PROJECT FINAL REPORT

The Role of ocean dynamics and Ocean-Atmosphere interactions in Driving cliMAte variations and future Projections of impact-relevant extreme events

Project acronym: ROADMAP

Starting date: 01.06.2020

End date: 31.10.2024 (originally 31.05.2023)

Date of submission of this report: 30.09.2024

Website address: http://roadmap.rd.ciencias.ulisboa.pt/

Project coordinator: Dr. Daniela Matei

Name, title and organization of the representative of the project's coordinator:

Max Planck Institute for Meteorology, Hamburg, Germany

Reporting period: March 2022 - Sept 2024

Tel: +49 40 41173 460

E-mail: daniela.matei@mpimet.mpg.de

Publishable summary

ROADMAP aimed to expand current understanding of how the Northern Hemisphere ocean surface state and ocean dynamics influence the extratropical atmospheric circulation, as well as associated impact-relevant weather and climate extremes, across time scales under both present day and future climate conditions. Within the second half of the project period, key results of ROADMAP are as follows:

- The North Atlantic Ocean exhibits prominent multi-decadal variability, modulating the climate and weather of the surrounding continental regions. A relevant fraction of this variability is explained by the interplay between ocean circulation and heat transport, leading to coordinated, basin-wide fluctuations in surface temperatures. In ROADMAP we analyzed the stationarity of this interaction in a suite of climate model simulations, providing evidence for the occurrence of spontaneous breaks in the connection between ocean circulation and ocean surface temperatures. These events can be abrupt in time, last from decades to centuries, and are associated with synchronous changes in the characteristics of the oceanic variability.
- Specially designed model experiments suggest that a correct description of the ocean in the Subpolar North Atlantic is important for successful decadal predictions in the downstream region towards the Arctic.
- In atmospheric reanalysis data, a positive phase of the North Atlantic Oscillation (NAO) emerges two weeks after the Madden Julian Oscillation (MJO) phase 3, consistent with past observational studies. In ROADMAP, we demonstrate that this remote influence can be reproduced in a dry GCM, where the positive phase of the NAO emerges after 3 weeks of imposed idealized MJO phase 3.
- In ROADMAP we could demonstrate that ensemble simulations with a size of 10-member is enough to deduce a robust driving role of the tropical Atlantic for other tropical basins. We found a La Niña response 15 months after a tropical Atlantic warming. This response is induced by a Matsuno-Gill response, which diminishes the wind and the associated latent heat flux in the Indian Ocean. After six months, the warm tropical Atlantic SST decays, which in turn causes a warming in the tropical Indian Ocean affecting the Walker tropical circulation in the Indo-Pacific, with stronger trade winds over the Pacific Ocean.
- In ROADMAP we could demonstrate that a significant portion of the multidecadal variability in North Atlantic climate can be explained by coupled oscillations linking stratospheric and tropospheric jets with ocean circulation and Arctic sea-ice. We could also demonstrate that the consideration of these coupling mechanisms in statistical prediction is crucial for predicting the climate over the next 35 years.
- Skillful prediction of atmospheric and oceanic extreme events is challenging with state-of-the-art climate prediction systems. In ROADMAP we could demonstrate that heat waves over Europe and their precursors are more realistically simulated with high-resolution grid configurations as well as that the MPI-M ocean-eddy-resolving climate prediction system can skillfully reforecast strength and extent of both the record-cold anomaly in the eastern subpolar North Atlantic and the strong heat waves over central Europe in the summer of 2015. We could also demonstrate that model biases generally reduce with finer horizontal resolution and shorter time step and that a shorter time step can be an effective way to reduce model biases at a smaller cost than increasing horizontal resolution.

- Traditionally, correlation analyses have been used to identify cause-effect relationships in climate studies. However, correlation does not imply causation, which justifies the need to use causal methods. In ROADMAP, we have used both the Liang-Kleeman information flow method and the PCMCI causal discovery algorithm to quantify cause-effect relationships in different studies on, e.g., ocean-atmosphere-sea ice interactions and tropical-extratropical teleconnections. A thorough intercomparison between the two approaches has been undertaken based on different types of paradigmatic mathematical models as well as a suite of climate index time series.

Objective on sustainable development

ROADMAP tools are expected to be used to support the implementation of strategies to prevent human impacts through the analysis of the exposure and vulnerability to extreme events (Goal 3). Goal 5 on Gender Equity, will also be aimed, by ensuring a good balance of women and men involved in this project proposal (6 out of 11 partners having at least one female PI). During the course of the project we intend to contribute to Goal 4 on Quality Education, by supporting the graduation of students (several BSc, MSc and PhD degrees). With the project results we intend to contribute to Goal 14 (Life below water) given that this proposal aims at modeling ocean circulation, currents, sea surface temperature and extreme events which are deeply important to the sustainable management of marine ecosystems that support, directly and indirectly large communities of fisherman, canning industry etc., being therefore crucial to fishery communities and also to marine organisms of higher trophic levels that depend on them such as larger fish, birds and marine mammals. Finally, ROADMAP considers climate change (Goal 13) and is expected to help in defining strategies to prevent or mitigate environmental and human impacts. The proposed research will help academia, policymakers and civil protection agencies to better assimilate the influence of climate change on the development of a desirable environmentally friendly society, raising awareness, through our outreach activities, of the consequences of climate change on the ocean.

Scientific report - Work progress and achievements during the period

Work package 1: Northern Hemisphere ocean processes important for atmospheric and climate variability

Task 1.1 How are ocean circulation changes impacting ocean surface temperature and salinity?

Two Distinct Phases of North Atlantic Eastern Subpolar Gyre and Warming Hole Evolution under Global Warming [MPI-M]

The North Atlantic subpolar gyre (SPG) plays a crucial role in determining the regional ocean surface temperature (SST), which has profound implications on the surrounding continental and coastal climate. Here, we analyze the Max Planck Institute-Grand Ensemble global warming experiments and show that the SPG can evolve in two distinct phases under continuous global warming. In the first phase, as the global mean surface temperature approaches 2-K warming, the eastern SPG

intensifies in combination with a weakening Atlantic meridional overturning circulation (AMOC), accompanied by a cooling of subpolar North Atlantic SST, known as the warming hole. The associated oceanic fingerprint matches with the observations over the last 15 years, where an intensification and cooling of the eastern SPG is related to salinity reduction at the eastern side of the SPG. However, for further warming beyond 2 K, in spite of a continuous decline in the AMOC, a northward shift of the mean zonal wind extends the subtropical gyre northward with an associated disruption of the eastern SPG intensification, resulting in the cessation of the warming hole. Therefore, a shift from the initially dominating oceanic drivers to the atmospheric driver results in a two-phase evolution of the North Atlantic Ocean SPG circulation and the associated SST under continuous global warming.

Nonstationarity in AMOC-AMV connection [CNR]

We inspected the connection between the Atlantic meridional overturning circulation (AMOC) and the Atlantic multidecadal variability (AMV) in a suite of pre-industrial integrations from the 6th phase of the Coupled Model Intercomparison Project (CMIP6), using a change-point detection method to identify different AMOC-AMV co-variability regimes. A key finding of this study is that models robustly simulate multi-decadal windows where the AMV and the AMOC are essentially uncorrelated. These regimes coexist with longer periods with relatively high correlation. Drops and recoveries of correlation are found to be often abrupt and confined in a temporal window of the order of 10 years. Phenomenological evidence suggests that the no-correlation regimes may be explained by drops in the variance of the AMOC: a less variable meridional heat transport leads to a suppressed co-variability of the AMV, leaving a larger role for non-AMOC drivers, consistent with a non-stationary AMOC-stationary noise interpretative framework. Results of this study can be found in Bellucci et al. (2022).

The relationship between sea surface temperature anomalies and North Atlantic tropical cyclone rainfall over ocean and land [MU]

In the study we found that for a 1°C sea surface temperature (SST) increase in the tropical cyclone main development region (MDR), there is a 6% increase in the tropical cyclone precipitation (TCP) rate over the Atlantic, which rises to over 40% over land (US states) and appears linked not only to the Clausius-Clapeyron relationship but also to the increase in tropical cyclone (TC) intensity associated with increasing SSTs. Total annual TCP is significantly correlated with the SST. Over the Atlantic there is an increase of 116% and over land there is an increase of 140% in total TCP for a 1°C rise in SST in the MDR (Hallam et al., ERC 2023).

Can we trust projections of AMOC weakening based on climate models that cannot reproduce the past? [MU]

The Atlantic Meridional Overturning Circulation (AMOC), a crucial element of the Earth's climate system, is projected to weaken over the course of the twenty-first century. As our confidence in future climate projections depends largely on the ability to model the past climate, we take an in-depth look at the difference in the twentieth century evolution of the AMOC based on observational data (including direct observations and various proxy data) and model data from climate model ensembles. We show that both the magnitude of the trend in the AMOC over different time periods and often even the sign of the trend differs between observations and climate model ensemble mean, with the magnitude of the trend difference becoming even greater when looking at the CMIP6 ensemble compared to CMIP5. We discuss possible reasons for this observation-model

discrepancy and question what it means to have higher confidence in future projections than historical reproductions. (McCarthy & Caesar, 2023)

The Marine heatwave west of Ireland in June 2023 [MU, IDL]
A severe marine heatwave (MHW) developed in the eastern North Atlantic, west of Ireland in June 2023. Except for a narrow band close to the coast from Greenland to Canada, SSTs everywhere in the North Atlantic were above the 41-year average (1982–2023), with many regions experiencing temperatures 2 degC higher than average. In the study region west of Ireland, the SST reached an impressive 4 degC above average. Globally, MHWs have been increasing in frequency and duration largely in response to rising mean ocean temperatures. However, since 2007, temperatures in Irish waters have been cooling, linked by some authors to a decline in the AMOC. The observed increase in MHWs in Irish waters presented here suggests that these waters are not immune from the effects of extreme ocean warming. (McCarthy et al., Weather 2023)

Multi-model analysis of the decadal prediction skill for the North Atlantic ocean heat content [IDL]
Important differences in upper ocean temperature across decadal prediction systems and their respective uninitialized historical ensembles are explored. Particular attention has been given to the Labrador Sea (LS) and its surroundings since this is found to be a region where upper ocean heat content has low observational uncertainties, yet high inter-model spread in both decadal predictions and historical experiments. In the LS, no clear picture emerges from the multi model ensemble of how much predictive capacity for the OHC arises from external forcings, given the large inter-model differences in OHC anomaly correlation coefficients of the historical experiments, linked to the different mean state biases across models. (Teresa-Costa submitted)

A Perspective Paper on *Windows of opportunity for robust predictions of the Atlantic Meridional Overturning Circulation* (Matei, McCarthy, Bellucci et al., 2024) **[MPI-M, MU, CNR, CMCC, UiB, NERSC, LOCEAN, GEOMAR, RMIB]** is in preparation for Nature Climate Change. While the IPCC rate as 'very likely' the prospect of the AMOC weakening in future decades, they assign 'low confidence' to the 20th century AMOC change, leading to questions about how we can trust future projections from models that disagree with observational reconstructions. Despite limitations, initialized climate models, better reproduce observed 20th century AMOC. Recent studies have shown that there exist 'windows of opportunity' where strong AMOC signals are associated with a stronger climate signal. In this perspective, we argue that the AMOC is less predictable when the AMOC matters less, and more predictable when the AMOC matters more. In this perspective, we consider the limits of AMOC predictability on decadal to climatic timescales, in a broad range of model-based products. Special attention will be devoted to the ability of initialized climate models, known as decadal climate predictions, to predict future AMOC state, variability, and relationship to key climate variables. However, while the effect of initialisation for AMOC can persist on timescales of 10–20 years, the skill of these models to capture AMOC decadal variability is often limited. We consider factors such as model resolution, model bias, missing feedbacks and processes that limit the simulated AMOC accuracy.

Observed winter Barents Kara Sea ice variations induce prominent sub-decadal variability and a multi-decadal trend in the Warm Arctic Cold Eurasia pattern [MPI-M, NERSC, LOCEAN, CNR]
The observed winter Barents-Kara Sea (BKS) sea ice concentration (SIC) has shown a close association with the second empirical orthogonal function (EOF) mode of Eurasian winter surface air temperature (SAT) variability, known as Warm Arctic Cold Eurasia (WACE) pattern. However, the

potential role of BKS SIC on this WACE pattern of variability and on its long-term trend remains elusive. Here, we show that from 1979 to 2022, the winter BKS SIC and WACE association is most prominent and statistically significant for the variability at the sub-decadal time scale for 5–6 years. We also show the critical role of the multi-decadal trend in the principal component of the WACE mode of variability for explaining the overall Eurasian winter temperature trend over the same period. Furthermore, a large multi-model ensemble of atmosphere-only experiments from 1979 to 2014, with and without the observed Arctic SIC forcing, suggests that the BKS SIC variations induce this observed sub-decadal variability and the multi-decadal trend in the WACE. Additionally, we analyze the model simulated first or the leading EOF mode of Eurasian winter SAT variability, which in observations, closely relates to the Arctic Oscillation (AO). We find a weaker association of this mode to AO and a statistically significant positive trend in our ensemble simulation, opposite to that found in observation. This contrasting nature reflects excessive hemispheric warming in the models, partly contributed by the modeled Arctic Sea ice loss.

Studies described in detail in mid-term report:

- Prediction of upper ocean heat content [IDL]
- Developing an ocean coupled potential intensity hurricane model for the subtropical Atlantic around Bermuda [MU]
- Identifying and Characterizing Subsurface Tropical Instability Waves in the Atlantic Ocean in Simulations and Observations [MPI-M]

Task 1.2 What is the likely future of western boundary current extensions: More eddying or meridional shifts?

Western boundary circulation and coastal sea-level variability in Northern Hemisphere oceans [MU]

We investigated, using reconstructions based on tide gauge data, the western boundary currents of the Kuroshio, Pacific and Gulf Stream, Atlantic. The results show for each basin that the inshore sea level upstream of the separation points is in sustained agreement with the meridional shifts of the western boundary current extension over the period studied, i.e. the past 7 (5) decades in the Atlantic (Pacific). Decomposition of the coastal sea level into principal components allows us to discriminate this variability in the upstream sea level from other sources of variability such as the influence of large meanders in the Pacific. Long-duration tide gauges could therefore be used as proxies for the past meridional shifts of the western boundary current extensions. (Diabaté et al., Ocean Sci. 2021)

The relationship between SST gradients and ocean heat content along the Gulf Stream and Kuroshio Currents and the 250mb Jet Stream [MU]

In North Atlantic the SST gradient and mean jet latitude position show close alignment in winter and spring along the western boundary in the Gulf Stream region where the SST gradient is strongest. The SST gradient has declined since 1871 in the Gulf Stream between 35-40N, 55-65W and we find a significant anti-correlation between jet latitude and SST gradient. For the period since 1940 we find a weaker SST gradient in the region 35-40N 55-65W leads to a northward shift in the winter (DJF) jet stream and vice versa. The ocean leads by up to 6 months. (Hallam et al., in preparation)

Work package 2: Extra-tropical ocean–atmosphere interaction controls on the eddy-driven jet, the stratospheric polar night jet and atmospheric blocking

Task 2.1 Identify changes of TEDJ, SPNJ, blocking and associated cyclone and extremes that can be driven by the oceanic variability (mainly Atlantic SST, Pacific SST) from seasonal to multidecadal time-scales

More extreme summertime North Atlantic Oscillation under climate change [MPI-M]
Extreme states of the North Atlantic Oscillation (NAO) in summer can lead to severe weather events such as heatwaves and floods in Europe. But how the summer NAO extremes evolve in response to climate change remains unexplored. Here we show that the statistical distribution of summer NAO index grows wider with increasing global warming in large ensembles of climate change simulations as well as reanalysis data. The amplified internal variability by global warming leads to a higher probability of internally generated summer NAO extremes --- for both positive and negative phases --- accompanied by an amplification of their impacts on surface temperature over northwestern Europe. This study highlights that global warming may counteract our predictive skill for the summer NAO by amplifying its internal variability, and thus exacerbate risks of the associated severe weather events in Europe. (submitted to Nature Climate Change)

<u>Studies described in detail in mid-term report:</u>

- Mid-latitude North Atlantic SST biases and their relation to blocking and the jet [CMCC, UiB]
- The atmospheric response to meridional shifts of the Gulf Stream SST front assessed using HighResMIP forced atmosphere-only historical ensemble simulations [CMCC, CNR]
- Meridional energy transport extremes and the general circulation of NH mid-latitudes: dominant weather regimes and preferred zonal wavenumbers [CNR]
- Analysis of the influence of anthropogenic warming on the statistics of large-scale circulation modes in the Atlantic sector [MPI-M]
- The role of North Atlantic SST variability on European summer climate [PIK/H2]

Task 2.2 Understanding the feedback-mechanisms linking different climate components (e.g. troposphere, stratosphere, ocean, sea-ice and continental snow cover) in the identified coupled ocean atmosphere variability (see T2.1) and testing our understanding in large ensemble prediction systems

The influence of western boundary currents on the seasonal to decadal variability of the Northern Hemisphere jet stream [MU]
We analyzed the seasonal to decadal variations in Northern Hemisphere jet stream latitude and speed over land (Eurasia, North America) and oceanic (North Atlantic, North Pacific) regions between the period 1871–2011 using the Twentieth Century Reanalysis dataset. Significant regional differences are seen on seasonal to decadal timescales. Seasonally, the jet latitude range is lower over the oceans compared to land, reduced 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 currents of the North Pacific and North Atlantic, where the land-sea contrast and SST gradients are strongest and effectively anchoring the storm track. Long term trends are generally overlaid by multidecadal variability, particularly evident in the North Pacific, where 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, suggesting that different mechanisms are influencing the jet latitude and speed.

Coupled stratosphere-troposphere-Atlantic multidecadal oscillation and its importance for the near-future climate projection [UiB]

Using long-term forced model simulations, real-world observations, and model reanalysis data, we demonstrated that a significant portion of the multidecadal variability in the North Atlantic climate components of the climate system can be explained by coupled oscillations linking stratospheric polar night jet (SPNJ) and tropospheric eddy-driven jet (TEDJ) with ocean circulation and Arctic sea-ice (Omrani et al., 2022). Physical mechanisms for this Oscillation were proposed. We also demonstrated that the consideration of these coupling mechanisms in statistical prediction is crucial for predicting the climate over the next 35 years.

Identifying the predictable atmosphere/ocean-coupled Atlantic multidecadal variability and its link to external forcing [UIB]

One of the major challenges in climate prediction is identifying and isolating the predictable signals within the climate system. Building on the mechanisms proposed by Omrani et al. (2022), we developed a simplified conceptual oscillatory model to isolate the coupled multidecadal atmosphere-ocean variability in the north Atlantic regions. This model links the North Atlantic Oscillation (NAO) with the Atlantic Multidecadal Variability (AMV) via changes in the Atlantic Meridional Overturning Circulation (AMOC). Using this model, we successfully replicated the historical multidecadal evolution of both the NAO and AMV. Through various model experiments, we demonstrate that this coupled oscillation can exist independently of external forcing. External factors such as solar variations and volcanic activity modify the period and increase the amplitude of this variability.

Skillful decadal-scale prediction of fish habitat and distribution shifts [MPI-M, UiB]

This work can be seen as implication of decadal coupled atmosphere/ocean variability for the fish stock (Payne et al., 2022)**.** It applies the decadal-scale climate predictions to the habitat and distribution of marine fish species. It shows statistically significant forecast skill of individual years that outperform baseline forecasts 3–10 years ahead; forecasts of multi-year averages perform even better, yielding correlation coefficients more than 0.90 in some cases. It also demonstrates that the habitat shifts underlying conflicts over Atlantic mackerel fishing rights could have been foreseen. These results show that climate predictions can provide information of direct relevance to stakeholders on the decadal-scale.

Nonstationarity in the NAO–Gulf Stream SST Front Interaction [CMCC, UiB, CNR]

This study assesses the mechanisms and shows nonstationarity in the decadal NAO–GS-Front (GSF) interaction and associated time lags during 1950–2020, using reanalysis data. The response of the GSF to the NAO at the decadal time scale can be interpreted as the joint effect of the fast response of wind-driven oceanic circulation, the response of deep oceanic circulation, and the propagation of Rossby waves. However, there is evidence of Rossby wave propagation only during 1972–90. The study suggested that the nonstationarity of Rossby wave propagation caused the shift in the time lag between NAO and the GSF on the decadal time scales (Famooss Paolini et al., 2024).

