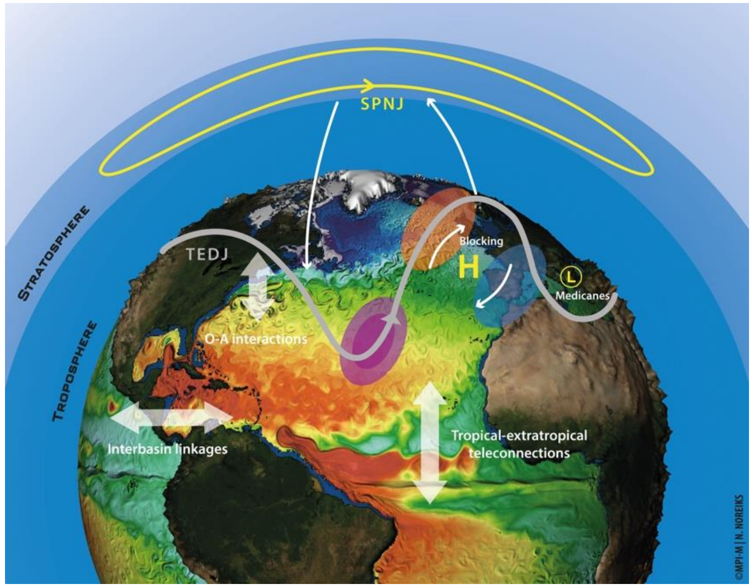
Next Generation Climate Science in Europe for Oceans: End-Term Meeting

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

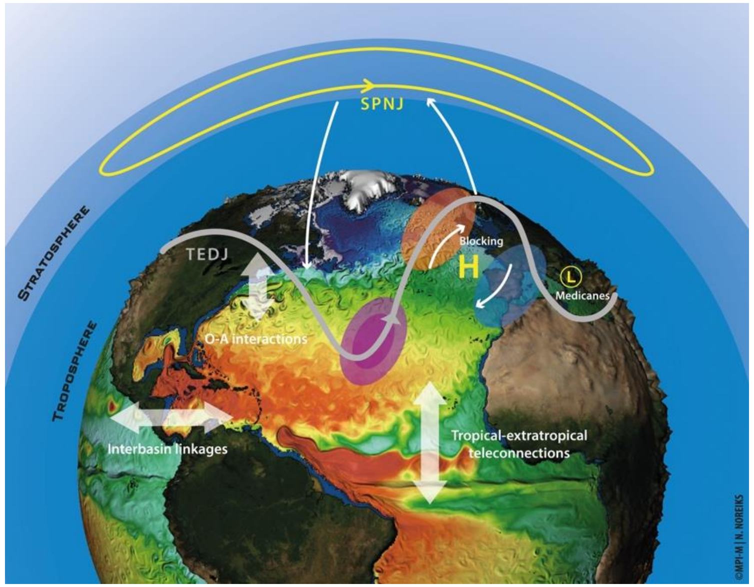
Coordinator: Daniela Matei, Max Planck Institute for Meteorology
Dep. Coordinator: Noel Keenlyside, University of Bergen
June 2020 – May (Oct.) 2024

29 April 2024

ROADMAP's main objective is ***to better understand how the ocean shapes northern hemisphere climate and associated extreme events on short seasonal and long climate-change time scales.***



To answer, ROADMAP strives to integrate dynamical understanding with advanced statistical techniques and information theory applied to frontier high-resolution climate model simulations, large single model ensembles and observations.

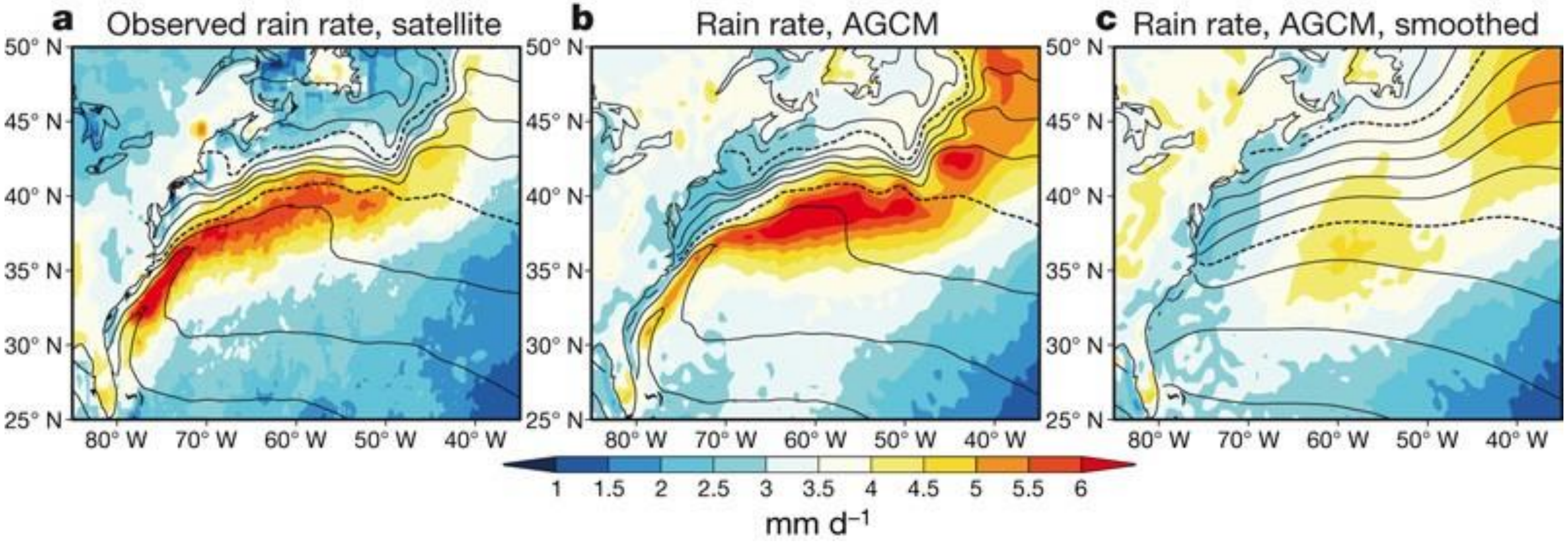


Summary of work carried out, key results and achievements

Key scientific questions:

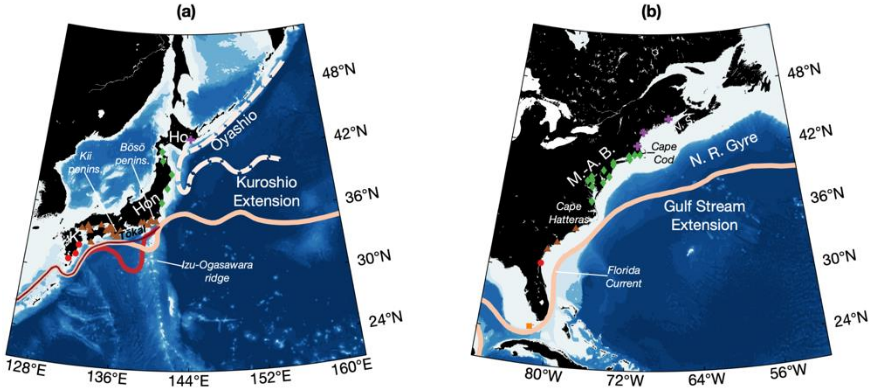
- *How will future changes in northern hemisphere ocean circulation—western boundary currents and the Atlantic meridional overturning circulation—influence SST fronts and large-scale SST variability patterns?*

Influence of the Gulf Stream on the troposphere (Minobe et al., 2008)



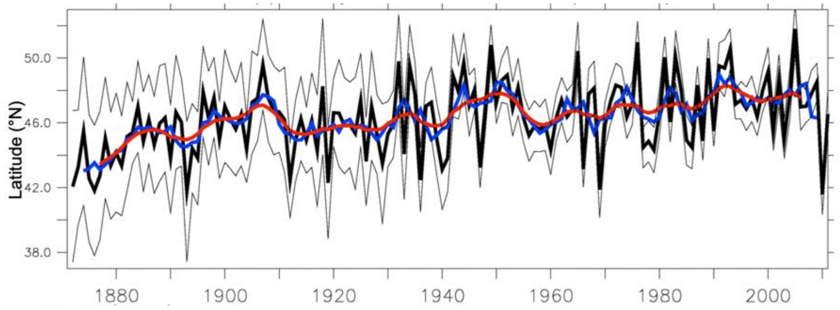
Work Package 1 (2&4) – Maynooth University - 4 Papers

1. Kuroshio and Gulf Stream Extension



The Kuroshio (a) and Gulf Stream (b) are the intense Western Boundary Currents (WBC) found in the Atlantic and Pacific oceans, and the variability of these currents and their extensions has a significant impact on the climate system. **Diabaté et al (2021)** highlights that the inshore sea level upstream of the separation points is aligned with the meridional shifts in the WBC extensions.

2. land-ocean contrast of the 250mb jet stream

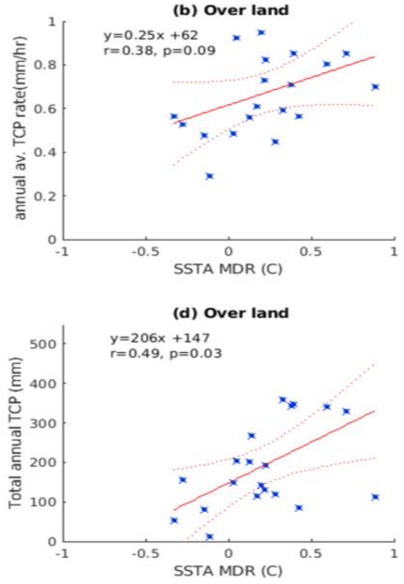


Hallam et al (2022) highlights that in the North Atlantic the winter jet latitude has migrated 3 degrees poleward over the 141-time period and an increase in jet speed of 10mph is observed, both have implications for European Weather.

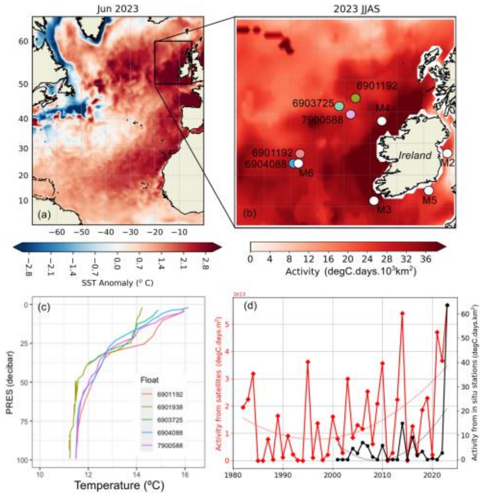
29 April 2024

3. Tropical Cyclone Rainfall with rising SSTs

Hallam et al. (2023) show a 40% rise in hurricane rainfall rate and 140% increase in total rainfall over land when ocean temperatures in the North Atlantic main hurricane development region are 1°C warmer than normal, during the period 1998-2017

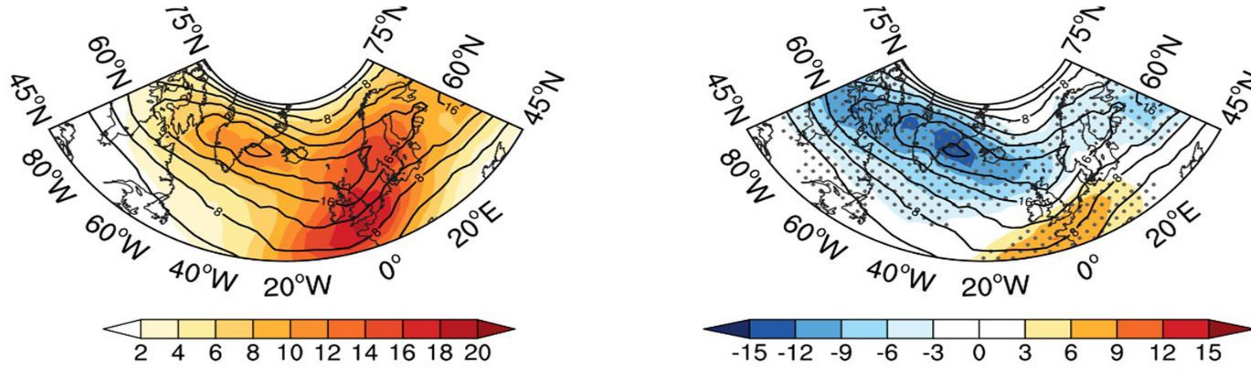


4. Marine Heat Waves



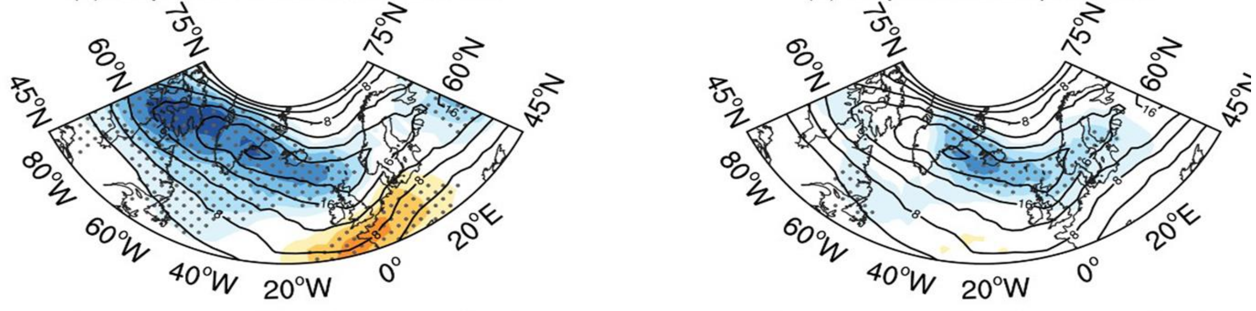
McCarthy et al (2024) shows the Marine Heat Wave (MHW) around Ireland in 2023. The MHW activity in June 2023 was the highest of any MHW in the waters west of Ireland since records began in 1982

Importance of the Pacific Kuroshio current for the North Atlantic Jet stream and blocking



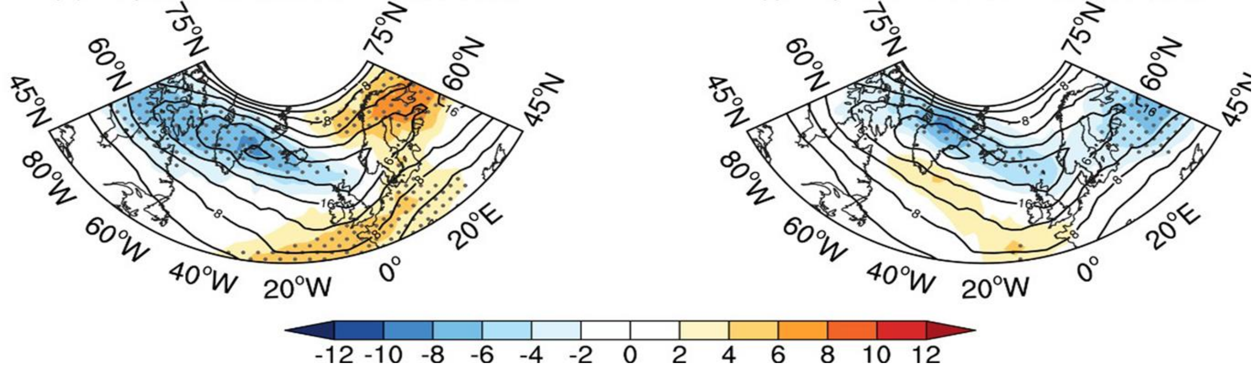
(a) Blocking with (without) SS-front, shaded (contour), NDJ

(b) Blocking response to SST-fronts, shaded, NDJ



(c) response to two oceanic fronts

(d) response to tropical SST



(e) response to Atlantic oceanic front

(f) response to Pacific oceanic front

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Pacific oceanic front amplifies the impact of Atlantic oceanic front on North Atlantic blocking

Ho-Nam Cheung[1,2,3], Nour-Eddine Omrani[3,4], Fumiaki Ogawa[5], Noel Keenlyside[3,4,6,7], Hisashi Nakamura[8] and Wen Zhou[9]

1 November 2022 ATHANASIADIS ET AL.

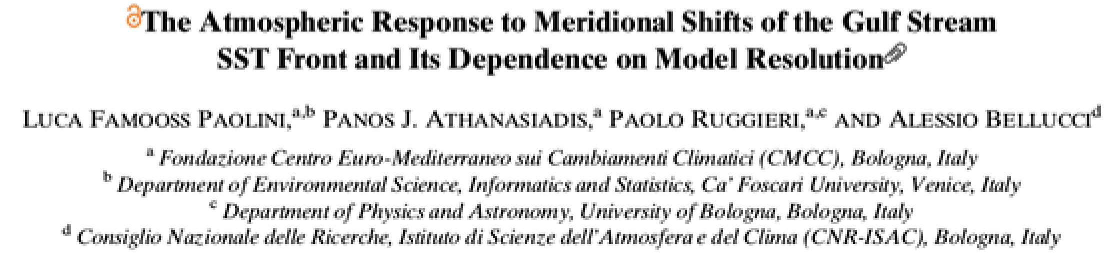
Mitigating Climate Biases in the Midlatitude North Atlantic by Increasing Model Resolution: SST Gradients and Their Relation to Blocking and the Jet

Panos J. Athanasiadis,[a] Fumiaki Ogawa,[b,c,d] Nour-Eddine Omrani,[b,c] Noel Keenlyside,[b,c,e]

Not only the Gulf Stream but also the Kuroshio current, are maintaining the wintertime mid-latitude jet, storm track and North Atlantic blocking frequency with significant implications for Eurasian climate.

Gulf Stream meridional shifts cause homodirectional shifts in the North Atlantic eddy-driven jet and stormtrack, though only HR models are able to reproduce this response.

