European perspective: global high resolution modelling plans

Malcolm Roberts

with many thanks to
Noel Keenlyside, Dian Putrasahan, Johann Jungclaus,
Pier Luigi Vidale, Thomas Jung,
Chris Roberts, Eduardo Moreno-Chamarro

Projects including global high resolution modelling component

- EU projects
  - Finished:
    - PRIMAVERA
  - Ongoing:
    - nextGEMS – next generation Earth Modelling Systems is building prototypes for a new generation of earth system models to advance science, guide policy, and inform applications to support the sustainable management of our planet.
  - Starting 2023:
    - EERIE – European Eddy-rich Earth System Models
    - Use global coupled ~10km resolution in atmosphere and ocean, and run for centennial-multi-centennial timescales
- International
  - HighResMIP
    - successfully contributed to IPCC AR6 with ~25km resolution atmosphere+coupled models, 1950-2050 timescale
    - now discussing experimental designs, resolutions etc moving forwards towards CMIP7

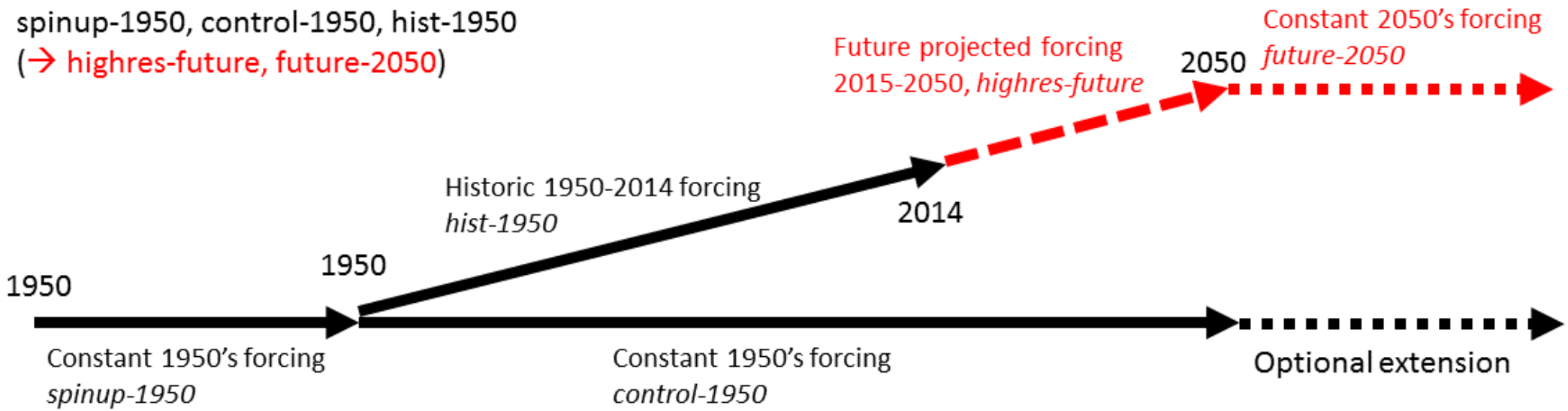
CMIP6 HighResMIP simulations

Physical model only x 2 resolutions, simplified aerosol optical properties (MACv2-SP) recommended

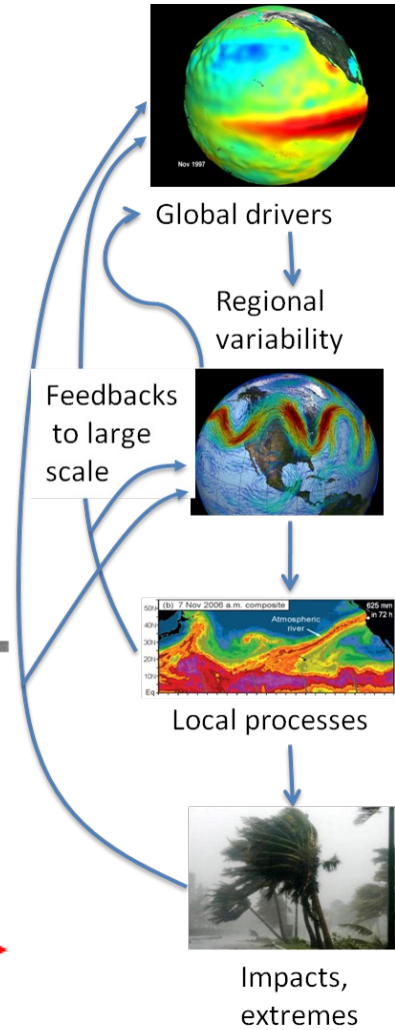
Atmosphere-land-only, 1950-2014 (→ 2050)
Forced by observed SST and sea-ice and historic forcings (→ projected)
highresSST-present (→ highresSST-future)

1950 — Historic forcings *highresSST-present* — 2014 — Future forcings *highresSST-future* — 2050

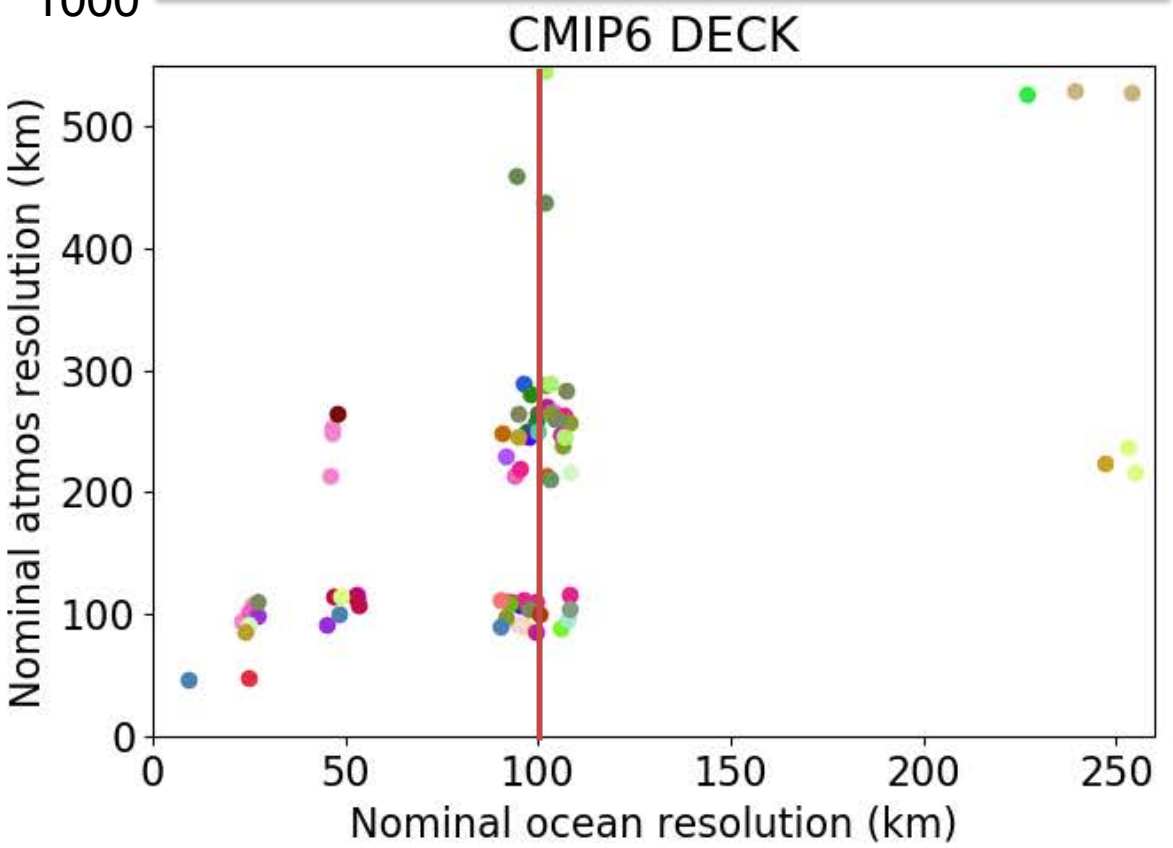
Coupled climate, 1950-2014 (→ 2050)
Forced by constant 1950 and historic forcings (→ projected)
Initial coupled spin-up period ~ 30-50 years from 1950 EN4 ocean climatology
spinup-1950, control-1950, hist-1950
(→ highres-future, future-2050)