Pacific oceanic front amplifies the impact of Atlantic oceanic front on North Atlantic blocking [UiB]

We use semi-idealised experiments with an atmospheric general circulation model (Cheung et al., 2023) to demonstrate that the mid-latitude Pacific oceanic front is crucial for climatological Atlantic

blocking activity. The front intensifies the Pacific eddy-driven jet that extends eastward towards the North Atlantic. The eastward-extended Pacific jet reinforces the North Atlantic circulation response to the Atlantic oceanic front, including the storm track activity and the eddy-driven jet. The strengthening of the eddy-driven jet reduces the Greenland blocking frequency. Moreover, the Pacific oceanic front greatly strengthens the stationary planetary-scale ridge in Europe. Together with a stronger northeastward extension of the Atlantic storm track, enhanced interaction between extratropical cyclones and the European ridge favours the occurrence of Euro-Atlantic blocking. Therefore, the North Atlantic circulation response amplified remotely by the Pacific oceanic front substantially increases Euro-Atlantic blocking frequency while decreasing Greenland blocking frequency.

Oceanic Temperature Fronts: Their Crucial Role in Arctic-Antarctic Asymmetry of Sudden Stratospheric Warmings and Polar Stratospheric Cloud Formation [UiB, to be submitted]
The polar stratosphere exhibits a dramatic asymmetry in Sudden Stratospheric Warmings (SSWs) and Polar Stratospheric Clouds (PSCs): SSWs are common in the Arctic, while PSCs are prevalent in the Antarctic. Previous explanations have focused on land-sea contrast and orography. Our study introduces a novel element: oceanic sea surface temperature (SST) fronts. Through semi-idealized model experiments, we demonstrate that SST fronts are key to these differences. They enhance planetary wave propagation, strengthen the Brewer-Dobson Circulation, and lead to more frequent SSWs in the Arctic, while drastically reducing PSC formation. This groundbreaking finding sheds light on the significant yet previously less explored role of SST fronts in polar stratospheric phenomena.

Mechanisms Governing the Future Wintertime Response of the Northern Hemisphere tropospheric Eddy-driven jet [UIB, in preparation]
We investigated the response of the Northern Hemisphere eddy-driven jet (NHTEDJ) to future climate change using atmosphere-only general circulation model (AGCM) experiments and finite Amplitude Wave Activity (FAWA) theory. The jet's response is primarily governed by tropical SST shifts, with extratropical SST changes exerting a modulating influence. Our FAWA analysis reveals that non-conservative processes (NCPs) in the upper troposphere enhance background baroclinicity, triggering increased baroclinic wave activity. This, in turn, augments the FAWA contribution in the lower troposphere, offering new insights into the jet's sensitivity to both tropical and extratropical factors.

Revealing the Critical Impact of Cloud-Radiative Effects on Wintertime Euro-Atlantic Blocking [UIB to be submitted]
Mid-latitude atmospheric blocking, a key driver of extreme weather, is often underestimated by climate models, especially over the Euro-Atlantic region. Our research highlights the significant role of cloud radiative effects (CREs) in this phenomenon. Using the U.S. DOE's Energy Exascale Earth System Model with a cloud-locking technique, we find that CREs can increase blocking frequency by up to 1.67% blocked days, equivalent to a 21.6% relative rise. This increase is driven by enhanced diabatic wave activity upstream of the blocking region, which boosts wave development and block formation downstream. Our study emphasizes the critical need to incorporate CREs accurately in models to enhance forecasting of blocking events.

Case studies of information transfer [RMIB, CNR]
We have applied the Liang-Kleeman rate of information transfer (Liang & Kleeman, 2005; Liang, 2014; Liang, 2021) to different case studies in which ocean-atmosphere-sea ice interactions were

investigated. In a first case study, realized in partnership with Fudan University (X. S. Liang) and SMHI (K. Wyser), we have quantified the contribution of both ocean and atmospheric drivers in the recent and future loss of Arctic sea ice (1970-2100) using outputs from the EC-Earth3 global climate model. We found that there is a two-way influence between changes in Arctic sea ice on the one hand and air temperature, sea-surface temperature and ocean heat transport on the other hand. We also found a progressive decrease in the influence of sea-ice area and volume on air temperature and ocean heat transport through the twenty-first century. These results have been published in Geophysical Research Letters (Docquier et al., 2022). In a second case study, we have quantified interactions between the ocean and atmosphere at the global scale over the period 1988-2017. We have looked at influences between sea-surface temperature (SST), SST tendency and turbulent heat flux (THF) in satellite observations. We found a strong two-way influence between SST and/or SST tendency and THF in many regions of the world, with the largest values in the eastern tropical Pacific and Atlantic Oceans, as well as in western boundary currents. Overall, we found that the influence of SST and SST tendency on THF was larger than the reverse, suggesting a stronger influence of the ocean compared to the atmosphere. These results have been published in Earth System Dynamics (Docquier et al., 2023).

Role of snow cover [LOCEAN]

The two-way interactions between snow cover and the stratospheric polar night jet were investigated in a large multi-model ensemble by Gastineau et al. (2023). The results suggest a driving role of the stratospheric polar night jet for the snow cover anomalies. The snow cover was not found to have a specific role for the stratospheric anomalies.

Task 2.3 Contrasting the influence of the extra-tropical Pacific and Atlantic Oceans on the TEDJ, SPNJ, blocking and cyclones under different externally forced background states (e.g. natural external and anthropogenic radiative forcing) with more focus on anthropogenic future climate change

Stratosphere-Troposphere Circulation Changes [MPI-M]

Within the framework of the "Dynamics and Variability Model Intercomparison Project" (DynVarMIP, Gerber and Manzini 2016), we have contributed to the analysis of stratosphere-troposphere circulation changes in the CMIP6 (Climate Model Intercomparison Project Phase 6) experiments, with a focus on the Northern winter season (Karpechko et al 2022, 2024). The CMIP6 analysis is motivated by the relationship between the uncertainty in the changes of the stratospheric vortex and in surface climate change, previously reported for the CMIP5 ensemble of models (Manzini et al 2014). We have shown that the uncertainty in the changes of the stratospheric vortex remains high for the CMIP6 ensemble of models (Karpechko et al 2022). As for the previous CMIP phase, individual models show robust but opposite changes in the strength of the stratospheric vortex, as measured by the zonal mean zonal wind. We further characterized the stratospheric vortex changes by assessing changes in the vortex center. We find that only the longitudinal change in the vortex position is robust across the models. For the large majority of models, the vortex shifts eastward by 8°–20° degrees in longitude relative to its historical location. The magnitude of this shift increases for larger global warming levels. The latitudinal shift in the vortex position is instead not robust across models. The direction and magnitude of the latitudinal shift indeed correlate with the changes in the zonally averaged vortex strength so that vortex weakening / strengthening corresponds to a southward / poleward shift. To search for the drivers of the inter-model spread in stratospheric climate change, we have further analyzed the projections from both the CMIP5 and CMIP6 ensembles (Karpechko et al 2024). We have found that about half of the inter-model spread in stratospheric polar vortex (SPV) projections by CMIP6 models, but less than a third in CMIP5

models, can be attributed to the inter-model spread in stationary planetary wave driving. In CMIP6, SPV weakening is mostly driven by increased upward wave flux from the troposphere, while SPV strengthening is associated with increased equatorward wave propagation away from the polar stratosphere. Moreover, the dependence of the SPV spread on the model biases in the basic state winds offers a possible emergent constraint. However, a large uncertainty prevents a substantial reduction of the projected SPV spread. The lack of the dependence to the basic state in CMIP5 further calls for better understanding of the underlying causes. Overall, our results emphasize the need to reduce climate projection uncertainty of the tropospheric circulation by narrowing the inter-model spread in projected stratospheric circulation changes.

Arctic Troposphere Warming Driven by External Radiative Forcing and Modulated by the Pacific and Atlantic [NERSC]

Based on multi-model large-ensemble atmospheric simulations, we isolated the contributions of combined external radiative forcing (ERF-AL), interdecadal Pacific variability (IPV), Atlantic multidecadal variability (AMV), and Arctic sea-ice changes to Arctic tropospheric warming (ASIC) from 1979-2013 (Suo et al., 2022). We showed that the ERF-AL is the primary driver of the April–September tropospheric warming during 1979–2013, and its warming effects vary at decadal time scales. The IPV and AMV intensify the warming during their transitioning periods to positive phases and dampen the warming during their transitioning periods to negative phases. The IPV impacts are prominent in winter and spring and are stronger than AMV impacts on 1979–2013 temperature trends. The warming impacts of ASIC are generally restricted to below 700 hPa and are strongest in autumn and winter. The combined effects of these factors reproduce the observed accelerated and step-down Arctic warming in different decades, but the intensities of the reproduced decadal variations are generally weaker than in the observed.

More extreme summertime North Atlantic Oscillation under climate change [MPI-M]

Extreme states of the North Atlantic Oscillation (NAO) in summer can lead to severe weather events such as heatwaves and floods in Europe. But how the summer NAO extremes evolve in response to climate change remains unexplored. We showed that the statistical distribution of summer NAO index grows wider with increasing global warming in large ensembles of climate change simulations as well as reanalysis data. The amplified internal variability by global warming leads to a higher probability of internally generated summer NAO extremes — for both positive and negative phases — accompanied by an amplification of their impacts on surface temperature over northwestern Europe. The findings show that global warming may counteract our predictive skill for the summer NAO by amplifying its internal variability, and thus exacerbate risks of the associated severe weather events in Europe.

Impact of volcanic forcing on the variability of the AMV [MPI-M]

Earlier studies indicate an internal multidecadal (40- to 60-year) oscillation that differs from climate noise in the North Atlantic. Though numerous studies have attributed the AMO to internal oscillatory behavior tied to the Atlantic Meridional Overturning Circulation (AMOC), others have dismissed the AMO as the response of North Atlantic surface temperatures to stochastic atmospheric forcing or external radiative forcing. In particular, more recent studies assume that this so-called Atlantic multidecadal variability (AMV) is instead an expression of competing, temporally variable effects of anthropogenic greenhouse gasses and sulfate aerosols. We analyze two transient mid-Holocene – approximately 8000 long - simulations, one of which is additionally driven by volcanoes (sulfate aerosols) and the other is not. We investigate the role of the influence of the external forcing on the statistics of the AMV index and a possible influence on the spatial AMV

pattern in the North Atlantic. First results show that the variability in the runs with volcanoes increases significantly. The increase in variability is not limited to the interannual time scale, but also extends to the multi-decadal and centennial time scales. One focus will be a better understanding of the processes involved on the various time scales, in particular the interaction between the SSTs (turbulent heat-fluxes) and the large-scale atmospheric circulation modes – like the North Atlantic Oscillation. This study is being carried out as part of a Master's thesis.

Studies described in detail in mid-term report:

- Key role of the non-conservative diabatic processes and tropical ocean for stratospheric dynamical response to climate change [UiB]
- The role of the external forcing on the centennial climate variability [MPI-M]
- Investigating the impact of horizontal resolution on the synoptic-to-large scale circulation in the PRIMAVERA historical coupled simulations [CNR]
- Identification of factors controlling Greenland blocking [PIK/H2]

Work package 3: Tropical-extratropical teleconnections and interbasin linkages

Task 3.1 Tropical-Extratropical teleconnections

Influence of the Madden Julian Oscillation on the North Atlantic Oscillation [LMD]
The influence of the Madden Julian Oscillation (MJO) on the North Atlantic Oscillation (NAO) has been investigated using the dry DYNAMICO GCM recently developed at IPSL and comparing to ERA5 reanalysis datasets. In ERA5 reanalysis, the dipolar pattern of the positive phase of the NAO emerges 2 weeks after MJO phase 3, consistent with past observational studies. Here we demonstrate that this remote influence can be reproduced in a dry GCM. A long-term run of the model has been first performed following the procedure of Chang (2006) to get a model climatology close to that of ERA5 in winter. We then performed many short-term sensitivity experiments with the model (480 runs) by imposing steady heating anomalies similar to MJO phase 3 and looking at their effect onto the North Atlantic region. We do see that the positive phase of the NAO emerges after 3 weeks of imposed idealized MJO phase 3 in the model, similarly to the reanalysis (see also major results at end of document).

Directional dependencies of different climate indices [RMIB]
The directional dependencies of different large-scale climate indices were explored using the Liang-Kleeman information flow (Liang, 2014). Seven key indices (Niño3.4, Atlantic Multidecadal Oscillation [AMO], North Atlantic Oscillation [NAO], Pacific-North America [PNA] pattern, Arctic Oscillation [AO], Pacific Decadal Oscillation [PDO], Tropical North Atlantic [TNA]), collected from the NOAA website, together with three local time series located in Belgium, were selected. The analysis was performed on time scales from a month to 5 years by using a sliding window as a filtering procedure. Beside a very complex network of dependencies, the approach allowed to isolate a few key new results: (i) the AO plays a key role at short time (monthly) scales on the dynamics of the North Pacific and North Atlantic; (ii) the NAO plays a global role at long time scales (several years); (iii) the PDO is slaved to other influences; (iv) the local observables over Western Europe influence the variability on the ocean basins on long time scales. These results were published in Tellus A (Vannitsem and Liang, 2022). Additionally, a comparison of the Liang-Kleeman information flow method with the Peter & Clark momentary conditional independence (PCMCI) algorithm on these climate indices showed that, while there were similarities between the two causal methods, the AO

is the largest driver at monthly time scale according to the former method, while ENSO is the main influencing variable according to PCMCI (Docquier et al., 2024).
This study is also relevant to Task 3.2. It reveals the dependencies resulting for the interbasin linkages, as found for example between the PDO and other indices.

Nonlinearity and asymmetry of the ENSO Stratospheric Pathway [MPI-M]
Nonlinearities and asymmetries of El Niño Southern Oscillation (ENSO) stratospheric pathway to the North Atlantic and Europe have been examined in large ensembles conducted with fully coupled climate models during wintertime. The analysis was centered on historical experiments of the Max Planck Institute Grand Ensemble (Maher et al 2019) and expanded to six other ensembles of more limited size. Within the ENSO stratospheric pathway, the link between sea surface temperature anomalies in the Equatorial Pacific to climate variability of the North Atlantic— European regions is mediated by the stratospheric polar vortex because the latter is sensitive to the anomalies in planetary waves triggered by ENSO over the North Pacific region (Cagnazzo and Manzini 2009). We assess the sensitivity of the ENSO stratospheric pathway as the magnitude of the sea surface temperature anomalies increases, for each ENSO phase. To this end, ENSO events are grouped in three intensity categories (weak, moderate and strong) according to the magnitude of SSTAs. We have found (Manzini et al. 2024) linear relationships for either El Niño or La Niña key diagnostics that characterize the ENSO pathway. However, these relationships are generally weaker for the cold La Niña than for the warm El Niño so that asymmetries between them develop as the events intensify. Specifically, for strong events, the extra-tropical North Pacific and stratospheric responses are asymmetric, with substantially larger responses for El Niño events. The reason of this asymmetry in the stratospheric response is due to the patterns of the geopotential height anomalies associated with El Niño and La Niña in the North Pacific, which are different for strong events. The stratospheric asymmetry in strong events may thereafter contribute to the asymmetry in strong events in the North Atlantic-Europe response in the troposphere in late winter.

Identifying quasi-periodic variability using multivariate empirical mode decomposition: a case of the tropical Pacific [UiB]
Quasiperiodic climate variability in climate systems is highly predictable. In this work, we tested the multivariate extension of a method called Empirical Mode Decomposition in climate science using ENSO and developed a new test for extracting the oscillatory mode of coupled atmosphere-ocean variability from data (Boljka et al., 2023). This method offers a new perspective in identifying and understanding the oscillatory mode of coupled atmosphere-ocean variability and associated teleconnections in all latitudes.

Assessing the influence of sea surface temperature and Arctic sea ice cover on the uncertainty in the boreal winter future climate projection [UiB]
In this work we used multi-model coupled atmosphere/ocean CMIP5-simulations and atmosphere-only model experiments to show that the uncertainties in the future mid-latitude sea level pressure (SLP) in response to climate change are linked to both tropical Pacific forcing and extratropical air-sea interactions in the Atlantic (Cheung et al., 2022).

Assessing the influence of the Indian Ocean on tropical climate [UiB]
Understanding the tropical atmosphere/ocean coupled variability is crucial for the tropical-extratropical teleconnection. in this context, we studied the variability of the Indian Ocean and its influences on the two major patterns of intra-seasonal and interannual tropical climate variability:

the Madden Julian Oscillation and the El Niño Southern Oscillation (Chandra et al. 2024; Wu et al. 2024). These two influence the weather over the extra-tropics.

Simulated contribution of the interdecadal Pacific oscillation to the west Eurasia cooling in 1998–2013 [NERSC, MPI-M, LOCEAN]

In this work we used coordinated multi-model large ensemble simulations to show that the internally driven interdecadal Pacific oscillation has caused a cooling trend over the western Eurasian region during 1998-2013 (Suo et al., 2022). In addition to global warming, the Pacific and Atlantic multi-decadal variability jointly contribute to fluctuations in the Arctic climate over the historical period (1900 to present) through ocean and atmospheric teleconnections (Svendsen et al. 2021).

Tropical and mid-latitude causal drivers of the eastern Mediterranean Etesians during boreal summer [PIK/H2, MPI-M]

During boreal summer, large scale subsidence and a persistent northerly flow, known as the Etesians, characterize the tropospheric circulation over the eastern Mediterranean. The Etesians bring clear skies and alleviate the impact of heat waves over the region. The intraseasonal variability of the Etesians and subsidence over the eastern Mediterranean has been thought to be influenced by the South Asian monsoon and atmospheric processes over the North Atlantic. Here, we employ causal effect networks and causal maps, obtained by applying the Peter and Clark Momentary Conditional Independence (PCMCI) causal discovery algorithm, to identify causal precursors of Etesians. We find that both wave train activity over the North Atlantic/North American region and convective activity over South Asia associated with the Indian summer monsoon (ISM) are causally related to the Etesians at 3-day time scale. Thus, intraseasonal ISM variability affects the eastern Mediterranean circulation, though its influence is conveyed via a Middle East ridge. On a longer weekly time scale, the mid-latitude influence weakens, while the influence of the tropical convective activity via the Middle East ridge remains stable. Moreover, the heat low over the Arabian Peninsula, a feature strongly responsible for the development of the Etesians, is caused by a stronger Middle East ridge and not by North Atlantic wave activity. Finally, we discuss potential implications for circulation changes in the eastern Mediterranean due to anthropogenic global warming.

<u>Studies described in detail in mid-term report:</u>

- Dynamical interlinkages between tropical and extratropical extreme events [PIK/H2]
- Tropical-extratropical teleconnections in reanalysis data and S2S forecasts [PIK/H2]
- Tropical and extratropical controls on Eastern Mediterranean summer climate [PIK/H2]

Task 3.2 Interbasin linkages at the multidecadal time scale

Role of external forcings [LOCEAN]

The role of external forcing in driving interbasin linkages at multi-decadal time scale was investigated in a set of large ensembles of historical simulations, including the large ensembles available from MPI-M and IPSL. A convolutional neural network was designed to disentangle the external and internal variability using the spatio-temporal features of the surface air temperature evolution (Bône et al. 2024).

