The Danish Meteorological Institute

DMI Report 21-25 Toward providing reliable climate information for the next few years to a decade ahead

Final scientific report of the 2020 National Centre for Climate Research Work Package 2.1.1, Decadal Climate Predictions

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The Danish Meteorological Institute

Colophon

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Content

1 Abstract

Reliable climate prediction for the next few years is often vital for many decision makers. In this work package we have established a prototype procedure for performing experimental ensemble decadal climate forecast using the prediction system, EC-Earth3-CPSAI. The procedure enables us to obtain the initial conditions for atmosphere, ocean and sea ice on Nov. 1 every year, and perform ensemble forecast for 10 year ahead. Currently we use an ensemble of 10 members, with the possibility to enlarge the ensemble by perturbing these initial states.

A full suite of 10 member ensemble 10-year hindcasts starting on Nov. 1 every year for the period of 1960 to 2018 are completed using the EC-Earth3-CPSAI prediction system and following the protocol for the Decadal Climate Prediction Project (DCPP), a subproject endorsed by the Coupled Model Intercomparison Project phase 6 (CMIP6). This ensemble, together with another 5 members of the hindcast using the same model system but performed at the SMHI, constitute the contribution to the CMIP6 DCPP from the EC-Earth consortium. The data of this suite of ensemble hindcasts, and the ensemble forecasts starting at 2019 have also been provided to the WMO Lead Centre for Annual-to-Decadal Climate Prediction (LCACP) for international collaboration of producing hindcasts, forecasts and verification on decadal time scales.

With these ensemble hindcasts experiments, we are able to assess the decadal prediction skills of the system and investigate where there are potentials for skillful decadal predictions and for what reasons. Our study shows that, for lead-times beyond 4-5 years little effect of initialization is found except in the subpolar North Atlantic (SPNA) region. However, this enhanced skill seems mostly related to the abrupt warming in the mid 1990's. A more thorough study on the predictability in the SPNA is in process.

The prediction system EC-Earth3-CPSAI also enables us to investigate the processes giving rise to decadal predictability. Performing sensitivity experiments by applying different initialization approaches, in particular for sea ice initializations, we demonstrate the benefit of initializing Arctic sea ice, especially the sea ice thickness, to decadal predictions in the Arctic. The winter preconditioning of perennial ice in the central Arctic Ocean may lead to increased skills of sea ice cover in the following years for the seasonal ice. The next step will be to study the impact of the sea ice initialization on decadal predictions outside of the Arctic, eg. in the European regions.

Another dedicated study using EC-Earth3-CPSAI is to investigate the role of SPNA on decadal prediction of remote regions. We perform pacemaker prediction experiments for which the ocean state in SPNA is restored to the observed anomalies during the 2015 extreme cold anomaly events. Our results indicate that constraining the ocean in SPNA to the observed state significantly improves the prediction skills in the entire North Atlantic for lead time several years ahead, especially in the Nordic Seas, implying the possible role of the SPNA as a source of skillful predictions on interannual to decadal time scale.

2 Resumé

Troværdige klima-forudsigelser for de nærmeste få år er ofte vigtige for mange beslutningstagere. I denne arbejdspakke har vi etableret en prototype-procedure til at foretage eksperimentelle dekadiske ensemble forudsigelser baseret på EC-Earth3-CPSAI. Denne procedure gør det muligt at generere begyndelsesbetingelser for atmosfæren, oceanet, og havis den 1. november hvert år, og at fortage ensemble forudsigelser 10 år frem. Vi bruger nu 10 ensemble medlemmer med mulighed for at øge ensemblet yderligere ved at perturbere begyndelsesbetingelserne.

En samling af 10 års ensembler, hvert med 10 medlemmer, begyndende den 1. november hvert år i perioden 1960-2018 er færdiggjort med EC-Earth3-CPSAI. Disse experimenter følger protokollen fra Decadal Climate Prediction Project (DCPP), et projekt under Coupled Model Intercomparison Project phase 6 (CMIP6). Dette ensemble, sammen med yderligere 5 medlemmer med den samme model foretaget af SMHI, udgør EC-Earth konsortiets bidrag til CMIP6 DCPP. Data fra disse eksperimenter sammen med en tilsvarende ensemble forudsigelse begyndende i 2019 er også blevet leveret til WMO Lead Centre for Annual-to-Decadal Climate Prediction (LCACP), som er et internationalt samarbejde for dekadiske forudsigelser.

Med disse ensemble forudsigelser for den historiske periode er vi i stand til at vurdere kvaliteten af systemets forudsigelser, og til at undersøge i hvilke regioner og i hvilke sæsoner, der er potentiel for troværdige dekadiske forudsigelser. Vores studier viser, at der kun er lille effekt af begyndelsesbetingelserne for forudsigelser længere end 4-5 år frem i tiden. En undtagelse er fundet for det subpolære Nord Atlantiske område. Denne forbedret kvalitet af forudsigelserne, synes dog at være relateret til en pludselig opvarmning af området i midten af 90erne. Et dybere studie af forudsigelses-kvaliteten i dette område er sat i værk.

EC-Earth3-CPSAI gør det også muligt at underøge de processer, der giver årsag til dekadisk forudsigelighed. Sensitivitets-eksperimenter foretaget med forskellige metoder for initialisering, har demonstreret fordelen for forudsigeligheden i Arktisk ved at initialisere Arktisk havis, specielt tykkelsen af isen. Den flerårige havis om vinteren i det centrale Arktiske Ocean kan sætte den betingelse, der fører til øgede færdigheder inden for havisen i de følgende år for sæsonis. Det næste skridt vil være, at studere effekten af havis-initialiserinegen for dekadiske forudsigelser udenfor det Arktiske område, fx i Europa.

Et andet studie med EC-Earth3-CPSAI gør ud på, at det undersøger subpolære Nord Atlantiske områdes rolle for dekadiske forudsigelser i fjernere områder. Vi har foretaget 'pacemaker' eksperimenter i hvilke havets tilstand i det subpolære område følger de observerede anomalier for den ekstremt kolde periode i 2015. Vores resultater indikerer, at dette forbedrer forudsigelserne flere år ud i fremtiden i hele Nord Atlanten og specielt i de Nordiske have.

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3 Introduction

The Danish National Centre for Climate Research (Nationalt Center for Klimaforskning, NCKF) has completed its first year in 2020. It has been a source of funding for the Danish Meteorological Institute and collaborators for climate change related research during this year. The 18 work packages fall under 4 general themes:

1. Arctic and Antarctic Research
2. Climate change in the near future
3. Use of climate data
4. Support for the IPCC

Work Package 2.1.1 is to develop a prototype decadal climate prediction system to deliver experimental decadal predictions for assessing the benefit of the initialization for predictions on decadal timescales. The system is also used to investigate the processes that result in variability and that give rise predictabilities on decadal time scales.

Accurate climate information for the coming years to a decade ahead is of great interest to society. It can be used to increase efforts at resilience and aid sustainable development. With the help of such information, the society, eg., authorities, businesses and other stakeholders, can better plan how to deal with the immediate challenges and opportunities that a changing climate brings. Work Package 2.1.1 is to develop a prototype climate prediction system using the climate model EC-Earth3 with anomaly initialization (i.e., EC-Earth3-CPSAI) for experimental, semi-operational climate predictions on decadal timescales, and to enhance our knowledge on decadal predictability and the associated mechanism.