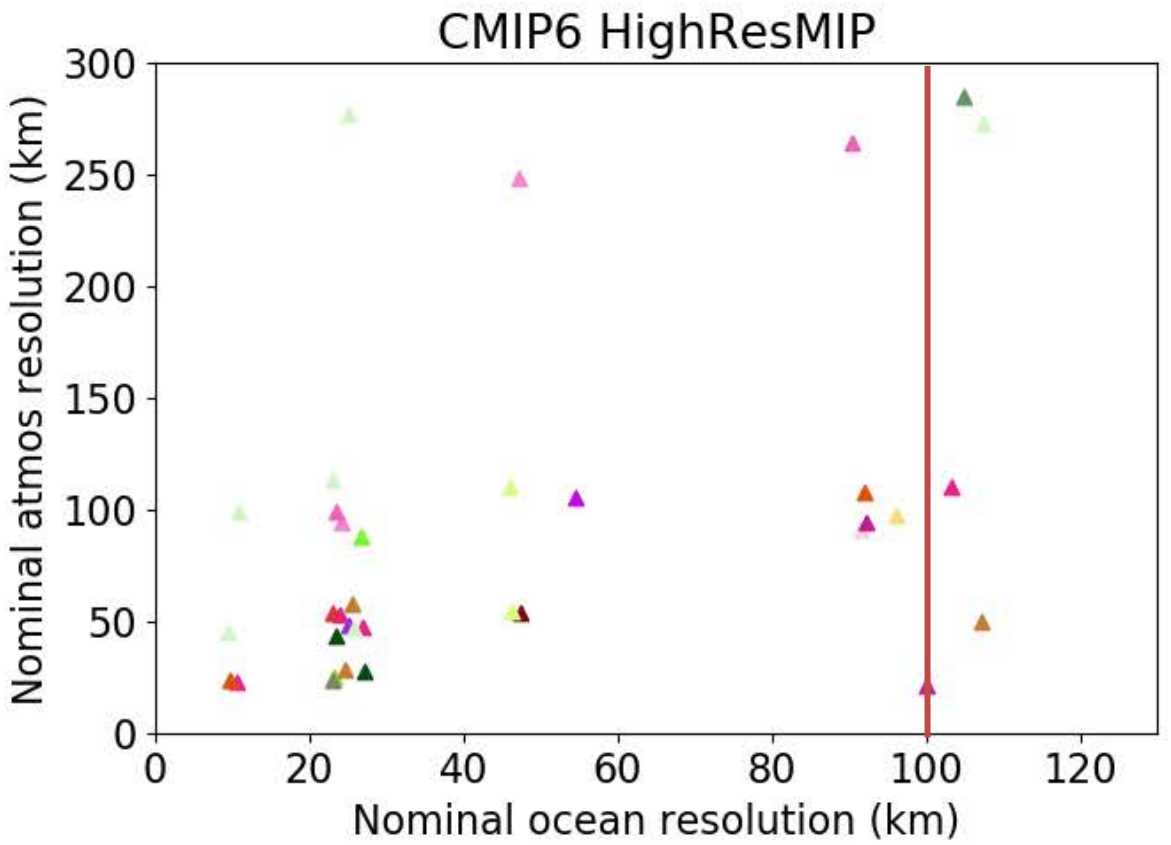


1950 — Constant 1950's forcing *spinup-1950*
1950 — Historic 1950-2014 forcing *hist-1950* — 2014
Constant 1950's forcing *control-1950*
2014 — Future projected forcing 2015-2050, *highres-future* — 2050
2050 — Constant 2050's forcing *future-2050*
Optional extension



1000





ACCESS-CM2, AWI-CM, BCC-CSM2, BESM-2, BNU-ESM, CAMS-CSM1, CAS-ESM2, CESM1-1, CESM2, CIESM, CMCC-CM2, CNRM-CM6, CSIRO-Mk3L, CanESM5, E3SM-1, EC-Earth3, EMAC-2, FGOALS-f3, FIO-ESM, GFDL-CM4, GISS-E2, HadGEM3-GC31, IITM-ESM, INM-CM4, IPSL-CM6A, KACE-1, KIOST-ESM, MCM-UA, MIROC-ES2H, MIROC6, MPI-ESM, MRI-ESM2, NESM3, NorCPM1, NorESM1-F, NorESM2-LM, SAM0-UNICON, TaiESM1, UKESM1-0, UofT-CCSM4, VRESM-1

AWI-CM-1-1-HR, BCC-CSM2, CAMS-CSM1, CAS-ESM2, CESM2, CIESM, CMCC-CM2, CNRM-CM6, EC-Earth3, ECMWF-IFS, FGOALS-f3, GFDL-CM4C192, HadGEM3-GC31, HiRAM-SIT, MIROC6, MPI-ESM1, NorESM2-HH, VRESM-1

Atmos deformation radius ~1000 km

Ocean deformation radius ~100 km (at low latitudes)

Source:
https://github.com/WCRP-CMIP/CMIP6_CVs/blob/master/CMIP6_source_id.json

PRIMAVERA/HighResMIP papers related to Gulf Stream/air-sea interaction

Bellucci, A., and Coauthors, 2021: Air-sea interactions over the Gulf Stream in an ensemble of HighResMIP present climate simulations. Clim. Dyn., accepted. https://doi.org/10.1007/s00382-020-05573-z.

Grist, J.P., S. A. Josey, B. Sinha, J. L. Catto, M. J. Roberts, A.C. Coward, 2021: Future evolution of an eddy rich ocean leads to enhanced east Atlantic storminess in a coupled model projection. GRL, https://doi.org/10.1029/2021GL092719.

Moreno-Chamarro, E., L.-P. Caron, P. Ortega, S. L. Tomas, M. J. Roberts, 2021: Can we trust CMIP5/6 future projections of European winter precipitation? ERL, https://doi.org/10.1088/1748-9326/abf28a.

Moreton, S. and coauthors, 2021: The importance of the ocean-atmosphere resolution ratio for SST- heat flux feedbacks over mesoscale eddies in coupled climate models. Geophys. Res. Lett., https://doi.org/10.1029/2021GL095407.

Tsartsali, E. E., Haarsma, R. J., Athanasiadis, P. J., Bellucci, A., de Vries, H., Drijfhout, S., de Vries, I. E., Putrasahan, D., Roberts, M. J., Sanchez-Gomez, E., Roberts, C. D., 2021: Impact of resolution on the atmosphere-ocean coupling along the Gulf stream in global high resolution models. Clim. Dyn. https://doi.org/10.1007/s00382-021-06098-9.,

Wu, P., M. Roberts, G. Martin, X. Chen, T. Zhou, P. L. Vidale, 2018: The impact of horizontal atmospheric resolution in modelling air-sea fluxes. QJRMS, 145, 3271-3283, https://doi.org/10.1002/qj.3618.

Co-funded by the European Union

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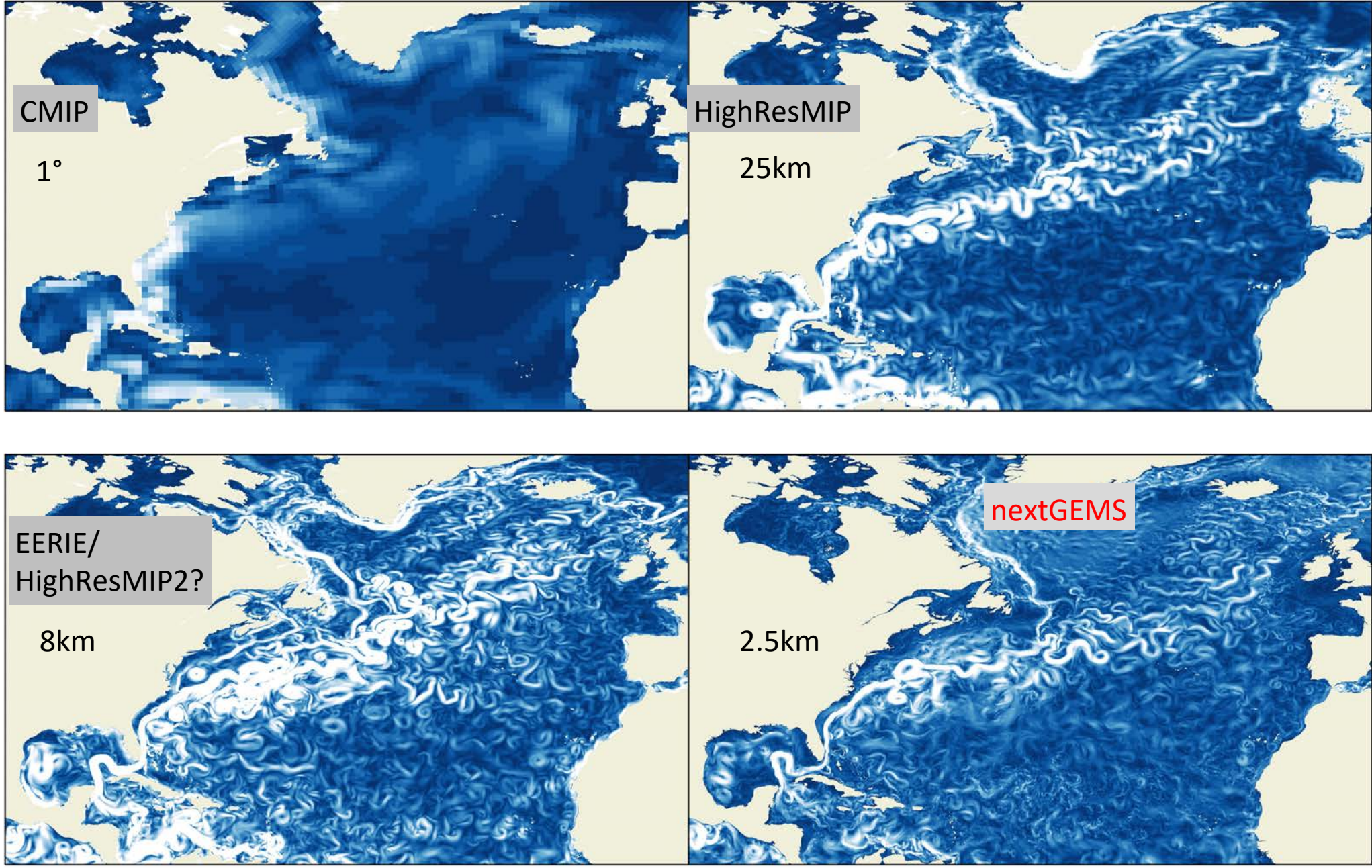
Snapshots of ocean surface current speed at different ocean model resolutions

