The role of the oceans for predictability across weather and climate timescales

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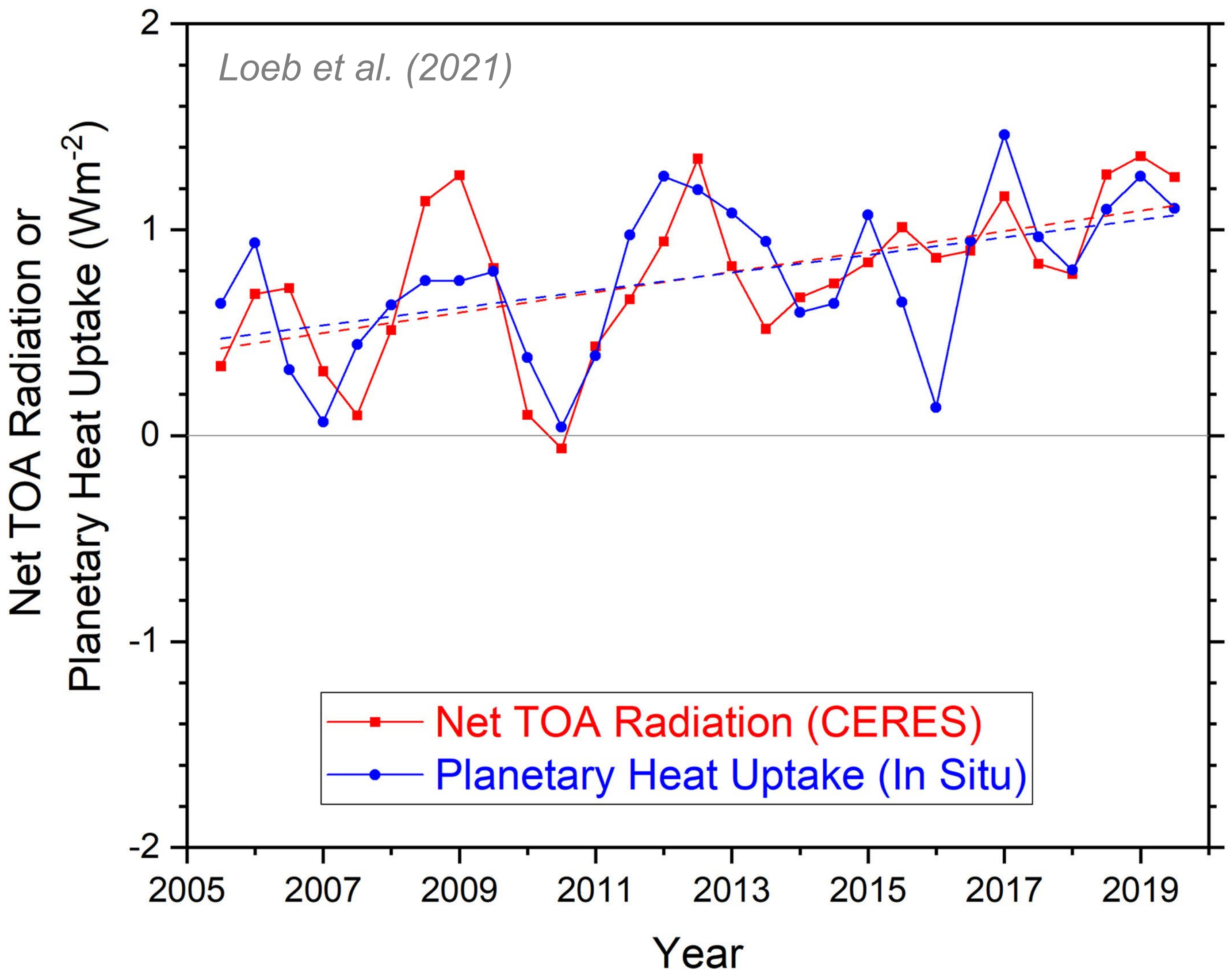
With thanks to Matthias Aengenheyster, Magdalena Balmaseda, Sarah Keeley, Kristian Mogensen, Charles Pelletier, Frederic Vitart, Hao Zuo, and many other colleagues at ECMWF.

ECMWF

Earth's energy budget is (mostly!) balanced by ocean heat uptake



About 90% of the excess energy associated with top-of-atmosphere (TOA) radiative imbalance is stored in the ocean (*von Schuckmann et al., 2023*).

Global energy balance in response to climate change can be approximated:

$$\Delta T = (F - N)/\alpha$$

Global mean surface temperature change (K)

Climate forcing (W m^{-2})

Net TOA radiation ≈ ocean heat uptake (W m^{-2})

Climate sensitivity parameter (W m^{-2} K^{-1})

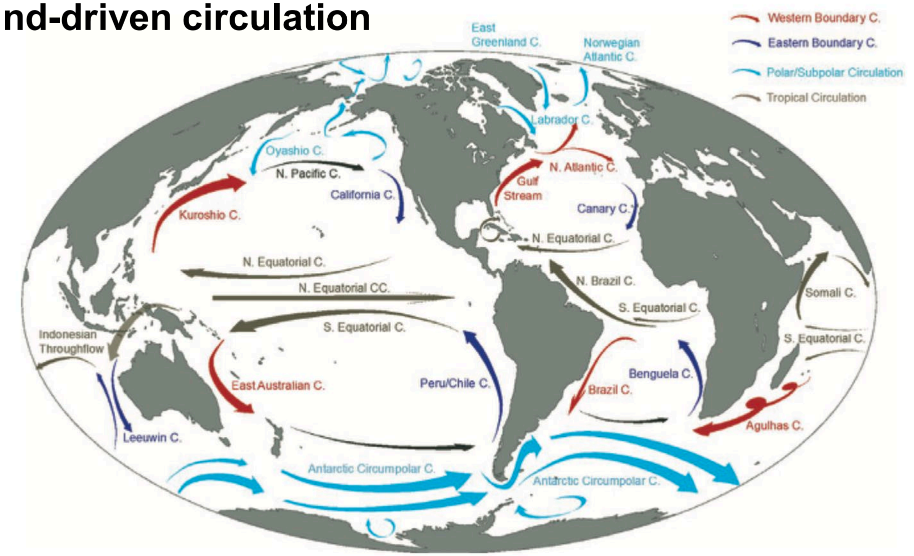
At steady state, N→0 and ΔT → F/α. However, ocean heat uptake (N) moderates the rate of <u>time-dependent</u> climate change.

For given forcing (F) and climate sensitivity (α), the transient climate response (ΔT) is reduced when ocean heat uptake (N) is higher.

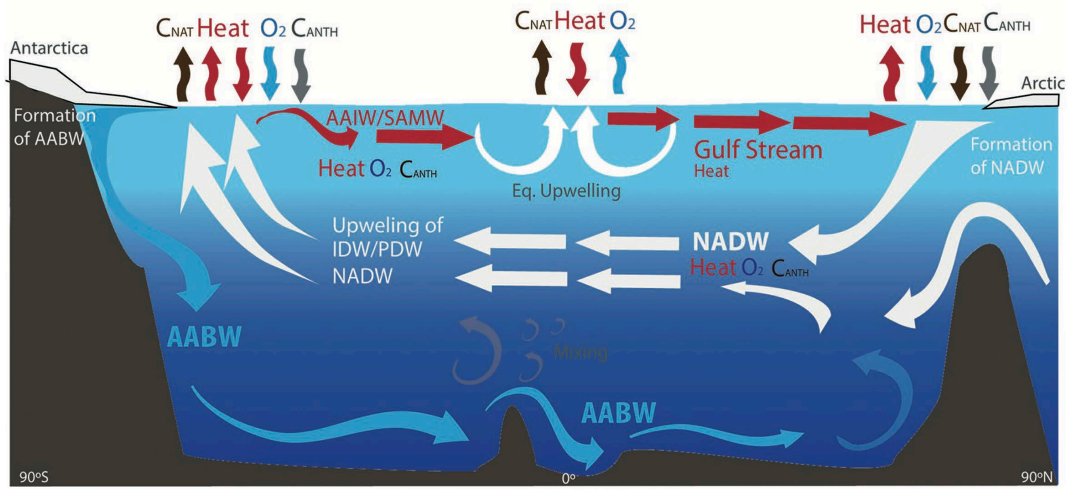
See Kuhlbrodt and Gregory (2012), Gregory and Forster (2008) for discussion of heat uptake "efficiency" in climate models.

