Toward resolving the ocean mesoscale: challenges and potential benefits

An ECMWF S2S perspective

Chris Roberts, Earth System Predictability Section @ ECMWF

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ECMWF

Motivation

- The ECMWF IFS is a coupled atmosphere-ocean-ice-wave-land forecast model.
- Ocean coupling improves the representation of air–sea interactions...
- … but introduces the potential for systematic errors in sea-surface temperature (SST).
- In particular, eddy-permitting ocean models struggle to accurately simulate the location and structure of the Gulf Stream and its associated sharp gradients in SST.

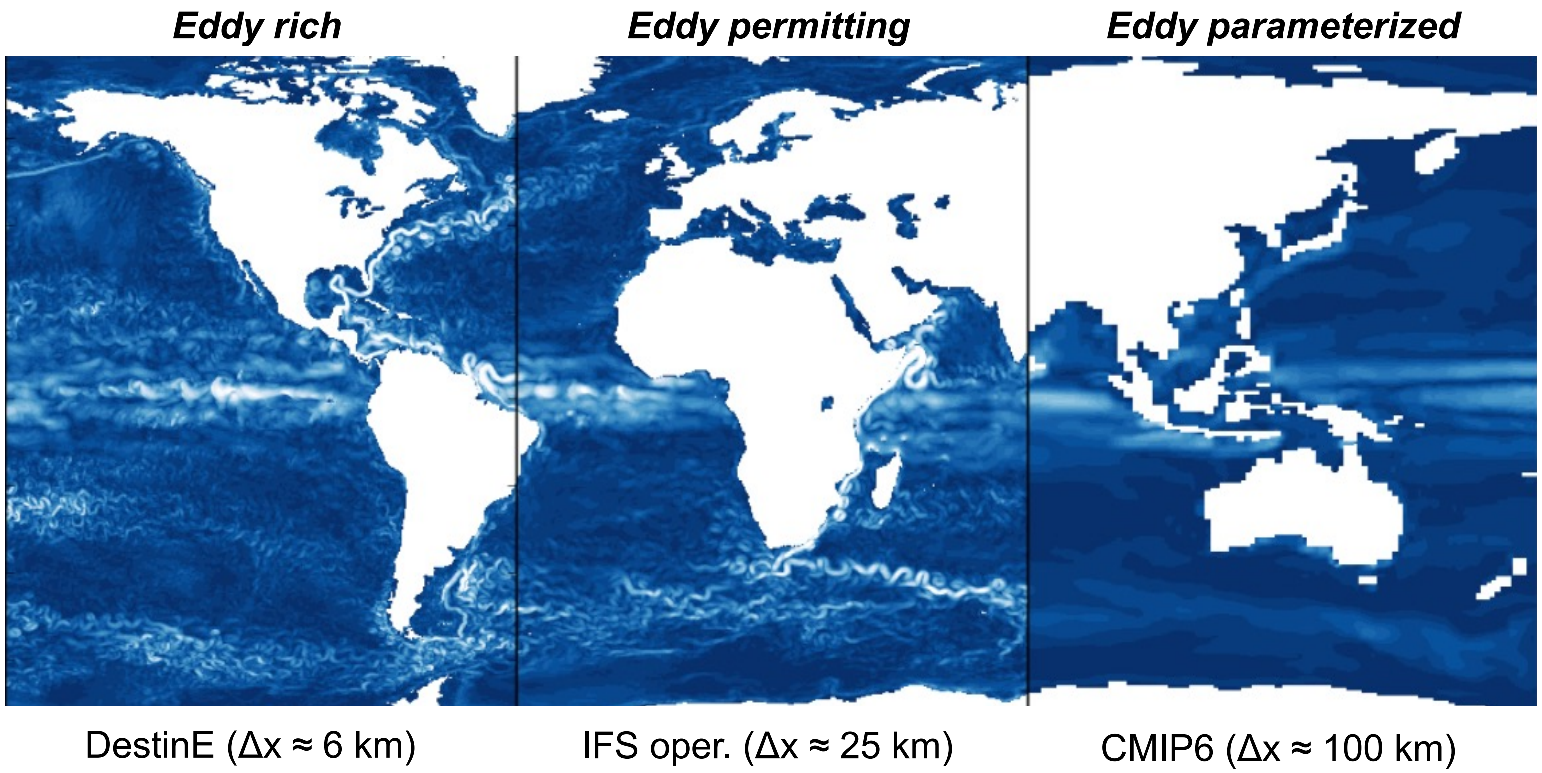


Image credit: Malcolm Roberts and Helene Hewitt (UKMO)

The ECMWF extended-range (aka S2S) forecasting system

	Current system (Cycle 47r3)
Real-time ensemble	50+1 members each Mon/Thu
IFS resolution	Day 1-14: Tco639 L137 (18 km) Day 15-46: Tco319 L137 (36 km)
Ocean/sea-ice resolution	¼ degree ORCA025 Z75 (eddy-permitting)
On-the-fly reforecasts	10+1 members, previous 20 years, each Mon/Thu
Data produced each week	~68 years

Ocean/ice model accounts for ~40-50% of total cost of 48R1 S2S configuration.

Eddy-rich ocean models are ~30(ish) times more expensive than eddy-permitting configurations!

ECMWF

Mid-latitude air-sea interactions are scale-dependent

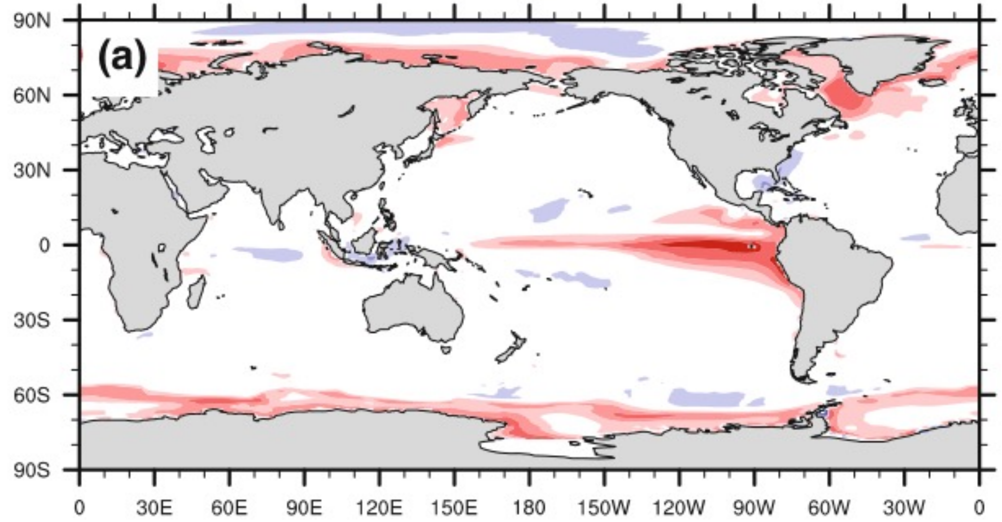
Large-scale (> 1000 km): ***Stronger winds → heat loss → SST cooling → atmosphere driving ocean.***

"Mesoscale"[1] (10-1000 km): ***Warmer SSTs → heat loss → stronger winds → ocean driving atmosphere.***

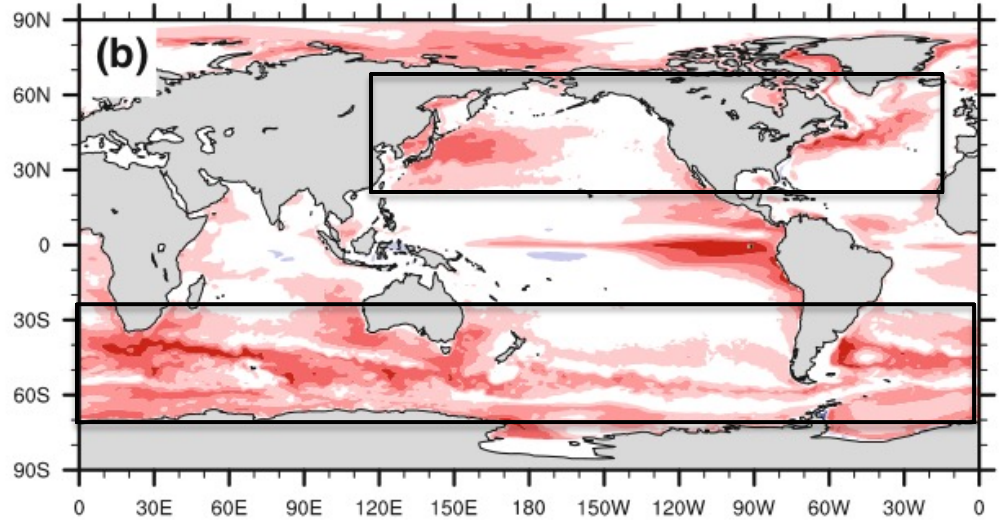
[1] *Including ocean eddies, fronts, and other other features with length scales close to the Rossby radius of deformation.*

Simultaneous correlations between monthly mean SST and heat flux out of the ocean.