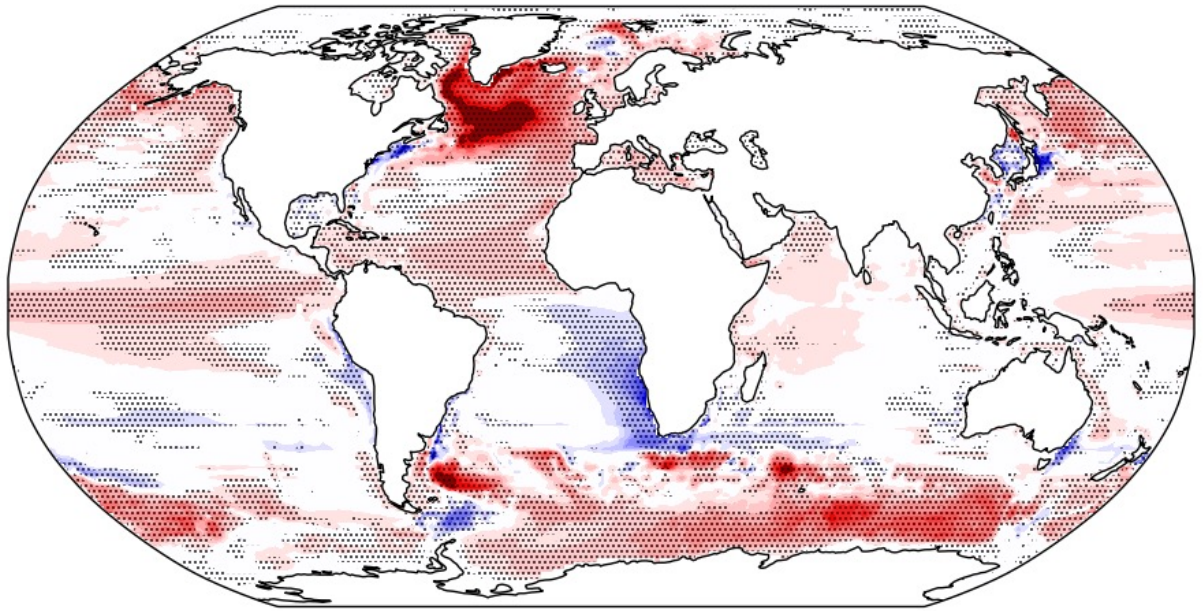
CMIP multi-centennial timescales 1850-2100

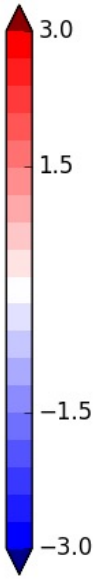
CMIP6 HighResMIP multi-decadal timescales 1950-2050

EERIE both centennial & multi-centennial 1950-2100 & 1850-2100

nextGEMS years - several decades



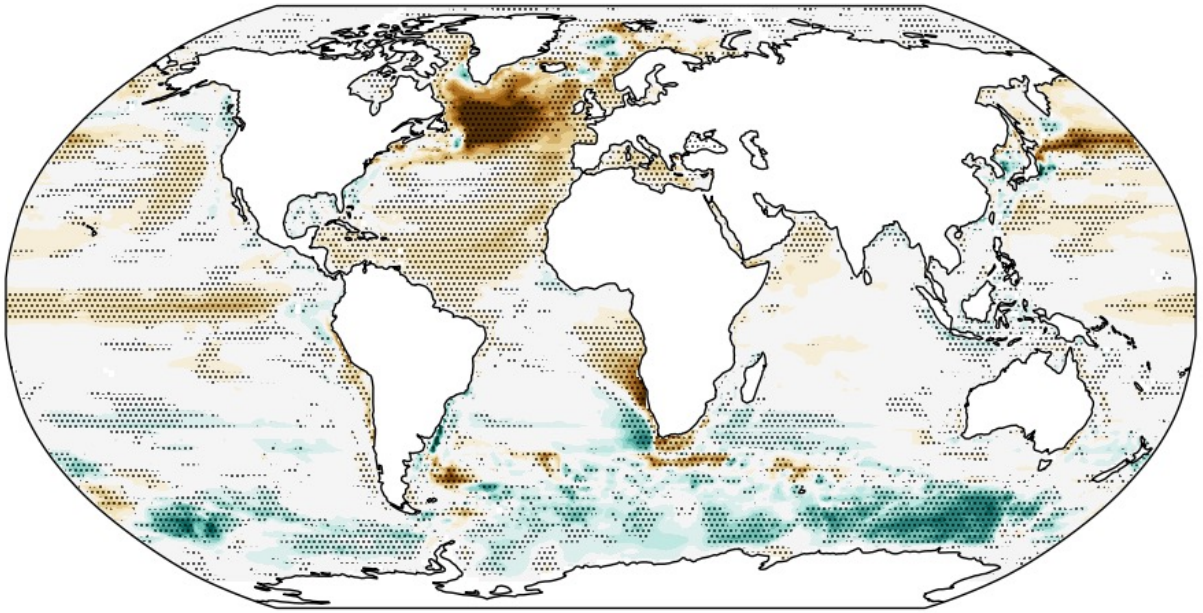


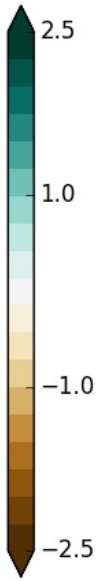


Resolution difference

$$\sum_{models} \frac{(HRi - LRi)}{nmodels}$$

Multi-model mean SST difference between high and low resolution coupled models
5 models used, which have a different ocean resolution
Stippling indicates where at least half the models agree on the sign





Resolution RMSE difference

$$\sum_{models} \frac{(RMSE(HRi) - RMSE(LRi))}{nmodels}$$

Multi-model mean of the change in SST bias between high and low resolution coupled models (using RMS difference from EN4 1950-54 mean)
5 models used, which have a different ocean resolution
Stippling indicates where at least half the models agree on the sign

Models with different ocean resolutions: HadGEM3-GC3.1, ECMWF-IFS, EC-Earth3P, AWI-CM1.0, CNRM-CM6