Ocean circulation changes contribute to uncertainty in regional climate predictions

Wind-driven circulation

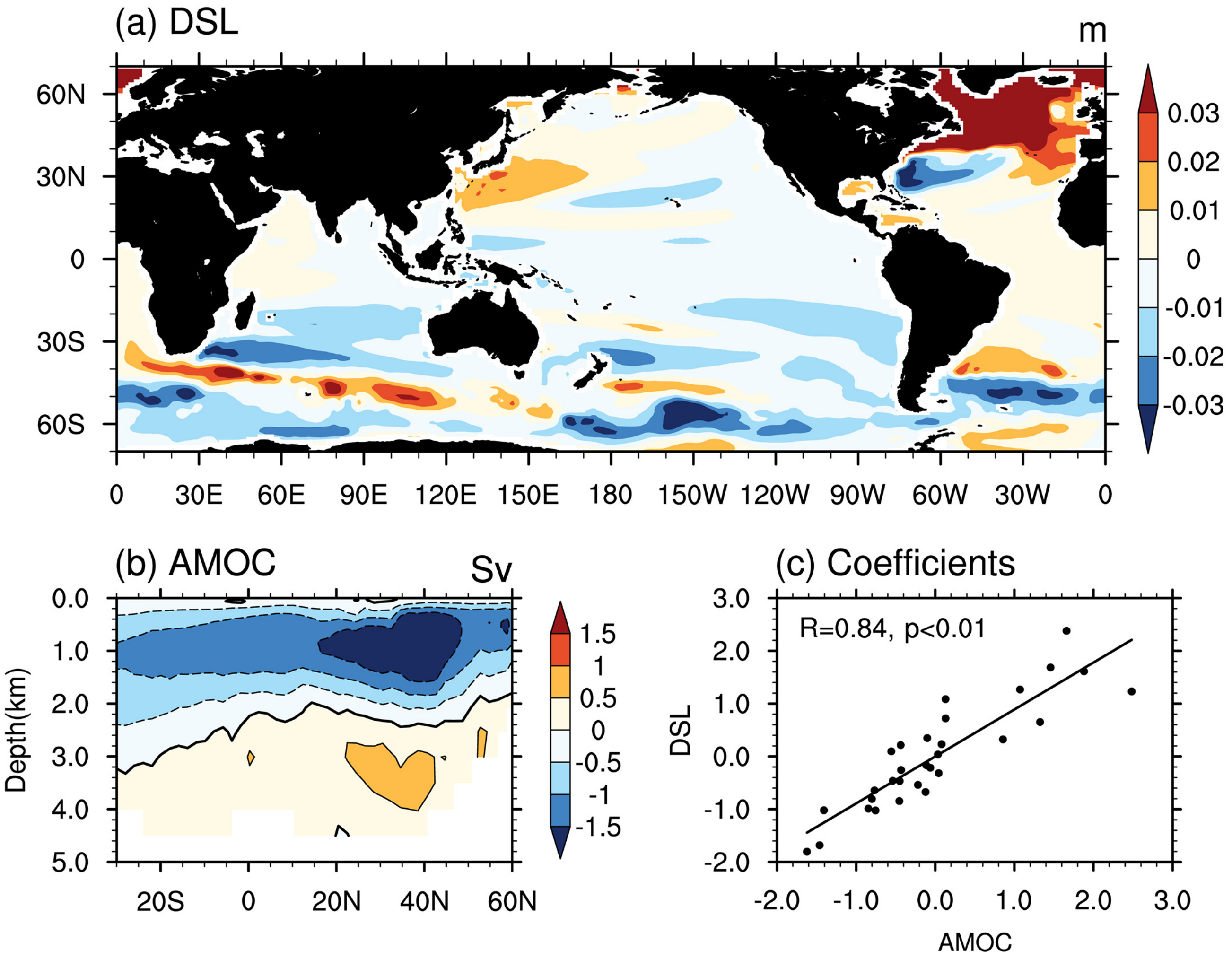


Overturning circulation



Bertrand Delorme and Yassir Eddebbar

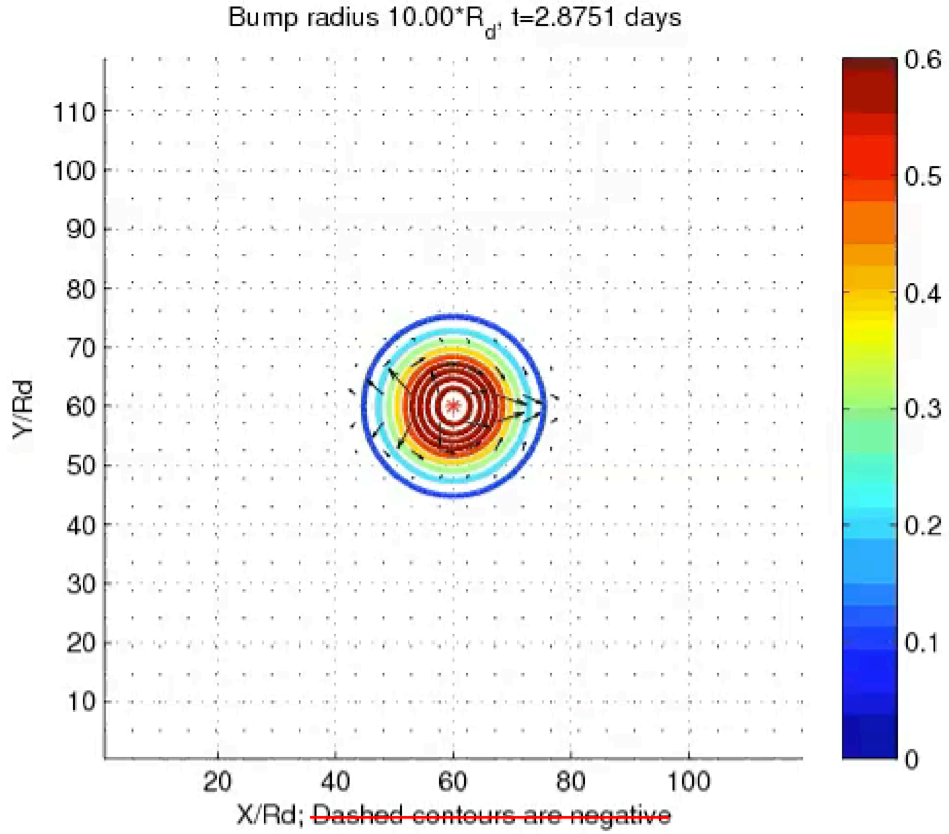
Example: Spatial patterns of changes in the (a) dynamic sea level (DSL) and (b) Atlantic meridional overturning circulation (AMOC) for the first inter-model singular value decomposition mode (accounting for 68.7% of total covariance) in CMIP5 models under the RCP4.5 scenario.



Chen et al. (2018)

Internal ocean waves are an important process for coupled climate variability

Rossby and Kelvin wave response to an equatorial disturbance in a reduced-gravity shallow water model

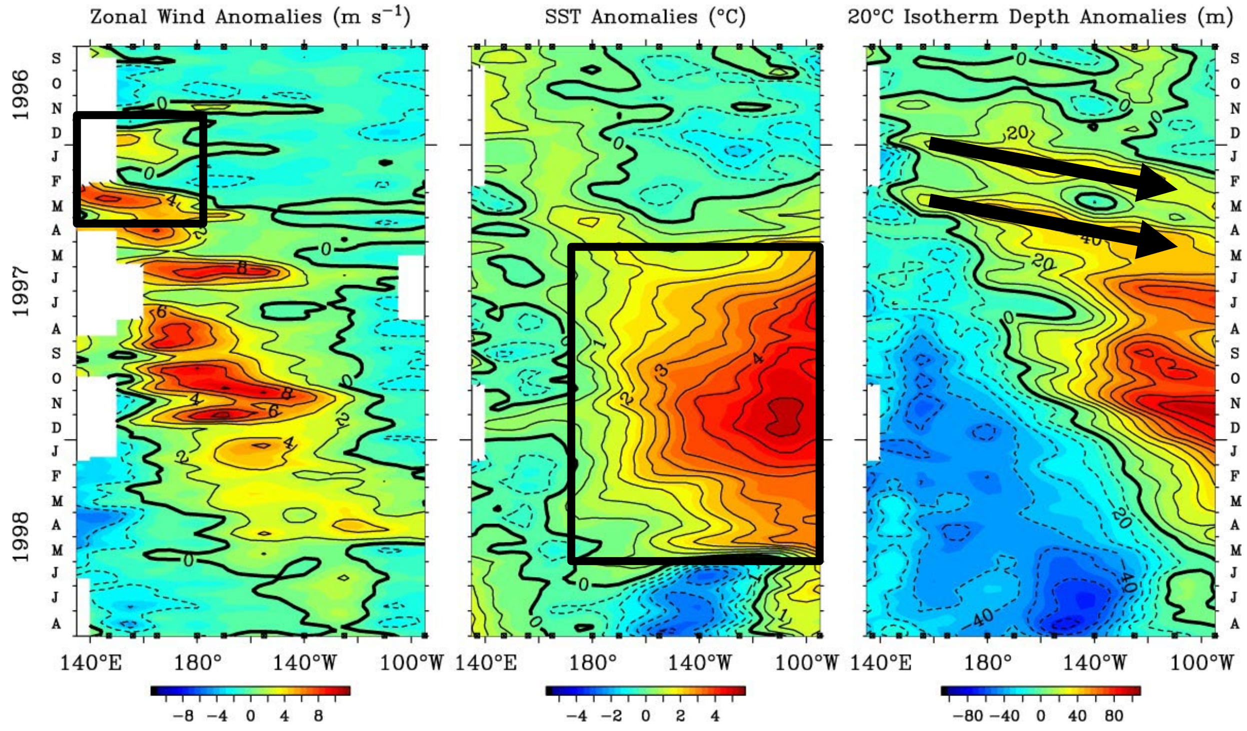


Negative contours should be dashed!

James Pringle, https://oxbow.sr.unh.edu/WaveMovies/

Large-scale equatorial wave dynamics are well-resolved by global ocean models and provide a source of predictability for modes of coupled ocean-atmosphere variability (e.g. ENSO).

