC fluctuations and the atmosphere, we have considered other potential simultaneous forcings that may contribute to or explain the observed correlations (Kretschmer et al. 2016). The regression analysis performed has indicated if there were synchronous SST and snow cover anomalies. The level of field significance is established with the false discovery rate (FDR, Wilks 2016). We found that, over the observational period, negative / positive SST anomalies in the Equatorial Pacific / North Atlantic ocean are concomitant with the interannual pan-Arctic November SIC fluctuations. Similarly, positive snow cover anomalies are found over eastern Siberia in November (not shown). To separate the effect of the sea ice from that of other forcings, we use a multivariate regression on dPC1, together with snow cover and SST indices corresponding to regions with the largest simultaneous anomalies. An index of the quasi-biennial oscillation was also considered. We verified that the variance inflation factors remain moderate (variance inflation factor below 2) so that the multicollinearity is limited. The results show that November sea ice (dPC1) has no field significant tropospheric impact in the North Atlantic sector, even if there is a locally significant negative NAO-like pattern (Fig. 1.2, upper-right). On the other hand, the snow cover seems to have a strong impact on the stratosphere in December, as illustrated by the field significance in Fig. 1.2 (middle), and a tropospheric impact over the Arctic, North America, and Europe in January. The sign of the relationship, positive over the Arctic in the stratosphere and troposphere, and the time lag support a stratospheric pathway of influence. The Pacific SST anomalies have impacts instead largely limited to the North Pacific (troposphere), without stratospheric impacts.

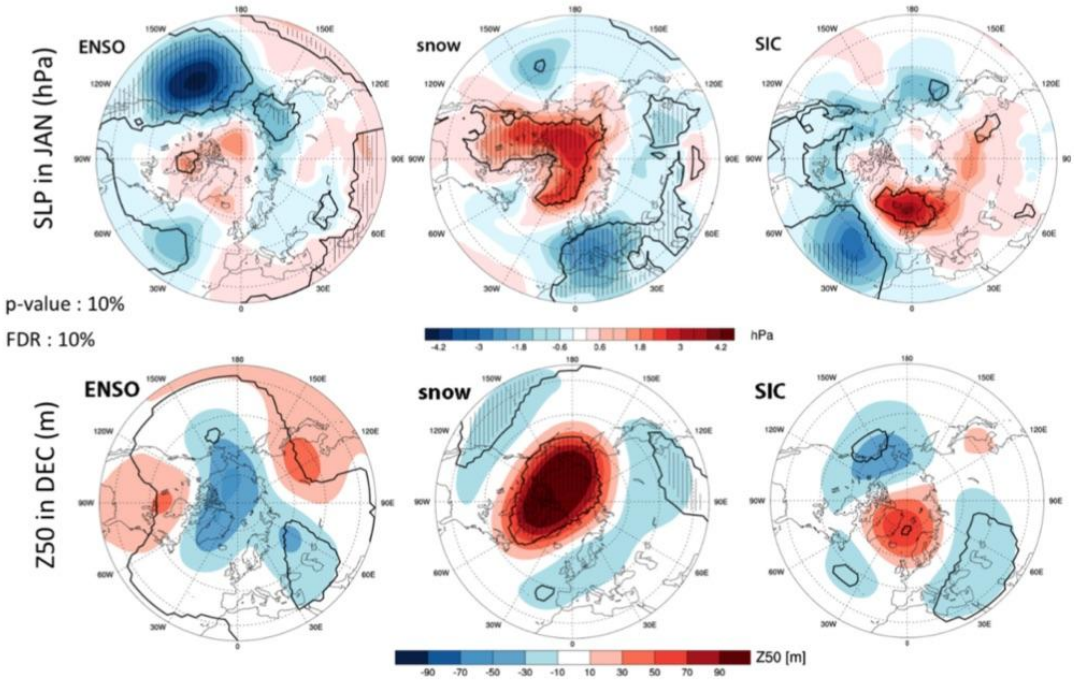

Fig. 1.2 Regression slopes of the January (top) SLP and (bottom) 50-hPa geopotential height of the multivariate regression onto the November (left) Equatorial Pacific SST (center) snow cover and (right) dPC1. The contours indicate 10% significance and hatching FDR significance at the 10% level.

We repeated the same analysis with the December, January and February sea ice (dPC1), using different SST and snow cover indices based on associated regression maps. The results always find a more robust sea ice signature when using multivariate regression, with a January negative NAO-like pattern associated with sea ice retreat in December (Fig. 1.3, left). A similar result is found for February SLP (not shown). Consistent with the negative NAO-like response to sea-ice reduction, we also found a southward shift of the low-level jet at 700-hPa and more frequent blocking over Greenland and the Nordic Sea (not shown). We did not find any robust signal in the stratosphere so that the response to the pan-Arctic sea-ice changes is consistent with a tropospheric pathway. We also noted that the response in February to a sea-ice retreat in January (Fig. 1.3) is an intensification of the Ural anticyclone as identified by Mori et al. (2014) as the main driver of the warm Arctic cold continent pattern. However, this response appears less robust, and a negative NAO-like response appears in March (Fig. 1.3, right).

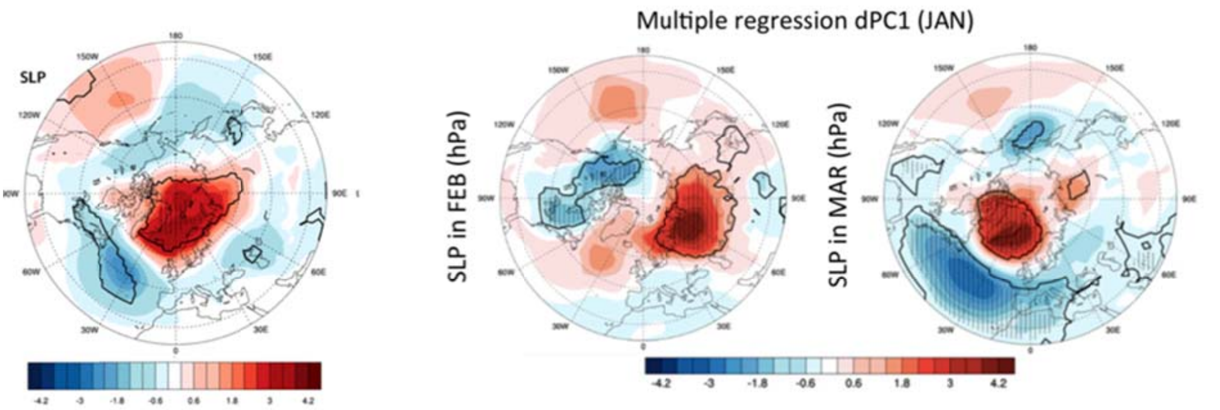

Fig. 1.3 *Regression slopes associated with the sea-ice from the multivariate regression of the SLP: in January when using December dPC1 (left), in February (middle) and March (right) when using the January dPC1. The contours indicate 10% significance and hatching FDR significance at the 10% level.*

2. Coordinated experiments on Arctic warming impact and its variation on decadal timescale (Partners: WHOI, NCAR, CNRS, NERSC, DMI, CMCC, MPI, UoS, IAP-NZC, NLeSC)

2.1. Warm Arctic Cold Eurasia in winter surface air temperature: driven by Barents Sea Ice loss or internal atmospheric variability? (Lead: MPI-M)

The Warm Arctic Cold Eurasia (WACE) pattern in the winter (DJF) surface air temperature (SAT) trend is one of the most debated topics in the last decade. Extensive analysis of observations and from climate models have led to differing conclusions about the role of the Arctic sea ice (SIC) for the cooling of Eurasia. The observed study mainly suggests a role of Arctic SIC (e.g., Mori et al. 2014), whereas research with climate models claims it to be due to the internal atmospheric variability (e.g., McCusker et al. 2016). Here, we use the coordinated experiments and ERA-interim reanalysis to investigate if there is any fundamental underlying dynamical difference between the model response to the Arctic SIC and observations. For this purpose, we first identify the region (74N-80N, 20E-68E), that has seen the highest winter Arctic SIC loss in the last decades, which is confined over the Barents Sea (Fig. 2.1.1a). The SAT over this region has a close association with the SIC changes (Mori et al. 2014). Hence, we use the SAT over the Barents Sea as our index to understand the associated response over the Northern Hemisphere (NH) SAT, in reanalysis and model outputs. Our analysis first focuses on reanalysis and the 10-member ensemble of the ECHAM6.3 and then it is extended to include the results from 8 models (Table 1). We construct the Barents Sea SAT index for each ensemble members of EXP1 and EXP2, to evaluate the associated SAT response in the model experiments with and without observed SIC variations over the Arctic (Fig 2.1.1c, d).