CCSM – 100 km ocean



CCSM – 10 km ocean



Kirtman et al. (2012)

Air-sea interactions at the ocean mesoscale

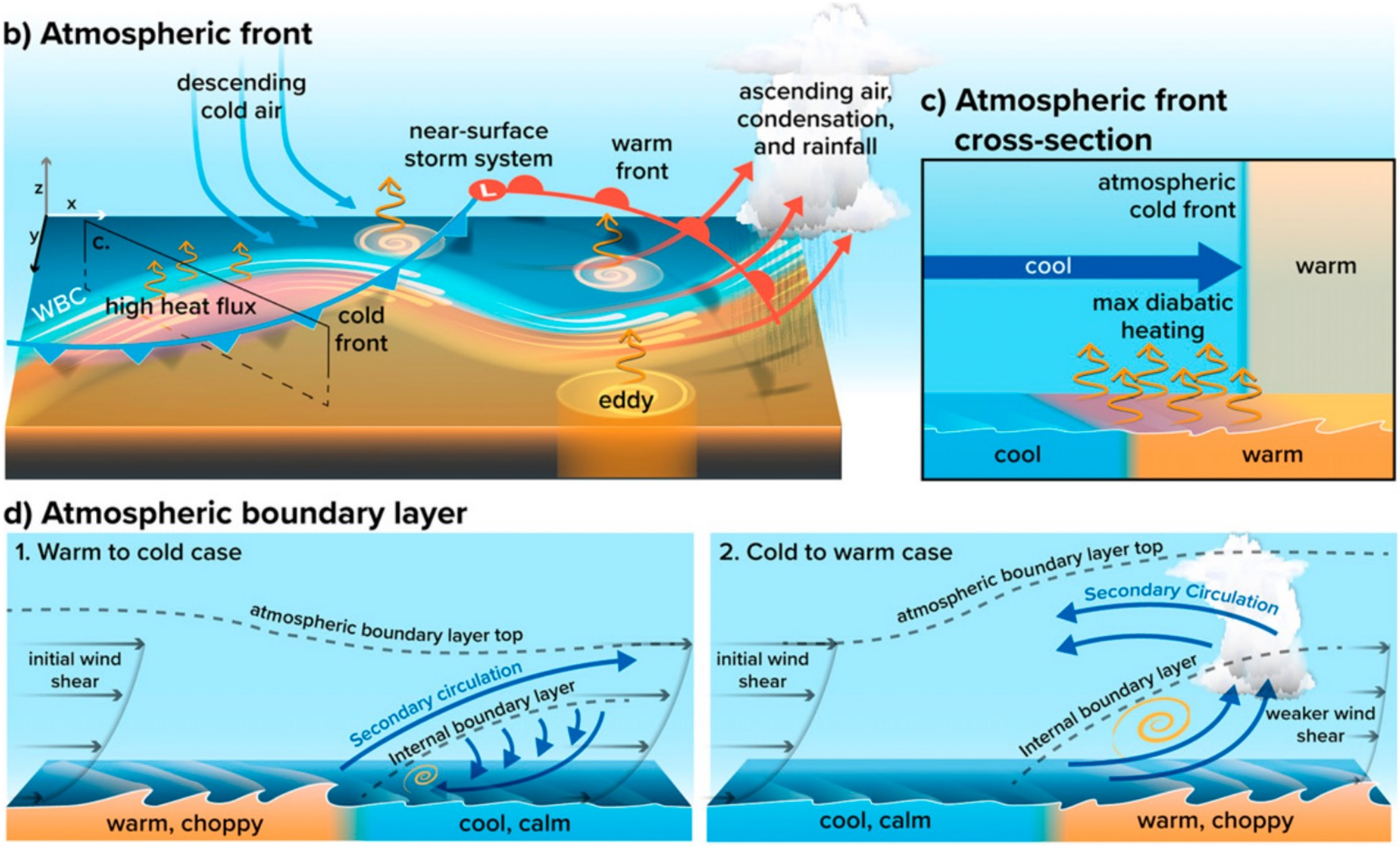
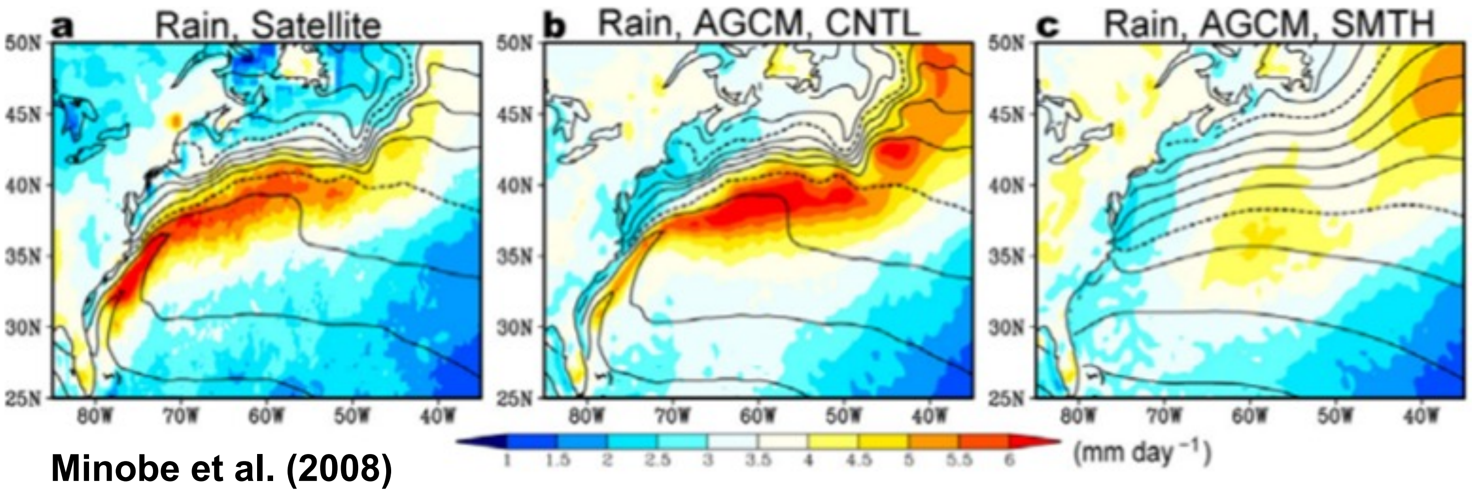