The Atlantic Ocean: a driver of the Pacific decadal variability [LOCEAN]

The influence of the Atlantic meridional overturning circulation (AMOC) is first investigated using a novel methodology constraining the AMOC intensity without applying any flux correction. The links between the oceanic energy transport between basins has been investigated (Jiang et al. 2023). Pacemaker experiments using the IPSL climate model were analysed to show the driving influence of the tropical Atlantic for other tropical basins at interannual time scales (Jiang et al. in prep). We focus on coupled climate simulations where the North Atlantic SST was nudged toward 12-month running mean SST observations over the 1920-2014 period. Although a relatively small SST nudging toward observed SST anomalies was used, we showed that an ensemble simulation with a size of 10-member is enough to deduce a robust driving role of the tropical Atlantic. We define a tropical Atlantic SST index, called T_{Trop}, the projection of the SST on the tropical part of the Atlantic Multidecadal Variability pattern. The influence of the tropical Atlantic was inferred in these simulations with regressions on T_{Trop}, using the existing large ensemble simulation of the same model to remove the influence of external forcings. We found a La Niña response 15 month after a subtropical Atlantic warming. This response is induced by a Matsuno-Gill response to the tropical Atlantic SST warming, which diminishes the wind and the associated latent heat flux in the Indian Ocean. After six months, the warm tropical Atlantic SST decays, which in turn causes a warming in the tropical Indian Ocean affecting the Walker tropical circulation in the Indo-Pacific, with stronger trade wind over the Pacific Ocean. The stronger trade wind provides the driving force of a La Niña SST anomaly in the equatorial Pacific, which is maximum 14-month after the initial tropical Atlantic warming. A small impact of the Pacific decadal oscillation (PDO) is noted, with a cold PDO phase lagging the tropical Atlantic warming by 2-yr. Lastly, new pacemaker experiments were repeated using the same SST nudging as the one described above, but restricting the nudging to the subpolar Atlantic, defined as 30°N-60°N 80°W-0°E. In these simulations, the subpolar Atlantic SST are not linked to the following La Niña pattern, the tropical SST anomaly playing the dominant role.

North Atlantic and North Pacific Atmosphere-Ocean Interactions [MPI-M, PIK/H2, CNR]

We have addressed the role of atmospheric large-scale variability in linking the variability of the North Atlantic and North Pacific Oceans. To this end, we used standard statistics and Causal Effect Network (CEN, Runge et al 2019, Di Capua et al 2020) analysis, applied to the outputs of Large Ensembles (LEs, ~30 member each) of historical simulations by six CMIP6 models and by the MPI-GE, a set of 95 members (Maher et al 2019). We have found a global reduction of the Northern hemisphere atmospheric quasi-stationary near-surface eddy heat flux with warmer mid-latitude North Atlantic sea surface temperature anomalies (SSTA). This global reduction is not the manifestation of an internal variability pattern of the atmospheric eddies, because atmospheric internal variability typically reports anti-correlation between the Atlantic and Pacific atmospheric near surface meridional heat fluxes (Manzini et al 2024). A global role of Northern Atlantic SSTA is therefore caller for. To evaluate if atmosphere to ocean interactions have the potential to strengthen these global extratropical anomalies, we have designed a CEN analysis at monthly time scale, in collaboration with WP5. We found that a weaker Aleutian low leads to warm North Pacific SSTA and decreased near surface heat flux over the North Pacific. Over the Atlantic, the most prominent result is a direct negative link between the near surface heat flux (HF850A) and the North Atlantic SSTA (AMV ET). Overall, our findings support the results of Zhang and Delworth (2007) that atmosphere-ocean interaction can play a role in the hemispheric reduction of the Northern atmospheric near-surface eddy heat flux associated with warmer mid-latitude North Atlantic SSTA.

Contribution from the Pacific Ocean and the Atlantic Ocean on the Arctic [NERSC, MPI-M, LOCEAN]
Results described in the mid-term report has been published: Based on a unique set of atmospheric model simulations, we have better understood the contributions to the Arctic tropospheric warming in 1979-2013 (Suo et al. 2022a), and the cooling over western Eurasia in 1998-2013 (Suo et al., 2022b).

Pacemaker experiments in the North Atlantic [NERSC, LOCEAN]
As described in the mid-term report, we have performed pacemaker model experiments. Constraining the Subpolar North Atlantic region toward observed values, using NorCPM and IPSL-CM6, we found that the salinity variability in the Norwegian Sea and towards the Arctic Ocean is improved (Langehaug et al. in progress). Furthermore, applying the pacemaker method on retrospective predictions, shows that a correct description of the ocean in the Subpolar North Atlantic is important for successful decadal predictions in the downstream region (Drews et al. 2024). Constraining the larger North Atlantic region in NorCPM, we found that the North Pacific multidecadal variability is also largely improved (Suo et al. in progress). Climate models, both historical runs and predictions from the CMIP6 experiments, struggle to represent the correct temperature anomalies along the warm Atlantic water pathway from the North Atlantic Ocean towards the Arctic Ocean (Langehaug et al. 2022). The pacemaker experiments described above are thus important in terms of demonstrating the key role of decadal variability in the Subpolar North Atlantic for the Arctic region. Using observational data, we find the presence of warm (cold) anomalies in the eastern Subpolar North Atlantic Ocean every ten years or so. Warm (cold) anomalies lead to increased surface-forced water mass transformation in light (greater) density classes (Passos et al. 2024).

Studies described in detail in mid-term report:

- Modes of variability in warmer quasi-equilibrium climates [CNR]
- Reconstruction of the Atlantic Multidecadal variability during the last millennium [LOCEAN]

Work package 4: Ocean role in driving weather and climate extremes under present day and future climate change conditions

Task 4.1 Assessing the response of atmospheric extremes (AE) on sub-daily to seasonal timescales to various oceanic-driven surface forcings

Precursors of European summer heat waves [GEOMAR]
We used reanalysis data over the period 1979-2020 to identify European summer heat events and the atmosphere and oceanic anomalies that preceded them (Krüger et al. 2024). We found that a heat event is associated with a ridge over Europe, which leads to clear skies and warm air temperatures, as well as a trough upstream over the North Atlantic Ocean. The North Atlantic trough leads the European ridge and the trough is preceded by a negative anomaly in North Atlantic sea-surface temperature which is persistent throughout the summer season. We also identified a similar chain of events in coupled climate models but found that models with a coarse-resolution ocean (eddy-parameterised) fail to capture the relevant mechanisms while high-resolution (eddy-rich) models reproduces the observed mechanisms much better (Krüger et al. 2024, in prep (see also major results at end of document).

Simulation of atmospheric circulation for different grid resolutions [GEOMAR]
We also performed a set of atmosphere-only simulations with the OpenIFS model to study how well the model can reproduce the observed atmospheric circulation at different horizontal resolutions and time steps (Savita et al. 2024). We found that model biases generally reduce with finer horizontal resolution and shorter time step and that a shorter time step can be an effective way to reduce model biases at a smaller cost than increasing horizontal resolution. For example, the amplitudes of wintertime Rossby waves in midlatitudes are more realistic with either finer horizontal resolution or shorter time step, possibly due to better representation of topography (in the case of resolution) and vertical momentum transfer (in the case of time step). Using a relatively coarse horizontal resolution (100 km) configuration with a shorter time step (30 min) we performed a 45-member ensemble of historical simulations over the period 1950-2013. With the ensemble, we studied to what extent sea-surface temperature anomalies can drive NAO-like variability (Savita et al. 2024, in prep). We found that some strong NAO events, e.g. 2010, are reproduced by most ensemble members, indicating that the event is driven by ocean surface anomalies. We are also working on understanding the relative roles of oceanic variability, i.e. the AMV and IPV, versus intrinsic atmospheric variability, e.g. NAO, for recent decadal air temperature trends (Savita et al. 2024, in review).

Extremely warm European summers preceded by sub-decadal North Atlantic ocean heat accumulation [MPI-M]
The internal variability of European summer temperatures has been linked to various mechanisms on seasonal to sub- and multi-decadal timescales. We find that sub-decadal timescales dominate summer temperature variability over large parts of the continent and determine mechanisms controlling extremely warm summers on sub-decadal timescales. We show that the sub-decadal warm phases of bandpass-filtered European summer temperatures, hereinafter referred to as extremely warm European summers, are related to a strengthening of the North Atlantic Ocean subtropical gyre, an increase in meridional heat transport, and an accumulation of ocean heat content in the North Atlantic several years prior to the extreme summer. This ocean warming affects the ocean–atmosphere heat fluxes, leading to a weakening and northward displacement of the jet stream and increased probability of occurrence of high-pressure systems over Scandinavia. Thus, our findings link the occurrence of extremely warm European summers to the accumulation of heat in the North Atlantic Ocean and provide the potential to improve the predictability of extremely warm summers several years ahead, which is of great societal interest.

<u>Studies described in detail in mid-term report:</u>

- Representation of marine heatwaves and trends in climate models [IDL]

Task 4.2 Response of Mediterranean cyclones (“Medicanes”) to surface climate change

Large scale patterns associated to intense Mediterranean cyclones [CMCC]
As described from previous reports, where we studied the large-scale variables of a list of intense cyclones in the Mediterranean using ERA5 reanalysis and CMIP5 models (lower resolution) calculating their frequencies, variability, trends and future probability of having these extreme events in the Mediterranean basin, we have done the same type of study but with higher resolution models. In these models we have made a comparison with the results of the reanalysis and lower resolution models in order to study the changes in their frequencies, trends and probability of occurring in the future (Álvarez-Castro, et al to be submitted). In this way we have found that the increase in resolution does not change the previous message with the lower resolution models. In

the future scenarios of the CMIP6 models, the probabilities of having intense cyclones in the Mediterranean are lower than in the historical period, but these existing cyclones will be more intense and will last longer. The method we used for this analysis is based on dynamical systems theory and consists in measuring two main properties of the underlying attractor (already defined in the previous report) that give us some insights into the predictability of the system using a large-scale field such as the sea level pressure (SLP) in the North Atlantic Sector. We found that the persistence will be higher in the future and the local size will be lower giving us a signal of higher predictability related to these events. However, the analogues (fields with similar properties in the reference period) in the future scenarios have a worse quality (larger distance to the reference fields) compared to the historical period. One of the reasons could be that the large-scale pressure fields that currently bring intense cyclones to the Mediterranean will most likely change in the future. In order to explore how the conditions are more prone to generate an Intense Mediterranean cyclone and how it is changing in the future climate we have to go further in the research of the favorable meteorological conditions that can determine an environment for the development of cyclones with tropical characteristics in the Mediterranean basin. For this purpose, we have selected some of the most intense Medicanes occurring during the last years such as Rolf, Apollo, Ianos and similars. Using ERA5 data we study variables such as Convective available potential energy (CAPE), coupling index (CI; Bosart & Lackmann, 1995), Wind shear, Geopotential in 500 hPa and Sea surface temperature (SST). The findings reveal that the development of cyclones with tropical characteristics in the Mediterranean is strongly linked to the formation of an intense trough, which is exposed to strong convective processes (high CAPE and CI values), low wind shear at high levels and a Mediterranean Sea temperature above 15ºC. The combination of all these conditions at the same time is quite uncommon, so this could explain the infrequent and extreme nature of this type of cyclones. We have created an index that has been applied in ERA5 data (Gutierrez et al, in preparation) and that we will recreate as well in CMIP models in order to assess the changes better in the future.

Task 4.3 Compound extreme events and feedbacks between atmospheric and marine events (AE and ME)

Skillfully reforecasting the 2015 summer "cold blob" in the subpolar North Atlantic and heat waves over central Europe with the MPI-ESM1.2 ocean-eddy-resolving climate prediction system [MPI-M]

We have performed a first set of hindcasts with our new ocean-eddy-resolving climate prediction system aiming at the case study of the record-cold anomaly in the eastern subpolar North Atlantic and the strong heat waves over central Europe in the summer of 2015: 20 hindcasts initialized in November 2014 and 10 hindcasts initialized in November 2013, as well as 3 hindcasts initialized in November every other year between 1992 and 2012 to bias-correct the hindcasts initialized in 2013 and 2014. Individual hindcasts initialized in November 2014 and November 2013 reforecast both strength and extent of the observed SST anomaly in the eastern subpolar North Atlantic in summer 2015. Based on the area-average perspective, most hindcasts simulate negative SST anomalies in the eastern subpolar North Atlantic in the summer of 2015, in contrast to Maroon et al. (2021, doi:10.1175/JCLI-D-20-0750.1). Regarding the drivers of the simulated cold anomaly, the "coldest" hindcasts are those reproducing the observed strongly positive phase of the atmospheric circulation and associated large surface heat loss in the two preceding winters. Strong heat loss due to an oceanic heat transport divergence across the subpolar North Atlantic contributes to the simulated cold anomaly in several hindcasts. Individual hindcasts initialized in November 2014 and November 2013 also reforecast warm SAT anomalies over central Europe in summer 2015, which agree in

duration and strength with the observed anomalies. There is, however, only little overlap between these „heat wave members“ and the „subpolar cold members“. The SST anomalies in summer 2015 in the „heat wave members“ indicates that apart from cool conditions in the eastern subpolar North Atlantic especially the rather warm conditions in the western Mediterranean Sea played a key role in the occurrence of the strong heat waves over central Europe (see also major results at end of document).

Studies described in detail in mid-term report:

- Potential link between marine and atmospheric heatwaves in both the Mediterranean and the North Atlantic [IDL]

Work package 5: Empirical inference of dynamical links across space and timescales using advanced tools of nonlinear sciences

Task 5.1 Identifying key spatio-temporal variability patterns in large atmospheric and oceanographic data

Studies described in detail in mid-term report:

- Multivariate empirical mode decomposition und scale-specific scaling characteristics [RMIB, PIK/H2]
- Nonlinearity of ENSO [IDL]

Task 5.2 Analysis of LFV and causal inference in reanalyses and climate model runs

Implementing the Liang-Kleeman information flow method [RMIB, IDL]
We have implemented the Liang-Kleeman information flow method (Liang & Kleeman, 2005; Liang, 2014; Liang, 2021) in Python. The codes have been published online and are publicly available on GitHub and Zenodo. This method allows to identify the direction and magnitude of the cause-effect relationships between variables, and thus goes beyond classical correlation analyses. It can be used with multiple variables and can be normalized to assess the importance of the different cause-effect relationships. Statistical significance of this method is tested based on bootstrap resampling with replacement. This method has been applied to two cases studies involving ocean-atmosphere-sea ice interactions that are described in Task 2.2 (Docquier et al., 2022; Docquier et al., 2023), as well as two case studies about tropical-extratropical teleconnections described in Task 3.1 (Vannitsem and Liang, 2022; Docquier et al., 2024). Finally, a nonlinear estimate of the Liang-Kleeman information flow method has been developed and applied to different synthetic models (Pires et al., 2024; Vannitsem et al., 2024). All these studies demonstrate the large potential of the Liang-Kleeman information flow method in identifying causal links between variables.

Comparison of two causal method [RMIB, PIK/H2, IDL]
We have compared the Liang-Kleeman information flow (LKIF) method with PCMCI as well as classical correlation, and applied them to four different artificial models of increasing complexity and one real-world case study. We showed that both methods are superior to the classical correlation analysis, especially in removing spurious links. LKIF and PCMCI displayed some strengths and weaknesses for the three simplest models, with LKIF performing better with a smaller number of variables and with PCMCI being best with a larger number of variables. Detecting causal links from the fourth model (Lorenz, 1963) was more challenging as the system is nonlinear and chaotic.

Results from the real-world case study with climate indices was already discussed in Task 3.1. The results of this comparison have been published in Nonlinear Processes in Geophysics (Docquier et al., 2024).

Task 5.3 Cross-scale causal coupling between different variability modes of ocean and atmosphere

Studies described in detail in mid-term report:

- Dynamical properties of complex variability patterns [PIK/H2]

References (not part of ROADMAP; for ROADMAP references see "Dissemination" below)

Bosart, L. F., & Lackmann, G. M. (1995). Postlandfall tropical cyclone reintensification in a weakly baroclinic environment: A case study of Hurricane David (September 1979). Monthly Weather Review, 123(11), 3268–3291. https://doi.org/10.1175/1520-0493(1995)123<3268:ptcria>2.0.co;2

Cagnazzo, C., and E. Manzini (2009) Impact of the stratosphere on the winter tropospheric teleconnections between ENSO and the North Atlantic and European Region. J. Climate 22, 1223-1238. DOI 10.1175/2008JCLI2549.1

Di Capua, G., J. Runge, R. V. Donner, B. van den Hurk, A. G. Turner, R. Vellore, R. Krishnan, and D. Coumou (2020) Dominant patterns of interaction between the tropics and mid-latitudes in boreal summer: causal relationships and the role of timescales Weather Clim. Dynam., 1, 519–539, 2020 https://doi.org/10.5194/wcd-1-519-2020

Emanuel, K. (2005). Genesis and maintenance of" Mediterranean hurricanes". Advances in Geosciences, 2, 217-220.

Gerber, E. P., & Manzini, E. (2016). The dynamics and variability model intercomparison project (DynVarMIP) for CMIP6: Assessing the stratosphere-troposphere system. Geoscientific Model Development, 9, 3413–3425. https://doi.org/10.5194/gmd--9--3413--2016

Liang, X. S., R. Kleeman (2005). Information transfer between dynamical system components. Physical Review Letters, https://doi.org/10.1103/PhysRevLett.95.244101.

Liang, X. S. (2014). Unraveling the cause-effect relation between time series. Physical Review E, https://doi.org/10.1103/PhysRevE.90.052150.

Liang, X. S. (2021). Normalized Multivariate Time Series Causality Analysis and Causal Graph Reconstruction. Entropy, https://doi.org/10.3390/e23060679.

Lorenz, E. N. (1963). Deterministic nonperiodic flow. Journal of the Atmospheric Sciences, https://doi.org/10.1175/1520-0469(1963)020%3C0130:DNF%3E2.0.CO;2.

Maher, N., S. Milinski, L. Suarez-Gutierrez, M. Botzet, M. Dobrynin, L. Kornblueh, J. Kröger, Y. Takano, R. Ghosh, C. Hedemann, C. Li, H. Li, E. Manzini, D. Notz, D. Putrasahan, L. Boysen, M. Claussen, T. Ilyina, D. Olonscheck, T. Raddatz, B. Stevensand J. Marotzke (2019) The Max Planck Institute Grand Ensemble – Enabling the Exploration of Climate System Variability. Journal of Advances in Modeling Earth Systems, 11. https://doi.org/10.1029/ 2019MS001639.

Mantua N. J., S. R. Hare, Y. Zhang, J. M. Wallace & R. C. Francis (1997) A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Am. Meteor. Soc., 78: 1069-1080.

Manzini, E., C. Cagnazzo, P. G. Fogli, A. Bellucci, W. Müller (2012) Stratosphere - Troposphere coupling at inter-decadal time scales: Implications for the North Atlantic Ocean. Geophys. Res. Lett., 39, L05801. DOI 10.1029/2011GL050771.

Manzini, E., et al. (2014). Northern winter climate change: Assessment of uncertainty in CMIP5 projections related to stratosphere troposphere coupling. Journal of Geophysical Research: Atmospheres, 119(13), 7979–7998. https://doi.org/10.1002/2013JD021403

Reichler, T., J. Kim, E. Manzini, J. Kröger (2012) A stratospheric connection to Atlantic climate variability. Nature Geoscience, 5, 783-787. DOI 10.1038/ngeo1586.

Runge, J., P. Nowack, M. Kretschmer, S. Flaxman, D. Sejdinovic (2019) Detecting and quantifying causal associations in large nonlinear time series datasets. Sci. Adv. DOI: 10.1126/sciadv.aau4996

Zhang, R. and T. L. Delworth (2007) Impact of the Atlantic Multidecadal Oscillation on North Pacific climate variability. Geophys. Res. Lett., 34, L23708, doi:10.1029/2007GL031601

Zhang, R., Sutton, R., Danabasoglu, G., Kwon, Y.-O., Marsh, R., Yeager, S. G., et al. (2019). A review of the role of the Atlantic Meridional Overturning Circulation in Atlantic Multidecadal Variability and associated climate impacts. Reviews of Geophysics, 57, 316–375. https://doi.org/10.1029/2019RG000644

Deliverables and Milestones

Deliverables

The synthesis of the scientific results of ROADMAP through peer-reviewed publications, including multi-partner perspective publications, has been accomplished throughout the project's lifetime and is still ongoing. A final project meeting (in-person) in October 2024 will further foster this synthesis.

D1.1 Report detailing ongoing and future oceanic circulation and AMOC changes relevant to climate variability and extremes [MPIM]

Papers relevant to this DL (see also Task 1.1):

(1) A Perspective Paper on *Windows of opportunity for robust predictions of the Atlantic Meridional Overturning Circulation* (Matei, McCarthy, Bellucci et al., 2024) is in preparation for Nature Climate Change.

(2) Bellucci, A., D. Mattei, P. Ruggieri, L. Famooss Paolini (2022) Intermittent behavior in the AMOC-AMV relationship. Geophysical Research Letters, 49, e2022GL098771.