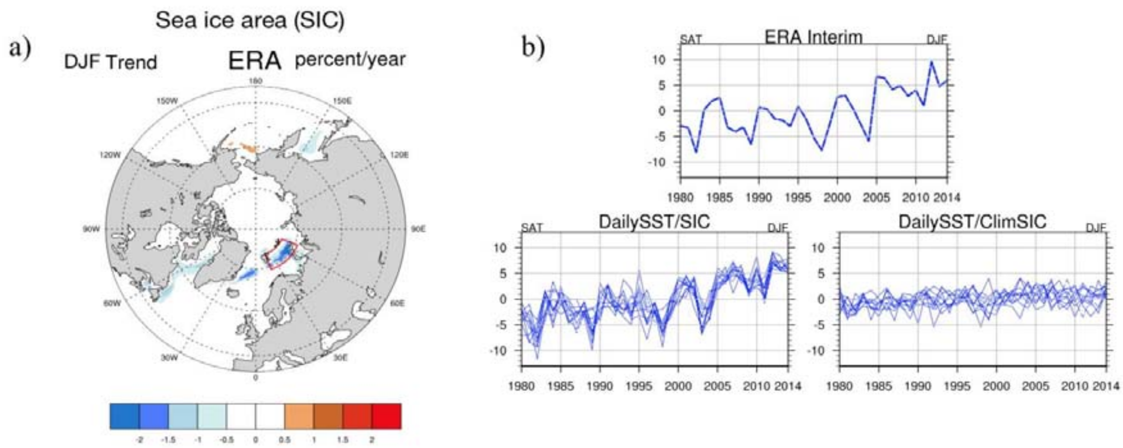

Fig. 2.1.1 *a) The winter (DJF) mean sea ice area (SIC) trend in percent/year over the Northern Hemisphere in ERA-Interim reanalysis for the period 1980 to 2013. b) The time series of area averaged 2-meter air temperature (SAT) anomaly over the red box in figure a), which is showing the highest negative trend in the Barents Sea for the period 1980 to 2013 (top), the same time series of SAT anomalies but for the 10 ensemble members of the ECHAM6.3 in EXP1 (bottom left) and for the EXP2 (bottom right). All units for the SAT anomalies are in Kelvin (K).*

The full-field regression of the SAT on the Barents Sea SAT index in the reanalysis shows the WACE (Fig. 2.1.2a). The warmer Arctic condition is centered over the Barents-Kara Sea region, while the colder Eurasia is centered around the central-to-eastern Eurasia. The full field regression of EXP1 (with daily varying SST and SIC) does not show a similarly strong cooling pattern over Eurasia in association with the warming over Arctic (Fig 2.1.2b). Whereas in the EXP2 (Fig 2.1.2c), with the daily climatological SIC, we find a clearly prominent WACE, similar to reanalysis. This finding implies that the observed WACE also exists in the model. Though under the forcing of observed daily SIC variations, this WACE association weakens in the model. The regression analysis with the detrended (quadratic) field of SAT on the detrended Barents Sea SAT index reveals a similar warm anomaly of the WACE pattern over the Arctic in reanalysis as seen with the full-field (Fig 2.1.2d). However, the center of the negative anomalies over Eurasia shifts eastward with more prominent anomalies over eastern Eurasia. Interestingly, the regression analysis of the detrended fields for the EXP1 reveals a prominent WACE pattern (Fig 2.1.2e). In association to a warm Arctic, it shows negative anomalies encompassing central to eastern Eurasia. This finding indicates that the WACE pattern also exists in the EXP1 under the forcing of observed SIC variations. Therefore, it is the trend related part of the variations which weakens in the model. Consistently with the experimental design, the changes over Eurasia from full-field to detrended are much more striking for the EXP1 than EXP2 (Fig 2.1.2b,c,e,f). Indeed, the presence of WACE in EXP2 shows that the WACE is not dependent on either the inter-annual variation or the trend of the Arctic SIC, suggesting that it is a feature of atmospheric internal variability, possibly associated with Ural blocking. However, the detrended field EXP1 also shows a WACE (Fig 2.1.2e), indicating that the observed interannual SIC variation might have an association with the Eurasian SAT. There is therefore a possibility for the coupling of the WACE internal mode of variability with the interannually varying Barents SIC forced SAT.

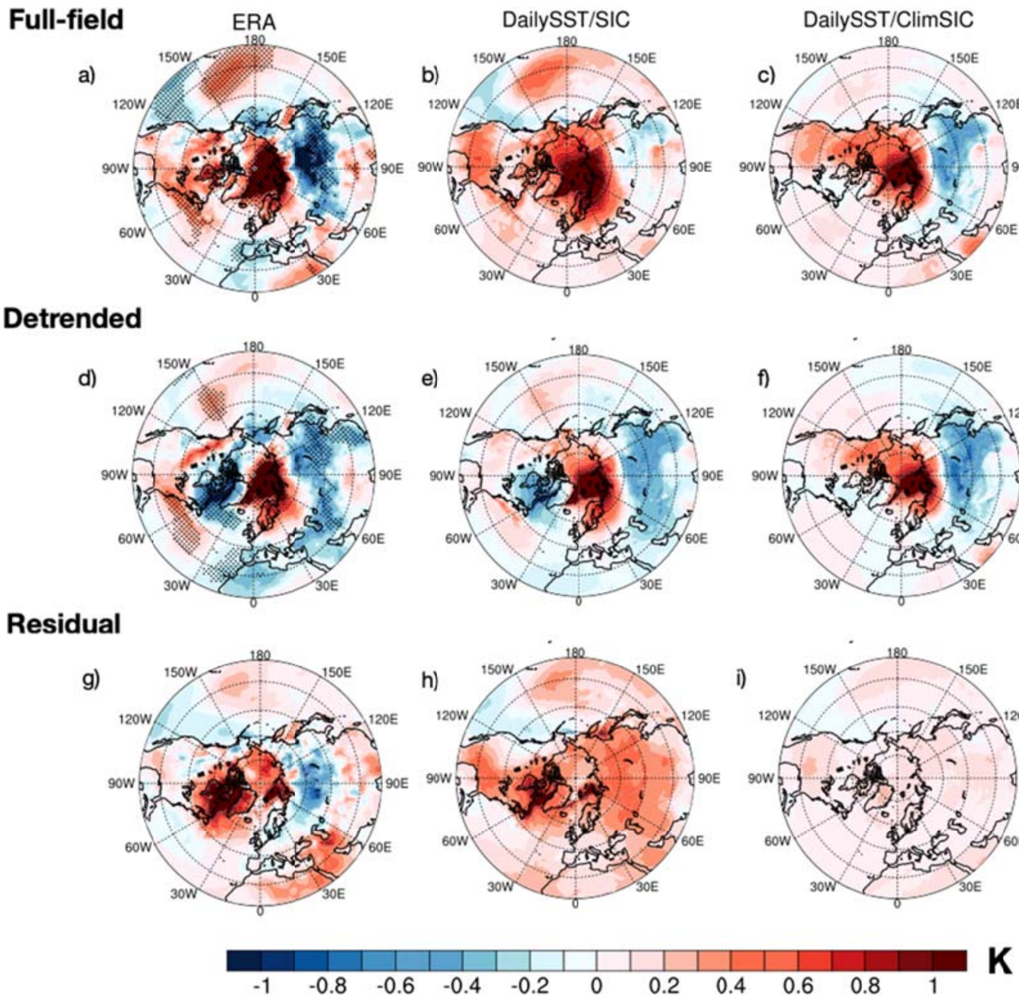

Fig. 2.1.2 *a) Reanalysis, NH SAT change for 1 standard deviation change in the Barents Sea SAT index. b) the same as in a) but EXP1 ensemble mean, ECHAM6.3 model. c) the same as in b) but EXP2 ensemble mean. d) Reanalysis, detrended (quadratic) NH SAT change for 1 standard deviation change in the detrended (quadratic) Barents Sea SAT index. e) the same as in d) but EXP1 ensemble mean. f) the same as in e) but EXP2 ensemble mean. g) Reanalysis, residual: (a)-(d) difference. h) EXP1 residual: (b)-(e). i) EXP2 residual (c)-(f). All units are in Kelvin. Stippling in figure a) and c) represents the regions significant at p> 0.05.*

The residual of the full-field regression still shows a cooling over Eurasia (albeit of smaller amplitude) in the reanalysis (Fig. 2.1.2g). In the EXP1 and EXP2, the residual or the trend pattern does not bring any cold anomalies over Eurasia (Fig 2.1.2h,i). Instead both the experiments show warm anomalies though out the Eurasian continent. The warm anomalies are larger in magnitude in EXP1 than in EXP2, as it can be expected because of the Arctic warming trend in EXP1. In EXP2, the warm anomalies mainly depict the effect of radiative forcing and SST trends. In EXP1, in addition there is the warming from the long-term trend in SIC. The question is therefore, why are the observed and simulated SAT trends different over Eurasia? To answer this question, we perform the EOF analysis of the SAT over Eurasia to compare the nature of variations of SAT in the model with the observations (Fig.2.1.3).