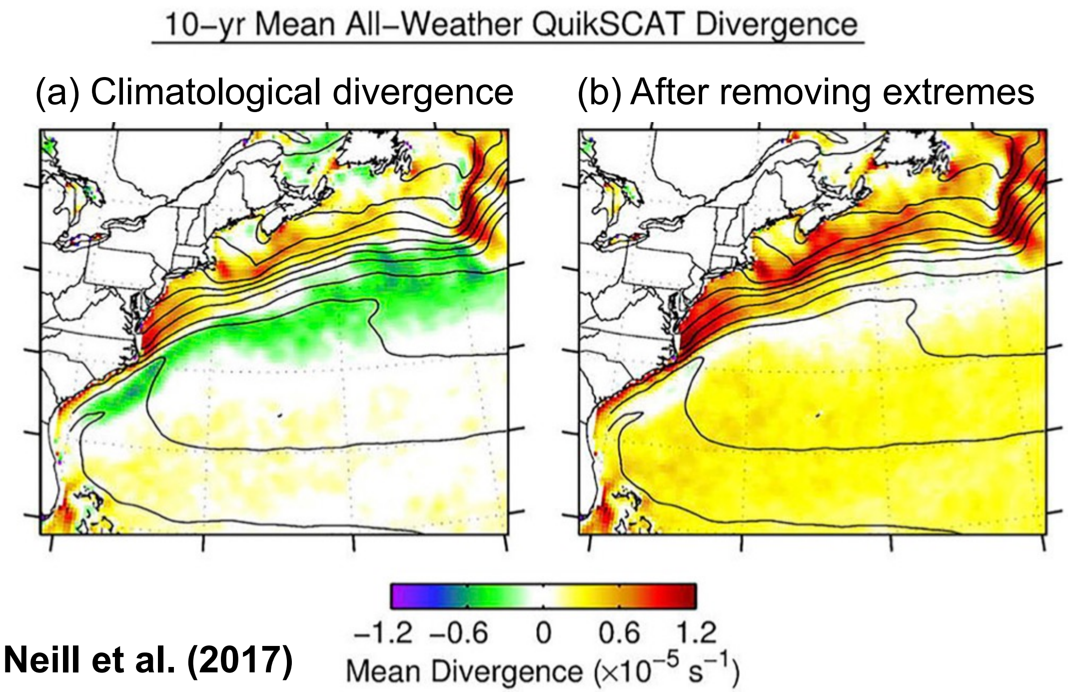
Image credit: Seo et al. (2023), J. Climate.

Gulf stream SST gradients influence the storm track



Minobe et al. (2008)

The Gulf Stream is associated with a pattern of near-surface wind convergence (NSWC) and vertical motion, which anchors precipitation along warm edge of SST front.



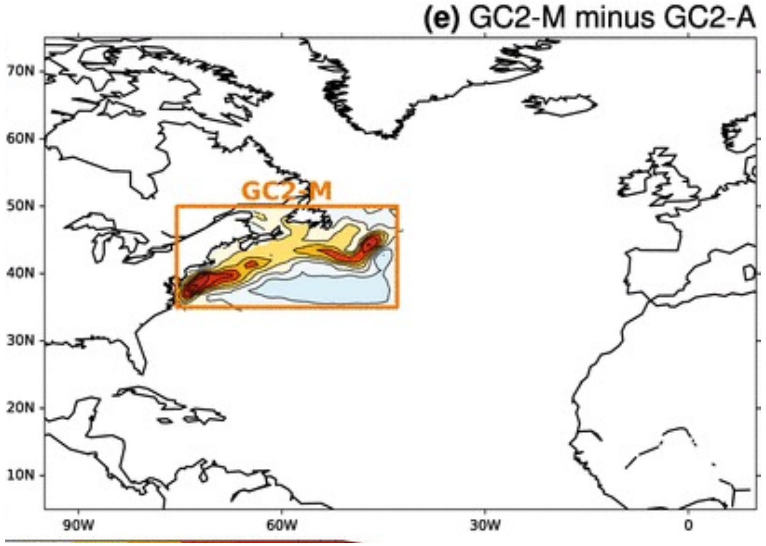
O'Neill et al. (2017)

The climatological structure of NSWC is dominated by infrequent but extreme events linked to vertical motion in atmospheric fronts.

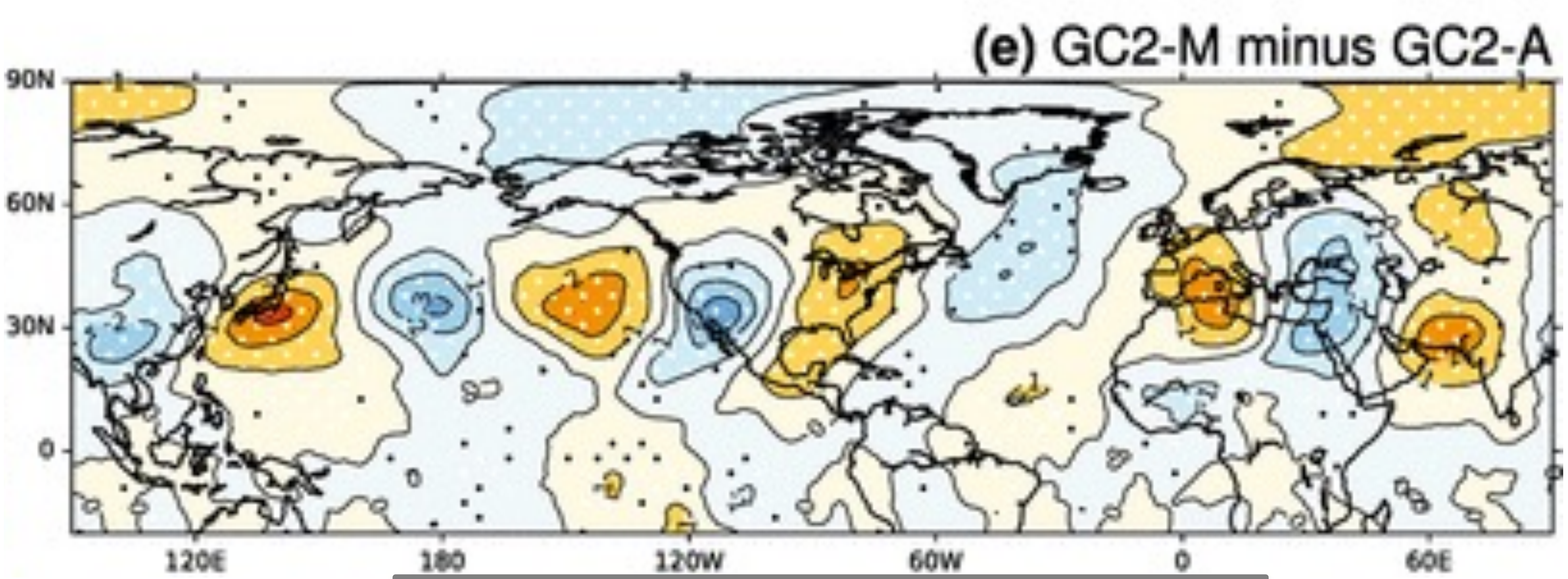
SST fronts modulate the location of these extreme events.

SST biases associated with a shift of the Gulf Stream can thus impact the timing, location, and magnitude of these interactions.

Gulf stream SST biases impact the remote atmosphere



Imposed SST bias



Response of meridional wind at 250 hPa

Lee et al. (2018) imposed Gulf Stream SST biases from a coupled climate simulation in an atmosphere-only configuration of the same model.

The resulting heating anomalies stimulated spurious vertical motions and a planetary wave response that propagated throughout the entire northern hemisphere.