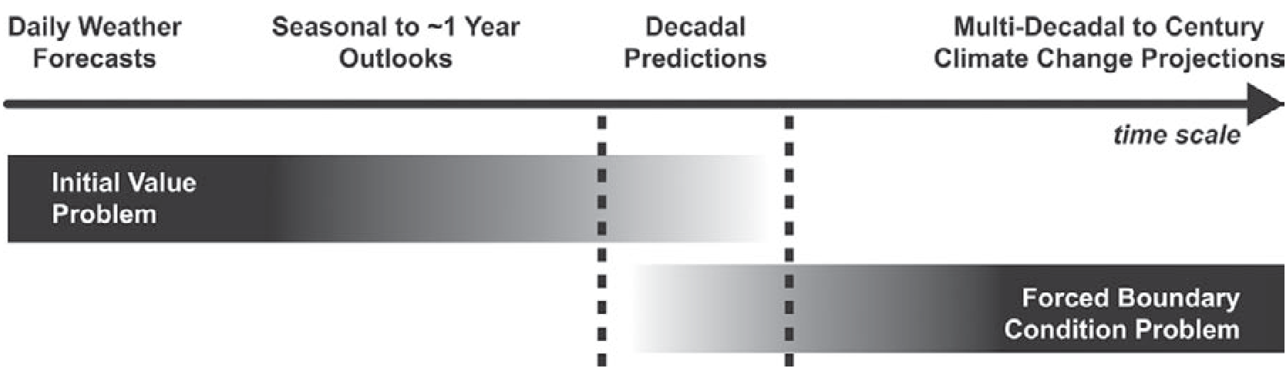


Figure 1. Schematic illustrating progression from initial value problems with daily weather forecasts at one end, and multidecadal to century projections as a forced boundary condition problem at the other, with seasonal and decadal prediction in between (from Meehl et al., 2009, Figure 2).

Decadal climate prediction is a new research area. As illustrated in Fig. 1, the daily weather forecasts and shorter-term seasonal predictions can be thought of as "initial value problems", for which detailed knowledge of the observed current conditions of the atmosphere, land, ocean, and sea ice are crucial to define the initial state for starting the integration of the prognostic equations. In contrast, projections of how climate will respond to the anticipated changes in greenhouse gases and aerosols over time scales of several decades to centuries can be considered primarily as “boundary condition problems”. Such model-based projections seek to describe climate trends, not the details of individual days, seasons, or years. On decadal time scale climate variables are characterized by a forced climate change signal that is often weaker than or comparable to the magnitude of internally generated climate variations. In the past decades, profound advances have been made in understanding the observed climate modes or anomalies that result from complex interactions among all the components of the Earth climate system at various time scales. These climate modes and anomalies, such as El Niño and the Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Pacific Decadal Variability (PDV), Atlantic Multi-Decadal Variability (AMV), sea ice anomalies and snow cover anomalies, etc. extending over a long period of time that is far beyond the limit of atmospheric predictability from initial conditions alone, constitute the scientific basis for prediction from seasons to decades and could potentially contribute to prediction skill (Meehl et al, 2009; Kirtman et al, 2013; Merryfield et al, 2020).

Skillful climate predictions are made using a realistic climate model with the present and projected anthropogenic forcing in the same way as long-term climate change projections do, but starting from the observed climate state at the beginning of the prediction similar to weather forecasts. Advanced statistical methods are applied to better synchronize the climate model to observed climate states (Yang et al, 2020). Over recent decades tremendous progress have been made in advancing the knowledge and capability in climate predictions, and it has been shown that such predictions have skill over a period of several years (Smith, et al, 2013; Meehl et al, 2014; Smith at el 2019). However, there are still a number of technical and scientific outstanding issues that need to be overcome for obtaining reliable climate predictions (Kushnir et al, 2019; Merryfield et al, 2020). One of the main technical challenges is to realistically initialize the model with observed climate, especially for the sea ice conditions. Furthermore, there are many unknowns regarding the sources and mechanisms giving rise to decadal predictability. For example, it is not clear how predictable the fast changing climate in the Arctic is, and how the Arctic climate changes impact the climate in the North Atlantic and Europe, including Denmark.

In this Work Package, we have further developed the procedure for using the climate prediction system EC-Earth3-CPSAI to make experimental ensemble forecasts for the coming decade. We used the system to complete the full suite of ensemble hindcasts for the historical period in order to gain knowledge of the prediction skill of the system. We evaluated the role of the sea ice initialization for predictions of the Arctic regions, and investigated the predictability of over the North Atlantic and its role on decadal predictions of the remote regions.

4 Toward providing reliable climate information for the next few years to a decade ahead

4.1 The climate prediction system EC-Earth3-CPSAI

In the past years, DMI has developed a decadal climate prediction system in close collaboration with the Swedish Meteorological and Hydrological Institute (SMHI) and other partners in the EC-Earth consortium with the support of the NordForsk Centre of Excellence-funded project *Arctic Climate Predictions: Pathways to Resilient, Sustainable Societies* (ARCPATH) and the European H2020 project *Blue-Action: Arctic Impact on Weather and Climate*. The prediction system, EC-Earth3-CPSAI, is based on the global climate model EC-Earth3 (Döscher et al., 2021). The ocean and sea ice is initialized using the anomaly initialization method (Pierce et al., 2004; Volpi et al. 2017) that combines the anomaly from ORAS5 (Ocean Re-Analysis System 5) reanalysis for ocean and sea ice (Zuo et al, 2019) with the model's own climatology. The atmosphere is initialized using full field initialization with the atmospheric reanalysis data set ERA-Interim (for 1979-2018, Dee et al., 2011) and ERA40 (for 1960-1978, Kållberg et al, 2004). These ocean and atmosphere reanalyses are data assimilations using observations and thus considered to be realistic climate states. Following the guideline of the Decadal Climate Prediction Project (DCPP), a sub-project under the international Coupled Model Intercomparison Project phase 6 (CMIP6) organized by the World Climate Research Program (WCRP), our climate prediction experiment starts from November 1 each year and run 10 year ahead (Boer et al, 2016). For the CMIP6 future period starting from 2015, the DCPP recommends that the predictions follow the emission and land use forcing of the SSP2-4.5 scenario. The system runs at the standard EC-Earth3 resolution, with the atmosphere at T255 (equivalent to ~80 km in grid space) and 90 levels and the ocean and sea ice at 1° and 75 levels. The details of the prediction system are documented in a recent paper by Tian et al (2020).

As for extended range weather forecast, it is desirable to use an ensemble strategy in decadal prediction to represent the possible uncertainties in the initial conditions. We take advantage of five member ensemble in ORAS5 and use them to construct the first five members of initial states. We then apply perturbations at the surface to get another five members, which makes a total of 10 members in the decadal prediction ensemble. The experimental climate prediction using EC-Earth3-CPSAI is a joined venture with SMHI. The five initial states generated with the ORAS5 ensemble are thus also made available to SMHI which perform five extra members of decadal predictions by perturbing the atmospheric component in the corresponding initial states.

