



From Ocean to Atmosphere: Coupled Climate Dynamics and Their Euro- Mediterranean Impacts

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Ocean circulation in Atlantic “memory”: Atlantic Meridional Overturning Circulation (AMOC)

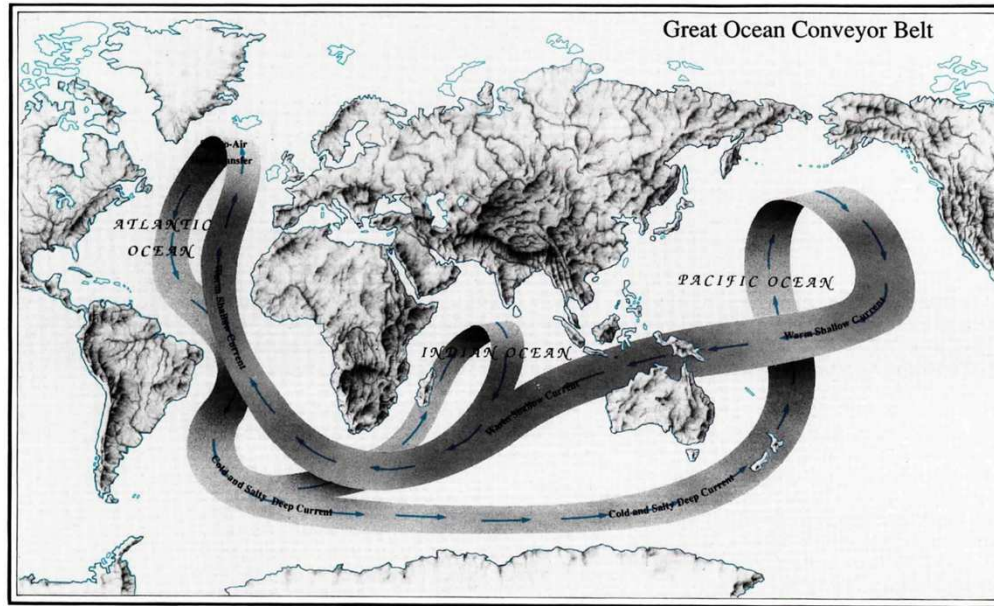


Fig. 1: The great ocean conveyor logo (Broecker, 1987). (Illustration by Joe Le Monnier, Natural History Magazine.)

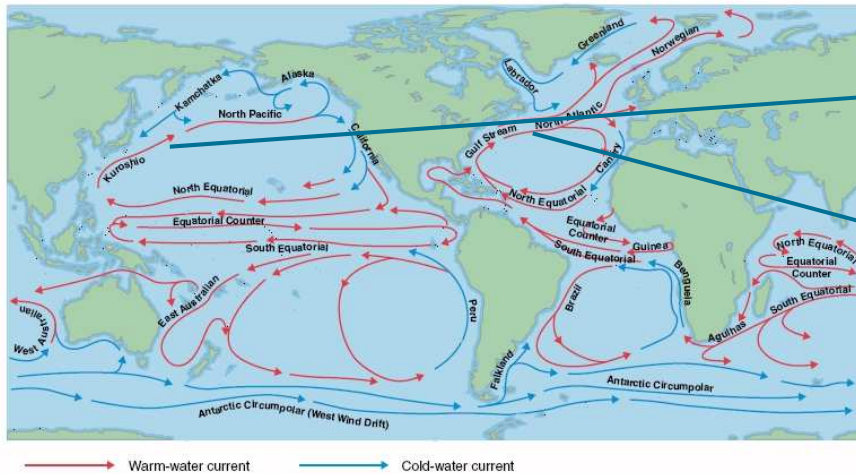
Broecker, W. S. (1991). The great ocean conveyor. *Oceanography*, 4(2), 79–89.
<https://doi.org/10.5670/oceanog.1991.07>

- **Surface branch:** warm and salty waters flow northward; ocean releases heat to the atmosphere
- **Salt import matters:** higher salinity preconditions the subpolar Atlantic for densification
- **Sinking:** cooling + high salinity → dense water → **deep-water formation**
- **Deep return:** cold, dense water flows southward at depth
- **Memory:** slow variability (multi-year → decades)

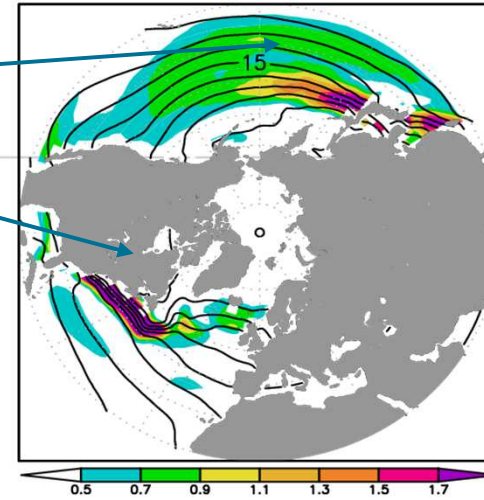


Wind-driven circulation. Gyres

<https://ugc.berkeley.edu/background-content/ocean-circulation/>



SST [C] grad [C/deg] Pac&Atl_Clim
JFM mean Hadl (1950–2008)



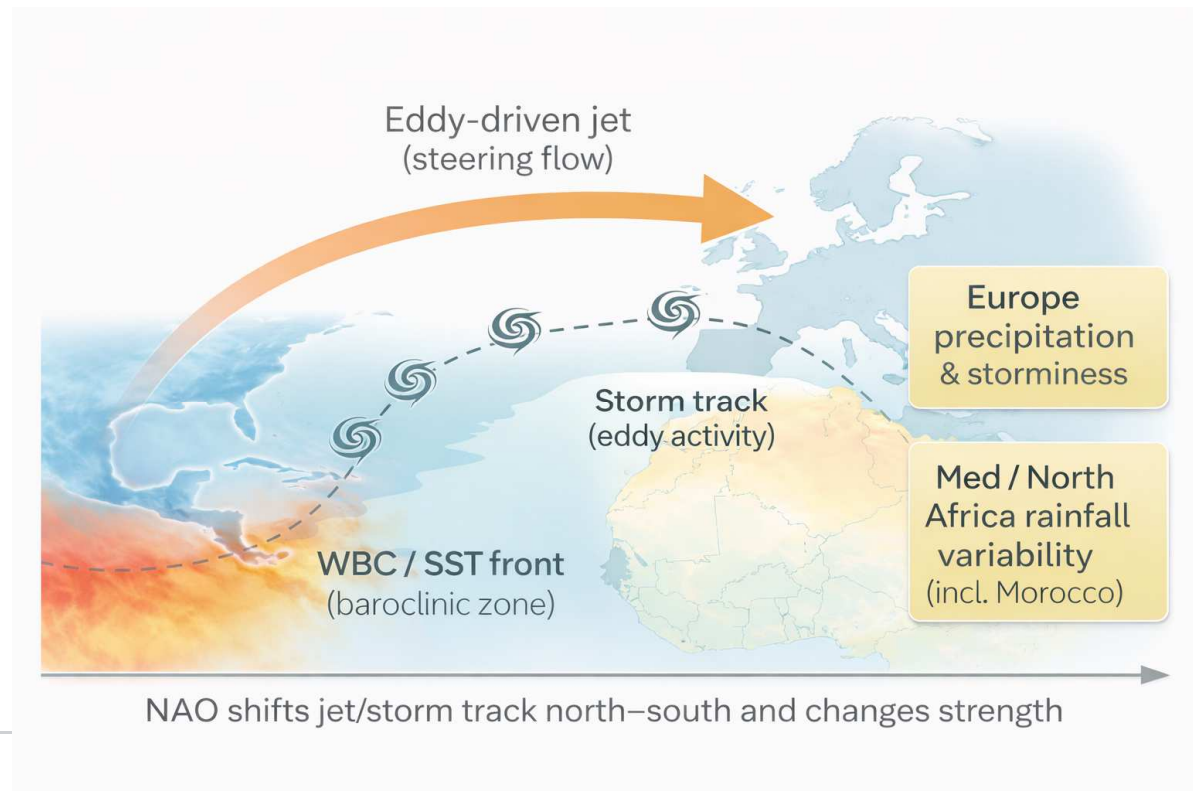
- **Subtropical gyre (clockwise)** → western boundary current **Gulf Stream / Kuroshio** (fast heat conveyor)
- **Subpolar gyre (counterclockwise)** → recirculates colder waters; strong air–sea interaction
- **Meeting zone:** warm WBC + cold subpolar waters → **heat convergence + sharp SST fronts**
- **Why it matters:** SST fronts anchor **eddies/storm tracks/NAO** → Euro-Med & North Africa rainfall