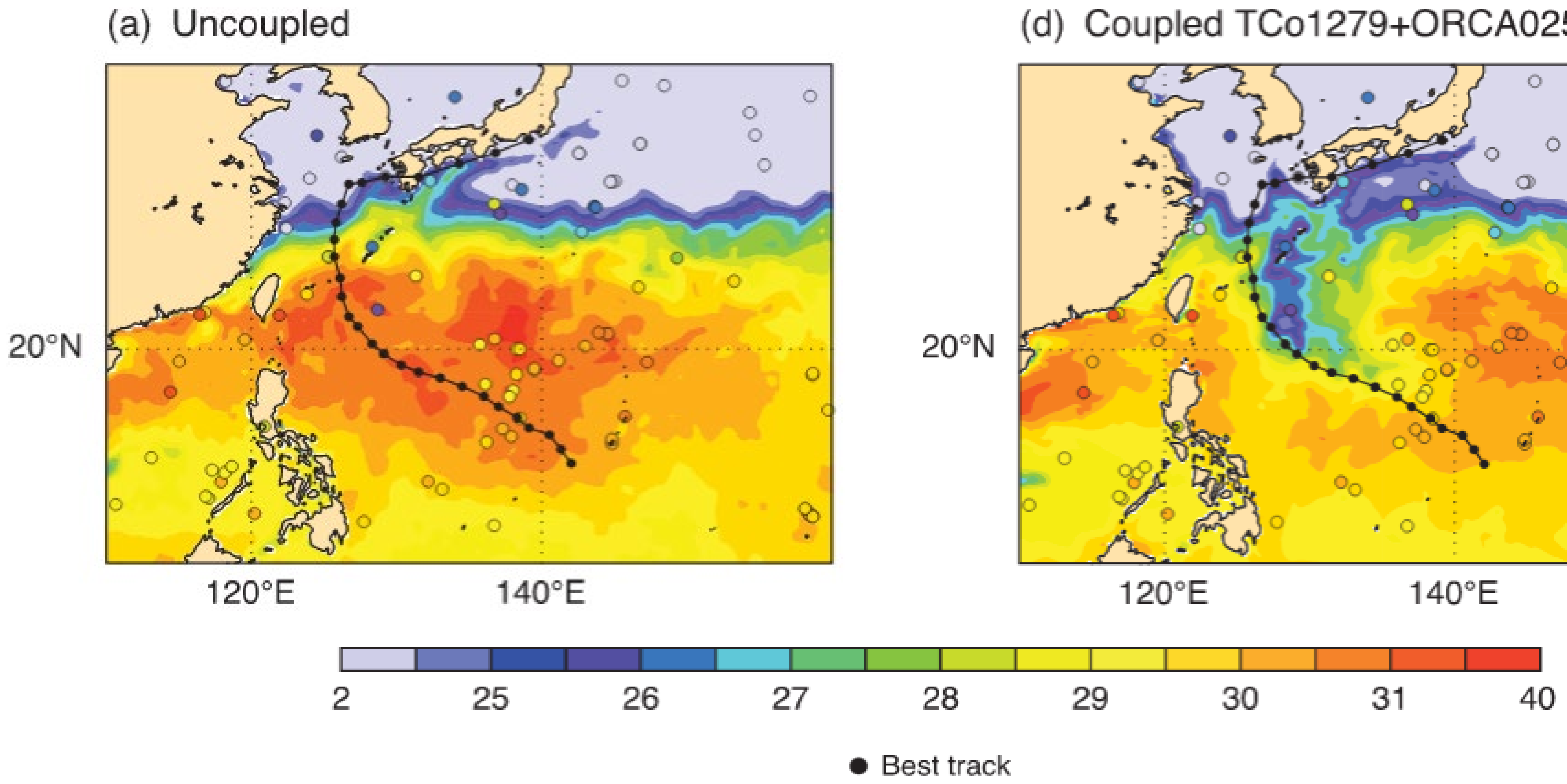
Example: The 1997-98 El Niño was preceded by MJO-related westerly wind events that generated equatorial Kelvin waves.



McPhaden (1999)

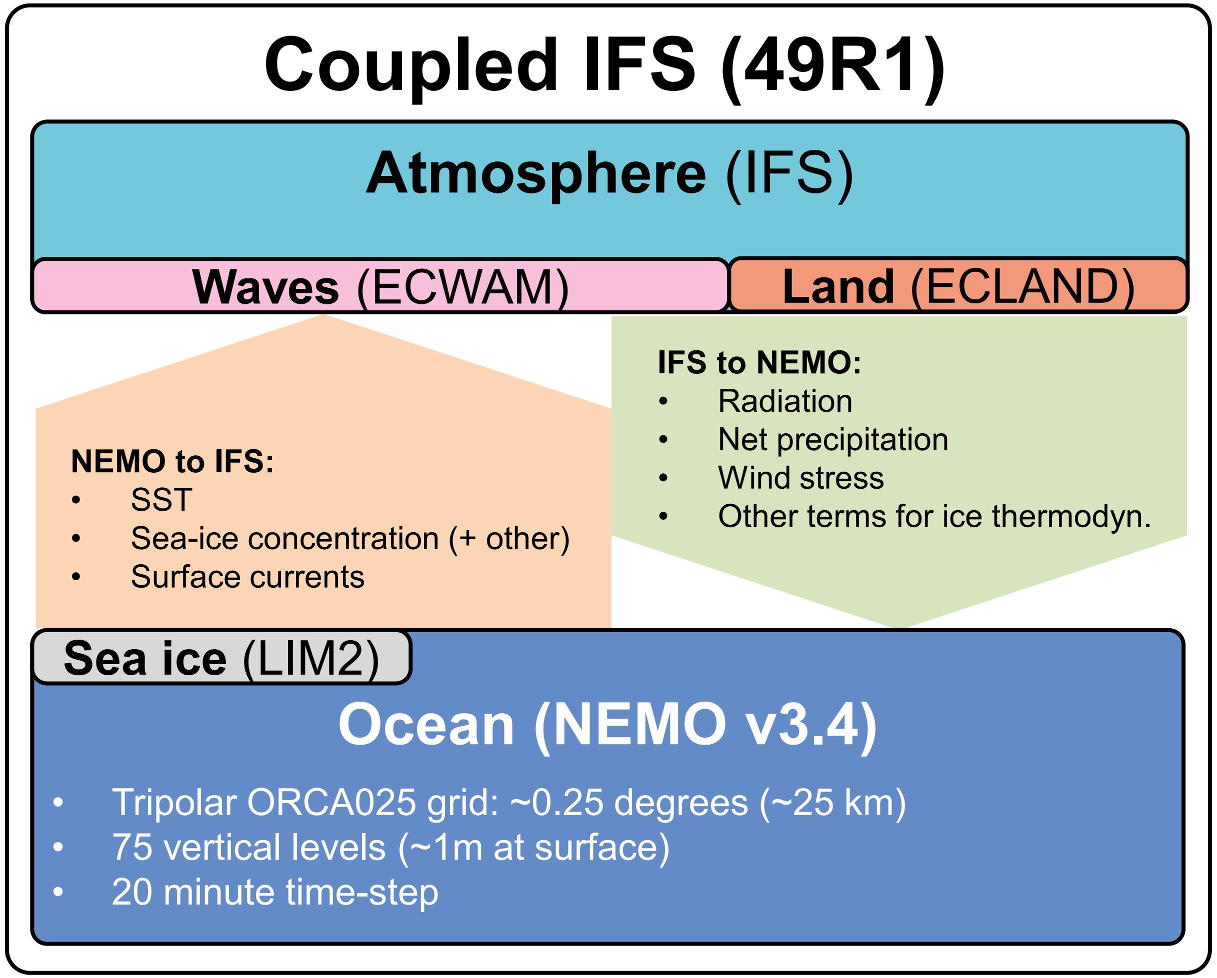
Air-sea interactions and coupled feedbacks are important for NWP

Case study of tropical cyclone Neoguri (2014) with/without ocean coupling. Inclusion of a dynamic ocean allows simulation of a strong cold wake, which in turn impacts the evolution of the overlying cyclone.



Mogensen et al. (2017)

All operational ECMWF forecasts are coupled to ocean and sea ice models



See Mogensen et al. (2012) for technical details of the ECMWF single-executable coupling.

All operational configurations of ECMWF IFS include dynamic representations of the ocean, atmosphere, sea ice, land surface, and ocean waves.

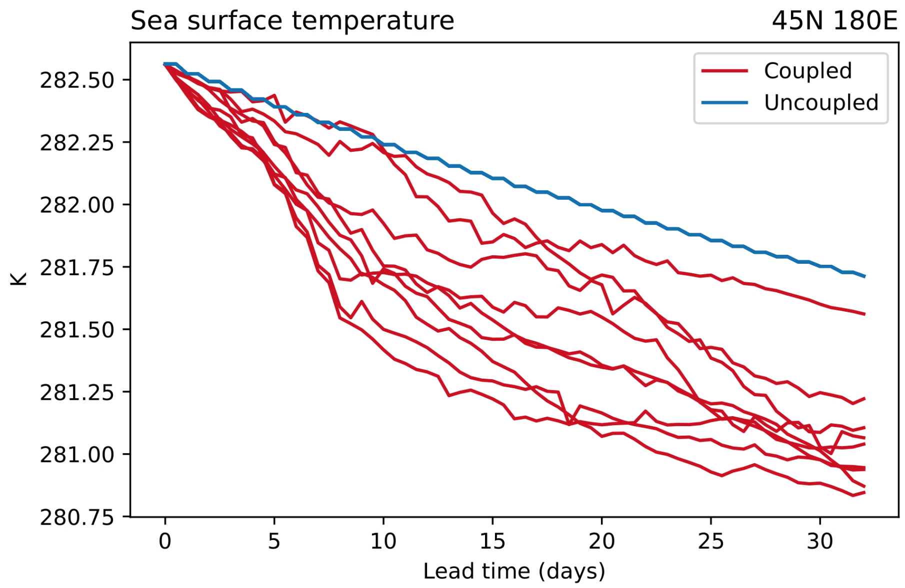
System	Atm Res	Ocn Res	Max Lead time
Medium range	~9 km	~25 km	15 days
Sub-seasonal	~35 km	~25 km	46 days
Seasonal	~35 km	~25 km	13 months