The prototype climate prediction system EC-Earth3-CPSAI thus consists of

1. The climate model EC-Earth3 with the forcing of SSP2-4.5 scenario;
2. Preparation of the 10-member ensemble of initial states on November 1 utilizing the ECMWF reanalysis data sets ORAS5 and ERA5. Specifically, the ocean and sea ice initial states are obtained using the anomaly initialization method which combines the model climatology and the observed anomaly from the ORAS5 reanalysis. Here the model climatology is calculated using a CMIP6 historical (uninitialized) simulation for the period 1979-2014, and the observed anomaly is from the ORAS5 climatology for the same period. The daily ocean and sea ice state of the ORAS5 reanalysis are available from the ECMWF archive file system about one month behind the real time. The atmospheric reanalysis ERA5 (Hersbach et al, 2020) is used after 2018 because

the ERA-Interim reanalysis stopped in October 2018. The ERA5 is available via the Copernicus data storage https://cds.climate.copernicus.eu/cdsapp#!/search?type=dataset&text=era5 at nearly real time. Three institutes in EC-Earth consortium, i.e., BSC (Barcelona Supercomputer Center), SMHI and DMI, share the same atmospheric initial states which are adopted from the ERA5 reanalysis for the use of EC-Earth3 prediction runs;
3. Performing the 10-year ensemble predictions on DMI's HPC;
4. Reformatting the prediction output following the CMIP6 standard and compliance for further analysis and for exchange of data with national and international collaborators.

Following this procedure, we have made the ensemble of 10-year climate predictions starting from Nov. 1, 2019. The same procedure has also been applied to perform the decadal hindcasts described in the next section.

4.2 Hindcast/forecast experiments with EC-Earth3-CPSAI and outlook for the climate change in the coming years

In order to understand the forecast capability of EC-Earth3-CPSAI, we have carried out the full suite of 10- member ensemble climate hindcasts starting every year for the period 1960-2018. These hindcasts follow the experiment protocol defined by the DCPP (Boer et al, 2016). The assessment of these ensemble hindcasts forms the basis on where and when the model predictions may be skillful. The data from these hindcast experiments, together with the forecasts from 2019, have been converted to common standard following the CMIP6 compliance and provided to our Nordic as well as international collaborators for common analysis and assessment of the future climate in the coming years. We are now working on publishing the data on the WCRP's data infrastructure for CMIP6, i.e., the Earth system Grid Federation (ESGF) data node.

We have joined the WMO Lead Centre for Annual-to-Decadal Climate Prediction (LCACP, https://hadleyserver.metoffice.gov.uk/wmolc/), which collects and provides hindcasts, forecasts and verification data from a number of contributing institutes. Together with 14 other institutes, we contributed with the above hindcasts and forecasts ensembles to the news release by the LCACP, *WMO Global Annual to Decadal Climate Update for 2020–2024,* released in July, 2020 (https://public.wmo.int/en/media/press-release/new-climate-predictions-assess-global-temperatures-coming-five-years). In the news release, it is predicted that the annual global temperature is likely to be at least 1°C warmer than preindustrial levels in each of the coming 5 years. In 2020, large land areas in the Northern Hemisphere are likely to be over 0.8°C warmer than the recent past, and the Arctic is likely to have warmed by more than twice as much as the global mean. Over 2020-2024, almost all regions globally, except parts of the southern oceans, are likely to be warmer than the recent past, with the high latitude regions and the Sahel being wetter whereas northern and eastern parts of South America dryer (Fig. 2).

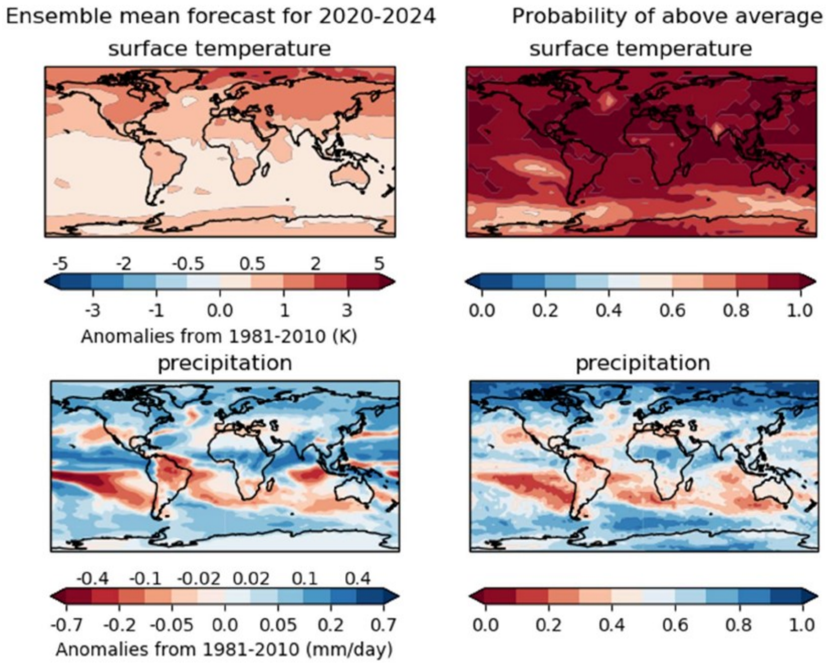


Figure 2. Ensemble predictions for 2020-2024 anomalies relative to 1981-2010 average produced by the WMO Lead Centre for Annual-to-Decadal Climate Prediction, with contributions from 13 model systems from 14 institutes worldwide including DMI. Ensemble mean (left column) and probability of above average (right column). As this is a two-category forecast, the probability for below average is one minus the probability shown in the right column. (Figures from the WMO Press Release, figure 8, https://public.wmo.int/en/media/press-release/new-climate-predictions-assess-global-temperatures-coming-five-years).

4.3 The role of sea ice initialization on the Arctic decadal prediction skill

Our approach of initializing the sea ice state, i.e., the sea ice concentration (SIC), ice volume (SIV) and snow volume (SNV) over ice is novel. The sea ice volume, as the product of sea ice concentration and ice thickness (SIT), is often not taken into account in sea ice initialization due to lack of long-term reliable global observation. In order to investigate the role of sea ice initialization, two ensembles of decadal prediction experiments with (AI2) and without (AI0) sea ice initialization were performed, and their prediction skills are compared. Here the skills are assessed based on forecast anomalies and the assessment always uses the full 20-year period 1997-2016. We focus on the recent two decades when the Arctic sea ice has being experiencing rapid decline, as the impact of Arctic sea ice on decadal prediction skill in the last two decades is expected to be more representative for the coming decades than a skill assessment with a full 60 year period from 1960 to present.

Fig. 3 compares the Root Mean Square Error (RMSE) of the AI2 (with sea ice initialization) ensemble with the AI0 (no sea ice initialization) experiments. Specifically, the skill score (SS) relative to AI0 indicating benefit from sea ice initialization are shown in the upper two rows, while the lower row shows skill improvement from both ocean and sea ice initialization, by comparing AI2 to FREE (no initialization). On the top row (Fig. 3a-c), there is strong imprint from initialization in the first winter. The SS in SIT seen in Fig. 3b is effectively enhanced in the central Arctic Ocean and in the East

Greenland Current, except the stippled areas where SIT initialization is not implemented as the sea water is shallow (less the 100 m). On decadal time-scales (Fig. 3d-f), the added skill to SIC from sea ice initialization is minor, but the skill of SIT in the stippled area in the Arctic Basin has enhanced. The benefit in TAS from sea ice initialization is consistently found in the lower latitude, outside of the polar cap circle. By contrast, the lower row (g-i) suggests a dominant contribution from ocean-anomaly initializaiton to SIC prediction skill in the marginal ice zone, and SIT prediction skill in the Arctic Basin and East Greenland Current, and TAS in low latitudes.