Ocean resolution impacts are sensitive to lead time

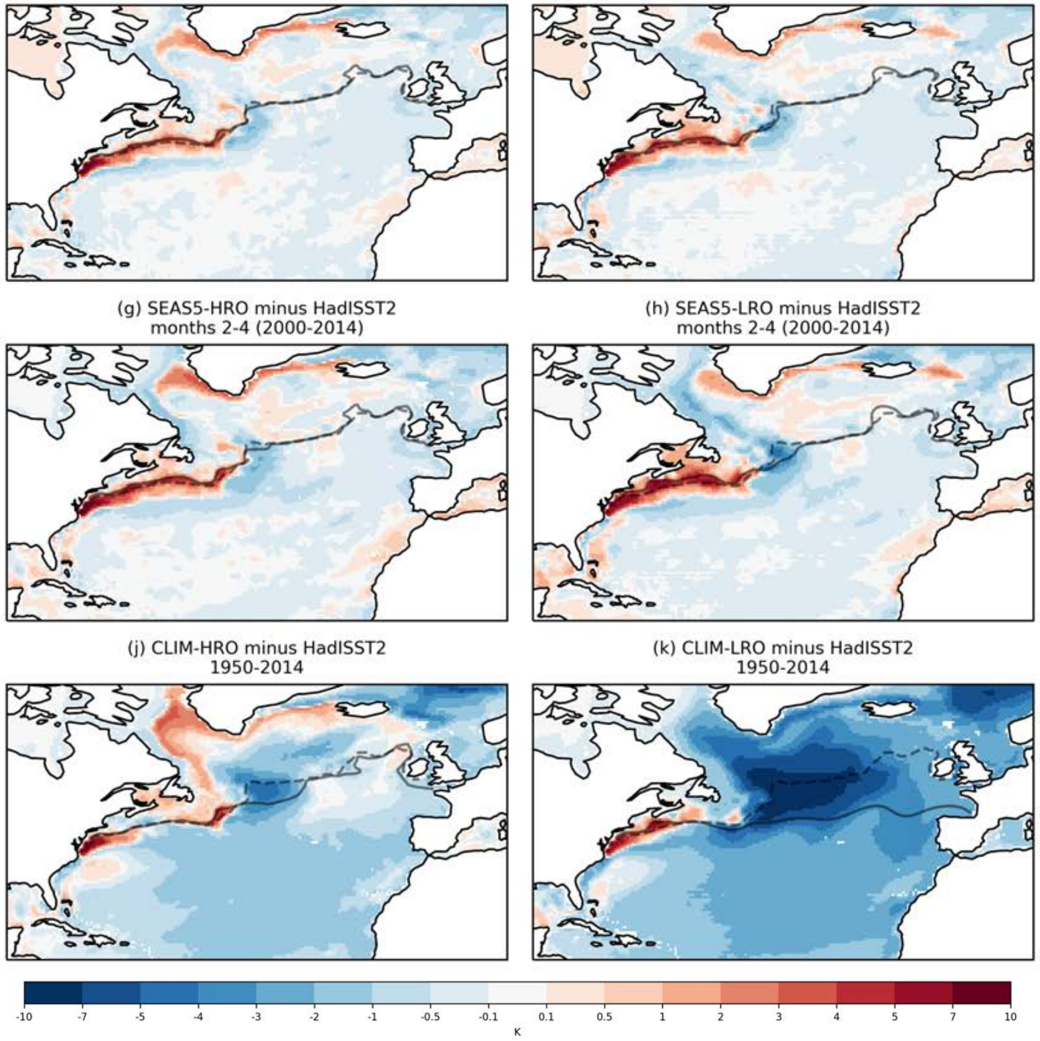
DJF SST biases in IFS coupled model

25 km ocean | **100 km ocean**

S2S (weeks 1-4)

Seasonal (months 2-4)

Climate (1950-2014)

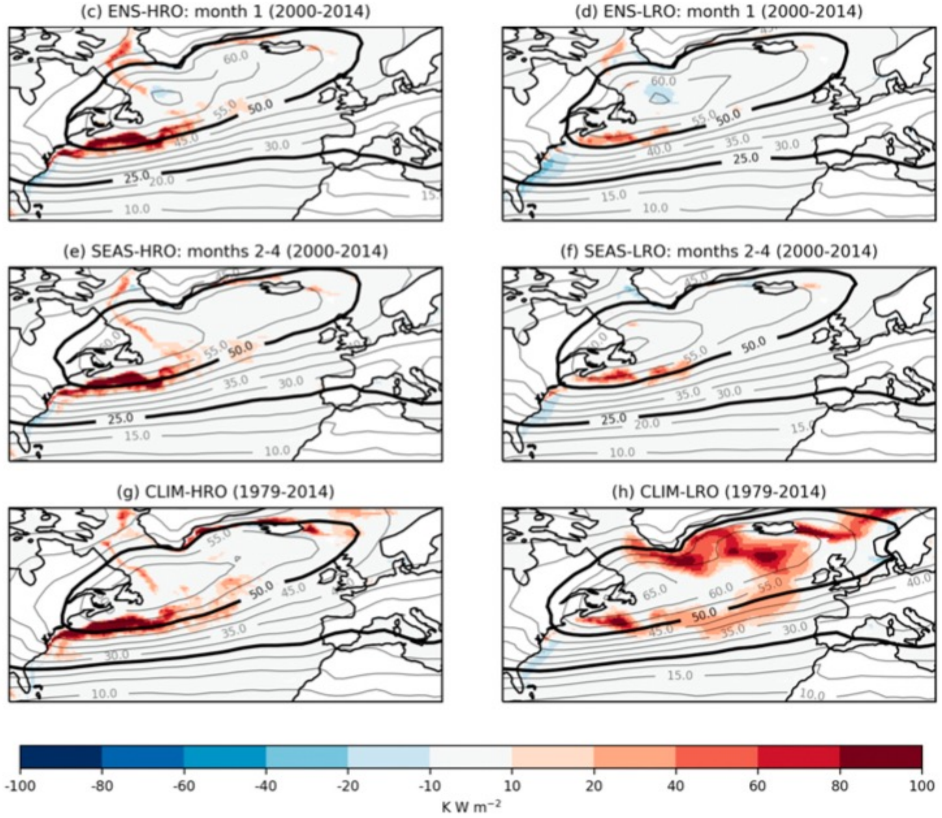


Roberts et al. (2020), *J. Clim.*

- Some impacts of increased ocean resolution (e.g., stronger air-sea interaction) are immediate and evident at all lead times.
- Other impacts scale with local and/or remote SST biases, which take time to develop and can be mitigated at short lead times with accurate ocean initialization.

Monthly covariance(SST, Q_{turb}) and Var($Z850_{2\text{-}6\ day}$)

25 km ocean | **100 km ocean**



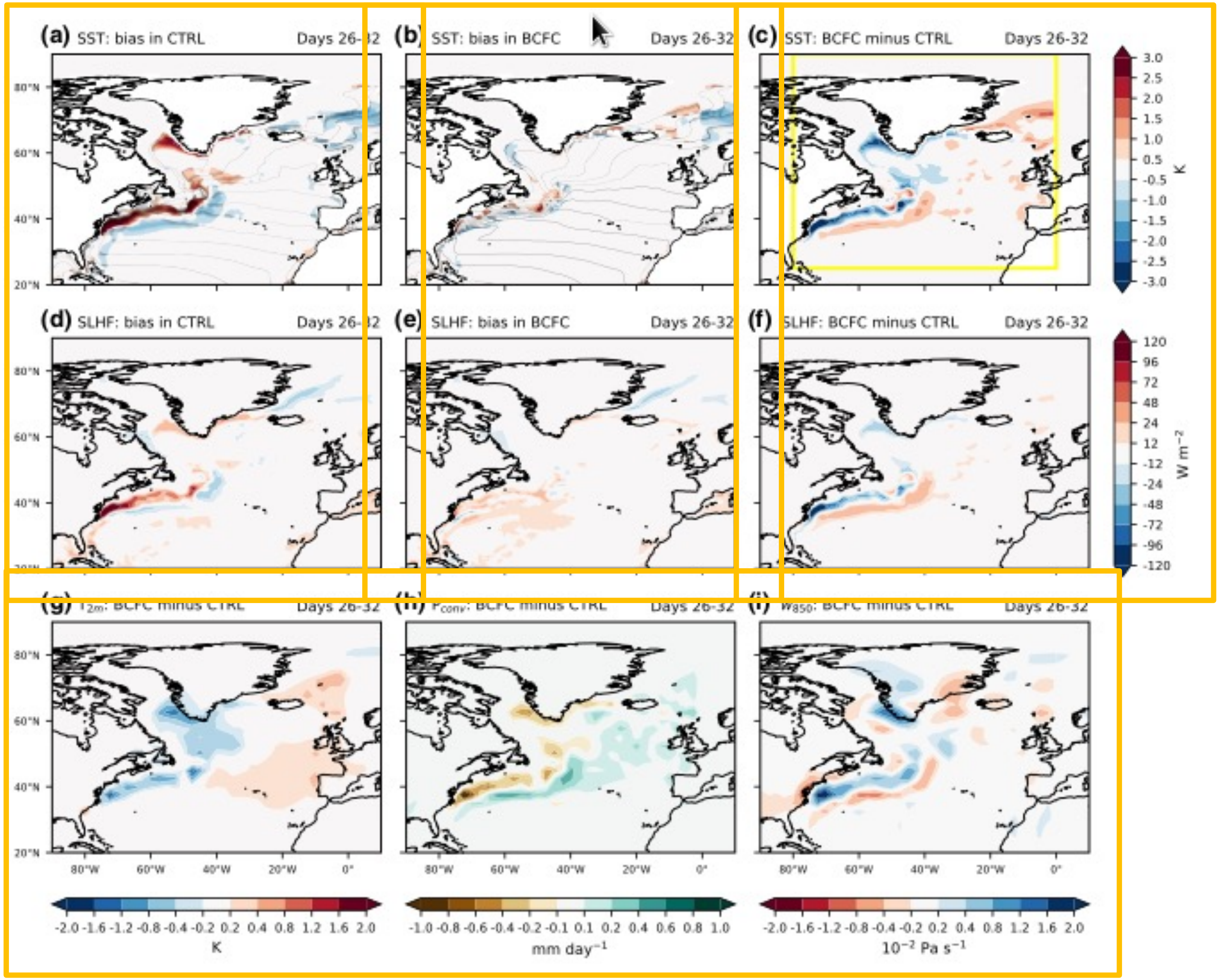
Impact of Gulf Stream SST biases in S2S reforecasts

- **Control (CTRL)** is a reference reforecast experiment, which is used to evaluate SST biases as a function of location, start date, and lead-time.