Eddy-driven jet + storm tracks: the moving bridge of storms and precipitation

- › **Eddy-driven jet:** band of strongest midlatitude westerlies (steers storms)
Maintained by **synoptic eddies** (weather systems) that transport momentum
- › **Storm track:** region of frequent/intense cyclones and transient eddies
- › **The transient eddies and storms** pick up moisture and heat from warm pole of oceanic SST-fronts

Storm tracks are usually computed as variance or standard deviation of the high pass filtered (2-12 days) Z200 or V200



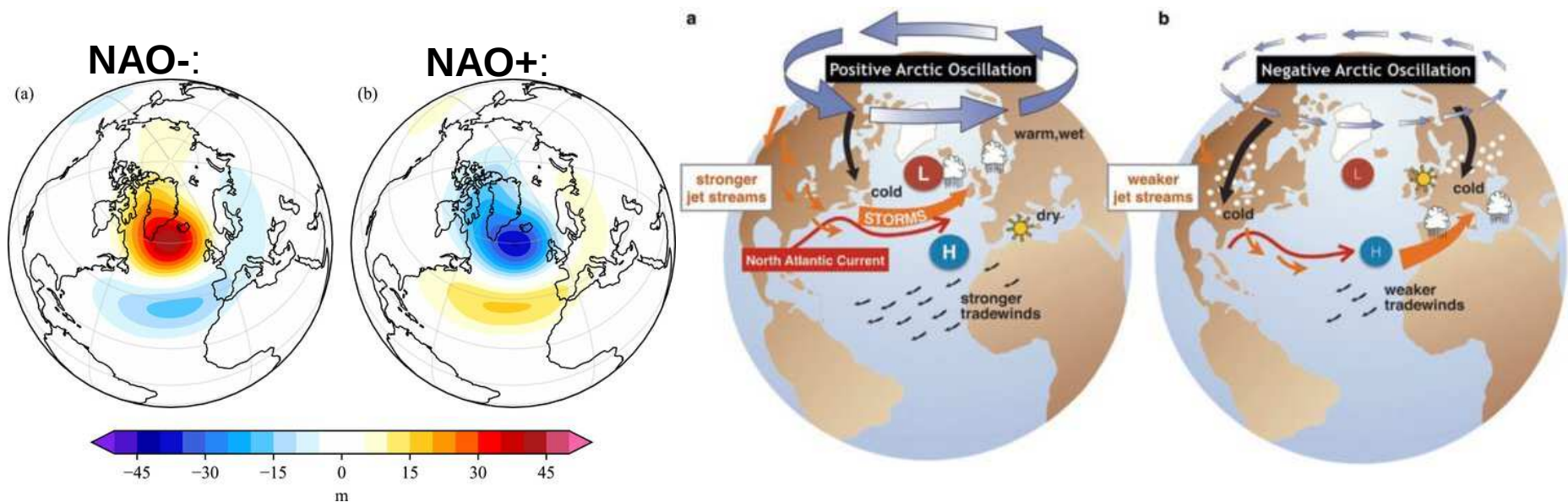


North Atlantic Oscillation (NAO) or Northern Annular Mode (NAM)

NAO: North Atlantic pressure dipole (subtropical Atlantic ↔ Icelandic region) that Captures **westerly jet strength** + **north-south shift** of the eddy-driven jet storm track and precipitation band

NAO+: stronger westerlies; storm track, eddy jet and precipitation band tend to be shifted more northward and North Africa and South Europe tend to dry

NAO-: weaker westerlies; storm track tends to shift southward; more blocking likelihood

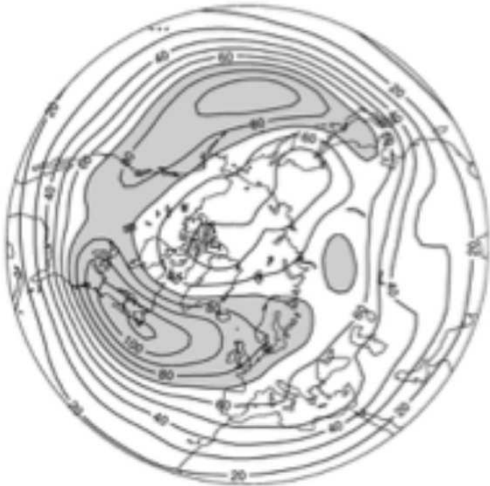




North Atlantic Oscillation (NAO) and Euromediterranean precipitation

Mean Storm Track (DJFM) 1958-1998

$(Z^{-2})^{1/2}$ 300 hPa (gpm)

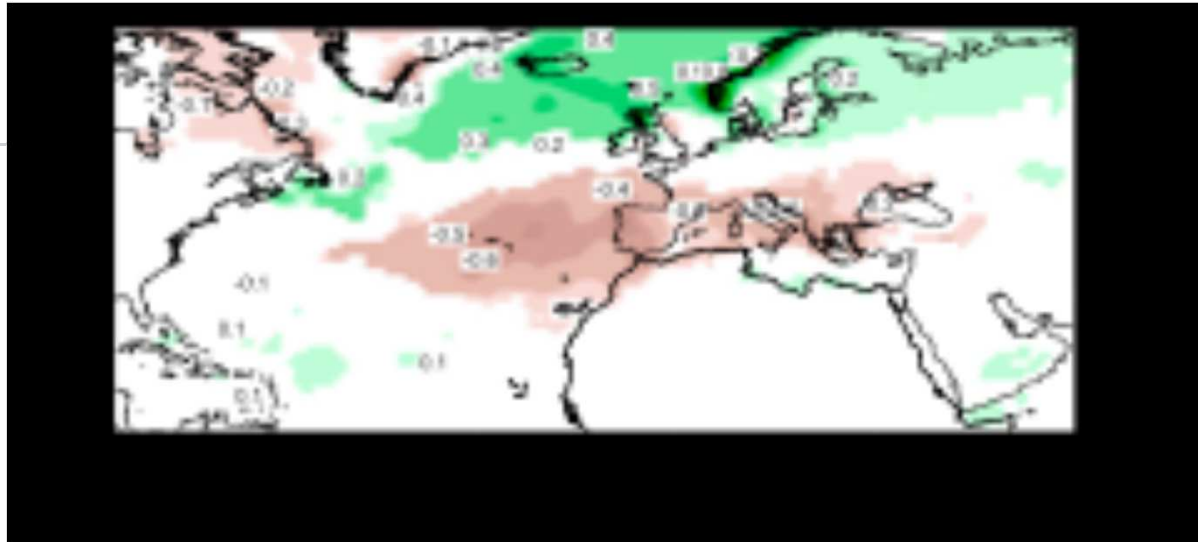


Regression onto NAO Index (gpm)



