Book of Abstracts

This workshop is a collaboration between the projects Blue-Action, ROADMAP and the Bjerknes Climate Prediction Unit, together with the CLIVAR Climate Dynamics Panel, the CLIVAR Atlantic Region Panel and CLIVAR Northern Oceans Region Panel. It is the final event for the H2020 Blue-Action project (GA 727852 https://blue-action.eu/)

Blue-Action has received funding from the European Union's Horizon 2020 R&I programme, grant 727852. Bjerknes Climate Prediction Unit is co-funded by the Trond Mohn Foundation. ROADMAP is jointly funded by JPI Climate and JPI Oceans.

Contents

Session 1 – Mechanisms and Predictability: Talks

Topic (Invited Speaker): External forcing on AMV
Author(s) & Affiliation(s): Katinka Bellomo, ISAC (IT)

Abstract: *forthcoming*

Title: On the (non)stationarity of the AMOC-AMV relationship
Author(s) & Affiliation(s): Alessio Bellucci (CNR-ISAC), Denis Mattei (University of Modena), Paolo Ruggieri (University of Bologna), Luca Famooss Paolini (University of Bologna)

Abstract: In this study we investigate the stationarity of the AMOC-AMV relation in a multi-model set of CMIP6 pre-industrial multi-century integrations. A methodology is devised to identify different AMOC-AMV co-variability regimes relying on a change-point detection algorithm applied to the time-evolving AMOC-AMV cross-correlation. Based on this analysis, the AMOC-AMV relationship reveals sharp transitions between correlated (CR) and non-correlated regimes (NCR), with individual regimes lasting several decades and the transitions occurring in a comparatively shorter (O(10) years) time span. The detected CR/NCR alternation is associated with a consistent non-stationarity in the spectral features of the AMV and AMOC signals, with the transitions from CR to NCR occurring in concomitance with a substantial reduction of the spectral energy in the multi-decadal frequency range. The connection between the detected changes in the correlation regimes and the magnitude of the variability is also inspected. Using the same sliding-window approach adopted for the AMOC-AMV cross-correlation, the time-evolving standard deviation and lag-1 autocorrelation ($\sigma(t)$ and $a1(t)$, respectively) are diagnosed. A robust feature emerging from this analysis is the strong connection between the degree of AMOC-AMV coupling, as portrayed by the CR and NCR regimes, and the variability, as evaluated by $\sigma(t)$ and $a1(t)$ of AMV and AMOC. It is found that during CR phases, $\sigma(t)$ and $a1(t)$ tend to be higher, compared to NCR phases.

The detection of spontaneous AMOC-AMV de-correlation episodes in an ensemble of high-dimensional, state-of-the-art climate models raises concern about the potential occurrence of similar decoupling episodes in the future, and the need for adequately long observational records to fully represent the long-term modulation of multi-decadal scale variability modes in the Atlantic sector.

Title: Decadal surface temperature prediction in the North Atlantic region in CMIP6
Author(s) & Affiliation(s): Leonard F. Borchert1,2, Matthew Menary1,2, Didier Swingedouw3, Giovanni Sgubin3, Daniel J. Befort4, Leon Hermanson5, Vimal Koul6,7, Juliette Mignot2 1: Laboratoire de Météorologie Dynamique (LMD), École Normale Supérieure (ENS), Paris, France 2: Sorbonne Universités (SU/CNRS/IRD/MNHN), LOCEAN Laboratory, Institut Pierre Simon Laplace (IPSL), Paris, France 3: EPOC, Université de Bordeaux, Pessac, France 4: Atmosphere, Ocean and Planetary Physics, Department of Physics, University of Oxford, UK 5: Met Office Hadley Centre, Exeter, UK 6: Institute

of Coastal Systems Analysis and Modeling, Helmholtz-Zentrum Geesthacht, Germany
7: Institute for Oceanography, University of Hamburg, Germany

Abstract: We assess decadal prediction skill for North Atlantic sea surface temperature (SST) and European summer temperature (EUST) in simulations from the CMIP6 archive. Both SST and EUST exhibit high prediction skill for the period 1970-2014 in CMIP6 multi-model ensembles. However, the added value of hindcast initialization is found to be low in CMIP6, indicating a larger role for external forcing in decadal predictions of North Atlantic surface temperature than previously thought. In this work, we explore the origins of skill for forced decadal North Atlantic SST changes, and then illustrate that a dynamical-statistical approach can help harvest the added value from initialization for decadal prediction of unforced EUST variations.

For North Atlantic SST, we find a particularly strong role of external forcing after the 1980s, which can be attributed to natural sources (i.e., solar and volcanic forcing). A conceptual model confirms that volcanic eruptions may be a major driver of decadal North Atlantic SST prediction skill after 1980.

An observed link between unforced EUST variations and spring Eastern North Atlantic SST helps overcome the limited skill for unforced EUST in CMIP6. Using this observed link and the predicted spring SST from the decadal predictions allows skillful dynamical-statistical predictions of EUST for lead-times of 2-9 years. Our work illustrates that dynamical-statistical models can serve to harvest the benefit of correct initialization and resulting prediction skill in the ocean to improve predictions of atmospheric variables over Europe, which have limited skill beyond the forcing.

Title: Are predictability timescales for Atlantic upper ocean heat content in models consistent with observations?

Author(s) & Affiliation(s): <u>Martha Buckley</u> (George Mason University, GMU), Laurie Trenary (GMU), Timothy DelSole (GMU), Laure Zanna (NYU)

Abstract: Increasingly, global coupled models are being used for decadal prediction. For example, CMIP5/CMIP6 models include a suite of decadal prediction experiments. A number of studies have focused on recent changes in the North Atlantic subpolar gyre, claiming that these changes are predictable. However, models differ substantially on the degree of predictability of Atlantic SST and upper ocean heat content (UOHC). In this work, predictability timescales for UOHC are estimated from gridded ocean observations and historical runs from CMIP5/CMIP6 Large Ensembles. For both observations and models, predictability timescales are estimated using a measure of the decorrelation timescale based on the local autocorrelation. Observations indicate that predictability timescales for UOHC are longest in the subpolar gyre, with timescales of 4—6 years in this region. Furthermore, spatial variations in wintertime mixed layer depths explain 50-70% of spatial variations in predictability timescales. Predictability timescales in models are also longest in the subpolar gyre, but the magnitude differs substantially among models. Spatial variations in predictability timescales are related to spatial variations in mixed layer depths in models, but the relationship is weaker than in observations. Predictability

timescales in some models are consistent with observations, but other models exhibit predictability timescales well outside the observational estimates.

Title: The forced signals and predictabilty in the NAO and AMO.

Author(s) & Affiliation(s): Bo Christiansen, Shuting Yang (Danish Meteorological Institute), and Dominic Matte (University of Copenhagen).

Abstract: We study the forced variability in the Northern Hemisphere with focus on the AMO and the AMO. We use a set of large model ensembles including the historical, hist-nat, and hist-GHG CMIP6 multi-model ensembles and the CMIP6 decadal forecasts.

For the forced NAO signal (ensemble mean) we find a significant correlation (0.51) between the historical CMIP6 and observations for the period after 1970. However, the signal is non-stationary and in earlier periods insignificant even negative correlations can be found. Conversely, the forced AMO signal reproduce well the observed low-frequency variability with a very statistical significant correlation for full period with observational data (1900--2012) of 0.55.

The forced AMO signal saturates fast with ensemble size and is fully saturated for a size around 10. However, for the NAO the correlation with observations (after 1970) increases and the amplitude decreases without any sign of saturation. The behavior with ensemble size -- both the mean and the spread -- can be explained by a simple model which includes the signal-to-noise ratios of the observations and the models.

Using the common sub-sample of models in CMIP6 historical and decadal forecasts we find that the ensemble mean forecast improves the skill of the NAO for most lead-times and averaging lengths although very little is statistical significant.

The non-stationary of the NAO signal, the huge ensemble needed to isolate it, and the seemingly small effect of initialization question the possibility of skillful NAO predictions on decadal timescales.

Title: Interactions Between the Stratospheric Polar Vortex and Atlantic circulation on seasonal and multi-decadal timescales

Author(s) & Affiliation(s): Oscar Dimdore-Miles, Lesley Gray, Scott Osprey

Abstract: Variations in the strength of the Northern Hemisphere winter polar stratospheric vortex can influence surface variability in the Atlantic sector. Disruptions of the vortex, known as sudden stratospheric warmings (SSWs), are associated with an equatorward shift and deceleration of the North Atlantic jet stream, negative phases of the North Atlantic Oscillation as well as cold snaps over Eurasia and North America. Despite clear influence at the surface on sub-seasonal timescales, how stratospheric vortex variability interacts with ocean circulation on decadal to multi-decadal timescales is less well understood. In this study we use a 1000-year pi-control of the UK Earth System Model to study such interactions using a wavelet analysis technique to examine non-stationary periodic signals in the vortex and ocean. We find that intervals which exhibit persistent anomalous vortex behaviour lead to oscillatory responses in the Atlantic Meridional Overturning Circulation (AMOC). The origin of these responses appears to be highly non-stationary spectral power in the vortex and the AMOC at periods of 30 and 50 years as well as feedbacks with the stratospheric influence over

the NAO. On longer timescales (near 90-year periods) the signals in the AMOC influence the vortex through a pathway involving the equatorial Pacific and Quasi-biennial Oscillation. Using the relationship between persistent vortex behaviour and the AMOC established in the model, we also estimate the contribution of the 8-year SSW hiatus interval in the 1990s to the recent negative trend in AMOC observations. Using a regression analysis, we estimate that approximately 10% of such a trend may be attributed to the hiatus. This result is significant for the recent discussion regarding anthropogenic forcing of the AMOC over the past decade and into the future.

Title: Variability of the North Atlantic Oscillation in the 20th century

Author(s) & Affiliation(s): André Düsterhus (1), Leonard Borchert (2) Vimal Koul (3, 4), Holger Pohlmann (5, 6), Sebastian Brune (4) (1) Irish Climate Analysis and Research UnitS (ICARUS), Department of Geography, Maynooth University, Maynooth, Ireland (2) Laboratoire de Météorologie Dynamique (LMD), École Normale Supérieure (ENS), Paris, France (3) Institute of Coastal Systems Analysis and Modeling, Helmholtz-Zentrum Geesthacht, Geesthacht, Germany (4) Institute of Oceanography, Center for Earth System Research and Sustainability, Universität Hamburg, Hamburg, Germany (5) Deutscher Wetterdienst, Hamburg, Germany (6) Max Planck Institute for Meteorology, Hamburg, Germany

Abstract: The North Atlantic Oscillation (NAO) has over the year a major influence on European weather. In many applications, being it in modern or paleo climate science, the NAO is assumed to varying in strength, but otherwise often understood as being a constant feature of the pressure system over the North Atlantic.
Recent studies stressed the variability of the NAO in features like position and strength. ""It can be shown in reanalyses that this variability is connected with the North Atlantic SST variability over the 20th century. Additionally, this variability coincides with the varying prediction skill of seasonal hindcasts. This opens the question, why this is the case and how well models are able to represent the NAO in all its variability over the 20th century.
To investigate this further we take a look at connections of the NAO and the North Atlantic SST on a seasonal to inter-annual time period. We analyse how it has changed over the 20th century within the model framework of the Max Planck Institute Earth System Model (MPI-ESM). We look at the ERA20C reanalysis as well as seasonal predictions and show that models are currently not in the position to represent the variability of the NAO appropriately. Finally, we discuss the implications of these findings for the Signal-to-Noise problem (SNP).

Title: The atmospheric response to meridional shifts of the Gulf Stream SST front in a multi-model ensemble of atmosphere-only simulations

Author(s) & Affiliation(s): Luca Famooss Paolini (Ca' Foscari University, Venice, Italy), Alessio Bellucci (Institute of Atmospheric Sciences and Climate - National Research Council (ISAC-CNR), Bologna, Italy), Paolo Ruggieri (dUniversity of Bologna, Department of Physics and Astronomy, Bologna, Italy), Panos Athanasiadis (Euro-Mediterranean Centre on Climate Change, Bologna, Italy)

Abstract: The Gulf Stream has been shown to play a key role in shaping the North Atlantic climate. Moreover, the associated SST front undergoes interannual to decadal variability that, on one hand is affected by atmospheric variability, and on the other hand is thought to force significant atmospheric circulation anomalies. However, general circulation models do not accurately reproduce the atmospheric response to prescribed SST front variability as estimated from observations. This aspect has been assessed in single-model studies using idealized forcings and finding the atmospheric resolution to be a limiting factor.
In this work we analyse the atmospheric response to Gulf Stream SST front shifting in a multi-model ensemble of historical atmosphere-only simulations forced with observed SSTs (1950–2014). In agreement with previous studies, the atmospheric response is found to be resolution dependent. Only the high-resolution simulations produce a wintertime response similar to the one implied by observations. More specifically: (i) analysis of the atmospheric thermodynamic balance at the vicinity of the SST front showed that the anomalous diabatic heating associated to displacements of the SST front is balanced mainly by vertical motion and by meridional transient eddy heat transport (not the case for low-resolution models), while (ii) the large-scale response includes a meridional shift in the North Atlantic eddy-driven jet and stormtrack that is homo-directional to the SST front displacement. This atmospheric response, which is stronger but similar in the observations, is found to be accompanied by changes in low-level baroclinicity to the north of the Gulf Stream extension, arguably resulting from the oceanic forcing and leading to changes in baroclinic activity (shown) and, ultimately, to the detected changes in the jet via eddy–mean flow interaction.
Considering coupled feedbacks and the two-way nature of air–sea interactions, the use of forced historical atmosphere-only simulations is a powerful way to isolate the impact of realistic oceanic variability on the atmosphere. Our results suggest that interannual to decadal predictability may be higher than what models currently indicate.

Title: Role of ocean dynamics in Atlantic sea surface temperature variability

Author(s) & Affiliation(s): <u>Olivia Gozdz</u>, Martha Buckley, and Tim DelSole (George Mason University)

Abstract: The North Atlantic has been shown to be the only region where ocean initialization leads to enhanced sea surface temperature (SST) predictability, thus understanding the mechanisms of SST variability has implications for predictability in this region. There is currently disagreement within the community regarding the role of active ocean dynamics in driving Atlantic SSTs. We investigate this by comparing North Atlantic SST variability between coupled models with a dynamical ocean (henceforth fully coupled model or FCM) and models where the ocean is represented by a motionless slab (henceforth slab ocean model or SOM). We implement a rigorous statistical method which tests whether SST in FCMs and SOMs are different and, if so, determines the spatial pattern that explains the differences as well as the associated variate time series. We show that SST variability in FCMs and SOMs are significantly different, due primarily to dissimilarities in internal variability opposed to differences in the mean states. The SST response to the North Atlantic Oscillation and the Atlantic Multidecadal Variability (AMV) have higher variance in the SOM compared to the FCM. This suggests that ocean dynamics are not necessary to construct the AMV and, in fact, may be damping it. Atlantic Nino and a mode of low frequency variability over the subpolar North Atlantic are found in the FCM, but not in the SOM. We show the mode of subpolar SST variability is associated with large sea surface height variations along the path of the North Atlantic current, suggesting the role of wind-driven ocean dynamics. We conclude that active ocean dynamics are more important for setting SST in the subpolar North Atlantic as well as the tropical Atlantic, also in line with previous studies.

Topic (Invited Speaker): Limits of predictability and the signal-to-noise problem.

Author(s) & Affiliation(s): Leon Hermanson, UK Met Office (UK)

Abstract: *forthcoming*

Title: Multi-year predictability of the atmospheric blocking stemming from the North Atlantic Ocean

Author(s) & Affiliation(s): Young-Oh Kwon (1), Panos Athanasiadis (2), Hyodae Seo (1), Caroline Ummenhofer (1), Terrence M. Joyce (1), Stephen G. Yeager (3), Alessio Bellucci (2), David W. Smith (4), and Stefano Tibaldi (2) (1: WHOI, USA; 2: CMCC, Italy; 3: NCAR, USA; 4: Northeastern Univ, USA)

Abstract: There exists a coherent multidecadal variability between North Atlantic atmospheric blocking frequency and the SST Atlantic Multidecadal Variability (AMV). In this study, we discuss the role of AMV in modulating blocking variability on multidecadal time scales using observational and reanalysis datasets for 1901-2010. The second mode of the empirical orthogonal function for winter (December–March) atmospheric blocking variability in the North Atlantic exhibits oppositely signed anomalies of blocking frequency over Greenland and the Azores. Following the warm phase of AMV, the warm SST anomalies emerge in the western subpolar gyre over 3–7 years. The ocean–atmosphere interaction over these 3–7-yr periods is characterized by the damping of the warm SST anomalies by the surface heat flux anomalies, which in turn reduce the overall meridional gradient of the air temperature and thus weaken the meridional transient eddy heat flux in the lower troposphere. The anomalous transient eddy forcing then shifts the eddy-driven jet equatorward, resulting in enhanced Rossby wave breaking and blocking on the northern flank of the jet over Greenland. In addition, we will present how such relationship render a significant multi-year predictability of the blocking over the high latitude North Atlantic in a state-of-the-art large ensemble decadal prediction experiment.