(3) Bellomo, K., Meccia, V.L., D'Agostino, R., Fabiano F., Larson S.M., von Hardenberg J., and Corti S. Impacts of a weakened AMOC on precipitation over the Euro-Atlantic region in the EC-Earth3 climate model. Clim Dyn (2023)

(4) Meccia, V.L., Simolo C., Bellomo, K., and Corti S., Extreme cold events in Europe under a reduced AMOC 2024 Environ. Res. Lett. **19** 014054 (2024)

D1.2 Report assessing changing modes of variability and projected future changes to western boundary current extension region, [MU]

Papers relevant to this DL (see also Task 1.2):

(1) Famooss Paolini, Luca & Omrani, Nour-Eddine & Bellucci, Alessio & Athanasiadis, Panos & Ruggieri, Paolo & Patrizio, Casey & Keenlyside, Noel. (2024). Nonstationarity in the NAO–Gulf Stream SST Front Interaction. Journal of Climate. 37. 1629–1650.

(2) Famooss Paolini, L., Athanasiadis, P., Ruggieri, P., Bellucci, A.: The atmospheric response to meridional shifts of the Gulf Stream SST front and its dependence on model resolution; J. Clim.

(3) Hallam, S., Josey, S.A., McCarthy, G.D., HIrschi, J.J.M (2022). A regional (land–ocean) comparison of the seasonal to decadal variability of the Northern Hemisphere jet stream 1871–2011. *Clim Dyn* 59, 1897–1918

(4) Diabaté, S. T., Swingedouw, D., Hirschi, J. J.-M., Duchez, A., Leadbitter, P. J., Haigh, I. D., and McCarthy, G. D.: Western boundary circulation and coastal sea-level variability in Northern Hemisphere oceans, Ocean Sci., 17, 1449–1471 (2021)

D2.1 Report on the role of oceanic variability and atmospheric dynamics in forcing TEDJ, SPNJ, blocking and cyclones from seasonal to multidecadal time-scales [UiB]

Cheung et al (2023) showed that the Pacific oceanic front amplifies the impact of the Atlantic oceanic front on North Atlantic blocking. Omrani et al. showed the Crucial Role of the Pacific SST-front in setting Arctic-Antarctic Asymmetry of Sudden Stratospheric Warmings and Polar Stratospheric Cloud Formation (to be submitted). Sandro et al. (to be submitted) showed the importance of Cloud-Radiative Effects in Wintertime Atmospheric Blocking over the Euro-Atlantic Sector. (to be submitted). Famooss et al. 2022 analyzed the mechanisms of the atmospheric response to meridional shifts of the Gulf Stream SST front and its dependence on model resolution;

D.2.2 Report on the dynamics of the coupled ocean-atmosphere variability involving the TEDJ, SPNJ, JPNJ, blocking and cyclones and their possible dynamical linkages to extremes [UiB]

In Omrani et al. 2022, we presented the mechanisms of the Northern Hemisphere coupled multidecadal TEDJ, SPNJ and North Atlantic variabilty including the Arctic Sea-ice and showed the importance of this variability for the near future climate prediction. Payne et al. 2022 showed the implementation of such coupled variability for the prediction of fish habitats. Famooss et al 2024 showed Nonstationarity in the NAO–Gulf Stream SST Front Interaction (NAO describes the the most important mode of the north Atlantic TEDJ-variability).

.

D2.3 Report contrasting the impact of external natural and anthropogenic forcing on the TEDJ, SPNJ, blocking, cyclones and associated extreme [MPIM]

Omrani et al. (to be submitted**)** identified the predictable atmosphere/ocean-coupled Atlantic multidecadal variability using a conceptual model and used different model experiments to understand the role of external forcing in impacting the predictable Atlantic multidecadal variability (UIB). Cheung et al. 2022 assessed the influence of sea surface temperature and arctic sea ice cover on the uncertainty in the boreal winter future climate projections. Omrani et al. identified the importance of the tropical SST-response to climate change and the non-conservative processes

(such as mixing and diabatic heating) for the future response of SPNJ (submitted) and TEDJ (in progress) to climate change. Two further publications fulfill the deliverables. Liu et al. (submitted) investigate the influence of increased anthropogenic CO2 on extreme changes in the North Atlantic Oscillation (NAO). They find an increase in the occurrence of extremes - both negative and positive extremes - in the NAO in a warming world. Furthermore, the impact of these extremes on the temperature over northwestern Europe is increasing. In addition, the impact of natural external influences on the variability was analyzed (Bader and Jungclaus, to be submitted). A focus was on the influence of volcanoes on the low-frequency temperature variability. The clustering of volcanoes has a considerable influence on the low-frequency (multi-decadal to centennial) variability - especially in the tropics. The increase in variability is not spatially homogeneous. The increase in tropical variability is more pronounced in the Indian Ocean and the western Pacific (warm-pool region), while it is weaker in the eastern Pacific.

D3.1 Report on tropical - extratropical teleconnections and their sensitivity to global warming [MPIM]

Manzini et al. 2024 investigated the nonlinearity and asymmetry of the ENSO teleconnection to Northern Europe along the stratospheric pathway during boreal winter. Manzini et al showed that the extratropical North Pacific, stratospheric and tNorth Atlantic-Europe responses to either El Niño or La Niña are linear. However, the response is weaker for the cold La Niña than for the warm El Niño so that asymmetries between the teleconnections of the two phases of ENSO develop as the events intensify. Key to the asymmetry for strong events was found to be the difference in the patterns of the geopotential height anomalies associated with El Niño and La Niña in the North Pacific. Suo et al. 2022a investigated the Simulated contribution of the interdecadal Pacific oscillation to the west Eurasia cooling in 1998-2013. Suo el al. 2022b showed that the Arctic Troposphere Warming can be Driven by External Radiative Forcing and Modulated by the Pacific and Atlantic. In Boljka et. 2023 we tested a new method called multivariate empirical mode decomposition for identifying the quasiperiodic oscillations and we developed a new statistical test for this method. The method was applied to the tropical Atlantic. Ashnel et al 2024 Investigated the Processes Driving Subseasonal Variations of Upper Ocean Heat Content in the Equatorial Indian Ocean. Pires and Hannachi (2021) investigated the nonlinear characteristics and predictability of ENSO, a major driver of tropical-extratropical teleconnections. By analyzing the nonlinear interactions within ENSO, the study contributes to understanding how ENSO events can influence weather and climate patterns in extratropical regions. Docquier et al. (2024) compared causal inference methods for climate data, which are essential tools for studying teleconnections. By evaluating methods like Convergent Cross Mapping and Transfer Entropy, the study helps improve the identification of causal links between tropical and extratropical regions, enhancing our understanding of teleconnections. In summary, all these articles contribute to the broader understanding of tropical-extratropical teleconnections by providing theoretical frameworks, analytical methods, and specific case studies that shed light on how different parts of the climate system interact and influence each other.

D3.2 Report on atmospheric interbasin linkages and their sensitivity to global warming [LOCEAN]

The interbasin linkages were assessed in Wu et al. 2024, that focus on the driving role of the Indian Ocean. They investigated the strong western pole of the Indian Ocean Dipole on the decay of El Niño events. Two papers investigated the driving role of the Atlantic Ocean: (1) in Jiang et al. (2023), the interbasin linkages between the Atlantic Ocean and other basins are investigated using sensitivity experiments where the oceanic heat transport is perturbed; (2) in Jiang et al. (in prep) we focus on

the linkages between the tropical Atlantic and other tropical basins with Atlantic pacemaker experiments. The role of global warming and the issue of separation between the internal and external variability was studied in Bône et al. (2024). The sensitivity of interbasin linkages to global warming were investigated in Simon et al. (2022), where the sea ice loss is shown to reduce the teleconnections associated with the Pacific decadal oscillation. Suo et al. (2022) focuses on the tropospheric Arctic warming and also decomposes the respective role of external forcing, Pacific Ocean and Atlantic ocean variability, together with their interaction. Manzini et al. (in preparation) addressed the role of atmospheric large-scale variability in linking the variability of the North Atlantic and North Pacific Oceans. The analysis of large ensembles of CMIP6 historical experiments has enabled the detection of a global reduction of the Northern hemisphere atmospheric quasi-stationary near-surface eddy heat flux with warmer mid-latitude North Atlantic sea surface temperature anomalies. This finding may support the hypothesis that atmosphere-ocean interaction can play a role in the global response to North Atlantic sea surface anomalies.

D4.1 Report on weather extremes driven by surface forcing and maintenance of planetary waves including the impact of climate change and model resolution [GEOMAR]

Three papers from GEOMAR are relevant to this DL (see also Task 4.1):
(1) Krüger et al. (2024) showed a connection between North Atlantic SST anomalies, planetary and Rossby waves, and European heat extremes.
(2) Savita et al. (2024) showed that atmospheric models of low resolution have biases in the amplitude and phase speed of Rossby waves.
(3) Krüger et al. (to be submitted, GEOMAR&MPI-M) showed that biases in the surface climate in coupled climate models can weaken the connection between North Atlantic SST anomalies and European heat extremes.

D4.2 Report on recent changes in intensity and frequency of Mediterranean mesoscale cyclones using different model simulations [CMCC]

Three papers from CMCC are relevant to this DL (see also Task 4.2):

(1) Alvarez-Castro C., Gutierrez-Fernandez, J., Faranda D. , Gualdi S., Gallego D., Peña-Ortiz C: “Large scale predictability leading intense Mediterranean cyclones”
(2) Gutiérrez-Fernández, J., Alvarez-Castro, C., Scoccimarro, E., Cavicchia, L., Gualdi, S. Gonzalez-Aleman, J.J. , Miglietta, M.M.: "Investigating the Development Conditions for Cyclones with Tropical Features in the Mediterranean Basin".

D4.3 Assessment of compound AE and ME events based on observations, models’ simulations and remote sensing datasets [IDL]

One paper and one thesis led by IDL are relevant to this DL: 1) Simon et al. (2024) identified the significant roles of long-term warming and interannual variability in driving the frequency and intensity of marine heatwaves in the Mediterranean. The paper shows how atmospheric anomalies, radiative fluxes, and heat fluxes contribute to the frequency, intensity, and duration of MHWs in the Mediterranean, highlighting the interconnectedness of atmospheric and oceanic processes. The thesis from Lourenço (2023) analysed atmosphere-ocean interactions, focusing on compound extreme events in South America. This thesis was expanded to analyze Europe and the European sector of the Atlantic, which resulted in a MSc thesis and a paper (to be submitted next month).

D5.1 Identification of the coupled modes of atmospheric-oceanic variability on time scales ranging from seasons to the decade and clarification how those modes change in different forcing scenarios [IDL]

Two papers from IDL and RMIB are relevant to this DL. Both papers are related through their focus on understanding information transfer and causal dependencies in complex systems, particularly in the context of atmospheric models. The first paper by Pires, Docquier, and Vannitsem (2023) develops a general theory to estimate how information is transferred within nonlinear systems. This is crucial for understanding how different parts of a system influence each other, especially in chaotic environments. The second paper by Vannitsem, Pires, and Docquier (2024) applies these concepts to a reduced-order atmospheric model. It examines how information flows and how entropy is managed within the system, providing practical insights into the theoretical framework discussed in the first paper. In essence, the first paper lays the theoretical groundwork for estimating information transfer, while the second paper applies these theories to a specific atmospheric model to analyze causal relationships and entropy dynamics. This connection highlights the practical application of theoretical concepts to real-world systems.

D5.2: Report on the links between the ocean and the atmosphere over different ocean basins (North Atlantic and North Pacific), in particular associated with the role of ocean currents and the jet-streams, based on nonlinear analysis [RMIB]

4 papers (3 led by RMIB) fulfill this deliverable: (1) Vannitsem & Liang (2022), who show the causal links between different large-scale atmospheric and oceanic indices based on LKIF; (2) Docquier et al. (2023), in which the two-way interactions between the ocean and the atmosphere are shown using LKIF; (3) Docquier et al. (2024), who compare two causal methods (LKIF and PCMCI) to identify relationships between different atmospheric and oceanic indices. (4) Hallam et al. (2022) A regional (land–ocean) comparison of the seasonal to decadal variability of the Northern Hemisphere jet stream 1871–2011. *Clim Dyn* 59, 1897–1918

D5.3: Report on the links between tropical and extra-tropical regions based on nonlinear analysis [RMIB]

3 papers led by RMIB fulfill this deliverable: (1) Vannitsem & Liang (2022), who use a combination of climate indices in both tropical and extra-tropical regions and apply LKIF to them; (2) Docquier et al. (2023), who look at ocean-atmosphere interactions over the whole globe using LKIF, and identify differences between tropical and extra-tropical regions; (3) Docquier et al. (2024), who complement the analysis of Vannistem & Liang (2022) in terms of climate indices.

Milestones

Milestone Nr.	Milestone Title	due	Milestone achieved	Comments on deviation
MS 2	LMDZ atmosphere-only experiments & KCM pacemaker experiments	M27	experiments completed	Experiments not analysed in ROADMAP due to loss of personnel. Experiments with OpenIFS atmosphere and FOCI-OpenIFS coupled model used instead (MS 3).

MS 3	Atmosphere-only experiments & coupled model experiments	M27	experiments completed	Some delay in coupled-model experiments due to one postdoc on maternity leave and due to problems during hardware upgrade at HPC. Two manuscripts in preparation; also used by SCENIC project at GEOMAR.
MS 5	Validated algorithms for unsupervised feature selection in big climate data sets	M24	Results published in peer-reviewed journal	The task was relatively accomplished. Work presented in IMI-CSIRO workshop on "Weather & Climate Extremes and Machine Learning: Recent Development and Prospective" and one paper in preparation (Pires, Hannachi and Vannitsem. Probabilistic forecasting based on Copulas relying on nonlinear correlations). A scientific paper was published in QJRMS.
MS 7	Finalizing the analyses of key spatio-temporal variability and the causal relationships between the different components (and different regions) of the climate system, in the context of reanalysis data sets, several available long CMIP runs and of the runs of the models envisaged in WPs 2-4	M36	results published in peer-reviewed journals	Vannitsem and Liang (2022), Docquier et al. (2023, 2024) Di Capua et al. (2023, 2024)

Financial Status

Name of partner	Grant budgets spent (in EUR and %)	Comments (if necessary) planning
MPI-M	til mid-term report 128,718 EUR (17%) til end-term report 718.310 EUR (96%)	MPI-M 's part with BMBF has been cost neutrally extended till 31.10.2024
UiB	til mid-term report 89,809 EUR (29%) til end-term report 309,690 EUR (100%)	
Geomar	til mid-term report 39,495 EUR (11%) til end-term report 351,565 EUR (97%)	lower equipment costs than expected
PIK and H2	til mid-term report 114,649 EUR (38%) til end-term report 270,606 EUR (99%)	h2 's part with BMBF has been cost neutrally extended till 31.10.2024
NERSC	til mid-term report 158,680 EUR (49%) til end-term report 325,000 EUR (100%)	
RMIB	til mid-term report 74,319 EUR (31%) til end-term report 242,250 EUR (100%)	

IDL	til mid-term report 20,833 EUR (21%) til end-term report 99,205 EUR (100%)	
CMCC	til mid-term report 39,671 EUR (31%) til end-term report 127,970 EUR (100%)	
CNR	til mid-term report 24,100 EUR (28%) til end-term report 114.690,51 EUR (100%)	Total expected budget euro 85.714,12. Total budget reported 114.690,51
MU	til mid-term report 61,314 EUR (31%) til end-term report 198,587 EUR (100%)	We will report 198 587 EUR (that's including an estimate for the final meeting in Hamburg rather than final number)
LOCEAN	til mid-term report 0 EUR (0%) til end-term report 113,354 EUR (100%)	
LMD	til mid-term report 94,911 EUR (69%) til end-term report 131,472 EUR (96%)	reduced travel activity due to the epidemic conditions

Dissemination activities in the period in question

Publications:

Type (Peer-reviewed journals, Books or chapters in books)	Partners involved	Title and authors	doi (if available) or link
Peer-reviewed journal	RMIB	Docquier, D., S. Vannitsem, R. Ragone, K. Wyser, X. S. Liang (2022). Causal links between Arctic sea ice and its potential drivers based on the rate of information transfer. Geophysical Research Letters, 49(9): e2021GL095892.	10.1029/2021GL095892
Peer-reviewed journal	RMIB	Vannitsem, S., X. S. Liang (2022). Dynamical dependencies at monthly and interannual time scales in the climate system: Study of the North Pacific and Atlantic regions. Tellus A: Dynamic Meteorology and Oceanography, 74: 141-158.	10.16993/tellusa.44
Peer-reviewed journal	RMIB, CNR	Docquier, D., S. Vannitsem, A. Bellucci (2023). The rate of information transfer as a measure of ocean-atmosphere interactions. Earth System Dynamics, 14(3): 577-591.	10.5194/esd-14-577-2023
Peer-reviewed journal	RMIB, PIK/H2, IDL	Docquier, D., G. Di Capua, R. V. Donner, C. A. L. Pires, A. Simon, S. Vannitsem (2024). A comparison of two causal methods in the context of climate analyses. Nonlinear Processes in Geophysics, 31(1): 115-136.	10.5194/npg-31-115-2024
Peer-reviewed journal	IDL, RMIB	Pires, C., D. Docquier, S. Vannitsem (2024). A general theory to estimate Information transfer in nonlinear systems. Physica D: Nonlinear Phenomena, 458: 133988.	10.1016/j.physd.2023.133988
Peer-reviewed journal	RMIB, IDL	Vannitsem, S., C. A. Pires, D. Docquier (2024). Causal dependencies and Shannon entropy budget: Analysis of a reduced-order atmospheric model. Quaterly Journal of the Royal Meteorological Society.	10.1002/qj.4805
Peer-reviewed journal	RMIB	Vannitsem, S., D. Docquier, S. Wauthy,, M. Corkill, J.-L. Tison (in review). Sources of low-frequency d18O variability in	10.48550/arXiv.2405.02471

		coastal ice cores from Dronning Maud Land. Under review for Climate Dynamics.	
Peer-reviewed journal	CNR, CMCC	Bellucci, A., D. Mattei, P. Ruggieri, L. Famoos Paolini (2022) Intermittent behavior in the AMOC-AMV relationship. Geophysical Research Letters, 49, e2022GL098771.	10.1029/2022GL098771
Peer-reviewed journal	CNR	Simolo, C., Corti, S. Quantifying the role of variability in future intensification of heat extremes. Nat Commun **13**, 7930 (2022).	10.1038/s41467-022-35571-0
Peer-reviewed journal	CNR	Bellomo, K., Meccia, V.L., D'Agostino, R., Fabiano F., Larson S.M., von Hardenberg J., and Corti S. Impacts of a weakened AMOC on precipitation over the Euro-Atlantic region in the EC-Earth3 climate model.Clim Dyn(2023)	10.1007/s00382-023-06754-2
Peer-reviewed journal	CNR	Meccia, V.L., Simolo C., Bellomo, K., and Corti S., Extreme cold events in Europe under a reduced AMOC 2024 Environ. Res. Lett. **19** 014054 (2024)	10.1088/1748-9326/ad14b0
Peer-reviewed journal	CNR	Fabiano, F., Davini, P., Meccia, V.L., Zappa, G., Bellucci, A., Lembo, V., Bellomo, K., and Corti, S., Multi-centennial evolution of the climate response and deep-ocean heat uptake in a set of abrupt stabilization scenarios with EC-Earth3. Earth Syst. Dynam., 15, 527–546 (2024)	10.5194/esd-15-527-2024
Peer-reviewed journal	LOCEAN	Jiang, W., Gastineau, G., & Codron, F. (2023). Climate response to Atlantic meridional energy transport variations. *Journal of Climate*, *36*(16), 5399-5416.	10.1175/JCLI-D-22-0608.1
Peer-reviewed journal	LOCEAN	Bône, C., Gastineau, G., Thiria, S., Gallinari, P., & Mejia, C. (2024). Separation of internal and forced variability of climate using a U-Net. *Journal of Advances in Modeling Earth Systems*, 16, e2023MS003964.	10.1029/2023MS003964
Peer-reviewed journal	LOCEAN	Gastineau, G., Frankignoul, C., Gao, Y., Liang, Y.-C., Kwon, Y.-O., Cherchi, A., Ghosh, R., Manzini, E., Matei, D., Mecking, J., Suo, L., Tian, T., Yang, S., and Zhang, Y. (2023): Forcing and impact of the Northern Hemisphere continental snow cover in 1979–2014, The Cryosphere, 17, 2157–2184	10.5194/tc-17-2157-2023
Peer-reviewed journal	GEOMAR	Latif, M., Bayr, T., Kjellsson, J., Lübbecke, J.F, Martin, T., Nnamchi, H.C., Park, W., Savita, A., Sun, J., Dommenget, D. (2023) Strengthening atmospheric circulation and trade winds slowed tropical Pacific surface warming. Nat. Communications Earth & Environment, 4	10.1038/s43247-023-00912-4
Peer-reviewed journal	GEOMAR	Krüger, J., Kjellsson, J., Pilch Kedzerski, R., Claus, M. (2023) Connecting North Atlantic SST variability to European heat events in recent decades. Tellus A: Dynamic Meteorology and Oceanography, 75(1), 358-374	10.16993/tellusa.3235
Peer-reviewed journal	GEOMAR	Savita, A., Kjellsson, J., Pilch-Kedzierski, R. (2024) ECMWF-OpenIFS climate sensitivity to horizontal resolutions and model time step. Geoscientific Model Development. 17, 1813–1829	10.5194/gmd-2023-101
Peer-reviewed journal	GEOMAR	StPierre, M., Latif, M., Kjellsson, J., Park, W., Borchert, L., (2024) Evident decrease in future European soil moisture in the Kiel Climate Model grand ensemble. Submitted to Climate Dynamics.	Submitted
Peer-reviewed journal	GEOMAR	Savita, A., Kjellsson, J., Latif, M., Nnamchi, H., Wahl, S., (2024) Causes of Eurasian Winter-Cooling During the late 20th and Early 21st Century. Submitted to Geophysical Research Letters.	Submitted
Peer-reviewed journal	GEOMAR	Kjellsson, J., Park, W. Multi-centennial variability of AMOC variability in the FOCI-OpenIFS climate model. In review for Nature Communications Earth & Environment	Submitted
Peer-reviewed journal	NERSC	Passos, L., H. R. Langehaug, M. Årthun, and F. Straneo, 2024: On the relation between thermohaline anomalies and water mass transformation in the Eastern Subpolar North Atlantic. J. Climate	10.1175/JCLI-D-23-0379.1