Hurrell et al. 2003

Seager et al. 2005



Positive (Negative) NAO is associated with poleward (southward) shift of the storm tracks and associated precipitation band

Positive NAO less precipitation and negative NAO more precipitation in the Euro-Mediterranean regions



Stratosphere/troposphere downward coupling

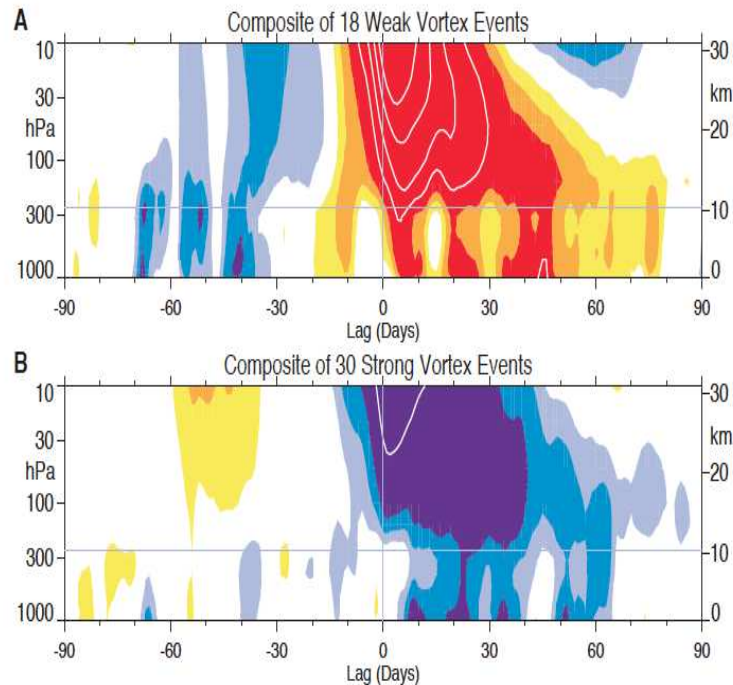


Fig. 2. Composites of time-height development of the northern annular mode for (A) 18 weak vortex events and (B) 30 strong vortex events. The events are determined by the dates on which the 10-hPa annular mode values cross -3.0 and $+1.5$, respectively. The indices are nondimensional; the contour interval for the color shading is 0.25 , and 0.5 for the white contours. Values between -0.25 and 0.25 are unshaded. The thin horizontal lines indicate the approximate boundary between the troposphere and the stratosphere.

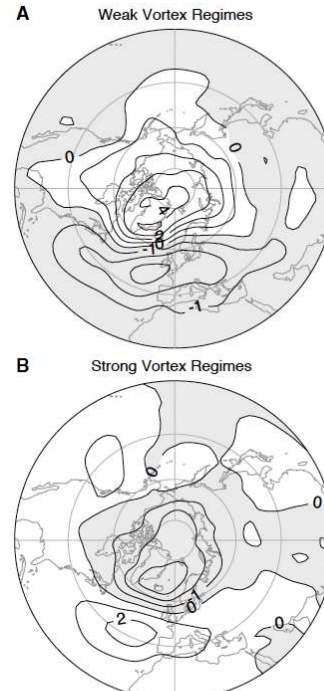


Fig. 3. Average sea-level pressure anomalies (hPa) for (A) the 1080 days during weak vortex regimes and (B) the 1800 days during strong vortex regimes.

In addition to the NAO Northern Annular Mode (NAM) (called also Arctic Oscillation, AO) it is the hemispheric version of NAO

- During positive NAM phase NAOI is mostly Positive: strong Stratospheric polar vortex (SPV) and vice versa for negative NAM phase

Wind anomalies associated with NAM propagate down from Str. Into Trop. Causing changes in the surface climate

The stratospheric dynamics is controlled by planetary waves where the Land/sea thermal contrast is important



Local pathways

- › **SST-fronts controlling the low level atmospheric baroclinicity**, which impact the storm track and eddy-driven Jet (direct impact on troposphere)
- › **land-sea contrast controlling the planetary waves**. This important for the stratospheric tropospheric circulations and their variability.
- › **Storm-tracks and associated tropospheric circulation in response to SST**: can act as source of planetary waves important for the stratospheric circulation and its variability

Remote teleconnections pathways :

- › **Inter-basin extratropical teleconnection**: Changes in the extratropical SST in one basin can lead to changes in the atmospheric circulation in the in other basin through downstream extension of the eddy-driven jet and associated Rossby wave train
- › **Tropical-extratropical teleconnection**: Zonal tropical SST-asymmetry for example associated with ENSO can can impact the Euro Atlantic Climate through tropospheric bridge (Rossby wave train). And stratospheric bridge (upward injection of planetary waves) associated with Aleutian Low

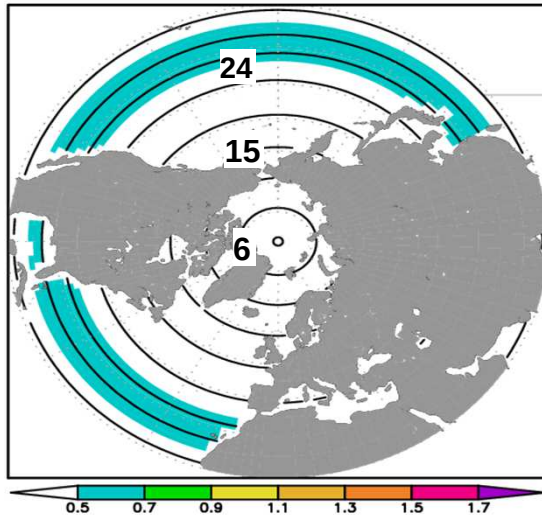


SST-front controlling the low level Baroclinicity

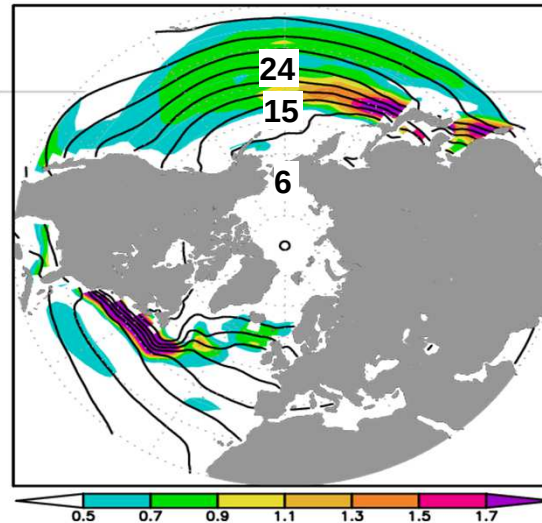


Impact of the SST-fronts: experiments (Atlantic & Pacific SST-fronts) Experimental evidence

a) SST and SST-gradient: NF-experiment (ZUNF)



b) SST and SST-gradient: BCF-experiment (EXT_ALL)