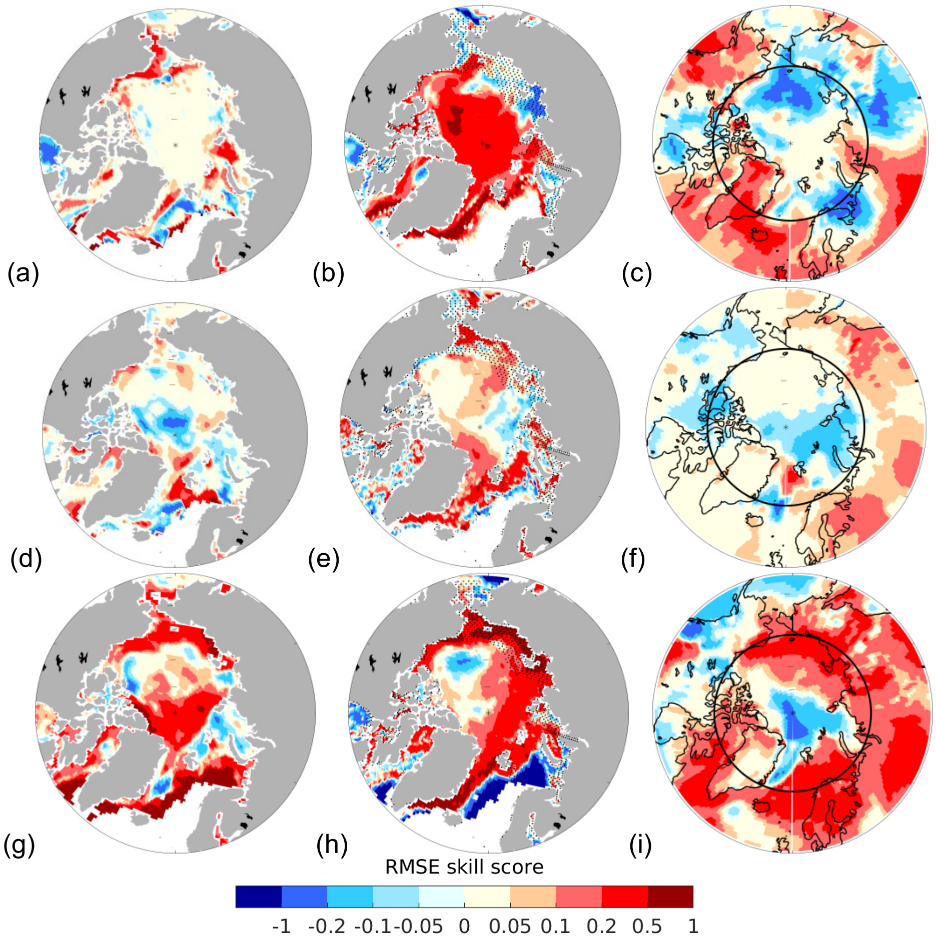


Figure 3. RMSE skill score for SIC (left), SIT (middle) and TAS (right). The RMSE skill score is calculated as 1-($RMSE_{AI2}$ /$RMSE_{ref}$), where *ref* denotes either AI0 (no sea-ice initialization) or FREE (no initialization). The added skill by sea ice initialization (AI2 relative to AI0) are shown in (a)-(c) for the first wintertime (DJF) forecast and (d)-(f) for forecast years 2-9. The added skills of initialization (AI2 relative to FREE) are shown in (g)-(i) for forecast years 2-9. Scores above (below) 0 denote more (less) accurate in AI2 than *ref*, and vice versa. The stippled areas in the middle panels indicate where sea water depth is below 100 m thus no SIT initialization in is applied in AI2. (Figures are taken from Tian et al (2020).

To identify the linkage between the thickness of multiple year ice in the central Arctic to the prediction skills for seasonal ice free regions, the temporal evolution of SS is calculated on a monthly basis, first for each grid points and then averaged over the area of interest to represent the regional benefit of sea ice initialization.

The most skillful region in SIC prediction is the Barents Sea (69-80°N, 15-52.5°E) and the second is the GIN Seas (63-80°N, 50W-15°E). Both regions are mostly covered by seasonal ice. As shown in Fig.4, initializing ocean and sea ice improves the SIC prediction greatly, especially from late summer to winter. However, the high prediction skills in winter SIC are mainly gained from the initial ocean temperature anomalies, consistent with other studies. The enhanced skills from sea-ice initialization are only evident between August and October and for longer lead years (Fig.4b, d). This result supports the hypothesis of winter preconditioning (Day et al, 2014) that initialized local SIV anomaly in the central Arctic Ocean constrains the seasonal ice expansion from next September in the marginal ice zone.

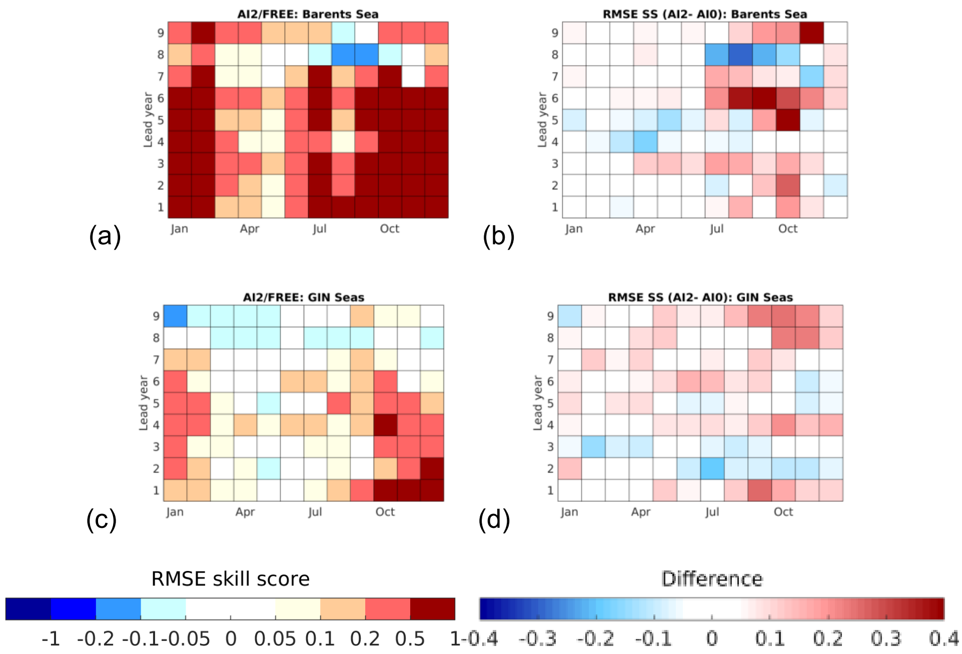


Figure 4. Skill comparison for SIC in the Barents (upper panels) and GIN (lower panels) Seas: (a) and (c) RMSE skill score of AI2 relative to FREE (AI2/FREE); (b) and (d) the difference of RMSE skill score between AI2 and AI0. The ratio of RMSE in AI2 to FREE is averaged over regions, and then AI2/FREE is calculated as 1-($RMSE_{AI2}$ /$RMSE_{FREE}$). White colors denote 0 score, which means RMSEs in AI2 and FREE are equal. The difference is calculated as AI2/FREE - AI0/FREE. Red (blue) colors denote higher (lower) skill score than the reference. (Figures from Tian et al., 2020).