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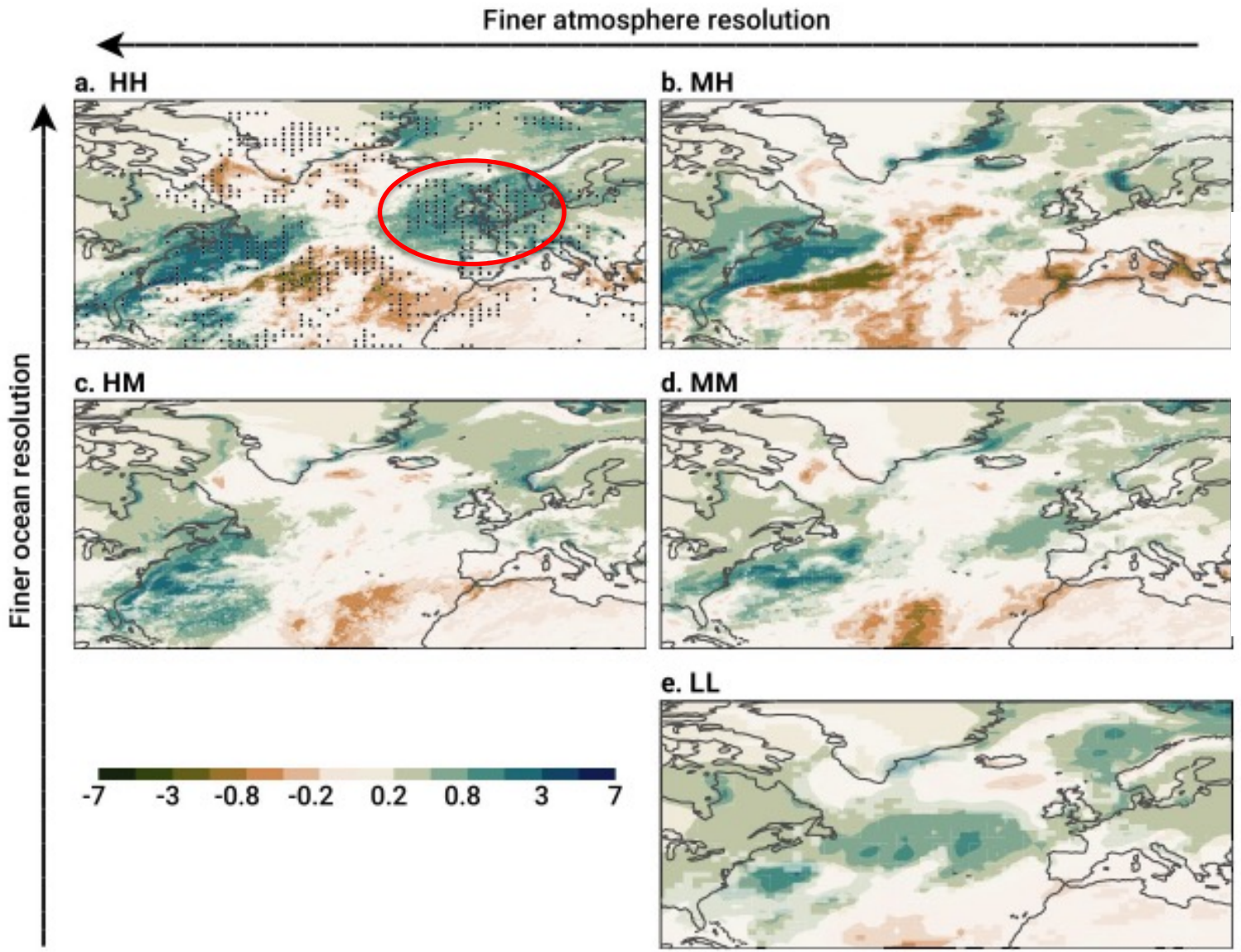
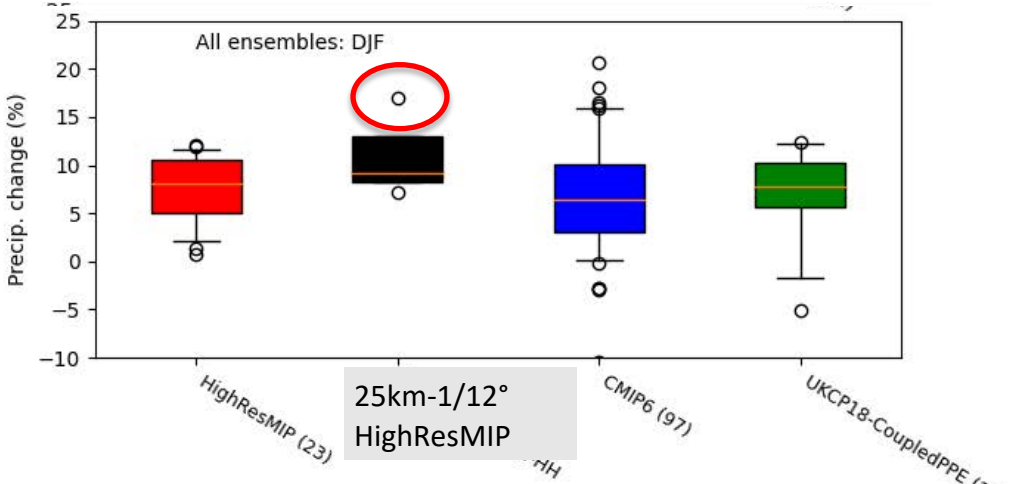
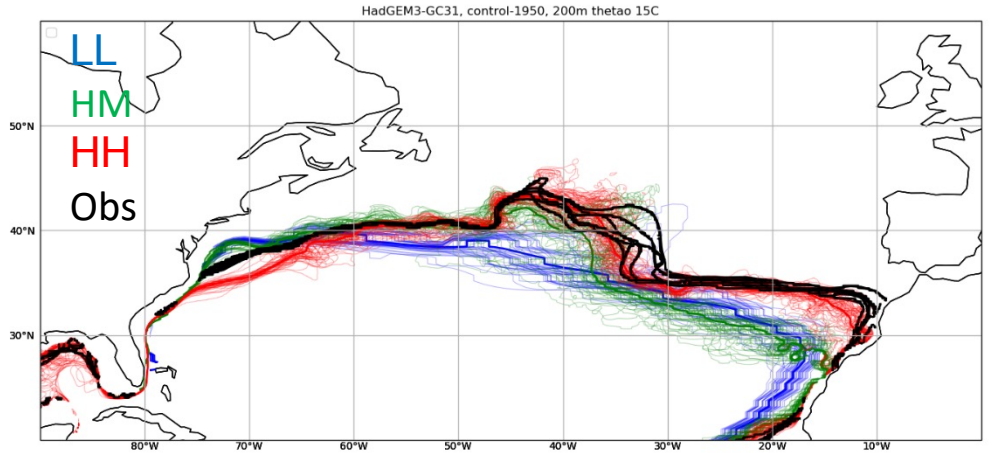


Anomalies in winter precipitation between 2030–2050 and 1960–1980
Stippling in (a) indicates anomalies in HH falling outside a distribution including anomalies from all the other resolutions

Result needs **both** atmosphere and ocean resolution

Rainfall %age change, DJF, 2030-50 - 1960-80, over Europe 20W-30E, 40-65N from different multi-model ensembles





Moreno-Chamarro et al., ERL, 2021;
Grist et al., GRL, 2021.

PRIMAVERA

Hemispheric impact of Gulf Stream errors in subseasonal forecasts

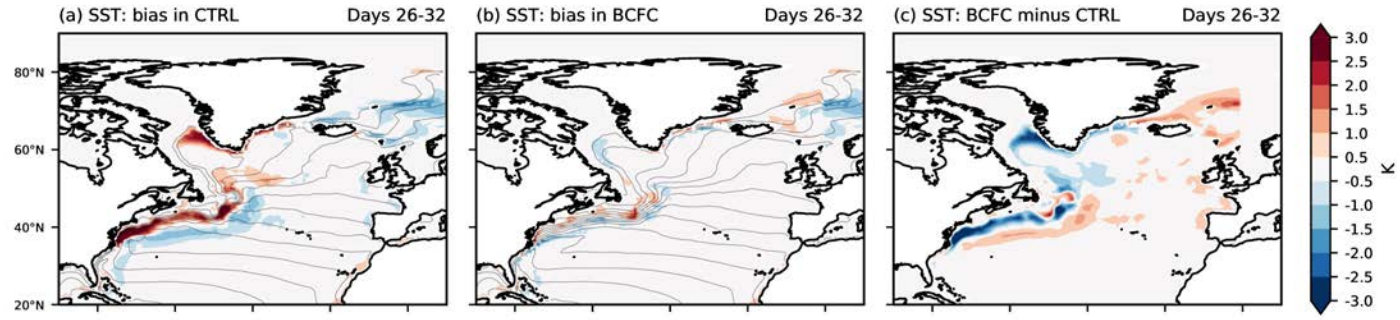
Chris D. Roberts (chris.roberts@ecmwf.int), F. Vitart, and M. A. Balmaseda ECMWF