- **Bias-corrected forecast (BCFC)** is a second reforecast experiment in which the ocean receives atmospheric fluxes as normal, but North Atlantic SSTs seen by the atmosphere are adjusted using the model SST bias derived from CTRL.

Experiment	CTRL	BCFC
Description	Reference coupled reforecasts.	Coupled reforecasts with online bias-correction of SSTs in the North Atlantic domain.
Atm. config.	IFS cycle 43r1, Tco399 L91 (~25 km)	
Ocn/ice config.	NEMO v3.4/LIM2, ORCA025 Z75 (~25 km)	
Initial conditions	ERA interim (atmosphere, land, waves) and ORAS5 (ocean/ice).	
Reforecast config.	15-members initialized on the first and fifteenth of each month of an extended winter period (November-March) from 1989 to 2015 (i.e., 270 start dates).	

Impact of Gulf Stream SST on the mean state (week 4)



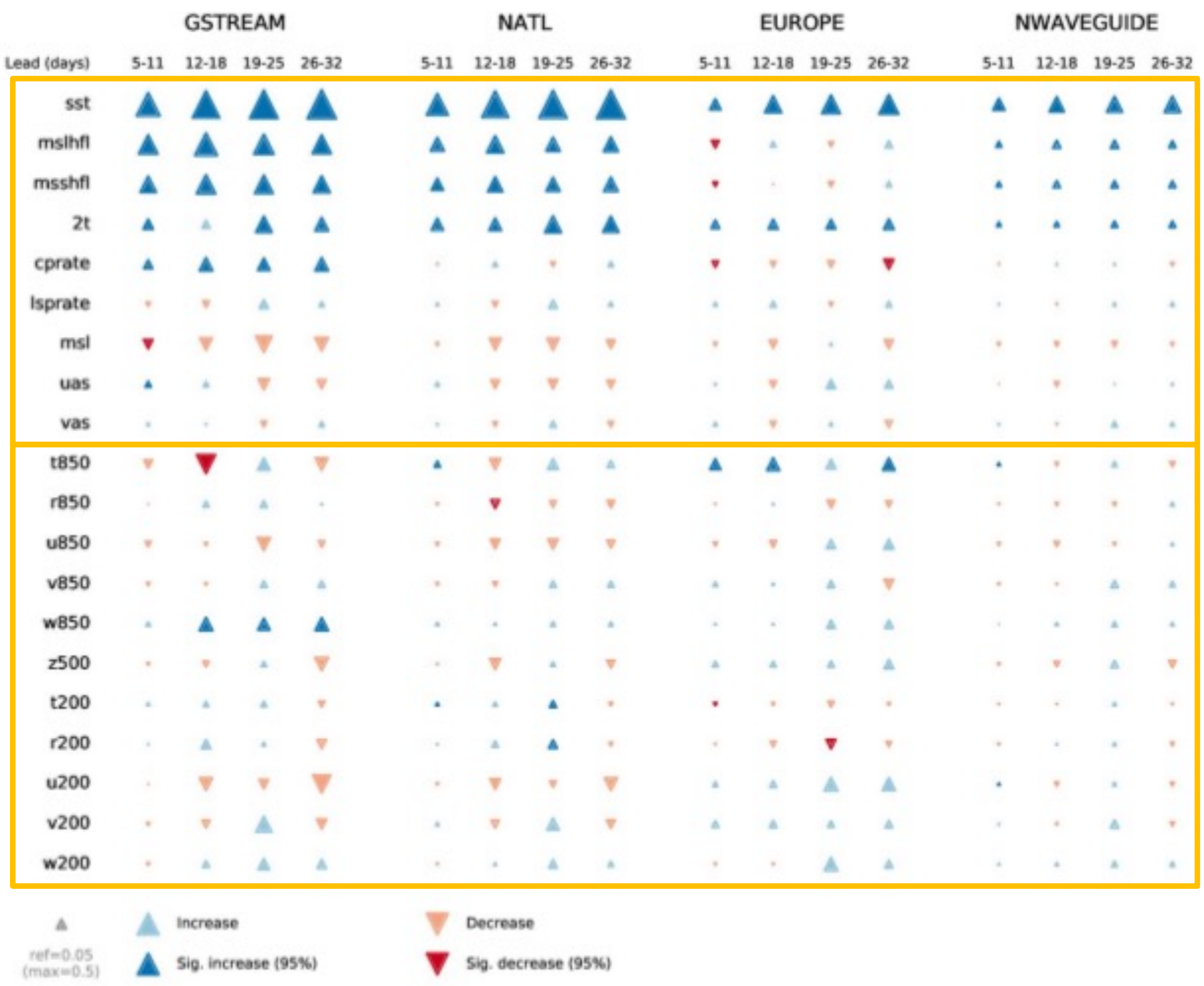
The largest North Atlantic SST biases in CTRL are associated with errors in the position and structure of the Gulf Stream.

North Atlantic SST errors are effectively reduced in BCFC.

Changes in SST are associated with significant changes in turbulent heat fluxes, 2m temperature, convective precipitation, and vertical motion.

Roberts et al. (2021), *GRL*

Impact of Gulf Stream SST on the mean state (weekly means)



Blue triangles indicate a reduction in the mean absolute bias integrated over grid points and start dates.

Near-surface fields are improved (SST, heat fluxes, 2m temperature).

Other than precipitation over the Gulf Stream, little impact on the mean state of variables in the free atmosphere (geopotential height, meridional/zonal wind, temperature, humidity).

Roberts et al. (2021), *GRL*

Impact of Gulf Stream SST on forecast skill (weekly anomalies)

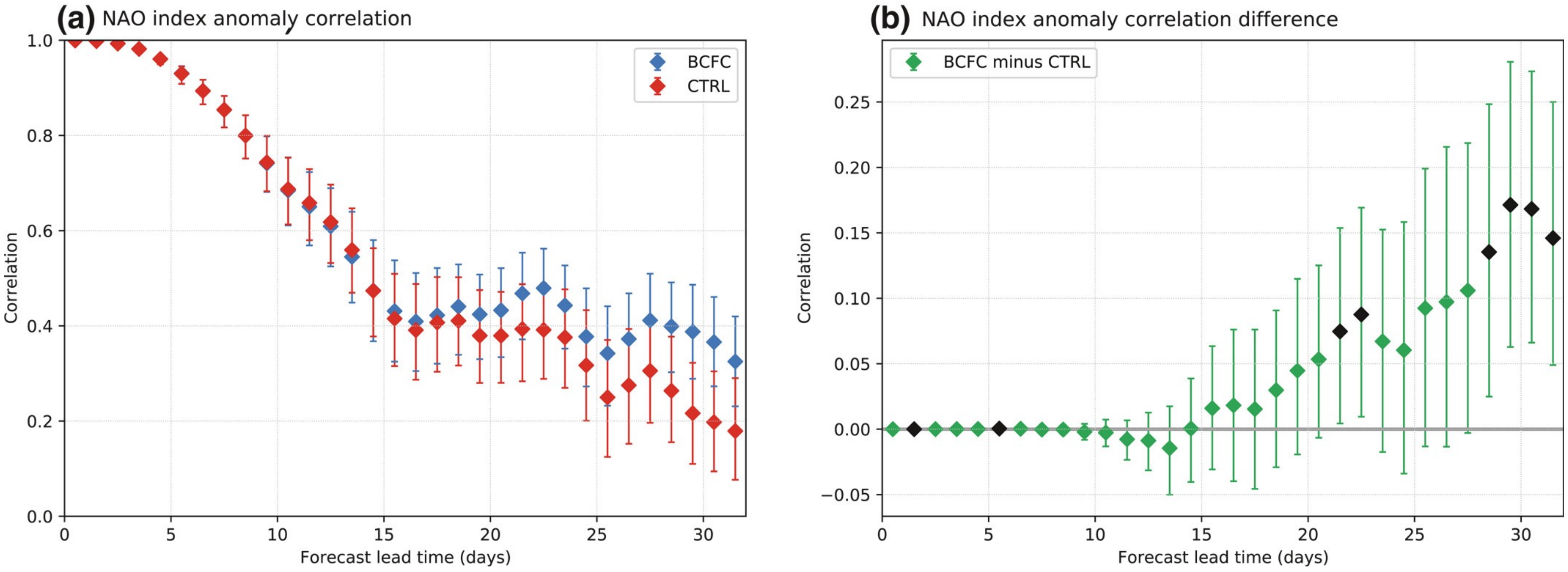
Blue triangles indicate an improvement in the continuous ranked probability skill score (CRPSS).