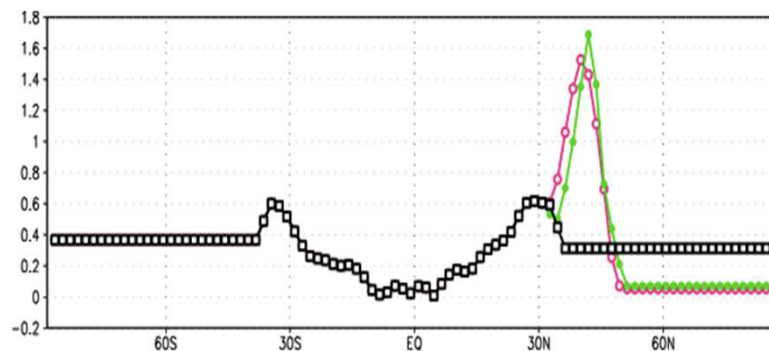
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Key Role of the Ocean Western Boundary currents in shaping the Northern Hemisphere climate

Nour-Eddine Omrani , Fumiaki Ogawa, Hisashi Nakamura, Noel Keenlyside, Sandro W. Lubis & Katja Matthes

c) Zonally averaged SST-gradient in NF-, ASF- and PSF-experiments



- **Goal:** isolate the impact of **midlatitude SST fronts** on eddies/jet/storm tracks
- **Approach:** prescribe SSTs, but **modify the SST gradient** in targeted regions
- **NF (No-Front):** smoothed SST → **weak gradients** (fronts removed)
- **ASF / PSF:** restore a sharp **Atlantic** or **Pacific** SST front (Gulf Stream / Kuroshio extension)
- **Diagnosis:** compare **Front – NoFront** to quantify the atmospheric response



First order impact of the Western boundary current (Omrani et al. 2019)

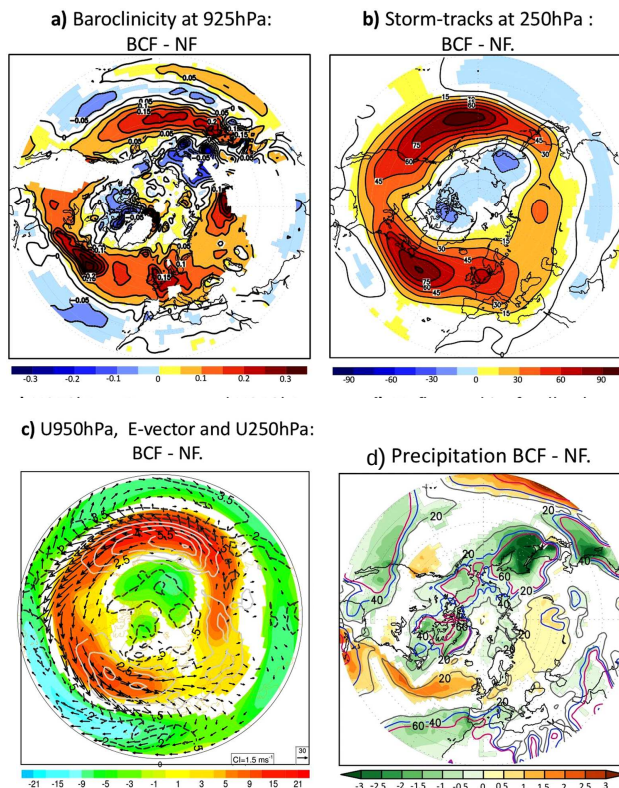
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Response to Both SST-fronts

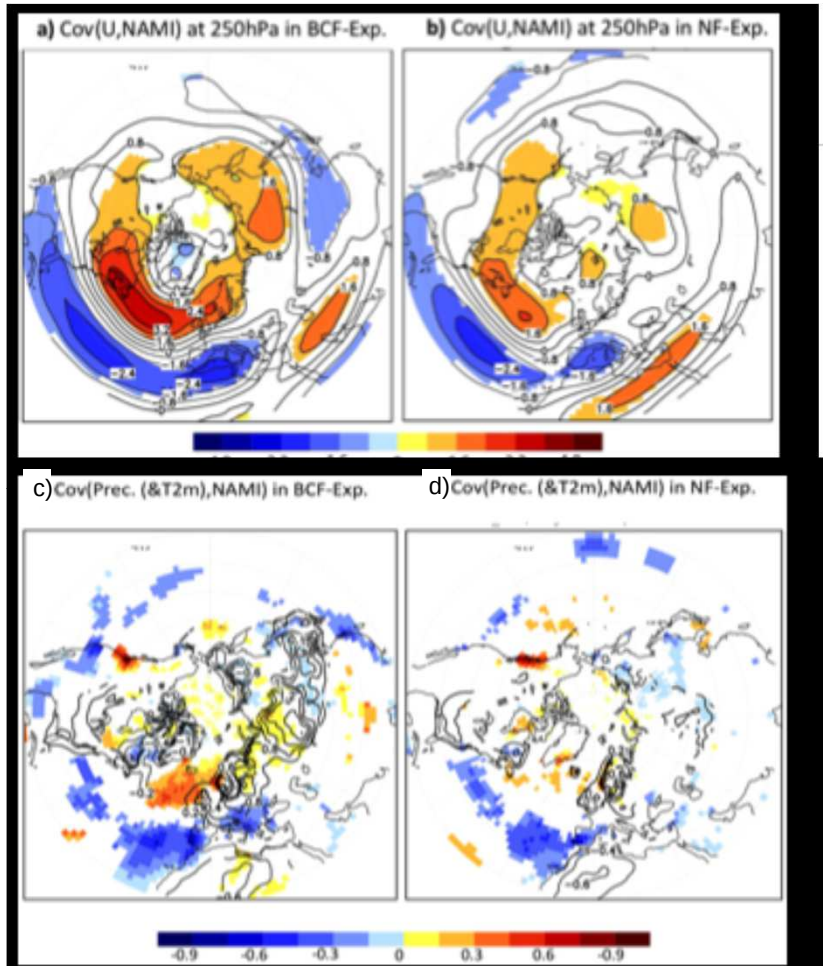


- **BCF – NF isolates** the impact of **WBC/SST fronts** (Gulf Stream + Kuroshio extensions)
- Fronts **restore low-level baroclinicity** (via turbulent heat fluxes) → **stronger storm tracks**
- Storm-track changes project onto an **NAO+–like response** (stronger, poleward-shifted westerlies)
- **Impact (panel d): wetter N/W Europe and drier Mediterranean / North Africa (incl. Morocco)**



Impact of the SST-fronts on the NAM

Response to Both SST-frontts



Western boundary current SST fronts play a crucial role in controlling the variability associated with the NAM:

(a). (b) Without the Oceanic SST-front the Strong westerlies and high zonal annularity of the NAM is more localized, and the westerly anomalies are much weaker

(c) and (d) The strong impact of the NAM on the precipitation is strongly reduced without the SST-fronts



