Improved simulation of extratropical North Atlantic atmosphere–ocean variability in HighResMIP models

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Motivation

- Climate models generally misrepresent extratropical atmosphere–ocean interactions, which can lead to biases in the simulated mean state and *variability* of the ocean and atmosphere in the North Atlantic region (e.g., Simpson et al. 2018).
- May be related to issues in climate model *predictions*, such as the signal to noise problem (e.g., Scaife et al. 2018)
- Increased model resolution leads to improved simulation of (for example):
  - *Mean* SSTs, extratropical jet, and atmospheric blocking in the North Atlantic (e.g., Athanasiadis et al. 2022)
  - The *variability* of SSTs and air–sea heat fluxes over the Gulf Stream region (e.g., Small et al. 2019, Bellucci et al. 2021)
  - The atmospheric response to Gulf Stream variability (Famooss Paolini et al. 2022)

What are the primary impacts of increased model resolution on the simulation of *large-scale, extratropical atmosphere–ocean variability* in the North Atlantic?

Model output & Methods

- Analyzed extratropical North Atlantic atmosphere–ocean variability in the HighResMIP simulations:
  - *Historical* (1950-2014) and *control* simulations (100 years of output with constant external forcings)
  - Focused on models with > 1 member (ECMWF, EC-Earth and HadGEM).
  - Compared simulations with ERA5 reanalysis (1959–2020) when possible
  - Remove linear component of global mean SST for ERA5 and historical runs, and linear trend for control runs.

LR: ocean model horizontal resolution = 1.0°, atmospheric model horizontal resolution ≥ 0.5°
HR: ocean model horizontal resolution = 0.25°, atmospheric model horizontal resolution < 0.5°

Institute	Model Name	Atm. (~km)	Ocean (~km)	# members (historical)	# members (control)
ECMWF	ECMWF-IFS-LR	50	100	8	1
	ECMWF-IFS-HR	25	25	6	1
EC-Earth	EC-Earth3P	70	100	3	3
	EC-Earth3P-HR	35	25	3	3
MOHC	HadGEM-GC31-LL	135	100	8	1
	HadGEM-GC31-HM	25	25	3	1

Improved simulation of large-scale SST variability in the high-resolution (HR) models

- There is a severe bias in the leading EOF of extratropical wintertime SST anomalies and the associated SLP anomalies in the LR models, which is largely reduced in the HR models (Fig. 1a)
- The overestimated subpolar SST anomalies in LR models is related to the low-frequency component of variability (Fig. 1b)
- The large-scale atmospheric forcing by the NAO is broadly similar in LR and HR models (Fig. 2), which suggests that the ocean heat flux convergence anomalies may be overly strong in the LR models.
- Results below are for historical runs (similar for control runs).

Fig 1. MSLP and SST regressed onto PC1 of North Atlantic SST anomalies

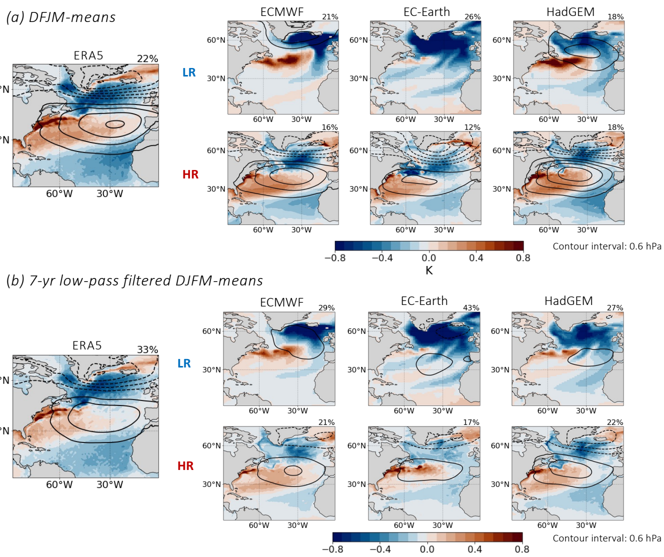
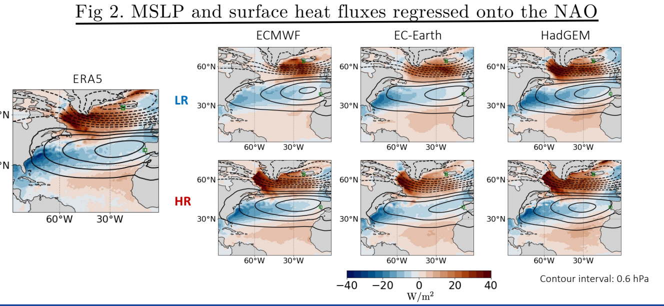