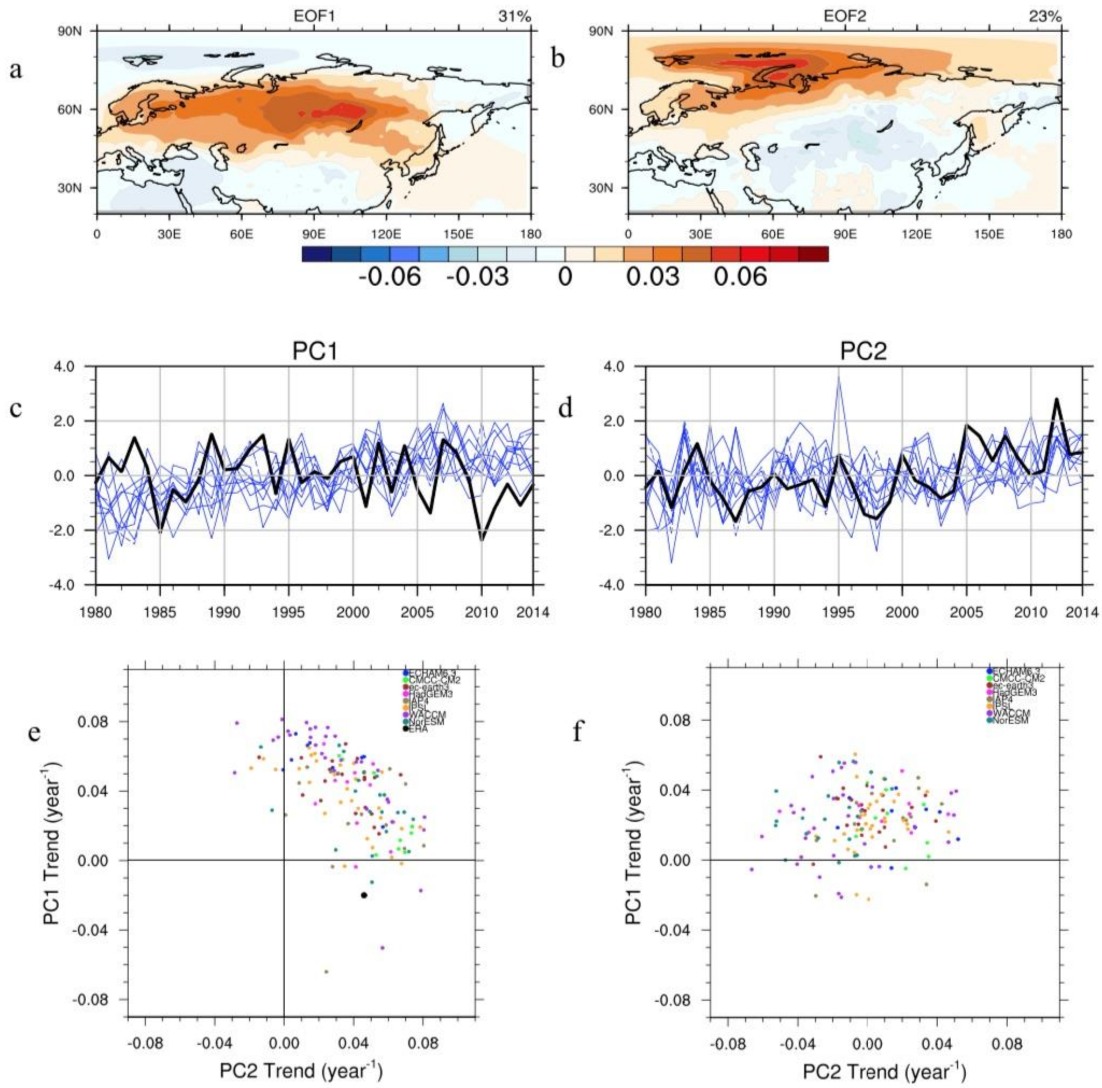

Fig. 2.1.3 *a) The EOF1 and b) EOF2 patterns of the winter SAT in the ERA-Interim reanalysis over the Eurasian region (20-90N, 0-180E) for the observed period of 1980 to 2014. c) The associated normalized PC1 (in black) and the blue time series are also the same but for the 10 ensemble members of the EXP1 with observed daily SIC and SST boundary forcing. d) the same as in a) but for the PC2. e) Scatter plot of the normalized PC1 and PC2 trends of Eurasian SAT (in year-1) in EXP1 for the 8 models participated in coordinated experiments (in colored dots) and in the ERA (black dot) and f) the same as in c) but for the EXP2 with climatological daily SST/SIC forcing.*

The first mode of SAT variations in the reanalysis shows continent wide warming pattern, which has its center at the middle of Eurasia, where we find the cooling trend of the Eurasian continent (Fig 2.1.3a, Fig. 2.1.2g). This mode of variations is suggested to be related to the Arctic Oscillation (Mori et al. 2014). The second mode of variations is the WACE mode, which has its Warm center over the Barents Kara Sea and cold center over the central to eastern Eurasia (Fig. 2.1.3b). Interestingly, the region of cooling trend in the reanalysis is influenced by both modes and hence the trend over this region is determined by the combination of the evolution of both modes. However, PC1 in the reanalysis does not yet show any long-term trend (black line in Fig. 2.1.3c), but its negative phase at the end of the time period may play a major role to bring an enhanced cooling trend. Therefore, a part of the observed cooling is influenced by the internal variability of the PC1 which does not show any long-term trend and also no association with the Barents SIC variations. The long-term changes in the SIC gets associated with the PC2, which shows a positive trend with correlation of 0.91 with the SIC variations (black line Fig. 2.1.3d), which means it is bringing more cooling over the central-to-eastern Eurasia with the warming Arctic. Compared to the reanalysis, the model simulated PC1 shows a clear positive trend in EXP1 (blue lines in Fig. 2.1.3c). A positive trend in the first mode of SAT variations, whose positive phase leads to a continent-wide warming, would naturally lead to an overall warming trend. The second mode of variations also shows an upward trend (blue lines in Fig. 2.1.3d). By extending the analysis to the project models (Table 1) and in so doing extending the ensemble size to 145 members, we find a general positive trend in both PC1 and PC2 for EXP1 (Fig. 2.1.3e). The trends in the PC1 and PC2 seems to be have a complimentary relation where if one trend increases the other decreases. The observed trend (black dot in Fig. 2.1.3e) lies at the side of a significant positive trend in PC2 with no significant trend in PC1 (though not significant, a negative trend is present in the observed PC1 due to the intense negative phase at the end of the time period). The trend of the PCs in the EXP2 reveals the role of SIC in driving a positive trend in PC2. Without SIC forcing (EXP2), there is no negative PC2 trend emerging from the ensemble, while. PC1 mostly shows positive trends, though very few are significant (Fig. 2.1.3f). However, it seems SIC forcing also affect the trend in the PC1, given its slight increase (compare Fig. 2.1.3e and 2.1.3f).