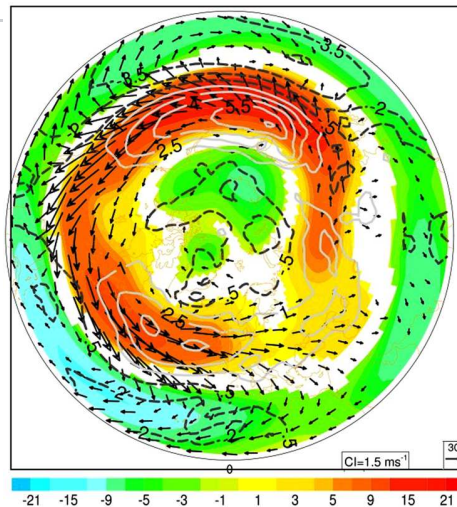
Inter basin teleconnection



Inter-basin teleconnection:

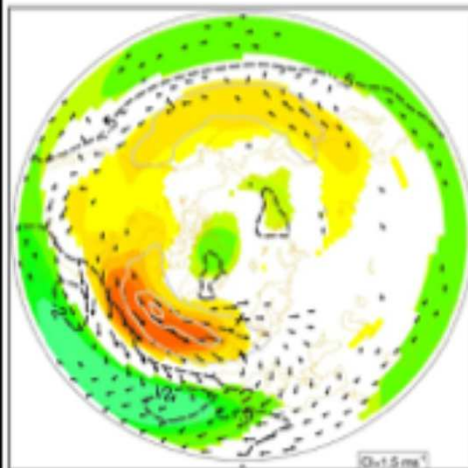
Response to Both SST-fronts

c) U950hPa, E-vector and U250hPa:
BCF - NF.



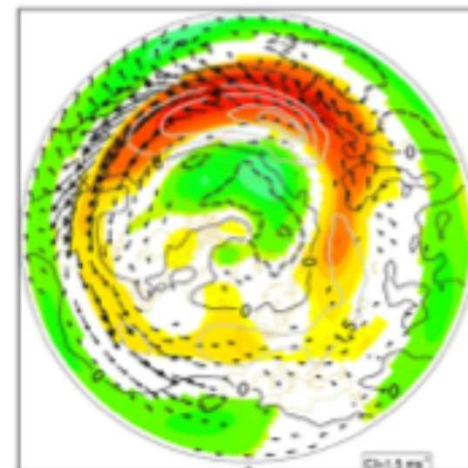
Response to Atlantic SST-fronts

a) U950hPa, E-vector and U250hPa :
ACF - NF.



Response to Pacific SST-fronts

b) U950hPa, E-vector and U250hPa:
PCF - NF.



- Atlantic Front Alone: Intensifies the eddy-driven jet locally and extends upstream into the North Pacific basin.
- Pacific Front Alone: Propagates across North America and directly shapes North Atlantic atmospheric circulation.

Ocean SST fronts in both basins exercise a two-way inter-basin teleconnection, synchronizing storm tracks and eddy-driven jets on a planetary scale.



Impact of the Ocean on the planetary waves



Impact of the SST-fronts on Stratosphere through planetary wave propagation

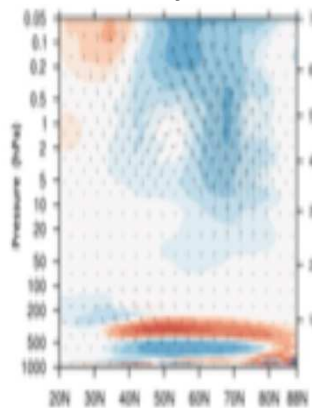
nature communications



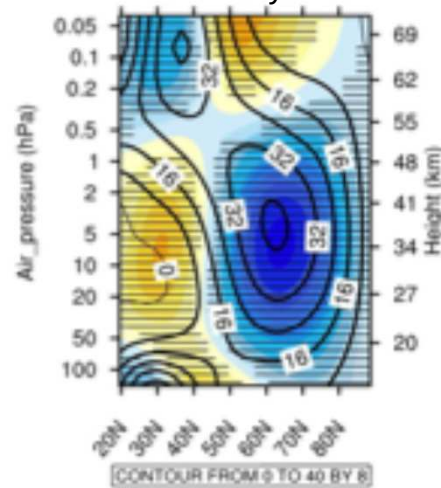
<https://doi.org/10.1038/s41467-026-71998-5>

Response to Both SST-fronts

Planetary waves



Westerly wind

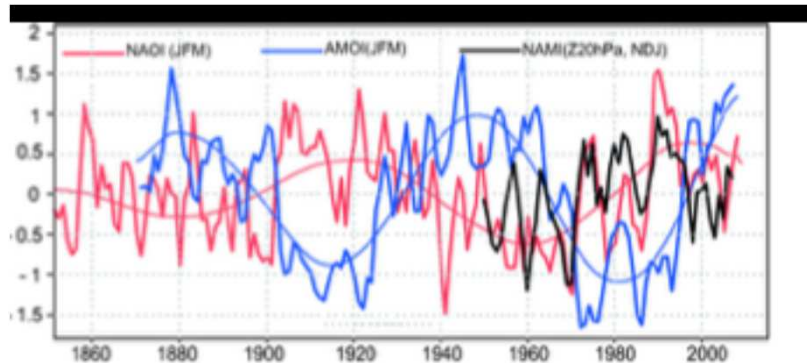


- Through its impact on the storm tracks and eddy-driven jet the SST-fronts generate planetary wave that propagate into the stratosphere and weaken the polar stratospheric Vortex

This wave generation is important to explain the Climatological frequency of Sudden Stratospheric warming in the NH



The coupled NAO AMV Oscillation

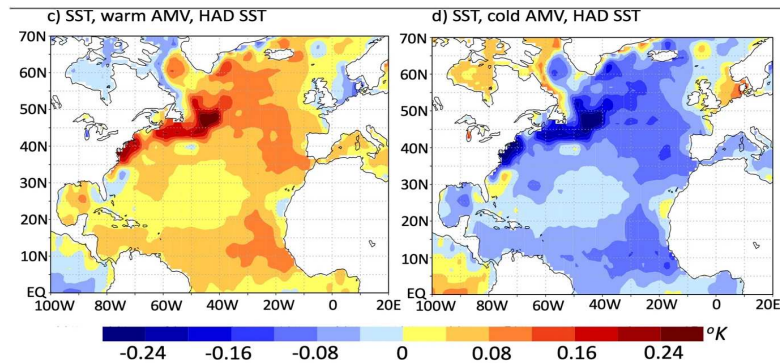


Clim Dyn (2014) 42:649–663
DOI 10.1007/s00382-013-1860-3

Stratosphere key for wintertime atmospheric response to warm Atlantic decadal conditions

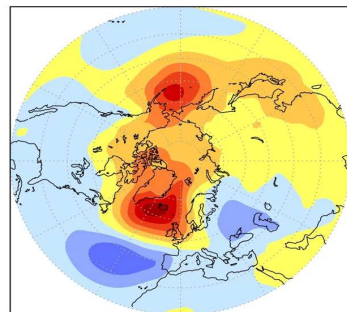
N.-E. Omrani · N. S. Keenlyside · Jürgen Bader · Elisa Manzini