Peer-reviewed journal	NERSC	Drews, A., Schmith, T., Tian, T., Wang, Y., Devilliers, M., Keenlyside, N. S., et al. (2024). The crucial role of the subpolar North Atlantic for skillful decadal climate predictions. Geophysical Research Letters	10.1029/2024GL109415
Peer-reviewed journal	MPI-M	Karpechko, A. Y., Afargan-Gerstman, H., Butler, A. H., Domeisen, D. I.V., Kretschmer, M., Lawrence, Z., E. Manzini, M. Sigmond, I. R. Simpson, Z. Wu (2022). Northern hemisphere stratosphere-troposphere circulation change in CMIP6 models: 1. Inter-model spread and scenario sensitivity. Journal of Geophysical Research: Atmospheres, 127, e2022JD036992	10.1029/2022JD036992
Peer-reviewed journal	MPI-M	Karpechko, A. Y., Wu, Z., Simpson, I. R., Kretschmer, M., Afargan-Gerstman, H., Butler, A. H., Domeisen, D.I.V., Garny, H., Lawrence, Z., Manzini, E., Sigmond, M. (2024) Northern Hemisphere stratosphere-troposphere circulation change in CMIP6 models: 2. Mechanisms and sources of the spread. Journal of Geophysical Research: Atmospheres, 129	10.1029/2024JD040823
Peer-reviewed journal	MPI-M	Manzini, E., Ayarzagüena, B., Calvo, N., & Matei, D. (2024). Nonlinearity and asymmetry of the ENSO stratospheric pathway to North Atlantic and Europe, revisited. Journal of Geophysical Research: Atmospheres, 129, e2023JD039992	10.1029/2023JD039992
Peer-reviewed journal	MU	Hallam, S., Josey, S.A., McCarthy, G.D., HIrschi, J.J.M (2022). A regional (land–ocean) comparison of the seasonal to decadal variability of the Northern Hemisphere jet stream 1871–2011. *Clim Dyn* 59, 1897–1918	10.1007/s00382-022-06185-5
Peer-reviewed journal	MU	Hallam, S., McCarthy, G.D., Feng, X., Harris, E., Düsterhus A., Ogungbenro, S., Hirschi, J.J.M. (2023) The relationship between sea surface temperature anomalies, wind and translation speed and North Atlantic tropical cyclone rainfall over ocean and land. Environ. Res. Commun. 5 025007	10.1088/2515-7620/acb31c
Peer reviewed Journal	MU	McCarthy G.D., Caesar, L. (2023) Can we trust projections of AMOC weakening based on climate models that cannot reproduce the past? Philosophical Transactions of the Royal Society A. 381, 2262	10.1098/rsta.2022.0193
Peer-reviewed journal	MU, IDL	McCarthy G.D., Plecha S., Charria G., Simon A., Poppeschi C., Russo, A. The marine heatwave west of Ireland in June 2023	10.1002/wea.4498
Peer-reviewed journal	IDL	Gain A.K., Bühler Y., Haegeli P., Molinari D., Parise M., Peres D.J., Pinto J.G., Schröter K., Trigo R.M., Llasat M.C., Kreibich H. (2022) Brief communication: Key papers of 20 years, in Natural Hazards and Earth System Sciences, Nat. Hazards Earth Syst. Sci., 22, 985–993, 2022	10.5194/nhess-22-985-2022
Peer-reviewed journal	IDL	Simon A, Plecha S, Russo A, Teles-Machado A, Donat M, Auger P-A, Trigo RM (2022) Hot and cold marine extreme events in the Mediterranean over the period 1982-2021. Frontiers in Marine Science, August 2022, vol. 9.	10.3389/fmars.2022.892201

Peer-reviewed journal	IDL, LOCEAN	Simon A, Gastineau G, Frankignoul C, Lapin V, Ortega P (2022) Pacific Decadal Oscillation modulates the Arctic sea-ice loss influence on the midlatitude atmospheric circulation in winter, Weather Clim. Dynam., 3, 845–861	10.5194/wcd-3-845-2022
Peer-reviewed journal	IDL	Pérez-Alarcón A., Fernández-Alvarez J.C., Sorí R., Liberato M.L.R., Trigo R.M., Nieto R., Gimeno L. (2023) How much of precipitation over the Euroregion Galicia – Northern Portugal is due to tropical-origin cyclones?: A Lagrangian approach, Atmospheric Research, Volume 285, 106640	10.1016/j.atmosres.2023.106640
Peer-reviewed journal	IDL	Plecha S.M., Teles-Machado A., Tomé R., Mateus P. (2023) Offshore wind data assessment near the Iberian Peninsula over the last 25 years. Environmental Research: Climate 2:025008	10.1088/2752-5295/accf2d/meta
Peer-reviewed journal	IDL	Simon A., C. Pires, T. L. Frölicher, A. Russo, Long-term warming and interannual variability contributions to marine heatwaves in the Mediterranean. Weather and Climate Extremes, 100619	10.1016/j.wace.2023.100619
Peer-reviewed journal	IDL	Simon A., Poppeschi C., Plecha S., Charria G., Russo A. Coastal and regional marine heatwaves and cold spells in the northeastern Atlantic, Ocean Sci., 19, 1339–1355	10.5194/os-19-1339-2023
Peer-reviewed journal	IDL	Monteiro dos Santos D., Libonati R., Garcia B.N., Geirinhas J.L., Salvi B.B., Lima e Silva E., Rodrigues J.A.,Peres L.F., Russo A., Gracie R., Gurgel H., Trigo R.M. (2024) " Twenty-first-century demographic and social inequalities of heat-related deaths in Brazilian urban areas. PLoS ONE 19(1): e0295766.	10.1371/journal.pone.0295766
Peer-reviewed journal	UIB	Boljka, Lina; Omrani, Nour-Eddine; Keenlyside, Noel Sebastian: Identifying quasi-periodic variability using multivariate empirical mode decomposition: a case of the tropical Pacific (2023), Weather and Climate Dynamics (WCD)	10.5194/wcd-2022-51
Peer-reviewed journal	UIB	Cheung, Ho Nam; Omrani, Nour-Eddine; Ogawa, Fumiaki; Keenlyside, Noel Sebastian; Nakamura, Hisashi; Zhou, Wen (2023): Pacific oceanic front amplifies the impact of Atlantic oceanic front on North Atlantic blocking: npj Climate and Atmospheric Science	10.103 /s41612-023-00370-x
Peer-reviewed journal	NERSC, MPI-M, LOCEAN	Suo, Lingling; Gao, Yongqi; Gastineau, Guillaume; Liang, Yu-Chiao; Ghosh, Rohit; Tian, Tian; Zhang, Ying; Kwon, Young-Oh; Matei, Daniela; Otterå, Odd Helge; Yang, Shuting (2022): Arctic Troposphere Warming Driven by External Radiative Forcing and Modulated by the Pacific and Atlantic: Journal of Geophysical Research (JGR): Atmospheres	10.1029/2022JD036679
Peer-reviewed journal	UIB	Cheung, Ho-Nam; Keenlyside, Noel Sebastian; Koenigk, Torben; Yang, Shuting; Tian, Tian; Xu, Zhiqing; Gao, Yongqi; Ogawa, Fumiaki; Omrani, Nour-Eddine Qiao, Shaobo; Zhou, Wen (2022): Assessing the influence of sea surface temperature and arctic sea ice cover on the uncertainty in the boreal winter future climate projections: Climate Dynamics	10.1007/s00382-022-06136

Peer-reviewed journal	UIB	Omrani, Nour-Eddine; Keenlyside, Noel Sebastian; Matthes, Katja;Boljka, Lina; Zanchettin, Davide; Jungclaus, Johann H.; Lubis, Sandro W. (2022): Coupled stratosphere-troposphere-Atlantic multidecadal oscillation and its importance for near-future climate projection: npj Climate and Atmospheric Science	10.1175/JCLID-21-0515.1
Peer-reviewed journal	NERSC, UiB, MPI-M, LOCEAN	Suo, Lingling; Gastineau, Guillaume; Gao, Yongqi; Liang, Yu-Chiao; Ghosh, Rohit; Tian, Tian; Zhang, Ying; Kwon, Young-Oh; Otterå, Odd Helge; Yang, Shuting; Matei, Daniela (2022): Simulated contribution of the interdecadal Pacific oscillation to the west Eurasia cooling in 1998-2013: Environ. Res. Lett.	10.1088/1748-9326/ac88e5
Peer-reviewed journal	UIB	Payne, Mark R.; Danabasoglu, Gokhan; Keenlyside, Noel Sebastian; Matei, Daniela; Miesner, Anna K.; Yang, Shuting; Yeager, Stephen G. (2022): Skilful decadal-scale prediction of fish habitat and distribution shifts:Nature Communications	10.1038/s41467-022-30280-0
Peer-reviewed journal	CMCC, UIB, CNR	Famooss Paolini, Luca & Omrani, Nour-Eddine & Bellucci, Alessio & Athanasiadis, Panos & Ruggieri, Paolo & Patrizio, Casey & Keenlyside, Noel. (2024). Nonstationarity in the NAO–Gulf Stream SST Front Interaction. Journal of Climate. 37. 1629–1650.	10.1175/JCLI-D-23-0476.1
Peer-reviewed journal	CMCC, CNR, UIB	Famooss Paolini, L., P. J. Athanasiadis, P. Ruggieri, and A. Bellucci, 2022: The Atmospheric Response to Meridional Shifts of the Gulf Stream SST Front and Its Dependence on Model Resolution. J. Climate, 35, 6007–6030.	10.1175/JCLI-D-21-0530.1.
Peer-reviewed journal	CMCC, LOCEAN	Patrizio, C. R., P. J. Athanasiadis, C. Frankignoul, D. Iovino, S. Masina, L. Famooss Paolini, and S. Gualdi, 2023: Improved Extratropical North Atlantic Atmosphere–Ocean Variability with Increasing Ocean Model Resolution. J. Climate, 36, 8403–8424.	10.1175/JCLI-D-23-0230.1.
Peer-reviewed journal	UIB	Ashneel Chandra, Noel Keenlyside, Lea Svendsen and Awnesh Singh (2024): Processes Driving Subseasonal Variations of Upper Ocean Heat Content in the Equatorial Indian Ocean: GJR Ocean	10.1029/2023JC020074
Peer-reviewed journal	UIB	Jia Wu, Hanjie Fan, Shuheng Lin, Wenxiu Zhong, Shan He3, Noel Keenlyside, and Song Yang: Boosting effect of strong western pole of the Indian Ocean Dipole on the decay of El Niño events: npj climate and atmospheric sciences.	10.1038/s41612-023-00554-5
Peer-reviewed journa	.. UIB	Nour-Eddine Omrani, Noel Keenlyside, Noburu Nakamura, Sandro Lubis and Fumiaki Ogawa: Response of Northern Hemisphere stratospheric polar night jet to climate change: key role of tropical Ocean and nonconservative effects	Submitted

Peer-reviewed journal	LMD	Gwendal Rivière, Fabio D'Andrea, Daniela Domeisen, Alice Portal: Opposite Trends in the Northern Hemisphere Stratosphere Between Mid-Winter and Early Spring Linked to Surface Temperature Anomalies	10.1029/2024GL109746
Peer-reviewed journal	PIK/H2,MPI-M	Di Capua, G., Tyrlis, E., Matei, D. & Donner, R. (2024). Tropical and mid-latitude causal drivers of the eastern Mediterranean Etesians during boreal summer. *Climate Dynamics*.	10.1007/s00382-024-07411-y
Peer-reviewed Book Chapter	MPI-M	Daniela Matei & Johann Jungclaus (2024): Die Rolle der Erwärmung der Meere und mariner Hitzewellen für Extremereignisse über Land. In: J. Lozan, H. Graßl, D. Kasang, M. Quante, J. Sillmann (Eds.). *Warnsignal Klima Herausforderung Wetterextreme: Ursachen, Auswirkungen & Handlungoptionen.*(pp. 145-154).	
Peer-reviewed journal	MPI-M	A. Hu, I. Richter, Y. Okumura, N. Burls, N. Keenlyside, R. Parfitt, K. Bellomo, A. Bellucci, R. Farneti, A. Fedorov, B. S. Ferster, C. He, W. Kim, Q. Li, D. Matei (2024): Unraveling the Complexity of Global Climate Dynamics: ENSO, AMOC, and tropical basin Interactions. Submitted.	
Peer-reviewed journal	MPI-M	Wallberg, L., Suarez-Gutierrez, L., Matei, D., D. Krieger and Müller, W. A. (2024): Extremely Warm European Summers predicted more accurately by considering Sub-Decadal North Atlantic Ocean Heat Accumulation. Revised for GRL.	
Peer-reviewed journal	MPI-M	Ghosh, *R.*, D. Putrasahan, E. Manzini, K. Lohmann, P. Keil, R. Hand, J. Bader, D. Matei,J. H. Jungclaus (2023) Two distinct phases of North Atlantic Eastern Subpolar Gyre and Warming Hole evolution under Global Warming. J Climate, 36.	10.1175/JCLI-D-22-0222.1.
Peer-reviewed journal	MPI-M, NERSC, LOCEAN, CNR	Ghosh, R., E. Manzini, Y. Gao, G. Gastineau, A. Cherchi, C. Frankignoul, Y.-C. Liang, Y.-O. Kwon, L. Suo, E. Tyrlis, J. V. Mecking, T. Tian, Y. Zhang, D. Matei, 2023: Observed winter Barents-Kara Sea ice variations induce prominent sub-decadal variability and a multi-decadal trend in the Warm Arctic Cold Eurasia pattern. Environmental Research Letters. Environmental Research Letters, 19: 024018.	10.1088/1748-9326/ad1c1a

The synthesis of the scientific results of ROADMAP through peer-reviewed publications has been accomplished throughout the project's lifetime (publications before 2022 are listed in the mid-term report) and is still ongoing (several manuscripts are in preparation and will be submitted within the next months).

Valorization:

Workshop organization

- Workshop on *"Climate Prediction and Services over the Atlantic-Arctic region"* (27-30 Mai 2024 in Bergen, Norway) together with Bjerkness Climate Prediction Unit, Horizon Europe Impetus4Change and Aspect projects
- ROADMAP PI Prof. Dr. Noel Keenlyside has been part of the Scientific Organising Committee of WCRP Clivar ICTP 4th Summer School on Theory, Mechanisms and Hierarchical Modeling of Climate Dynamics: Atlantic Variability and Tropical Basin Interactions at Interannual to Multi-Decadal Time Scales, 31.07-11.08.2023, Trieste, Italy.
- Workshop on *Rossby Waves, heatwaves and compound extreme events* jointly organised by CNR-ISAC (Dr. Valerio Lembo) and University of Trento in Bologna, 28-30 Nov. 2023.
- Final ROADMAP Meeting will take place in MPI-M on 14th-15th October 2024.

Oral presentations

- Lohmann, Katja, Oliver Gutjahr, Johann Jungclaus, Daniela Matei: Skillful prediction of the 2015 summer "Cold Blob" in the subpolar North Atlantic with the MPI-ESM1.2 "eddy-resolving" climate prediction system. IUGG General Assembly, Berlin, 13. July 2023. (in person)
- Manzini, Elisa, Blanca Ayarzagüena, Natalia Calvo, Daniela Matei: Nonlinearity and Asymmetry of the ENSO Stratospheric Pathway, Revisited. IUGG General Assembly, Berlin, 12. July 2023. (in person)
- Quan Liu, Jürgen Bader, Johann Jungclaus, Daniela Matei: External forcing increases the occurrence of internally generated extreme events of North Atlantic Oscillation and East Atlantic pattern. IUGG General Assembly, Berlin, 12. July 2023. (in person)
- Lara Hellmich, Daniela Matei, Laura Suarez-Gutierrez, Wolfgang Müller: Improved prediction skill of extremely warm European summers by using sub-decadal North Atlantic heat inertia. IUGG General Assembly, Berlin, 13. July 2023. (in person)
- Matei Daniela (invited presentation): Two distinct phases of the Subpolar North Atlantic variability and change under global warming conditions at 4th Summer School on Theory, Mechanisms and Hierarchical Modeling of Climate Dynamics: Atlantic Variability and Tropical Basin Interactions at Interannual to Multi-Decadal Time Scales, 31.07-11.08.2023, Trieste, Italy. (in person)
- Quan Liu: Warmer is different: Increasing Occurence and Impact of internally generated extreme summer North Atlantic Oscillation in a warmer climate. Workshop on Rossby Waves, heatwaves and compound extreme events jointly organised by CNR-ISAC and University of Trento in Bologna, 28-30 Nov. 2023.
- Matei, Daniela: Towards an MPI-ESM-ER "eddy-resolving" climate prediction system: Predicting the 2015 subpolar record "Cold-Blob" and its impacts. PIK "Climate and weather extremes" seminar, Potsdam, 20. November 2023.
- Manzini, Elisa: Remote Forcing of Sudden Stratospheric Warming events by Atmosphere - Ocean Interactions. PIK Climate and weather extremes seminar, Potsdam, 20. November 2023.
- Bellucci, Alessio, Denis Mattei, Paolo Ruggieri, Luca Famooss Paolini: Intermittent behavior in the AMOC-AMV relationship. EGU General Assembly 2023, Vienna, April 2023 (in person)
- Bellucci, Alessio, Denis Mattei, Paolo Ruggieri, Luca Famooss Paolini: Intermittent behavior in the AMOC-AMV relationship. Workshop on "Theory, Mechanisms and Hierarchical Modeling of Climate Dynamics: Atlantic Variability and Tropical Basin Interactions at Interannual to Multi-Decadal Time Scales", ICTP meeting, Trieste (Italy), August 2023 (in person)
- Bellomo Katinka: The influence of a weakened AMOC on weather regimes, blocking, and extreme events in idealized climate model experiments. Workshop on "Theory, Mechanisms and Hierarchical Modeling of Climate Dynamics: Atlantic Variability and Tropical Basin Interactions at Interannual to Multi-Decadal Time Scales", ICTP meeting, Trieste (Italy), August 2023 (in person)
- Bellucci, Alessio, Luca Famooss Paolini, Nour-Eddine Omrani, Panos Athanasiadis, Paolo Ruggieri, Casey Patrizio, Noel Keenlyside: Non-stationarity in the NAO–Gulf Stream SST front interaction. EGU General Assembly 2024, Vienna, April 2024 (in person)