Title: Advancing climate predictions from mid-latitude North Atlantic to the Arctic

Author(s) & Affiliation(s): The WP4 team in Blue-Action, presented by Helene R. Langehaug, NERSC & BCCR (NO)

Abstract: Dynamical climate predictions are receiving much attention, such as through IPCC, WCRP, CMIP6, and there are continuous efforts to improve their predictive skill. This presentation is synthesizing results from WP4 in Blue-Action, which have focused on 'Enhancing the capacity of seasonal-to-decadal prediction in the

Arctic and over the Northern Hemisphere'. We thus summarize research related to predicting the mid- and high latitude North Atlantic including the Arctic region. The presentation mostly focuses on interannual to decadal timescales, with less emphasis on seasonal predictions.
We demonstrate that variability in ocean temperature and salinity are key sources of predictability both in the subpolar North Atlantic and Arctic regions. In particular, the melting of the Greenland ice sheet and external forcing, such as the impact of volcanic eruptions, contribute to predictability in the subpolar North Atlantic Ocean. At the same time, Arctic freshwater export anomalies as identified in the Fram Strait is found to have limited predictability. We find that the predictability in the ocean transfers to 1) predictability in Arctic Sea ice, although limited in climate predictions systems to a few years, and 2) predictability in the North Atlantic atmospheric circulation, notably when averaged on the decadal time scale, but also for interannual events. The ocean likely plays an essential role for predicting climate extremes over Europe, such as the European heatwave in 2015. However, it is still a challenge for current state-of-the-art climate prediction systems to reproduce such extreme events both in the ocean and its impacts over land. Large ensembles of high-resolution climate predictions might be needed to forecast such an extreme climate event.
During the Blue-Action project, most decadal prediction systems have been going through an overall improvement, while all systems involved in Blue-Action are providing data to CMIP6 DCPP. Data assimilation and initialization techniques are advancing, e.g., including updates for sea ice in addition to updates for the ocean, notably at depth. In addition, pacemaker experiments have been performed to build a better understanding of sources of predictability in our focus regions. However, decadal climate predictions are still facing several challenges, such as difficulties in representing key mechanisms and reducing systematic biases. In addition, there is a big challenge of the computational cost for producing climate predictions with high resolution and large ensembles. In the end of the presentation, we touch upon the potential of decadal climate predictions in long-term management, for instance by transferring predictions to useful information for climate services in Europe.

Title: Assessing the role of internal variability on projections of Northern Europe winter temperature at near-term (2020-2040) using a storyline approach

Author(s) & Affiliation(s): <u>Aurélien Liné,</u> Christophe Cassou, and Rym Msadek (CERFACS/CECI, France)

Abstract: Climate fluctuates under the dual influence of external forcings (natural and anthropogenic) and internal variability linked to the intrinsic properties of the climate system. The weight of the latter source gets stronger at regional scale and at near term. In this study, we focus on Northern Europe climate changes over the next two decades (2020-2040) using large ensembles of historical and scenario simulations conducted with the CNRM-CM6-1 model. We show that the uncertainty on wintertime temperature anomalies is dominated by internal variability, as the difference between the forced responses estimated from the 4 core-set socio-economic scenarios (SSP) assessed here appears secondary. We further explore, assess, and communicate this uncertainty through the determination of physical storylines defined as self-consistent and plausible unfoldings of a physical trajectory of the climate system, conditioned on specific explanatory elements, here drivers of internal variability. We identify the two main drivers in CNRM-CM6-1, namely the state of the Atlantic Meridional Overturning Circulation (AMOC) and the phase of the North Atlantic Oscillation (NAO), and obtain 4 storylines corresponding to the combination of these two drivers. In the high-impact storyline, characterized by the strongest warming, precipitation significantly increases, snow cover is reduced, and the probability for cold events drops with 10-yr return period episodes becoming a 32-yr one in that case. In the low-impact storyline, internal variability almost entirely cancels out the forced response leading to no-significant climate changes over the next two decades over Northern Europe. Epistemic uncertainty is then documented using large ensembles from other models as well as preliminary results regarding the probabilisation of the obtained storyline through observational constraint.

Topic (Invited Speaker): The role of ocean as a source of decadal predictability and the prediction of the cold blob

Author(s) & Affiliation(s): Elizabeth Maroon, University of Wisconsin (USA)

Abstract: *forthcoming*

Title: Skilful decadal predictions of subpolar North Atlantic SSTs using CMIP model-analogues

Author(s) & Affiliation(s): Matthew Menary (LOCEAN), Juliette Mignot (LOCEAN), Jon Robson (NCAS, University of Reading)

Abstract: Predicting regional climate variability is a key goal of initialised decadal predictions and the North Atlantic has been a major focus due to its high level of predictability and potential impact on European climate. These predictions often focus on decadal variability in sea surface temperatures (SSTs) in the North Atlantic subpolar gyre (NA SPG). In order to understand the value of initialisation, and justify the high costs of such systems, predictions are routinely measured against technologically simpler benchmarks. Here, we present a new model-analogue benchmark that aims to leverage the latent information in uninitialised climate model simulations to make decadal predictions of NA SPG SSTs. This system searches through more than one hundred thousand simulated years in CMIP archives and yields skilful predictions in its target region comparable to initialised systems. Analysis of the underlying behaviour of the system suggests the origins of this skill are physically plausible. Such a system can provide a useful benchmark for initialised systems within the NA SPG and also suggests that the limits in initialised decadal prediction skill in this region have not yet been reached.

Topic (Invited Speaker): Air-sea interactions

Author(s) & Affiliation(s): Shoshiro Minobe, Hokkaido University (JP)

Abstract: *forthcoming*

Title: Wind Stress-Induced Multiyear Predictability of Annual Sea Surface Temperature Anomalies in the Extratropical North Atlantic

Author(s) & Affiliation(s): Annika Reintges (GEOMAR), Mojib Latif (GEOMAR), Mohammad Hadi Bordbar (IOW), and Wonsun Park (GEOMAR)

Abstract: Predictability of North Atlantic Sea surface temperatures (SSTs) on timescales on several years and beyond is commonly attributed to buoyancy-forced changes of the Atlantic Meridional Overturning Circulation and associated poleward heat transport.

Here we examine the role of the wind stress anomalies in decadal hindcasts for the prediction of annual SST anomalies in the extratropical North Atlantic. A global climate model (KCM) is forced by ERA-interim wind stress anomalies over the period 1979-2017. The resulting climate states serve as initial conditions for decadal hindcasts.

We find significant skill in predicting annual SST anomalies over the central extratropical North Atlantic with anomaly correlation coefficients exceeding 0.6 at lead times of 4 to 7 years. The skill of annual SSTs is basically insensitive to the calendar month of initialization. We suggest that this skill is linked to a gyre-driven upper-ocean heat content anomaly that leads anomalous SSTs by several years.

Title: Dynamical and thermodynamical drivers of variability in European summer heat extremes

Author(s) & Affiliation(s): Laura Suarez-Gutierrez, Wolfgang A. Müller, Chao Li & Jochem Marotzke (Max Planck Institute for Meteorology)

Abstract: We use the 100-member Max Planck Institute Grand Ensemble (MPI-GE) to disentangle the contributions from colocated dynamic atmospheric conditions and local thermodynamic effects of moisture limitation as drivers of variability in European summer heat extremes. Using a novel extreme event definition, we find that heat extremes with respect to the evolving mean climate increase by 70% under a moderate warming scenario during the twenty-first century. With a multiple regression approach, we find that the dynamical mechanisms representing blocking and anticyclonic conditions are the main driver of variability in extreme European summer temperatures, both in past and future climates. By contrast, local thermodynamic drivers play a secondary role in explaining the total variability in extreme temperatures. We also find that considering both dynamical and thermodynamical sources of variability simultaneously is crucial. Assessing only one type of drivers leads to an overestimation of their effect on extreme temperatures, particularly when considering only thermodynamical drivers. Lastly, we find that although most past and future heat extremes occur under favorable dynamical atmospheric conditions; this occurs 10–40% less frequently over Central Europe in the twenty-first century. By contrast, heat extremes over Central Europe occur 40% more frequently under concurrent extreme moisture limitation in the twenty-first Century. Our findings highlight a new type of neutral-atmosphere, moisture-driven heat extremes, and confirm that the increase in European heat extremes and associated variability increase are dominated by the local thermodynamic effect of moisture limitation.

Title: Recent trends in summer atmospheric circulation in the North Atlantic/European region: is there a role for anthropogenic aerosols?

Author(s) & Affiliation(s): Buwen Dong and <u>Rowan Sutton</u>, National Centre for Atmospheric Science, University of Reading

Abstract: The variability of the westerly jet stream and storm track is crucial for summer weather and climate in the North Atlantic/European region. Observations for recent decades show notable trends in the summer jet from 1970s to 2010s, characterized by an equatorward migration over the North Atlantic accompanied by a poleward migration and weakening of the Mediterranean jet over Europe. These changes in atmospheric circulation were associated with more cyclonic storms traveling across the UK into northern Europe, and fewer over the Mediterranean, leading to wet summers in northern Europe and dry summers in southern Europe.

In this study we investigate the potential drivers and processes that may have been responsible for the observed changes in summer atmospheric circulation, with a particular focus on the role of anthropogenic aerosols (AA). We conduct attribution experiments with an atmospheric general circulation model (AGCM) forced with observed changes in sea surface temperatures/sea ice extent (SST/SIE), greenhouse gas concentrations and AA precursor emissions. Comparison between the model results and observations strongly suggests that fast responses to AA changes were likely the primary driver of the observed poleward migration and weakening of the Mediterranean jet, with changes in SST/SIE playing a secondary role. The simulated response shows good agreement with the observed changes in both magnitude and vertical structure, which suggests that common mechanisms - involving aerosol-radiation and aerosol-cloud interactions - are responsible. By contrast, changes in the North Atlantic jet are influenced in the model experiments by changes in both Atlantic SST/SIE (which may themselves have been influenced by changes in AA) and fast responses to AA. In this case, however, there are significant differences between the model response and the observed changes; we argue these differences may be explained by biases in the model climatology.

Title: Mechanisms of Decadal North Atlantic Climate Variability and Implications for the Recent Cold Anomaly

Author(s) & Affiliation(s): <u>Marius Årthun</u>; R.C.J. Wills; H.L. Johnson; L. Chafik; H.R. Langehaug

Abstract: There has recently been much focus on identifying the mechanisms responsible for Atlantic multidecadal variability (AMV). However, decadal-scale variability embedded within the AMV has received less attention, despite being a prominent feature of observed North Atlantic Sea surface temperature (SST) and important for the climate of adjacent continents. These decadal fluctuations in the North Atlantic Ocean are also a key source of skill in decadal climate predictions. However, the mechanisms underlying decadal SST variability remain to be fully understood. This study isolates the mechanisms driving North Atlantic SST variability on decadal time scales using low-frequency component analysis, which identifies the spatial and temporal structure of low-frequency variability. Based on observations, large ensemble historical simulations and pre-industrial control simulations, we identify a decadal mode of atmosphere-ocean variability in the North Atlantic with a

dominant time scale of 13-18 years. Large-scale atmospheric circulation anomalies drive SST anomalies both through contemporaneous air-sea heat fluxes and through delayed ocean circulation changes, the latter involving both the meridional overturning circulation and the horizontal gyre circulation. The decadal SST anomalies alter the atmospheric meridional temperature gradient, leading to a reversal of the initial atmospheric circulation anomaly. The temporal development and spatial pattern of observed decadal SST variability are consistent with the recent observed cooling in the subpolar North Atlantic. This strongly suggests that the recent cold anomaly in the subpolar North Atlantic is, in part, a result of decadal SST variability, and that we might expect it to become less pronounced over the next few years. The mechanism identified here furthermore represents the genesis mechanism of SST anomalies that are observed to progress northwards toward the Arctic in observations.

Session 1 – Mechanisms and Predictability: Posters

Title: Variable Nordic Seas inflow linked to shifts in North Atlantic circulation

Author(s) & Affiliation(s): Helene Asbjørnsen (1), Helen L. Johnson (2), Marius Årthun (1); (1) Geophysical Institute, University of Bergen and Bjerknes Centre for Climate Research, (2) Department of Earth Sciences, University of Oxford

Abstract: The inflow across the Iceland-Scotland Ridge determines the amount of heat supplied to the Nordic Seas from the subpolar North Atlantic (SPNA). Consequently, variable inflow properties and volume transport at the ridge influence marine ecosystems and sea ice extent further north. Here, we identify the upstream pathways of the Nordic Seas inflow, and assess the mechanisms responsible for interannual inflow variability. Using an eddy-permitting ocean model hindcast and a Lagrangian analysis tool, numerical particles are released at the ridge during 1986-2015 and tracked backward in time. We find an inflow that is well-mixed in terms of its properties, where 64% comes from the subtropics and 26% has a subpolar or Arctic origin. The local instantaneous response to the NAO is important for the overall transport of both subtropical and Arctic-origin waters at the ridge. In the years before reaching the ridge, the subtropical particles are influenced by atmospheric circulation anomalies in the gyre boundary region and over the SPNA, forcing shifts in the North Atlantic Current (NAC) and the subpolar front. An equatorward shifted NAC and westward shifted subpolar front correspond to a warmer, more saline inflow. Atmospheric circulation anomalies over the SPNA also affect the amount of Arctic-origin water re-routed from the Labrador Current toward the Nordic Seas. A high transport of Arctic-origin water is associated with a colder, fresher inflow across the Iceland-Scotland Ridge. The results thus demonstrate the importance of gyre dynamics and wind forcing in affecting the Nordic Seas inflow properties and volume transport.

Title: Trends, variability and predictive skill of the ocean heat content in North Atlantic: An analysis with the EC-Earth3 model

Author(s) & Affiliation(s): Teresa Carmo-Costa (1), Roberto Bilbao (2), Pablo Ortega (2), Ana Teles-Machado (1,3) and Emanuel Dutra (1,3). (1) IDL-FCUL; (2) BSC; (3) IPMA.

Abstract: In this study we investigate trends, variability and predictive skill of the upper ocean heat content (OHC) in the North Atlantic basin. This is a region where strong decadal variability superimposes the externally forced trends, introducing important differences in the local warming rates, and leading in the case of the Central Subpolar North Atlantic to an overall long-term cooling. Our analysis aims to better understand these regional differences, by investigating how internal and forced variability contribute to local trends, exploring also their role on the local prediction skill. The analysis combines the study of three ocean reanalyses to document the uncertainties related to observations, with two sets of CMIP6 experiments performed with the global coupled climate model EC-Earth3: a historical ensemble to characterise the forced signals; and a retrospective decadal prediction system, to additionally characterise the contributions from internal climate variability.

Our results show that internal variability is essential to understand the spatial pattern of North Atlantic OHC trends, contributing decisively to the local trends and providing high levels of predictive skill in the Eastern Subpolar North Atlantic and the Irminger and Iceland Seas, and to a lesser extent in the Labrador Sea. Skill and trends in other areas like the Subtropical North Atlantic, or the Gulf Stream Extension are mostly externally forced. Large observational and modeling uncertainties affect the trends and interannual variability in the Central Subpolar North Atlantic, the only region exhibiting a cooling during the study period, uncertainties that might explain the very poor local predictive skill.

Title: Decadal propagation of thermohaline pulses in the Arctic Ocean

Author(s) & Affiliation(s): Léon Chafik (MISU, Sweden), Marius Årthun (GFI, Norway), Helene Langehaug (NERSC, Norway) & Petteri Uotila (INAR, Finland)

Abstract: The Arctic has seen significant climatic changes over the last few decades. One of the major factors that drive the observed changes in the Arctic Ocean, and which is very likely to continue to do so in the future, is increased Atlantic Ocean heat transport. On decadal time scales, changes in Atlantic heat transport into the Arctic are thought to induce long-lived temperature and salinity (thermohaline) anomalies, as previously documented from in-situ observations. And although it is well established that thermohaline anomalies entering the Arctic Ocean have their source in the sub-Arctic seas and mainly arise as a result of changing northward supply of Atlantic Water along the main ocean current systems, less is understood regarding their spatio-temporal propagation and persistency within the Arctic Ocean. Using hydrographic observations and a suite of ocean reanalysis systems, we present evidence of decadal-scale cyclonic propagation of thermohaline anomalies around the Arctic Ocean along its boundary current system and discuss its triggering mechanism. We conclude that the spatial coherency and propagation time scale of the observed thermohaline anomalies have significant implications for an improved understanding of decadal Arctic Ocean climate variability and predictability.

Title: Anthropogenic aerosols and Arctic warming

Author(s) & Affiliation(s): Ioana Colfescu (NCAS, UK) and Massimo Bollasina (School of GeoSciences, U. Edinburgh, UK)

Abstract: Aerosols-climate interactions are one of the key unknowns that limit current understanding of the mechanisms of Arctic climate and Arctic amplification in the 20th century. This has important implications for the future warming during the 21st century. This study makes use of a series of CESM simulations to study the effects anthropogenic aerosol changes in driving recent changes in the Arctic and the underlying mechanisms. We analyse changes in the ice cover and gyre circulation as well as atmospheric patterns for the Arctic for different periods during the 20th century in a series of simulations with regional aerosol forcing over Europe and North America.