2.2. Relative variance of the Arctic sea ice-driven component in the winter atmospheric variability (Lead: WHOI and NCAR)

The relative variance of the Arctic sea-ice driven component in the winter (December-January-February, DJF) atmospheric circulation variability is determined using EXP1 and EXP2 outputs from the simulations carried out by WHOI, NCAR, CNRS, NERSC, DMI, CMCC, MPI, and UoS (first seven partners in Table 1), totaling to an ensemble size of 130 members. The total variance is decomposed into: (1) the variance of the internal atmospheric variability, (2) the variance of the variability driven by specified historical SST and greenhouse gases (GHG) variations, (3) the variance of the variability driven by specified historical sea-ice concentration variations, (4) the covariance between the sea ice-driven and SST-GHG driven components, and (5) residual. This decomposition works very well, i.e. the residual is negligible (e.g., Fig. 2.2.1f), as expected mathematically. The internal atmospheric variability in sea-level pressure (SLP) dominates the total variance (Fig. 2.2.1b). However, the sea ice-driven variability in SLP is 1-1.5 times as large as the variability driven by other forcings over the Arctic and northern Eurasia (Fig. 2.2.1k). In particular, the sea ice-driven component explains ~3% of the total variance of the SLP and ~23% of near-surface air temperature locally averaged in the Arctic Circle (>65°N) (Fig. 2.2.2).

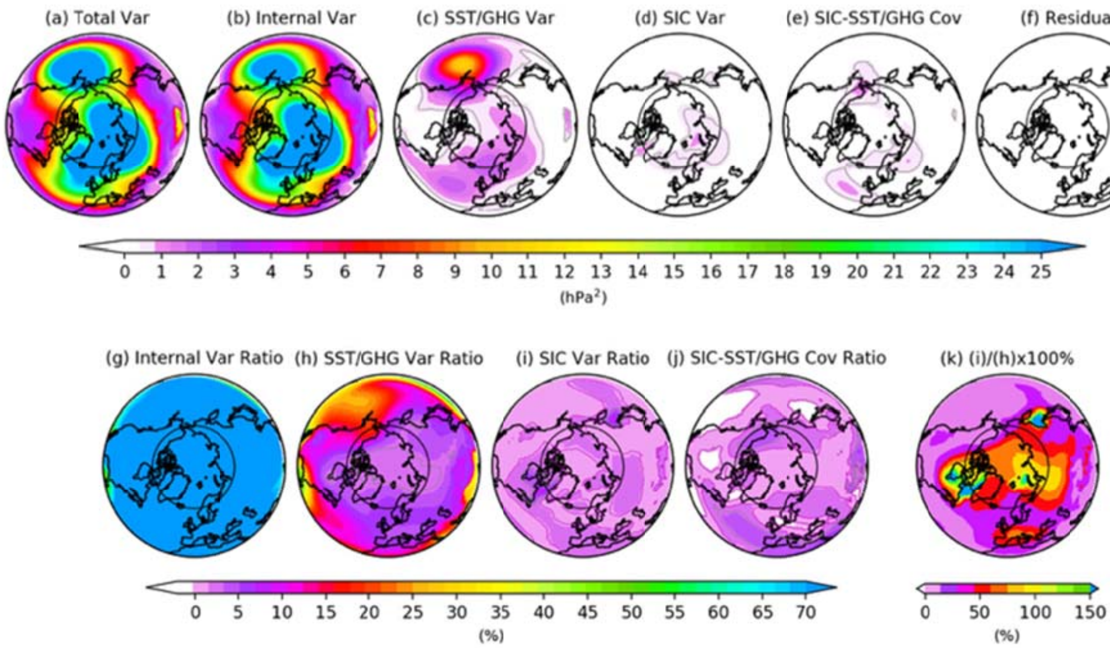

Fig.2.2.1 *(a-f) DJF SLP variance decomposition for seven models with 130-member ensembles. Unit is hPa^2. (g-j) The ratios of each component to total variance. (k) is the ratio between SIC-driven and SST/GHG-driven components, i.e., (d) divided by (c) in percentage.*

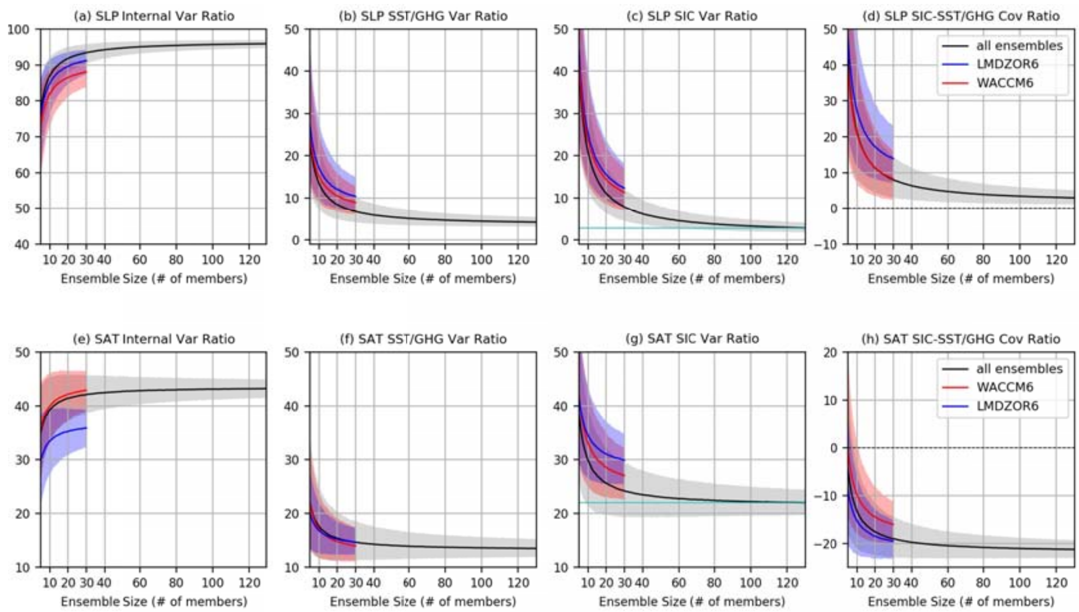

Fig.2.2.2 *Ensemble size dependence of the Arctic Circle-averaged (65°N-90°N) DJF (top) SLP and (bottom) near-surface air temperature variance decomposition. Each ensemble size is randomly sampled 10,000 times and the 95-percentile range is shown by the color shadings. The black is based on all models with 130 ensembles, the blue is based on the CESM2-WACCM6 and the purple is for the LMDZOR6 30-member ensembles. The solid cyan lines in (c) and (g) denote the mean ratio values with 130 members to inform potential convergence.*

The spatial patterns of the sea ice-driven winter SLP variance are consistent across the seven models with enhanced variance over the Barents-Kara Seas, and near the Icelandic and Aleutian Lows (not shown). However, the amplitude varies among the models with ~6% of the total variance for the models with 30 members to ~12% for the one with only 10 members. Comparison between the variability driven by sea ice and other forcings shows that similar amount of explained variance are found in the Eurasia and high latitudes. To further quantify the dependence on the ensemble size, all models with the ensemble size of 130 are used to randomly subsample the ensemble members for the different ensemble size (Fig. 2.2.2). The results show that at least 100 members are needed to reliably sample different component of the averaged SLP variability within the Arctic Circle, while more than 50-80 members are required for the surface air temperature.

2.3. Contrasting Summer and Winter Impact of Arctic sea-ice loss in the Northern Hemisphere (Lead: CMCC)

The response of the large-scale Northern Hemisphere atmospheric circulation to Arctic sea-ice loss is hard to unravel because of its inherent non-linearity (Overland et al 2016), model dependencies (Screen et al 2013) and low detectability within the internal variability (Screen et al 2014). The ocean-atmosphere coupling has been found important for the simulation of the response to sea-ice (Deser et al 2016) but the climatological background state could be crucial as well (Screen and Francis 2016). A recognized conclusion seems that a reduction in Arctic sea-ice tends to favor a negative phase of the North Atlantic Oscillation (NAO) with large implications for the winters over Europe (Screen 2017). Arctic sea-ice loss in summer is likely linked with increased snow cover over Eurasia in the following autumn thus leading to a cooling over the area (Wegmann et al 2015). Reduction in the poleward temperature gradient weakens the zonal wind and the atmospheric circulation in summer (Coumou et al 2015). This analysis intends to investigate the above changes in the project coordinated experiments (A-EXP1 and A-EXP2) to assess the sensitivity to the models' diversity, to the initial conditions and to the Arctic sea-ice climatology. A comparison with recent results from Ogawa et al (2018) with a complementary suite of atmospheric model simulations will help in the diagnosis. The analysis is decomposed into winter and summer season defined as DJF and JJA, respectively, for the period 1979-2014.