The reduction of SST biases significantly improves forecasts of weekly mean atmospheric circulation anomalies at a lead time of 26–32 days (i.e. “week 4”).

The impacts over Europe are most evident when forecasts have an active MJO in the initial conditions.

Roberts et al. (2021), *GRL*

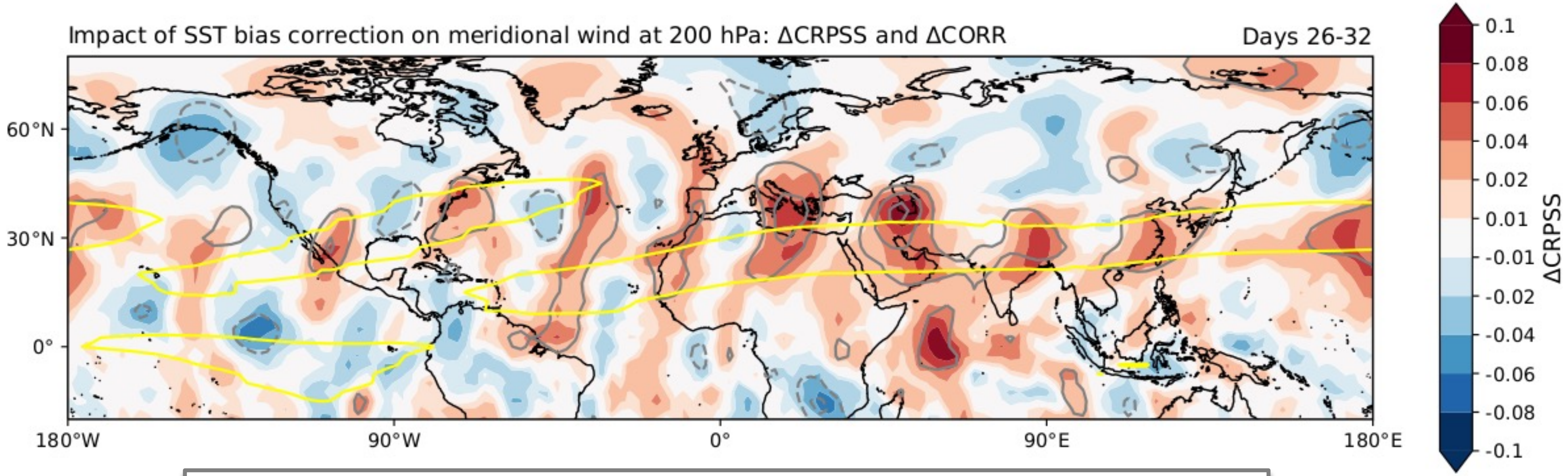
Impact of Gulf Stream SST on the North Atlantic Oscillation



North Atlantic SST bias correction also improves predictions of the North Atlantic Oscillation (NAO) at lead times of 15–32 days.

Roberts et al. (2021), *GRL*

Gulf Stream SST impacts propagate along the waveguide



Yellow contours show the 3 × 10^{-11} m^{-1} s^{-1} contour of the meridional gradient of absolute vorticity

- North Atlantic SST bias correction impacts upper atmosphere (200 hPa) forecast skill throughout the northern hemisphere.
- The spatial structure of the response is characteristic of stationary wave activity propagating along the northern hemisphere tropospheric waveguide.

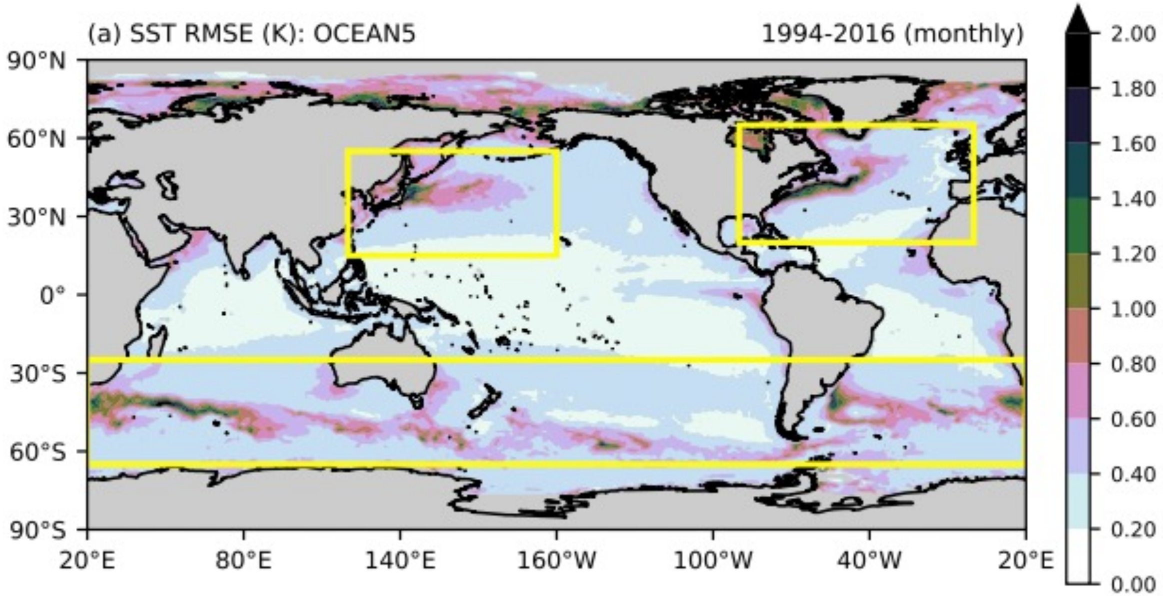
Roberts et al. (2021), *GRL*

Hybrid ocean initial conditions

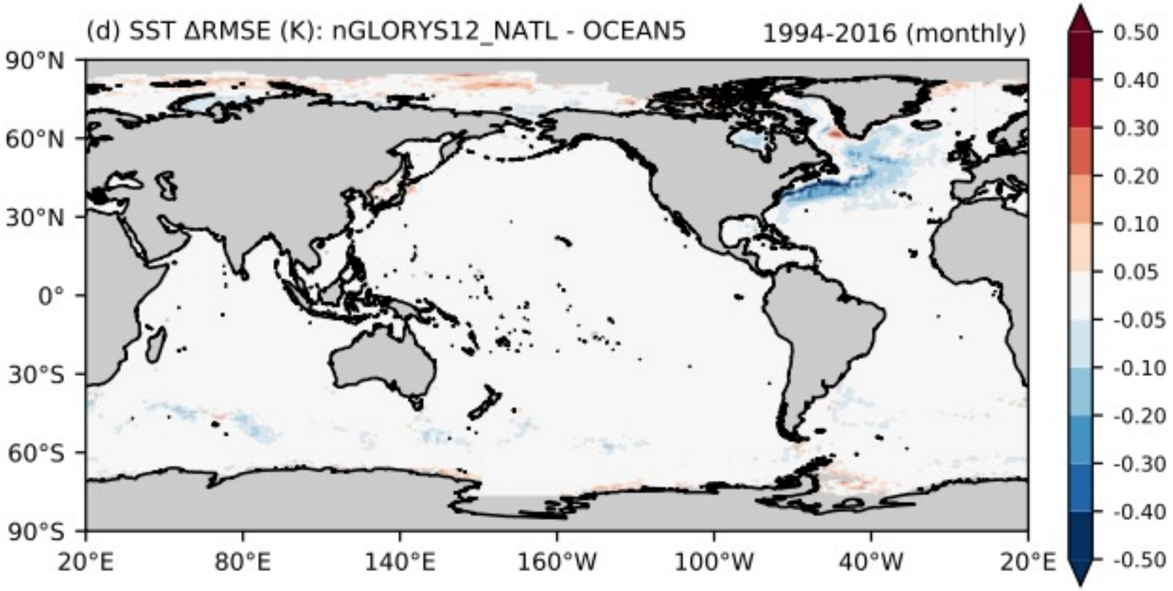
Errors in Gulf Stream position at S2S lead times are (in part) inherited from errors in the ECMWF ocean analysis.