Title: Causes of recent and future Arctic sea-ice changes

Author(s) & Affiliation(s): David Docquier (Royal Meteorological Institute of Belgium), Stéphane Vannitsem (Royal Meteorological Institute of Belgium), Francesco Ragone (Royal Meteorological Institute of Belgium, and Université catholique de Louvain), Klaus Wyser (Swedish Meteorological and Hydrological Institute), X. San Liang (Nanjing Institute of Meteorology)

Abstract: Arctic sea ice has substantially changed over the past four decades, with a large decrease in sea-ice area and volume. These changes have been strongly driven by anthropogenic global warming, but also by internal climate variability. The exact causes of these changes are not entirely known due to the complex interplay between climate factors. In our study, we make use of the Swedish Meteorological and Hydrological Institute Large Ensemble (SMHI-LENS), consisting of 50 members realized with the EC-Earth3 global climate model. Model simulations cover the period 1970-2014 for the historical period, and 2015-2100 for the future period. We apply the Liang-Kleeman information flow method to analyze the cause-effect relationships between Arctic sea ice and its potential drivers, including atmospheric and sea surface temperature, atmospheric and ocean heat transport, Arctic Oscillation index. This technique allows to go beyond classical correlation analyses by quantifying the causality from one variable to the other. We show that the causal relationship between Arctic sea ice and its potential drivers changes over time, varies from one season to the other, and can sometimes be two-way, e.g. for near-surface atmospheric temperature and Arctic ocean heat transport. Our understanding of climate processes in polar regions (and at other latitudes) could greatly benefit from using this information flow method.

Title: The Sun's Role for Decadal Climate Predictability in the North Atlantic

Author(s) & Affiliation(s): Annika Drews1,2, Wenjuan Huo1, Katja Matthes1, Kunihiko Kodera3,4, and Tim Kruschke5 /// 1 GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany 2 SINTEF Ocean AS, Norway 3 Meteorological Research Institute, Japan 4 RIKEN Nishina Center for Accelerator-Based Science, Japan 5 SMHI – Rossby Centre, Sweden

Abstract: Despite several studies on decadal-scale solar influence on climate, a systematic detection of solar-induced signals at the surface and the Sun's contribution to decadal climate predictability is still missing. Here, we disentangle the solar-cycle-induced climate response from internal variability and from other external forcings such as greenhouse gases. We utilize two 10-member ensemble simulations with a state-of-the-art chemistry climate model, to date a unique data set in chemistry climate modelling. We quantify the potential predictability related to the solar cycle and demonstrate that the detectability of the solar influence on surface climate depends on the magnitude of the solar cycle. Further, we show that a strong solar cycle forcing organizes and synchronizes the decadal-scale component of the North Atlantic Oscillation, the dominant mode of climate variability in the North Atlantic region.

Title: The slowdown and recovery of the Atlantic meridional overturning circulation and the emergence of the North Atlantic warming hole in response to Arctic sea ice decline

Author(s) & Affiliation(s): Brady Ferster1, Amélie Simon1, Alexey Fedorov1,2, Juliette Mignot1, Eric Guilyardi1,3. 1LOCEAN-IPSL (Sorbonne Université, CNRS, IRD, MNHN), Paris, France. 2Department of Earth and Planetary Sciences, Yale University, New Haven, CT, USA. 3NCAS-Climate, University of Reading, Reading, UK.

Abstract: Arctic sea ice has been declining by 13% per decade between 1979-2018, with CMIP projections estimating a summer ice-free Arctic by 2050. The climate impacts of this sea ice decline are not solely confined to the Arctic region, but can extend globally. The global response conversely varies across different coupled climate models and at the same time strongly depends on the timescales considered (initial transient versus longer periods). Here, we conduct a sea-ice loss experiment with a coupled climate model from the Institut Pierre Simon Laplace (IPSL-CM5A2) and compare the results to similar experiments of the different modelling groups.

The transient to near-equilibrium climate response to Arctic sea ice loss is examined, with emphasis on drivers and mechanisms to AMOC variations. The experimental procedure, detailed in Simon et al. (2021), reduces the sea ice and snow cover albedo by -22.5% in IPSL-CM5A2, which results in a significant decline of sea ice within the Labrador, Irminger, and Nordic Seas, the latter two regions known for their importance to deep convection in this model. Reducing sea ice shows a robust southward shift of the subpolar gyre and the westerlies, which reduces deep convection and dense water formation across the subpolar region. The corresponding weakening of AMOC (-1.5 Sv) persists for the initial 100 years, which is later compensated by the opening of the Labrador Sea convection. In addition, the weakening and southward shift of the subpolar gyre allows for the increased salt and heat transports into the Nordic Seas, eventually forcing a local response in convection following the initial response (after years 100). This leads to a robust AMOC recovery (+0.5 Sv; years 151-200) due to the combined responses in the Labrador and Nordic Seas, compensating for the decline in the Iceland basin. In summary, we demonstrate that in the IPSL-CM5A2 model compensating deep convection changes in the Iceland basin (decrease) and Labrador and Nordic Seas (increase) could drive AMOC decrease and recovery in response to sea ice decline.

We also find that Arctic sea ice decline leads to the formation of the North Atlantic "warming hole" – a cold SST anomaly persisting despite the general warming of the North Atlantic. The southward shift of the westerlies appears to be the main cause of the warming hole as it emerges during the very first decade and continues strengthening throughout the experiment, despite the AMOC recovery.

Title: Predicatbility of Barents Sea Phytoplankton Concentration

Author(s) & Affiliation(s): Filippa Fransner, University of Bergen & BCCR (NO), et al.

Abstract: In this work we are investigating the predictability of Barents Sea phytoplankton concentration using two versions (with different initialization) of decadal predictions produced with NorCPM1 together with satellite chlorophyll products. We find the chlorophyll to be predictable up to lead year 2-5 along the ice edge, which most probably is linked to the predictability of sea ice (will be

investigated). A stronger predictability is found in the simulations with initialization of sea ice. A more detailed look into seasonal development of the phytoplankton blooms will be done.

Title: Exploring the influence of the Northeastern Pacific-generated atmospheric Rossby wave sources on interannual variability of summer precipitation and surface temperature over the Northern Hemisphere

Author(s) & Affiliation(s): Ramon Fuentes-Franco, Torben Koenigk, David Docquier, Federico Graef, Klaus Wyser (Swedish Meteorological and Hydrological Institute)

Abstract: The influence of Rossby wave sources (RWS) emitted on the Northeastern Pacific Ocean in the Northern Hemisphere during summer is analysed in the ERA5 reanalysis and new large ensemble performed with the EC-Earth3 model. We found a causal influence of the Rossby waves generated over the Northeastern Pacific Ocean, on a global climate response. Both the reanalysis ERA5 and the EC-Earth3 model show that RWS triggers wave-like patterns arising from the upper troposphere Northeastern Pacific region. We show that an increased Rossby wave sources intensity is related to negative temperature anomalies over western North America, and positive temperature anomalies over eastern North America concurrently increased precipitation over Northern Europe during summer and sea-ice concentration decrease in the Arctic. We also show that the North Atlantic plays a very important role in hindering or permitting that Rossby waves generated in the Pacific reach the Atlantic and modulate the atmospheric conditions over Europe. Such conditions were found in ERA5 and SMHI-LENS during colder and icier conditions over the North Atlantic.

Title: Assessment of the interannual variability of the continental snow cover in 1979-2014 and its climate impact

Author(s) & Affiliation(s): Gastineau Guillame et al.; UMR LOCEAN, Sorbonne Université/IRD/MNHM/CNRS, IPSL, Paris

Abstract: The interactions between the ocean, the atmospheric variability and the continental snow cover are investigated in different observational datasets and two large ensembles of atmosphere-only simulations, with prescribed sea surface temperature and sea ice concentration. A first ensemble uses observed surface boundary conditions, while a second ensemble is integrated with the same boundary conditions, but uses a repeated climatological sea ice concentration. The continental snow cover variability in these simulations is well represented, and shows the dominant forcing from the tropical Pacific and North Pacific sea surface temperature, while no robust influence of the sea ice concentration variability is found. The sea ice concentration influence is largest over the east European plain and north-eastern North America, with only up to 0.3% of the variance associated with sea ice. We also investigate the influence of Eurasian snow cover anomalies for the Northern Hemisphere atmospheric circulation. In observations, the interaction between snow cover and atmosphere is not robust, but a majority of observations find that the Ural blocking is important in forcing the snow cover over Eastern Eurasia November, which

is then linked to a negative Arctic oscillation one month later. In January, a larger snow cover over Eurasia in observations also tends to precede a negative Arctic oscillation phase one month later. In models, no influence of the snow cover anomalies in November or April is found. However, an influence of the January snow cover is found in most models, with a larger snow cover over Eurasia preceding a negative Arctic oscillation phase by one or two months. Depending on the models, the Eurasian snow cover variability in January can be generated by the Arctic Oscillation or the Ural blocking. In conclusion, we discuss the relative influence of Eurasian snow cover and Pacific sea surface temperature in models and observations.

Title: The impact of land-ocean contrast of the seasonal to decadal variability of the northern hemisphere jet stream 1871 -2011

Author(s) & Affiliation(s): Samantha Hallam, ICARUS, Maynooth University, Ireland; Gerard McCarthy, ICARUS, Maynooth University, Ireland; Joel Hirschi, National Oceanography Centre, Southampton, UK

Abstract: Seasonal to decadal variations in Northern Hemisphere jet stream latitude and speed over land (Eurasia, North America) and oceanic (North Atlantic, North Pacific) regions are presented for the period 1871 – 2011 from the Twentieth Century Reanalysis dataset.

Significant regional differences are seen on seasonal to decadal timescales. Seasonally the ocean acts to reduce the seasonal jet latitude range from 20° over Eurasia to 10° over the North Atlantic where the ocean meridional heat transport is greatest. The mean jet latitude range is at a minimum in winter (DJF) particularly along the western boundary of the North Atlantic and North Pacific, where the land-ocean contrast and sea surface temperature (SST) gradients are strongest.

The 141-year trends in jet latitude and speed show differences on a regional basis. The largest increasing trends in jet latitude and jet speed are observed in the North Atlantic, with increases in winter of 3° and 4.5ms-1, respectively. There are no trends in jet latitude or speed over the North Pacific.

Long term trends are overlaid by multi decadal variability. Over the North Atlantic in winter, jet latitude and NAO are in phase and show significant coherence explaining over 30% of the variance. In the North Pacific, 20-year variability in jet latitude and jet speed are seen, associated with the Pacific Decadal Oscillation which explains 50% of the winter variance in jet latitude since 1940.

The results highlight that northern hemisphere jet variability and trends differ on a regional basis (North Atlantic, North Pacific, Eurasia and North America) on seasonal to decadal timescales, indicating that different mechanisms are influencing the jet latitude and speed. This is important from a climate modelling perspective and for climate predictions in the near and longer term.

In addition, initial findings and future work planned on ocean circulation variability/western boundary currents, and links to the atmosphere will be presented.

Title: Atmospheric wind biases: A challenge for simulating the Arctic Ocean in coupled models?

Author(s) & Affiliation(s): Claudia Hinrichs, Q. Wang, N. Koldunov, L. Mu, T. Semmler, D. Sidorenko, and T. Jung (AWI, Germany)

Abstract: Many state-of-the-art climate models do not simulate the Atlantic Water (AW) layer in the Arctic Ocean realistically enough to address the question of future Arctic Atlantification and its associated feedback. Biases concerning the AW layer are commonly related to insufficient resolution and exaggerated mixing in the ocean component as well as unrealistic Atlantic-Arctic Ocean exchange. Based on sensitivity experiments with FESOM1.4, the ocean-sea ice component of the global climate model AWI-CM1, we show that even if all impediments for simulating AW realistically are addressed in the ocean model, new biases in the AW layer develop after coupling to an atmosphere model. By replacing the wind forcing over the Arctic with winds from a coupled simulation we show that a common bias in the atmospheric sea level pressure (SLP) gradient and its associated wind bias can disrupt the circulation of AW at intermediate depth and that an underestimation of sea ice can amplify the problem.

Title: Climate predictions with MIROC6

Author(s) & Affiliation(s): Takahito Kataoka (JAMSTEC), Hiroaki Tatebe (JAMSTEC), Hiroshi Koyama (JAMSTEC), Takashi Mochizuki (Kyushu University), Koji Ogochi (JAMSTEC), Hiroaki Naoe (MRI), Yukiko Imada (MRI), Hideo Shiogama (NIES), Masahide Kimoto (U Tokyo), and Masahiro Watanabe (U Tokyo)

Abstract: Climate predictability is examined using the latest version of a climate model MIROC (MIROC6) contributing to the CMIP6. MIROC6 is initialized every year for 1960-2018 by assimilating observed ocean temperature and salinity anomalies and full-fields of sea-ice concentration and by prescribing atmospheric initial states from reanalysis data. The impacts of updating the system on prediction skills are then evaluated by comparing hindcast experiments between the MIROC6 prediction system and a previous system based on MIROC version 5 (MIROC5). Skill of seasonal prediction is overall improved in association with representation and initialization of El Niño/Southern Oscillation (ENSO), the Quasi-Biennial Oscillation (QBO), and the Northern hemisphere sea-ice concentration in MIROC6. In particular, the QBO is skillfully predicted up to 3 years ahead with a maximum anomaly correlation exceeding r=0.8. The prediction skill for the North Atlantic Oscillation in winter is also enhanced, but the prediction still suffers from the model's inherent errors. On decadal timescales, MIROC6 has a larger fraction of areas of the globe with better surface temperature skill at all lead times than MIROC5, and it has predictive skill in the annual mean sea surface temperature (SST) in the North Atlantic and the Pacific. In particular, MIROC6 hindcasts at 2-5 years lead time can capture the spatial structure of SST changes in the North Pacific and the eastern tropical Pacific associated with the 1970s regime shift better than MIROC5 hindcasts.

Title: NAO predictability from external forcing in the late 20th century

Author(s) & Affiliation(s): Jeremy Klavans (University of Colorado Boulder), Mark Cane (LDEO, Columbia University), Amy Clement (RSMAS, University of Miami), Lisa Murphy-Goes (RSMAS, University of Miami)

Abstract: The North Atlantic Oscillation (NAO) is predictable in climate models at near-decadal timescales. Predictive skill derives from ocean initialization, which can capture variability internal to the climate system, and from external radiative forcing. Herein, we show that predictive skill for the NAO in a very large uninitialized multi-model ensemble is commensurate with previously reported skill from a state-of-the-art initialized prediction system. The uninitialized ensemble and initialized prediction system produce similar levels of skill for northern European precipitation and North Atlantic SSTs. Identifying these predictable components becomes possible in a very large ensemble, confirming the erroneously low signal-to-noise ratio previously identified in both initialized and uninitialized climate models. Though the results here imply that external radiative forcing is a major source of predictive skill for the NAO, they also indicate that ocean initialization may be important for particular NAO events (the mid-1990s strong positive NAO), and, as previously suggested, in certain ocean regions such as the subpolar North Atlantic ocean. Overall, we suggest that improving climate models' response to external radiative forcing may help resolve the known signal-to-noise error in climate models.

Title: Bjerknes Compensation between Poleward Atmospheric and Oceanic Heat Transports in CMIP6 Climate Simulations

Author(s) & Affiliation(s): Prajvala Kurtakoti1,2, Wilbert Weijer3 , and Milena Veneziani2; 1 Center for Nonlinear Studies (CNLS), Los Alamos National Laboratory; 2 Fluid Dynamics and Solid Mechanics (T-3), Los Alamos National Laboratory; 3 Computational Physics and Methods (CCS-2), Los Alamos National Laboratory

Abstract: The term 'Bjerknes Compensation' is used to describe the hypothesis that variations in the atmospheric and oceanic heat transport balance each other given the fluxes at the top of the atmosphere and the ocean heat content remain approximately constant. This study focuses on Bjerknes Compensation in polar latitudes across the Coupled Model Intercomparison Project Phase 6 (CMIP6) experiments and the mechanisms through which it occurs. The compensation in the northern polar latitudes is present in almost all CMIP6 experiments. While only a few historical simulations show compensation in the southern polar latitudes, it is enhanced in the 21st century, as seen in 1pctCO2 and abrupt-4XCO2 experiments. We investigate whether the compensation at higher latitudes (northern and southern) becomes stronger or weaker in a changing climate and the role of AMOC (Atlantic Meridional Overturning Circulation) and retreating sea ice in it.

Title: Predicting the 2015 North Atlantic Cold Blob and European Heat Wave

Author(s) & Affiliation(s): Jenny Mecking (National Oceanography Centre), Sybren Drijfhout (University of Southampton), Bablu Sinha (National Oceanography Centre), Joel Hirschi (National Oceanography Centre)

Abstract: In 2015 the eastern North Atlantic subpolar g¬¬¬yre had record cold conditions while globally it was the warmest year on record at that time. Observation based studies have found evidence that these SST anomalies can be linked to the heat wave experienced over Europe that summer. In the years following the cold blob the temperatures remained anomalously cold and anomalously fresh in the upper layers of the eastern North Atlantic Subpolar gyre. Being able to predict the development, enhancement and persistence of such an anomaly is essential for good seasonal and longer predictions. At present modelling systems have difficulties in simulating/maintaining the 2015 cold blob. In this work we apply a novel initialization technique using anomalies obtained from a forced ocean simulation to simulate the 2015 heat wave. The anomalous initialization technique was successful in re-forecasting the 2015 heat wave when initialized from May 1, 2015. To successfully model the heat wave the atmosphere, ocean and sea ice initial conditions have to work together well. This technique was then used again to study the 2015 cold blob initialized from Nov. 1, 2014. The winter of 2014/15 had a persistent positive NAO which led to a strengthening of the already cold North Atlantic SPG. Our experiments do capture a further reduction in heat content (often at the same time as a persistent positive NAO) in the cold blob region. However, the timing is off and typically 2-3 years too late (i.e. 2017 or 2018 and not 2015). This result suggests that the anomalous ocean conditions do not force a deterministic NAO response but affect the likelihood of occurrence of extreme NAO events.