Fig. 2.3.1 (a-c) shows the winter trend of temperature at 2 m (C/decade) comparing A-EXP1 and A-EXP2 multi-models ensemble means (see Table 1 for the available models) with ERA-Interim as reference. In ERA-Interim the typical winter feature is characterized by a larger warming over the Arctic (polar amplification) and a cooling over the eastern Asian continent. This last feature is missing in the A-EXP1 ensemble mean, even though the warming over the Asian continent as a minimum. In fact, looking at single members fews in each model (about 2 over 10) are able to reproduce that dipole. This result is symptomatic of the large internal variability over the mid-latitudes. Weaknesses and differences between the different models could help understand that performance. The larger warming over the Arctic is reproduced in the A-EXP1 (Fig 2.3.1b) ensemble but not in the A-EXP2 (Fig. 2.3.1c), confirming the link between the decline of sea-ice in the region and the acceleration of the warming there. Over the Pacific Ocean the temperature trend (Fig 2.3.1a-c) is realistic in both ensembles, suggesting that prescribed SST there may have a dominant role, on the other hand over the Atlantic Ocean, the warming is overestimated likely because air-sea interactions are missing. In summer the warming trend is much reduced than in winter (Fig. 2.3.1d-f). An interesting aspect is the largest warming over eastern Europe, well reproduced by the A-EXP1 ensemble (Fig. 2.3.1d-f). When the Arctic sea-ice is climatological the pattern of warming trend is not much different.

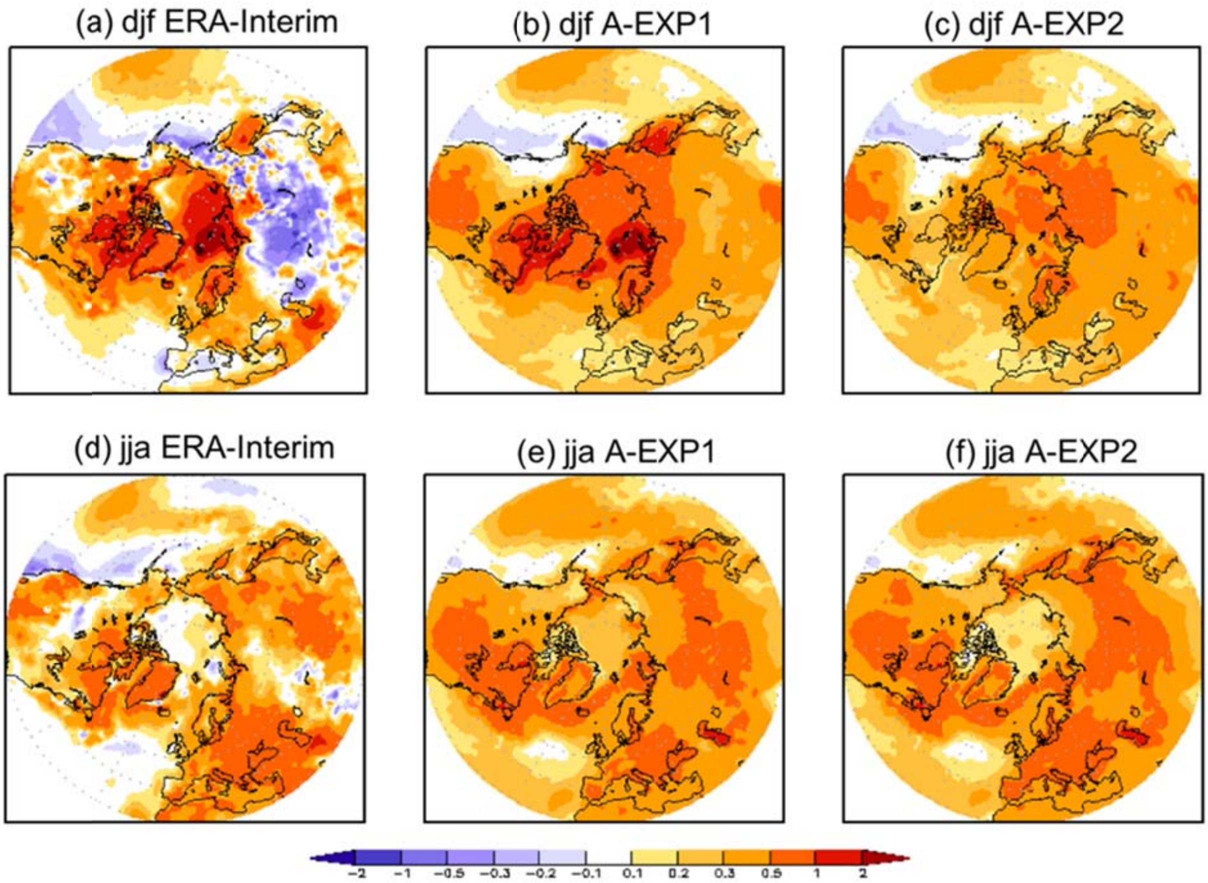

Fig. 2.3.1 *(a, b, c) DJF and (d, e, f) JJA trend of temperature at 2 m (C/decade) for ERA-Interim, A-EXP1 and A-EXP2 multi-models ensemble mean, respectively. .*

In terms of SLP the trend is characterized by an east-west dipole with higher pressures over the eastern Asian continent and over the Pacific and with lower pressure over Europe and North America (not shown). This dipole is partially reproduced by A-EXP1 even if the positive values are weaker than observed and more confined toward the Arctic circle. When the sea-ice is climatological over the Arctic the positive values over the Pacific are reproduced, but the negative ones over Europe and over North America are not, suggesting linkages with the sea-ice melt. In summer the simulated pattern reproduces a lowering of pressure almost everywhere but the patterns are not comparable. Even in summer the signature over Europe and the Mediterranean is of lowering sea level pressure, and the pattern seems to be independent from the sea-ice in the Arctic (not shown).

To discuss the changes in the atmospheric circulation comparing winter and summer we consider the jet stream in winter and the low-level kinetic energy in summer. As a first approximation the changes in the jet stream are verified in terms of changes in the zonal wind in the upper troposphere (Fig. 2.3.2). The DJF trend shows a weakening of the zonal wind component over the Arctic and an intensification in the mid-high latitudes band (Fig 2.3.2a). The feature is realistically reproduced by the multi-model ensemble mean in the A-EXP1 experiments, even though the simulated intensities are weaker (Fig 2.3.2b). When the sea-ice is climatological over the Arctic the main features remain (Fig 2.3.2c). Further identification of specific indices for the continents would help to understand the relative changes and the role of sea-ice in the changes.

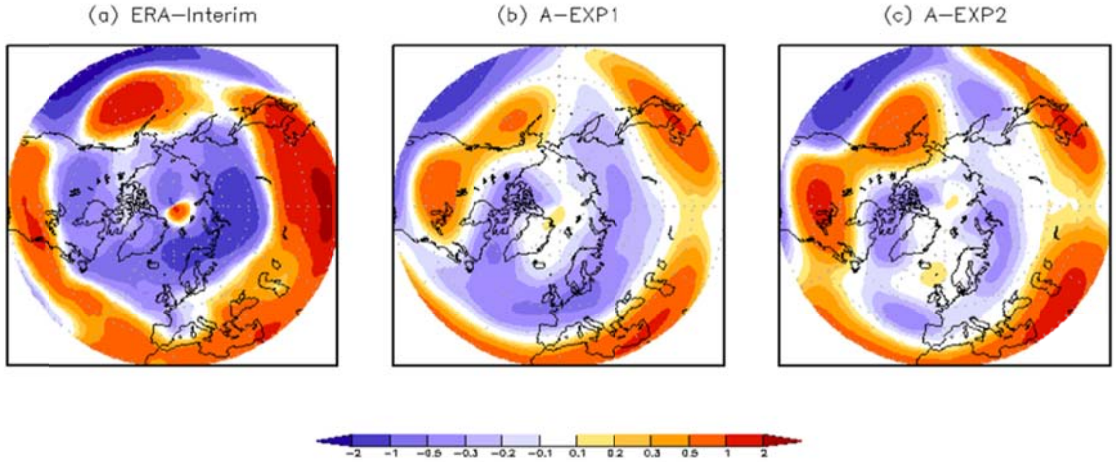

Fig. 2.3.2 *DJF trend of of zonal wind at 200 hPa (m/s/decade) for (a) ERA-Interim, (b) A-EXP1 and (c) A-EXP2 multi-models ensemble mean.*

On the other hand, in summer, the changes in the atmospheric circulation can be measured in terms of kinetic energy in the lower troposphere (Comou et al 2015; Petrie et al 2015). Fig. 2.3.3a indicates a weakening of the atmospheric circulation over Europe. The pattern is sort of reproduced in A-EXP1 multi-model ensemble mean (Fig 2.3.3b) even if with much larger intensities. When the sea-ice is climatological over the Arctic (Fig 2.3.3c), the pattern over Europe seems more realistic. Differences between single-model ensemble means and between single members should be considered to understand the simulated features.