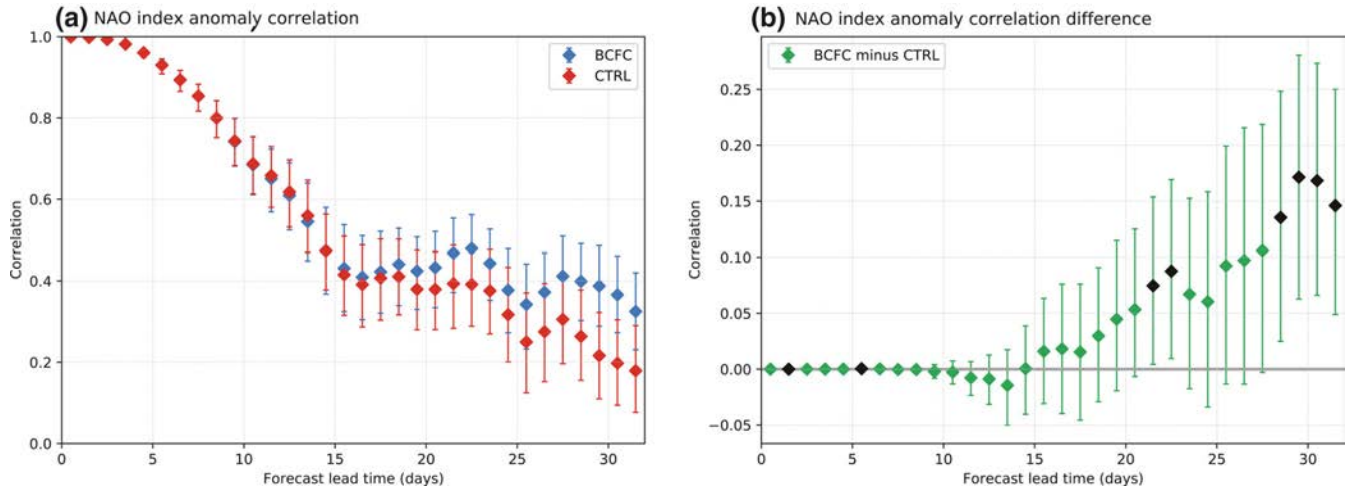
ECMWF S2S forecasts have errors in the position of the Gulf Stream.

Correcting these errors improves the atmospheric mean state and simulation of circulation anomalies.

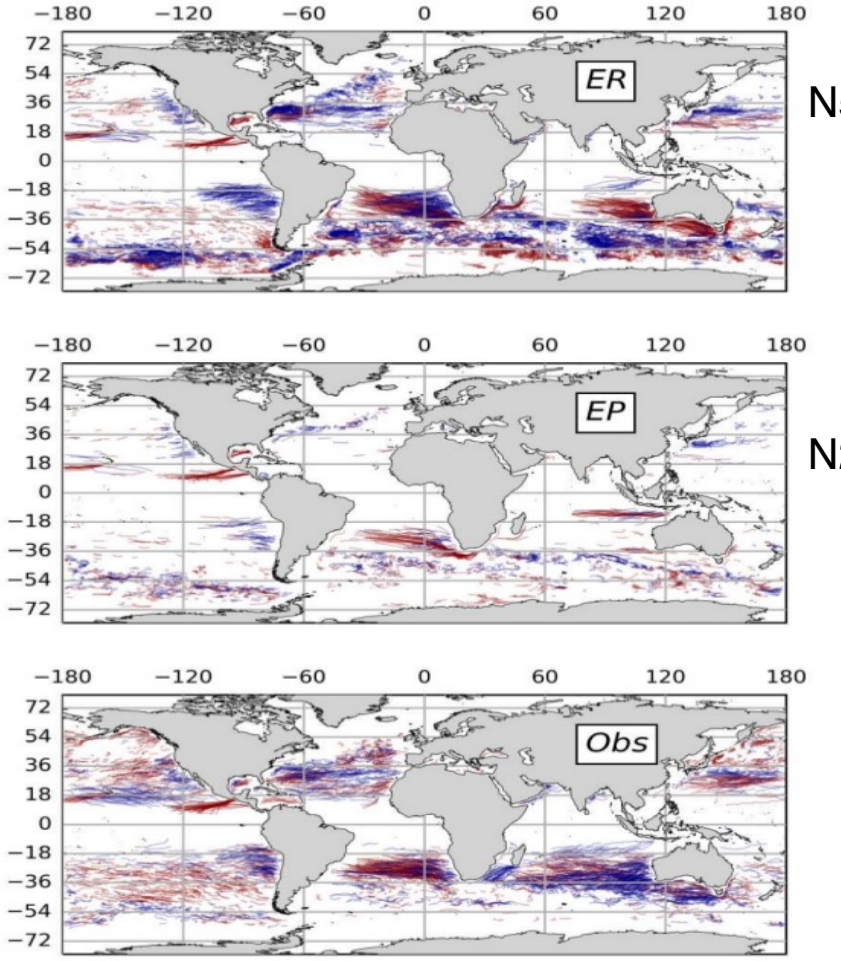
Forecast skill is improved in the Atlantic and beyond, with impacts following the subtropical waveguide.

These results demonstrate the potential benefits of higher-resolution ocean models that can better resolve the position of the Gulf Stream.





Roberts, C. D., Vitart, F., & Balmaseda, M. A. (2021). Hemispheric impact of North Atlantic SSTs in subseasonal forecasts. *Geophysical Research Letters,* 48, e2020GL091446. https://doi.org/10.1029/2020GL091446



N512-ORCA12

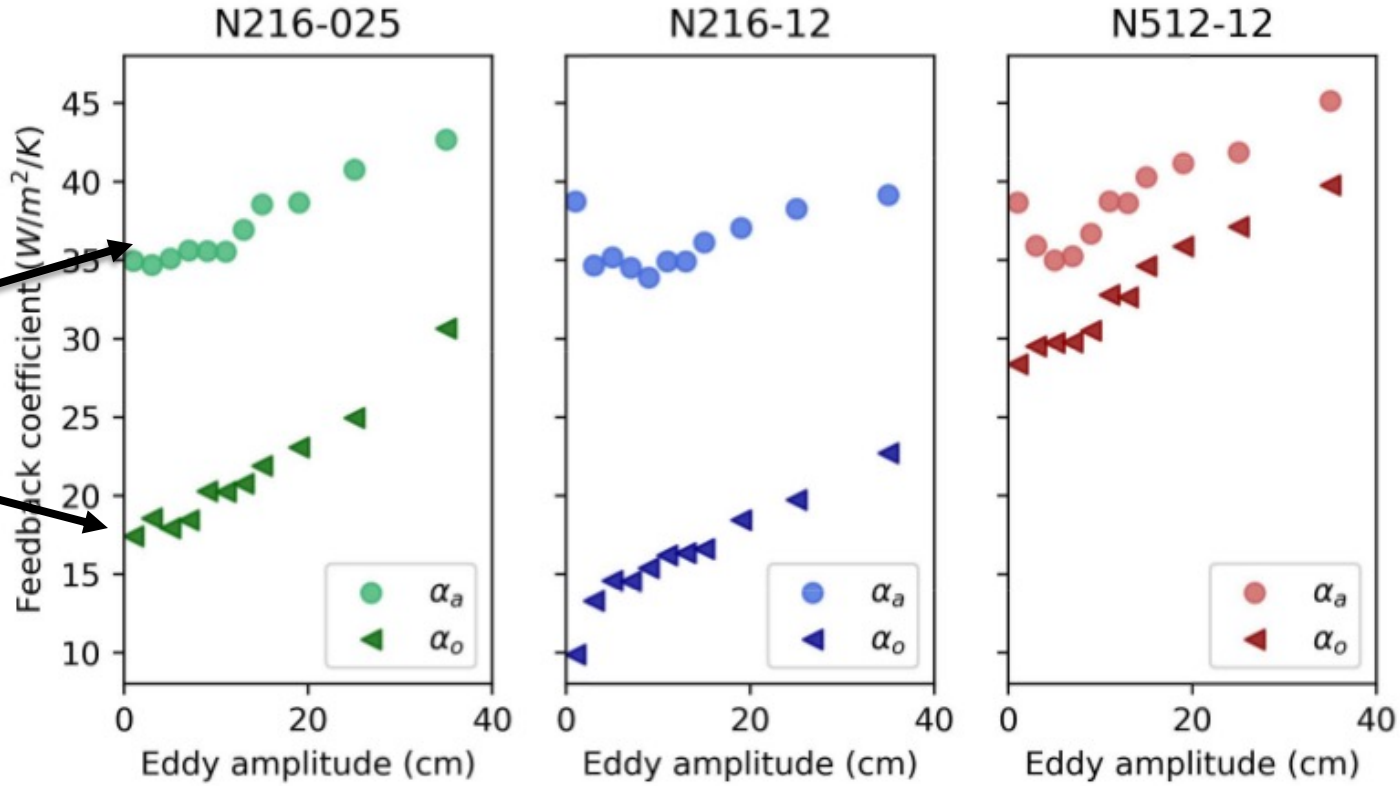
N216-ORCA025

- Turbulent heat flux anomaly over composited eddies
- $< THF' >= \alpha < SST' >$