Title: Sulphate-aerosol forced North Atlantic decadal variability in HadGEM3-GC3.1

Author(s) & Affiliation(s): Michael Lai (University of Reading), Jon Robson (NCAS), Laura Wilcox (NCAS), Nick Dunstone (UK Met Office)

Abstract: The response of the North Atlantic climate system to the varying levels of sulphate aerosol emissions from North America and Europe is investigated using an idealised experiment with HadGEM3-GC3.1. The results show that the overall response of North Atlantic SST is the result of two competing effects. First is the fast, wide-spread Northern Hemisphere cooling associated with the aerosol radiative effects. Second, is the slower aerosol-induced AMOC strengthening, which leads to a warming in the subpolar North Atlantic. This AMOC strengthening is driven by an increase in upper ocean density caused by high-latitude surface cooling. This surface cooling is in turn driven by both a decrease in incoming solar radiation and an increase in turbulent heat loss. Furthermore, atmospheric circulation changes appear to be largely unimportant, indicating a predominantly thermodynamic mechanism. Interestingly, the subtropical arm of Atlantic Multi-decadal Variability, which is a feature of both the historical and pre-industrial control simulations of the same model, is missing here. This suggests that the subtropical North Atlantic SST is not forced by sulphate aerosols alone.

Title: Decadal coastal sea level variability along the North American east coast

Author(s) & Affiliation(s): Christopher Little, Atmospheric and Environmental Research, Inc

Abstract: Interannual to multi-decadal fluctuations in sea level often overwhelm long-term secular trends, driving changes in the frequency and severity of coastal flooding, salt water intrusion and coastal erosion events, with important consequences for coastal communities. The prediction of such sea level anomalies is thus of considerable societal value, but requires additional efforts to: 1) characterize the nature of observed variability, including its amplitude and spatial structure; and 2) identify underlying physical mechanisms.

The North American east coast tide gauge record, extending into the 19th century, provides a valuable record of the amplitude and spatiotemporal structure of coastal sea level variability. Here, using wavelet analyses, I present evidence for multidecadal epochs of enhanced decadal (10-15 year period) sea level variability at almost all long (>70 years) east coast tide gauge records. Within this frequency band, large-scale spatial covariance is time-dependent; notably, coastal sectors north and south of Cape Hatteras exhibit multidecadal epochs of coherence (1960-1990) and incoherence (1990-present).

While presence of large-amplitude, quasi-periodic, variability comprises an opportunity for skillful sea level prediction, a better understanding of the underlying mechanisms -- both for decadal variability and its modulation in space and time -- are required. In this talk, I describe a few leading hypotheses, highlighting potential associations with the North Atlantic sea surface temperature tripole and Atlantic Multidecadal Variability.

Title: Labrador Slope Water Connects the Subarctic with the Gulf Stream

Author(s) & Affiliation(s): Adrian L. New1, D. A. Smeed1, A. Czaja2, A. T. Blaker1, J. V. Mecking1, J. P. Mathews2 and A. Sanchez-Franks1 1. National Oceanography Centre, European Way, Southampton, SO14 3ZH, UK 2. Imperial College, Westminster, London, SW7 2AZ, UK

Abstract: Labrador Slope Water (LSLW) is found in the Slope Sea on the US-Canadian eastern shelf-slope as a relatively fresh and cool water mass, lying between the upper layer water masses and those carried by the Deep Western Boundary Current. It originates from the Labrador Current in the Subarctic and has potential densities of 27.4-27.65 kg m-3. Using the EN4 gridded database and the Line W hydrographic observations, we show here for the first time that the LSLW penetrates as a boundary current into the Western Slope Sea (west of 66°W) where it is brought into close contact with the Gulf Stream. The LSLW also spreads across the entire Slope Sea north of the Gulf Stream, bringing fresher and thicker waters to the region in this layer. This spreading is investigated in a high-resolution ocean general circulation model, and is found to occur through the extrusion of fine-scale filaments from the boundary current following interaction with Gulf Stream meanders and eddies, and resulting in downward vertical motion as the filaments are entrained into the Gulf Stream. The water mass is also found to be fresher and thicker between 2003-2008 than between 2009-2014. During the former period the Atlantic Meridional Overturning Circulation at 26°N is higher (by 3 Sv), and the Shelf Slope Front (SSF) at Line W is further south (by 1°), than during the latter period. The thicker LSLW causes lighter isopycnals to rise over the shelf slope, and through increasing the density gradient across the Gulf Stream is likely to contribute an additional 1.5 Sv to the Gulf Stream transport. These changes to the

LSLW and the SSF are likely to result from an enhanced flow of the Labrador Current into the Slope Sea, caused by changes in the wind stress in the subpolar gyre. The transport of the LSLW (as opposed to the deeper Labrador Sea Water) thereby offers a potential new mechanism, not resolvable in the current suite of climate models, for decadal variability in the Atlantic climate system, through connecting changes in the Subarctic with subsequent variability in the Gulf Stream and AMOC.

Title: Interaction of Atlantic Meridional Overturning Circulation and Sub-Polar Gyre on decadal timescale

Author(s) & Affiliation(s): Stephen Ogungbenro, Leonard Borchert, Sebastian Brune, Vimal Koul, Levke Caesar and André Düsterhus Maynooth University, ICARUS, Geography Department, Co. Kildare, Ireland • Sorbonne Universités (UPMC/CNRS/IRD/MNHN), LOCEAN Laboratory, Institut Pierre Simon Laplace (IPSL), Paris, France • Institute of Oceanography, CEN, Universität Hamburg, Bundesstr. 53, 20146 Hamburg, Germany • Institute of Coastal Systems Analysis and Modeling, Helmholtz-Zentrum Geesthacht, Geesthacht, Germany • Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, P.O. Box 60 12 03, D-14412 Potsdam, Germany.

Abstract: The Atlantic Meridional Overturning Circulation (AMOC) is responsible for the northward transport of mass and heat, and the distribution of nutrients and chemicals within the North Atlantic. In addition, large-scale changes in the subpolar North Atlantic are associated with activity in the Subpolar Gyre (SPG). Changes in the strength, intensity, and position of the constituent currents of the SPG affect the heat and salt distribution in the region. Therefore, understanding the interaction between the AMOC and SPG is critical for more accurate forecasting and to document their respective influence on the climate of the region.

Our contribution investigates the interaction between AMOC and SPG within the Max Planck Institute for Meteorology Earth System Model (MPI-ESM). In an effort to establishing a decadal to multi-decadal prediction system for AMOC and SPG, we extended our prediction for up to twenty lead years. We analysed the model's capability in predicting AMOC and SPG, as well as their interdependence. We investigate the relationships between AMOC and SPG on timescales up to twenty years and demonstrate that predictions are possible on time scales greater than 10 years. This study opens new opportunities for a better understanding of the impact of the North Atlantic onto important marine ecosystems and their changes in the upcoming decade.

Title: Understanding the multidecadal Northern Hemisphere climate variably from the perspective of damped Coupled stratosphere/troposphere/Ocean oscillation

Author(s) & Affiliation(s): Nour-Eddine Omrani, University of Bergen and BCCR (NO)

Abstract: Using long term coupled atmosphere/ocean-simulation, we show that the framework of damped coupled stratosphere/troposphere/Ocean Oscillation can help understanding the observed Northern Hemispheric multidecadal variability. In this Oscillation, the Large-scale Atlantic cooling is associated with positive winter North Atlantic Oscillation (NAO), strengthening and cooling of the stratospheric polar vortex

and deepening of Labrador-seas mixed layer. This leads to delayed strengthening of the Atlantic Overturning circulation (AMOC) and subpolar gyre enhancing the Atlantic poleward heat transport. This Ocean circulation changes lead to a large-scale Atlantic warming and shift into negative NAO-phase in association with weakening and warming in the stratospheric polar vortex. The negative NAO acts in turn to weaken the AMOC and subpolar gyre, which shifts again the Oscillation into the large-scale Atlantic cooling.

Title: Incorporating missing volcanic impacts into future climate projections

Author(s) & Affiliation(s): Stephen Outten (Nansen Center), Ingo Bethke (UiB), and Peter Thorne (NUIM)

Abstract: Future climate projections for the 21st century generally do not include the effects of volcanic eruptions. While some attempt has been made to account for the integrated effect of multiple eruptions by incorporating a small continuous volcanic forcing, a recent study (http://nature.com/articles/doi:10.1038/nclimate3394) has already shown that this approach is insufficient to resolve the increased climate variance caused by individual eruptions, especially on decadal timescales. Increased climate variance exerts stresses on ecosystems and society, thus resolving the impacts of plausible future volcanic eruptions is of importance for certain adaptation and mitigation decisions.

We will briefly present out published work based on ensembles of NorESM simulations for future periods including plausible volcanic forcings and discuss the impacts these forcings have on future projections of global mean surface temperatures. We will also demonstrate a recently developed, computationally inexpensive method to incorporate the effects of plausible volcanic eruptions into future climate projections. This method uses stochastic volcanic emulators based on 2,500 years of past volcanic activity and the characterization of the response of the climate system to individual eruptions. We will discuss the requirements and potential for its application to the wider future projections of CMIP6 and for other variables of interest.

Title: Seasonal prediction in northern Atlantic Ocean and Norwegian Seas

Author(s) & Affiliation(s): Noel Keenlyside1,2,3, Sunil Pariyar1,3, Ingo Bethke1,3, Yiguo Wang2,3, and Francois Counillon2,3, 1University of Bergen, Geophysical Institute, Bergen, Norway, 2Nansen Environmental and Remote Sensing Center, Bergen, Norway, 3Bjerknes Centre for Climate Research, Bergen, Norway

Abstract: Recent operational systems are able to predict sea surface temperature (SST) on seasonal timescales in the extra-tropical North Atlantic and Nordic Seas to a high-degree and as high as in the tropical Pacific. While prediction on multi-year timescales is well documented, the source of the high skill on seasonal timescales is unclear and somewhat unexpected. Here, using the Norwegian Climate Prediction model, we show that the skill on seasonal timescales is associated primarily with low-frequency variability (timescales longer than five years). Consistently, there is high skill in predicting SST anomalies six seasons in advance, although there is a skill drop across boreal summer that seems associated with reduced vertical mixing. External forcing and initialized ocean variability contribute similarly to skill on seasonal timescales, as assessed through a heat budget analysis. Skill on these timescales can benefit fisheries and aqua culture.

Title: Multi-model assessment of decadal climate predictability in the North Atlantic

Author(s) & Affiliation(s): Leilane Passos1,2, Helene Langehaug2,3, Marius Årthun1,2 and Tor Eldevik1,2. 1-Geophysical Institute, University of Bergen; 2-Bjerknes Centre for Climate Research; 3-NERSC

Abstract: Variations of sea surface temperature and salinity in the North Atlantic play an important role in the climate of northwestern Europe (Årthun et al. 2017; Simpson et al. 2019). In the Subpolar North Atlantic, abyssal changes in ventilated deep water coming from the Labrador Sea were recently pointed out as the main driver of the predictable decadal changes in upper ocean heat content (Yeager 2020). Upper ocean thermohaline anomalies propagate from the Subpolar North Atlantic into the Nordic Seas, bringing predictability in the northern seas up to a decade ahead. However, significant predictive skill on decadal time scale in the Nordic Seas is not currently achieved by climate models (Langehaug et al. 2017). A better understanding of how climate models represent key mechanisms for predictability in the North Atlantic is needed. Identifying whether the lack of predictive skill is related to poor initialization or incorrect model physics, can contribute to more trustful long-term predictions. In this work, we investigate the physical mechanisms underlying North Atlantic prediction skill in observed-based data and climate models from the Decadal Climate Prediction Project of CMIP6. This will include both hindcasts, to assess skill, and North Atlantic pacemaker experiments, to assess key mechanisms. First, we evaluate water mass formation in the Labrador Sea and the spread of this water mass in the Subpolar North Atlantic, and secondly, how this spread is linked to upper ocean heat content in the Subpolar North Atlantic and the Nordic Seas. The main goal of this work is to address how much of the observed hydrographic variations in the Subpolar North Atlantic are captured by the models, and how the variable representation of subpolar water masses in models impacts the Nordic Seas and the Arctic. The preliminary results of this investigation are presented.

Title: How does anthropogenic aerosol forcing drive a strengthening of the AMOC in CMIP6 historical simulations?

Author(s) & Affiliation(s): Jon Robson, NCAS, University of Reading (UK)

Abstract: Previous work has shown that anthropogenic aerosol emissions drive a strengthening in the Atlantic Meridional Overturning Circulation (AMOC) in CMIP6 historical simulations over ~1850-1985. However, the mechanisms driving the increase are not fully understood. Previously, forced AMOC changes have been linked to changes in surface heat fluxes, changes in salinity, and interhemispheric energy imbalances. Here we will show that across CMIP6 historical simulations there is a strong correlation between ocean heat loss from the subpolar North Atlantic and the forced change in the AMOC. Furthermore, the model spread in the surface heat flux change explains the spread of the AMOC response and is correlated with the strength of the models' aerosol forcing. However, the AMOC change is not strongly related to changes in downwelling surface shortwave radiation over the North Atlantic, showing that anthropogenic aerosols do not drive AMOC change through changes in the local

surface radiation budget. Rather, by separating the models into those with 'strong' and 'weak' aerosol forcing, we show that aerosols appear to predominantly imprint their impact on the AMOC through changes in surface air temperature over the Northern Hemisphere and the consequent impact on latent and sensible heat flux. This thermodynamic driver (i.e. more heat loss from the North Atlantic) is enhanced both by the increase in the AMOC itself, which acts as a positive feedback, and by a response in atmospheric circulation.

Title: Influence of SST front along the Gulf Stream on the European climate

Author(s) & Affiliation(s): Emilia Sanchez-Gomez, Rym Msadek, Victor Rousseau, Marie-Pierre Moine CECI/CERFACS, Toulouse, France

Abstract: The Gulf Stream (GS) region is characterized by the presence of sharp SST gradients associated to strong mesoscale ocean activity. Observations and models reveal the presence of an extended wind convergence zone together with a large precipitation band over the GS. Previous studies have suggested that the Gulf Stream convergence zone can be interpreted as the local response of the marine atmospheric boundary layer (MABL) to the mesoscale SST, although the mechanisms at play and their respective contribution are still under debate. Moreover, it has been suggested that the SST front could affect not only the local MABL, but also the free troposphere and potentially the climate in remote regions such as Europe.
The goal of this study is to investigate the effect of the SST frontal zone along the GS over the European climate. In order to better isolate the influence of the SST front on the atmosphere, we have performed stand-alone idealized experiments in which the SSTs are smoothed only over the GS region to partly suppress the influence of the large gradients. This "smooth" experiment is compared with a control experiment in which the atmospheric model (ARPEGEv.6) is globally forced by very high resolution observed SSTs (1/12◦). The comparison between these two experiments shows that SST front locally influence the MABL and also the free troposphere. In particular, the precipitation band over the GS is decreased in the smooth experiment. We also find that the SST front induces a northward shift of the storm-tracks, eddy heat and humidity transports. This shift is consistent with a poleward shift of the jet stream. We show that together with the jet stream changes, weather regimes in the North Atlantic are also influenced by the SST front. As a result, the response of the large-scale atmospheric circulation yields changes in temperature and precipitation over Europe, suggesting a non-downstream influence of the SST frontal zone along the GS.

Title: Long-Range Predictability of the Length of Day and Extratropical Climate

Author(s) & Affiliation(s): Adam Scaife(1,2), Hermanson, L.(1), van Niekerk, A.(1), Baldwin, M. P.(3), Belcher S.(1), Bett, P.(1), Comer, R. E.(1), Dunstone N. J.(1), Geen R.(2), Hardiman S. C.(1), Ineson S.(1), Knight J.(1), Nie Y.(4), Ren H.-L.(5), and Smith D.(1). 1 - Met Office, Fitz Roy Road, Exeter, EX1 3PB, UK. 2 - College of Engineering, Mathematics and Physical Sciences, University of Exeter, UK. 3 - Department of Mathematics and Global Systems Institute, University of Exeter, UK. 4 - Beijing Climate Centre, China Meteorological Administration, Beijing, China. 5 - State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, China Meteorological Administration, Beijing, China.

Abstract: Angular momentum is fundamental to the structure and variability of the atmosphere and hence regional weather and climate. Total atmospheric angular momentum (AAM) is also directly related to the rotation rate of the Earth and hence the length of day. However, the long-range predictability of fluctuations in the length of day, atmospheric angular momentum and the implications for climate prediction are unknown. Here we show that fluctuations in AAM and the length of day are predictable out to more than a year ahead and that this provides an atmospheric source of long-range predictability of surface climate. Using ensemble forecasts from a dynamical climate model we demonstrate predictable signals in the atmospheric angular momentum field that propagate slowly and coherently polewards into the northern and southern hemisphere due to wave-mean flow interaction within the atmosphere. These predictable signals are also shown to precede changes in extratropical surface climate via the North Atlantic Oscillation. These results provide a novel source of long-range predictability of climate from within the atmosphere, greatly extend the lead time for length of day predictions and link geodesy with climate variability.

Title: The North Atlantic Oscillation at synoptic time scale and beyond

Author(s) & Affiliation(s): Torben Schmith, Steffen M. Olsen, Shuting Yang (DMI), Jens H. Christensen (University of Copenhagen)

Abstract: The North Atlantic Oscillation (NAO) is the leading mode of atmospheric variability in the North Atlantic region which influences the weather and climate in North Atlantic-European sector and is therefore the pivot in advancing understanding of long-term predictability in the region.