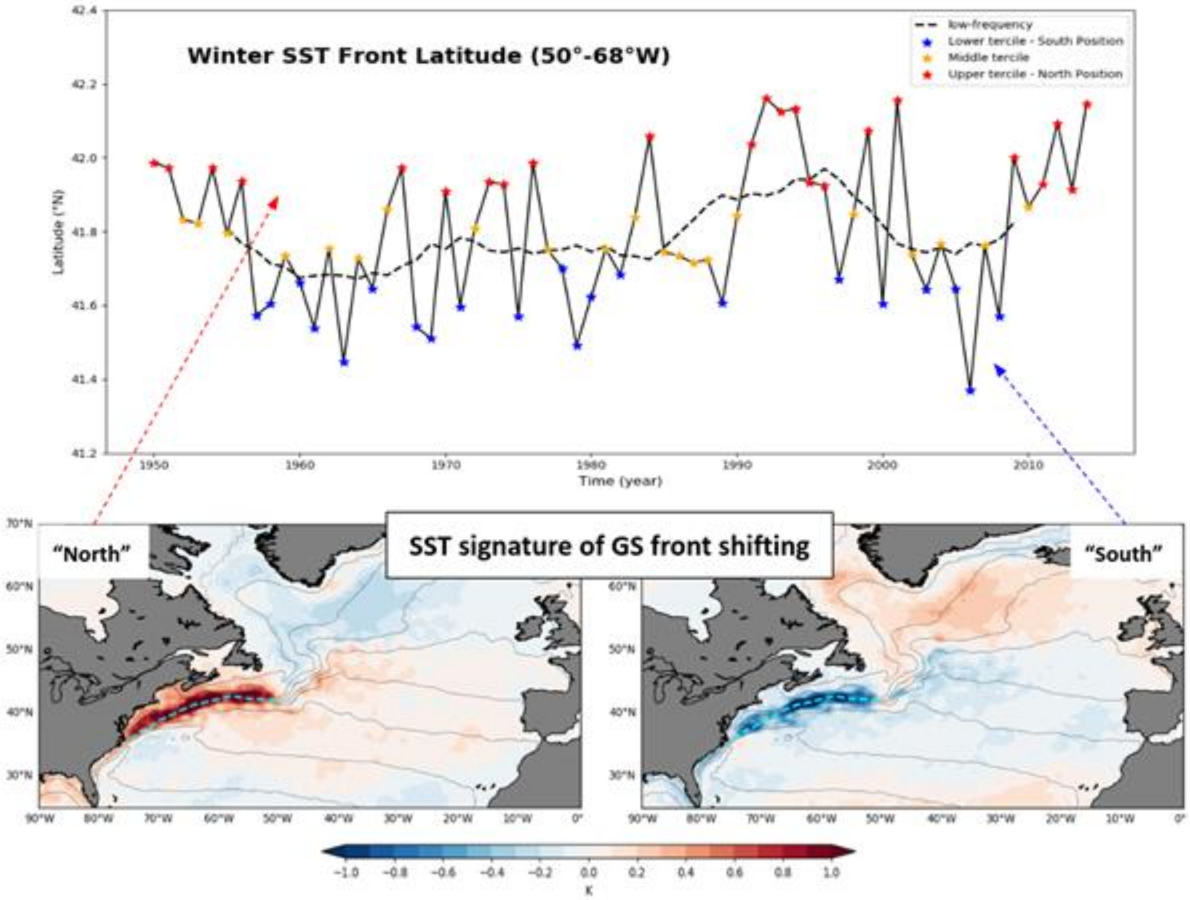
Famooss Paolini et al., 2022

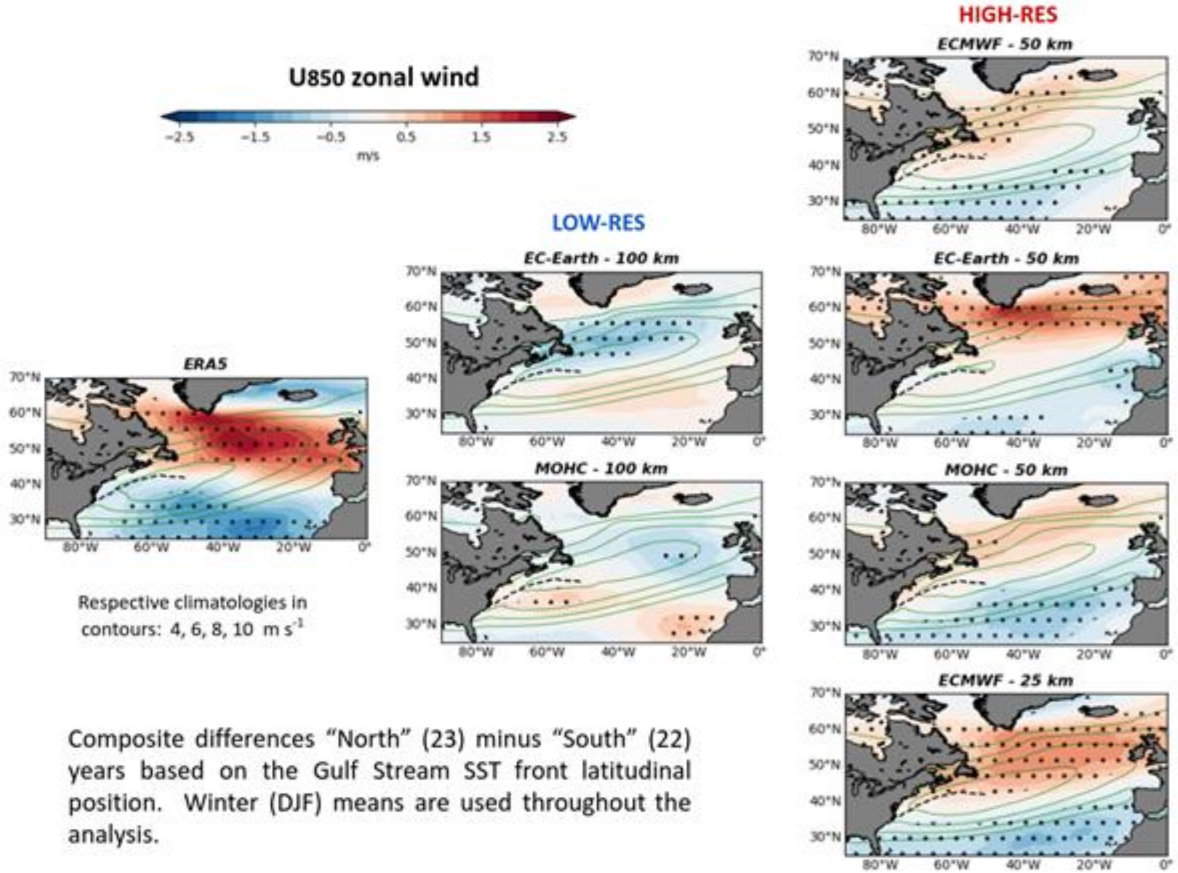


The Atmospheric Response to Meridional Shifts of the Gulf Stream SST Front and Its Dependence on Model Resolution

Luca Famooss Paolini,[a,b] Panos J. Athanasiadis,[a] Paolo Ruggieri,[a,c] and Alessio Bellucci[d]

[a] *Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Bologna, Italy*
[b] *Department of Environmental Science, Informatics and Statistics, Ca' Foscari University, Venice, Italy*
[c] *Department of Physics and Astronomy, University of Bologna, Bologna, Italy*
[d] *Consiglio Nazionale delle Ricerche, Istituto di Scienze dell'Atmosfera e del Clima (CNR-ISAC), Bologna, Italy*



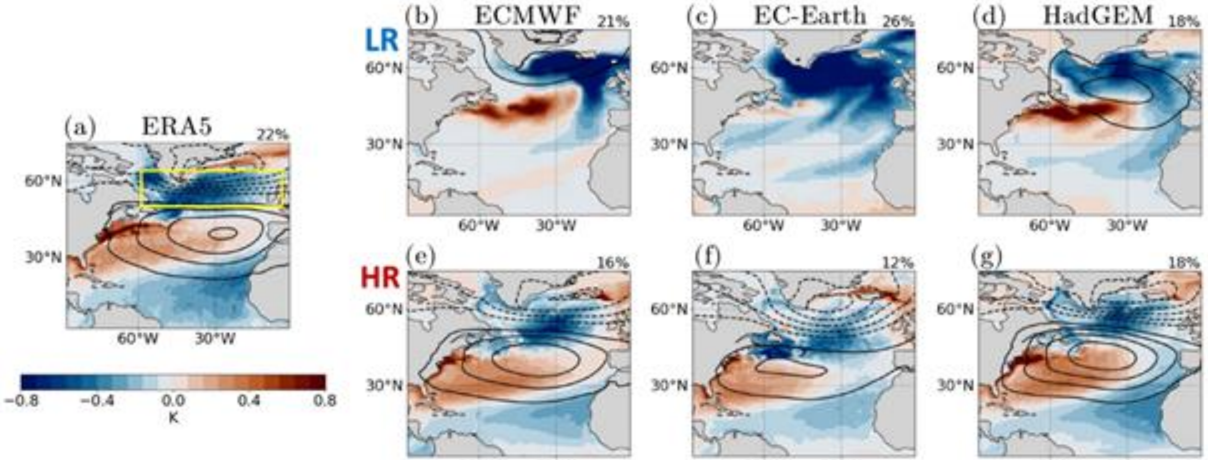


Respective climatologies in contours: 4, 6, 8, 10 m s^{-1}

Composite differences "North" (23) minus "South" (22) years based on the Gulf Stream SST front latitudinal position. Winter (DJF) means are used throughout the analysis.

LR models (1° ocean) fail to reproduce fundamental aspects of ocean–atmosphere variability in the N. Atlantic due to cold & fresh biases in areas of deep convection that promote a positive AMOC feedback (salinity-controlled density)

Patrizio et al., 2023



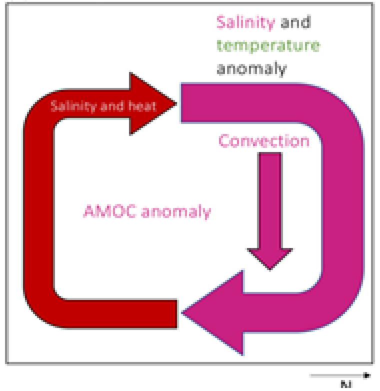
Leading EOF of winter-mean (DJFM) SST anomalies calculated over the North Atlantic domain between 0°–70°N and 0°–90°W (shading; K), and **SLP anomalies regressed onto the leading PCs** of the SST anomalies (contours; 0.6 hPa interval) for ERA5 and the LR and HR control runs from ECMWF, EC-Earth and HadGEM.

Improved Extratropical North Atlantic Atmosphere–Ocean Variability with Increasing Ocean Model Resolution

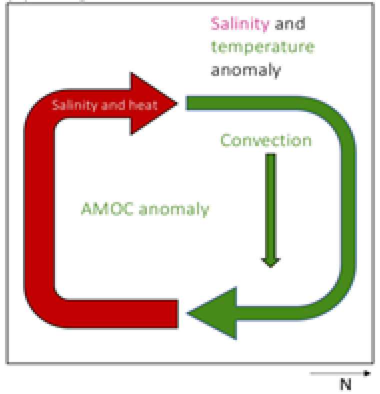
Casey R. Patrizio,[a] Panos J. Athanasiadis,[a] Claude Frankignoul,[b,c] Doroteaciro Iovino,[a]
Simona Masina,[a] Luca Famooss Paolini,[a,d] and Silvio Gualdi[a]

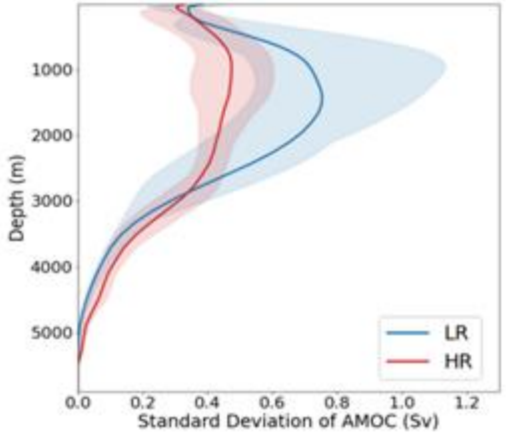
[a] *Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Bologna, Italy*
[b] *Sorbonne University, Paris, France*
[c] *Woods Hole Oceanographic Institution, Woods Hole, Massachusetts*
[d] *Department of Physics and Astronomy, University of Bologna, Bologna, Italy*

(a) Salinity-controlled models



(b) Temperature-controlled models





Standard deviation of low-pass filtered overturning streamfunction anomalies averaged over 40°–60°N. The multi-model mean standard deviation is calculated from the LR (blue line) and HR (red line) control runs using ECMWF, EC-Earth and HadGEM. The transparent shading indicates the associated spread across model runs.

The NAO induces meridional shifts in the Gulf Stream (strong sub-decadal covariability) with a lag that varies in time (2–3 years). This non-stationarity results from the superposition of different influencing mechanisms (e.g. propagation of Rossby waves) that also vary in time.

Famooss Paolini et al., 2023

Nonstationarity in the NAO–Gulf Stream SST Front Interaction

LUCA FAMOOSS PAOLINI,[a,b,c] NOUR-EDDINE OMRANI,[d] ALESSIO BELLUCCI,[e] PANOS J. ATHANASIADIS,[a]
PAOLO RUGGIERI,[a,c] CASEY R. PATRIZIO,[a] AND NOEL KEENLYSIDE[d,f]

[a] *Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici, Bologna, Italy*
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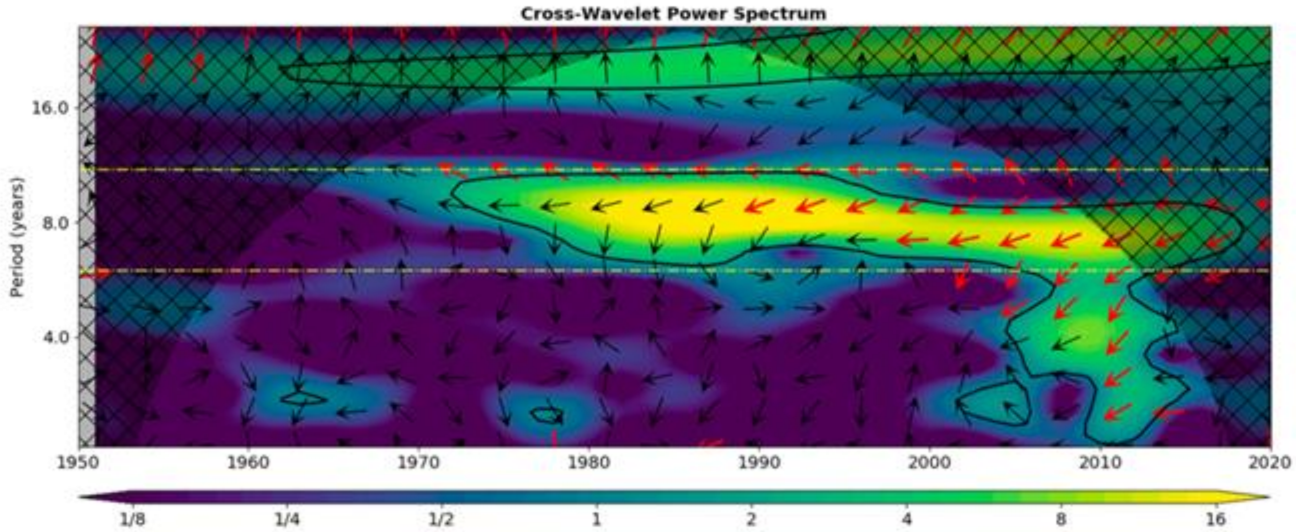


FIG. 1. Cross-wavelet transform of the detrended and standardized winter GSF and NAO time series. Thick black contours enclose the cross-wavelet power spectrum values that are statistically significant at the 90% confidence level. The phase relationship between the winter GSF and NAO time series is indicated by the vectors, following the convention in Torrence and Webster (1999). In the case of in-phase signals, vectors point upward; in the case of antiphase signals, vectors point downward. If the GSF leads the NAO, vectors point to the right; if the NAO leads the GSF, vectors point to the left. Thick red vectors indicate phase relationship in which squared wavelet coherence is statistically significant at the 90% confidence level (Kohyama et al. 2021). The lower and upper dot–dashed yellow lines represent the 6- and 11-year periods, respectively. Cross-hatched light shades indicate the cone of influence where edge effects may alter the power spectrum.