- Meccia Virna, Simolo Claudia, Bellomo Katinka and Corti Susanna: Extreme cold events in Europe under a reduced AMOC, Workshop on Climate Prediction and Services over the Atlantic-Arctic region, 27-30th May 2024, Bergen (Norway) (in person)
- Quan Liu: The North Atlantic Oscillation gets more extreme under global warming.Workshop on Climate Prediction and Services over the Atlantic-Arctic region, 27-30th May 2024, Bergen (Norway) (in person)
- David Docquier: Identifying causes of Arctic sea-ice extent reduction in CMIP6 large ensembles using information transfer.Workshop on Climate Prediction and Services over the Atlantic-Arctic region, 27-30th May 2024, Bergen (Norway) (in person)
- Luca Famooss Paolini: Non-stationary NAO–Gulf Stream SST front interaction.Workshop on Climate Prediction and Services over the Atlantic-Arctic region, 27-30th May 2024, Bergen (Norway) (in person)
- Helene R. Langehaug: Marine heatwaves: Can we predict them in the Barents Sea?Workshop on Climate Prediction and Services over the Atlantic-Arctic region, 27-30th May 2024, Bergen (Norway) (in person)
- Lara Wallberg: Improved Prediction Skill of Extremely Warm European Summers.Workshop on Climate Prediction and Services over the Atlantic-Arctic region, 27-30th May 2024, Bergen (Norway) (in person)
- Simolo Claudia, Corti Susanna: Heat extremes in scenario projections: the role of variability, Workshop on Climate Prediction and Services over the Atlantic-Arctic region, 27-30th May 2024, Bergen (Norway) (in person)
- Bellomo Katinka: Influence of the Atlantic Meridional Overturning Circulation on future climate change impacts, WCRP Open Science Conference 23-27 October 2023 Rwanda
- Docquier, D.: Ocean - Sea Ice - Atmosphere interactions measured by the rate of information transfer. Climate Coffees, Online seminar organized by EU H2020 Blue-Action and ECRA, 5 May 2022
- Docquier, D., S. Vannitsem, F. Ragone, K. Wyser, X. S. Liang: Causal links between Arctic sea ice and its potential drivers based on the rate of information transfer. Symposium on Ocean, Sea Ice and Northern Hemisphere Climate in memory of Y. Gao, Bergen (Norway), 8 September 2022
- Docquier, D., S. Vannitsem, A. Bellucci, C. Frankignoul: The rate of information transfer as a measure of ocean-atmosphere interactions. EGU General Assembly 2023, Vienna, 24 April 2023
- Docquier, D., F. Massonnet, F. Ragone, A. Sticker, T. Fichefet, S. Vannitsem: Drivers of summer Arctic sea-ice extent in CMIP6 large ensembles revealed by information flow. Workshop on Climate Prediction and Services over the Atlantic-Arctic region, Bergen (Norway), 27 May 2024
- Julian Krüger, The relation between European heat waves and North Atlantic SSTs: a two-sided composite study, EGU 2022
- Joakim Kjellsson, Multi-centennial modulation of Atlantic multi-decadal variability in a 2000-year climate integration, EGU 2023
- Gutiérrez-Fernández, J., Alvarez-Castro, C., Scoccimarro, E., Cavicchia, L., and Gualdi, S.: Investigating the Development Conditions for Cyclones with Tropical Features in the Mediterranean Basin. , EMS Annual Meeting 2024, Barcelona, Spain, 1–6 Sep 2024, EMS2024-1055, https://doi.org/10.5194/ems2024-1055, 2024. (In person)
- Abhishek Savita, ECMWF-OpenIFS climate sensitivity to horizontal resolution and time step, EGU 2023
- Joakim Kjellsson, Multi-centennial modulation of Atlantic multi-decadal variability in a 2000-year climate integration, IUGG Berlin 2023
- Abhishek Savita, ECMWF-OpenIFS climate sensitivity to horizontal resolution and time step, IUGG 2023
- Helene R. Langehaug, Marine heatwaves: Can we predict them in the Barents Sea?, EGU General Assembly 2024, Vienna.
- Plecha SM, Teles-Machado AM, Soares PMM, Peliz (2022) Temperature and Salt extremes in the Iberian Basin. Encontro da Associação Portuguesa de Oceanografia,6-7 June 2022, Vieira de Leiria, Portugal.

- Simon A, Plecha S, Russo A, Teles-Machado A, Donat M, Trigo R (2022) Hot and Cold Marine Extreme Events in the Mediterranean over the last four decades, EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-6141, https://doi.org/10.5194/egusphere-egu22-6141, 2022
- Simon A, Plecha SM, Russo A, Teles-Machado A, Donat MG, Auger P-A, Trigo RM (2022) Hot and Cold Marine Extreme Events in the Mediterranean over the last four decades. Encontro da Associação Portuguesa de Oceanografia,6-7 June 2022, Vieira de Leiria, Portugal.
- Russo, A., Libonati, R., Geirinhas, J. L., Ramos, A. M., Silva, P. S., Sousa, P. M., DaCamara, C. C., Miralles, D. G., and Trigo, R. M.: Complex interactions of extreme events in Southern Europe and Brazil: a compound event perspective, EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-12508, https://doi.org/10.5194/egusphere-egu22-12508, 2022.
- Russo, A., Santos, R., and Gouveia, C. M.: Compound occurrence of marine and atmospheric heatwaves with drought conditions over the Mozambique Channel and Madagascar Island, EGU General Assembly 2023, Vienna, Austria, 24–28 Apr 2023, EGU23-8156, https://doi.org/10.5194/egusphere-egu23-8156, 2023.
- Simon, A., Pires, C., Frölicher, T. L., and Russo, A.: Long-term warming and interannual variability contributions' to marine heatwaves in the Mediterranean, EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-5083, https://doi.org/10.5194/egusphere-egu24-5083, 2024.
- Trigo, R., Barriopedro, D., Garrido-Pérez, J., Simon, A., Plecha, S., Teles-Machado, A., Russo, A., and García-Herrera, R.: The outstanding European and Mediterranean heatwave activity during summer 2022, EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-4315, https://doi.org/10.5194/egusphere-egu24-4315, 2024.
- Pires, C., Vannitsem, S., Docquier D. Evaluation of Shannon Entropy-based information transfer in nonlinear systems. EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-2460, https://doi.org/10.5194/egusphere-egu24-2460, 2024.
- Hallam, S., Josey, S., McCarthy, G., and Hirschi, J.: A regional (land – ocean) comparison of the seasonal to decadal variability of the Northern Hemisphere jet stream 1871-2011, EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-1309, https://doi.org/10.5194/egusphere-egu22-1309, 2022.
- Hallam, S., Guishard, M., Josey, S.,Hyder, P. and Hirschi, J.: Increasing tropical cyclone intensity and potential intensity in the subtropical Atlantic around Bermuda from an ocean heat content perspective 1955-2019. Ocean Sciences, Virtual Meeting, Feb 2022. https://osm2022.secure-platform.com/a/gallery/rounds/3/details/4078
- Hallam, S., McCarthy, G.D., Feng, X., Harris, E., Düsterhus A., Ogungbenro, S., Hirschi, J.J.M The relationship between sea surface temperature anomalies, wind and translation speed and North Atlantic tropical cyclone rainfall over ocean and land. Royal Meteorological Society Conference November 2022 https://www.atmosphericscienceconference.uk/november-abstracts
- Hallam, S., Josey, S., McCarthy, G., and Hirschi, J.: The influence of land/ocean contrast on the seasonal to decadal variability of the Northern Hemisphere jet stream 1871-2011. AGU Fall meeting in Chicago December 2022. https://agu.confex.com/agu/fm22/meetingapp.cgi/Paper/1106080
- Hallam, S., Josey, S., McCarthy, G., and Hirschi, J. (invited): A regional (land – ocean) comparison of the seasonal to decadal variability of the Northern Hemisphere jet stream 1871-2011. Hotspot2 Conference Japan "Mid-latitude ocean-atmosphere interaction hotspots under the changing climate' June 2023. https://www.jamstec.go.jp/apl/hotspot2/meeting_202306_Toyama.html
- Nour-Eddine Omrani, Ho-Nam Cheung, Noel Kennlyside, Fumiaki Ogawa, Hisashi Nakamura and Wen Zhou: Pacific oceanic front amplifies the impact of Atlantic oceanic front on North Atlantic blocking, US CLIVAR Workshop: Blocking and Extreme Weather in a Changing Climate Workshop 18-20 Mar. 2024 in US Denver
- Nour-Eddine Omrani, Ho-Nam Cheung, Noel Kennlyside, Fumiaki Ogawa, Hisashi Nakamura and Wen Zhou: Pacific oceanic front amplifies the impact of Atlantic oceanic front on North Atlantic blocking, 104rd AMS Annual Meeting, 12-16 Jan. 2024. Denver US

- Nour-Eddine Omrani1, Noel Keenlyside, Katja Matthes, Lina Boljka, Davide Zanchettin, Johann H. Jungclaus and Sandro Lubis: Coupled Stratosphere-Troposphere-Atlantic multidecadal variability and its importance for the near-future climate projection, 103rd AMS Annual Meeting, 8-12 Jan. 2023 US Denver
- Nour-Eddine Omrani and Noel Keenlyside (invited): Internal climate dynamics as key source of recent Atlantic climate decadal variability. DynVar/SNAP workshop 9-13 Okt. 2023 Munich Germany.
- G. Di Capua: Causal interactions between tropics and mid-latitudes in reanalysis data and S2S forecasts (AGU Fall Meeting, online, 01-17.12.2020)
- G. Di Capua: Causal mapping and relationships of dominant tropical-midlatitude interaction patterns during boreal summer. AMS Annual Meeting, 14.01.2021 (online)
- R.V. Donner: Complex systems approaches for disentangling tropical climate variability across regions and time scales. CLIVAR Workshop on Climate Interactions Among the Tropical Basins, February 2021 (online)
- R.V. Donner: Complex network and causal discovery approaches for disentangling monsoon dynamics across regions and time scales. ICTP Workshop on Indian Ocean Variability and Teleconnections, März 2021 (online)
- G. Di Capua: Causal maps versus correlation maps: visual analysis of tropical-extratropical atmospheric teleconnections using causal discovery. EGU General Assembly, 29.04.2021 (online)
- G. Di Capua: Using causal discovery to understand misrepresentations of boreal summer tropical-extratropical teleconnections in S2S forecasts. AGU Fall Meeting, 15.12.2021 (online)
- G. Di Capua: Using Causal Discovery Algorithms to Identify Tropical and Extratropical Drivers of Boreal Summer Climate Variability and Extremes over the Mediterranean Region. AMS Annual Meeting, Houston (USA), 25.01.2022 (online)
- R.V. Donner: Causal inference from multivariate time series using ordinal patterns, graphlets and event synchrony. ORPATT22 Workshop, Dresden, 01.03.2022
- L.E. Aviles Podgurski: Causal Drivers and Mechanisms of Monsoon Rainfall Over the Northern Indian Subcontinent. EGU General Assembly, Wien (Austria), 24.05.2022
- G. Di Capua: Causal drivers of eastern Mediterranean tropospheric circulation during boreal summer. EGU General Assembly, Wien (Austria), 26.05.2022
- G. Di Capua: Increasing trend in the Greenland blocking Index: can causal inference help to explain discrepancies between observations and models? EGU General Assembly, Wien (Austria), 27.05.2022
- R.V. Donner: Empirical analysis of coupling among dynamical systems based on the timing of events - achievements, applications and perspectives. UNDERPIN Summer School, Erice (Italy), 29.07.2022
- G. Di Capua: Remote and local causal drivers of the eastern Mediterranean tropospheric circulation during boreal summer. AGU Fall Meeting, Chicago (USA), 14.12.2022
- L.E. Aviles Podgurski: Causal Drivers Behind Enhanced Rainfall Activity Over Northern India. EGU General Assembly, Wien (Austria), 26.04.2023
- G. Di Capua: Indian summer monsoon versus mid-latitude drivers of boreal summer tropospheric circulation and heat extremes in the eastern Mediterranean. EGU General Assembly, Wien (Austria), 26.04.2023
- R.V. Donner: Quantifying statistical associations among persistent events:From event coincidence analysis to interval coverage analysis. Extreme Value Analysis (EVA) 2023, Milano (Italy), 27.06.2023
- R.V. Donner: Some examples of subtropical and tropical hydro-climate phenomena as seen through the lenses of complex system methods. JAMSTEC, Yokohama (Japan), 06.09.2023
- R.V. Donner: Quantifying statistical associations between atmospheric circulation patterns and heatwaves based on event coincidence analysis. NKUA, Athens (Greece), 11.09.2023

- R.V. Donner: Towards a better understanding of seasonal climate variability using causal discovery methods. EGC, Dijon, 24 January 2024 (invited keynote)
- R.V. Donner: Zwei neue statistische Ansätze zur Verbesserung von Prozessverständnis und saisonaler Vorhersagbarkeit von Hitzewellen. 13. Deutsche Klima-Tagung, Potsdam, 13 March 2024
- R.V. Donner: Studying statistical dependency among short and persistent events: recent developments and application to mid latitude circulation anomalies associated with heatwaves. EGU General Assembly, Vienna, 18 April 2024
- G. Di Capua: Indian summer monsoon as a driver of summer heatwaves in the Eastern Mediterranean. EGU General Assembly, Vienna, 19 April 2024
- R.V. Donner: Statistical dependency among persistent events - Jet stream configurations and their impact on the formation on mid latitude summer heatwaves in the northern hemisphere. International Meeting on Statistical Climatology, Toulouse, 28 June 2024

Poster presentations

- Docquier, D., S. Vannitsem, A. Bellucci: The rate of information transfer as a measure of ocean-atmosphere interactions. Study day on Belgian contributions to Earth Sciences in a Changing World, Brussels, 4 November 2022
- Docquier, D., G. Di Capua, R. V. Donner, C. A. L. Pires, A. Simon, S. Vannitsem: A comparison of two causal methods in the context of climate analyses. EGU General Assembly 2024, Vienna, 18 April 2024
- Simolo C., Corti S. Heat extremes in scenario projections: The role of variability. WCRP Open Science Conference 23-27 October 2023 Rwanda
- Corti S., Meccia V.L, Simolo C. and Bellomo K., Extreme cold events in Europe under a reduced AMOC. EGU General Assembly 2024, Vienna, 14-19 April 2024
- Fabiano Federico, Paolo Davini, Virna L. Meccia, Giuseppe Zappa, Alessio Bellucci, Valerio Lembo, Katinka Bellomo, and Susanna Corti: Multi-centennial evolution of the climate response and deep ocean heat uptake in a set of abrupt stabilization scenarios. EGU General Assembly 2024, Vienna, 14-19 April 2024
- Pires, C. and Hannachi, A.: Probabilistic nonlinear lagged teleconnections of the sea surface temperature field, EGU General Assembly 2023, Vienna, Austria, 24–28 Apr 2023, EGU23-9986, https://doi.org/10.5194/egusphere-egu23-9986, 2023.
- Simon, A., Poppeschi, C., Plecha, S., Charria, G., and Russo, A.: Coastal and regional marine heatwaves and cold spells in the northeastern Atlantic, EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-15362, https://doi.org/10.5194/egusphere-egu24-15362, 2024.
- Hallam, S., McCarthy, G.D., Feng, X., Harris, E., Düsterhus A., Ogungbenro, S., Hirschi, J.J.M The relationship between sea surface temperature anomalies, wind and translation speed and North Atlantic tropical cyclone rainfall over ocean and land. AGU Fall meeting in Chicago and online December 2022.
- Hallam, S., Josey, S., McCarthy, G., and Hirschi, J.: A regional (land – ocean) comparison of the seasonal to decadal variability of the Northern Hemisphere jet stream 1871-2011. US CLIVAR workshop on mesoscles and frontal scale air-sea Interactions Workshop March 2023
- Hallam, S., McCarthy, G.,: The relationship between SST gradients and ocean heat content along the Gulf Stream and Kuroshio Currents and the 250mb Jet Stream. Ocean Sciences, New Orleans, Feb 2024.

Popularized publications

- Docquier, D.: How over-consumption leads to reduced sea ice: Visualization through artwork. Blog post written for the EGU Cryosphere Blog, 2 June 2023
- Docquier, D.: For Dummies: How Arctic sea ice and the AMOC interact. Blog post written for the EGU Cryosphere Blog, 9 December 2022
- Nasirova, H., D. Docquier: Did you know the differences between Arctic and Antarctic sea ice? Blog post written for the EGU Cryosphere Blog, 14 October 2022
- Burgard, C., D. Docquier, M. Scheel, L. van der Laan: Ice-hot news: A cryo-summary of the new IPCC assessment report. Blog post written for the EGU Cryosphere Blog, 13 May 2022
- Nour-Eddine Omrani: Variations in the North Atlantic influence global temperature: published in 2022 in the news of Bjerknes Center for climate research.
- Elen Viste: Multidecadal oscillation not to be confused with reduced warming (2022). Publisher in the news of Bjerknes Center of climate research, Phys.org and alphagalilio.org.
- Nour-Eddine Omran: Importance of Pacific oceanic front for the North Atlantic blocking (2023), published in Nature Portfolio by Springer Nature publisher.
- Damien Altendorf: Vers un ralentissement (temporaire) du réchauffement climatique? Published in sciencepost.fr, 2022
- Howe, S. and Hallam, S. Will temperatures up to 17C become the norm in November? RTE Brainstorm
- ROADMAP PIs have been continuously giving press interviews in Newspaper, Magazines, Radio Podcasts on societal relevant scientific topics: e.g Potential AMOC Collapse and Its impacts, Role of the record warm North Atlantic Ocean during the summer 2023 on European climate variability and extremes, Impacts of a record warm Mediterranean on a background of continuously global warming on the frequency and intensity of European Floodings.

Dissemination of the scientific results of ROADMAP has been accomplished throughout the project's life time (activities before 2022 are listed in the mid-term report).