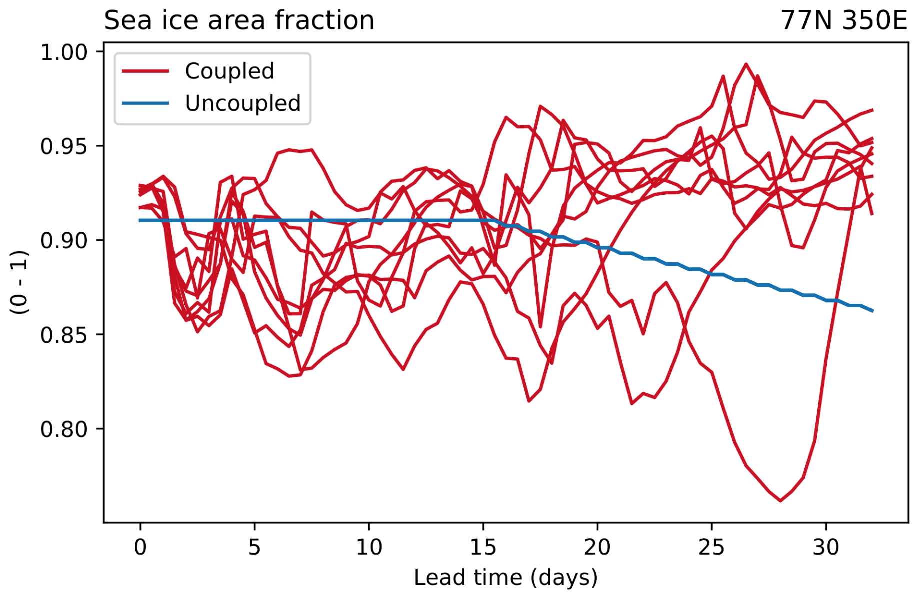
Importantly, ocean configurations also need to accurately represent longer timescales in the reanalyses that provide initial conditions for reforecasts.

Poor simulation of slower ocean processes can lead to non-stationary reforecast biases that influence real-time forecast products through calibration (e.g. *Tietsche et al. 2020*).

When and where do we see the impacts of ocean coupling?

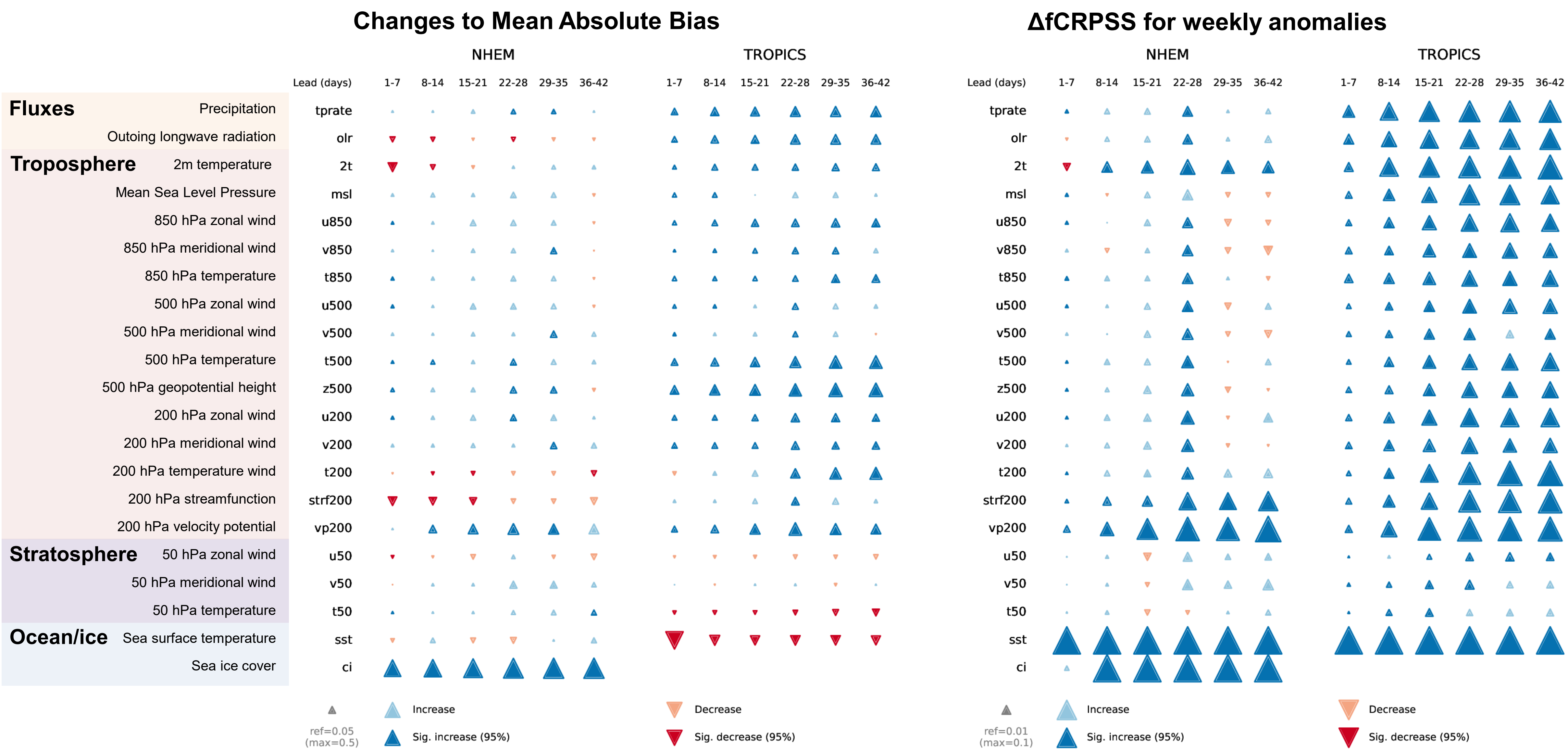
	"Coupled"	"Uncoupled"
Atmosphere	IFS Cycle 49R2, Tco319 L137 (~35 km)	
SSTs	NEMO4 eORCA025_Z75 (~25 km)	Climatology + persistence of initial SST anomaly
Sea ice cover	SI3 eORCA025_Z75 (~25 km)	Day 1-15: persistence of initial ice cover. Day 16-45: blends persistence → climatology. Beyond day 45: ice cover climatology.
Initial conditions	ERA5, OCEAN6	ERA5
Reforecast	10+1 members, 46 days from 1st of each month, 216 start dates, 2006-2023	





Impact of ocean coupling in sub-seasonal ensemble reforecasts

Reforecast configuration
- 10 perturbed members
- 46 days
- 216 start dates, 2006-2023



Improved with ocean coupling **Degraded with ocean coupling**

Impact of ocean coupling on 200 hPa temperature anomalies

Reforecast configuration
- 10 perturbed members
- 46 days
- 216 start dates, 2006-2023

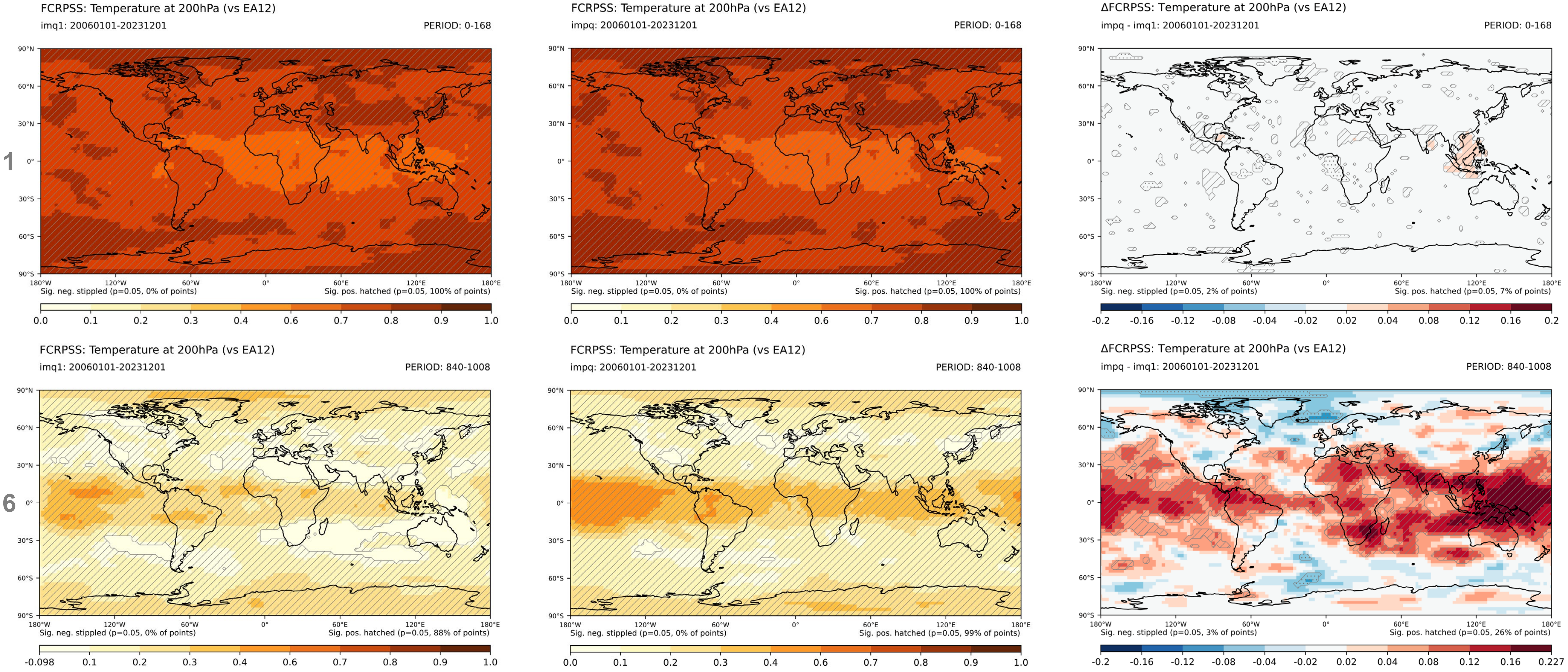
Fair version of the continuous ranked probability skill score (fCRPSS)