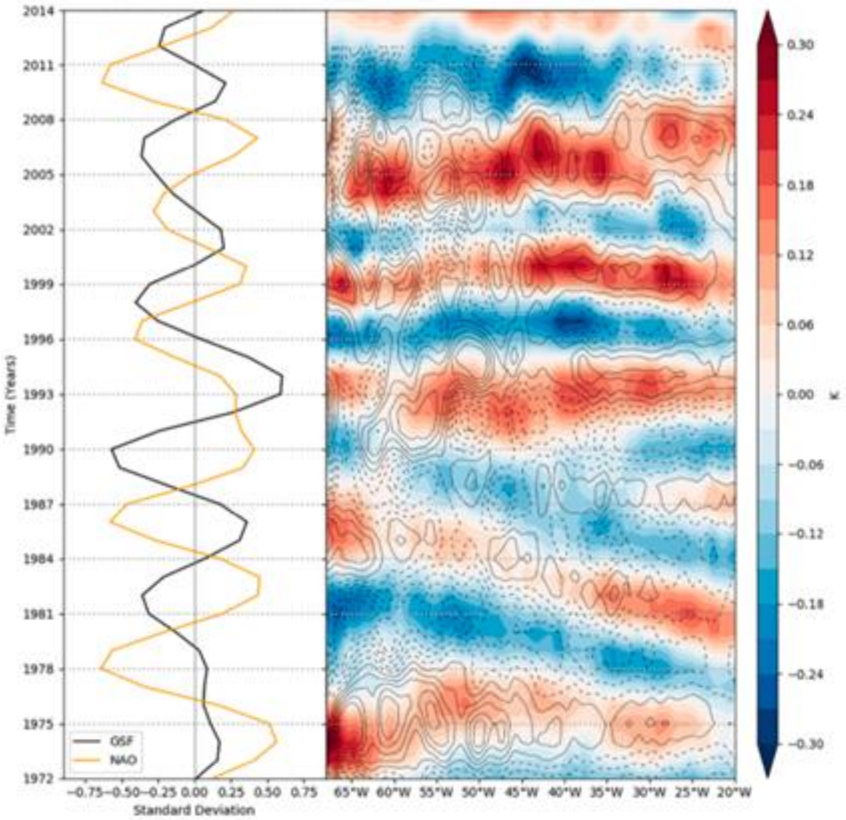
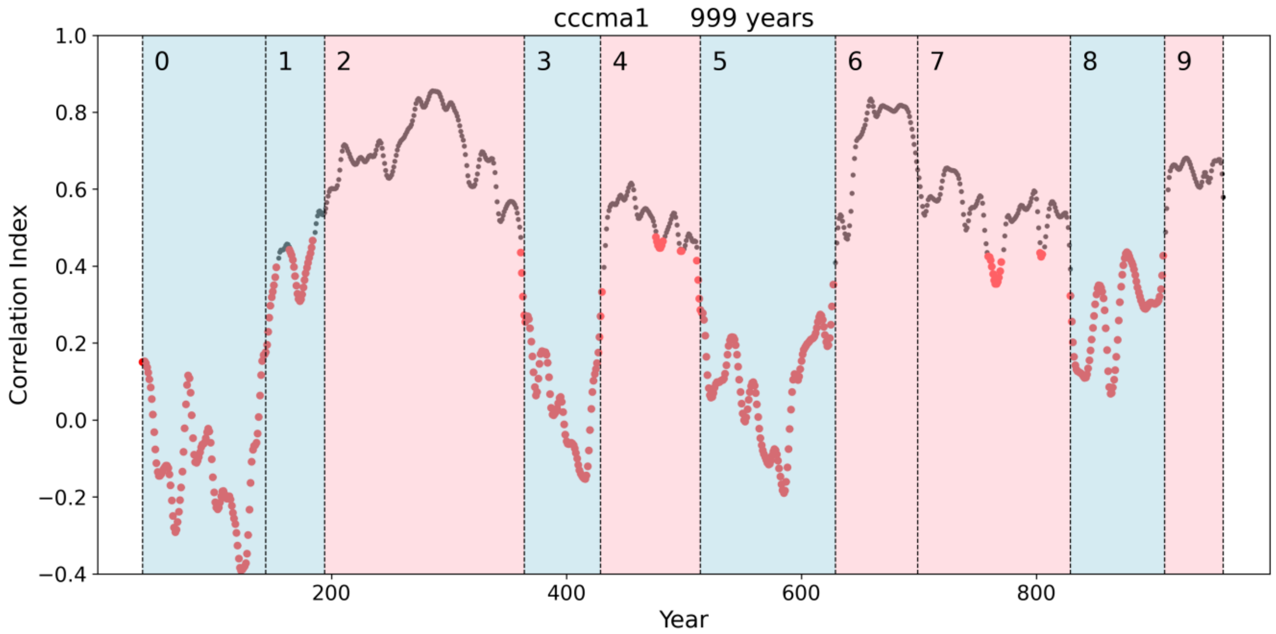
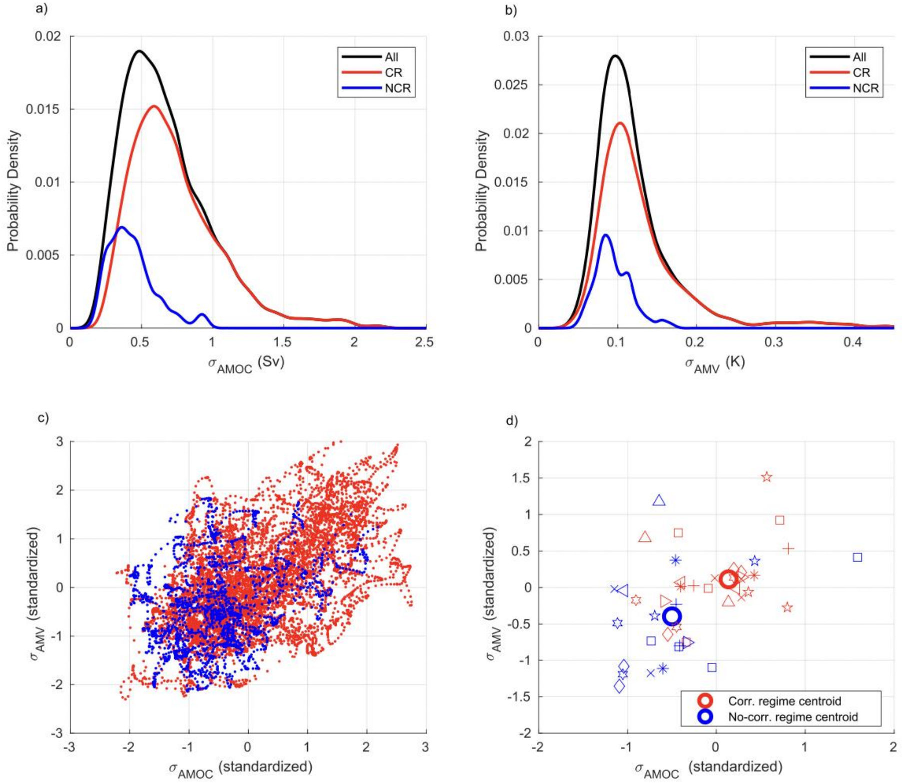


FIG. 8. (left) Bandpass-filtered winter GSF (black) and NAO (orange) time series between 1972 and 2014. (right) Hovmöller diagram of the bandpass-filtered SST (K; color shading) and SSH anomalies (cm; black contours, with contours every 0.5 cm from −1.75 cm) averaged in the 35°–38°N latitudinal range during 1972–2014. It is specified that 6 years are lost at each border of the time series because of the application of the Lanczos filter (see detail in section 2).

Intermittent Behavior in the AMOC-AMV Relationship





A change-point detection methodology was devised to identify shifts in the AMOC-AMV covariability regimes in a suite of multi-century pre-industrial simulations from CMIP6 archive

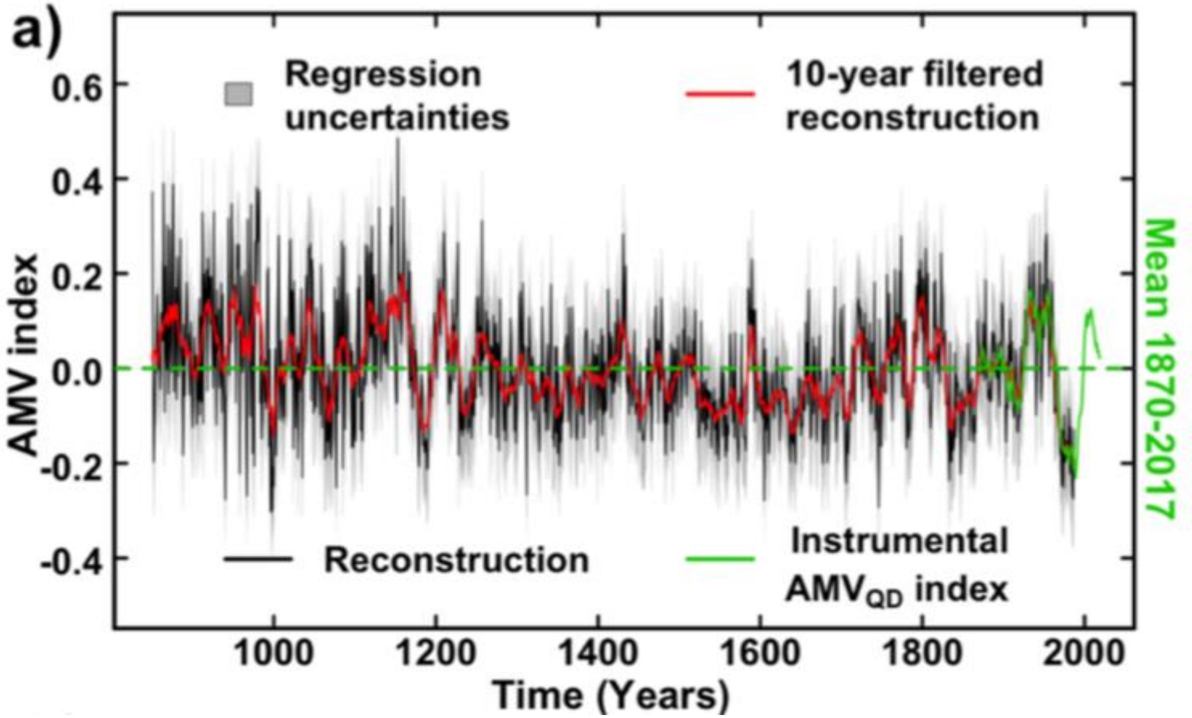
Spontaneous breakings of the AMOC-AMV connection are found in all analysed models..

Decoupling between the AMOC and AMV is more likely to occur when the amplitude of their variability (σ_{AMOC} and σ_{AMV}) is low.

[illegible]

Early warning signal for a tipping point suggested by a millennial Atlantic Multidecadal Variability reconstruction

Simon, Swingedouw, Ortega, Gastineau, Mignot, McCarthy, Khodri, Nature Communications (2022)

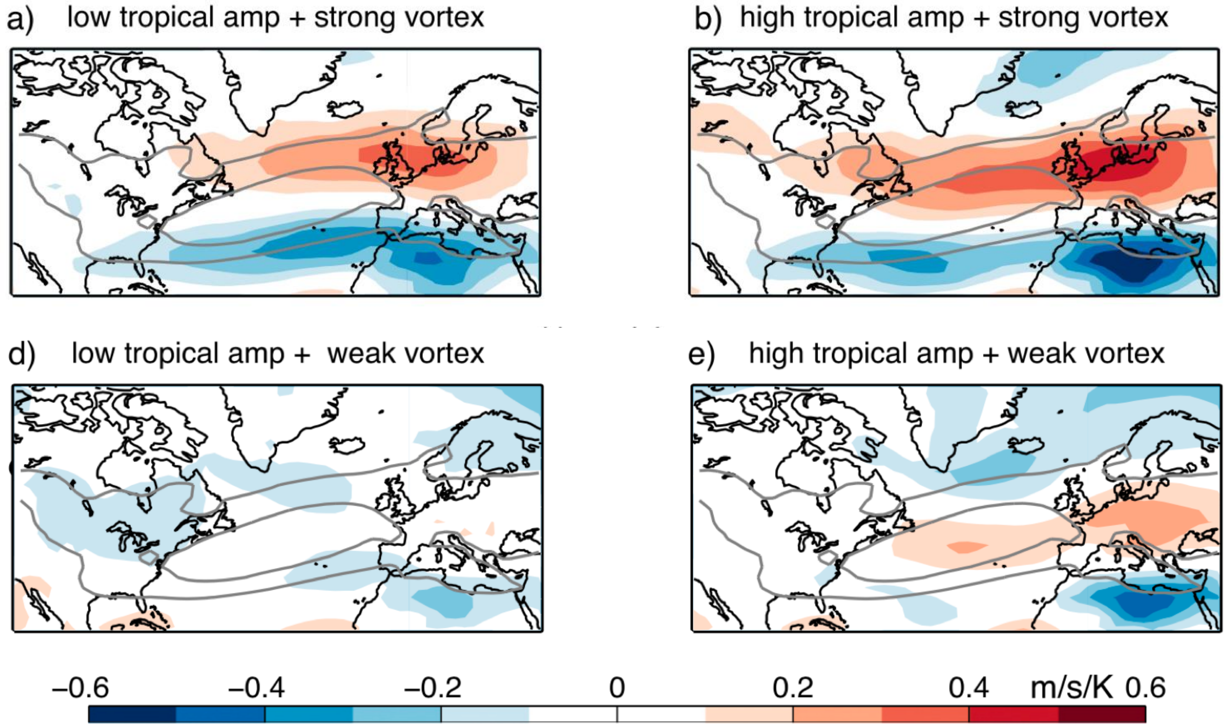


- Reconstruction of the AMV established using land proxy data and advanced statistical methods (random forest),

- LOCEAN plans to use the reconstruction to evaluate the variability generated in CMIP6 models in future research.

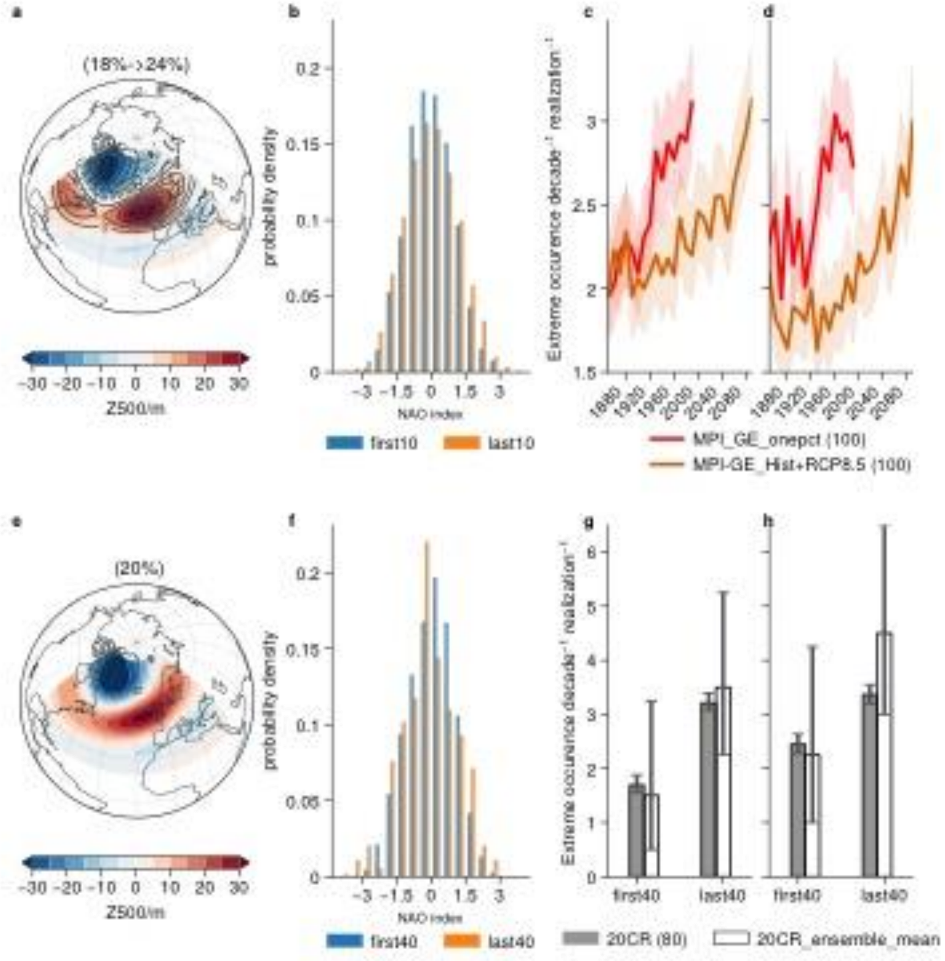
Key scientific questions:

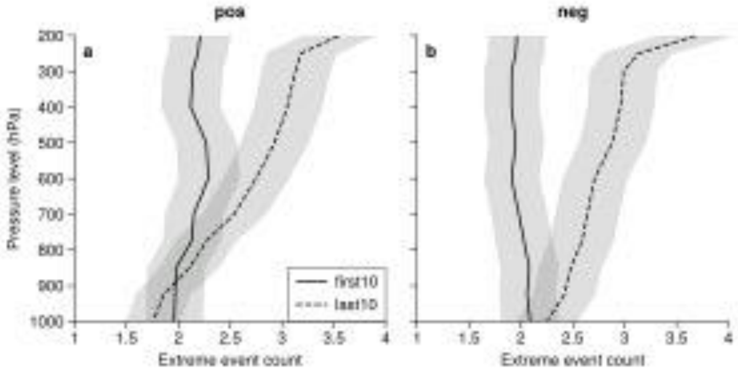
- *How do ocean–atmosphere interactions and teleconnections influence the northern hemisphere tropospheric eddy-driven jet, the stratospheric polar night jet and atmospheric blocking on seasonal and longer time-scales? How are the interactions and teleconnections affected by global warming?*



Nov-Apr. 850hPa zonal wind response per degree of global warming in four plausible storylines of climate change conditioned on the tropical amplification and stratospheric vortex responses (Zappa and Shepherd 2017)

The North Atlantic Oscillation gets more extreme under global warming





Summer NAO extremes generated by internal variability are changing in a simulated greenhouse warming:

- **Robust increases in the occurence**
- **Significantly amplified impacts over North Europe**

Quan Liu, J. Bader, J. Jungclaus and D. Matei, 2024 (to be submitted)

MJO-NAO teleconnexion using idealized numerical experiments

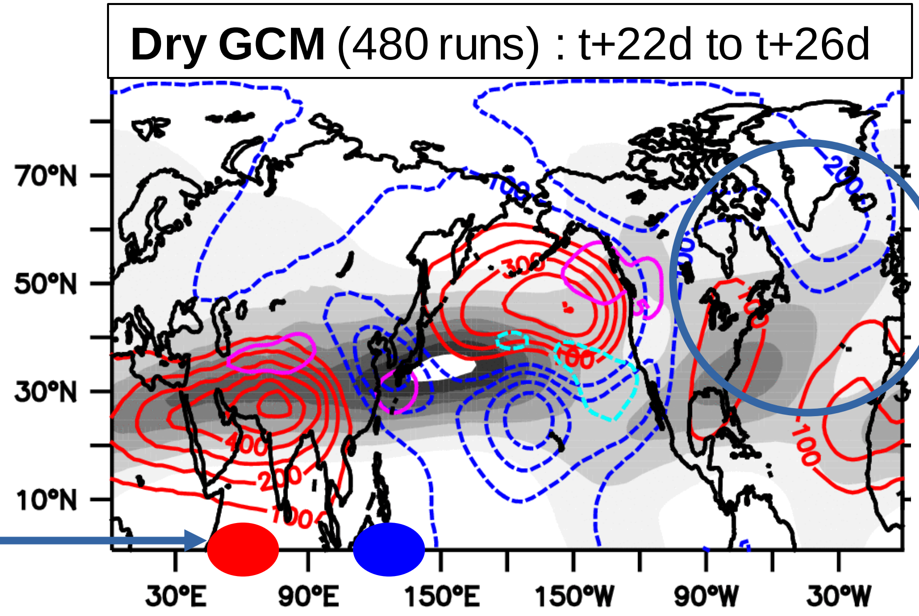
Use of Dry version of the new atmospheric model developed at LMD-IPSL (DYNAMICO) with ~200 km horiz res° and 14 vertical levels in the troposphere