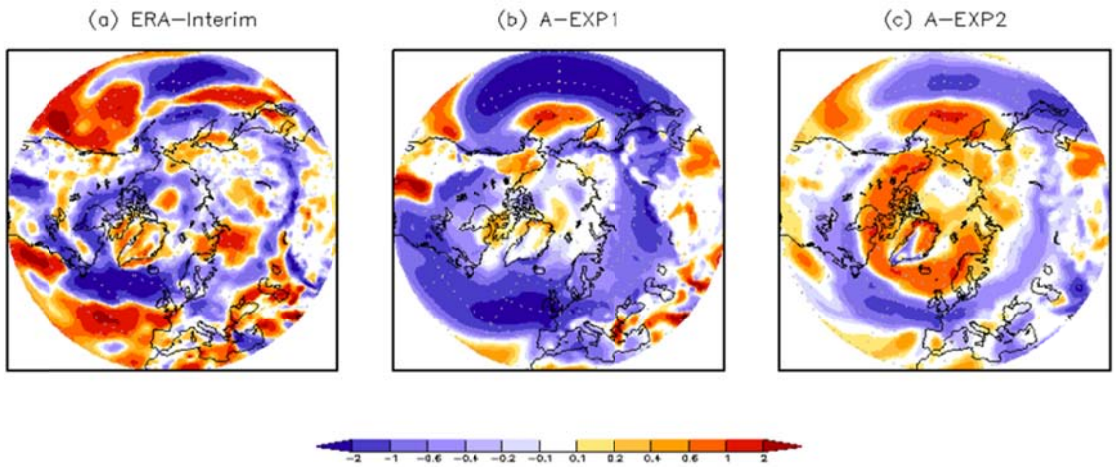

Fig. 2.3.3 *JJA trend of kinetic energy at 850 hPa (m2/s2/decade) for ERA-Interim (left), A-EXP1 ensemble mean (middle) and A-EXP2 ensemble mean (right)***.**

2.4. Role of IPV and AMV

Partner CNRS: Experiments EXP3 (with the low frequency component of the SST variability related to the IPV removed) and EXP4 (with the low frequency component of the SST variability related to the AMV removed) are analyzed to show how the SST decadal variability might modulate the Arctic Warming and its impacts. The 1979-2014 period shows a large trend from a positive IPV to a negative IPV. Consistently, the Aleutian low decreased in EXP1 simulation when compared to EXP3 (Fig. 2.4.1, left). This might have led to a larger atmospheric heat and moisture transport toward the Arctic and is consistent with a large warming in the LMDZOR model. This impact of the IPV is consistent to that found in Screen and Francis (2016), and it means that the IPV can modulate the intensity of polar warming. The EXP1-EXP4 difference is smaller, in comparison (Fig. 2.4.1, right). The 1979-2014 period shows a trend from a negative to a positive AMV, which only caused a weakening of the SLP over the Atlantic basin, and a warming over South Eastern Asia.

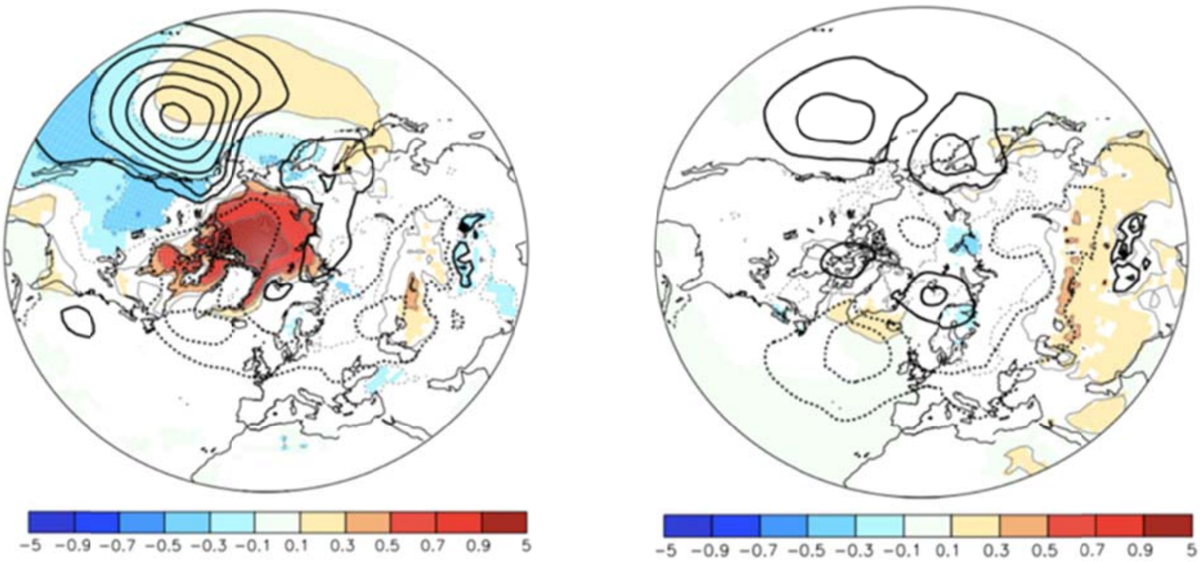

***Fig. 2.4.1** T2m trend in 1979-2013 of EXP1-EXP3 in the LMDZOR6 models, in K decade^{-1} (color) and associated SLP trend (contour, 0.1 hPa decade^{-1}) in the 30 (20) members of EXP1 (EXP3 and EXP4). Colors are masked if statistical significance is above 5% for the student t-test of the ensemble means.*

Partner DMI: The ensembles of the averaged climate state and the trend in the past decades in the four experiments using EC-Earth3 are examined. The all-time average of the surface air temperature in the four experiments shows no significant difference in their ensemble means, except on the sea ice edges in the EXP2, in which the time variations of the sea ice are removed. However, large differences are evident in the simulated trends in the four experiments. Fig. 2.4.2 shows the surface air temperature trends in ensemble mean of EXP1 and reanalysis ERA-Interim, and the difference in trends between the sensitivity experiments, with respect to EXP1. The strong Arctic warming trend is mainly contributed by the Arctic sea ice declining in the recent years. Furthermore, the Arctic ice sea ice declining also leads to less warming in the West and central Canada, but not over Eurasia (EXP1-EXP2) (see also sections 2.1

and 2.2). The decadal variability in SST in the North Pacific also influences the temperature trend over North America, but not over the Arctic (EXP1-EXP3) over the considered period (EXP1-EXP3). The multi-decadal variation in SST in the North Atlantic (AMV) contributes a warming trend over Eurasia. However, in general it has only minor impact on the temperature trends (EXP1-EXP4).