Fig 2. MSLP and surface heat fluxes regressed onto the NAO



The role of the upper-ocean circulation

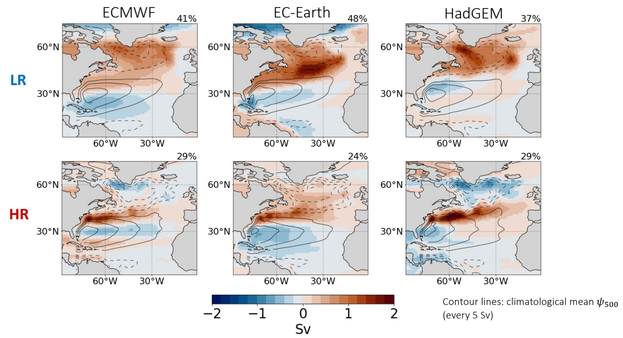
- Here it is shown that the anomalous upper-ocean horizontal circulation, as quantified by an anomalous upper-ocean streamfunction, ψ'_{500}, likely plays an important role in explaining the biased subpolar SST variability in LR models.
- ψ_{500} is calculated like the barotropic streamfunction (e.g., Marzocchi et al. 2014), except the integration is only over the upper 500m:

$$\Psi_{500}(x,y) = \int_{x}^{x_L} \int_{-500}^{0} v(x,y,z)\,dz\,dx'$$

x_L: eastern boundary (land)
v: meridional current

- Results below are for 7-year low-pass filtered annual-mean anomalies from the *control runs.*
- Simulated currents are not compared with ocean reanalyses due to sparse/limited observational record of ocean currents, particularly below the surface.

Fig 3. EOF1 of upper-ocean streamfunction anomalies, Ψ'_{500}



- In the HR models, EOF1 of ψ'_{500} is associated with variability of Gulf stream current, whereas in the LR models, EOF1 of ψ'_{500} is associated with variability of the subpolar gyre (Fig. 3)

Fig 4. Multi-model mean autocorrelations

- The LR models strongly *overestimate* the persistence of PC1 of SST and subpolar SSTs (Fig 4. a,c).
- PC1 of ψ'_{500} and subpolar ψ'_{500} are also more persistent in the LR models compared to the HR models (Fig. 4 b,d).
- NAO is *not* more persistent in LR models (Fig. 4e).
  - Is there a stronger *delayed* response of the oceanic circulation to the NAO in the LR models?

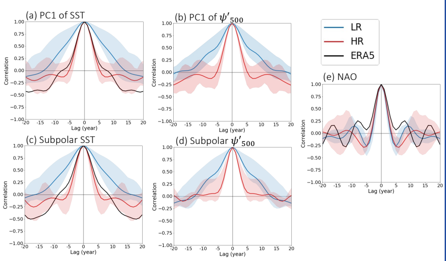
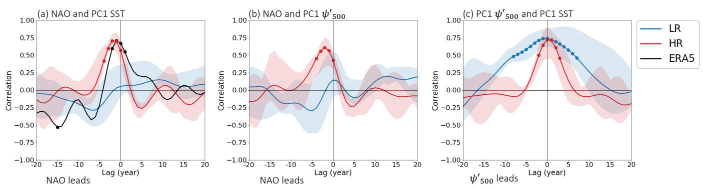


Fig 5. Multi-model mean cross-correlations



- *The ocean circulation-driven SST variability in the LR models has no apparent link with the NAO* (Fig. 5b,c)
  - "intrinsic" oceanic circulation variability.
- *The improved NAO–SST relationship in the HR models (Fig. 5a) is likely related to a reduction of intrinsic variability of the upper-ocean circulation, but also an improved response of the upper-ocean circulation to the NAO* (i.e., NAO-driven Gulf Stream variability is stronger in the HR models compared to the LR models).

Conclusions & Future Directions

- Increased model resolution leads to improvements in the simulation of large-scale, low-frequency atmosphere-ocean variability in the North Atlantic in a subset of models from HighResMIP (ECMWF, EC-Earth and HadGEM):
  - reduced low-frequency variability of subpolar SSTs
  - a more prominent tripole SST pattern with more prominent SST anomalies in the Gulf stream region
  - a stronger correlation between SSTs and the NAO
  - reduced "intrinsic" low-frequency variability of the subpolar upper-ocean circulation
  - more prominent NAO-driven ocean circulation variability in the Gulf stream/Intergyre region

Why do (some) LR models simulate too much "intrinsic" variability in the subpolar upper-ocean circulation?

- Role of Atlantic Meridional Overturning Circulation (AMOC)?
  - Low-frequency variability of the subpolar circulation is related to variability of AMOC.
- Role of mean biases in SSTs and sea-ice cover?
  - Upper-ocean density anomalies in the Labrador sea/subpolar region are generally controlled by salinity in LR models vs. temperature in HR models due to mean SST biases there (e.g., Menary et al. 2015).
  - The LR models examined here also exhibit excessive sea-ice cover in the Labrador sea (e.g., Docquier et al. 2021), which could affect the variability of the AMOC.
- Model dependency of results?
  - Some climate models appear to *overestimate* the variability of subpolar SSTs (e.g., Danabasoglu et al. 2016), while others appear to *underestimate* the low-frequency SST variability in the North Atlantic (e.g., Murphy et al. 2017)