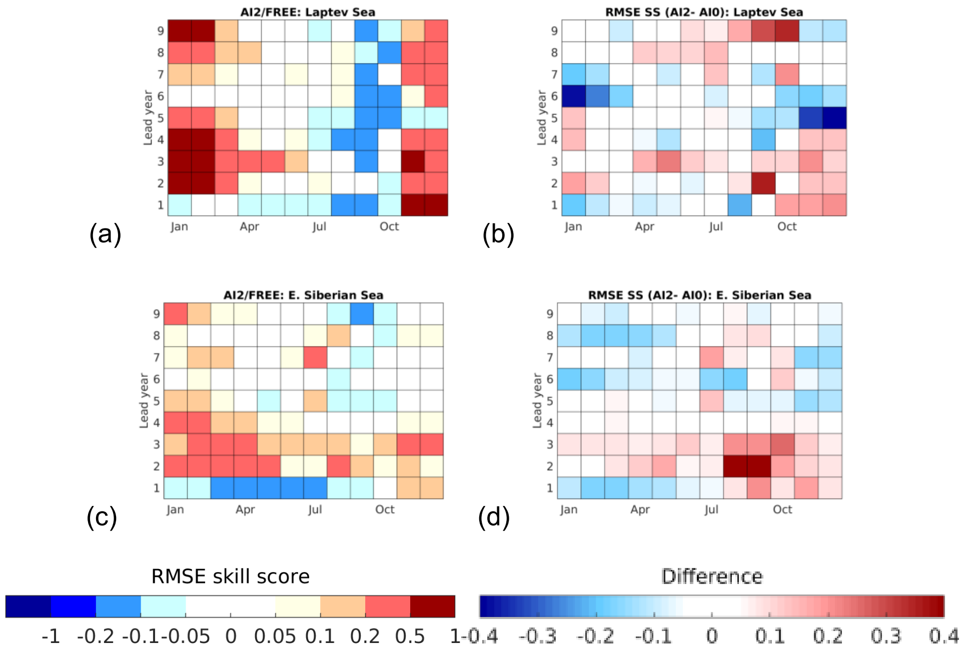


Figure 5. As Figure 4, but for SIT prediction in the Laptev (upper panels)/E. Siberian (lower panels) Seas. (Figures from Tian et al, 2020)

The skill score comparison also indicates that the regions with significant skill of SIT are consistently confined to the interior of the Arctic Basin. However, the winter preconditioning of SIT for the perennial ice in the central Arctic Ocean may also influence the predictions of SIT in the adjacent Arctic coastal waters. Fig. 5 shows the prediction skill score comparison for the Laptev Sea (70-80°N, 100 -142°E) and the East Siberian Sea (70-80°N, 142-180°E), where no SIT was applied. About 12-month lag of added skill for SIT can be seen in these regions. The regional SIT predictability is presumably associated with advective processes or winds (Guemas et al., 2016) with remote origins. Increased skill in SIT in turn improve skills in SIC (Fig.10 in Tian et al, 2020).

To summarize, by comparing the twin decadal prediction experiments with and without sea ice initialization, we have found some evidence of improved skill in the Arctic and in some atmospheric quantities (Tian et al, 2020). In particular, the results shown in Fig. 4 and Fig. 5 highlight the importance of initializing SIT for regional Arctic sea ice predictions at decadal time scale. This suggests that the persistence of multiple year ice thickness in the Central Arctic Ocean affects the interannual predictability of sea ice in its adjacent waters via advection process or wind, despite those regions can be seasonally ice free.

4.4 The predictability of the North Atlantic

To understand the prediction capability of the EC-Earth3-CPSAI, we analyzed the skill of decadal predictions for near surface temperature based on the above mentioned ensemble hindcast experiments for the period of 1960-2017. Here the prediction skill is measured by the correlation between the ensemble mean prediction at a specific forecast lead time and the observations. As

observations we use the NCEP (NOAA National Center for Environmental Prediction) reanalysis data set. As the forced variability is difficult to remove entirely, we assess the influence of initialization on the prediction skill by comparing the uninitialized
(historical) experiments with the initialized experiments. Such a comparison requires careful considerations of the statistical significance of skill and, in particular, differences in skill. Here this is done by Monte-Carlo methods.

Strong significant correlations are found for lead-time 1 year for both the historical and the hindcast ensemble. For longer lead-time good skill remain in many regions due to the forced variability. For the longest lead-times the skill of the forecasts is very close to the skill of the historical experiment (Fig. 6). Thus, for lead-times between 4-10 years little effect of initialization is found except in the subpolar North Atlantic (SPNA) region. This well-known result is found for other models also and is robust to temporal and spatial smoothing. It is also robust to different ways of estimating the significance.

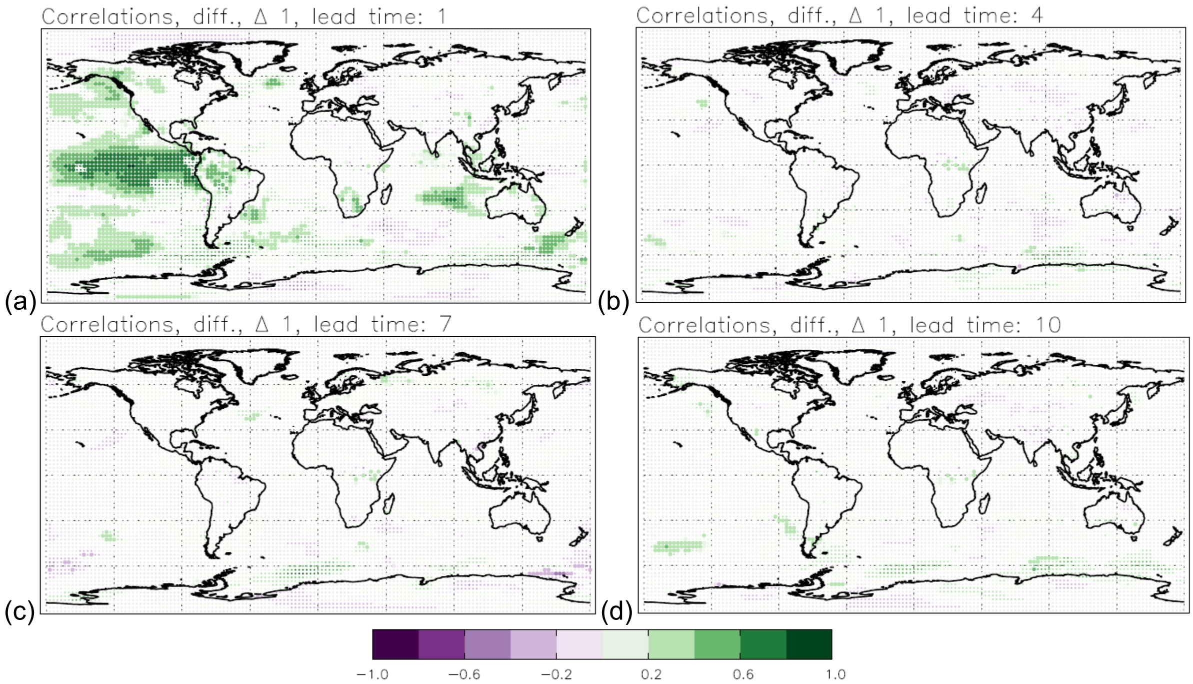


Figure 6. The difference of correlations for the forecast ensemble and the historical ensemble for lead-times of 1, 4, 7, and 10 years. Large dots are where the differences are significant to the 95 % level, i.e., where the initial conditions improve the skill. From Christiansen et al 2021, in preparation.

Fig. 7 shows time-series for the SPNA region. For this region large skill in the forecasts is found for all lead-times for the full period. However, for the periods before and after 1997 no or weak skill is found. Removing the jump in 1997 from observations by subtracting the means before and after, results in weak skills for lead-times larger than 1 year. Thus, the skill in the sub-polar gyre region is closely linked to the jump in 1997. This feature is also found in other models, but models disagree on whether this skill is due to forcing or initial conditions.