Geopotential anomalies

Z'>0

Z'<0

Imposed MJO phase 3 via temperature tendency

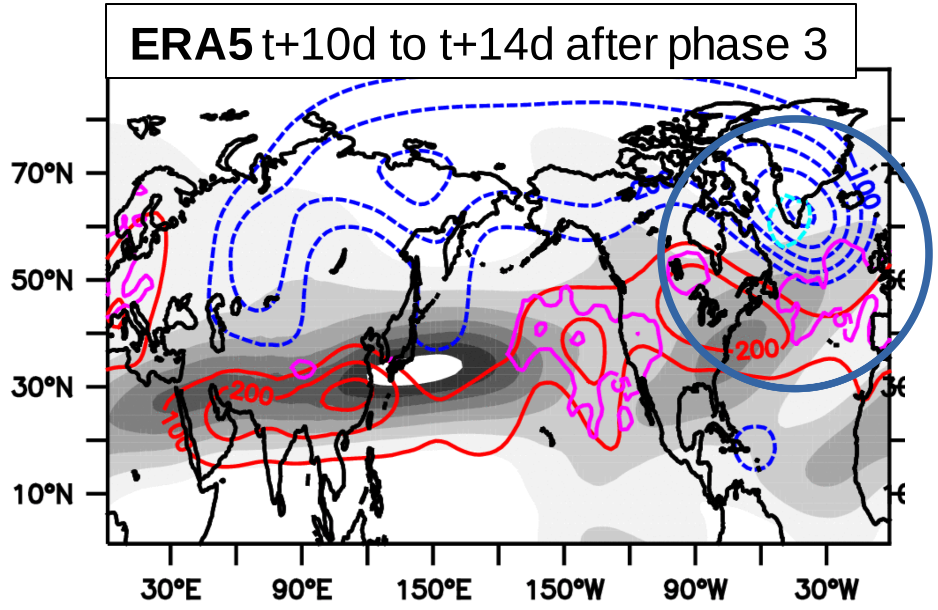


Dry GCM (480 runs) : t+22d to t+26d

NAO+

heating

cooling



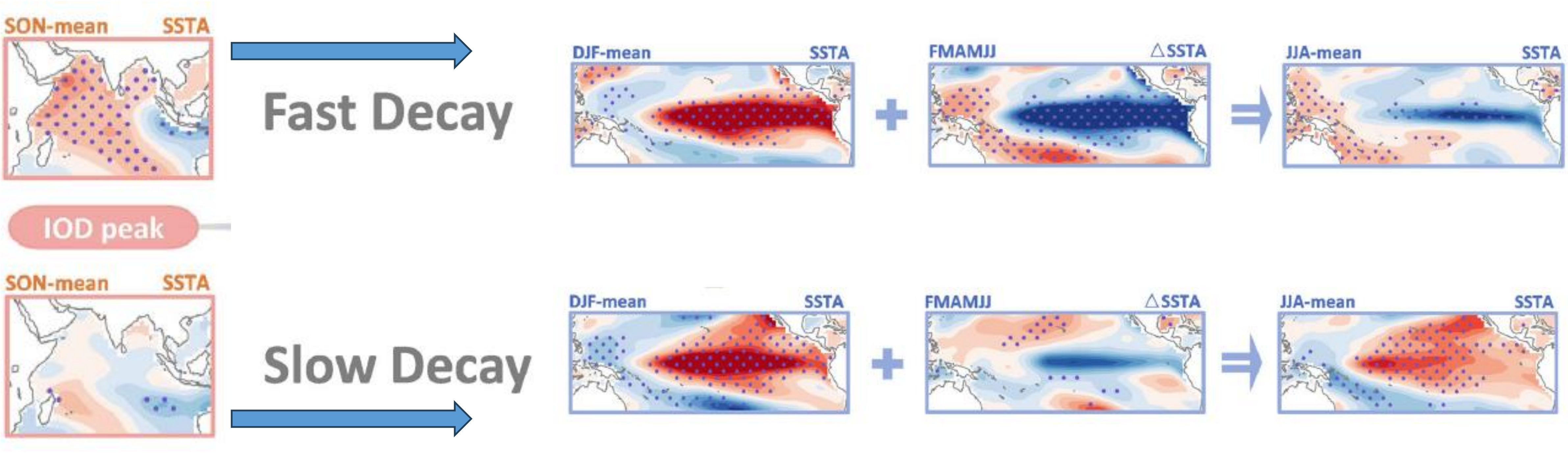
ERA5 t+10d to t+14d after phase 3

The dry GCM is able to represent the MJO-NAO teleconnexion via planetary wave excitation and propagation in the troposphere !

Work done at LMD (Paris) ; M. Saint-Lu, G. Riviere, S. Fromang

Boosting effect of strong western pole of the Indian Ocean Dipole on the decay of El Niño events

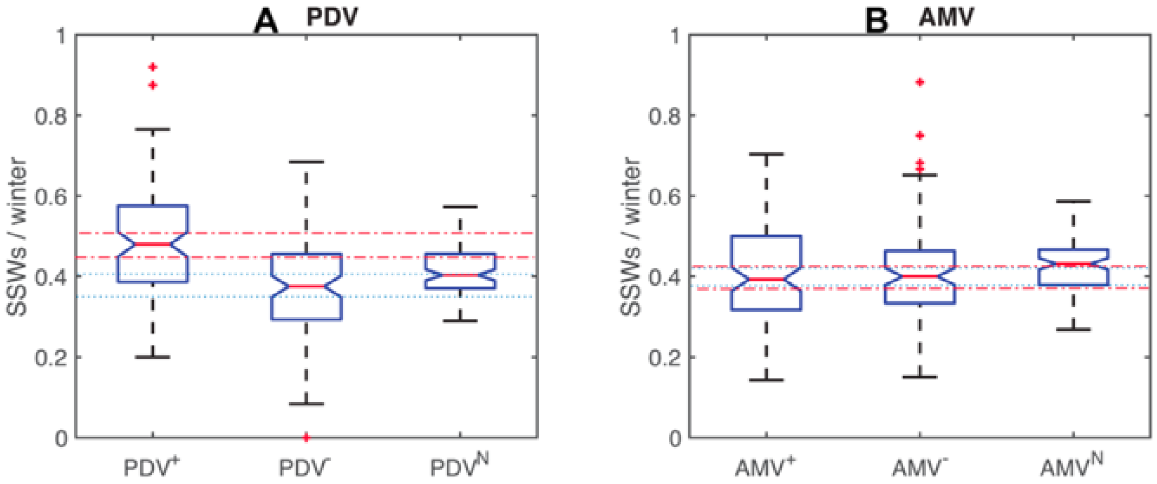
- Positive IOD with a strong western pole can accelerate El Niño termination
- Greater emphasis on IOD can improve the prediction of El Niño decay



Wu et al. NPJ Climate and Atmospheric Science, 2024

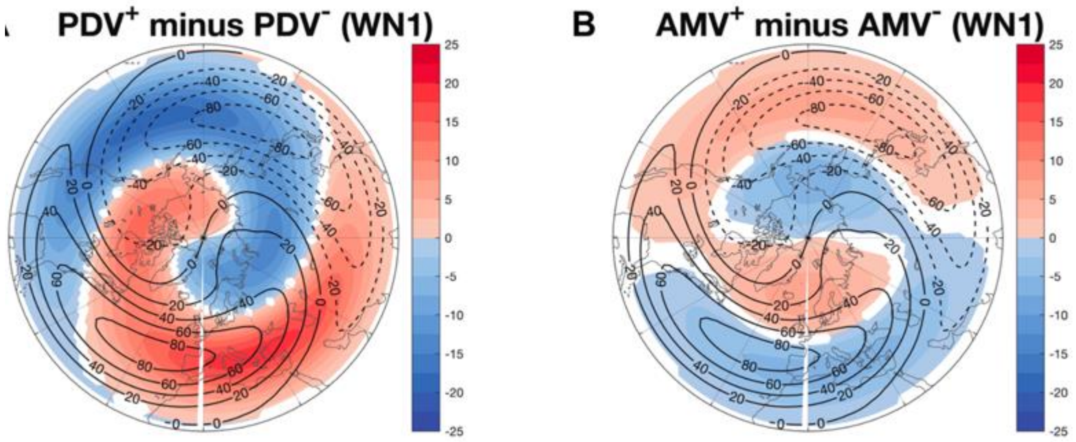
Interactions between ocean variability and Sudden Stratospheric warming (SSW) Events

- Analyzing a lager ensemble (95 members) of historical experiments (155 years) performed with the MPI-ESM, we show that:
    - the SSW frequency is modulated by the PDV but unaffected by the AMV
    - Key role for the response in SSW frequency is the modulation by the PDV of the tropospheric stationary waves and stratospheric mean flow


A PDV

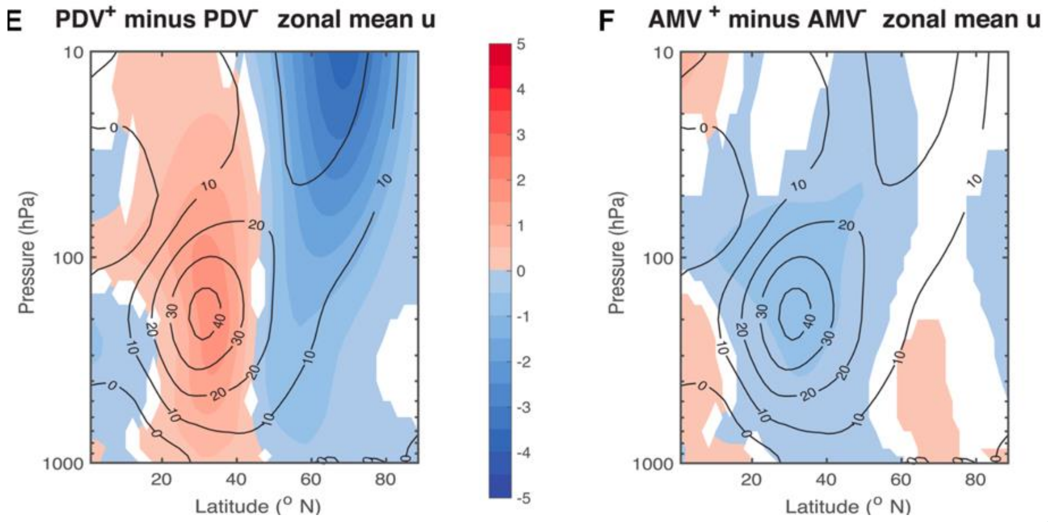
B AMV

PDV: Weaker stratospheric vortex zonal
AMV: Anomaly restricted to the troposphere


PDV$^+$ minus PDV$^-$ (WN1)

B AMV$^+$ minus AMV$^-$ (WN1)

PDV: Positive interference of stationary waves:
AMV: Negative interference of stationary waves.


E PDV$^+$ minus PDV$^-$ zonal mean u

F AMV $^+$ minus AMV$^-$ zonal mean u

Ayarzagüena, Manzini, Calvo and Matei, ANYAS 2021

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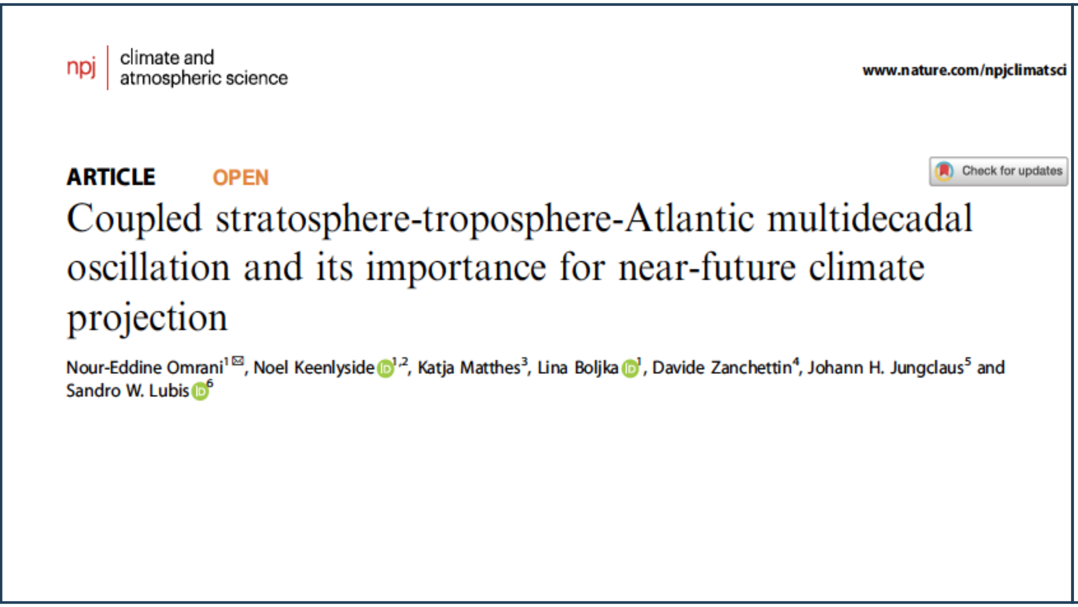
Coupled Stratosphere-troposphere-Atlantic multidecadal Oscillation



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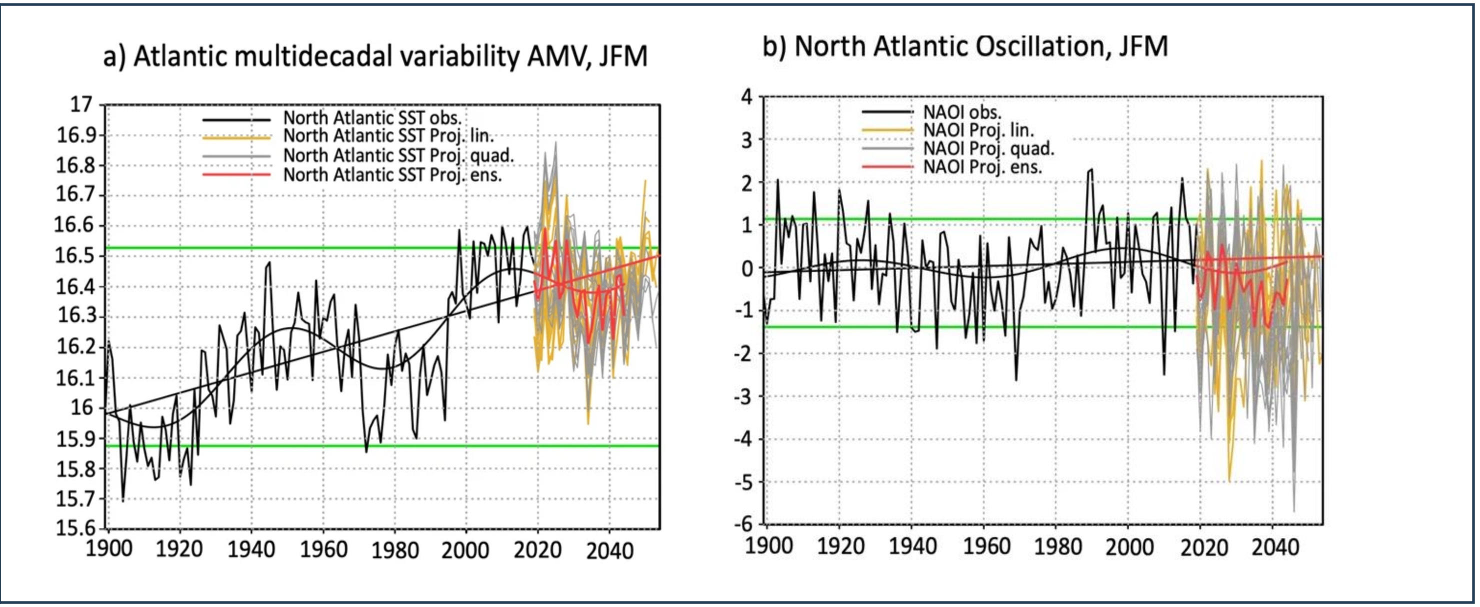
Coupled stratosphere-troposphere-Atlantic multidecadal oscillation and its importance for near-future climate projection

Nour-Eddine Omrani[1]✉, Noel Keenlyside[1,2], Katja Matthes[3], Lina Boljka[1], Davide Zanchettin[4], Johann H. Jungclaus[5] and Sandro W. Lubis[6]

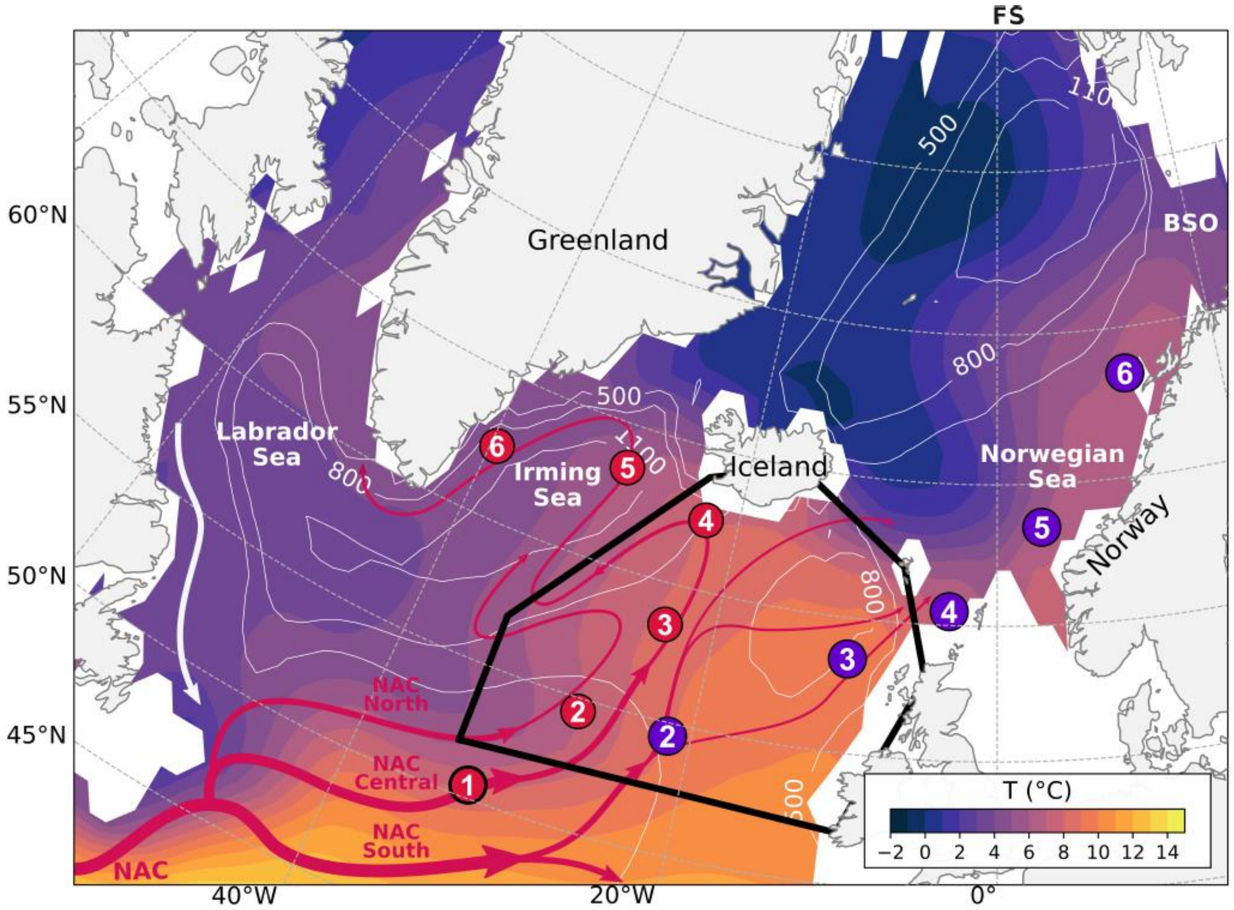


- The work can explain the observed coherent multidecadal variability of the North Atlantic SST, North Atlantic Oscillation (NAO), Polar Stratospheric Vortex (PSV), Arctic Sea-ice north of the Atlantic Basin as coupled quasiperiodic stratosphere-troposphere-Atlantic oscillation.
- The quasi-periodic nature of this oscillation enhances the predictability of all climate component involved.
- Our statistical model shows the best projection skill when all climate component involved and predict a cooling over the North Atlantic and weakening of NAO