The present understanding is that the NAO winter signal consists of positive and negative NAO 'events' with the well-known spatial NAO-pattern and duration up to 10 days. A negative (positive) NAO winter thus consists of mainly negative (positive) NAO events, while a near-neutral NAO winter consists of a mixture of positive and negative NAO events.

In the present work we examine the role of time scales beyond the synoptic time scale. We show that the spatial pattern and amplitude of the positive and negative NAO events dependent on the NAO 'precursor' 10-30 days prior to the event. A detailed statistical analysis reveals that the influence of the precursor is most pronounced for negative NAO events. The influence is seen in the MSLP-field, as well as in other important features, such as blocking frequency and distribution of temperature and precipitation. This new understanding could have a bearing on improving methods to predict the NAO on time scales from seasons to decades.

Title: Interannual variability and predictability of the Barents Sea temperature

Author(s) & Affiliation(s): Ilya V. Serykh, Kostianoy A.G., Shirshov Institute of Oceanology RAS, Geophysical Center RAS

Abstract: Analysis of monthly average temperature of the Barents Sea at various depths showed its significant increase for the period 1948-2016. Moreover, the temperature increase has markedly accelerated since the mid-1980s. Against the background of this growth, temperature fluctuations were found over periods of 2-7 years, about 10 years and about 15 years. An assumption has been put forward that these fluctuations are related to the El Nino - Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO) and changes in the North Atlantic Current (NAC), respectively. It is shown that temperature anomalies associated with ENSO, the NAO and changes in the NAC affect the upper 100-meter layer of the Barents Sea. The relationship between ENSO and the temperature of the Barents Sea is positive for periods from 2 to 4 years, and negative for periods from 4 to 7 years. Moreover, the unsteady behavior of these connections is observed: a shift in the time periods of oscillations, as well as calendar periods for their synchronization and desynchronization. The relationship between the temperature of the Barents Sea and the NAC over periods of about 10 years is positive and also demonstrates unsteady behavior: since the beginning of the 2000s, energy has been transferred downward in time scales - to periods of 5-7 years, more typical for ENSO. It has been hypothesized that the Global Atmospheric Oscillation (GAO), whose elements are the Southern Oscillation and NAO, can serve as the synchronizing mechanism of interannual fluctuations in the tropics of the Pacific Ocean, the North Atlantic, and the Barents Sea. The relationship between the interdecadal temperature fluctuations of the Barents Sea and changes in the temperature anomalies of the NAC over a period of about 15 years is positive for the considered calendar period, and is associated with the transfer of temperature anomalies from the North Atlantic to the Barents Sea region both through the atmosphere and ocean currents. Therefore, using the current states of ENSO, NAO and NAC, the predictability of the Barents Sea temperature for the several years ahead could be improved.
The study was carried out within the financial support of the Russian Science Foundation project No 21-77-30010.

Title: Phytoplankton bloom phenology along the Norwegian continental shelf
Author(s) & Affiliation(s): Edson Silva, NERSC & BCCR (NO)

Abstract: Understanding the phenology of blooms and their key drivers is extremely important for fishery management. While some studies have assessed the bloom phenology in local regions along the Norwegian shelf for short periods, there is a need for assessing the bloom phenology of the entire Norwegian shelf and investigate its evolution over the past 20 years. This assessment is done here by using validated remote sensing surface chlorophyll-a (chl-a) for a region that extends from the south of the North Sea (50°N) to the Barents Sea Opening (BSO) (80°N) and from 25°W to 40°E. We use the Ocean Colour Climate Change Initiative project chl-a data, which has a spatial resolution of 4 km estimated from MODIS, MERIS, OLCI, SeaWiFS, and VIIRS sensors, and re-arranged as 8-day averaged data to limit cloud pollution. First, the spatial variability of chl-a is clustered into 16 sub-regions with the k-means algorithm and the remote sensing data validated against in situ data. Second, the blooms phenology shifts and trends from 2000 to 2020 are estimated for each cluster. Third, we relate the characteristic of the bloom phenology shifts and interannual variability to

physical and biogeochemical parameters – e.g., sea surface temperature, mixed layer depth, wind speed, and suspended particulate matter (SPM).
In the North Sea, the spring blooms are more intense in the English Channel entrance and on the Danish coast (up to 4.5 mg m-3) than in the northern part (up to 1 mg m-3). The spring bloom starts in January and lasts up to March, while autumn bloom starts in July and ends in September. The spring and autumn bloom phenology is not showing a significant trend over the 20 years. Waters with low SPM seem an important driver of years with more intense spring bloom in the northern region (R^2=0.28).
In the Norwegian Sea, the spring bloom is relatively weak (up to 1.2 mg-3). The spring bloom starts in March close to the coast and in May in the offshore waters, while the autumn bloom begins in July and ends in September. The spring bloom intensity in the Norwegian coast and close to the Greenland Sea shows an increasing trend of 0.03 mg m-3 yr-1. The bloom intensity in its Southern part (near Scotland) relates to the temperature anomaly of the Norwegian Atlantic current (R^2=0.5). The autumn bloom onset and peak day show a pronounced trend and are being delayed by 1-day yr-1 in almost the entire Norwegian Sea.
In the BSO, the spring bloom starts in April and ends in May - June (with an intensity average up to 3 mg m-3). The spring bloom onset in the offshore waters shows a rapid decrease of - 0.75-day yr-1 in the past 20 years. Furthermore, there is a high variability of the spring bloom intensity, varying from 1 mg m-3 in the weakest year (2008) to 4.1 mg m-3 in the strongest year (2002).

Title: Modulation of the winter atmospheric response to Arctic sea-ice loss by the Pacific decadal variability

Author(s) & Affiliation(s): Amelie Simon, LOCEAN-IPSL/ IDL (FR)

Abstract: The winter atmospheric response to sea-ice loss is investigated in atmosphere-only and coupled ocean-atmosphere experiments of the IPSL-CM6A-LR model. In response to sea-ice loss, both the atmospheric and coupled experiments simulate a small negative North-Atlantic oscillation (NAO) like pattern. This pattern is associated with a weakening of the poleward flank of the eddy-driven jet and superposed onto lower-tropospheric warming over the Arctic. Nevertheless, the NAO-like pattern is larger in the coupled experiments, with a significant weakening of the polar vortex that is not present in the atmosphere-only experiments. By investigating the associated SSTs, we suggest that the Pacific decadal oscillation modulates non-linearly the response to sea-ice loss in the coupled experiment, resulting in a weakening of the polar vortex enhancing the dynamical changes. Indeed, all simulations starting from a negative PDO phase all result in a weakening of the Aleutian low which may further enhance the vertical propagation of planetary wave into the stratosphere.

Title: Nordic Seas Heat Loss, Atlantic Inflow, and Arctic Sea Ice cover over the last century

Author(s) & Affiliation(s): Lars H. Smedsrud, A. Brakstad, E. Madonna, M. Muilwijk, S. K. Lauvset, C. Spensberger, A. Born, T. Eldevik, H. Drange, E. Jeansson, C. Li, A. Olsen, Ø. Skagseth, D. Slater, F. Straneo, K. Våge & M. Årthun.

Abstract: Poleward ocean heat transport is a key process in the earth system. We detail and review the northward Atlantic Water (AW) flow, Arctic Ocean heat transport and heat loss to the atmosphere since 1900, in relation to sea ice cover. Our synthesis is largely based on a sea ice-ocean model forced by a reanalysis atmosphere (1900-2018) corroborated by a comprehensive hydrographic database (1950-), AW inflow observations (1996-), and key long-term time series. The Arctic Seas, including the Nordic and Barents Seas, have warmed since the 1970s, especially on the shelves. This warming is congruent with increased ocean heat transport and sea ice loss, and has contributed to the retreat of marine terminating glaciers on Greenland. Heat loss to the atmosphere is largest in the Nordic Seas (60% of total): with large variability linked to the frequency of Cold Air Outbreaks and cyclones in the region, but the long-term positive trend is small. Heat loss from the Barents Sea (~30%) and Arctic Seas farther north (~10%) is overall smaller, but have large positive trends. The AW inflow, heat loss to the atmosphere, and dense outflow have thus all increased since 1900. These are consistently related through theoretical scaling, but the AW inflow increase is also wind-driven. The Nordic, Barents and other Arctic Seas CO2 uptake constitutes ~8% of the global uptake and seems largely driven by heat loss. This uptake has increased by ~30% over the last century - consistent with Arctic sea ice loss allowing more regional air-sea interaction.

Title: Arctic warming: the driver and modulators

Author(s) & Affiliation(s): Lingling Suo, NERSC & BCCR (NO)

Abstract: The Arctic climate during the past several decades underwent both strong surface to upper tropospheric warming. However, the relative contributions from various potential drivers and modulators of the Arctic tropospheric warming are yet to be evaluated. Here, we utilize the coordinated multi-atmospheric large ensemble model simulations to quantify the respective contributions of the external radiative forcing (ERF), the Arctic sea-ice changes (ASIC), the interdecadal Pacific variability (IPV) and the Atlantic multidecadal variability (AMV) to the Arctic tropospheric warming during 1979-2013.

The warming trend during 1979-2013 was primarily driven by the atmospheric ERF and is notably modulated in decadal time scale by several factors, such as decadal variations of ERF and IPV and AMV phase transition. IPV and AMV in a negative-to-positive phase transition tend to intensify the warming. ASIC showed almost no impact on the interdecadal variations of the tropospheric warming above 700hPa.

Title: Potential Fram Strait circulation feedback freshens the Arctic Ocean

Author(s) & Affiliation(s): Tarun Verma, Los Alamos National Laboratory (USA)

Abstract: In recent decades, the upper Arctic Ocean has become increasingly fresher; meanwhile, the northern hemisphere sea ice extent and thickness have reduced. An increase in meteoric freshwater fluxes and a decrease in the rate at which freshwater is transferred from the ocean to the sea ice are often considered the primary drivers of pan-Arctic Ocean freshening. The relative role of changes in the freshwater transports through ocean gateways has gained less attention, and coupled with the circulation changes that accompany it, are not fully understood.

Here, we investigate multidecadal variations in gateway transports and their atmospheric and oceanic drivers in a large ensemble of fully-coupled historical CESM simulations and a comparable JRA55-do-forced ocean-sea ice simulation. We highlight the effect of gateway transports on the delicate balance between various sources and sinks of Arctic liquid freshwater, resulting in its accumulation. We show evidence of a potential Fram Strait circulation feedback that freshens the Arctic and illustrate the feedback mechanism within the forced ocean-sea ice simulation.

Title: On the multi-annual to decadal potential predictability of the Arctic Ocean state in the INM RAS climate model

Author(s) & Affiliation(s): Vasilisa V. Vorobyeva (Marchuk Institute of Numerical Mathematics, Russian Academy of Sciences (INM RAS); Moscow Institute of Physics and Technology (National Research University)), E. M. Volodin (Marchuk Institute of Numerical Mathematics, Russian Academy of Sciences (INM RAS))

Abstract: The potential predictability of basic ocean and ice fields in the North Atlantic-Arctic sector is studied on multi-annual to decadal timescales using idealized numerical experiments with the Institute of Numerical Mathematics Russian Academy of Sciences (INM RAS) climate model. It is shown that the signal-to-noise ratio for the projection of the 0-300m layer average annual mean water temperature to the first EOF exceeds 1 for 4-5 years of calculations. Meridional current velocity averaged over the region 68-72N, 10-15E and salinity in the upper 300 m water layer can also be predicted for about the same period. Positive water temperature and salinity anomalies are preceded by a state with an inflow of Atlantic water into the Arctic Ocean exceeding the average value for several years. The research on location of regions with significant potential oceanic fields predictability and their changes during the time is provided. Surface fields, including annual mean water temperature, salinity, ice concentration and mass, sea ice area in the Arctic have less signal-to-noise ratio than the average water temperature and salinity of the 0-300 m layer. For a time interval of 6-10 years, the signal-to-noise ratio for these fields does not exceed 1 almost everywhere.

Title: The critical role of the subpolar North Atlantic region in skillful climate predictions for high northern latitudes

Author(s) & Affiliation(s): Shuting Yang (DMI), Tian Tian (DMI), Yiguo Wang (NERSC), Torben Schmith (DMI), Annika Drews (SINTEF Ocean), Steffen M. Olsen (DMI) and Noel Keenlyside (UiB)

Abstract: Several recent studies based on observations have suggested that the Atlantic water pathway connecting the oceanic anomalies from the subpolar North Atlantic (SPNA) to the Arctic Ocean may lead to skillful predictions of sea surface temperature and salinity anomalies in the eastern Nordic Seas. In this study we investigate the role of SPNA on predictability of the high latitude North Atlantic and the Arctic using two climate prediction systems, the EC-Earth3-CPSAI and NorCPM1. We focus on the subpolar extreme cold anomaly in 2015 which is generally underestimated by the decadal prediction systems at any lead time. In order to force

the models to better represent the observed anomaly in the SPNA, we design a pacemaker prediction experiment that follows the protocol of the CMIP6 DCPP-A hindcasts and initialized on November 1, 2014, but the ocean temperature and salinity in the SPNA are restored to the observed conditions from the reanalyses in both model systems. Restoring is applied during the hindcasts from November 2014 to December 2019. Multi-member ensembles of 10-year hindcasts are performed with 10 members for the EC-Earth3-CPSAI and 30 members for the NorCPM1. The ensembles of pacemaker experiment are then compared with the ensembles of initialized CMIP6 DCPP-A hindcast experiment and the uninitialized experiment, as well as the observations from 2014 to 2020.
The assessment of the prediction skills demonstrates that restoring the ocean temperature and salinity anomalies in the SPNA region to the ocean reanalysis improves the prediction in the region quickly after the simulation starts during the restoring period, as expected. On the interannual to decadal time scales, the areas with improved prediction skills extend to over almost the entire North Atlantic and large part of the Arctic Ocean for both prediction systems. The improved skill over Nordic Seas is particularly significant, implying a critical role of the SPNA as a source of skillful predictions for high latitudes at annual to decadal lead time. Further analyses are carried out to understand the mechanism connecting the changes in SPNA and the high latitudes that gives rise to the predictability, differentiating between oceanic or atmospheric pathways.

Title: An Outsized Role for the Labrador Sea in the Multidecadal Variability of the Atlantic Overturning Circulation

Author(s) & Affiliation(s): Steve Yeager (NCAR/iHESP), Fred Castruccio (NCAR/iHESP), Ping Chang (TAMU/iHESP), Gokhan Danabasoglu (NCAR/iHESP), Elizabeth Maroon (UW), Justin Small (NCAR/iHESP), Hong Wang (OUC/iHESP), Lixin Wu (QNLM/iHESP), Shaoqing Zhang (OUC/iHESP)

Abstract: Climate models are essential tools for investigating intrinsic North Atlantic variability related to variations in the Atlantic meridional overturning circulation (AMOC), but recent observations have called into question the fidelity of models that emphasize the importance of Labrador Sea processes. A multi-century pre-industrial simulation that resolves ocean mesoscale eddies has a realistic representation of key observed subpolar Atlantic phenomena, including the dominance of density-space overturning in the eastern subpolar gyre, and thus provides uniquely credible context for interpreting short observational records. Despite weak mean surface diapycnal transformation in the Labrador Sea, multidecadal AMOC variability can be traced to anomalous production of dense Labrador Sea Water with local buoyancy forcing in the interior Labrador Sea playing a significant driving role.

Session 2 – Advances in Models and Initialisation: Talks

Title: High-resolution Ensemble Kalman Filter with a low-resolution model using a machine learning super-resolution approach

Author(s) & Affiliation(s): Sébastien Barthélémy, University of Bergen & BCCR (NO)

Abstract: Going from low- to high-resolution models is an efficient way to improve the data assimilation process in three ways: it makes better use of high-resolution observations, it represents more accurately the small scale features of the dynamics and it provides a high-resolution field that can further be used as an initial condition of a forecast. Of course, the pitfall of such an approach is the cost of computing a forecast with a high-resolution numerical model. This drawback is even more acute when using an ensemble data assimilation approach, such as the ensemble Kalman filter, for which an ensemble of forecasts is to be issued by the numerical model.

In our approach, we propose to use a cheap low-resolution model to provide the forecast while still performing the assimilation step in a high-resolution space. The principle of the algorithm is based on a machine learning approach: from a low-resolution forecast, a neural network (NN) emulates a high-resolution field that can then be used to assimilate high-resolution observations. This NN super-resolution operator is trained on one high-resolution simulation. This new data assimilation approach denoted ""Super-resolution data assimilation"" (SRDA), is built on an ensemble Kalman filter (EnKF) algorithm.

We applied SRDA to a quasi-geostrophic model representing simplified ocean dynamics of the surface layer, with a low-resolution up to four times smaller than the reference high-resolution (so the cost of the model is divided by 64). We show that this approach outperforms the standard low-resolution data assimilation approach and the SRDA method using standard interpolation instead of a neural network as a super-resolution operator. For the reduced cost of a low-resolution model, SRDA provides a high-resolution field with an error close to that of the field that would be obtained using a high-resolution model.