Feedback coefficient (W/m²/K) from SST on
(●) ocean grid (ideal)
(◀) atmosphere grid (actual, via coupler)
Damping is too weak when atmosphere grid is not fine enough – implications for fluxes and eddy lifetimes

What model should do

What model does

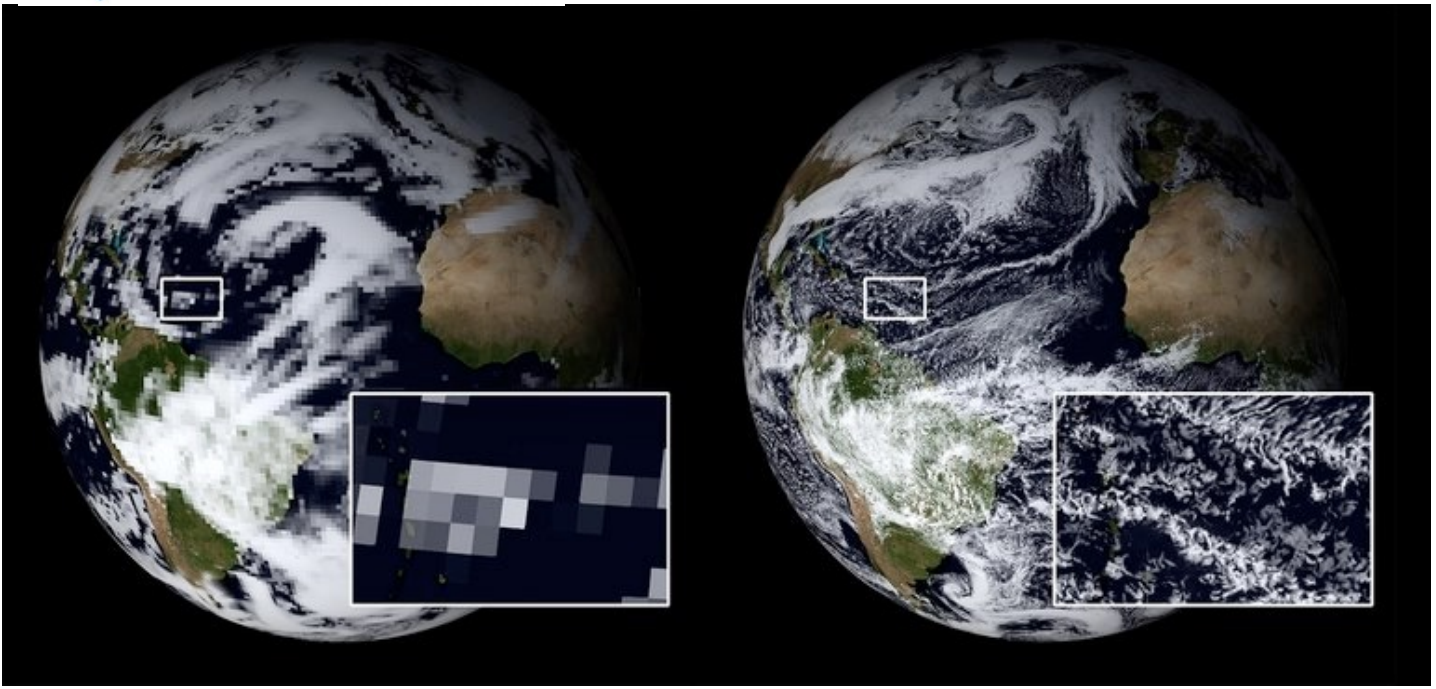


Eddy trajectories lasting longer than 6 months
Anti-cyclonic in red, cyclonic in blue
Moreton et al. 2020, Ocean Modelling

Moreton et al. 2020, 2021

The EU H2020 **NextGEMS** project

https://nextgems-h2020.eu/



ICON @ 80km and 5km

- two prototype storm-resolving ESMs (**ICON-A/O**, **IFS/FESOM**)
- produce multi-decadal projections of future climate change.

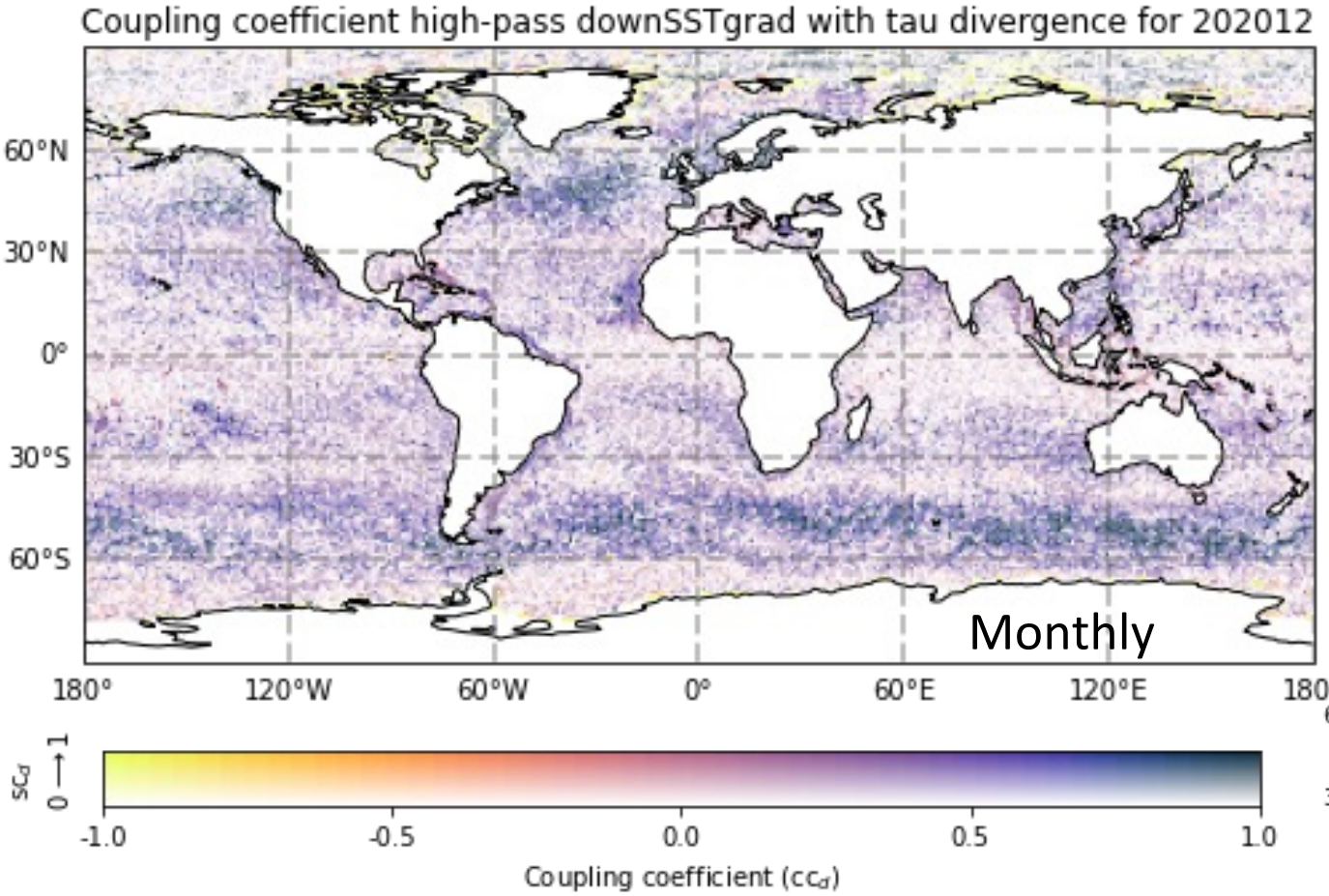
Models:
AWI-CM-XR: OpenIFS/FESOM:

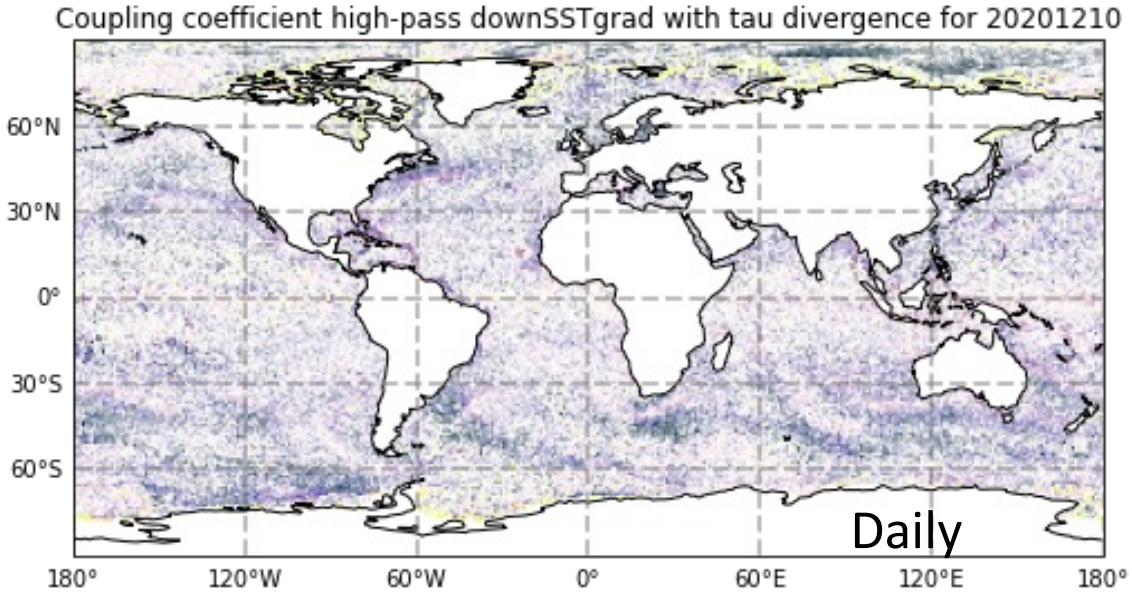
ICON-ESM: ICON-A/ICON-O:

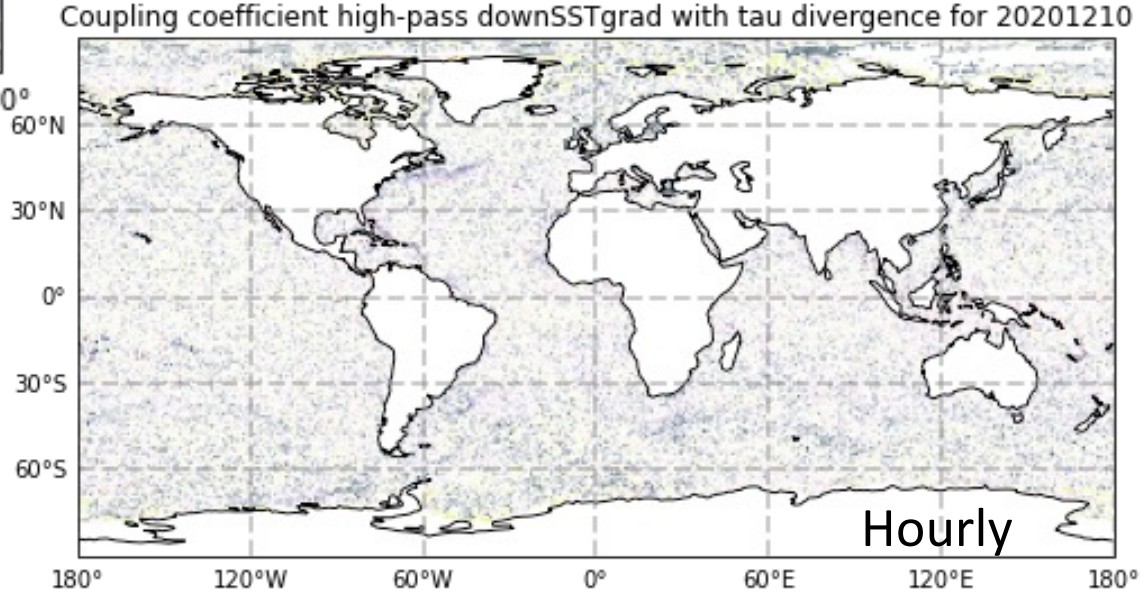
globally 2.5-5 km atm./ocean

Courtesy: Johann Jungclaus

Geographical distribution of coupling between downwind SST gradient & wind stress divergence







- On timescales shorter than daily, this coupling (if there is any) is masked by atmospheric synoptic variability
- Persistent is needed for the mechanism to be observed

Courtesy: Dian Putrasahan

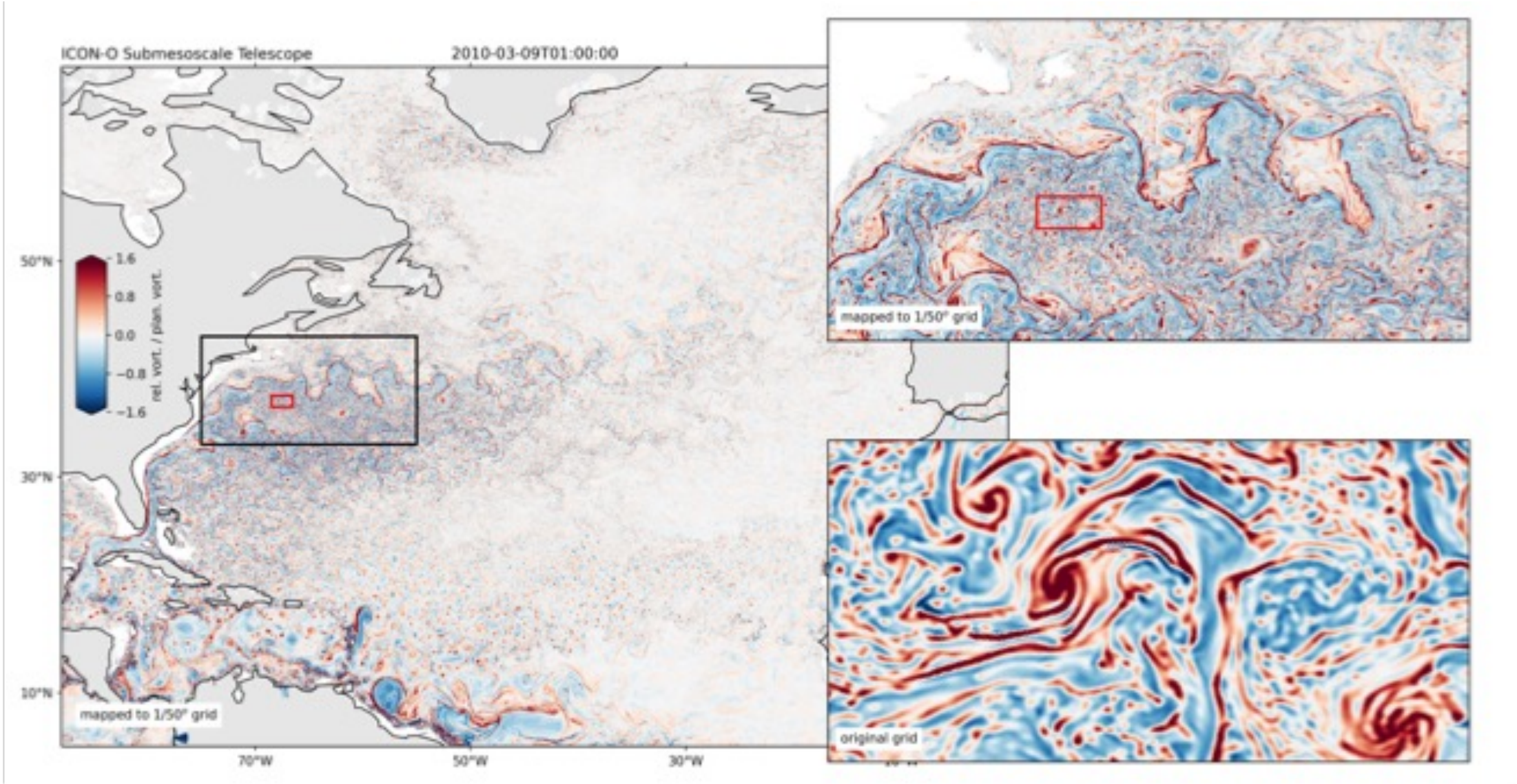


Figure 16. Map of the local Rossby number over the North Atlantic at 20-m depth for G_O_tel with close-ups of the grid focal region on the right.