Advancing understanding of North Atlantic decadal variability

- Clear signal of warm or cold anomalies reaching the eastern Subpolar North Atlantic (black box)
- Warm anomalies are related to more water mass transformation in light layers
- Cold anomalies are related to more water mass transformation in dense layers
- The above findings, based on observations, might have an impact on AMOC variability

Passos et al., 2024, *in final revision, Journal of Climate*



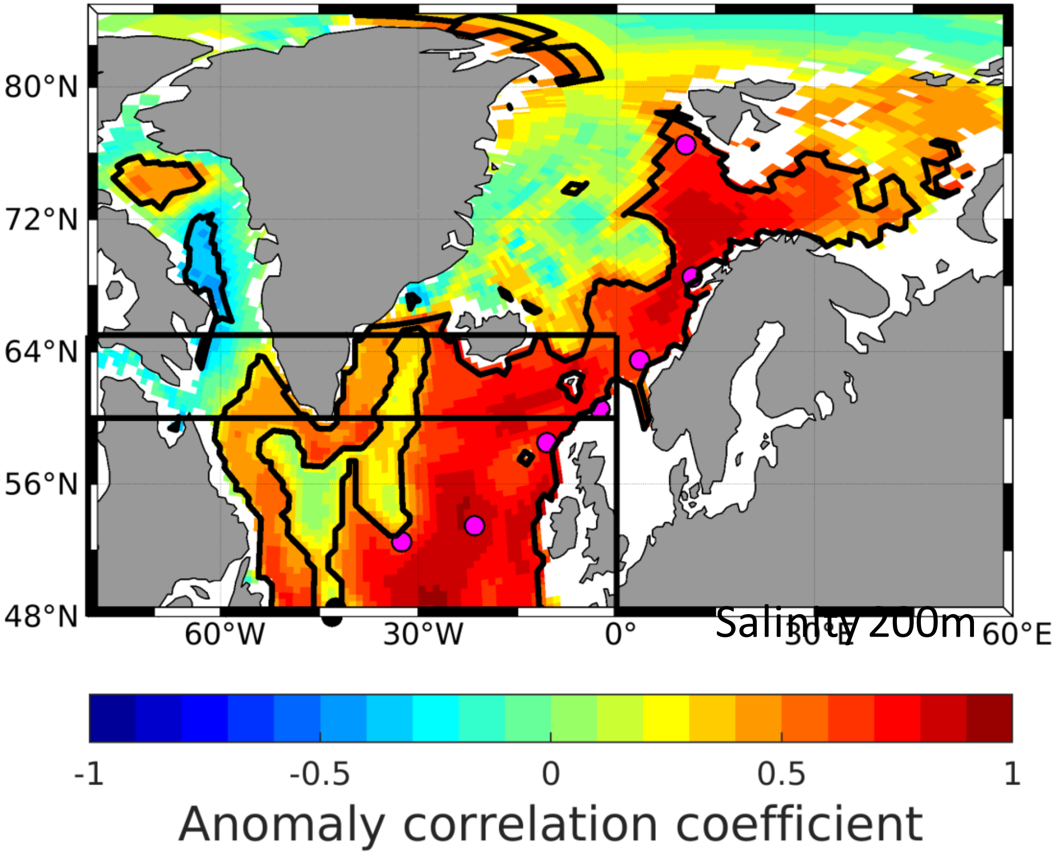
Understanding impacts of the Atlantic Ocean on the Arctic and the Pacific

- **We use advanced model simulations; pacemaker experiments.**
- **We find that salinity variability on decadal timescale in the Norwegian Sea and towards the Arctic Ocean is improved.**
- **We find that the North Pacific multi-decadal variability is largely improved.**
- **The correct description of the ocean in the Subpolar North Atlantic is important for successful decadal predictions in the downstream region.**

Suo et al.; Langehaug et al., *work in progress*

Drews et al., *Geophysical Research Letters, under review*

The Subpolar North Atlantic is kept as realistic as possible



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Drivers of the Arctic troposphere warming

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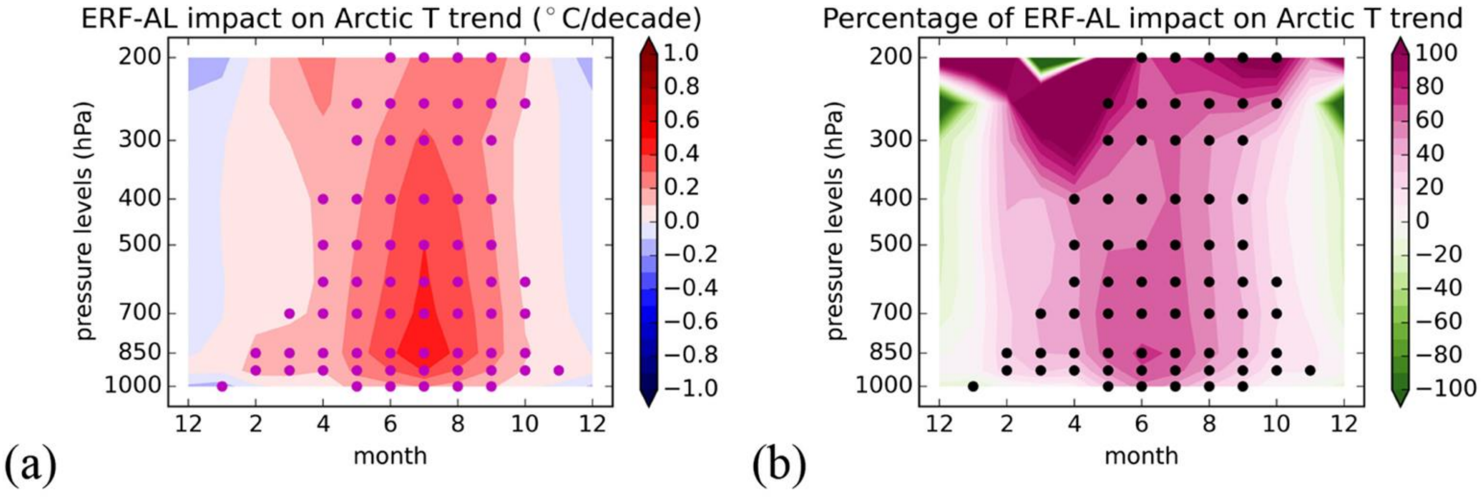
- **Based on a unique set of multi-model large-ensemble atmospheric simulations, we find:**
- **The external radiative forcing is the primary driver of the 1979–2013 warming for April–September**
- **The interdecadal Pacific and Atlantic multidecadal variability intensify/dampen the warming when transitioning to positive/negative phase**

Suo et al., 2022, *Journal of Geophysical Research: Atmospheres*



ROADMAP Oceans

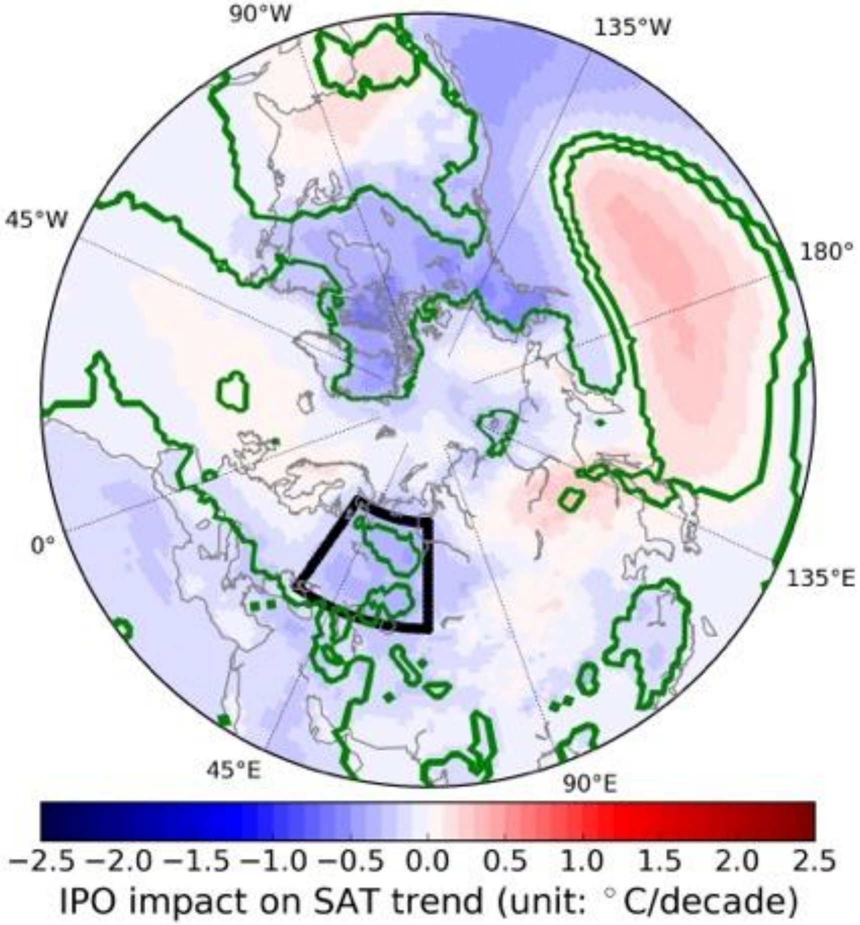
JPI OCEANS

JPI Climate

Understanding impacts of the Pacific on the Eurasia cooling

- **The study uses six-model large-ensemble simulations.**
- **The phase transition of the Interdecadal Pacific oscillation to a strong negative brings a cooling trend over west-central Eurasia in 1998-2013, about a quarter of observed Eurasia cooling in that area.**

Suo et al., 2022, *Environmental Research Letters*

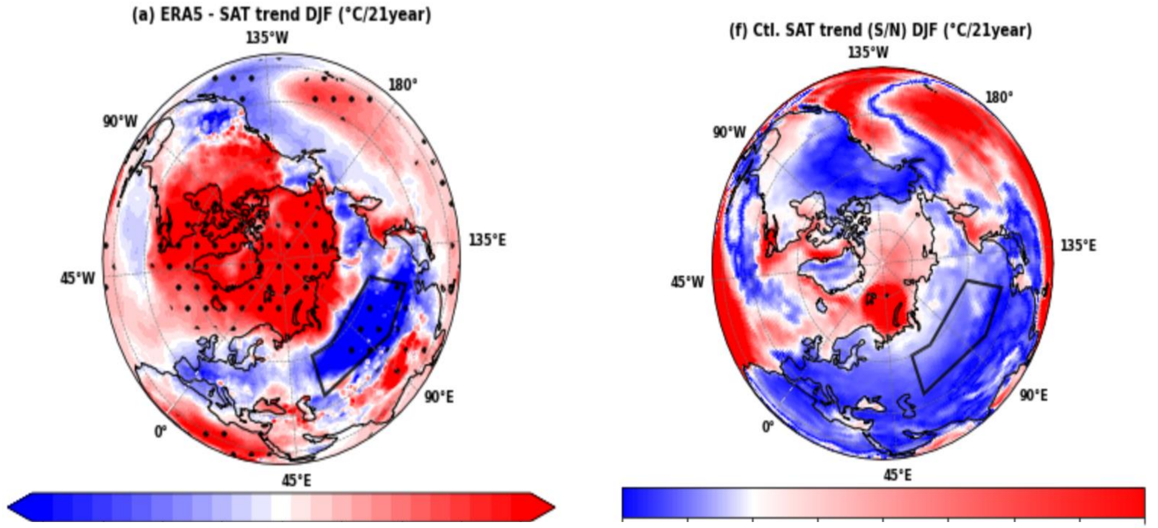


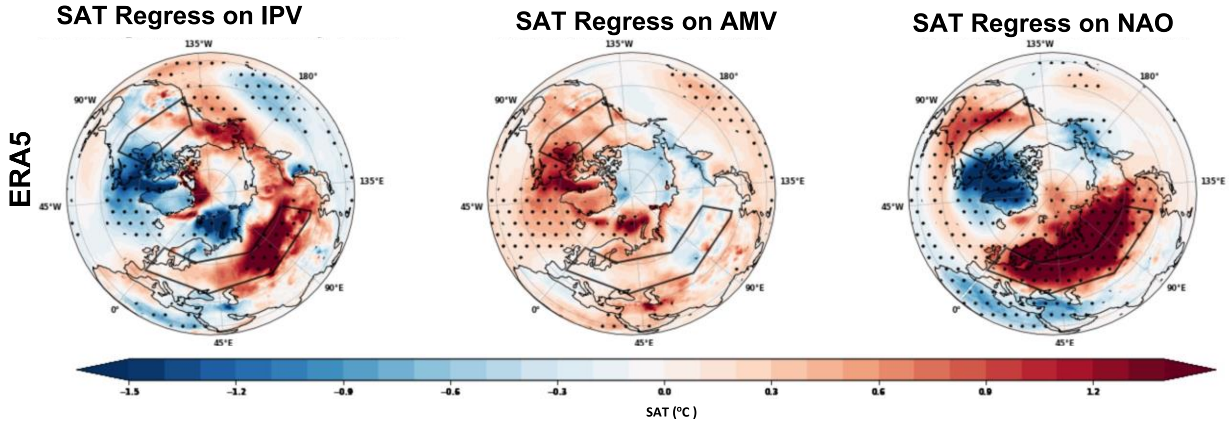
Unforced Eurasian cooling is mostly driven by NAO and partly by IPV

By performing 45-member ensembles simulations with OpenIFS atmospheric model we find that the recent cooling over Eurasian region mostly unforced (Fig. upper panel).

By analysing noAMV and noIPV simulations, we find that the unforced Eurasian cooling is mostly driven by NAO and partly by IPV, with no significant impact from AMV (Fig. bottom panel).

(Savita et al. manuscript in preparation)

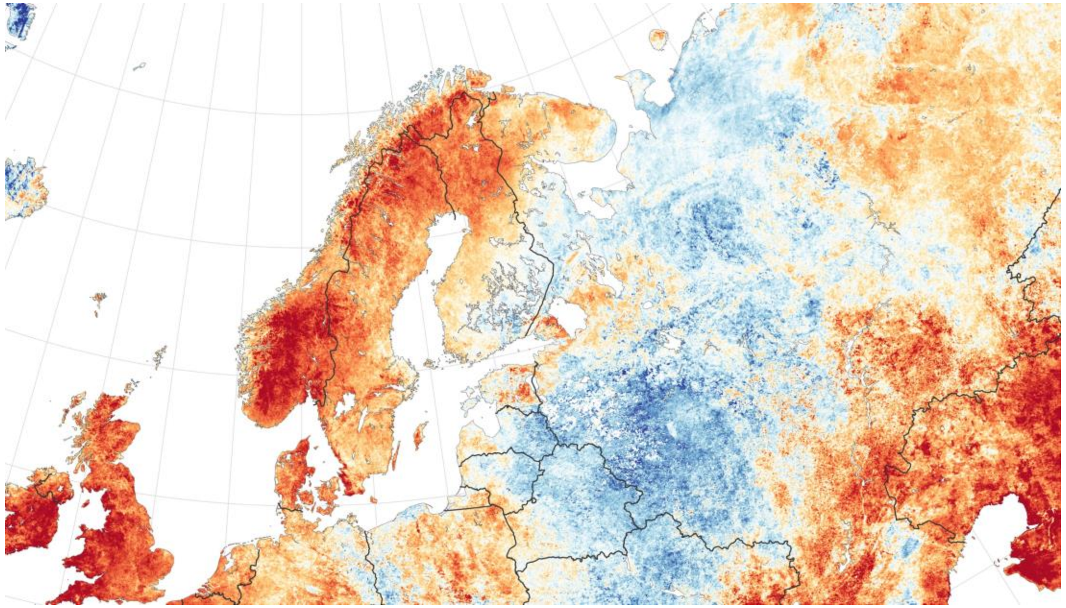




Key scientific questions:

- *How will changes in the major oceanic and atmospheric patterns impact atmospheric and marine extremes in the tropics and extra-tropics, including extra-tropical cyclones?*