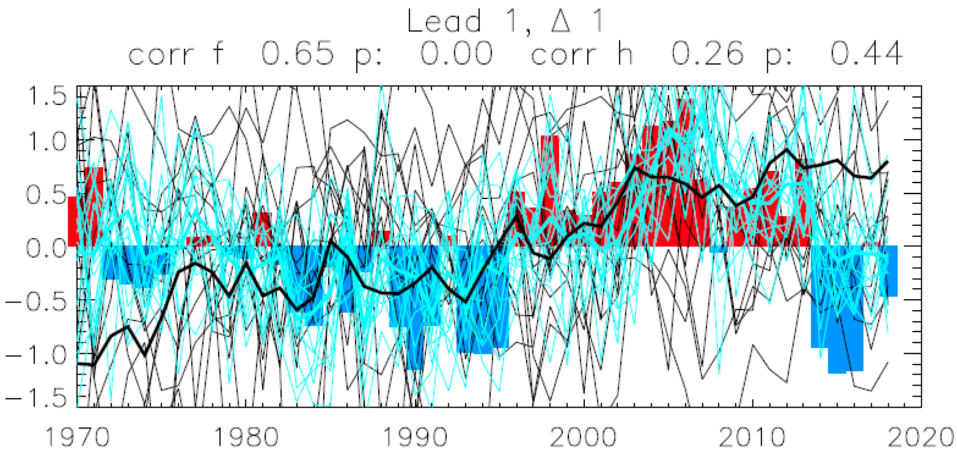


Figure 7. Time-series of the TAS in the subpolar gyre region (averaged over 15-40°W, 50-60°N). Bars are the observations. Thick black/cyan curve the ensemble mean of the historical/forecast experiments. Thin curves the individual ensemble members. (From Christiansen et al 2021, in preparation.)

The ensemble mean gives better skills than most individual ensemble members. The average skill improves with increasing ensemble size but large uncertainties are found. This suggests that it is important to include ensembles of the same size when comparing different models or model strategies.

The North Atlantic Oscillation (NAO) is the dominating mode of variability in the Atlantic and European regions. Recent work has indicated that the NOA may be predictable on decadal time-scales (Smith et al., 2019, 2020). However, the predicted NAO signal in the models is weak and requires huge ensembles to be identified. Here we have used both the EC-Earth3 ensemble and the 40 member ensemble from The Community Earth System Model (CESM) Large Ensemble Project (Kay et al., 2015) together with the corresponding Decadal Prediction Large Ensemble Project (Yeager et al., 2018) to investigate the predictability of the NAO. Figure 8 shows that for a lead-time of 1 year there is a small signal in the ensemble mean when forecasting the average NAO for the next 8 years (right panel). When forecasting only the next year, the skill is larger (left panel). In comparison, the historical ensemble does not show any signal for the next year but actually show a signal when the 8 year average is forecasted.

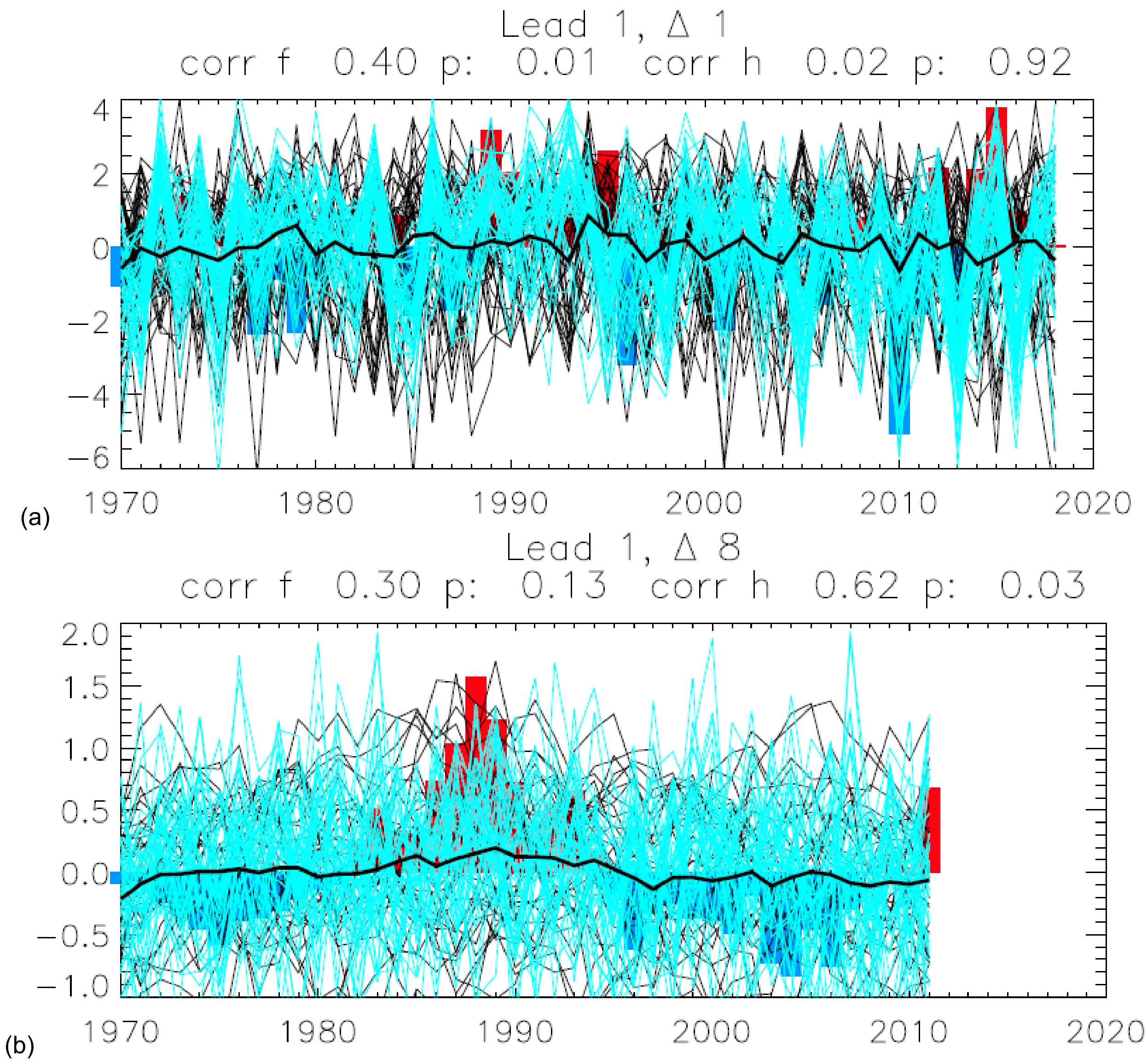


Figure 8. Time-series of NAO from the observations (solid), and as simulated by the climate model CESM in the initialized hindcast experiments (cyan) and in the uninitialized (historical) experiments (black). (a) Forecast for the first year; (b) Forecast for year 1-8. Thick curves are ensemble means, thin curves individual ensemble members.

To get an overall perspective we have calculated the skill (correlation between ensemble average and observations) for different lead-times and different averaging periods (Delta). This means, for example, that when the lead-time is 2 years and delta =4 then the average of the years 2-5 after the initialization is considered. Fig. 9 shows these correlations for the forecast ensemble (left) and historical (middel). Now the fragility of the skill is revealed. Most significant correlations are found for a lead-time of 1 year. The forecast has significant skill for Delta =1, 2, and 7, while the historical experiment has significant skill for Delta= 8 and 9. The difference in the correlations is shown in the right panel of Fig. 9. Only for a lead-time of 1 year does the initialization contribute significantly to the skill.