Impact

BSc theses

- Thies Johnsen, 2023, Impact of Ocean Model Resolution on the Representation of North Atlantic and European Blocking in the FOCI-OpenIFS Model, https://oceanrep.geomar.de/id/eprint/59267 (supervisors: Sayantani Ojha & Joakim Kjellsson, GEOMAR)
- Finn Könecke, 2024, What is the fingerprint of AMOC variability and its trends?, https://oceanrep.geomar.de/id/eprint/60220 (supervisors: Joakim Kjellsson & Hyacinth Nnamchi, GEOMAR)
- André Lourenço, 2022. Atmosphere-ocean interaction: extreme events analysis in South America, Meteorology Oceanography and Geophysics final graduation project, IDL, FCUL (supervisors: Ana Russo, Sandra Plecha).
- Sven Praast, 2023. Statistical Influence of Atmospheric Circulation Anomalies on Summer Heatwaves in Eurasia. h2 und Otto von Guericke University of Magdeburg (supervisors: Reik Donner & Giorgia Di Capua, h2/PIK)

- Dominik Diedrich, 2023. Statistical analysis of simultaneous occurrences of strong temperature anomalies and specific atmospheric circulation patterns. h2 und Otto von Guericke University of Magdeburg (supervisors: Reik Donner & Giorgia Di Capua, h2/PIK)
- Emily Henningsen, 2022. Causal drivers of central Amazon precipitation during austral summer. Technical University of Berlin (supervisors: Reik Donner & Giorgia Di Capua, h2/PIK)

MSc theses

- Fernandez, P.: Investigation of Atlantic Pacemaker experiments. March-August 2021. LOCEAN, CNRS, Sorbonne Université, Paris (France).
- Tabea Rahm, 2023, How will the dominant weather regimes change under the influence of climate warming? https://oceanrep.geomar.de/id/eprint/58633 (supervisors: Joakim Kjellsson & Wenjuan Huo, GEOMAR)
- Nasirova, Hayat (2024) Marine heat wave in subpolar North Atlantic in summer 2023. (MPI-M)
- L.E. Aviles Podgurski (2022) Causal Drivers and Mechanisms of Monsoon Rainfall Over the Northern Indian Subcontinent. Technical University of Berlin (supervisor: Reik Donner, h2)

PhD theses

- Hellmich, Lara (2020–2023) Sub-decadal Variability of European Summer Heat Extremes. (MPI-M)
- Liu, Quang (2021–) Ocean-atmosphere interactions and their links to weather patterns, teleconnections and climate extremes over the northern hemisphere. (MPI-M)
- Jiang, W.: Centennial AMOC variability: mechanism and impact. June 28th 2022. LOCEAN, CNRS, Sorbonne Université, Paris (France).
- Julian Krüger, 2023, On the Role of North Atlantic Sea Surface Temperatures for European Heat Events. Supervisors: Joakim Kjellsson & Martin Claus, GEOMAR
- Teresa Costa, 2024, Drivers of Ocean Heat Content variability and predictability in the North Atlantic. PhD in Geophysical Sciences and Geoinformation – Specialization in Oceanography, IDL/FCUL, Portugal (supervisors: Ana Margarida Silva Pereira Teles Machado, Emanuel Nemésio de Sousa Dutra and Pablo Ortega Montilla).
- Luca Famooss Paolini (2018–2022) Ocean–atmosphere interaction at the Gulf Stream sea surface temperature front: variability and impacts on midlatitude atmospheric circulation. Ca'Foscari University and CMCC (supervisors: Alessio Bellucci, Panos J. Athanasiadis, Paolo Ruggieri)
- G. Di Capua, 2021. The Indian Monsoon and its interaction with the mid-latitude circulation. Vrije Universiteit Amsterdam (Co-Supervisor: Reik Donner, h2)

Other trainings

- Docquier, D.: Training course: Advanced numerical methods for Earth System Modelling, ECMWF, Reading, 25-29 April 2022

Links build with other projects

- GEOMAR contribution to WP4 has benefited from collaborations with the SCENIC project (Helmholtz PoF IV Innovation Pool) which focused on atmospheric extreme events and compounding extremes over Europe.

- IDL contribution to WP4 has benefited from collaborations with the DHEFEUS project (FCT funding https://doi.org/10.54499/2022.09185.PTDC) which focused on atmospheric extreme events and compounding extremes over Europe and South America.
- ROADMAP PI Prof. Dr. Reik Donner (PIK/H2) and ROADMAP Coordinator Dr. Daniela Matei (MPI-M) lead the DAAD IKYDA CauseMED-Project (2021-2024) together with University of Athens on Identifying the causal drivers of climate variations and extremes in the Mediterranean. ROADMAP PhD Student Quan Liu (MPI-M), Dr. Giorgia Di Capua and Prof. Dr. Reik Donner had several research visits at the University of Athens that have been concretised in several publications (already published or in preparation).
-

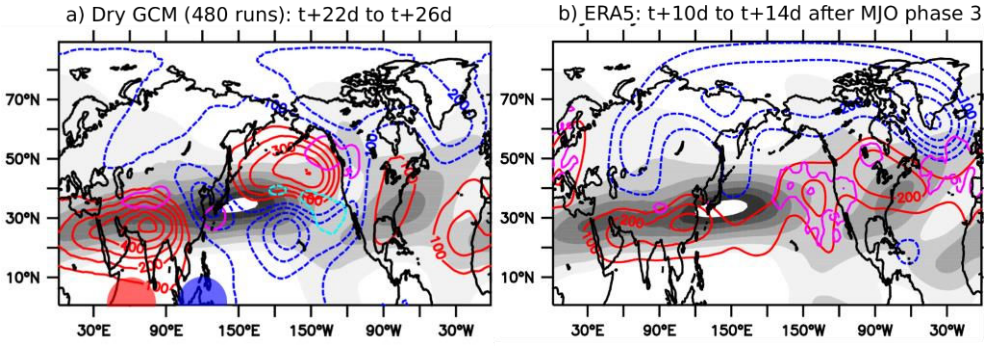
Career advancements

- Dr. Abhishek Savita (GEOMAR) is now a postdoc with Dr. Amy Clement at University of Miami, USA.
- Junior Prof. Dr. Joakim Kjellsson (GEOMAR) is now a climate modeller (permanent position) at SMHI, Sweden.
- Dr. Carmen Alvarez-Castro (CMCC) is now Profesora Permanente Laboral at the Universidad Pablo de Olavide (UPO), Seville, Spain. Before she was a Beatriz Galindo researcher at the Physical, Chemical and Natural Systems Department, Universidad Pablo de Olavide (UPO), Seville, Spain.
- Dr. Giorgia di Capua (former PhD Student) is now Project lead: Improved Predictability Of Extremes Over The Mediterranean From Seasonal To Decadal Timescales - PREVENT (HORIZON-RIA). RDI - Earth System Analysis, Potsdam Institute for Climate Impact Research, Germany.
- Dr. Ana Russo (IDL PI) is now Assistant Professor (Permanent Position) at ISA, University of Lisbon, Portugal. Before she was an Assistant Researcher (non-Permanent) at Instituto Dom Luiz, Portugal.
- Dr. Amelie Simon (IDL, Postdoctoral Researcher) is now Scientific Researcher (Permanent Position) at Ifremer/LOPS, Brest, France.

Results

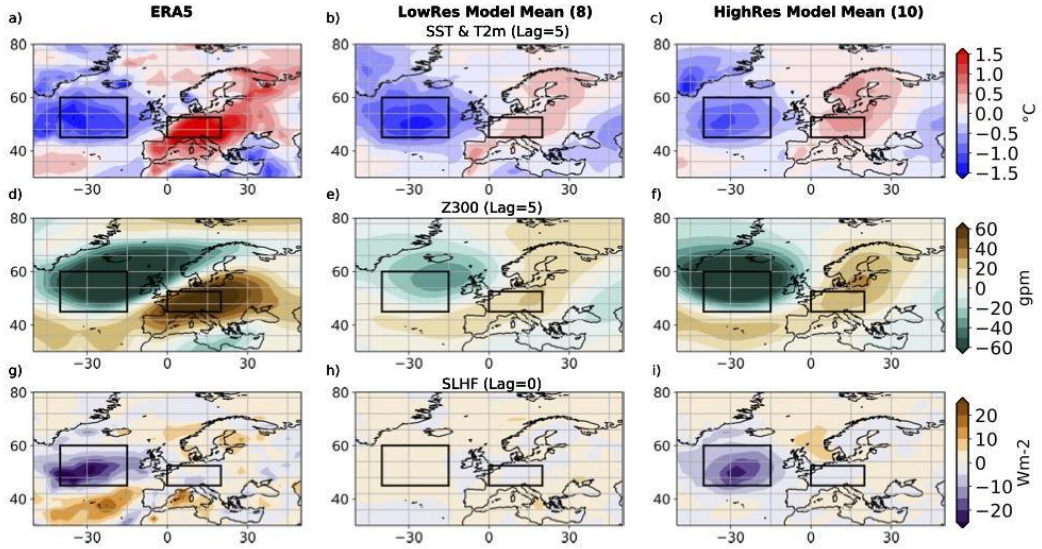
Major results that we could include in a valorization brochure

- In atmospheric reanalysis data, a positive phase of the North Atlantic Oscillation (NAO) emerges two weeks after the Madden Julian Oscillation (MJO) phase 3, consistent with past observational studies. In ROADMAP, we demonstrate that this remote influence can be reproduced in a dry GCM, where the positive phase of the NAO emerges after 3 weeks of imposed idealized MJO phase 3.

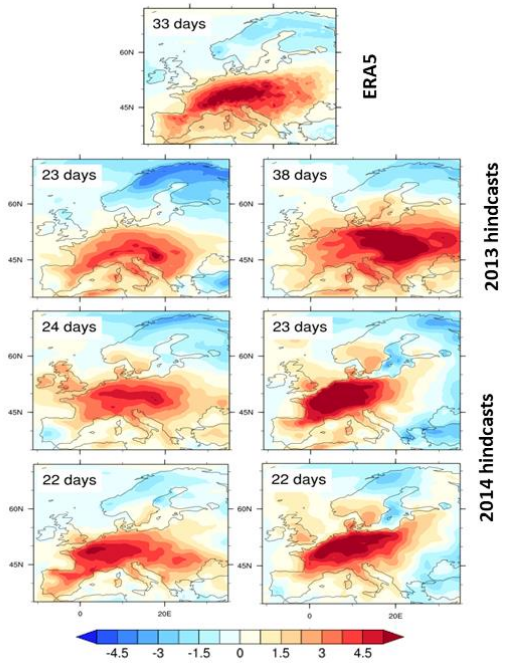


a) Ensemble mean of 480 simulations run with the dry GCM DYNAMICO forced with idealized heating anomalies mimicking phase 3 of the MJO (red and blue semi circles represent warming and cooling respectively), the mean is taken between 22 days and 26 days after imposing the forcing, b) MJO phase 3 composites using ERA5 datasets, the mean is taken between 10 days and 14 days. The gray shadings represent the zonal wind, the red and blue contours are the geopotential anomalies (red and blue for positive and negative values respectively; interval: 100 m^2s^{-2}), the magenta and cyan blue contours are the eddy kinetic energy (magenta and cyan blue for positive and negative values respectively; interval: 5 m^2s^{-2}) at 200 hPa.

- Skillful prediction of extreme events is challenging with state-of-the-art climate prediction systems. In ROADMAP we could demonstrate that heat waves over Europe and their precursors are more realistically simulated with high-resolution grid configurations as well as that the MPI-M ocean-eddy-resolving climate prediction system can skillfully reforecast strength and extent the strong heat waves over central Europe in the summer of 2015.

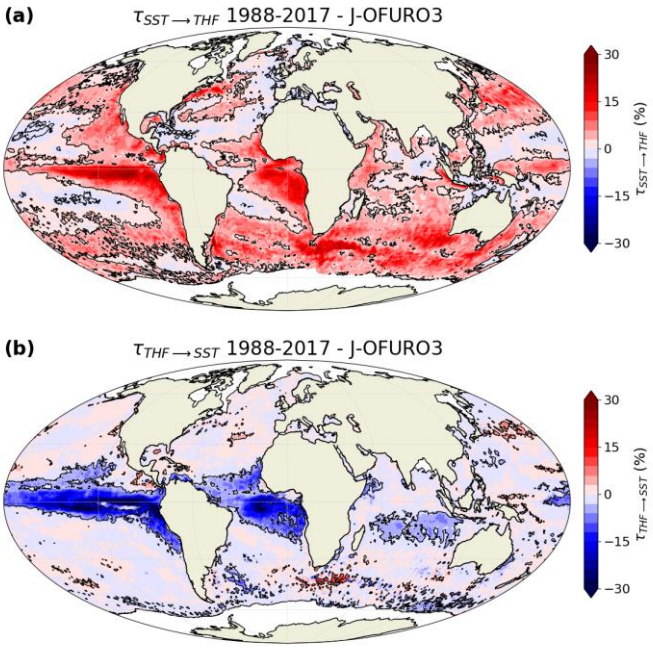


Left column: Composite-mean anomalies of 2-meter air temperature (a), 300 hPa geopotential height (d) and downward surface latent heat flux (g) for the identified European heat events in ERA-5. Middle column: Same but for low-resolution simulations in HighResMIP control-1950 experiments (b,e,h). Right column: Same but for high-resolution simulations (c,f,i).



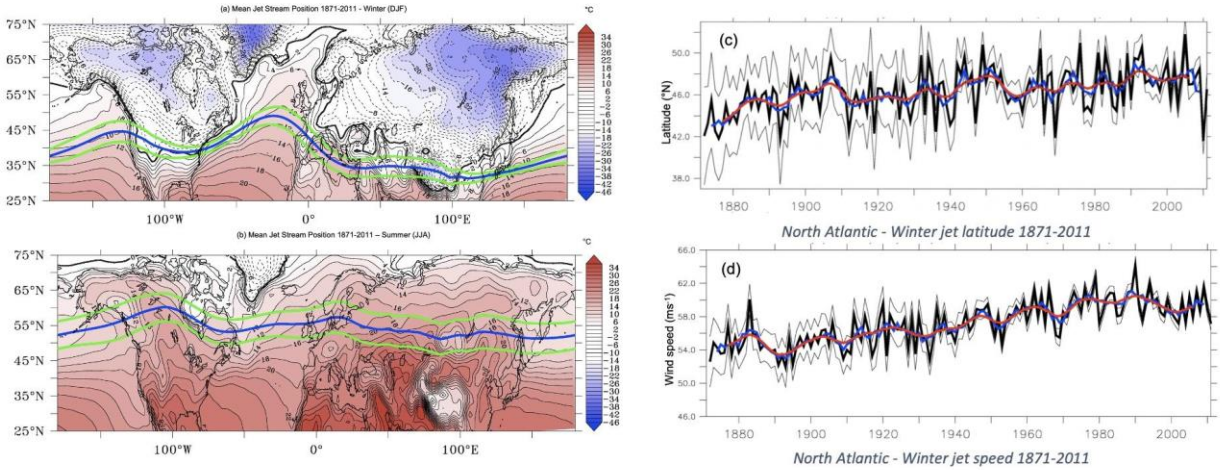
SAT anomalies [K] during heat days in summer 2015 in observations (ERA5) and in selected hindcasts initialized in November 2014 and in November 2013.

- Within ROADMAP, strong collaborations have been established between researchers working with global climate models and researchers who develop statistical tools. In particular, a causal method directly derived from the first principles of information theory was applied to different climate studies, including ocean-atmosphere interactions.



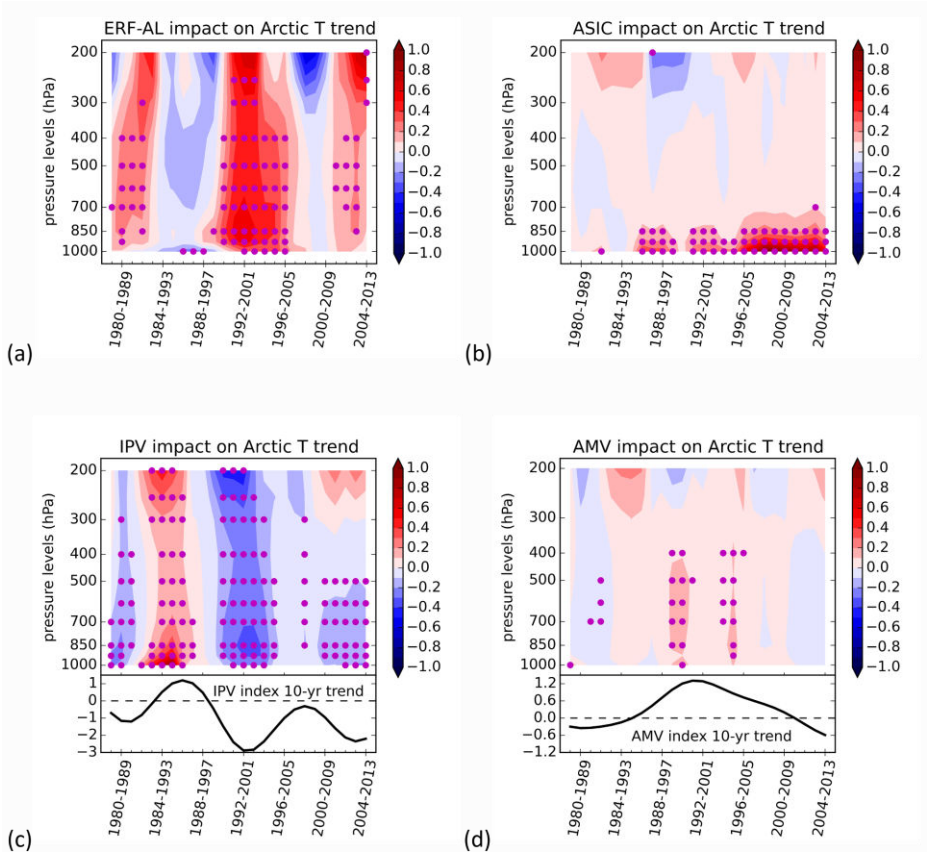
Rate of information transfer τ (a) from sea surface temperature (SST) to turbulent heat flux (THF) and (b) from THF to SST, based on J-OFURO3 satellite observations. Black contours are drawn around regions with a statistically significant transfer of information.

- For MU our highlight was our regional (land-ocean) jet stream paper, Hallam et al. (2022) We found that the mean jet latitude range is at a minimum in winter (DJF) along the western boundary currents of the North Pacific and North Atlantic. Over the North Atlantic the winter jet latitude has migrated 3 degrees poleward over the 141-time period and an increase in jet speed of 10mph is observed, whereas over the North Pacific no trends were identified, only interannual variability. This publication led to an invited talk at the HOTSPOT2 conference in Japan in June 2023, together with international and national news coverage.



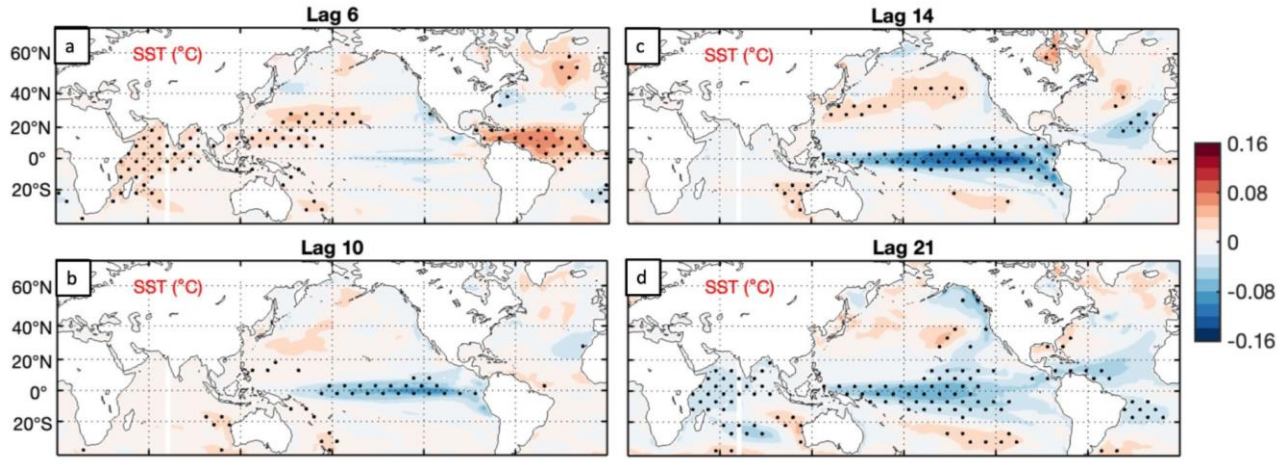
Mean Seasonal 250mb Jet Stream Position (a) winter (b) summer overlaying the 2 m air temperature for the period 1871 -2011. The dark blue line indicates the mean jet stream position and the green line ± 2 standard deviations of the 6 hourly jet latitude smoothed over 91 days, for the period shown, based on the 56 ensemble members. The cyan blue line is ±2 standard deviations based on the interannual variability for the period. (c) Winter 250mb Jet Latitude and (d) winter 250mb jet speed for North Atlantic (0-60W) from 1871 -2011. The thick black line indicates the seasonal mean. The red line indicates the seasonal mean smoothed over 11 years. The blue line indicates the 5-year running mean. The thin black lines indicate ±2 standard deviations based on the 6 hourly data for the 56 ensemble members smoothed over 91 days

- Within ROADMAP, we have investigated the drivers of the Arctic troposphere warming (Suo et al., 2022). Based on a unique set of multi-model large-ensemble atmospheric simulations, we find that the external radiative forcing is the primary driver of the 1979–2013 warming for April–September. The interdecadal Pacific and Atlantic multidecadal variability intensifies/dampens the warming when transitioning to positive/negative phase.