ΔfCRPSS for weekly anomalies

Uncoupled | **Coupled** | **Coupled minus Uncoupled**

Week 1

Week 6

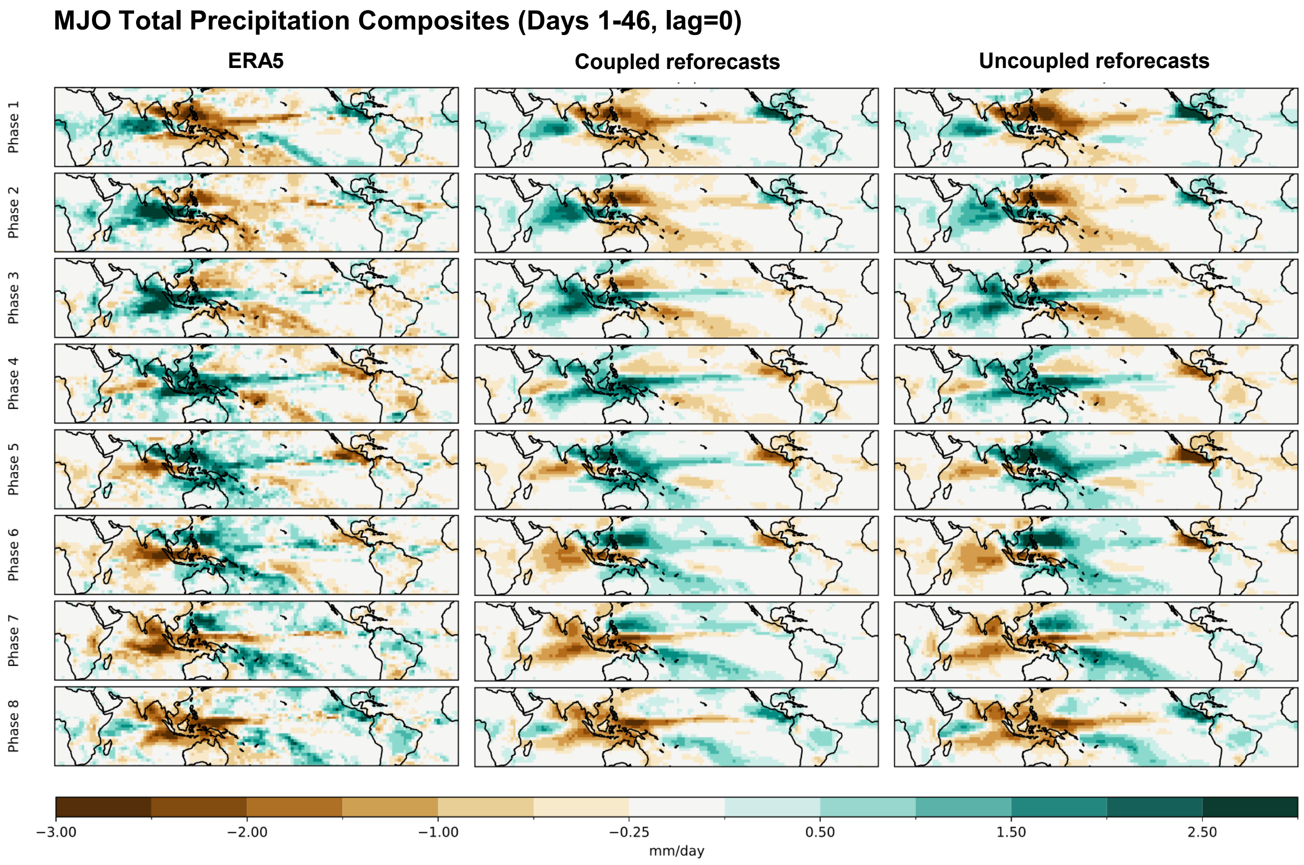


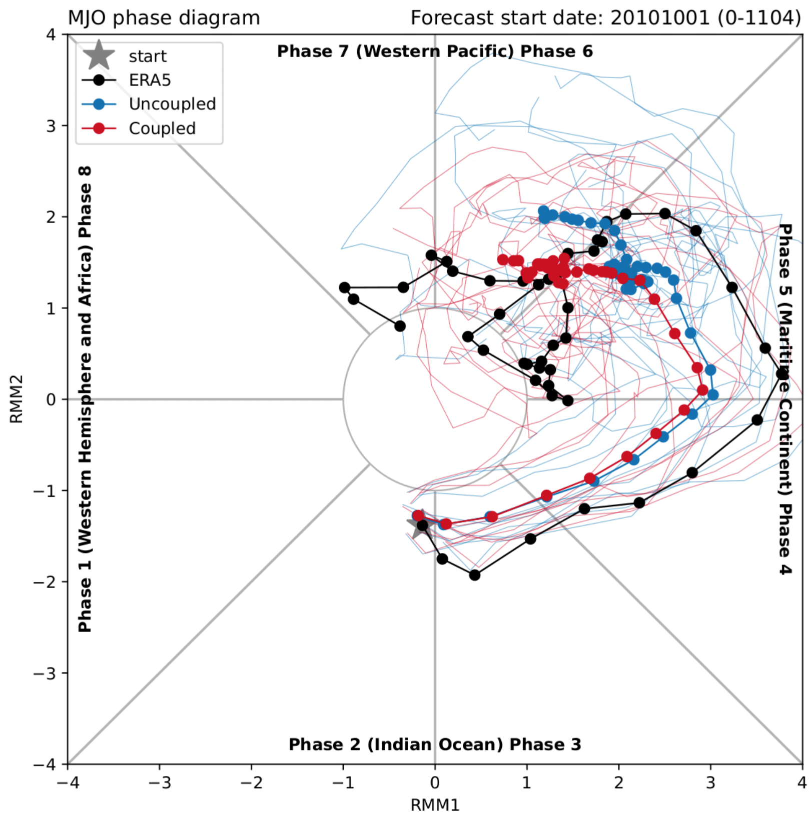
Improved with ocean coupling
Degraded with ocean coupling

Impact of ocean coupling on the Madden-Julian Oscillation (MJO)

The Madden-Julian Oscillation (MJO) has a timescale of ~30-60 days and is the leading mode of intraseasonal variability in the tropics associated with eastward propagating circulation and precipitation anomalies.

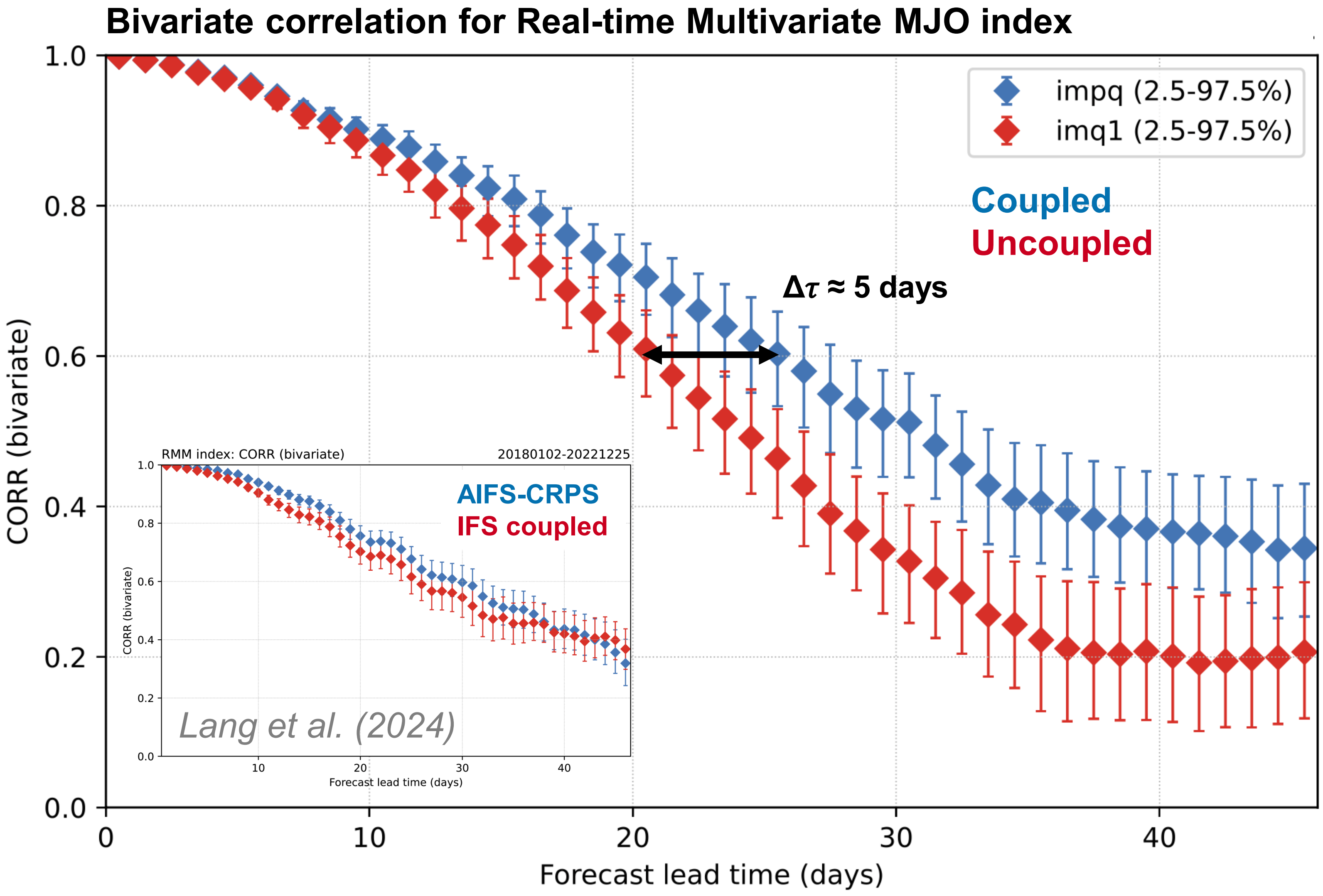
Both reforecasts simulate realistic MJO propagation and associated precipitation anomalies. It is difficult to discriminate between “coupled” and “uncoupled” simulations in case studies.