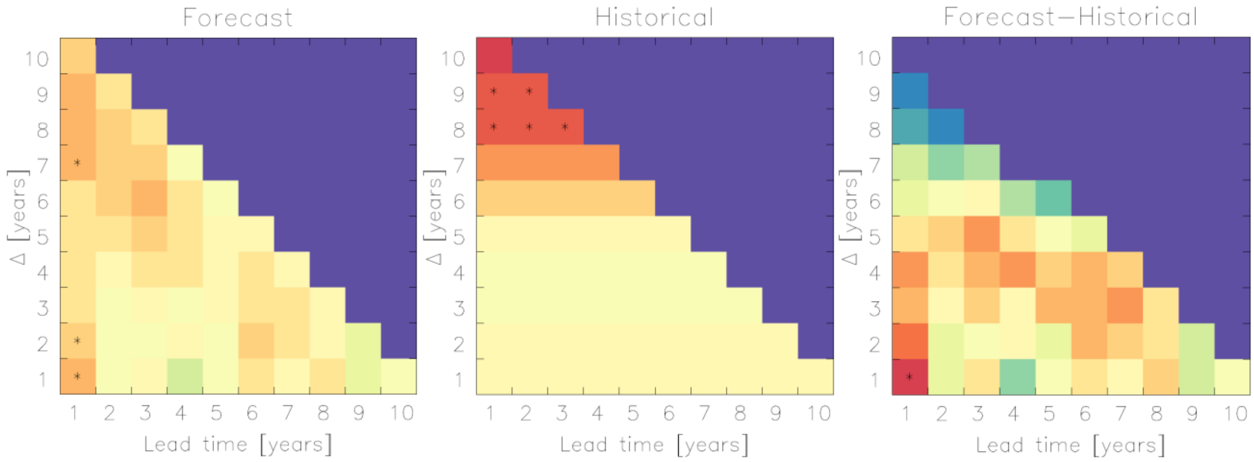
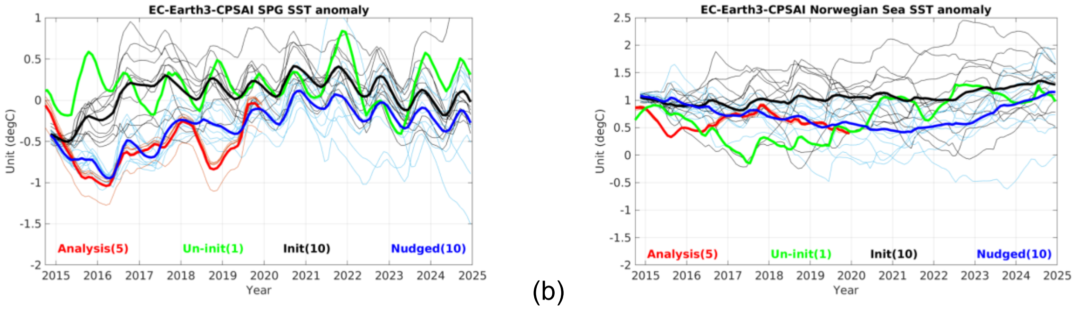


Figure 9. Correlations between observed and CESM model ensemble mean NAO as function of lead-time and averaging (Delta). Left: Initialized hindcasts; Middle: Unintialized Historical; Right: Difference.

4.5 Investigation of the subpolar North Atlantic as a possible source of predictability

The subpolar North Atlantic (SPNA) is a region experiencing substantial decadal variability which has been linked to important climate impacts. Recent studies have suggested that the connectivity with the SPNA may be a key to predictions in high latitudes. For example, retreat of the Barents Sea ice which contributes to the most pronounced Arctic sea ice loss in the recent years is a result of changes in poleward ocean heat transport from SPNA associated with the Norwegian Atlantic Current, the northernmost extension of the Gulf Stream (Li et al. 2017; Onarheim and Årthun 2017). The internal variability in the poleward ocean heat transport can lead to intermittent recoveries of the sea ice cover, superimposed on the long-term decline (Yeager et al. 2015; Årthun et al. 2017; Onarheim and Årthun 2017).

To understand the impact of the SPNA on predictability of North Atlantic-European sectors and the Arctic, we performed an ensemble of pacemaker experiments using EC-Earth3-CPSAI with a focus on the subpolar extreme cold anomaly event in 2015. The setup of the pacemaker experiments are the same as the CMIP6 DCPP-A hindcasts initialized on November 1, 2014, but with restoration of the ocean state in an extended subpolar North Atlantic region (i.e, 51.5°W - 13.0°W, 30.4°N - 57.5°N, and from surface to 1000 m depth in the ocean) to the observed state during the hindcasts. The restoration is implemented as a nudging of the ocean temperature and salinity in the given region following the ORAS5 reanalysis from the start of the hindcast in November 2014 to the end of 2019. The relaxation time of the nudging is set to 30 days. The 10-member ensemble of the initialized nudging hindcasts (EXP1) was compared to the (initialized) DCPP-A hindcast ensemble (EXP2) and the uninitialized ensemble (EXP3) for assessment of the prediction skill when the subpolar gyre cold anomaly is represented in the model. As can be seen in Fig. 10a, the nudging ensures that the modelled ocean temperature (e.g. SST) can represent the observed extreme cold anomaly in the region (blue lines), while the temperature in the initialized hindcasts (black) or the uninitialized runs (green) diverges from the observation quickly after the start of the hindcasts



(a) (b)

Figure 10. Time evolution of the monthly mean sea surface temperature (SST) anomalies averaged over (a) Subpolar North Atlantic defined as (40-15°W, 50-60°N) and (b) Norwegian Sea (10°W-15°E, 60-70°N) for initialized nudging hindcasts (blue), initialized hindcasts (black), uninitialized hindcasts (green) and the ORAS5 reanalysis (red). The thin lines present individual members while thick lines present the ensemble means. The numbers in parentheses presents the ensemble size for the respective experiments.

To investigate how the subpolar region affects the remote climate prediction skills, the time evolution of three sets of experiments are analysed and their skill scores are assessed. Fig. 11 illustrates the mean squared skill score (MSSS, Goddard et al, 2013) for the ensemble mean surface air temperature (tas) of the monthly predictions for the first year (left panels) and the annual prediction on multi-year time-scale covering year 2-6 (right panels) for the hindcasts starting at Nov. 1, 2014. To evaluate how well the model captures the observed/reanalysis variations, the model mean biases obtained using the baseline period 1979-2014 are removed from all ensemble hindcasts before the MSSS is calculated.

In the first prediction year, the initialized hindcasts (EXP2) performs generally better than the uninitialized hindcasts (i.e, the historical simulations, EXP3) over tropical pacific and Tropical Atlantic, and also over large areas of Eurasia and North America (Fig. 11a). However, the initialized experiment EXP2 is unable to predict, or shows even degraded skill comparing to EXP3 in the prediction of the extreme cold anomaly over SPNA developing during the 2014-2015. The predictions of tas over Greenland Sea, Norwegian Sea and Barents Sea are also degraded in EXP2 from EXP3. The poorly predicted tas anomaly in the subpolar North Atlantic in EXP2 expands in the following years, leading to the prediction skills further degraded over almost the entire North Atlantic except in the western subpolar region (Fig. 11b).