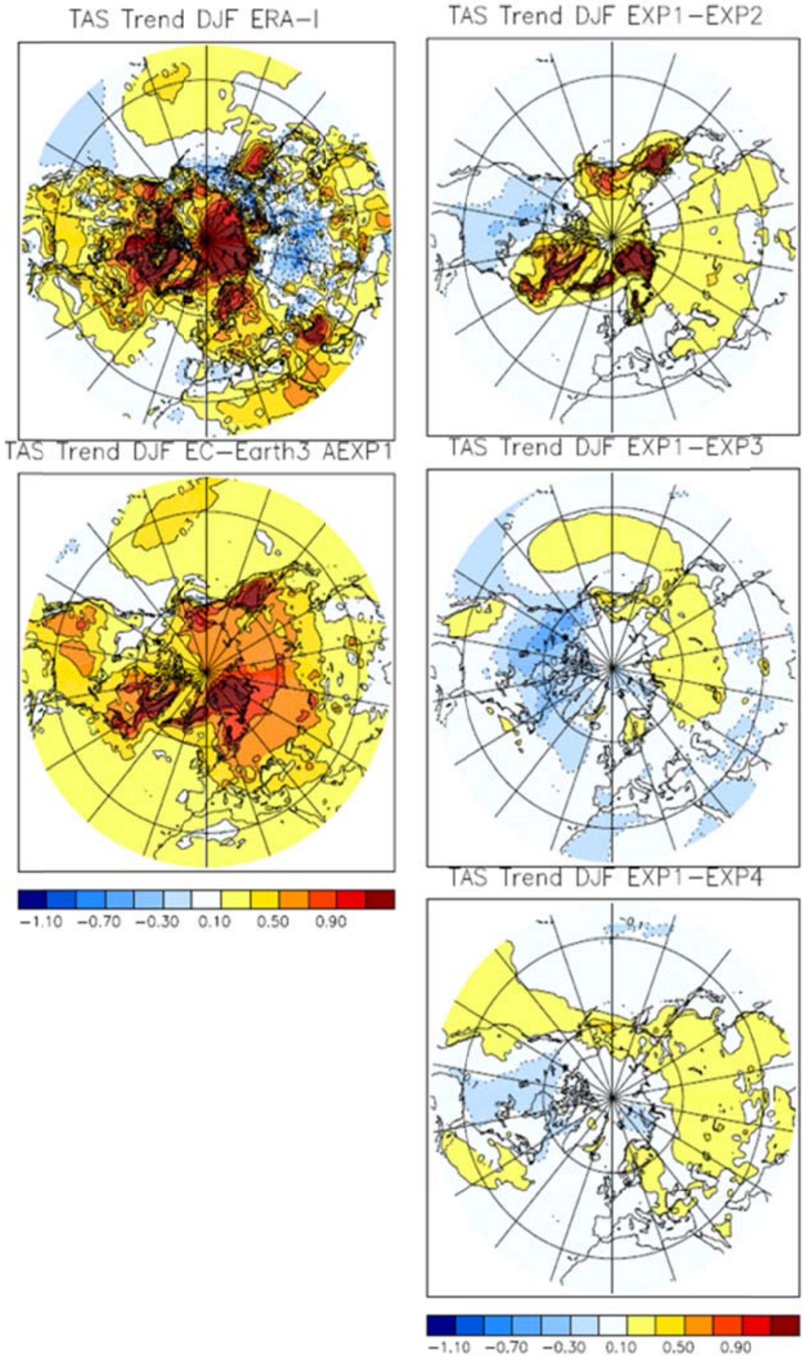

Fig. 2.4.2 *Ensemble mean of the surface air temperature trend in DJF in the reanalysis ERA-Interim (top left) and as simulated by EC-Earth3 in EXP1 (middle left). The right panels show the differences in the trends between EXP1 and EXP2 (top right), EXP1 and EXP3 (middle right), EXP1 and EXP4 (bottom right). Unit: K/decade.*

Progress beyond the state of the art

By taking into account multiple sources of Arctic atmospheric variability, the observational analysis has highlighted the role of a tropospheric pathway of influence for the sea-ice driven atmospheric variability (Fig. 1.1, 1.2). A covariation of sea-ice variability with Siberian snow cover may be responsible of previously proposed pathways of influences involving the stratosphere (Fig. 1.1).

By designing a set of coordinated experiments, a protocol has been established for the testing of theories on the impacts of sea ice variability at interannual and longer time scale, and how Atlantic and Pacific Ocean decadal variability may affect this variability, for the 1980-2014 period. From the ongoing analyses of the coordinated experiments, performed by the project atmospheric general circulation models, a number of novel results are emerging, including:

- Clear distinction between polar – midlatitude covariability at interannual and longer time scale. At shorter (interannual) time scales, the results of the coordinated experiments have distinctly shown for the first time that the WACE pattern, the large scale variability in lower atmospheric temperature associated to temperature variability over the Barents-Kara, can occur independently from sea-ice variability (Fig. 2.1.2c,f). While at longer (multiannual) time scales, this local (polar) to global (midlatitude) co-variability may be underestimated in the atmospheric model considered (Fig. Fig. 2.1.2g,h). Differences between the observed and modelled trends appear to be related to a longer time scale variations of the Eurasian near surface temperature, possibly associated with the Arctic Annular mode, not captured by the models (Fig. 2.1.3c,e).
- The variance decomposition method allowed to accurately quantify the Arctic sea-ice driven atmospheric circulation variability (Fig. 2.2.1). The results suggest that at least 100 members are required to robustly separate sea-ice driven variability from internal variability, and that driven by other forcings, including greenhouse gas and global sea-surface temperature variability (Fig. 2.2.2). Within the Arctic Circle, the sea-ice driven variability explains about 3% of the total variance for sea level pressure and about 23% for surface air temperature in boreal winter at interannual and longer time scales. Regionally, the sea-ice driven variability is 1-1.5 times as large as the variability driven by the other forcings over the Arctic and northern Eurasia (Fig. 2.2.1).
- Large scale features of atmospheric circulation trends over the period 1980-2014 are not reproduced by models, both in winter and summer (Fig. 2.3.1-3). While in winter internal atmospheric variability likely plays a role, the difference in summers may point to structural model deficiencies.
- The impact of decadal variability in SST in the North Pacific on the Arctic warming and consequently its impacts appears to be model dependent (contrast Fig. 2.4.1 and 2.4.2). Further investigation of the impact of decadal variability on the Arctic is found in deliverable D3.1.

Impact

<u>How</u> has this work contributed to the expected impacts of Blue-Action?

By contributing to the project objectives of quantifying the impacts of recent rapid changes in the Arctic on the Northern Hemisphere climate and identifying key processes controlling these impacts, the work of this deliverable is instrumental for the Blue-Action impact of improving the capacity of climate models to represent and predict Northern Hemisphere climate. Specifically, the knowledge generated by the deliverable leads to a proper understanding of the two-way linkages between the Arctic and lower latitudes. These two-way linkages are crucial because they are key to achieving a more realistic representation in model systems for predictive skill beyond seasons and they form the scientific basis for understanding the impacts of arctic changes on the global atmospheric circulation. It is indeed a necessity for climate model to capture realistically atmospheric teleconnections that may serve as an additional amplification of Arctic feedback mechanisms.

Impact on the business sector

The deliverable work contributes to the background knowledge needed by meteorological and climate services to deliver better climate predictions, at seasonal time scales and beyond. In so doing, this work indirectly contributes to better servicing the economic sectors that rely on improved climate predictions.

Lessons learned and Links built

The coordination of a set of experiments has enabled (and is enabling) a number of focused analysis on the role of sea-ice variability on the Northern hemisphere climate and, in so doing, it has facilitated and promoted international cooperation, exchange of ideas and knowledge. The D3.2 deliverable is closely connected to deliverable D3.1, by sharing the coordinated experiments, and it is relevant to WP4 by contributing to Objectives 3 and 4. Synergies have been created with other projects, specifically: H2020 APPLICATE, H2020 PRIMAVERA, HighResMIP, PAMIP and DynVarMIP. In particular, most of the models used for the Blue-Action coordinated experiments are also used for selected experiments of PAMIP, widening and possibly corroborating the Blue-Action intercomparison analysis.

Contribution to the top level objectives of Blue-Action

This deliverable contributes to the achievement of all the following objectives and specific goals indicated in the Description of the Action, part B, Section 1.1:

Objective 3 Quantifying the impact of recent rapid changes in the Arctic on Northern Hemisphere climate and weather extremes

The coordinated experiments and their analysis together with the observational analysis of the Arctic warming impacts contribute to Objective 3, by providing a framework for the testing of theories on the impacts of sea ice variability.

Objective 4 Improving the description of key processes controlling the impact of the polar amplification of global warming in prediction systems

The work contributes to Objective 4 by analyzing the coordinated experiments and identifying the key processes responsible for the Arctic- midlatitude linkages and in so doing informing on the processes that needs to be taken into account in prediction system and motivating improvements.