Also see Woolnough et al. (2007), Kim et al. (2010), Klingaman and Woolnough (2014), and DeMott et al. (2015).

Ocean coupling improves the skill of Madden-Julian Oscillation (MJO) predictions



Averaged over many cases, MJO forecast skill is improved with ocean coupling.

Predictability horizon (CORR > 0.6) extended by ~5 days.

In these simulations, improved skill is associated with reduced phase bias (≈ faster propagation).

Previous studies have emphasised the importance of coupling for more realistic interactions between convection, moisture advection, ocean mixing, and SSTs (*e.g. DeMott et al. 2015*).

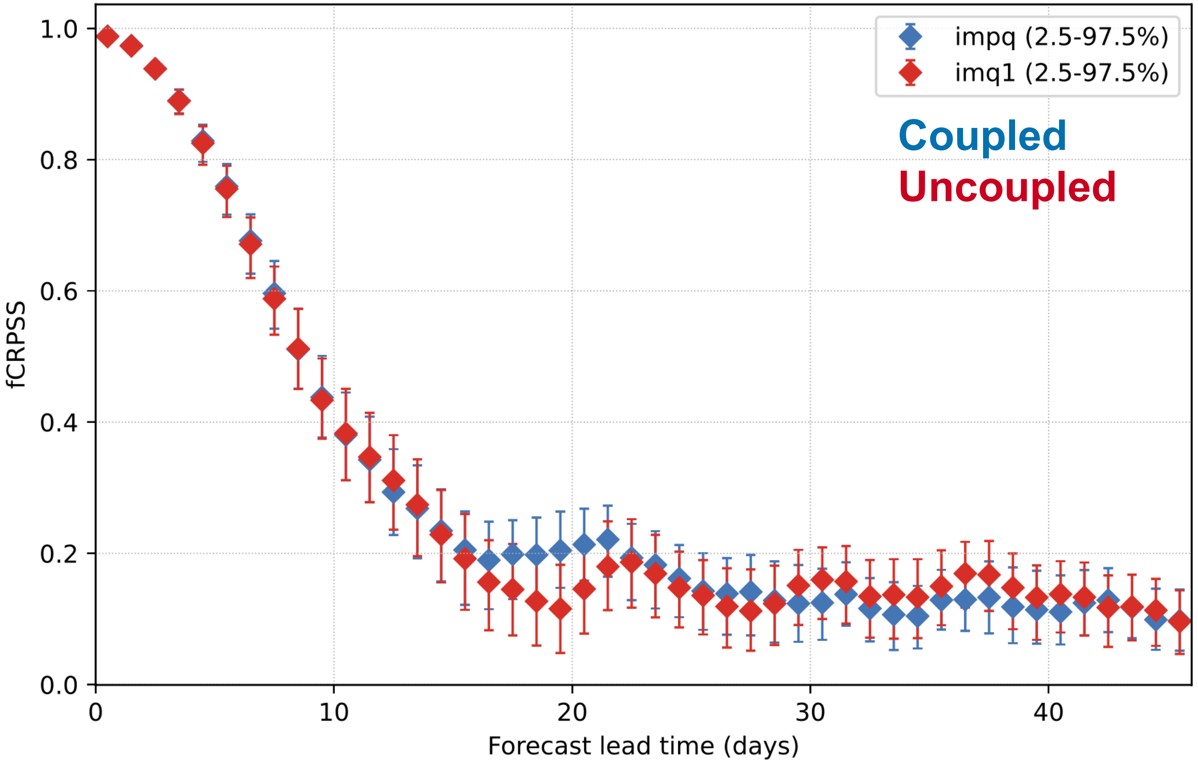
Also see Woolnough et al. (2007), Kim et al. (2010), Klingaman and Woolnough (2014), and DeMott et al. (2015).

Ocean coupling has limited impact on extratropical circulation indices

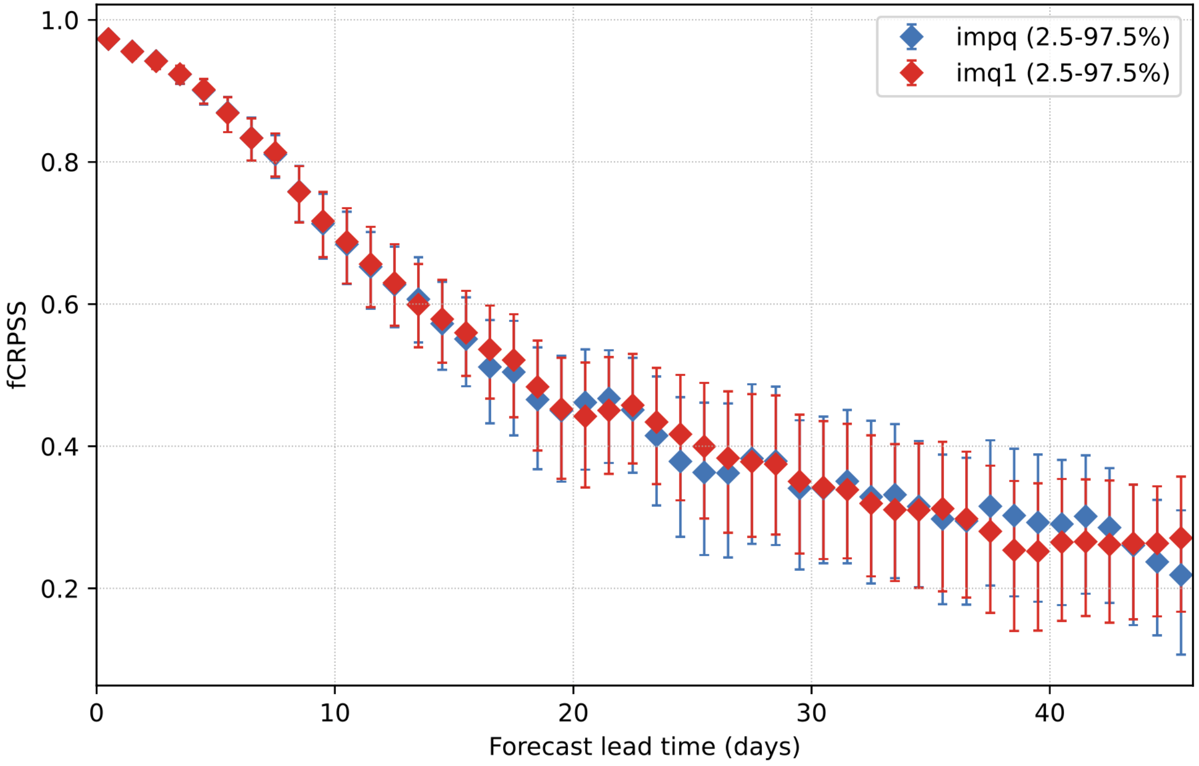
Sea surface temperature and sea-ice anomaly forecasts are dramatically improved by coupling. However, these improvements at the ocean/atmosphere interface do not translate to significant impacts on atmospheric circulation indices at S2S lead times.

Fair version of the continuous ranked probability skill score (fCRPSS)