Title: Decadal prediction skill of sea surface temperatures in the subpolar North Atlantic with and without ocean data assimilation

Author(s) & Affiliation(s): Sebastian Brune (1), Vimal Koul (1,2) and Johanna Baehr (1); (1) Institute of Oceanography, CEN, Universität Hamburg, Germany; (2) Helmholtz-Zentrum Hereon, Institute of Coastal Systems, Geesthacht, Germany

Abstract: Data assimilation experiments are carried out with the Max Planck Institute Earth System Model to assess the impact of initialisation on decadal prediction skill of surface temperatures in the subpolar North Atlantic. We compare the impact of initial conditions derived through full-field atmospheric nudging with those derived through an additional assimilation of observed oceanic temperature and salinity profiles using an ensemble Kalman filter. Our experiments suggest that assimilation of observed oceanic temperature and salinity profiles into the model reduces the warm bias in the subpolar North Atlantic heat content, and improves the modelled variability of the Atlantic meridional overturning circulation and ocean heat transport. These improvements enable a model consistent initialisation of model variables which leads

to an improved decadal prediction of surface temperatures. Our results reveal an important role of sub-surface oceanic observations in decadal prediction of surface temperatures in the subpolar North Atlantic.

Title: Data assimilation in coupled chaotic dynamics and its combination to machine learning to infer unresolved scale error

Author(s) & Affiliation(s): Alberto Carrassi 1, Laurent Bertino2, Marc Bocquet3, Julien Brajard2, Jonathan Demaeyer4, Stephane Vannitsem4
1 University of Reading and NCEO, UK, 2 NERSC Norway, 3 ENPC, France, 4 RMI, Belgium

Abstract: Data assimilation (DA) in systems with many scales of motions is a methodological and technological challenge. The core issue is the scale separation acting as a barrier to the propagation of the information across model components. We focus on coupled DA (CDA) using the ensemble Kalman filter (EnKF). We elucidate the mechanisms of information propagation by using a linear analysis and deduce that: (i) cross components effects are strong from the slow to the fast scale, but (ii) intra-component effects are much stronger in the fast scale. Thus, while observing the slow scale benefits the fast, the latter must be observed with high frequency before its error contaminates the slow scale. Numerical experiments are performed with the atmosphere-ocean model, MAOOAM. The
experiments confirm the need of observing the fast scale, but show also that, despite its slow temporal scale, frequent observations in the ocean are beneficial. The model coupling strength is responsible for the emergence of a degeneracy in the Lyapunov spectrum, with many quasi-neutral modes. By using the covariant Lyapunov vectors (CLVs) we show that they are related to coupling mechanisms and are natural manifestation of the atmosphere-ocean interactions. As opposed to the uncoupled case, they must be included in a CDA EnKF to achieve good performance. Finally, we show how CDA and machine learning can be combined to infer parametrization of the unresolved scales. It generates a data driven parametrization that is then added to the physical model to form a hybrid physical-data-driven model. Results show the goodness of the hybrid model and the importance of using CDA in the training so to embody coupled mechanisms otherwise absent in the raw data.

Title: Application of supermodeling to Earth system modelling

Author(s) & Affiliation(s): François Counillon1,2,3, Shuo Wang1,3, Shunya Koseki1,3, Alok Gupta1,3,4, Noel Keenlyside1,2,3,4, Mao-Lin Shen1,3, Marion Devilliers5 1.University of Bergen 2.Nansen Environmental and Remote Sensing Center 3.Bjerknes Center for Climate Research 4.NORCE 5. Université of Bordeaux

Abstract: A supermodel (SM) is an interactive ensemble in which different models are optimally combined so that their systematic errors compensate to achieve a model with superior performance. The synchronization of the models distinguishes this approach from super ensemble technique (SE) in which model outputs are combined a-posteriori. The ocean of three state-of-the-art earth system models (i.e., NorESM, MPIESM and CESM) are connected every month via their sea surface temperature.

Discrepancies in the grid, resolution and variables representativity are handled by generating pseudo-observations as a weighted average of the individual models and assimilating them back using the Ensemble Optimal Interpolation data assimilation scheme (EnOI) to ensure a dynamically consistent update of the full ocean state. The spatially and seasonally varying weights are estimated using a Bayesian framework trained from the reanalysis performance of the individual models. We have compared the performance of a free running SM to that of the SE for the period 1980—2006. Synchronization of SST is achieved in most oceans and in dynamical regimes such as ENSO with SM. The SST bias of the individual models of SM are reduced by [30-40%] compared to SE and the multi-model mean is further reduced by 45 %. SM also strongly mitigates the double Intertropical Convergence Zone precipitation bias in the tropics. SM tends to dampen the internal variability (nearly to the level of the SE mean) but the spatial pattern is improved. In a realistic framework, only partial synchronization can be achieved because: the synchronization frequency and the volume of data exchange between models are limited and the true solution can only be approached. Using a simple toy model, we show that with partial synchronisation, the weighted averaging of the unsynchronised variability changes the distribution of the pseudo observations acting as a deflation term. This can be counteracted by adding perturbation to the pseudo observation that mimics the unsynchronized parts or construct the pseudo observations only from the synchronised part.

Topic (Invited Speaker): High resolution ESM in decadal climate predictions

Author(s) & Affiliation(s): Helene Hewitt, UK Met Office (UK)

Abstract: *forthcoming*

Title: Towards an "eddy-resolving" climate prediction system

Author(s) & Affiliation(s): Katja Lohmann, Oliver Gutjahr, Johann Jungclaus, Daniela Matei (Max Planck Institute for Meteorology, Germany)

Abstract: We have developed, implemented and preliminary evaluated the performance of the first "eddy-resolving" decadal prediction prototype system based on the MPI-ESM-ER model configuration with the aim to investigate potential improvements due to resolving oceanic eddies in interannual to decadal climate variability and in the prediction skill of the North Atlantic circulation and climate of the regions impacted by it (Europe, Nordic Seas, and Arctic). The MPI-ESM-ER setup is employing an eddy-resolving ocean component with a global resolution of 10 km and an atmospheric component with a resolution of 100 km (T127). The eddy-resolving simulations were compared with similar MPI-ESM-HR experiments conducted within the CMIP6 DCPP-A framework employing an eddy-permitting ocean configuration of 0.4° (~40km). Since both the radiative forcing (CMIP6), the assimilation procedure and ensemble generation are exactly identical, has allowed us to isolate the effect of resolving oceanic eddies (and topographic features) in MPI-ESM-ER prediction system. The variability of the sea surface temperature (SST) in the subpolar North Atlantic over the last decades is well reproduced by the initialized predictions, in contrast to the uninitialized historical simulations. Both prediction systems are able to reproduce the

mid-1990s abrupt strong warming event, with a more realistic amplitude of the warming in the MPI-ESM-ER hindcasts. Moreover, there is a clear reduction in the systematic model bias by using an eddy-resolving ocean component in MPI-ESM-ER. All MPI-ESM-HR hindcasts are approximately 1°C too warm, but the MPI-ESM-ER hindcast ensemble is very close to the observations. Reducing the SST bias in the North Atlantic will have implications for other quantities than SST, such as storm tracks or blocking events over Europe.
We have also investigated the impact of an "eddy-permitting" and an "eddy-resolving" ocean configuration on the predictability of the 2015 record Subpolar North Atlantic "Cold Blob". Predicting such extreme coupled climate phenomena over the North Atlantic-European region has proved to be very challenging for state-of-art prediction systems. However, we could demonstrate that our prediction system is able to reproduce the observed anomalies, but in years where it is absolutely necessary to forecast the atmosphere conditions too, it will require a large ensemble of hindcasts (of the order of 10 or more): two (out of five) ensemble members in MPI-ESM-HR and six (out of ten) ensemble members in MPI-ESM-ER configuration simulate an eastern subpolar North Atlantic "Cold Blob"" in 2015. One of the MPI-ESM-ER ensemble members even reproduces the full observed strength of the ""Cold Blob"", underlining the potential of high-resolution climate predictions. We could also demonstrate that using an eddy-resolving ocean (0.1°) considerably improves the model systematic bias over the North Atlantic subpolar gyre. Based on these promising results, we plan to investigate other phenomena such as storm frequencies or blocking events over Europe.

Topic (Invited Speaker): Strongly coupled data assimilation, and combination of data assimilation and machine learning
Author(s) & Affiliation(s): Terence O'Kane, CSIRO (AU)

Abstract: *forthcoming*

Topic (Invited Speaker): Supermodel for correcting model error
Author(s) & Affiliation(s): Francine Schevenhoven, University of Bergen & BCCR (NO)

Abstract: *forthcoming*

Title: Parameter estimation for ocean biogeochemical component in a global model using Ensemble Kalman Filter: a twin experiment
Author(s) & Affiliation(s): Tarkeshwar Singh1, Francois Counillon1, Jerry F. Tjiputra2, and Mohamad El Gharamti3, Yiguo Wang1 ; 1Nansen Environmental and Remote Sensing Center and Bjerknes Centre for Climate Research, Bergen, Norway 2NORCE Norwegian Research Centre AS and Bjerknes Centre for Climate Research, Bergen, Norway 3National Center for Atmospheric Research, Boulder, Colorado, USA

Abstract: Ocean biogeochemical (BGC) models utilise a large number of poorly-constrained global parameters to mimic unresolved processes and reproduce the observed complex spatio-temporal patterns. Large model errors stem primarily from inaccuracies in these parameters whose optimal values can vary both in space and

time. This study aims to demonstrate the ability of ensemble data assimilation (DA) methods to provide high-quality and improved BGC parameters within an Earth system model in idealised twin experiment framework. We use the Norwegian Climate Prediction Model (NorCPM), which combines the Norwegian Earth System Model with the Dual-One-Step ahead smoothing-based Ensemble Kalman Filter (DOSA-EnKF). The work follows on Gharamti et al. (2017) that successfully demonstrates the approach for one-dimensional idealized ocean BGC models. We aim to estimate five spatially varying BGC parameters by assimilating Salinity and Temperature hydrographic profiles and surface BGC (Phytoplankton, Nitrate, Phosphorous, Silicate, and Oxygen) observations in a strongly coupled DA framework – i.e., jointly updating ocean and BGC state-parameters during the assimilation. The method converges quickly (less than a year), largely reducing the errors in the BGC parameters and eventually it is shown to perform nearly as well as that of the system with true parameter values. Optimal parameter values can also be recovered by assimilating climatological BGC observations and challenging sparse observational networks. The findings of this study demonstrate the applicability of the approach for tuning the system in a real framework.

Title: Coupled satellite data assimilation in intermediate complexity coupled model experiments

Author(s) & Affiliation(s): Andrea Storto1, Gianluigi Liberti1, Daniele Ciani1, Andrea Pisano1, Anna Lewinschal2, Rosalia Santoleri1 1 CNR-ISMAR, Rome, Italy 2 MISU, Stockholm University, Sweden

Abstract: In all the state-of-the-art ocean and sea-ice forecasting systems, it is customary to assimilate satellite observations in terms of their geophysical retrievals (L2 to L4) instead of radiometric quantities (L1). This is mostly due to the complexity of the radiance observation operator. However, long-standing experience in Numerical Weather Prediction (NWP) has proven that this approach is significantly sub-optimal, because the assimilation of geophysical retrievals implies an additional step (the retrieval algorithm), with assumptions therein and thus increased uncertainty, and because it neglects the cross-covariances between background fields and retrievals. The accuracy of the geophysical retrievals is also challenging to estimate in practice. Moreover, strongly coupled ocean-atmosphere assimilation algorithms, which are being developed in many research and operational centers, are expected to significantly change the way satellite data are assimilated, namely leading to synergistic and consistent corrections of upper-ocean and lower-troposphere parameters.

Here, we present ideas to fully exploit brightness temperature data in the context of uncoupled ocean and coupled atmosphere-ocean forecasts. Furthermore, we show preliminary results from coupled data assimilation experiments performed either with an ocean model coupled to an atmospheric boundary layer model, or with a single-column coupled atmosphere-ocean model based on NEMO-LIM and OpenIFS. The satellite data observation operator is obtained from the RTTOV radiative transfer model, used within a variational coupled or uncoupled data assimilation system to assess the impact of the satellite measurements.

Title: Strongly coupled data assimilation with the coupled ocean-atmosphere model AWI-CM: comparison with the weakly coupled data assimilation

Author(s) & Affiliation(s): Qi Tang1,2, Longjiang Mu1,3, Helge Goessling1, Tido Semmler1, Lars Nerger1 1. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, 27570 Bremerhaven, Germany 2. Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 100101 Beijing, China 3. Qingdao National Laboratory for Marine Science and Technology, 26623 Qingdao, China

Abstract: We compare the results of strongly coupled and weakly coupled data assimilation by analyzing the assimilation effect on the prediction of the ocean as well as the atmosphere variables. The AWI climate model (AWI-CM), which couples the ocean model FESOM and the atmospheric model ECHAM, is coupled with the parallel data assimilation framework (PDAF). Satellite sea surface temperature data are assimilated. For the weakly coupled data assimilation, only the ocean variables are directly updated by the assimilation while the atmospheric variables are influenced through the model. For the strongly coupled data assimilation, both the ocean and the atmospheric variables are directly updated by the assimilation algorithm. The results are evaluated by comparing the estimated ocean variables with the dependent/independent observational data, and the estimated atmospheric variables with the ERA-interim data. In the ocean, both the WCDA and the SCDA improve the prediction of the temperature and SCDA and WCDA give the same RMS error of SST. In the atmosphere, WCDA gives slightly better results for the 2m temperature and 10m wind velocity than the SCDA. In the free atmosphere, SCDA yields smaller errors for the temperature, wind velocity and specific humidity than the WCDA in the Arctic region, while in the tropical region, the errors are larger in general.

Title: A novel initialisation technique for decadal climate predictions

Author(s) & Affiliation(s): Danila Volpi, CNR-ISAC (IT)

Abstract: Model initialization is a matter of transferring the observed information available at the start of a forecast to the model. An optimal initialization is generally recognized to be able to improve climate predictions up to a few years ahead. However, systematic errors in models make the initialization process challenging. When the observed information is transferred to the model at the initialization time, the discrepancy between the observed and model mean climate causes the drift of the prediction toward the model-biased attractor. Although such drifts can be generally accounted for with a posteriori bias correction techniques, the bias evolving along the prediction might affect the variability that we aim at predicting, and disentangling the small magnitude of the climate signal from the initial drift to be removed represents a challenge. In this study, we present an innovative initialization technique that aims at reducing the initial drift by performing a quantile matching between the observed state at the initialization time and the model state distribution. The adjusted initial state belongs to the model attractor and the observed variability amplitude is scaled toward the model one. Multi-annual climate predictions integrated for 5 years and run with the EC-Earth3 Global Coupled Model have been initialized with this novel methodology, and their prediction skill has been compared with the non-initialized historical simulations from CMIP6 and with the same decadal prediction system but based on full-field initialization. We perform a skill assessment of the surface temperature, the heat content in the ocean upper layers, the sea level pressure, and the barotropic ocean circulation. The added value of the quantile matching initialization is shown in the North Atlantic subpolar region and over the North Pacific surface temperature as well as for the ocean heat content up to 5 years. Improvements are also found in the predictive skill of the Atlantic Meridional Overturning Circulation and the barotropic stream function in the Labrador Sea throughout the 5 forecast years when compared to the full field method.

Topic (Invited Speaker): Strongly coupled data assimilation, regional climate prediction, multiscale DA, breakthrough in using HPC

Author(s) & Affiliation(s): Shaoqing Zhang, Ocean University of China (CN)

Abstract: *Forthcoming*

Title: A New Ensemble-Based Approach to Correct the Systematic Ocean Temperature Bias of CAS-ESM-C to Improve Its Simulation and Data Assimilation Abilities

Author(s) & Affiliation(s): Fei Zheng, Institute of Atmospheric Physics, CAS, Beijing, China

Abstract: Over the past several decades, many efforts have been devoted to increasing the simulation performance of climate models, but significant biases remain that hinder the performance of coupled systems. Hence, bias correction is regarded not only as a useful tool for improving climate simulations but also as an important step before data assimilation, which depends on the hypothesis of unbiasedness. In this study, using sea temperature climatological data, a new ensemble-based approach is proposed for correcting the biases of the sea temperature in CAS-ESM-C. Through analyzing the results of the proposed bias correction method with various intensities and time windows, its performance in suppressing the simulation biases of ocean fields is evaluated. The simulation biases of atmospheric variables are also reduced via air-sea interactions, which will improve the ocean simulation performance. Additional benefits can be realized by applying the bias correction method. For example, a superior simulation of climate variabilities in a coupled model, such as ENSO (El Nino-Southern Oscillation), is realized due to the improvement of climatological fields. The ability to assimilate various ocean observations is also significantly improved with a better background mean state.

Session 2 – Advances in Models and Initialisation: Posters

Title: Added value of springtime Arctic sea ice concentration assimilation for summer and fall climate predictions

Author(s) & Affiliation(s): Juan C. Acosta Navarro1; Ortega, Pablo 1; Garcia-Serrano, Javier 2; Lapin, Vladimir 2. 1: Barcelona Supercomputing Center. 2: University of Barcelona.

Abstract: The primary goal of seasonal forecasting is to deliver climate information for the coming months/seasons to a wide range of potential users. Valuable predictions are limited in midlatitude land regions in the northern hemisphere and progress has been rather slow. Seasonal climate predictability largely originates from the evolution of predictable components of the climate system with slow variability such as the ocean, the land or the sea ice.

Northern hemisphere (NH) midlatitude regions are affected by Arctic sources of predictability, and sea ice is one of such sources due to its slow variability and the central role it plays in the Arctic climate system. In the satellite era, Arctic sea ice has declined, the lower atmosphere has warmed much faster than the global average, and the warming has been strongest in the fall and winter. The seasonality of the Arctic warming has motivated the majority of studies linking Arctic sea ice loss and midlatitude climate, which mainly focused on late fall and winter. Only a few studies have targeted the remaining parts of the year.