Hypothesis: Gulf Stream initial conditions derived from a state estimate with more realistic mesoscale features could benefit eddy-permitting forecast systems without changing forecast model resolution.

ECMWF ocean initial conditions (OCEAN5)



Hybrid initial conditions: OCEAN5 + GLORYS12 (N. Atl.)

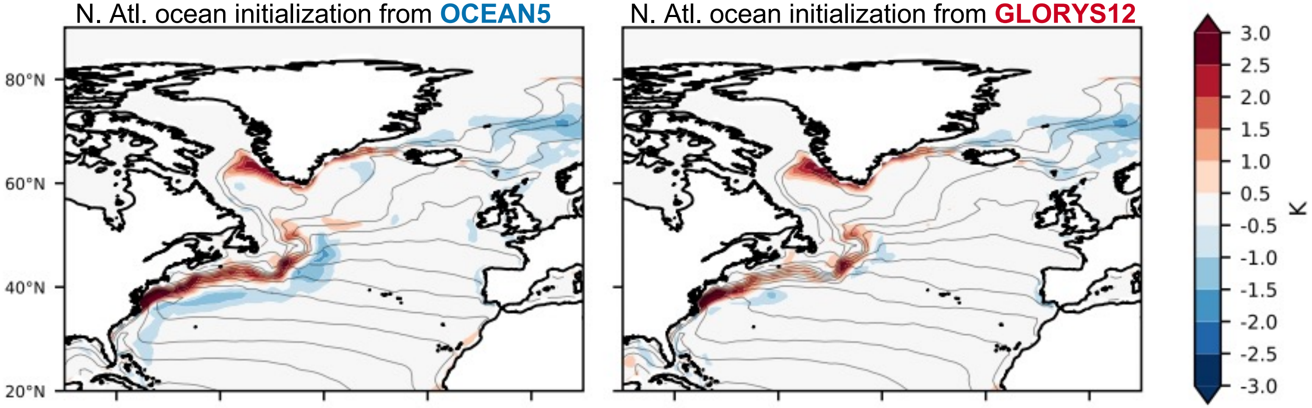


Roberts et al. (2022), *QJRMS*

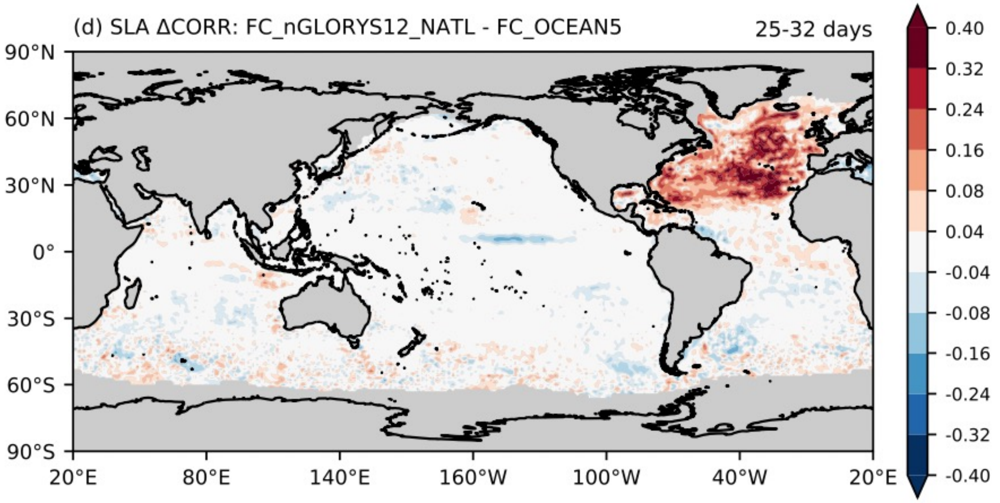
Coupled response to improved initialization of the Gulf Stream

- Gulf Stream SST biases are reduced (but not eliminated) and ocean forecast skill is improved.
- However, very limited impacts on atmospheric mean state and forecast skill.

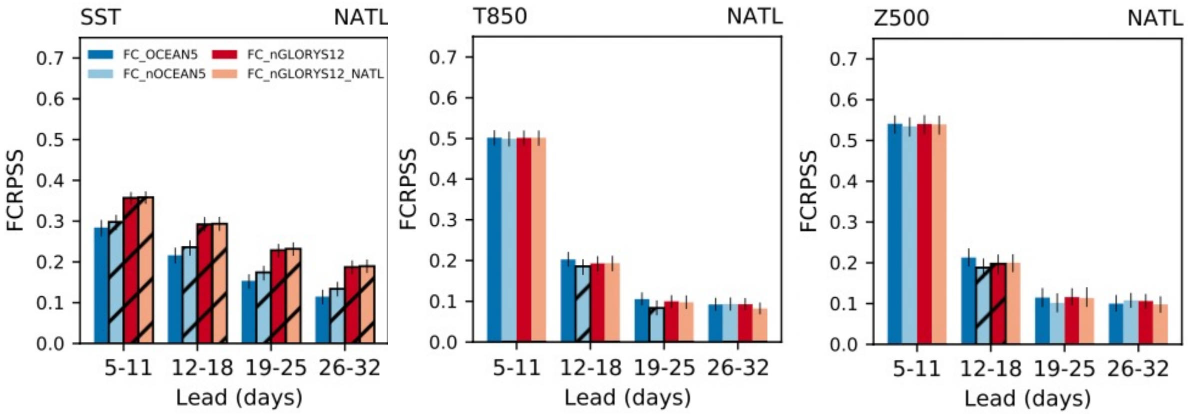
SST biases (week 4, NDJFM)



ΔCORR sea level anomaly vs altimeter



Probabilistic skill vs lead time



Roberts et al. (2022), *QJRMS*

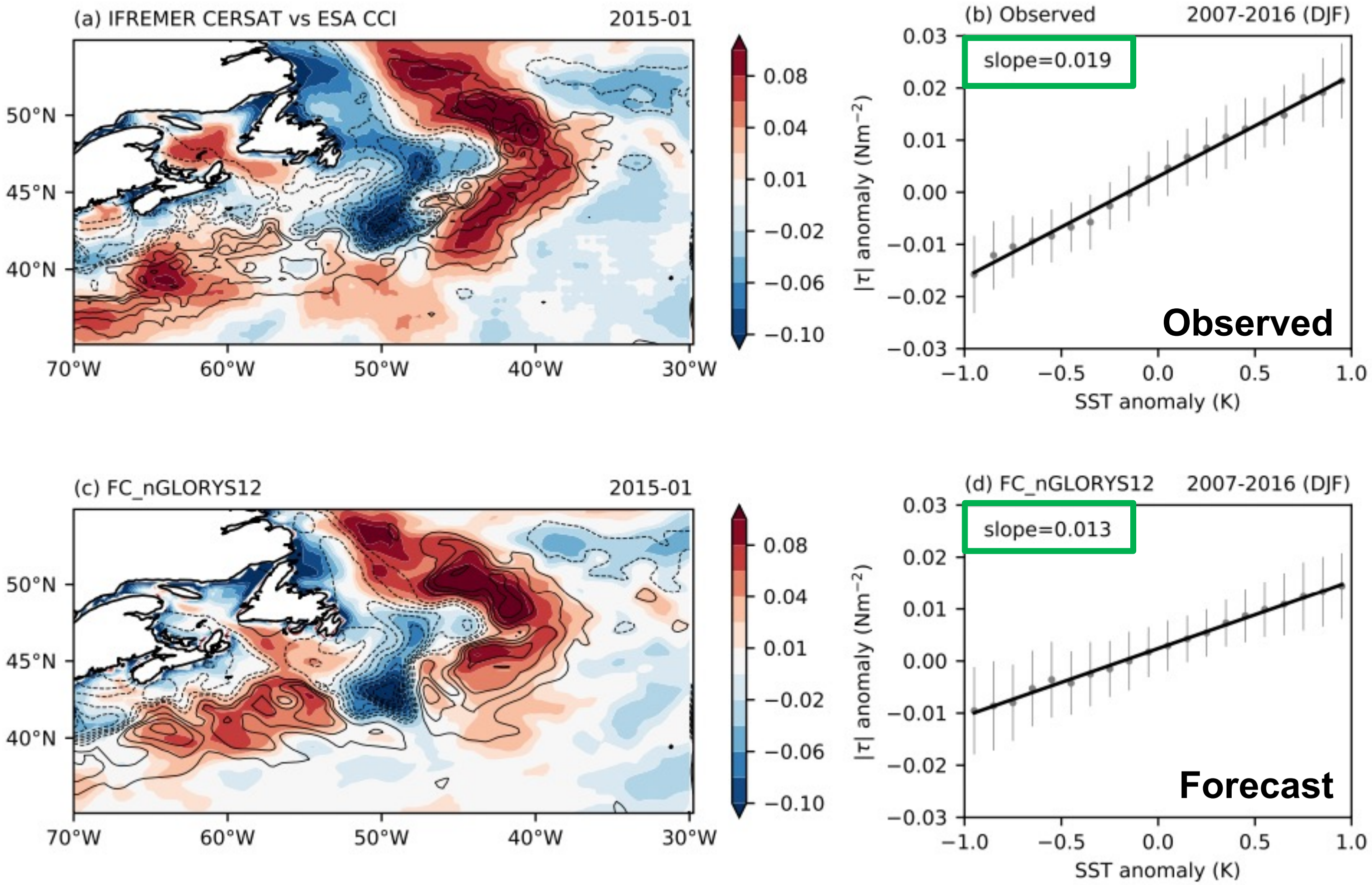
Atmospheric (in)sensitivity to improved SST forecasts