500 hPa North Atlantic Oscillation (NAO) index



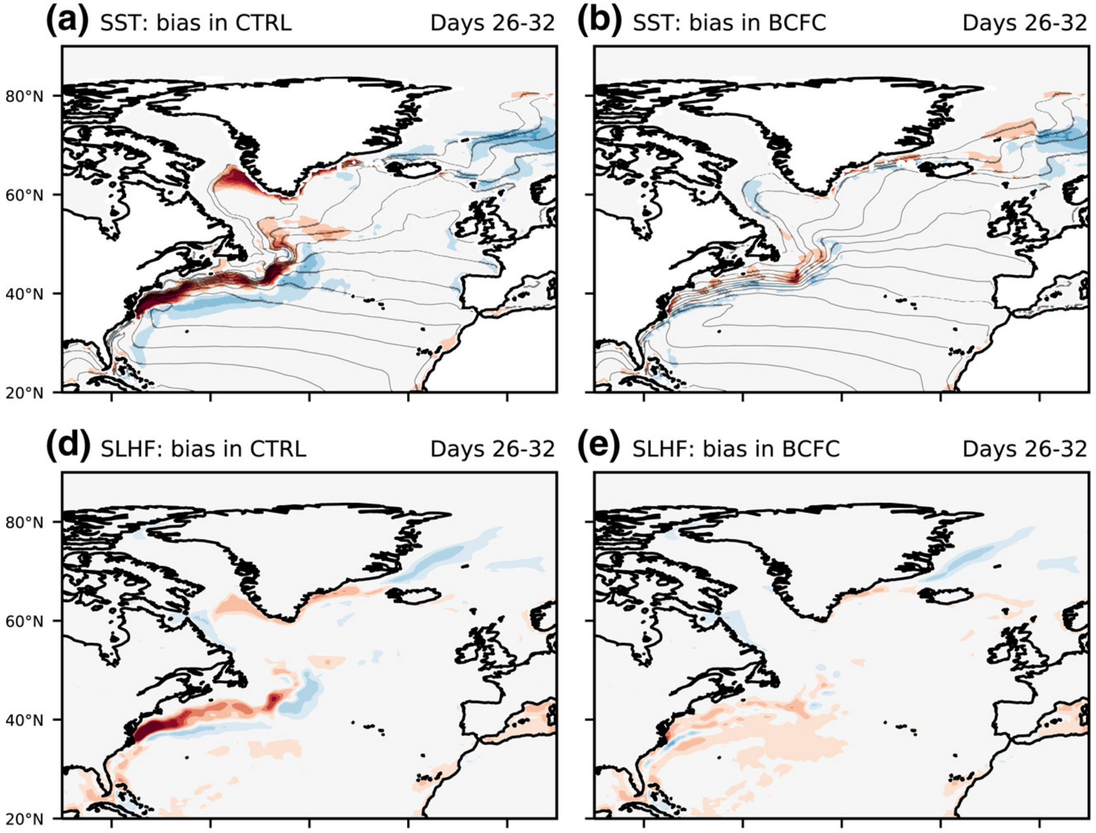
Zonal mean zonal winds at 50hPa and 60°N



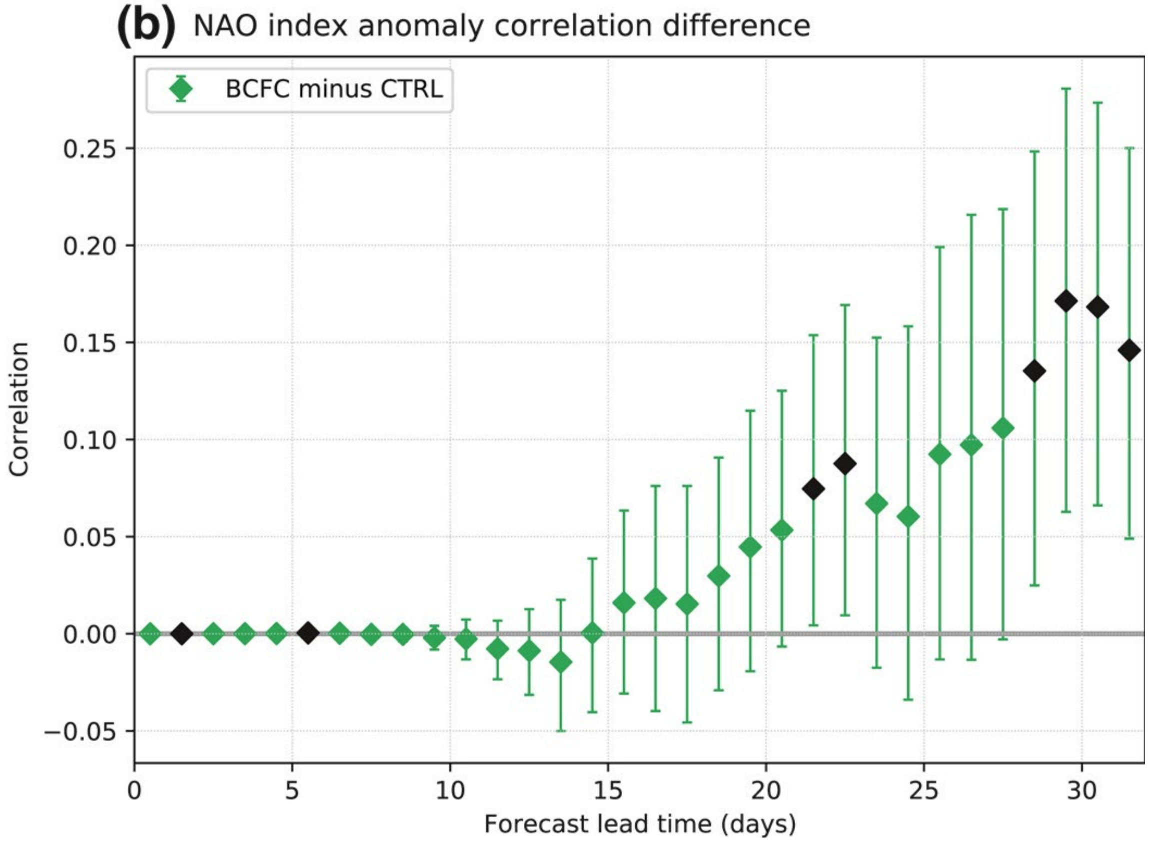
Where do coupled predictions have room for improvement?

Coupling provides more realistic air-sea interactions. However, additional “degrees of freedom” allow for the development of systematic errors in the ocean, which can impact the atmosphere mean state and variability (*e.g. Keeley et al. 2012; Lee et al. 2018; Scaife et al. 2011; Roberts et al 2021*).

Week 4 biases with/without online SST bias correction



Impact of Gulf Stream bias correction on NAO



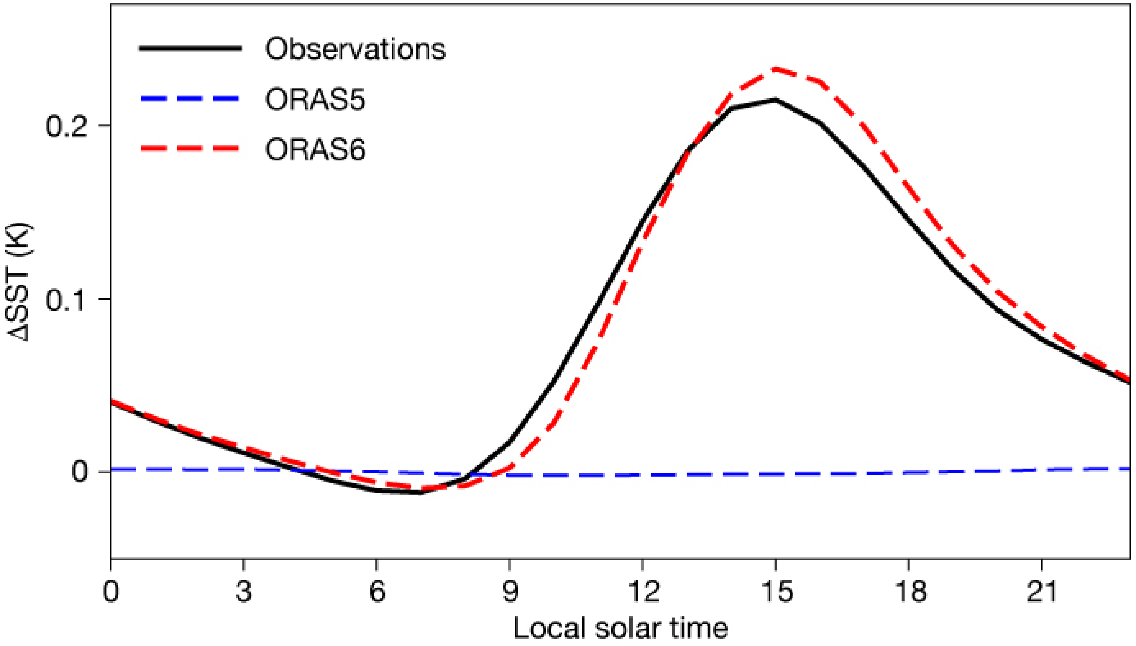
Roberts et al. (2021), Vitart and Balmaseda (2018)

Where do coupled predictions have room for improvement?

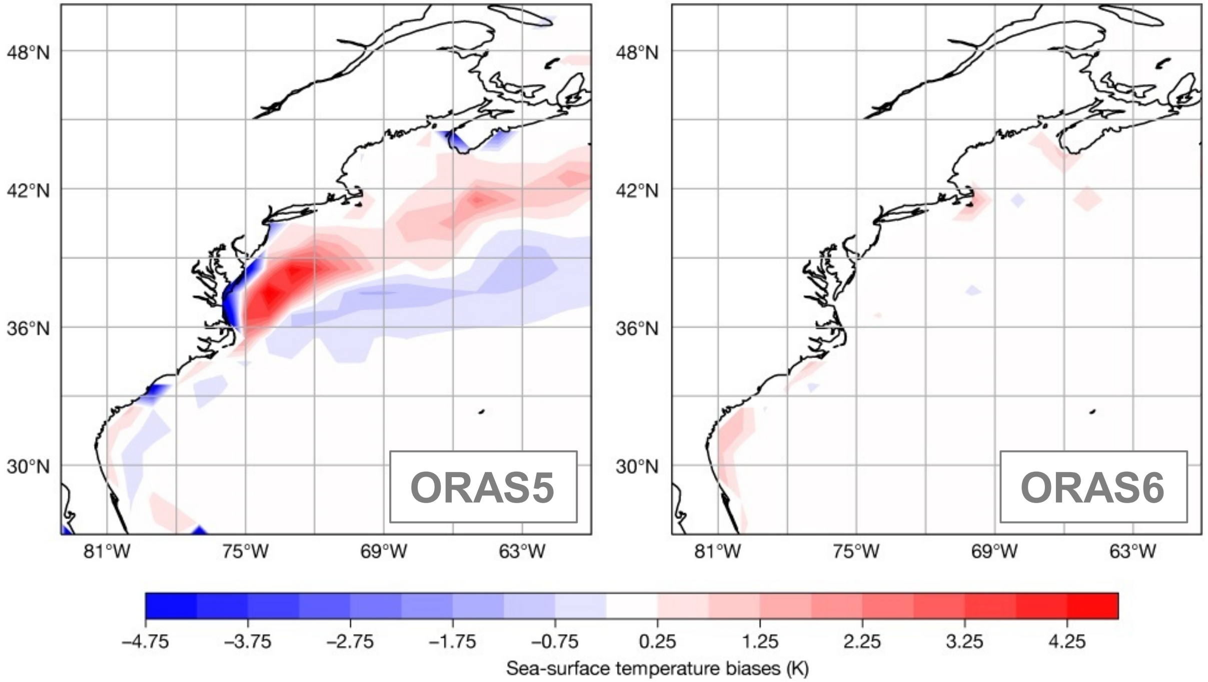
Ocean biases tend to grow slowly with lead time and can be effectively reduced in medium-range and sub-seasonal forecasts through accurate ocean initialization (*e.g. Roberts et al. 2020; 2022*).