Temperature anomaly in Northern Europe in July 2018

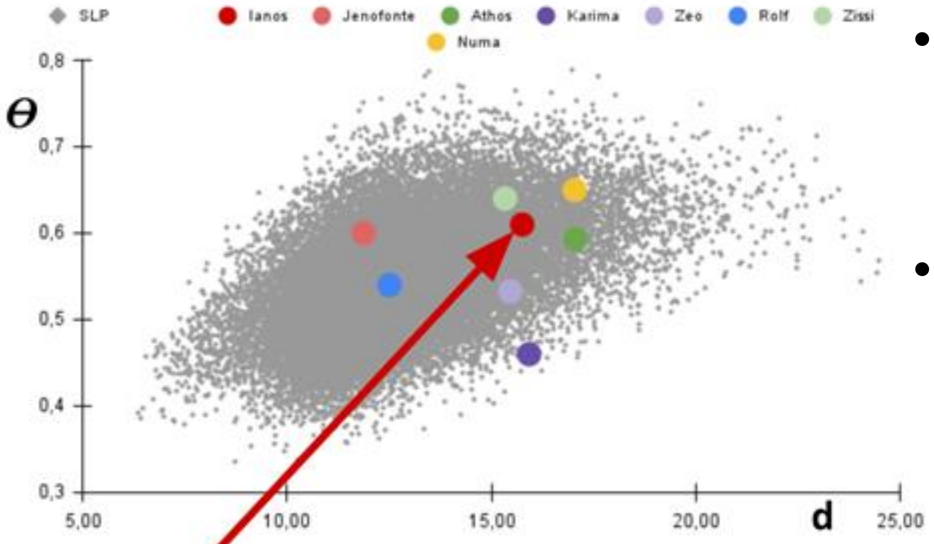


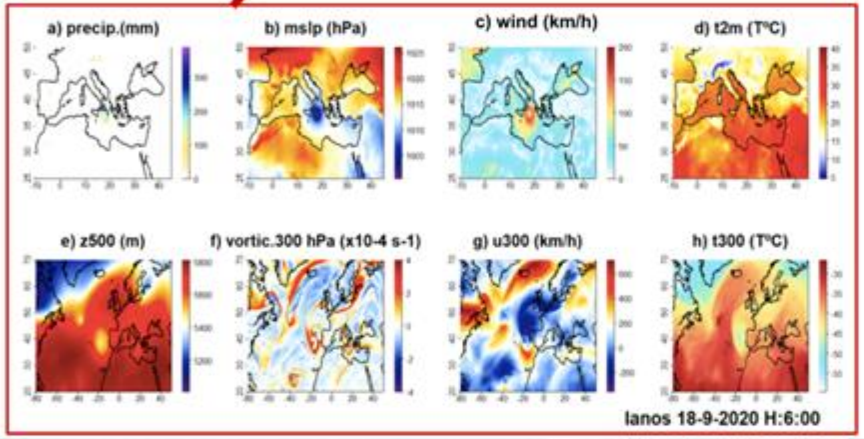
Source: NASA Earth Observatory

Medicane Zorbas September 28, 2018

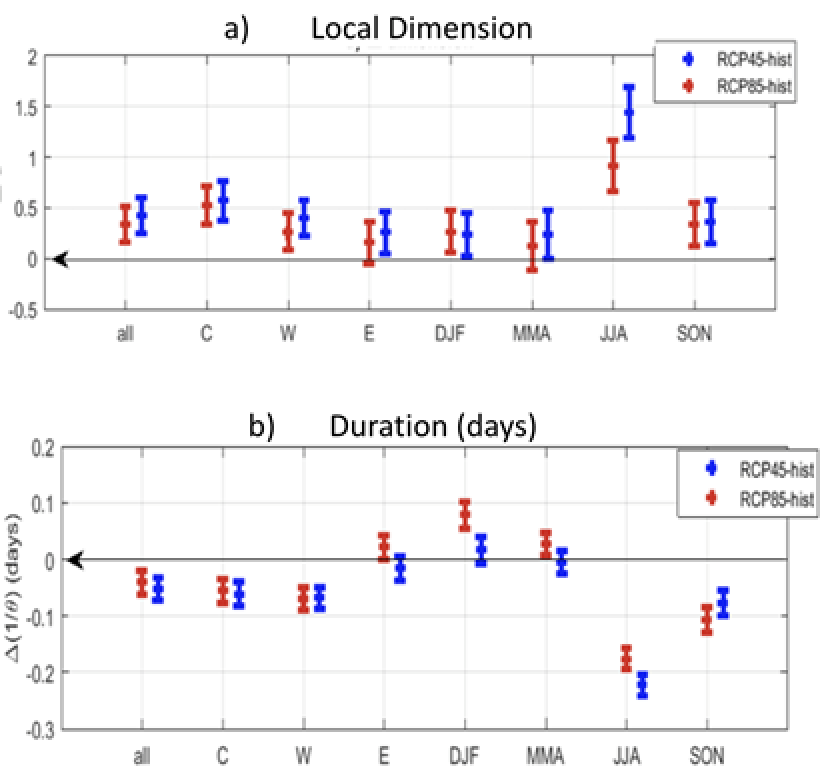
Source: NASA Aqua/MODIS

Response of intense Mediterranean cyclones to climate





- Using daily slp patterns (grey points) and the dynamical systems theory in the atmosphere (Faranda et al, 2017) we can study the predictability with two proxies: the local dimension (d, x-axis) and the inverse of the persistence (theta, y-axis).
- Higher predictability are states with low d and theta while low predictability are states with higher d and theta. We can see in the left figure that **high impact events such as Medicane Ianos** (red point, September 2020), **are going into a less predictable state.**



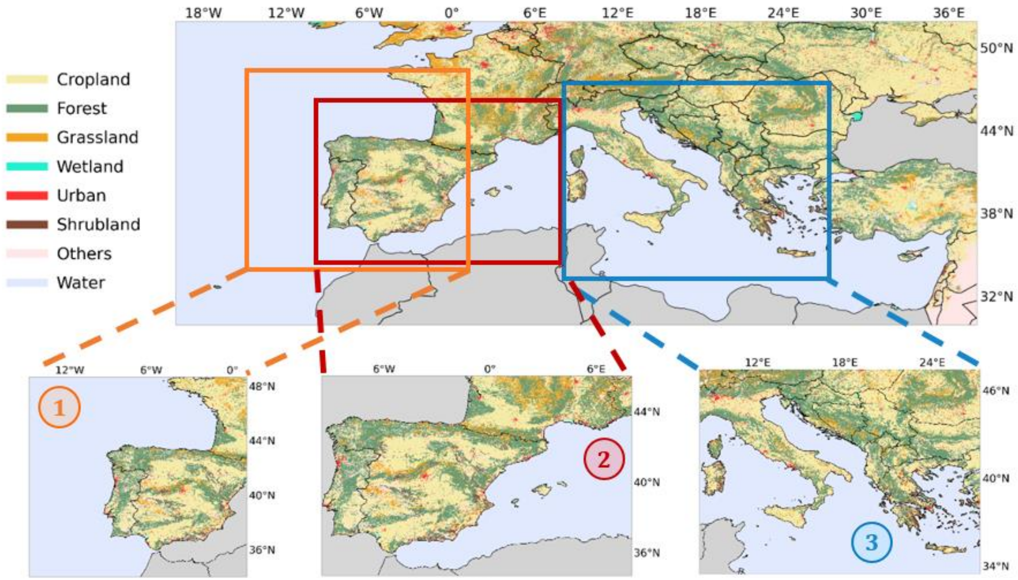
- Differences in RCP45-historical simulations (blue) and RCP85-historical simulations (red) measuring a) local dimension and b) Duration of large scale patterns of IMCs in all events by clusters (C:Central, W: Western,E: Eastern) and by season.
- The large scale drivers associated to IMC tend to be **reduced in the future, will be less predictable and last less.**
- Ongoing analysis using CMIP6 models

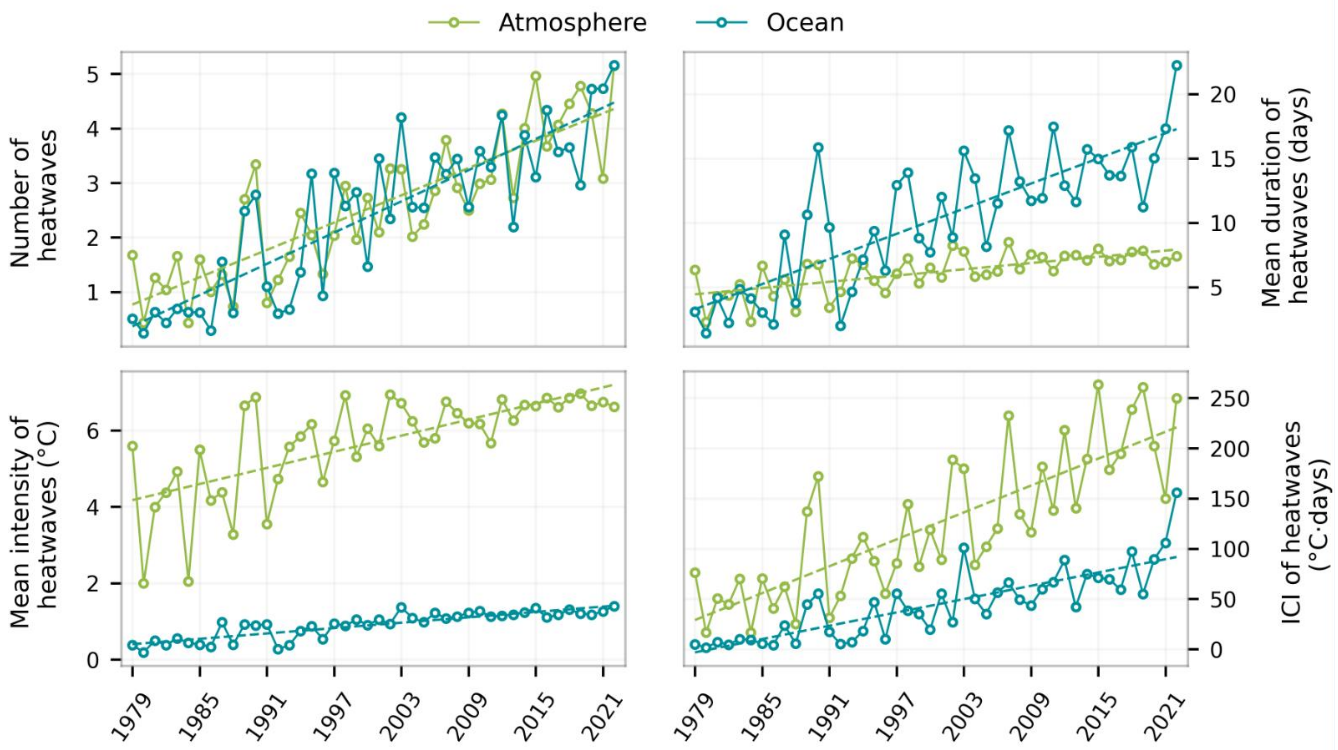
Marine and Atmospheric Heatwaves

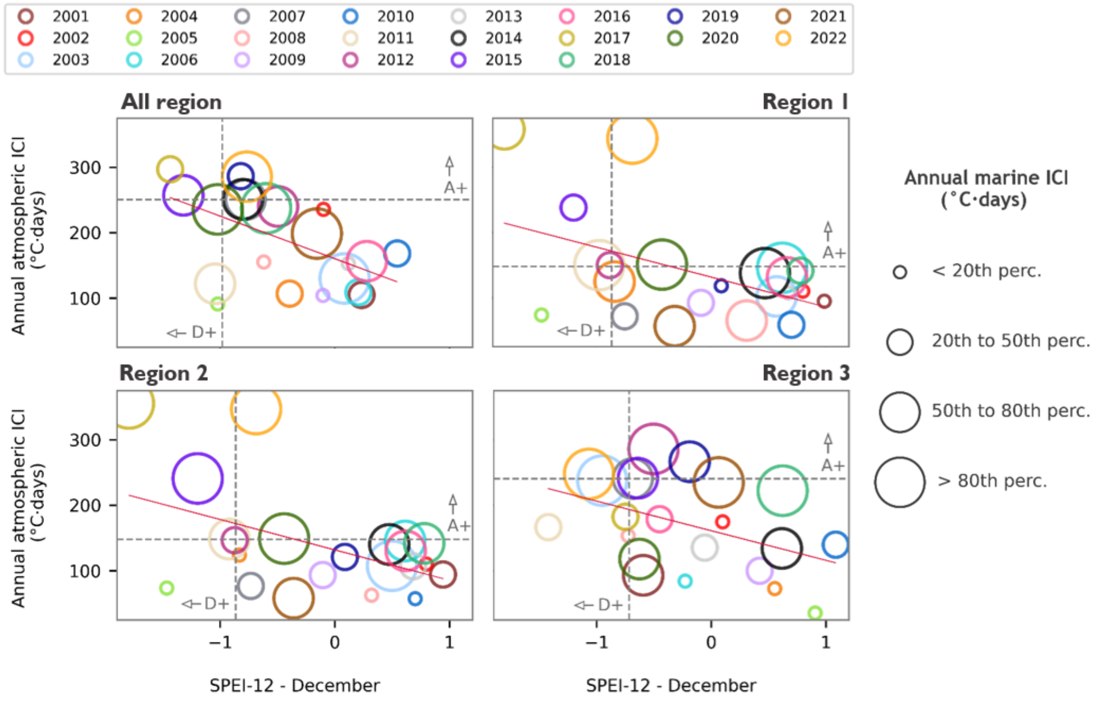
INSTITUTO
DOM LUIZ

Analyze the occurrence of marine heatwaves and the co-occurrence of heatwaves (marine and atmospheric), droughts and fires in the Mediterranean, Western Europe, Ireland, South America and South Africa from a historical and climate change perspective

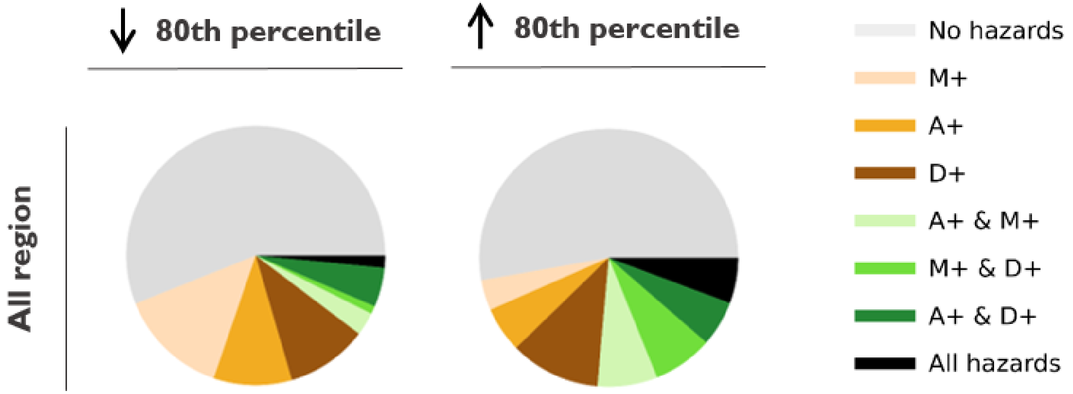
- Plecha SM, Soares PMM, Silva-Fernandes SM et al. On the uncertainty of future projections of Marine Heatwave events in the North Atlantic Ocean. Clim Dyn 56, 2027–2056 (2021).
- Simon A, Plecha S, Russo A, Teles-Machado A, Donat M, Auger P-A, Trigo RM (2022) Hot and cold marine extreme events in the Mediterranean over the period 1982-2021. Frontiers in Marine Science, Agost 2022, vol. 9.
- McCarthy G.D., Plecha S., Charria G., Simon A., Poppeschi C., Russo, A. The marine heatwave west of Ireland in June 2023.
- 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.
- 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.







Fires (burned areas) above



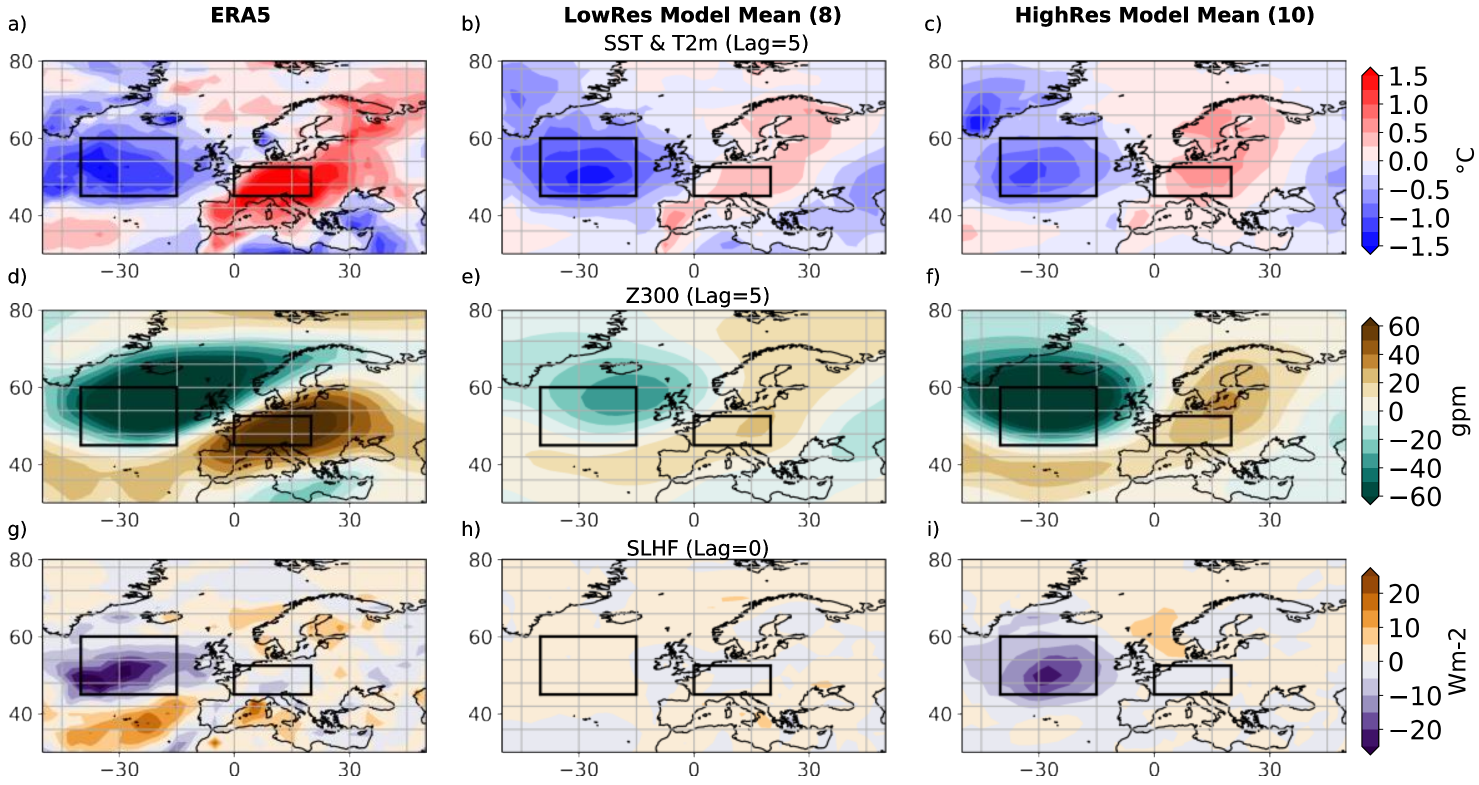
North Atlantic impacts on European temperature extremes

Analysis of ERA-5 revealed a connection between North Atlantic SST anomalies and European temperature extremes in summer.

Climate models with an eddy-parametrized ocean model struggle to represent the connection, likely due to biases in the mean state. Models with eddy-present or eddy-rich oceans are more realistic.