Figure 9c depicts the skill gained from nudging the ocean temperature and salinity in the SPNA (EXP1) over the initialized hindcasts (EXP2). As expected, nudging improved the predictions in the region quickly after the prediction starts. While no improved or even degraded skills are seen in many remote regions in Northern Hemisphere mid- and high latitudes in EXP1, the skills are generally higher in the low latitudes and in Southern hemisphere. On interannual to decadal time scales, the predictions in EXP1 over the entire North Atlantic improve greatly, with an increased MSSS in the EXP1 over EXP2 in particular outside of the nudging region, from the east subpolar gyre to the Nordic Seas, and also on the south and southwest of the subpolar region (Fig. 11d).

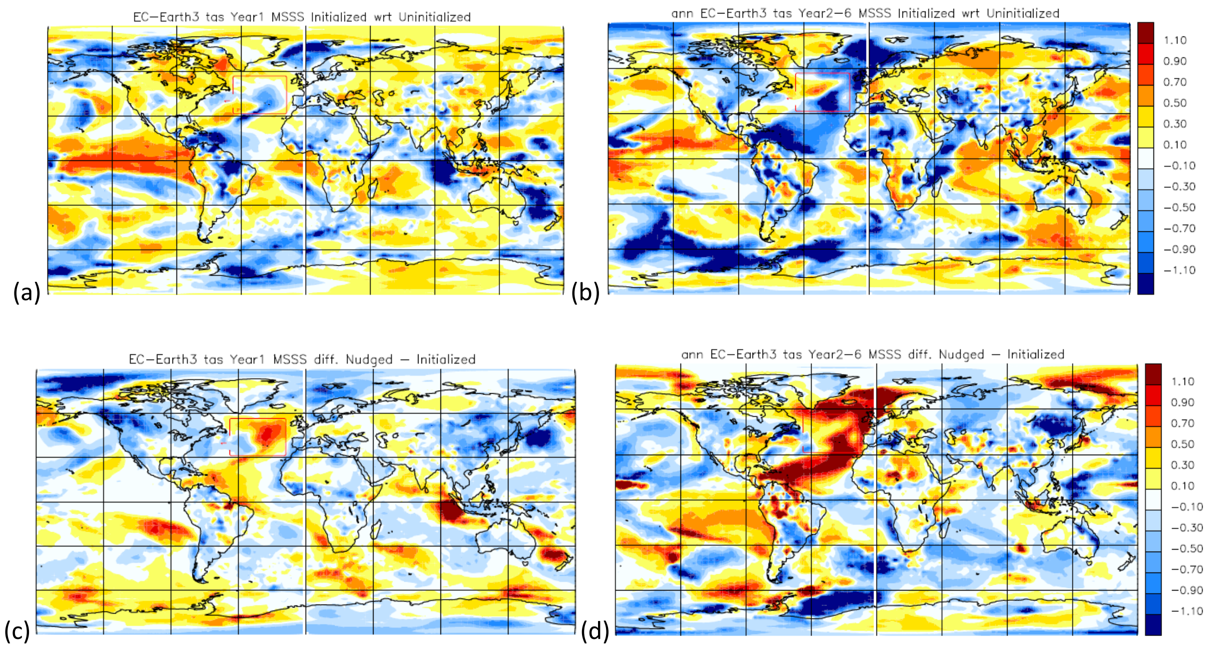


Figure 11. Upper row: Mean squared skill score (MSSS) for ensemble mean surface air temperature comparing EXP2 (initialized hindcasts) with EXP3 (uninitialized hindcasts) as reference. Bottom row: the MSSS difference between the EXP1 (nudged initialized hindcasts) and EXP2, both with the uninitialized hindcasts (EXP3) as reference. MSSS are calculated to measure the monthly prediction skill for the first year predictions (left panels, (a) and (c)) and the annual prediction skill on decadal time-scale covering year 2-6 (right panels, (b) and (d)) for the hindcasts starting at Nov. 1, 2014 using the EC-Earth3 prediction system. Warm colors indicate that the hindcasts of interest are more skillful than the reference hindcasts. The thin red box indicates there the nudging is applied. The red box indicates where the ocean restoration applied. (From Yang et. al., 2021)

The improved skill in Nordic seas in the EXP1 is clearly demonstrated in Fig. 10b, which shows the time evolution of the monthly mean sea surface temperature anomalies averaged over Norwegian Sea for the three experiments as well as the reanalysis ORAS5. In the beginning of the hindcast simulations, both the initialized nudging (EXP1, blue) and the initialized (EXP2, black) ensemble means are close to each other but away from the reanalysis ORAS5 (red), indicating the poor prediction skill in the region. However, the ensemble mean of EXP1 starts to diverge with EXP2 toward the OARS5 after about one and half years, and then following the variation of the ORAS5 thereafter.

To summarize, by restoring of the observed ocean state in the SPNA, we show that prediction skill in North Atlantic can be greatly improved, especially over the Nordic Seas, implying the importance of accurately represent the SPNA in climate models on climate predictions. Similar results are also found in the similar pacemaker experiments using the Norwegian climate model NorCPM1, in collaboration with the Nansen Environmental and Remote Sensing Centre and University of Bergen under the H2020 project Blue-Action. Subpolar North Atlantic as source of skillful predictions for the eastern Nordic Seas and the Barents Sea on interannual to decadal time scale has been suggested in several studies (Årthun et al, 2017, Langehaug et al, 2017). Our results support these previous studies.

4.6 Summary

In this WP, we have established a procedure for making ensemble climate predictions from seasonal-to-decadal timescales using EC-Earth3-CPSAI and reanalysis data sets for atmosphere, ocean and sea ice. We have used the system to perform the full suite of 10-member ensemble of the CMIP6 DCPP hindcast experiments for the period 1960-2018. An experimental ensemble forecast of 10 years, starting on Nov. 1, 2019, was also carried out.

Sensitivity experiments were performed using the prediction system to study the influence of sea ice initialization for seasonal to decadal timescales. We show that initializing the ocean state is important for prediction of the Arctic state on decadal time scales. The sea ice initialization may further improve the prediction skills in the Arctic. In particular, sea ice volume anomalies are found to play a dominant role for the prediction skill of September Arctic sea ice extent. Sea ice thickness in winter preconditions the perennial ice in the central Arctic Ocean, resulting in increased skill of sea ice concentration in the adjacent Arctic coastal waters.

In comparison with the uninitialized simulations, the added prediction skills by initialization are generally not very high on lead time longer than a few years. An exception may be the SPNA, where significant sill improvement is found. However, this improvement is likely linked to the abrupt warming in the mid 1990's. The SPNA is also a region with large influence on the predictability in remote regions. In an ensemble hindcast experiment in which the ocean conditions in SPNA are restored to the observed anomalies, we find that predictions in the entire north Atlantic are greatly improved for forecast several years ahead, especially in the Nordic Seas. The results suggest the possible role of the SPNA as a source of skillful predictions on interannual to decadal time scale, especially for high latitudes downstream of the North Atlantic pathways.

We expect to use the prototype prediction system for more experimental climate forecasts in the future to gain experience on predictions for climate variables/indicators on regions of interests (e.g., temperature and precipitations in Denmark/Europe, the ocean conditions of Nordic Seas, and the sea ice coverage in the Barents and Kara Seas, etc.). With this prediction system and the forecast experiments we will be able to further investigate in-depth the source of predictability, and thus improve our capability for providing useful and useable climate information in the coming decade.

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