We use ensembles of climate model simulations initialized in spring (retrospective climate predictions) with and without Arctic sea ice concentration assimilation from satellite observations, to diagnose the sea ice effect on NH midlatitude climate in the following summer and fall. Our strategy allows for a systematic quantification of climate prediction skill against observational products and a more realistic present day climate simulation state and variability than with a traditional non-initialized climate model approach. The advantages of sea ice concentration assimilation in terms of forecast skill will be discussed, as well as the mechanisms linking the Arctic and midlatitudes via sea ice-ocean-atmosphere interactions at different timescales.

Title: Background error covariance hybridization for climate prediction

Author(s) & Affiliation(s): Sébastien Barthélémy, University of Bergen & BCCR (NO)

Abstract: The Norwegian Climate Prediction Model (NorCPM) combines the Norwegian Earth System Model (NorESM) with the Ensemble Kalman Filter (EnKF) and aims at providing seasonal to decadal climate predictions. A new high-resolution version of the model improved the mechanisms of predictability, but it is not tractable to run a sufficiently large ensemble size at such resolution on our HPC.

To overcome this issue, hybridization methods derived from previous work from Hamill and Snyder, 2000 and Rainwater and Hunt, 2013 were investigated. These methods are based on the linear combination of a dynamical covariance estimated on top of the ensemble and another covariance matrix. The second matrix can be computed from a large static ensemble (static hybridization) or from another dynamical ensemble with coarser resolution (mixed-resolution).

These hybridization methods are first tested with the quasi-geostrophic model within the DAPPER package. It is shown that both methods outperform the standard implementation of the EnKF for very small ensemble size, less than 10 members. A classification of the performance of the methods in function of the ensemble size was established allowing for determining the hybridization strategy to choose given the available computational resources.
Static hybridization was also tested in NorCPM in the context of perfect twin experiments with assimilation of monthly SST observations. The seasonal static ensemble is composed of a long PI run. The static hybridization scheme has shown to improve the results compared to the standalone EnKF depending on the choice of the hybridization coefficient, the region considered and the depth. In the sub-surface the EnKF and the static hybridization provide similar results, while it is stronger at deeper levels.

Title: Weighing Traditional Mathematical and Novel Machine Learning Approaches to Climate Predictability in the Arctic

Author(s) & Affiliation(s): Thomas Y. Chen (Academy for Mathematics, Science, and Engineering)

Abstract: With the rise in the availability and importance of big data, machine learning approaches in the scope of climate, including specifically in the Arctic, have rapidly become more prevalent in the scientific literature. Artificial intelligence is a fast-changing field, with deep learning techniques (with important applications in computer vision) popularized in the last decade. Weather and climate forecasting using machine learning approaches has been shown to enhance conventional statistical techniques. Methods break down into a few major categories, including now-casting, short-range weather prediction, medium-range prediction, sub-seasonal forecasting, seasonal forecasting, and climate-change prediction. In this session, we raise the questions, will artificial intelligence totally replace numerical models? If not, how can they supplement or enhance the performance and results of traditional mathematical models? How can we continue to prioritize domain-specific knowledge in interdisciplinary collaborations? In this scope, the answer to these questions can be different for the various subareas of study within meteorological modelling. For instance, "Hard AI" refers to applications in which predictions on the corresponding timescales can be largely or completely replaced by artificial intelligence; in this case, physical constraints, like conservation laws, are able to be ignored as marginal errors that do not accumulate to a significant level over time. Mobile phone data is an excellent source of data for this purpose, as it provides a large database of information to work with, which is necessary for machine learning. In general, a wide range of machine learning algorithms and models have use cases in Arctic climate, from linear regression, to random forest ensembles (RFs), to convolutional neural networks (CNNs), to generative adversarial networks (GANs).

Title: Correlational Satellite Study of Ocean-Cryosphere Interactions with Climate Variability in Coupled Climate System to Develop Numerical Ocean-Cryosphere Climate Variability Prediction Model (NOC-CVPM) over the North Atlantic-Arctic Sector.

Author(s) & Affiliation(s): Virendra Goswami, Indian Institute of Technology (IIT) & 'Environment and Peace Foundation'(IN)

Abstract: The term "cryosphere" comes from the Greek word, "krios," which means cold e. g. Arctic, Greenland & Antarctica regions. The Canadian Scientists in 2016 found that the Ocean- Atmosphere- Cryosphere (OAC) interaction is more evident on North pole i. e. Arctic regions. In Feb'17, Researchers found that the unstoppably melting of the glacier into the ocean mainly because of warmer seawater lapping at its underside. Prof. Peter Clark, OSU attributed that the Glacier retreat was due to rising levels of Carbon Dioxide and other GHG, as opposed to other types of forces. If, this continues then the most of Glaciers would disappear in the next few centuries & the Glaciers loss in future will be contributing to rising sea levels, environmental pollution vis-à-vis Climate Change.

The understanding of impacts of multiple stressors on the ocean and the associated risks of abrupt state shifts can be explored through the comprehensive studies of Ocean Systems Interactions, Risks, Instabilities and Synergies (OSIRIS) as well as climate variability due to coupled Ocean-Cryosphere interactions in order to develop Ocean-Cryosphere Climate Variability Prediction Model (OCCV-PM), over the North Atlantic-Arctic regions.

It's imperative to investigate sub-mesoscale dynamics of Arctic ice sheet stability, ice and bedrock coring, ice sheet modelling, and ice sheet processes viz. physical, chemical, biological and oceanographic for the study of computational correlation of Climate variability due to coupled Ocean-Cryosphere interactions by developing the (OSIRIS) & (OCCV-PM) over North Atlantic-Arctic Sector.

The kinematic features of the mesoscale convective systems over Arctic- North Atlantic Ocean regions would be correlated with ocean-cryosphere Climate variability on time & Space Scales; at the local, regional and global levels through the extracted Sea Surface Temperature (SSTs) over the grid box(10-10) , attributing the regional change to natural and anthropogenic radiative forcing agents to bring out the few optimum values of these to develop (OSIRIS) & Ocean-Cryosphere Climate Variability Prediction Model (OCCV-PM), by using High Resolution Satellite imageries, data access, assimilation; HPC and cloud computing for real-time analysis.

Next, through the process of Initialization, Computation, Parameterization, within the (1 x 1) deg. grid-box by the computer algorithm, the Numerical Prediction Models for Ocean -Cryosphere Climate variability over Arctic & North Atlantic regions would be developed i. e. Numerical Ocean-Cryosphere Climate Variability Prediction Model (NOC-CVPM).

Title: Future evolution of an eddy rich ocean associated with enhanced east Atlantic storminess in a coupled model projection

Author(s) & Affiliation(s): Jeremy P. Grist, Simon A. Josey, Bablu Sinha, Andrew C. Coward (NOC), Jennifer L. Catto (University of Exeter) and Malcolm J. Roberts (UK Met Office)

Abstract: Improved representation of air-sea fluxes afforded by eddy-rich oceans in high-resolution coupled ocean-atmosphere models may modify the tracks and intensity of storms and their response to climate change. We examine changes in winter surface ocean conditions and storminess associated with moving from an eddy-permitting (1/4°, HM) to an eddy-rich (1/12°, HH) ocean in control and climate change (SSP585) simulations of the HadGEM3-GC3.1 model in which atmosphere resolution is kept at 25km. Differences in North Atlantic climate in the control runs stem from a revised location of the Gulf Stream in the eddy-rich model. Projections reveal greater warming in the western Atlantic in HH than HM and a pronounced increase in eastern Atlantic storminess in the eddy-permitting model. This increase is associated with the distinctive long-term evolution of the North Atlantic warming hole and the Gulf Stream separation in the eddy-rich model.

Title: Winter surface heat flux and SST analysis in the Nordic Seas and Arctic Ocean in NorCPM

Author(s) & Affiliation(s): Joan Mateus Horrach-Pou, Geophysical Institute, University of Bergen, Helene R. Langehaug, NERSC, Bergen, Norway

Abstract: A prediction skill analysis has been performed with the latest version of the Norwegian Climate Prediction Model (NorCPM) in the frame of the CMIP6 experiment. Our results so far are based on comparisons between NorCPM predictions and NorCPM reanalysis over the period 1960-2018 The results suggest that for winter Sea Surface Temperature (SST), significant skill exists up to lead time 4 years in large parts of the Nordic Seas and Barents Sea. The Norwegian Basin presents a growing negative correlation that expands with lead time. However, along the eastern rim of the Norwegian Basin, where the Norwegian Atlantic Current (NwAC) likely travels northward, significant skill is found for higher lead times (up to 10 years lead time). The skill in the Arctic Ocean is overall limited compared to the Nordic Seas. In winter, surface heat flux (HFLX) presents significant skill up to lead time 1 year only where the sea ice concentration is higher than 15% (where the East Greenland Current dominates), and up to lead time 2 years in most of the Barents Sea. The CMIP6 version of NorCPM includes two versions: one with only ocean update (i1) and one with both ocean and sea ice update (i2). The version with sea ice update (i2) shows overall better results, but shows significant negative correlation for SST in the Norwegian Basin. Interestingly, this version also shows significant positive correlation for HFLX in the Norwegian Basin. The summer SST presents limited skill compared to winter, with significant skill up to lead time 3 years, close to the sea ice edge. The NwAC path presents inconsistent skill. The Norwegian Basin has also negative correlation in summer. To better understand sources of skill, we have compared NorCPM predictions with NorCPM free run/historical run (i.e., without initializations). We find that the historical run has a similar skill pattern in the Nordic Seas as the predictions, but opposite in the subpolar North Atlantic, i.e., significant negative correlation in Norwegian/Lofoten Basin, significant positive correlation along NwAC, and no skill (or negative correlation) in subpolar North Atlantic. This suggests that external forcing is a source for skill in the Nordic Seas, and contributes to the negative correlation in the Norwegian Basin. We will extend our analysis to analyse surface velocities in the Nordic Seas to better understand how this is represented in NorCPM.

Title: The forcast of sea ice linear kinematic feature using a high resolution sea ice-ocean coupled model

Author(s) & Affiliation(s): Longjiang Mu, Qingdao National Laboratory for Marine Science and Technology; Nils Hutter, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research; Martin Losch, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research; Lars Nerger, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research; Xianyao Chen, Ocean University of China

Abstract: In terms of high resolution sea ice forecast, the linear kinematic feature (LKF) is prevalently observed in the Arctic simulations. We use a high resolution (~2km) Arctic sea ice-ocean coupled model to investigate the predictability of LKF when employing the ensemble Kalman filter on synoptic time scale. The sea ice model has processes with viscous-plastic dynamics and zero-layer thermodynamics considering the limited computation resources when using the ensemble. The hindcast experiments with different initialization method exploring such as localization, observation errors, and ensemble inflation are conducted. The forecast skill is evaluated against high resolution sea ice concentration observations. The effects of the dynamic related parameters such as elliptical ratio, ice strength on LKF forecast will be further investigated.

Title: Strongly Coupled Data Assimilation and Initialization with the Parallel Data Assimilation Framework

Author(s) & Affiliation(s): Lars Nerger (1), Qi Tang (1,2), Langjiang Mu (1,3); 1: Alfred Wegener Institute Helmholtz Center for Polar and Marine Research, Bremerhaven, Germany, 2: Institute of Geographic Sciences and Natural Resources Research, China and Chinese Academy of Sciences, China; 3: Qingdao National Laboratory for Marine Science and Technology, China

Abstract: The Parallel Data Assimilation Framework (PDAF, http://pdaf.awi.de) is an open-source software framework for highly efficient ensemble data assimilation with complex models on supercomputers. PDAF was developed to simplify the generation of a data assimilation system from existing models. For coupled data assimilation, PDAF is used for example with the coupled atmosphere-ocean model AWI-CM, with different coupled ocean biogeochemical models, and with the atmosphere-land surface-subsurface model TerrSysMP. However, there is a wide range of further applications of PDAF. PDAF provides functionality to perform ensemble integrations, which can be used for ensemble predictions and ensemble data assimilation. Further, PDAF provides several fully-implemented ensemble filter and smoother methods for data assimilation. One can build the data assimilation application either by using model restart files or by directly augmenting the different compartment models of a coupled system with data assimilation functionality. The ensemble data assimilation can then be applied in an efficient way with complex models like AWI-CM on supercomputers with excellent scalability and efficiency. PDAF directly supports both weakly and strongly coupled data assimilation. Discussed will be the features of PDAF and the structure of data assimilation systems for coupled data assimilation with PDAF.

Title: The importance of North Atlantic Ocean transports for seasonal forecasts

Author(s) & Affiliation(s): Steffen Tietsche, M. Balmaseda, H. Zuo, C. Roberts, M. Mayer, L. Ferranti (ECMWF)

Abstract: The Atlantic Meridional Overturning Circulation (AMOC) is a main driver for predictability at decadal time scales, but has been largely ignored in the context of seasonal forecasts. Here, we show compelling evidence that AMOC initialization can have a direct and strong impact on seasonal forecasts. Winter reforecasts with SEAS5, the current operational seasonal forecasting system by the European Centre for Medium-Range Weather Forecasts, exhibit errors of sea-surface temperature (SST) in the western part of the North Atlantic Subpolar Gyre that are strongly correlated with decadal variations in the AMOC initial conditions. In the early reforecast period 1981-1996, too warm SST coincide with an overly strong AMOC transporting excessive heat into the region. In the ocean reanalyses providing the forecast initial conditions, excessive heat transport is balanced by additional surface cooling from relaxing towards observed SST, and therefore the fit to observations is acceptable. However, the additional surface cooling contributes to enhanced deep convection and strengthens the AMOC, thereby establishing a feedback loop. In the forecasts, where the SST relaxation is absent, the balance is disrupted, and fast growth of SST errors ensues. The warm SST bias has a strong local impact on surface air temperature, mean sea-level pressure, and precipitation patterns, but remote impact is small. In the late reforecast period 2001-2016, neither the SST in the western North Atlantic nor the AMOC show large biases. The non-stationarity of the bias prevents an effective forecast calibration and causes an apparent loss of skill in the affected region. The case presented here demonstrates the importance of correctly initializing slowly varying aspects of the Earth System such as the AMOC in order to improve forecasts on seasonal and shorter time scales.

Title: A conceptual framework for the study of ensemble forecasts in coupled ocean-atmosphere systems

Author(s) & Affiliation(s): Stephane Vannistem (RMI, Belgium), J. Demaeyer (RMI,Belgium), S. Penny (NOAA, Boulder, USA)

Abstract: The use of several approaches to initialize ensemble forecasts is investigated in a coupled ocean–atmosphere system of reduced order, the Modular Arbitrary Order Ocean–Atmosphere Model (MAOOAM). Among these approaches, the Backward Lyapunov Vectors (BLVs), the Characteristic Lyapunov Vectors (CLVs), the Empirical Orthogonal Functions (EOFs), the modes obtained through the Dynamic Mode Decomposition (DMDs).

For the BLVs already investigated in Vannitsem and Duan (2020), it is found that overall the most suitable BLVs to initialize a (multiscale) coupled ocean–atmosphere forecasting system are the ones associated with near-neutral and slightly negative Lyapunov exponents. This unexpected result is related to the fact that these BLVs display larger projections on the ocean variables than the others, leading to an appropriate spread for the ocean, and at the same time a rapid transfer of these errors toward the most unstable BLVs affecting predominantly the atmosphere is experienced. The latter dynamics is a natural property of any generic perturbation in nonlinear chaotic dynamical systems, allowing for a reliable spread with the

atmosphere too. This result is compared with the use of CLVs which are covariant with the dynamics in the tangent space, showing a less effective ensemble forecast reliability.

These methods are then compared with the use of the EOFs and DMDs (together with their adjoint) that have the advantage to be easily computed from time series without implementing any tangent dynamics. Some preliminary results suggest that the EOFs are performing poorly, while the adjoint DMDs are providing good results. The reasons of the different performances are discussed.

References:

Demaeyer, J., S. Penny and S. Vannitsem, Identifying efficient ensemble perturbations for initializing subseasonal-to-seasonal prediction, in preparation, 2021.

Vannitsem S. & W. Duan, On the use of near-neutral backward Lyapunov vectors to get reliable ensemble forecasts in coupled ocean-atmosphere systems. Climate Dynamics, 55, 1125-1139, 2020.