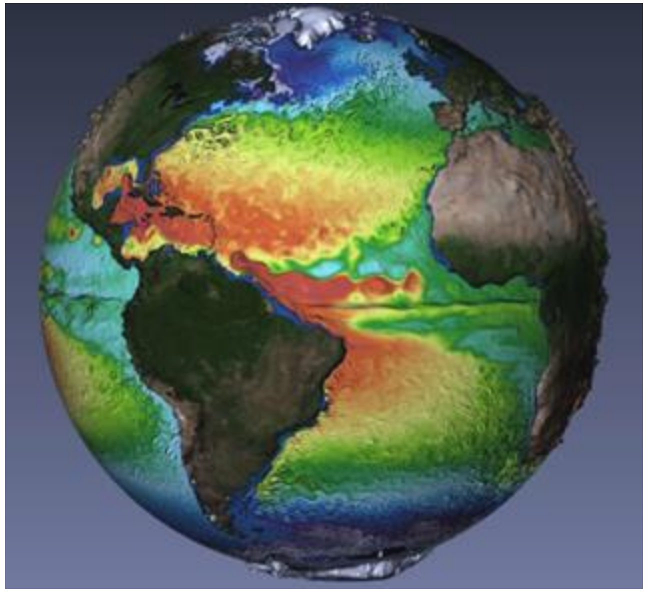
Krüger, Kjellsson, Pilch-Kedzierski, Claus (2023). Tellus A. Doi: 10.16993/tellusa.3235

Krüger, Kjellsson, Lohmann, Matei, Pilch-Kedzierski, in prep.



MPI-ESM-ER "eddy-resolving" climate prediction system

- Ocean component: tripolar grid with 0.1° nominal resolution, 40 z-levels
  Atmosphere component: T127 grid (1°), 95 levels (high-top)

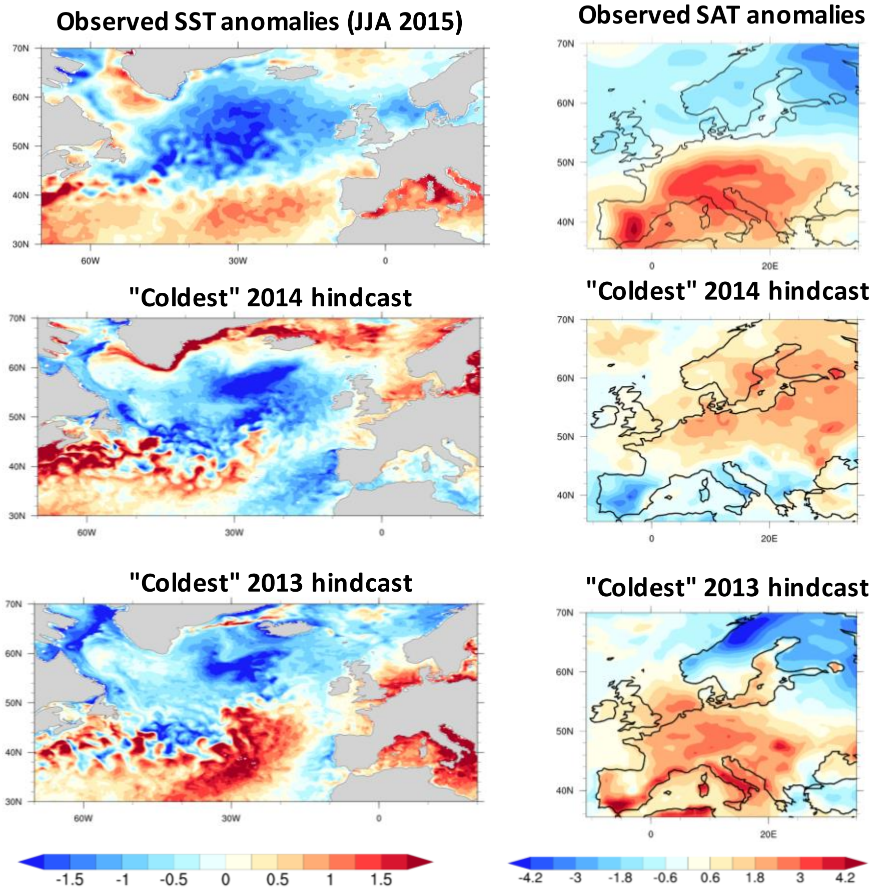


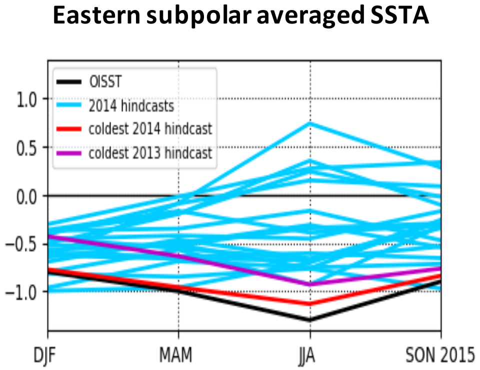
- Initialisation of 3D oceanic T and S anomalies (ORAS4), sea ice concentration (National Snow and Ice Data Center), atmospheric state (ERA40).
- 20 ensemble members initialized in Nov 2014 and 10 ensemble members initialized in Nov 2013.
- 3 ensemble members initialized in Nov every 2nd year between 1992 and 2012 for bias-correction

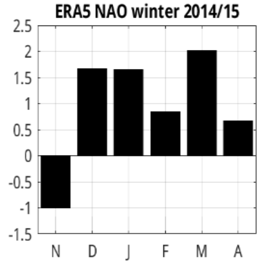
MAX-PLANCK-INSTITUT
FÜR METEOROLOGIE

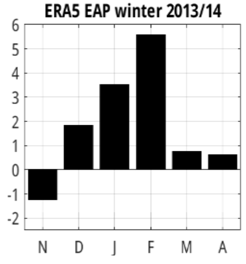
Can we predict impact-relevant recent climate extremes?

Observed and simulated 2015 record summer Cold Blob and European heatwave









- **MPI-ESM-ER prediction system can reforecast the subpolar North Atlantic "Cold Blob" in summer 2015 up to one year ahead.**
- **Individual forecast members could reforecast the full strength and extent of 2015 record "Cold Blob" due to the reproduction of strong positive atmospheric circulation state (NAO/EA).**
- **Individual members could also reforecast the 2015 European heatwave. However, cold subpolar ocean conditions are needed, but are not sufficient. For the exact location of the 2015 European heat waves a warm Mediterranean is key.**

Lohmann, K, O. Gutjahr, J. Jungclaus and D. Matei, 2024 (in prep.)

Extreme cold events in Europe under a reduced AMOC

Virna L. Meccia[1], Claudia Simolo[1], Katinka Bellomo[2,1] and Susanna Corti*[1]
[1]Consiglio Nazionale delle Ricerche (CNR) - Istituto di Scienze dell'Atmosfera e del Clima (ISAC) Bologna, Italy
[2]Politecnico di Torino, Torino (Italy)

1. Introduction

There is a consensus that a weakened Atlantic Meridional Overturning Circulation (AMOC) decreases mean surface temperature in the Northern Hemisphere, both over the ocean and the continents. However, the impacts of a reduced AMOC on cold extreme events have not yet been examined. We analyse the impacts of a reduced AMOC strength on extreme cold events over Europe using targeted sensitivity experiments with the EC-Earth3 climate model.

2. Simulations

- EC-Earth3: IFS T255L91; NEMO ORCA1Z75; LIM3; OASIS3.
- We started from a fully coupled water hosing simulation (Fig. 1) to provide the initial conditions (ICs) and boundary conditions (BCs) for a series of AMIP-like experiments.
- We selected three periods of 11 year duration in which the mean AMOC strength is about 17.5 Sv (*ctrl*), 14 Sv (*a14*) and 7 Sv (*a07*), respectively (Fig. 1).
- We run 20 ensemble members for each of the 3 sets of experiments.

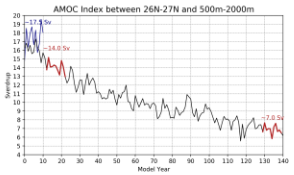


Figure 1: Annual AMOC for the coupled simulation with water hosing. Colours highlight the periods selected as BCs for the three sets of AMIP-like experiments

We considered the first year as a spin-up period to let the model adjust to the IC. The analysis is performed using 10 years for each simulation, thus covering 200 years of data for each set of experiment.

3. Results

3.1 Daily minimum near-surface temperature over Europe

An AMOC weakening yields a cooler winter climate over Europe with increased variability in which the coldest nights are expected to become more extreme (Fig. 2).

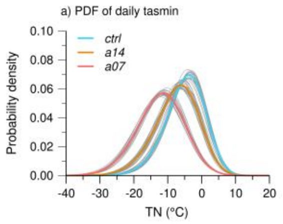


Figure 2: Probability density functions for the boreal winter daily tasmin in Europe.

3.2 The cold spells in Europe

The Cold Spell Duration Index (CSDI) is the count of days with at least six consecutive days when the *tasmin* falls below the 10th percentile in the calendar five day window.

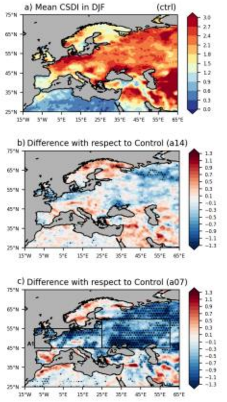


Figure 3: CSDI for DJF. (a) ensemble mean of the ctrl. (b) and (c) difference for a14 and a07 with respect to the ctrl run.

Although cooler mean winters occur with a reduced AMOC (Fig. 1), there are areas in which the CSDI decreases (Fig. 3). The latter occurs in central Europe, Ireland, the southern UK, and Eastern Europe (A1 and A2 in Fig. 3). The composites of geopotential height anomalies at 500 hPa (zg500) for the days belonging to cold spells in A1 and A2 resemble the pattern of the North Atlantic atmospheric blocking (Fig. 4).

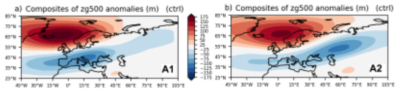


Figure 4: Composites of geopotential height anomalies at 500 hPa (m) for days belonging to cold spell events in the mean areal (a) A1 and (b) A2 for the ctrl experiment.

3.3 The North Atlantic atmospheric blocking

In both experiments with a reduced AMOC, the number of blocked days per winter is reduced in the North Atlantic, Nordic seas, and Greenland. (Fig. 5). We have found that the cold spell events in central and Eastern Europe are associated with a zg500 blocking pattern. We also found that less North Atlantic atmospheric blocking occurs in a climate with a reduced AMOC, which could explain why counting days belonging to extreme cold events in A1 and A2 is also reduced.

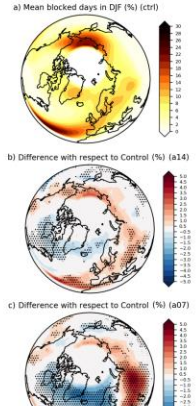


Figure 5: 2D blocking index for DJF. (a) for ctrl experiment, (b) and (c) difference for a14 and a07 with respect to the ctrl.

3.4 The jet stream

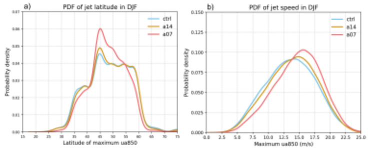
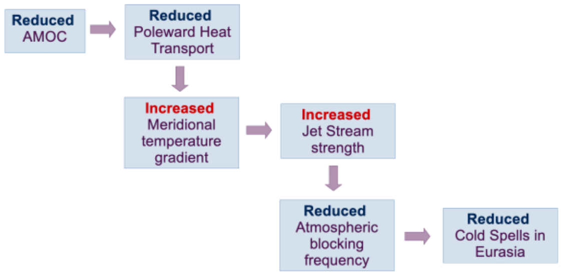


Figure 6: PDFs of (a) the daily jet-stream latitude index and (b) the daily jet-stream speed index for the three sets of experiments.

In a climate with a weaker AMOC, the PDF of the jet latitude index (Fig. 6a) exhibits an enhanced frequency in the central peak at around 45 N. Besides, the jet stream speed is larger in the cases of a weaker AMOC (Fig. 6b).

4. Discussion and conclusion

We have found that a reduced AMOC leads to an average cooling over Europe and intensified cold extremes. However, the frequency of cold spells is reduced. The mechanism we propose to explain this result is cartoned in Fig. 7. During the boreal winter, the cooling at the NH's high latitudes intensifies the near-surface temperature meridional gradient. As a consequence, the jet stream intensifies and tends to stick around 45º N. An intensified jet stream reduces the frequency of atmospheric blocking systems in the North Atlantic and northwestern Europe. Since the North Atlantic blocking during winter is associated with prolonged periods of extreme cold temperatures in Europe, the cold spells there are also reduced.



Reduced AMOC → **Reduced** Poleward Heat Transport → **Increased** Meridional temperature gradient → **Increased** Jet Stream strength → **Reduced** Atmospheric blocking frequency → **Reduced** Cold Spells in Eurasia

Figure 7: Cartoon illustrating the proposed mechanism to explain the reduction of extreme cold events in Europe under a reduced AMOC.

***Contact: s.corti@isac.cnr.it**

Details con be found here:

Meccia, V.L., Simolo C., Bellomo, K., and Corti S. (2024) Extreme cold events in Europe under a reduced AMOC.
Environmental Research Letters, 19, 014054. DOI 10.1088/1748-9326/ad14b0

Royal Meteorological Institute of Belgium
Contributors: David Docquier & Stéphane Vannitsem

- **Liang-Kleeman information flow (LKIF)** method used to identify causal links between different variables of the climate system, including:
  - Drivers of Arctic sea ice using the EC-Earth3 large ensemble (Docquier et al., 2022)
  - Interactions between climate indices of the North Pacific and Atlantic regions from observations and reanalyses (Vannitsem & Liang, 2022; Docquier et al., 2024)
  - Ocean-atmosphere interactions at the global scale using satellite observations (Docquier et al., 2023)
  - Connection of δ^{18}O measured in Antarctic ice cores to observed climate indices and sea ice (Vannitsem et al, in review)

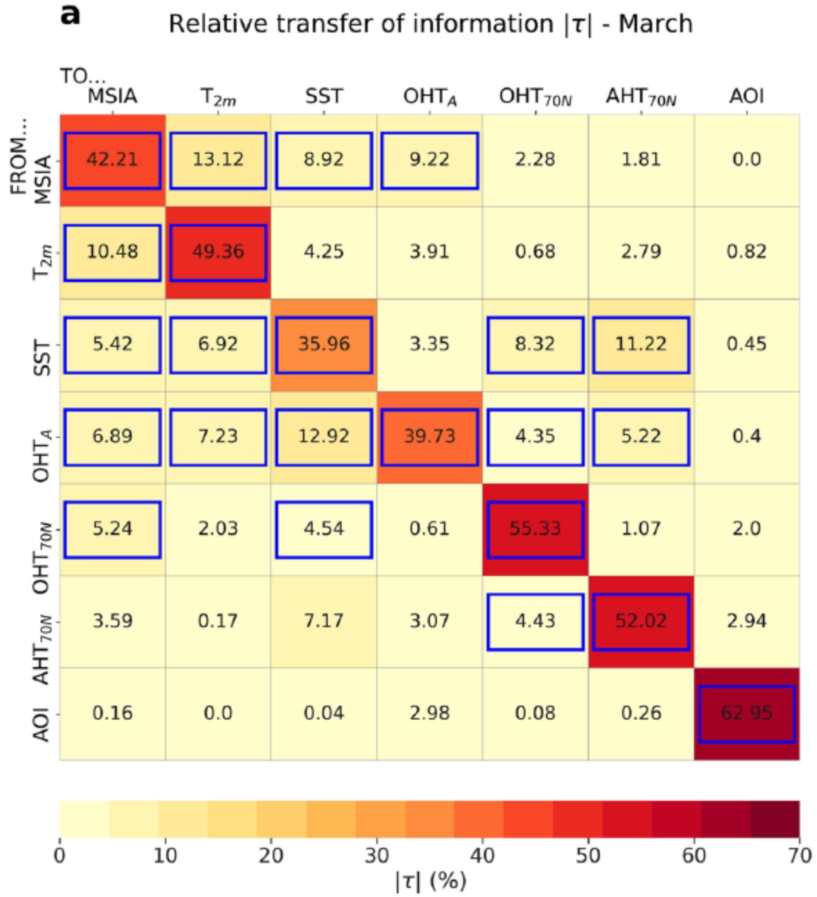
- **Comparison of 2 causal methods** in a linear framework (LKIF and PCMCI): Docquier et al. (2024)

- A **nonlinear version of LKIF** has been developed in ROADMAP (Pires et al., 2024) and applied to a reduced-order atmospheric model (Vannitsem et al., in review); this method will be further tested on real-world case studies in the future

Royal Meteorological Institute of Belgium
Contributors: David Docquier & Stéphane Vannitsem

Drivers of March Arctic sea-ice area

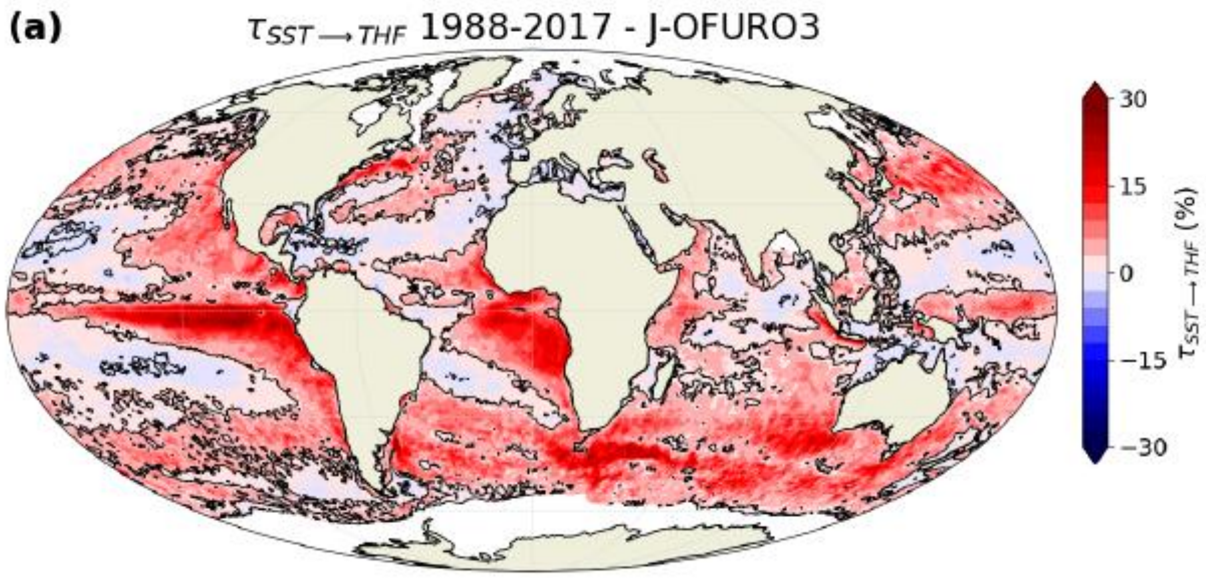
EC-Earth3 large ensemble 1970-2080



FROM... \ TO...	MSIA	T_{2m}	SST	OHT_A	OHT_{70N}	AHT_{70N}	AOI
MSIA	42.21	13.12	8.92	9.22	2.28	1.81	0.0
T_{2m}	10.48	49.36	4.25	3.91	0.68	2.79	0.82
SST	5.42	6.92	35.96	3.35	8.32	11.22	0.45
OHT_A	6.89	7.23	12.92	39.73	4.35	5.22	0.4
OHT_{70N}	5.24	2.03	4.54	0.61	55.33	1.07	2.0
AHT_{70N}	3.59	0.17	7.17	3.07	4.43	52.02	2.94
AOI	0.16	0.0	0.04	2.98	0.08	0.26	62.95