Clim Dyn (2016) 46:1397–1415
DOI 10.1007/s00382-015-2654-6

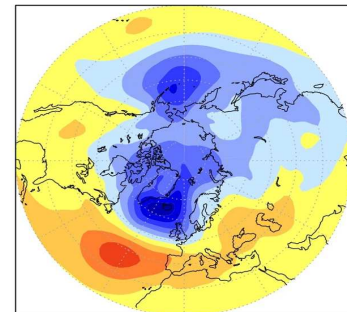


c) SST, warm AMV, HAD SST

d) SST, cold AMV, HAD SST



e) Z1000hPa, negative NAO, 20C NCEP



f) Z1000hPa, positive NAO, 20C NCEP

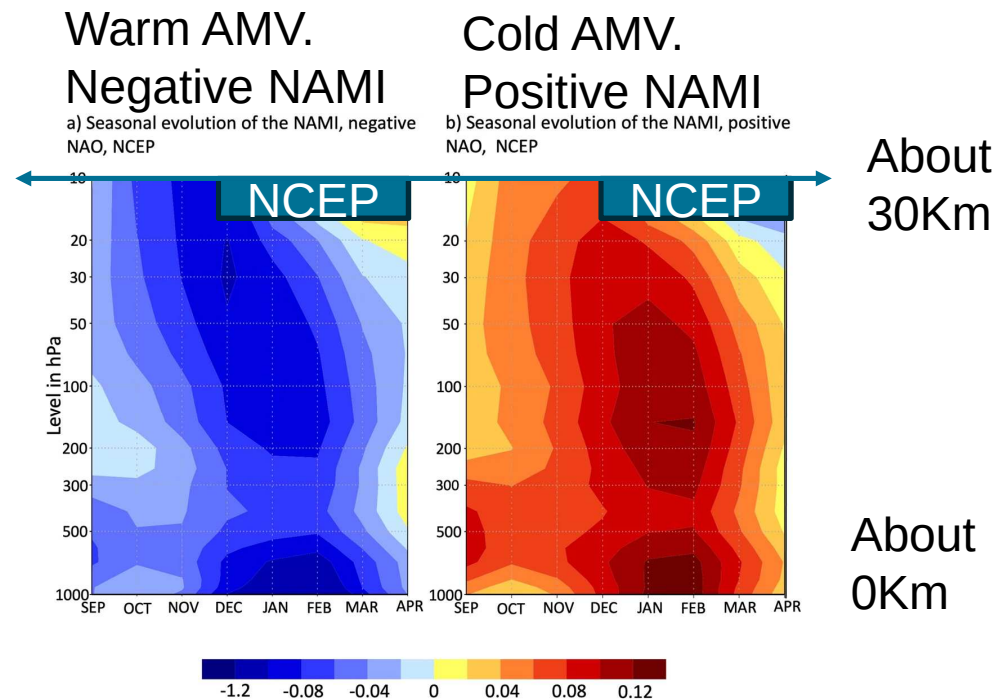
- **Warm AMV:** basin-scale North Atlantic warming (relative to global mean)
- **Cold AMV:** basin-scale North Atlantic cooling
- **Key link:** Warm (Cold) AMV tends to favor **NAO– (NAO+)**
- **Interpretation:** observed multidecadal NAO fluctuations can be viewed partly as a **response to AMV**
- **In Omrani et al. 2014&2015 we showed that** multidecadal NAO–(NAO+) can be seen as **response to warm (cold) AMV**



Role of the stratosphere (NCEP reanalysis)

NAM index is hemispheric version of the NAO and describe the eddy-driven jet and storm tracks in the same way as NAO.

During and after Warm (cold) AMV phase the NAO and NAM tend to be negative (positive) with the signal propagating from the stratosphere into troposphere. This signal is associated with stratospheric warming (cooling)





Mechanisms of the Atlantic Multidecadal Variability: Model simulation (Omrani et. al. 2022)

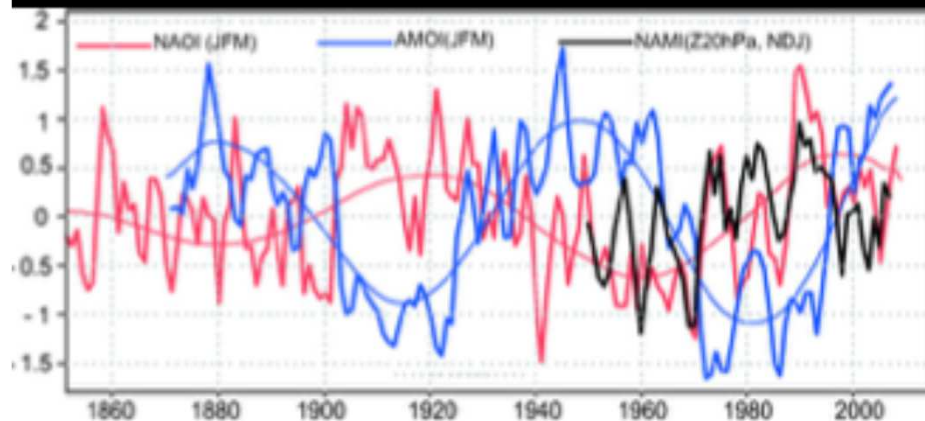
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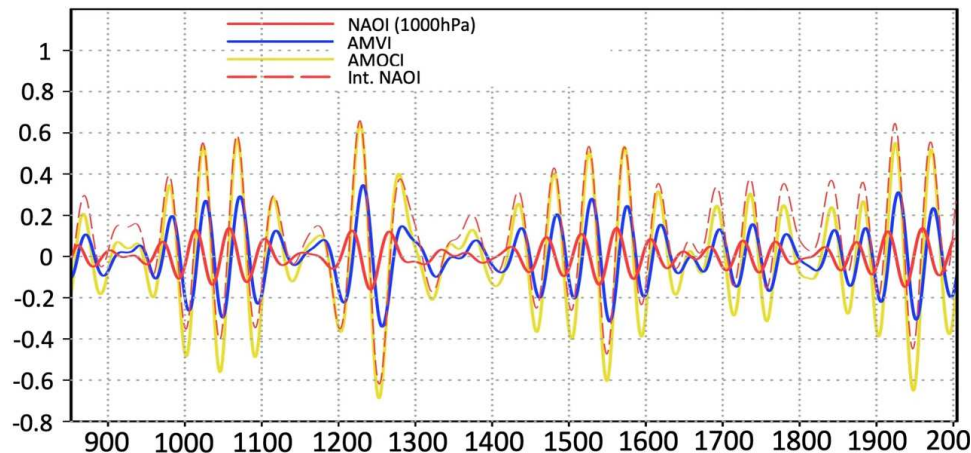
Coupled stratosphere-troposphere-Atlantic multidecadal oscillation and its importance for near-future climate projection

[Nour-Eddine Omrani](#) , [Noel Keenlyside](#), [Katja Matthes](#), [Lina Boljka](#), [Davide Zanchettin](#), [Johann H. Jungclauss](#) & [Sandro W. Lubis](#)

- › Model Simulation: Millennium run (850-2005) using stratosphere-troposphere-ocean coupled MPI Earth System Model (MPI-ESM) forced by reconstructed solar forcing, aerosol, volcano, greenhouse gases and ozone.
- › Statistical methods: Joined Multichannel Singular Spectrum Analysis (MSSA) to extract the coupled Atmosphere/Ocean multi-decadal mode of variability
- › Variables used: SST, AMOC, Z1000hPa (JFM), Z20hPa(NDJ)