Improvements to Gulf Stream initialization and SST forecast skill have a limited impact on the free atmosphere.

Possible explanations?

1. Gulf Stream initialization is improved (but imperfect) and still not good enough.
2. The impacts may be stronger in coupled models with higher ocean and atmosphere resolutions.
3. For example, ECMWF reforecasts underestimate mesoscale air-sea interaction coupling coefficients by 20-40% (see figure).

Spatially high-pass filtered wind-stress magnitude and sea-surface temperature following Maloney and Chelton (2006)



Roberts et al. (2022), *QJRMS*

Summary

ECMWF S2S forecasts suffer from SST biases associated with errors in the location of the Gulf Stream.

Artificially correcting these errors improves the mean state of the North Atlantic region and has a positive impact on forecasts of atmospheric circulation anomalies.

Improvements to forecast skill extend beyond the North Atlantic into Europe and along the northern hemisphere tropospheric waveguide.

We interpret these impacts as a response to the southward shift of the Gulf Stream, which changes the location, magnitude, and timing of convection and vertical motion associated with extratropical storms and planetary wave forcing in the upper troposphere.

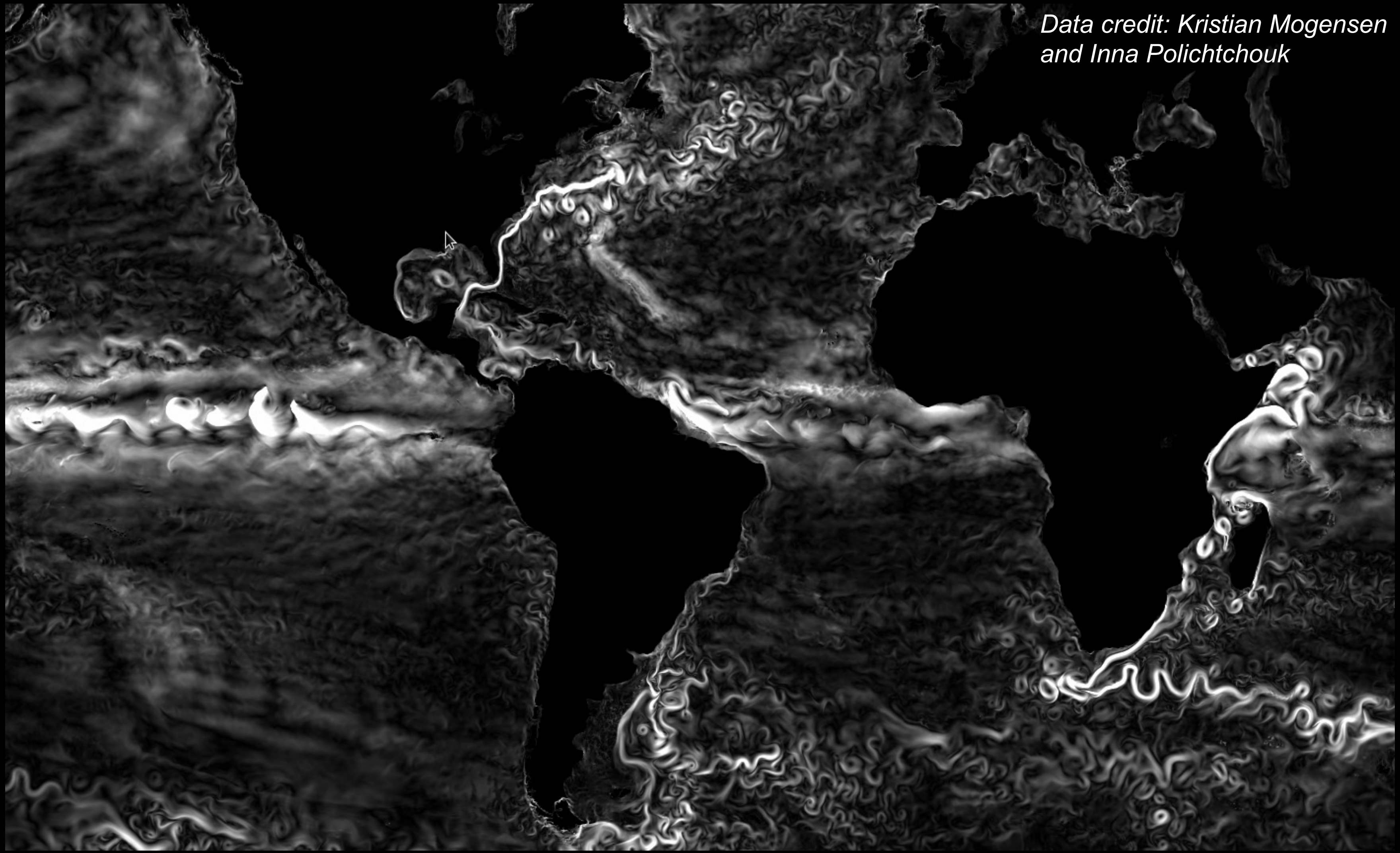
We can improve ocean forecasts without increasing forecast model resolution by improving Gulf Stream initialization, but the atmospheric impact is limited (*no substitute for resolution?*)

These studies provide evidence for the potential benefits of models that can better resolve the position of ocean fronts and mid-latitude air-sea interactions in (re)analyses and (re)forecasts.

The road to increased ocean resolution @ ECMWF

- Working towards implementation of eddy-permitting configuration of NEMO4/SI3 in all operational forecast systems (medium-range to seasonal).
- Aiming to run prototype eddy-rich ensemble S2S reforecasts within the next year.
- ECMWF contributing to various projects (e.g., NextGEMS, DestinE, EERIE) developing the science and technical infrastructure to efficiently run km-scale coupled ocean-atmosphere-ice models at scale.
- Idealized experimentation to characterize and understand the impact of SST fronts and eddies on weather and climate variability (EERIE).
- Despite the potential benefits, there are many scientific and technical challenges to running eddy-rich ensemble forecast systems.
- Ongoing work to prepare the path for the extensive use of eddy-rich ocean configurations at ECMWF includes:
  - Optimization work (e.g., single precision ocean/ice components) .
  - Efficient methods to process and store large volumes of input/output data (including restart files).
  - Generation of (ensemble) ocean and sea-ice initial conditions, including multi-scale ocean data assimilation methods.

The future of coupled forecasts at ECMWF?



This image shows a snapshot of surface current speeds in a prototype version of the ECMWF global forecast model (IFS ~4 km, NEMO ~8 km).