Docquier et al. (2022)

Causal influence of SST on atmospheric turbulent heat flux



Docquier et al. (2023)

Validation of boreal summer tropical–extratropical causal links in seasonal forecasts

Weather Clim. Dynam., 4, 701–723, 2023
https://doi.org/10.5194/wcd-4-701-2023

Validation of boreal summer tropical–extratropical causal links in seasonal forecasts

Giorgia Di Capua[1,2], Dim Coumou[2,3,4], Bart van den Hurk[3,5], Antje Weisheimer[6,7], Andrew G. Turner[8,9], and Reik V. Donner[1,2]

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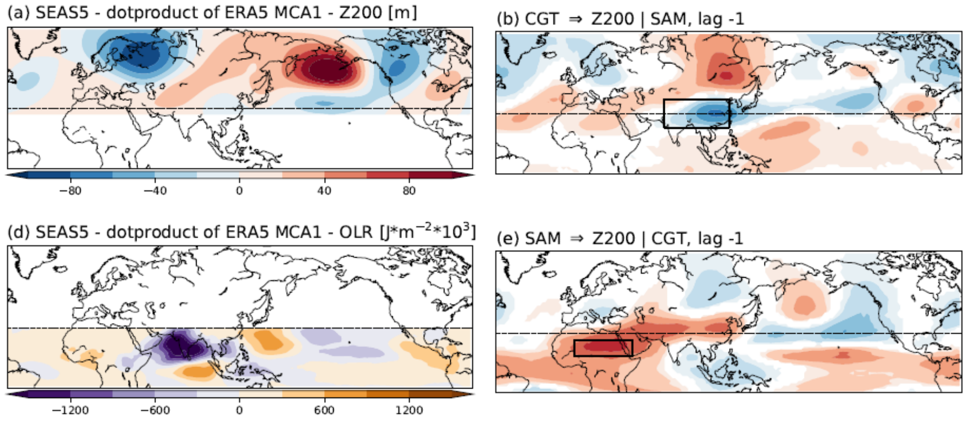
[2]Earth System Analysis, Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, P.O. Box 60 12 03, 14412 Potsdam, Germany
[3]Institute for Environmental Studies (IVM), Department of Water and Climate Risk, VU Amsterdam, Amsterdam, 1081 HV, the Netherlands
[4]Royal Netherlands Meteorological Institute (KNMI), De Bilt, 3730 AE, the Netherlands
[5]Department of Climate Adaptation, Deltares, Delft, 2629 HV, the Netherlands

Collaboration with:
A. Turner, A. Weissheimer

- Relationship between **tropical convective activity** and **mid-latitude circulation** in boreal summer
- Validation of 2D causal links in model and reanalysis
- Model can qualitatively reproduce the causal patterns
- The effect on the ISM on North Africa in consistently underestimated → potentially critical for extremes in the Mediterranean

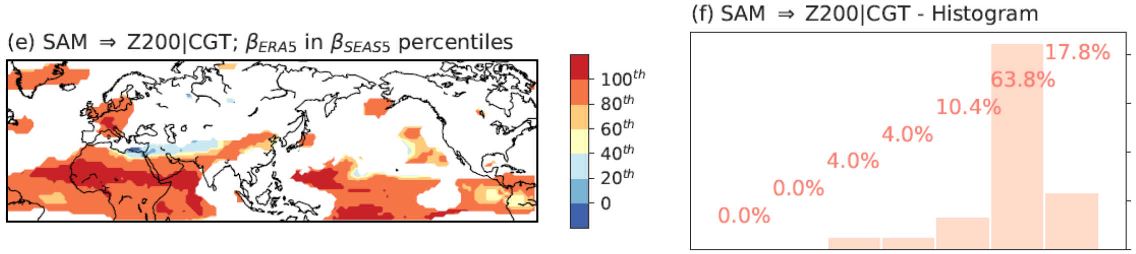


(a) SEAS5 - dotproduct of ERA5 MCA1 - Z200 [m]

(b) CGT $\Rightarrow$ Z200 | SAM, lag -1

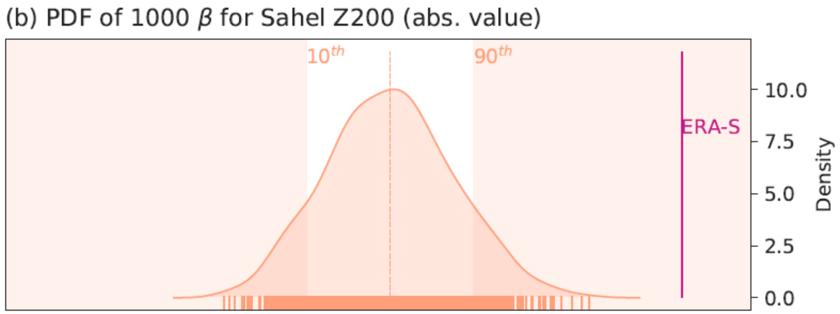
(d) SEAS5 - dotproduct of ERA5 MCA1 - OLR [J*m^{-2}*10^3]

(e) SAM $\Rightarrow$ Z200 | CGT, lag -1



(e) SAM $\Rightarrow$ Z200|CGT; β_{ERA5} in β_{SEAS5} percentiles

(f) SAM $\Rightarrow$ Z200|CGT - Histogram



(b) PDF of 1000 β for Sahel Z200 (abs. value)

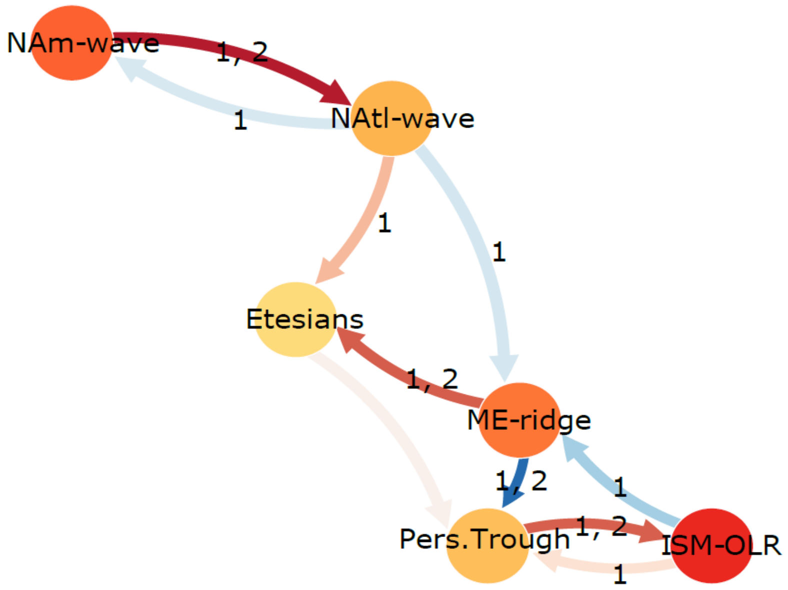
Tropical and mid-latitude causal drivers of the eastern Mediterranean Etesians during boreal summer

(in review in *Climate Dynamics*)

Colaboration with:
E. Tyrlis, D. Matei

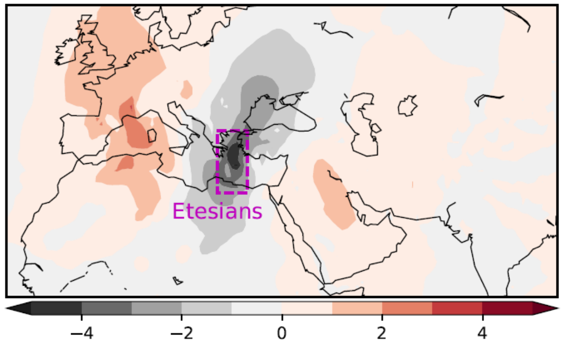
Research stay in Athens (2021, 2022, 2023)

- **Etesians** are important for climate and extremes in the eastern Mediterranean
- Causal links and dynamics of the mid-latitude and ISM influence on the Etesian variability

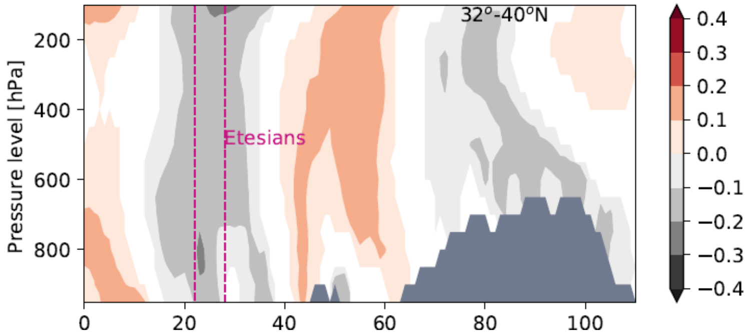


- ISM activity may provide potential for better forecasting heat waves in the Mediterranean

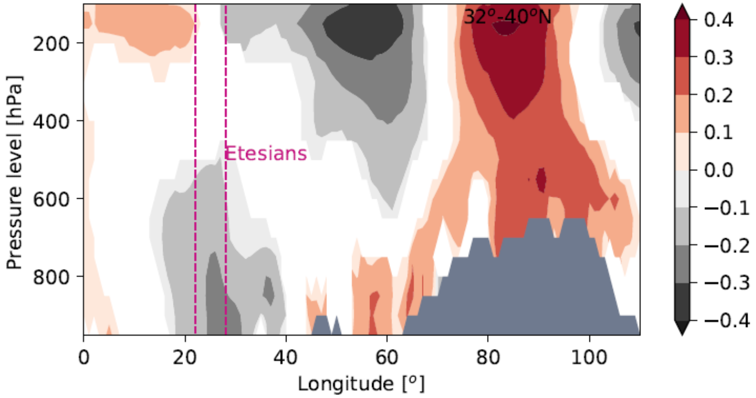
(a) V850 composite [m/s]



(i) NAtl-wave ⇒ V-wind | all, (3-day)



(g) ME-ridge ⇒ V-wind | all, (3-day)



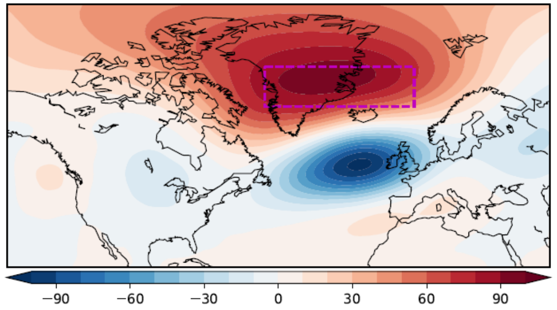
Observed and modelled trends in summer blocking over Greenland: climate change versus multidecadal variability

(in preparation)

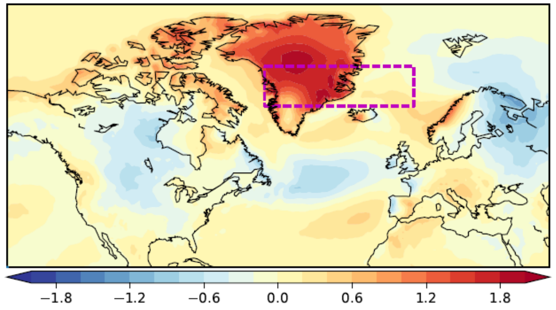
Collaboration with: J. Beckmann and P. Davini (ISAC)

- **Greenland blocking** is projected to decrease but historical trends show and increase

(a) ERA5 - 1979-2022 - Z500 (GHGS > 1. s.d.) [m]

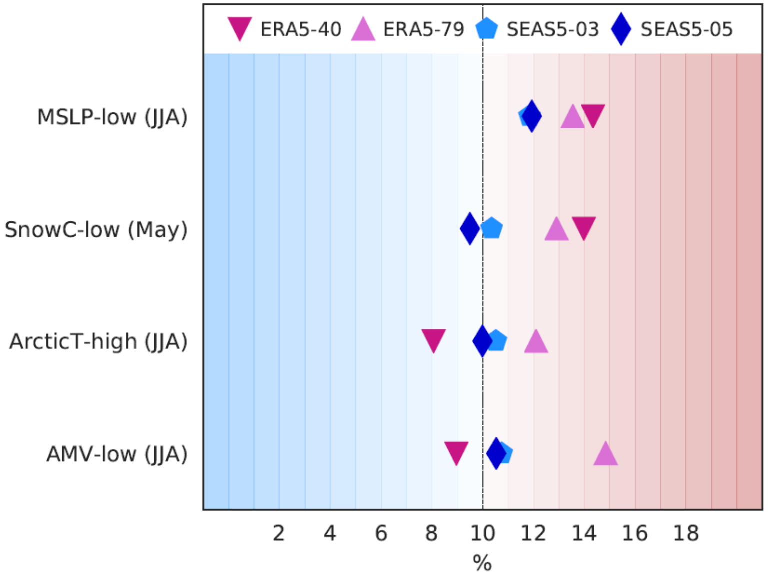


(c) ERA5 - 1979-2022 - T2m (GHGS > 1. s.d.) [K]

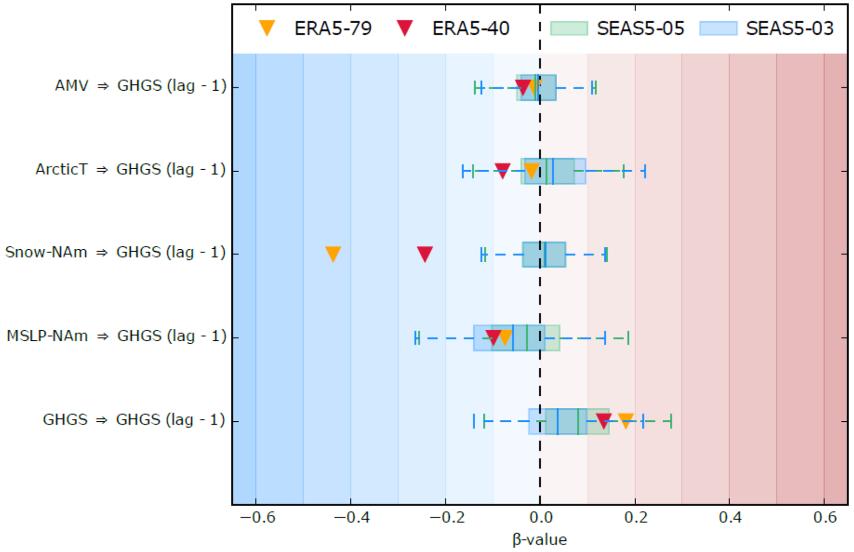


- Models cannot reproduce historical trend → is it a subsampling problem or is something missing in the model?

(e) GHGS (JJA) detrended, 90th quantile



(b) Causal inference - ERA5/SEAS5 comparison, MJJ ⇒ JJA



Methods

Development of new methods to highlight the importance of non-Gaussianity, non-linearity and causality

- Evaluation of the importance of non-Gaussianity and non-linearity in ocean processes (El Niño 3.4 index in the period 1870-2018).
  - Pires CAL, Hannachi A (2021) Bispectral analysis of nonlinear interaction, predictability and stochastic modelling with application to ENSO, Tellus A: Dynamic Meteorology and Oceanography, 73:1, 1-30, DOI: 10.1080/16000870.2020.1866393

- Development and implementation of causality methods

  - Pires C., Docquier D., Vannitsem S. A general theory to estimate Information transfer in nonlinear systems. Physica D: Nonlinear Phenomena, https://doi.org/10.1016/j.physd.2023.133988
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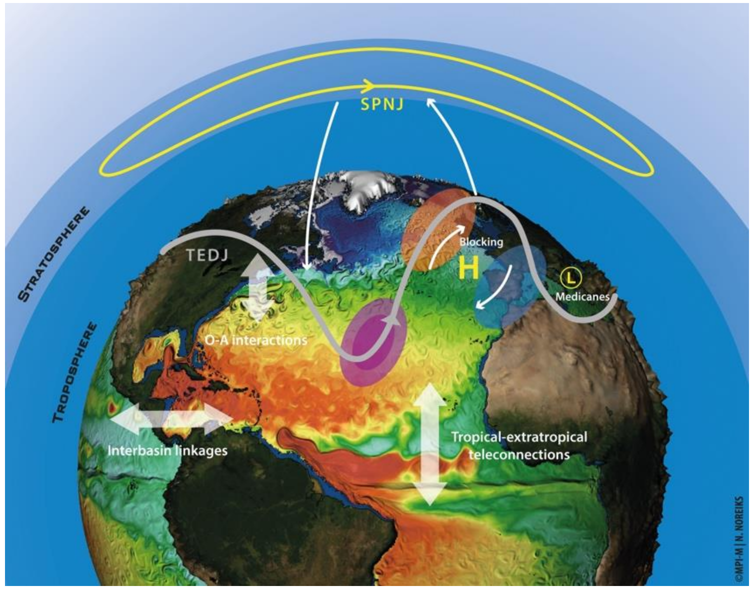
Next Generation Climate Science in Europe for Oceans: End-Term Meeting

Keywords: marine and atmospheric heat waves, teleconnections, western boundary currents, frontal regions, AMOC, AMV and its impacts, tropical-extratropical and interbasin linkages, causal methods, drivers of Artic changes and impacts, “eddy-resolving” climate predictions, Medicanes and tropical cyclones.



ROADMAP impacts:

- *a better understanding of regional climate variability and change, as well as more reliable predictions of regional weather and climate extremes, including statements about the incidence of extratropical cyclones.*
- *More reliable climate predictions and projections can improve disaster prevention as well as adaptation and mitigation strategies; can also make the business sector more resilient and competitive, and optimize stakeholder decision.*
- *ROADMAP ensures the dissemination of its key findings to the scientists, stakeholders, climate services and the general public.*
- *Several perspective papers:*
  - *Windows of opportunity for robust predictions of the Atlantic Meridional Overturning Circulation*
  - *Societal-relevant climate extreme events.*
  - *Climate prediction and services over Atlantic-Arctic Sector*

In Memoriam of Prof. Yongqi Gao

Bergen, May 2019


September 22, Lisbon


June 23, Brussels

THANK YOU!

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