Hohenegger et al., in prep.

The HEurope EU **EERIE** project **E**uropean **E**ddy-**R**i**c**h **E**SMs

17 partners
4 years starting Jan 2023

Key science question: what is the role of the ocean mesoscale in climate?

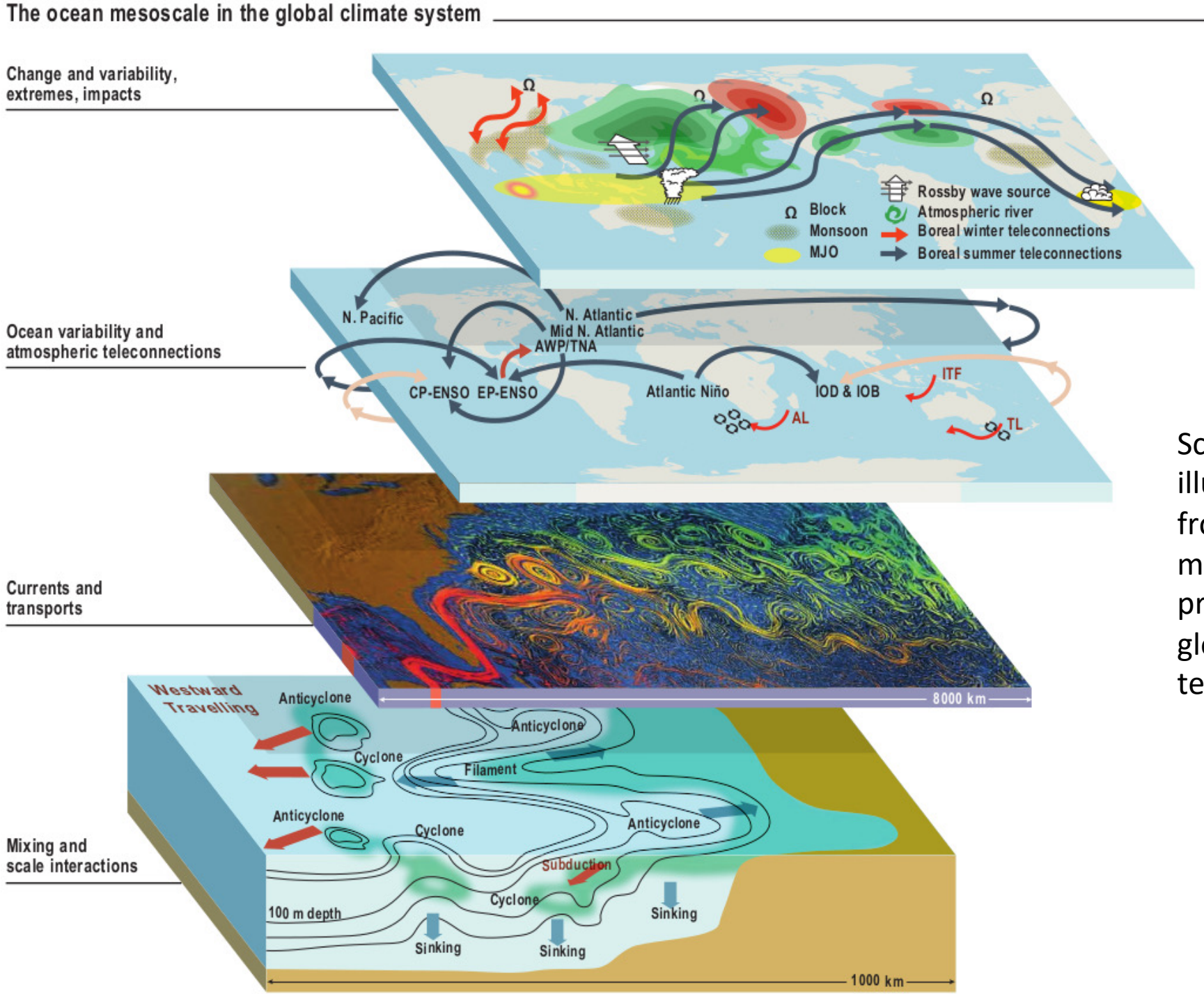
Key development: similar atmosphere and ocean resolutions

Simulations: four coupled models with eddy-rich (<10km) ocean and ~10km atmosphere, either full CMIP 1850-2100 or HighResMIP 1950-2100 experiments

Analysis: assess and understand ocean mesoscale (boundary currents, eddies) and interactions with atmosphere from sub-daily to decadal/centennial timescales

Experimental designs: work with HighResMIP and other communities to develop new experiments, tools to elucidate mesoscale impacts and compare to observations

Technical: *Develop in-line* and other tools for improved, automated diagnostic production (e.g. cyclone, eddy tracking) and assessment
Develop and improve models for these scales
Optimise throughput



Schematic illustrating links from local ocean mesoscale processes up to global teleconnections

Common themes with workshop

Experiments and experimental designs

- Additional HighResMIP experiments to help link with observations and understanding?
  - perhaps a case study that would bring in lots of observations and enable comparison without the mediation of reanalysis
- Multi-model results to help distinguish physical processes and resolution
- Pull in extra (non-climate) groups e.g. those not able to do multi-decadal

Diagnostics

- High frequency information needs to be automatically diagnosed
  - Multi-level high frequency outputs become overwhelming for storage and sharing

Resolution vs physics vs ensemble size

- Well defined questions to choose which axis to push down

Something not yet mentioned

Signal to noise

The real world has more NAO predictability than our models - what are we missing?

Is this physics, or resolution, or processes such as air-sea interactions?

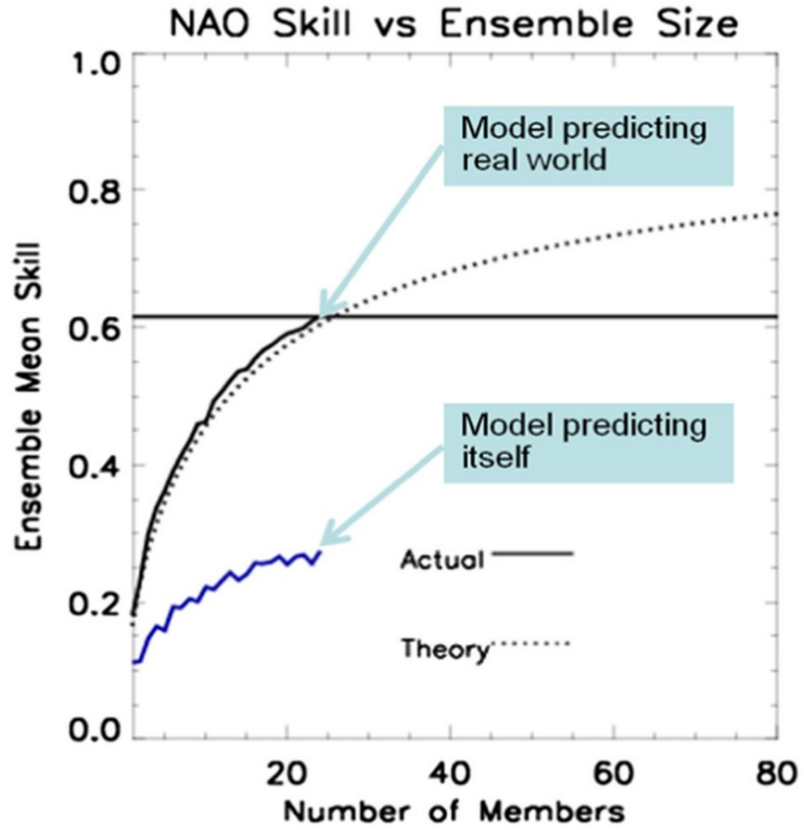


Fig. 1 Predictability of the North Atlantic Oscillation in the real world (black) is higher than the predictability in the model (blue). The effects of ensemble size on seasonal hindcasts of the winter North Atlantic Oscillation are plotted. The black line shows the average correlation score when different size ensemble averages are correlated with the observed NAO (r_{mo}). The blue line shows the same quantity when ensemble means are correlated with a single forecast member (r_{mm}). The black dotted line is a theoretical fit to the solid black line.[23] The skill grows with ensemble size due to the suppression of unpredictable noise, but in principle the curves should be the same. In practice the model is better able to predict the real world than itself. Data are from the GloSea5 forecast system[23]

Scaife and Smith, 2018