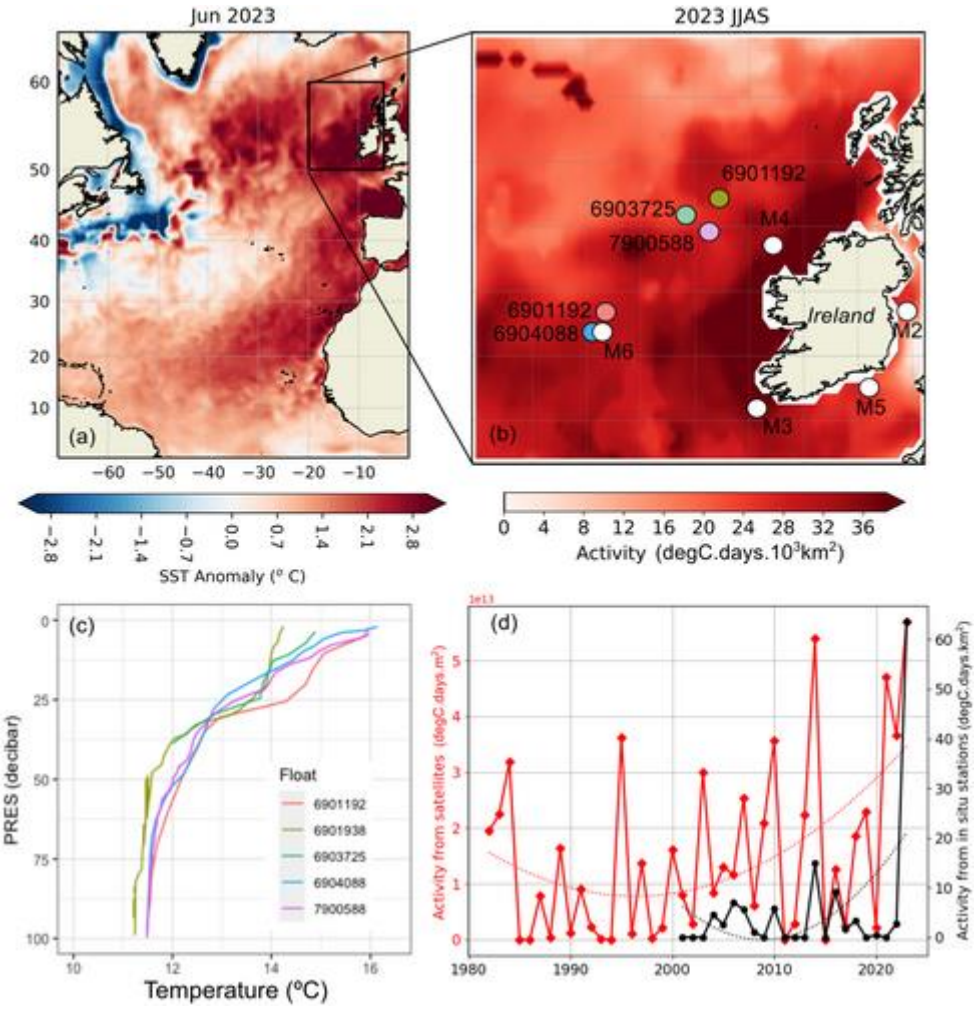
Impacts of (a) external radiative forcing (ERF-AL), (b) Arctic sea ice concentration (ASIC), (c) the interdecadal Pacific variability (IPV), and (d) the Atlantic multidecadal variability (AMV) on the 10-year running trends of annual-mean Arctic temperature (colored, unit: ℃/decade), and the 10-year running trend of the IPV/AMV index (line) shown below the IPV/AMV impacts. The years marked in the plot indicate the period for the calculation. The dots mark where the impacts are statistically significant.

- In the ROADMAP study, we revealed a dominant influence of the tropical Atlantic on other tropical basins at interannual timescales (Jiang et al., in prep), with La Niña typically following tropical Atlantic warming by a few months. This interaction between the Atlantic and Pacific Oceans is also observed. However, the mechanisms underlying this relationship remain uncertain. Using climate model simulations where the driving role of the Atlantic Ocean is isolated, we observed a La Niña response occurring 15 months after subtropical Atlantic warming. This response is induced by a Matsuno-Gill response to tropical Atlantic sea surface temperature (SST) warming, which reduces the surface wind and the associated latent heat flux in the Indian Ocean. After six months, the resulting warm tropical Indian Ocean affects the Walker circulation in the Indo-Pacific and causes stronger trade winds over the Pacific Ocean. These stronger trade winds influence the thermocline depth and lead into a La Niña SST anomaly in the equatorial Pacific, peaking 14 months after the initial tropical Atlantic warming.



Regression of SST, in °C, on T_{Trop}, the tropical Atlantic SST leading by (a) 6 months, (b) 10 months, (c) 14 months and (d) 21 months. Dotted regions have a significance level below 5%.

- Studies on marine heatwaves and climatic events in the Northeastern Atlantic and the Mediterranean provide critical insights into the changing climate and its impacts, emphasizing the severity of such events and their potential ecological and economic impacts (McCarthy G.D et al., 2023; Simon A et al., 2023) and identifying patterns and impacts that are essential for developing adaptive strategies to mitigate the effects of these extreme events (Simon A et al., 2023). The significant roles of long-term warming and interannual variability in driving the frequency and intensity of marine heatwaves in the Mediterranean was highlighted, which is crucial for understanding future climate scenarios. These studies collectively enhance our understanding of marine heatwaves, their drivers, and their broader implications, which is vital for informing climate policy and adaptation measures.



(a) Sea-surface temperature anomaly observed in June 2023 (degC) relative to 1982–2023. The black rectangle defines the study area (50–60°N, 20–5°W). (b) Activity of 2023 summer (June-July-August-September; JJAS) marine heatwave (MHW) (degC days 103 km2) in study area. In situ observations from Irish meteorological buoys are shown in white open circles. Locations of Argo floats are shown with coloured open circles. (c) Depth profiles of the MHW based on Argo profiling float profiles from 11 to 15 June. Colours correspond to the locations in (b). (d) Times series of (red) satellite-derived summer (JJAS) and (black) buoy-derived June marine heatwaves mean activity. Dashed line represents the regression of a third-order polynomial. Daily sea-surface temperature (SST) data are from the NOAA Optimum Interpolation SST product (OISSTV2; Huang et al., 2020).

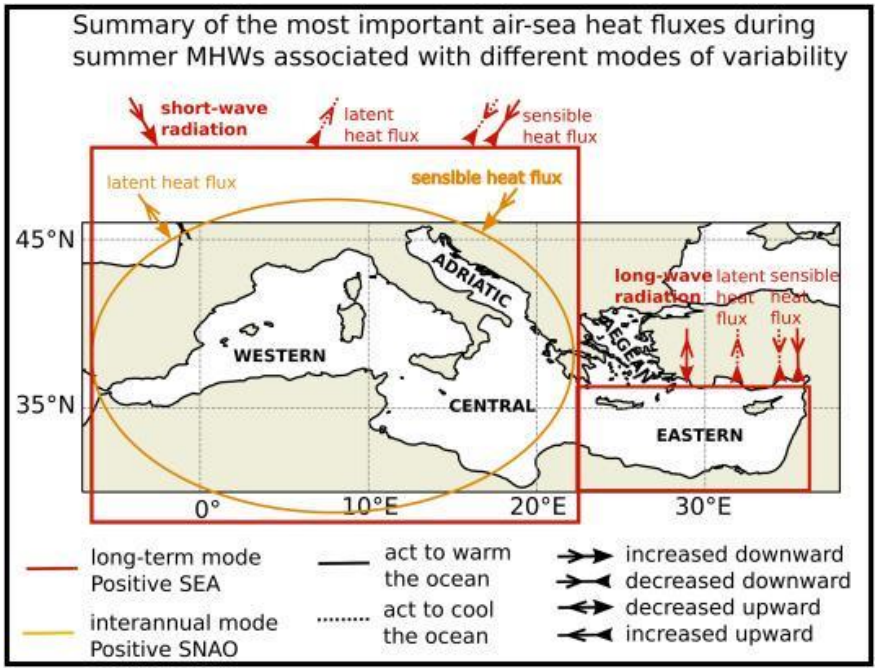
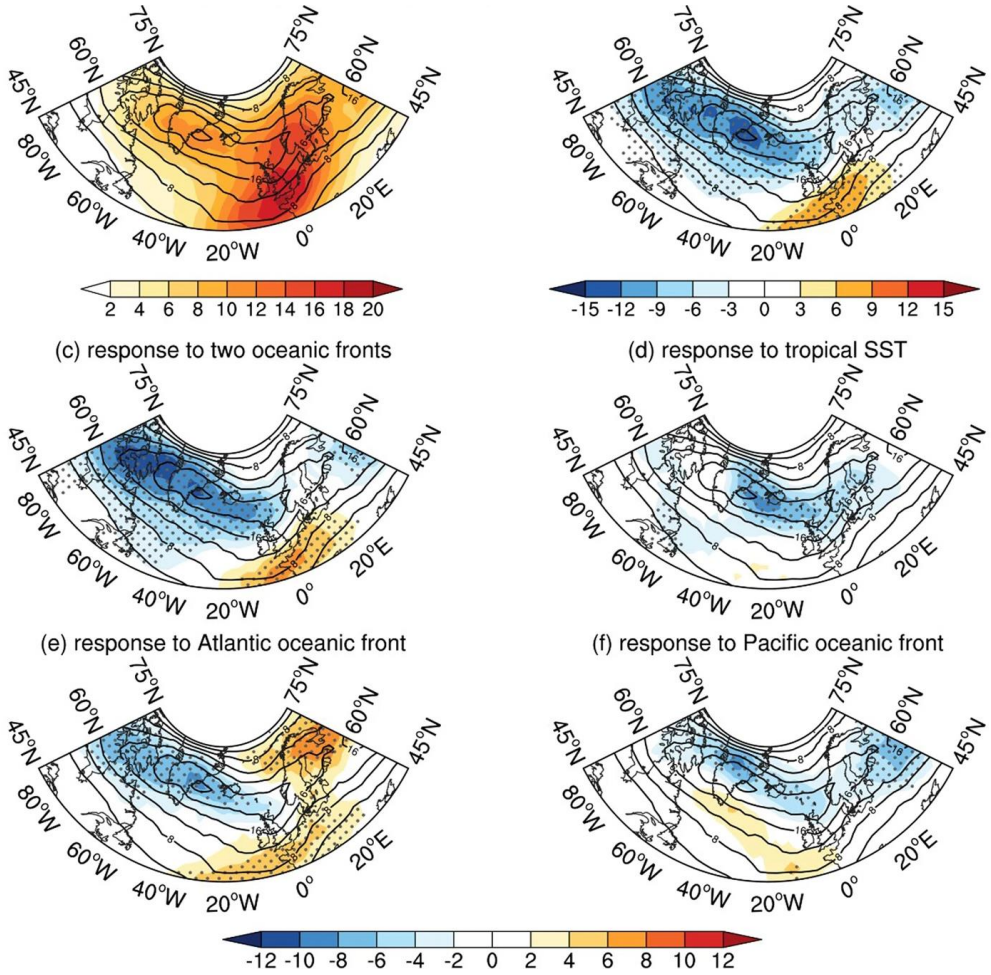


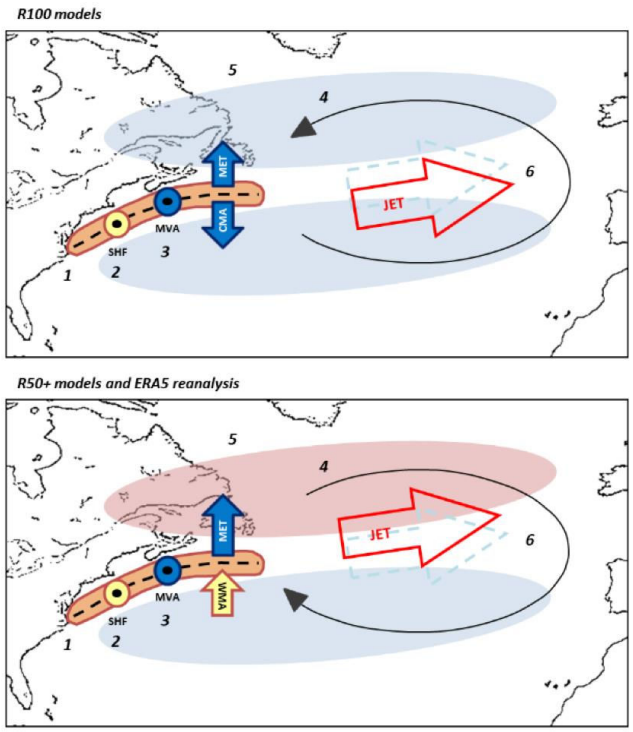
Illustration of the air-sea fluxes and atmospheric circulation associated with the long-term (in red) and interannual (in yellow) evolution of summer MHWs in the Mediterranean over the period 1982–2022. The acronym SEA stands for summer East Atlantic pattern and SNAO for summer North Atlantic Oscillation pattern. These atmospheric patterns are suggested to be linked with respectively the long-term mode and interannual mode. A bold style is used for the dominant air-sea heat flux for each mode. For the long-term mode, it is the short-wave radiation in the western, central and Adriatic basins and long-wave radiation in the eastern basin. For the interannual mode, it is the sensible heat flux in the western, central and Adriatic.

- Atmospheric blocking is a crucial driver of extreme weather events, but its climatological frequency is largely underestimated in state-of-the-art climate models, especially around the North. In ROADMAP project, we used semi-idealised experiments with an atmospheric general circulation model to demonstrate that the not only the North Atlantic oceanic front, but also the mid-latitude Pacific oceanic front are crucial for climatological Atlantic blocking activity (see Figure). The north Pacific oceanic front intensifies the Pacific eddy-driven jet that extends eastward towards the North Atlantic. The eastward-extended Pacific jet reinforces the North Atlantic circulation response to the Atlantic oceanic front, including the storm track activity and the eddy-driven jet. The strengthening of the eddy-driven jet reduces the Greenland blocking frequency. Moreover, the Pacific oceanic front greatly strengthens the stationary planetary-scale ridge in Europe. Together with a stronger northeastward extension of the Atlantic storm track, enhanced interaction between extratropical cyclones and the European ridge favours the occurrence of Euro-Atlantic blocking. Therefore, the North Atlantic circulation response amplified remotely by the Pacific oceanic front substantially increases Euro-Atlantic blocking frequency while decreasing Greenland blocking frequency.



Impacts of the midlatitude oceanic fronts and the tropical SST on the winter (DJF) climatological blocking frequency across the Euro-Atlantic region (see Cheung et al. 2023): Spatial distribution of the blocking frequency in (a) the FULL run (with realistic SST in the Northern Hemisphere and tropics; shading) and the ZUNF run (with zonally uniform tropical SST and without oceanic fronts; contour interval: 4%), (b)–(f) response in semi-idealised experiments (i.e. difference between the experiments and the ZUNF run; shading) and the climatology in the ZUNF run (contours): (b) tropical SST and two oceanic fronts (FULL run), (c) two oceanic fronts (EXT_ALL run), (d) tropical SST (TROP_ALL run), (e) Atlantic oceanic front (EXT_ATL run), and (f) Pacific oceanic front (EXT_PAC run). Stippling in (b)–(f) indicates differences exceeding the 95% confidence interval based on the two-tailed Students' t-test.

- In ROADMAP, we demonstrated the nature of the atmospheric response to interannual shifts of the Gulf Stream sea surface temperature front (GSF) during winter and that this response is resolution dependent. On a local scale, this response is characterized by anomalous diabatic heating mainly balanced by vertical motion and by meridional transient eddy heat transport. On a larger scale, this results in a meridional shift of the North Atlantic eddy-driven jet and storm track in the same direction as the GSF shift. However, only atmospheric models with a resolution finer than 50 km can accurately replicate the observed winter anomalies. In contrast, models with coarser resolutions show local diabatic heating anomalies balanced by vertical motion and mean advection, leading to a shift of the jet in the opposite direction relative to the GSF displacement.



Schematic of the atmospheric response to the GSF shifts in winter for (top) R100 models and (bottom) R50+ models and the ERA5 reanalysis. Black dashed line: winter climatological position of the GSF. Brown zone straddling the GSF: intense SST anomalies induced by a shift of the GSF from its "South" to its "North" position. SHF: Surface heat fluxes; MVA: Mean vertical advection; WMA: Warm meridional advection; CMA: cold meridional advection; MET: meridional sub-monthly eddy transport; JET: Eddy-driven jet; large-scale shades: positive (red) and negative (blue) anomalies in transient eddy activity.

- Computable formulas of causality assessment have been developed for nonlinear stochastic real-world systems, thus allowing for the quantification of causal/consequential interactions between the different system components (e.g. oceanic basins, atmosphere, cryosphere). The formalism also evaluates the single and synergetic driving influences of sets of variables upon chosen target variables or subsystems. Causality quantification is relevant in the control or mitigation of driving natural factors triggering extreme behavior as well as in the assessment of model's predictability in different space and time scales.

Annex I: Identification of project participants/beneficiaries

(1) Dr. Daniela Matei, Max Planck Institute for Meteorology, Hamburg, Germany
Dr. Katja Lohmann, Max Planck Institute for Meteorology, Hamburg, Germany
Dr. Elisa Manzini, Max Planck Institute for Meteorology, Hamburg, Germany
Dr. Jürgen Bader, Max Planck Institute for Meteorology, Hamburg, Germany
Dr. Johann Jungclaus, Max Planck Institute for Meteorology, Hamburg, Germany
Quan Liu, Max Planck Institute for Meteorology, Hamburg, Germany
(2) Prof. Dr. Noel Keenlyside, Geophysical Institute, University of Bergen, Bergen, Norway
Dr. Nour-Eddine Omrani, Geophysical Institute, University of Bergen, Bergen, Norway
(3) Prof. Dr. Joakim Kjellsson, GEOMAR, Kiel, Germany
Dr. Abhishek Savita, GEOMAR, Kiel, Germany (now: University of Miami, USA)
Prof. Dr. Mojib Latif, GEOMAR, Kiel, Germany
(4) Prof. Dr. Reik Donner, Magdeburg-Stendal University of Applied Sciences and Potsdam Institute for Climate Impact Research, Potsdam, Germany
Dr. Giorgia Di Capua, Magdeburg-Stendal University of Applied Sciences and Potsdam Institute for Climate Impact Research, Potsdam, Germany
(5) Dr. Helene Langehaug, Nansen Environmental and Remote Sensing Center, Bergen, Norway
Dr. Lingling Suo, Nansen Environmental and Remote Sensing Center, Bergen, Norway
(6) Dr. Stephane Vannitsem, Royal Meteorological Institute of Belgium, Brussels, Belgium
Dr. David Docquier, Royal Meteorological Institute of Belgium, Brussels, Belgium
(7) Dr. Ana Russo, Instituto Dom Luiz, Lisbon, Portugal
Dr. Ricardo Machado Trigo, Instituto Dom Luiz, Lisbon, Portugal
Dr. Sandra Plecha, Instituto Dom Luiz, Lisbon, Portugal
Dr. Ana Machado, Instituto Dom Luiz and IPMA, Lisbon, Portugal
Dr. Pedro Soares, Instituto Dom Luiz, Lisbon, Portugal
Dr. Alvaro Peliz, Instituto Dom Luiz, Lisbon, Portugal
Dr. Amelie Simon, Instituto Dom Luiz, Lisbon, Portugal
Dr. Carlos Pires, Instituto Dom Luiz, Lisbon, Portugal
(8) Dr. Panagiotis Athanasiadis, , Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy
Dr. Carmen Alvarez-Castro, Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy
(9) Dr. Alessio Bellucci, Consiglio Nazionale delle Ricerche, Italy
Dr. Susanna Corti, Consiglio Nazionale delle Ricerche, Italy
Dr. Valerio Lembo, Consiglio Nazionale delle Ricerche, Italy
(10) Dr. Gerard McCarthy, ICARUS, Maynooth University, Ireland
Dr. Samantha Hallam, ICARUS, Maynooth University, Ireland
(11) Dr. Guillaume Gastineau, Laboratoire d'Océanographie et du climat: Expérimentation et approches numériques, Institut Pierre Simon Laplace, Université Pierre et Marie Curie, Paris, France
Dr. Juliette Mignot, Laboratoire d'Océanographie et du climat: Expérimentation et approches numériques, Institut Pierre Simon Laplace, Université Pierre et Marie Curie, Paris, France
(12) Dr. Gwendal Riviere, Laboratoire de Météorologie Dynamique, Paris, France