Objective 6 Reducing and evaluating the uncertainty in prediction systems

The knowledge generated by the ongoing analysis of the coordinated experiments on the impact of Arctic warming can be used to evaluate the uncertainty in prediction systems.

Objective 8 Transferring knowledge to a wide range of interested key stakeholders, including the scientific community, via intensive dissemination activities, organisation/contribution to workshops with other projects, and scientific publications.

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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	Estimated budget	Type of Audience	Estimated number of persons reached	Link to Zenodo upload
Participation to a workshop	Claude Frankignoul (CNRS), The wintertime atmospheric response to the Atlantic meridional overturning circulation, and its link to the Atlantic Multidecadal Oscillation, Seminar in Woods Hole Oceanic Institute	Woods Hole (USA), 5 Sept 2017	See the form C of the partner involved	Scientific Community (higher education, Research)	40	https://doi.org/10.5281/zenodo.1187058
Participation to a conference	Amelie Simon (LOCEAN-IPSL), The influence of Arctic sea ice loss on mid-latitude climate in the cold season (poster) at EGU 2018	Vienna (AT), 8-13 April 2018	See the form C of the partner involved	Scientific Community	50	https://doi.org/10.5281/zenodo.2819889
Participation to a conference	Liang, Y.-C., et al (WHOI), Atmospheric responses to Arctic sea ice loss in a high-top atmospheric general circulation model. AGU Fall Meeting	Washington D.C. (USA), 10-14 December 2018		Scientific Community (higher education, Research)	50	It will be made available in Zenodo (publication in preparation)
Participation to a conference	Claude Frankignoul, et al., (CNRS), An observational estimate of the influence of Arctic sea ice loss on the atmospheric circulation in the cold season, Americal Meteorology Annual meeting	Phoenix (USA) 6-10 January 2019	See the form C of the partner involved	Scientific Community (higher education, Research)	50	https://lefe-ice.sciencesconf.org/
Participation to a conference	Amelie Simon (LOCEAN-IPSL), The influence of Arctic sea ice loss on mid-	Vienna (AT), 8-13 April 2018	See the form C of the partner	Scientific Community	50	https://doi.org/10.5281/zenodo.2819

	latitude climate in the cold season (poster) at EGU 2018		involved			889
Participation to a conference	Liang, Y.-C., et al (WHOI), Atmospheric responses to Arctic sea ice loss in a high-top atmospheric general circulation model. AGU Fall Meeting	Washington D.C. (USA), 10-14 December 2018		Scientific Community (higher education, Research)	50	It will be made available in Zenodo (publication in preparation)
Other	Guillaume Gastineau (CNRS), HDR thesis defense, Decadal climate variability: mechanisms and impacts, HDR thesis defense	Paris (FR) 18 January 2019	See the form C of the partner involved	Scientific Community (higher education, Research)	50	https://zenodo.org/record/3404011#.XXfRziXgpBw
Participation to a conference	Annalisa Cherchi et al (CMCC) Arctic sea-ice changes and Northern Hemisphere atmospheric circulation at EGU 2019	Vienna (AT), 7-12 April 2019	See the form C of the partner involved	Scientific Community (higher education, Research)	50	It will be made available in Zenodo (publication in preparation)
Participation to a conference	Liang, Y.-C., et al (WHOI), Atmospheric responses to Arctic sea ice loss in a high-top atmospheric general circulation model. AMS 15th Conference on Polar Meteorology and Oceanography	Boulder (USA), 19-23 May 2019		Scientific Community (higher education, Research)	50	It will be made available in Zenodo (publication in preparation)
Participation to a workshop	Claude Frankignoul (CNRS), An observational estimate of the direct atmospheric response to the Arctic sea ice loss in the cold season. Sea ice in the Earth System: a multidisciplinary perspective"	Brest (FR), 4-6 June 2019	See the form C of the partner involved	Scientific Community (higher education, Research)	40	https://lefe-ice.sciencesconf.org/
Participation to a workshop	Liang, Y.-C., et al (WHOI), Atmospheric responses to	Boulder (USA), 17-19 June		Scientific Community	50	It will be made

	Arctic sea ice loss in a high-top atmospheric general circulation model. 2019 CESM Workshop	2019		(higher education, Research)		available in Zenodo (publication in preparation)
Participation to a workshop	Liang, Y.-C., et al (WHOI), Atmospheric responses to Arctic sea ice loss in high-top Whole Atmosphere Community Climate Model version 6 (WACCM6). PAMIP Workshop	South Devon (UK) 25-27 June 2019		Scientific Community (higher education, Research)	50	It will be made available in Zenodo (publication in preparation)
Participation to a workshop	Rohit Ghosh (MPI) et al., The role of Arctic Amplification and atmospheric internal variability on Eurasian winter, PAMIP workshop	Totnes (UK), 24-27 June 2019	See the form C of the partner involved.	Scientific Community (higher education, Research)	40	It will be made available in Zenodo (publication in preparation)
Participation to a workshop	Guillaume Gastineau (CNRS) et al., Climate influence of sea-ice and its link with the Pacific and Atlantic Ocean, PAMIP workshop	Totnes (UK), 24-27 June 2019	See the form C of the partner involved	Scientific Community (higher education, Research)	40	https://zenodo.org/record/3404004#.XXfPxSXgpBw
Participation to a workshop	Yu-Chiao Liang (WHOI) et al., Atmospheric Responses to Arctic sea-ice loss in high-top Whole Atmosphere Community Climate Model version 6 (WACCM6), PAMIP workshop. Presented by pre-recording	Totnes (UK), 24-27 June 2019	See the form C of the partner involved	Scientific Community (higher education, Research)	40	https://zenodo.org/record/3387703#.XXFuKpNKg_V
Participation to a Conference	Rohit Ghosh (MPI-M), talk on "Reconciling the role of Arctic Amplification and atmospheric internal variability on Eurasian winter"	EGU 2019, Vienna, Austria, 7-12 April, 2019	See the form C of the partner involved.	Scientific Community (higher education, Research)	70-80	It will be made available in Zenodo (publication in preparation)

Participation to a Conference	Rohit Ghosh (MPI-M), talk on "Two distinct phases in the North Atlantic gyre circulation changes under global warming"	EGU 2019, Vienna, Austria, 7-12 April, 2019	See the form C of the partner involved.	Scientific Community (higher education, Research)	80-100	It will be made available in Zenodo (publication in preparation)
Participation to a workshop	Amelie Simon (CNRS), Direct and near-term climate responses to Arctic sea ice loss	Honolulu (USA), 22 August 2019	See the form C of the partner involved.	Scientific Community (higher education, Research)	25	https://zenodo.org/record/3402739#.XXYPh_zgo5k

Peer reviewed articles

Title	Authors	Publication	Is Blue-Action correctly acknowledged?	Status?	Open Access granted
The role of Arctic Amplification and atmospheric internal variability on Eurasian winter,	R.Ghosh, D. Matei, J. Bader, E. Manzini, et al.		Yes	In preparation	Yes, this is taken into account.
Quantification of the Arctic Sea Ice-Driven Atmospheric Circulation Variability in Coordinated Large Ensemble Simulations	Y.-C. Liang, Y.-O.. Kwon, C. Frankignoul, G. Danabasoglu, et al.	Geophysical Research Letters	Yes	Submitted Geophysical Research Letters d	Yes, this is taken into account.
An observational estimate of the direct response of the cold season atmospheric circulation to the Arctic sea ice loss	A. Simon, C Frankignoul, G. Gastineau, Y.O. Kwon	Journal of Climate	Yes	Submitted to Journal of Climate	Yes, this is taken into account.
Impact of Arctic sea-ice loss in the Northern Hemisphere atmospheric circulation in summer and winter: A multi-model comparison	Cherchi A.i, P. Ruggeri, Peano D, Navarra A. et al.		Yes	In preparation	Yes, this is taken into account.

Uptake by the targeted audiences

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

This is how we are going to ensure the uptake of the deliverables by the targeted audiences:
The content of the deliverable has been and will be disseminated at the scientific events and at the annual meeting of Blue-Action in October 2019. Further dissemination is in progress, by preparing original manuscripts to be submitted to scientific journals.