Model can simulate a 50 Year coupled NAO, AMV, AMOC Oscillation



Positive NAO

Negative NAO

Strong AMOC

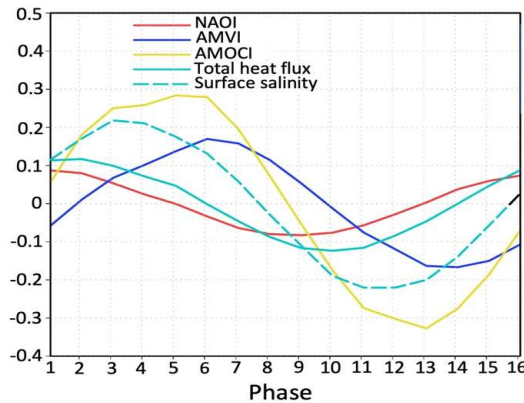
Weak AMOC

Warm AMV

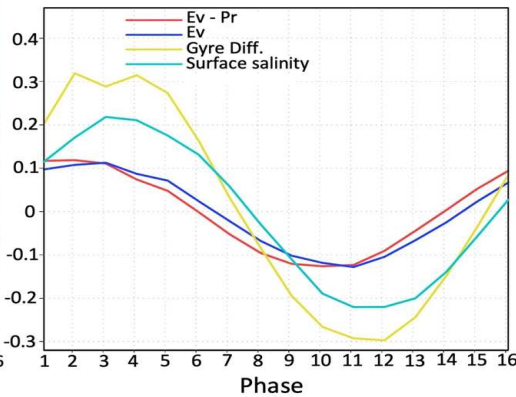
Cold AMV



c) Phase composite, mechanisms of the damped oscillation, model



d) Phase composite, role of salinity, model



Positive NAO

Enhanced density through HF and Salinity

Strong AMOC

Enhanced poleward heat transport by

Warm AMV

Negative feedback



$$\begin{cases} \frac{dAMOC(t)}{dt} = \alpha * NAO(t) - \frac{AMOC(t)}{\tau_{AMOC}} \\ \frac{dNAO(t)}{dt} = -\beta * AMOC(t) - \frac{NAO(t)}{\tau_{NAO}} \\ AMV(t) = k1 * AMOC(t - \tau) \end{cases}$$

Positive NAO

Enhanced density
through HF and
Salinity

Strong AMOC

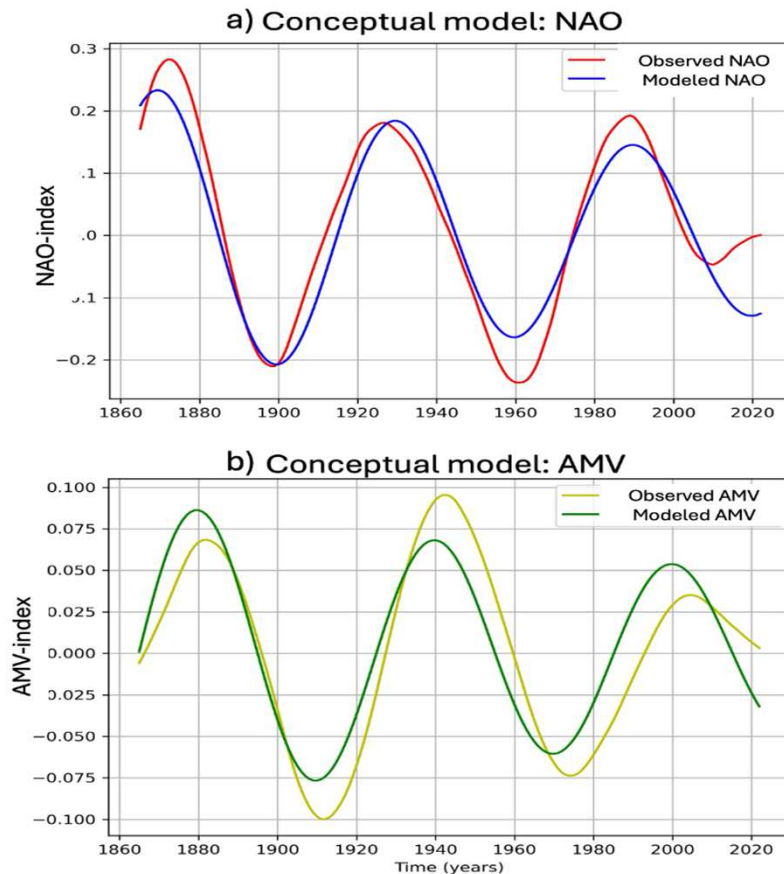
Enhanced
poleward heat
transport by

Warm AMV

Negative feedback



Model can reproduce the observed NAO and AMO



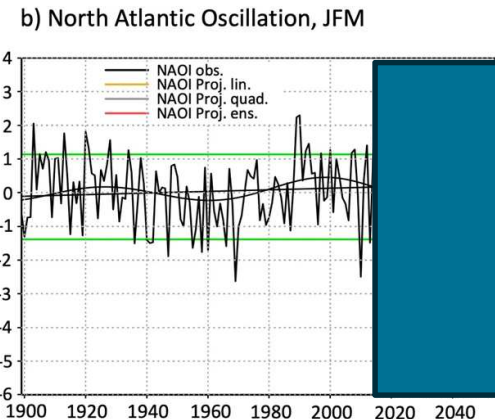
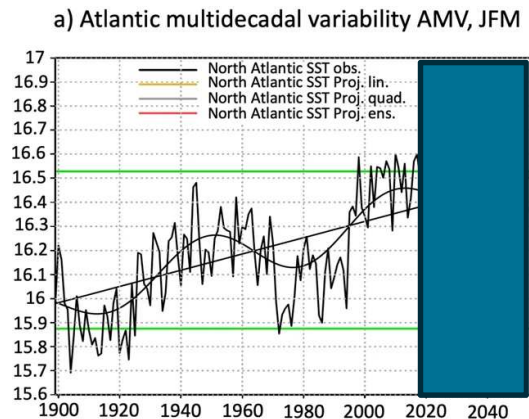
$$\begin{cases} \frac{dAMOC(t)}{dt} = \alpha * NAO(t) - \frac{AMOC(t)}{\tau_{AMOC}} \\ \frac{dNAO(t)}{dt} = -\beta * AMOC(t) - \frac{NAO(t)}{\tau_{NAO}} \\ AMV(t) = k1 * AMOC(t - \tau) \end{cases}$$

The observed predictable AMV and multidecadal NAO can be simulated using a coupled atmosphere/ocean Oscillation model and should be analyzed as multivariate process.

If the external forcing strongly in models affect the simulated AMO or NAO without affecting their coupled variability, the extraction of the observed variability using univariate analysis, as done by Menn et la 2020, can be misleading



Simple empirical projection using lagged regression model based on the coupled **AMV–NAO–sea-ice** framework (Omrani et al., 2022).