Session 3 – Applications and Services: Talks

Topic (Invited Speaker): Overview of C3S scope, progress and plans
Author(s) & Affiliation(s): Chiara Cagnazzo, ECMWF (UK)

Abstract: *forthcoming*

Topic (Invited Speaker): C3S_34c Prototype decadal climate services
Author(s) & Affiliation(s): Nick Dunstone, UK Met Office (UK)

Abstract: *forthcoming*

Topic (Invited Speaker): What happens to the data after they are produced?
Author(s) & Affiliation(s): Isadora Christel Jimenez, Barcelona Supercomputing Center (ES)

Abstract: *forthcoming*

Title: Towards providing more reliable regional climate change projections
Author(s) & Affiliation(s): Noel Keenlyside, UiB (30+ others from Climate Dynamics community)

Abstract: Model-based projections of future climate are remarkably unreliable at regional scales, severely limiting their societal relevant applications, such as developing cost-effective climate adaptation measures. Climate projections, however, can be made far more useful as model disagreement—not irreducible internal climate variability—dominates the uncertainties; accounting for 50-90% of the regional uncertainties in projections of precipitation and surface temperature. These model discrepancies are tied to atmospheric circulation patterns. Thus, while they stem from uncertain parameterisations of subgrid scale physical processes, they can be understood in terms of climate dynamics.
Climate dynamics offers a path to achieve more reliable regional climate projections. Firstly, statistical analysis and idealised experiments enable regional uncertainties to be robustly connected to systematic model errors. However, quantifying errors in simulated regional climate change is a challenge, given the uncertainties in observations, internal climate variability, and historical aerosols. Secondly, emergent constraint analysis is a powerful tool that can reduce uncertainties, through joint use of observational data and the wealth of available climate change projections. Here, multiple large initial condition ensembles are key to better quantify uncertainties. Finally, techniques that statistically correct the model climatological or dynamics during the simulation can mitigate the impacts of model errors. Developments in computing and internet architecture can accelerate the implementation of next generation Earth system models, but this also requires high-resolution observations for model validation and assessment. Modern data-driven techniques are augmenting

statistical analysis and numerical modelling to deliver more rapid progress towards reliable regional climate projections.

Title: An application of decadal climate predictions to forecast cod biomass in the North and Barents Sea

Author(s) & Affiliation(s): Vimal Koul (1, 2), Camilla Sguotti (3), Marius Arthun (4), Sebastian Brune (2), Andre Dusterhus (5), Bjarte Bogstad (6), Geir Ottersen (6, 7), Johanna Baehr (2), and Corinna Schrum (1, 2). (1) Helmholtz Zentrum Hereon, Institute of Coastal Systems, Geesthacht, Germany (2) Institute of Oceanography, Center for Earth System Research and Sustainability, University of Hamburg, Hamburg, Germany (3) Institute for Marine Ecosystem and Fisheries Science, Center for Earth System Research and Sustainability, University of Hamburg, Hamburg, Germany (4) Geophysical Institute, University of Bergen and Bjerknes Centre for Climate Research, Bergen, Norway (5) Irish Climate Analysis and Research UnitS (ICARUS), Department of Geography, Maynooth University, Maynooth, Ireland (6) Institute of Marine Research, Bergen, Norway (7) Centre for Ecological and Evolutionary Synthesis, Department of Biosciences, University of Oslo, Oslo, Norway

Abstract: In the North Atlantic, overwhelming evidence suggests strong climate-ecosystem linkages which can lend multiyear predictability to marine resources. However, a considerable gap remains between the success of decadal climate predictions and marine ecosystem predictions. The main challenge towards bridging this gap is posed by the poor performance of global coupled models (GCM) in the shallow shelf seas, such as the North and Barents Sea, where some of the highly productive fisheries reside as well as by the limited representation of trophic interactions in GCMs. Here, we assess decadal predictability of cod biomass in the North and Barents Sea using decadal climate predictions from the Max Planck Institute Earth System Model. We develop a unified dynamical-statistical prediction system wherein linear statistical models link cod biomass to dynamical predictions of sea surface temperature, while also considering various scenarios of fishing mortality. Our forecasts indicate that unfavourable oceanic conditions for the North Sea cod would continue in the coming decade which would inhibit its recovery at present fishing levels, and a decrease in cod stock in the Barents Sea compared to the recent high levels. Our results provide evidence that GCM-based initialized decadal climate predictions can be deployed for prediction of marine resources through climate-ecosystem linkages.

Title: Decadal predictions of the environmental conditions at North Atlantic Sponge habitats

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Abstract: Knowing the future ambient environmental conditions is of key relevance for elucidating how deep-sea sponge habitats in the North Atlantic will evolve in near-future climate. We have made an attempt for the first time to set up a regional downscaling prediction system to predict the interannual to decadal variations of the environmental conditions over deep-sea sponge habitats. The large-scale climate variability predicted by the coupled Max Planck Institute Earth System Model with low-resolution configuration (MPI-ESM-LR) is dynamically downscaled to the North Atlantic by providing surface and lateral boundary conditions to the regional coupled physical-ecosystem model HYCOM-ECOSMO. Retrospective ensemble predictions reveal a high potential for skillful predictions of the physical fields (temperature, salinity) and biogeochemical fields (concentrations of silicate and oxygen) several years in advance with distinct regional differences. In areas closely tied to large-scale climate variability (e.g. the subpolar gyre) and ice dynamics (e.g. the Arctic Ocean), both the physical and biogeochemical fields can be predicted more than four years ahead, while in areas under strong influence from upper oceans or open boundaries (e.g. the area east of the Strait of Gibraltar), the prediction of the two fields loses its skill within two years. The biogeochemical fields are more predictable than the physical fields at a large portion of the sponge habitats, partly due to the longer persistence of biogeochemical states than their physical counterparts. Predictability is significantly improved by initialization in areas away from the influence of Mediterranean outflow and areas with suppressed coupling between the upper and deep oceans. Our study highlights the ability of the downscaling regional system to predict the environmental variations at sponge habitats on time scales of management relevance. The downscaling system therefore will be an important part of an integrated approach towards the preservation and sustainable exploitation of the North Atlantic sponges.

Topic (Invited Speaker): Marine climate services

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Abstract: *forthcoming*

Title: Multi-year prediction of drought and heat stress for the wheat sector

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Abstract: Drought and heat stress negatively impact wheat production and food security globally and the impact of these climate hazards is expected to increase over the upcoming decades due to anthropogenic climate change. Therefore, there is a growing need for effective planning and adaptive actions to reduce the impact and the amount of related losses incurred at all timescales relevant to the stakeholders in the wheat sector. This work aims at assessing the forecast quality in predicting the evolution of drought and heat stress by using user-relevant agro-climatic indices such as Standardized Potential Evapotranspiration Index (SPEI) and Heat Magnitude Day Index (HMDI) on a multi-annual timescale, as this time horizon coincides with the

strategic planning of many stakeholders in the wheat sector. In particular, we present the probabilistic skill and reliability of initialized decadal forecast to predict these indices for the months preceding the harvest of wheat on a global spatial scale. We compare the unadjusted and calibrated decadal forecasts in all the cases. The results reveal that the decadal climate forecasts are skillful and reliable over several wheat harvesting regions. The forecast quality assessment shows that the calibration is a necessary step to obtain trustworthy predictions for providing high-quality climate services.

Title: A systematic investigation of the skill in air temperature prediction over Europe for potential applications to climate services

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Abstract: Decadal Climate Predictions (DCP) have gained considerable attention for their potential utility in promoting optimised plans of adaptation to climate change and variability. Their effective applicability to a targeted problem is nevertheless conditional on a detailed evaluation of their ability to simulate the near-term climate evolution under specific conditions. Here we explore the performance of the IPSL-CM5A-LR DCP system in predicting air temperature over Europe, by proposing a prototypical systematic approach consisting of assessing the prediction skill for different time windows (initialisation periods, forecast years and months of the year). In this framework, we also compare raw and de-biased hindcasts, in which the temperature outputs have been corrected using a quantile matching method. The systematic analysis allows to discern certain conditions conferring larger predictability, which we find to be intermittent in calendar time. The predictions appear more skilful around the 1960s and 1990s, in coincidence with large shifts of the Atlantic Multidecadal Variability, which are well reproduced in the hindcasts. Averages on longer forecast periods also generally produce better prediction skill, while the best predicted months appear to be those between spring and summer. Finally, we find an overall added value due to initialisation, while de-biased predictions significantly outperform raw predictions for a few specific time windows. The systematic exploration of opportunities for skilful predictions proposed here may have important implications on specific impact analyses, for example by indicating the time windows and the seasons over which the prediction is potentially more reliable, thus providing useful information for the optimal development of climate services based on DCP.

Title: A decadal prediction service for hydropower

Author(s) & Affiliation(s): Eirini Tsartsali [1], Panos Athanasiadis [1], Stefano Materia [1], Dario Nicolì [1] and Silvio Gualdi [1], [1]:Centro EuroMediterraneo sui Cambiamenti Climatici Foundation, Bologna, Italy

Abstract: Decadal predictions have rapidly evolved in the last decade, and now are produced operationally worldwide to bridge the gap between seasonal predictions and climate projections. Skillful decadal predictions present an emerging opportunity for the development of climate services to assist planning and decision-making by governments and businesses in various socio-economic sectors. On these grounds, the EU Copernicus Climate Change Service (C3S) aims at revealing the potential benefits of decadal predictions for different industries and at developing real-time, sector-specific decadal prediction products.
CMCC, participating in the C3S_34c tender, developed a prototype decadal prediction based climate service for a specific user from the energy sector (ENEL Green Power). For the hydropower investments and operations in three European drainage basins, forecasting interannual to decadal precipitation changes is most important. To meet the needs of the end-user, tailored decadal predictions were provided using a multi-model ensemble consisting of four prediction systems (DePreSys4, EC-Earth3, CMCC-CM2-SR5, MPI-ESM-HR). Assessing the direct multi-model output, statistically significant skill was found dependent on the calendar season and the geographical area (basin) considered. To further enhance the predictive skill, a hybrid approach was adopted based on the high skill for the North Atlantic Oscillation (NAO) and the observed linear relationship between precipitation and the respective index. Furthermore, we found promising evidence that large-scale teleconnection patterns, such as the NAO, can be also used for predicting indices related to daily precipitation extremes.

Session 3 – Applications and Services: Posters

Title: Optimal weighted ensemble for sub-seasonal forecasting

Author(s) & Affiliation(s): Julien Brajard (NERSC), F. Counillon (NERSC, UiB), Y. Wang (NERSC), M. Kimmritz (AWI)

Abstract: The Norwegian Climate Prediction Model (NorCPM) is providing skilful seasonal forecasts (Wang et al. 2019). A 60 member ensemble reanalysis has been recently produced by assimilating monthly sea-surface temperature (SST) and T-S profile data with the ensemble Kalman filter into the Norwegian Earth System Model. Retrospective hindcasts - initialised from the reanalysis - have been produced for the period 1985 to 2010 with 4 start dates per year and each hindcast consisting of 60 members and run for a year. A standard approach considers the ensemble arithmetic average as the most likely prediction and the ensemble spread as the uncertainty of the forecast. Here, we aim at testing a weighting average that can use independent data to enhance the skill of the forecast on a sub-seasonal time scale.
During the operational production of the NorCPM forecast (considering the buffer-time needed to ensure timely delivery), a week of unused SST data is available. We tested the potential of this unused data to estimate a weight for each ensemble member and provide a weighted mean instead of the standard arithmetic mean. This offline approach does not need a new model integration and is dynamic (not trained on historical performance). The spatially varying weights are computed using a Bayesian framework that favours members closer to observations. It is shown that the subsampling approach provides skills at 1 month lead time (global correlation of 0.61) that is close to that of the analysis (global correlation of 0.66) and substantially improves forecast skill up to 2 lead months (global correlation of 0.46) compared to the standard ensemble averaging (global correlation of 0.49 at 1 month lead time and 0.41at 2 months lead time). This improvement at a lead time of two months can be even more pronounced regionally: for example, the correlation in the Barents Sea is improved from 0.36 for the standard averaging to 0.50 for the weighted forecast. The improvement is significant (but less important) up to a lead time of 3 months. This approach can provide a flexible framework to update the forecast in between the intermittent forecast production cycle and can be extended to other independent data sets (e.g. snow, atmospheric data …).

Title: Do Models Generate Realistic Simulations of the North Atlantic SST?

Author(s) & Affiliation(s): Timothy DelSole and Michael K. Tippett (George Mason University, USA)

Abstract: A rigorous statistical method for comparing model simulations and observations is proposed. Importantly, the method accounts for correlations in both space and time. The basic idea is to fit each multivariate time series to a Vector Autoregressive (VAR) Model, and then test if the parameters of the two models are equal. In the special case of a first order VAR model, the model is a Linear Inverse Model (LIM), and the test constitutes a difference-in-LIM test. Another application of this test is to decide which of several dynamical models is "closest" to observations. This test is applied to the question of whether climate models generate realistic variability

of annual mean North Atlantic Sea Surface Temperature (NASST). Given the disputed origin of multidecadal variability in NASST (e.g., it could be forced by anthropogenic aerosols or arise naturally from internal variability), the time series are filtered in two different ways appropriate to the two driving mechanisms. In either case, only a few climate models out of three dozen are found to be consistent with the observed NASST. In fact, by comparing time series from every possible pair of climate models, it is shown that climate models not only differ from observations, but also differ significantly from each other, unless the models come from the same institution. These model-to-model and model-to-observation discrepancies raise considerable challenges for reaching a consensus on the relative role of internal variability and forcing in decadal fluctuations of NASST.

Title: Decadal Predictability of German Bight Storm Activity

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Abstract: Multiannual to decadal forecasts of storm activity are vital for coastal protection and management in the German Bight (southeastern North Sea). As there is no significant climate change signal in historical records of German Bight storm activity and future projections do not suggest consistent significant changes, emission-based climate projections may be of limited use for multiannual predictions. Thus, we see a potential in decadal prediction systems to provide reliable forecasts for storm activity on a multiannual time scale.

In our study, we evaluate the prediction skill for storm activity in the German Bight of a 64-member ensemble of yearly initialized decadal hindcast simulations based on the Max-Planck-Institute Earth System Model (MPI-ESM). We calculate an annual geostrophic wind-based index for German Bight storm activity from mean sea-level pressure (MSLP). We correlate the predictions of German Bight storm activity with observational time series to quantify the prediction skill of the hindcast system. To analyze the origin of the prediction skill, we also investigate how well large-scale atmospheric patterns over the North Atlantic are represented in the model.

We find that predictions of German Bight storm activity show the highest skill for long averaging periods. The longer the predicted period, the higher the correlation between predictions and observations. In addition, categorical predictions for longer averaging windows significantly exceed the skill of simple forecasts based on persistence or linear trends.

While the skill for MSLP predictions is mostly insignificant across the North Sea and adjacent regions, we find that the decadal hindcast system can sufficiently reproduce the leading modes of wintertime MSLP variability in the North Atlantic for longer averaging windows. These leading modes correlate significantly with the observed time series of German Bight storm activity. Hence, we conclude that the skill of the

hindcast system for large-scale atmospheric patterns drives the skill for German Bight storm activity.

Title: Northern midlatitude snow cover change and its potential causes research

Author(s) & Affiliation(s): Quan Liu, University of Chinese Academy of Sciences (CN)

Abstract: Since the late 1980s, northern midlatitudes have experienced more frequent heavy snowfalls. Satellite based remote sensing images and in situ observation records exhibited upward trends of snow cover over part of Eurasia and North America. Whether the increasing trends of snow in the past winters were robust remain controversial. Here, using fast multidimensional ensemble empirical mode decomposition method, we extract trends of four snow indices, including snow cover frequency (1966-2018), snow cover index (1980-2018), extreme snowfall frequency and intensity (1988-2018). The impacts of local near surface air temperature, equatorward moisture transmission and Arctic sea-ice decline on midlatitude snow are explored. Our results reveal that average snow exhibited a long-term decreasing trend during the whole timespan in the northern hemisphere overall, yet short-term increments from the late 1980s through to early 2010s over large areas of midlatitudes. Specificlly, from 1985 to 2000, in eastern Asia, western North America and south Europe, snow cover frequency increased by 3.7%, 3.5% and 3.0%; Snow cover index increased by more than 5.0% , 2.5% and -4.0%; Extreme snowfall frequency increased roughly by 0.06 days, 0.02days and 0.05days; Extreme snowfall intensity increased by 0.5mm, 0.5mm and 0.3mm, respectively. During the same period (i.e. 1985-2000), the winter-mean near surface air temperature temporally decreased, and the moisture transported from Arctic to midlatitudes at 600hpa level intensified, together with the strengthening of Siberia High and weakening of polar vortex. Such temporal coincidence suggests that the local cooling and amplification of moisture supply from the north, which were induced by anomalous atomospheric circulation, played important roles in the the short-term increments of mildaitude snow from the late 1980s through to early 2010s. Our further work shows no evident links between Arctic sea-ice decline and midlatitude snow cover increments.

Title: Seasonal climate predictions for marine risk assessment in the Barents Sea

Author(s) & Affiliation(s): Iuliia Polkova and Laura Schaffer (Uni Hamburg), and Øivin Aarnes (DNV)

Abstract: We investigated the potential of using seasonal climate predictions for marine risk assessment for the Barents Sea. Marine risk embraces the diagnostic of probability of extreme climate conditions and their consequences to identify time and regions vulnerable to climate hazards. The information on marine risks is operationally provided by Det Norske Veritas (DNV) to support sustainable and safe marine activities. So far, probability of extreme climate conditions was based on historical observations. In our study, we implemented predicted probabilities from an ensemble of seasonal predictions provided by the German Meteorological Service. We analyzed predicted probabilities for summer during the open-water season. We selected three indicators from the DNV's marine service: Two of them represent meteorological properties such as wind speed and 2-meter temperature (T2m). The third indicator, the wind chill index

(WCI), is a combination of the previous two. The prediction skill, the "trust level" for predictions, is assessed over 1990--2017 and suggests that T2m has the highest skill followed by WCI and wind speed. In addition, we used a real-time prediction to represent an actual application example. The real-time predicted probabilities for summer 2020 maps show that large areas of the Barents Sea represented favorable conditions for marine operations considering low likelihood for extreme WCI (>1000 W/m^2) and T2m (<0 degC) conditions in July and August. The wind speed is poorly predicted beyond the first lead month. Our study describes the workflow for an application of seasonal predictions as well as lessons learned for similar marine services that are based on risk assessment.