AMV: Two low frequency components:

- **Forced trend** (mainly GHG) → long-term Atlantic warming
- **Internal multidecadal variability (AMV)** → modulates the trend (cold AMV offsets, warm AMV amplifies)

• **NAO long term trends are weak:** multidecadal NAO changes and dominate the low-frequency NAO variability

• **Impacts for Morocco:**

• **NAO+** → storm track shifted north → **drier Morocco and West Med. Conditions**

• **NAO–** → storm track shifted south → **wetter Morocco and Med. Conditions**

› **Extremes (green lines = 5th/95th percentiles):**

› **NAO < 5th** → high likelihood of **extrem wet winters** in Morocco/Med

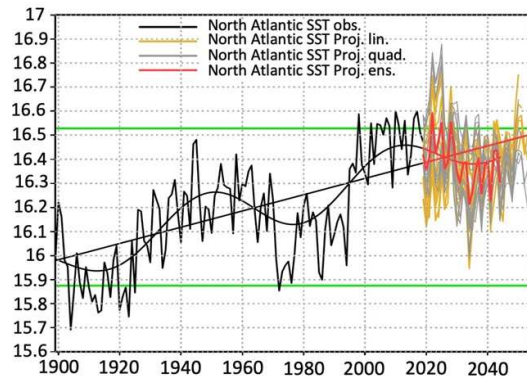
› **NAO > 95th** → high likelihood of **drought in wintertime**



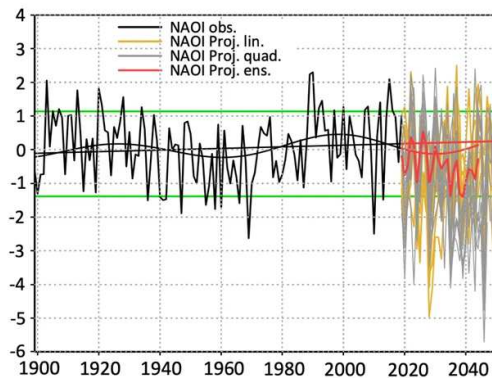
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a) Atlantic multidecadal variability AMV, JFM



b) North Atlantic Oscillation, JFM



Simple empirical projection (lagged regression) based on the coupled AMV–NAO–sea-ice framework (Omrani et al., 2022).

- AMV:** projection suggests a shift toward a **cooler AMV phase**, which will partially **offset the forced Atlantic warming** over the next decades.
- NAO:** projection suggests **more negative NAO conditions** → higher probability of **wetter winters in W. Euro-Mediterranean**.



What drive the coupled AMOC/NAO-Oscillation?

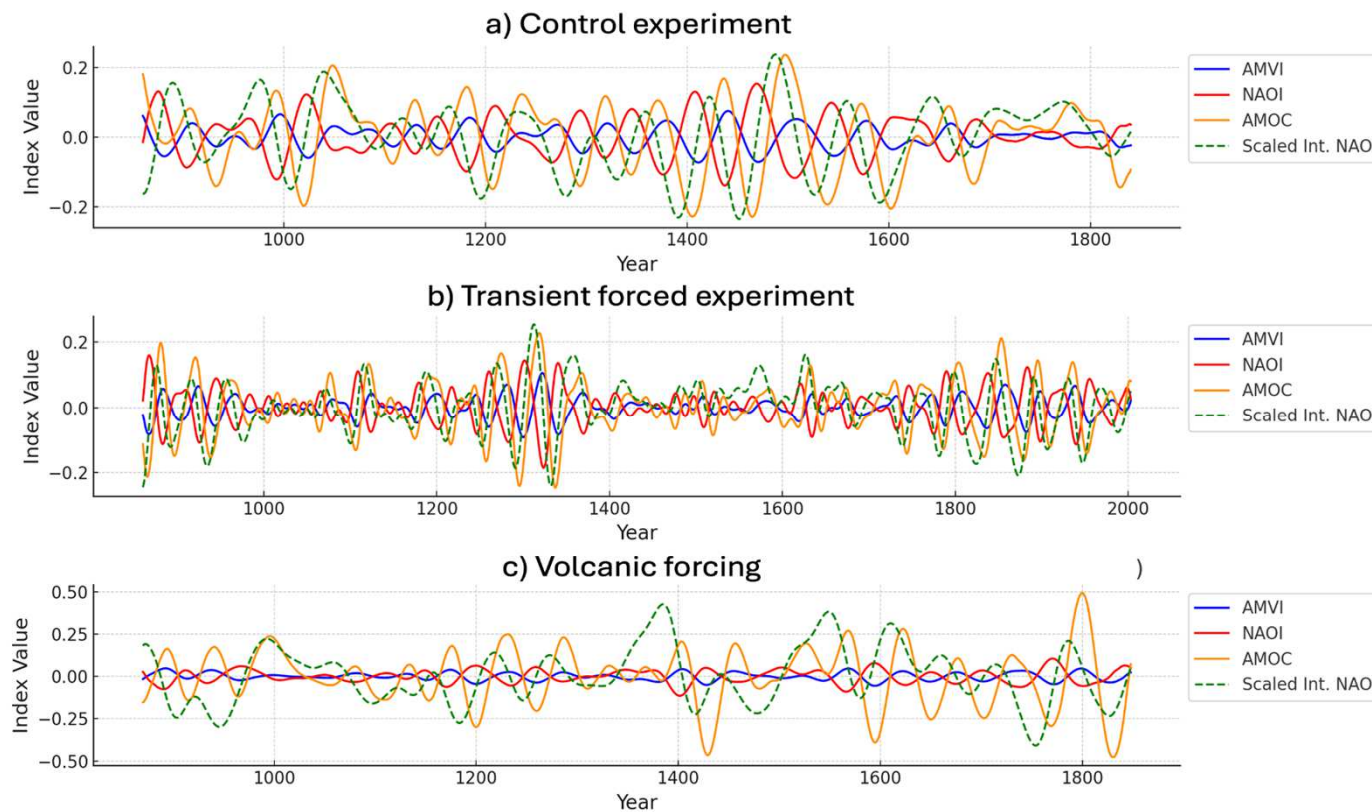
Atlantic Multidecadal Variability is analyzed using multivariate Singular Spectrum Analysis analysis (MSSA) applied to the multivariate fields composed from Z20hPa (NDJ), SLP(JFM), SST(JFM) and AMOC

Model experiments (NorESM):

1. Preindustrial (control, no external forcing)
2. Transient forced experiment with all external forcing (GHG + aerosols + solar + volcanos)
3. Volcanic-only forcing



Coupled Oscillation In NorESM and Role of external forcing versus internal variability



An Oscillation with period of about 66 year can be simulated without external forcing.

In all forcing experiment the oscillation can still be simulated, but the period became shorter (about 45 year)

The volcanic primarily affects the AMOC, but fails to fully activate the atmosphere ocean feedback



- › The ocean impacts the atmosphere through:
 - › (1) SST fronts that enhance baroclinicity and the storm track, impacting the eddy-driven jet and NAM variability and (2) Planetary waves that impact the stratosphere and therefore also the troposphere, through downward stratosphere-troposphere coupling.
- › Observational data show a coupled multidecadal NAO-AMV fluctuation, with the NAO driving the observed AMV (e.g., Edden and Young, 2002) and the AMV driving the multidecadal NAO (e.g., Omrani et al., 2014).
- › Stratosphere-resolving MPI-ESM model simulations indicate that the mechanisms of AMV-NAO coupling involve the AMOC and stratosphere-troposphere coupling.
- › A coupled NAO-AMV conceptual model based on these established mechanisms can reproduce the observed multidecadal NAO and AMV fluctuations.
- › A model based on lagged linear regression projects North Atlantic cooling and a tendency toward negative NAO.
- › Comparison of the coupled oscillation across different coupled-model configurations shows that the coupled NAO/AMV oscillation can occur without transient external forcing; combined external forcing only modulates the periodicity of the oscillation.



Thank you!