However, SST biases at short lead times can be inherited from errors in the ocean (re)analysis that provides ocean initial conditions. Then next ECMWF ocean analysis will improve upon it predecessor in several aspects.

Global mean SST diurnal cycle improved in ORAS6



Gulf Stream SST biases improved in ORAS6

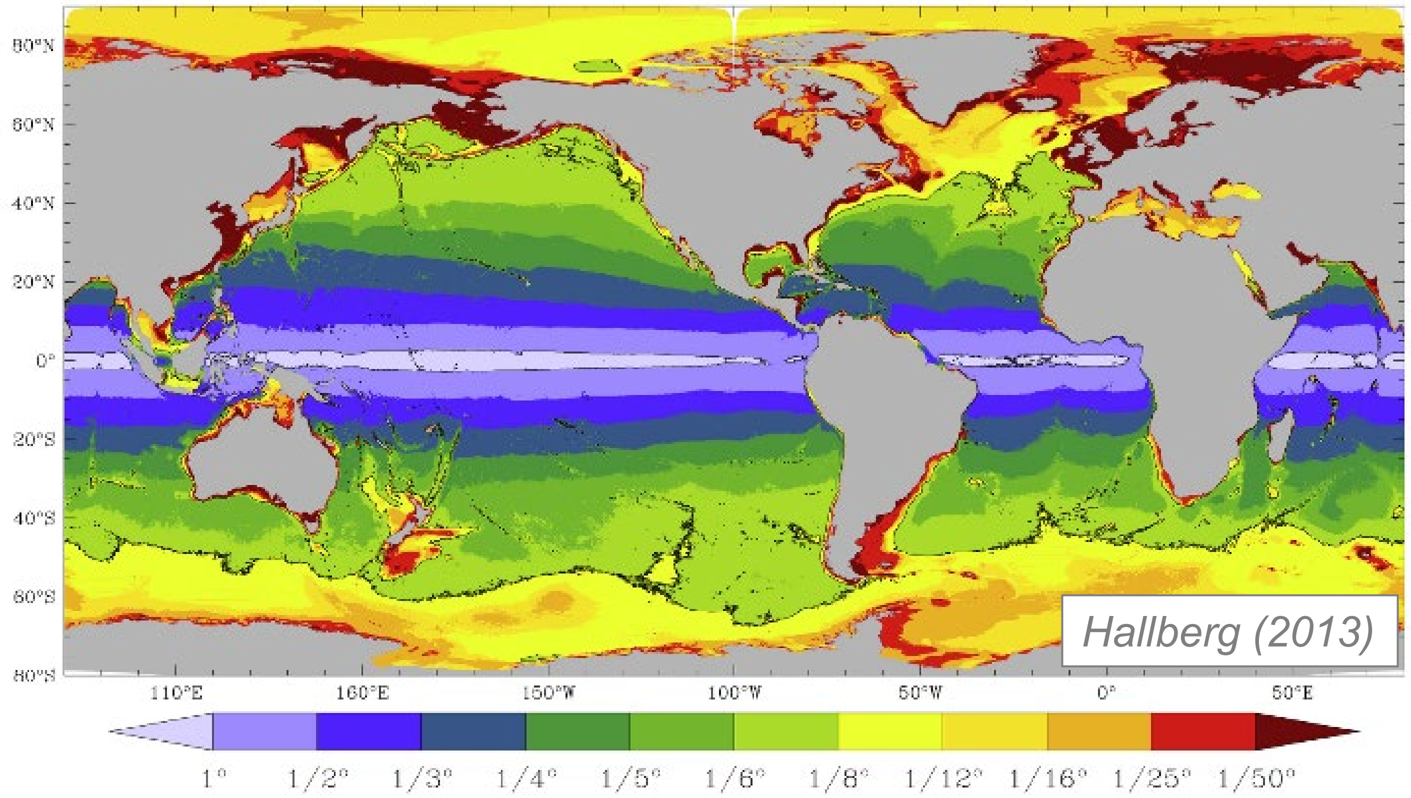


Figures from Zuo et al. (2024)

Where do coupled predictions have room for improvement?

ECMWF operational forecasts use an ¼° eddy-permitting ($\Delta x \approx 25$ km) ocean model, which struggles to simulate the location and structure of ocean mesoscale features, including sharp ocean fronts and eddies.

Grid resolution to resolve the first baroclinic Rossby radius of deformation (L_d) in the ocean



Also see review papers by Hewitt et al. (2017; 2020)

Ocean mesoscale processes can influence the atmosphere

Mesoscale eddies modulate ocean heat and salinity transports and *indirectly* influence air-sea interactions through large-scale changes in the ocean mean state and variability.

Ocean fronts and eddies also modulate turbulent fluxes that *directly* modify the atmospheric boundary layer. The response of the large-scale atmospheric circulation to direct thermodynamic forcing is an area of active research.

Observed imprint of Southern Ocean eddies on the atmosphere

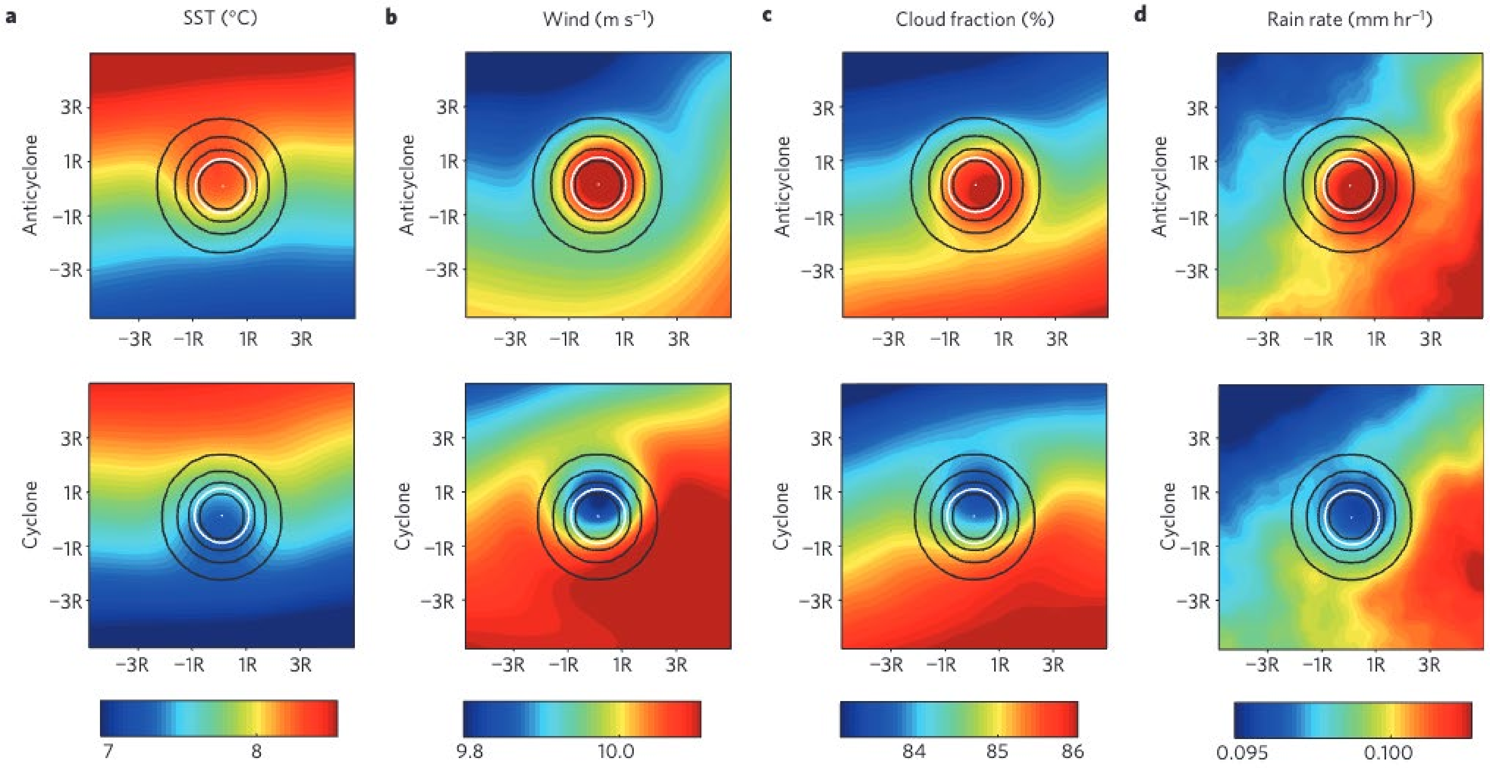
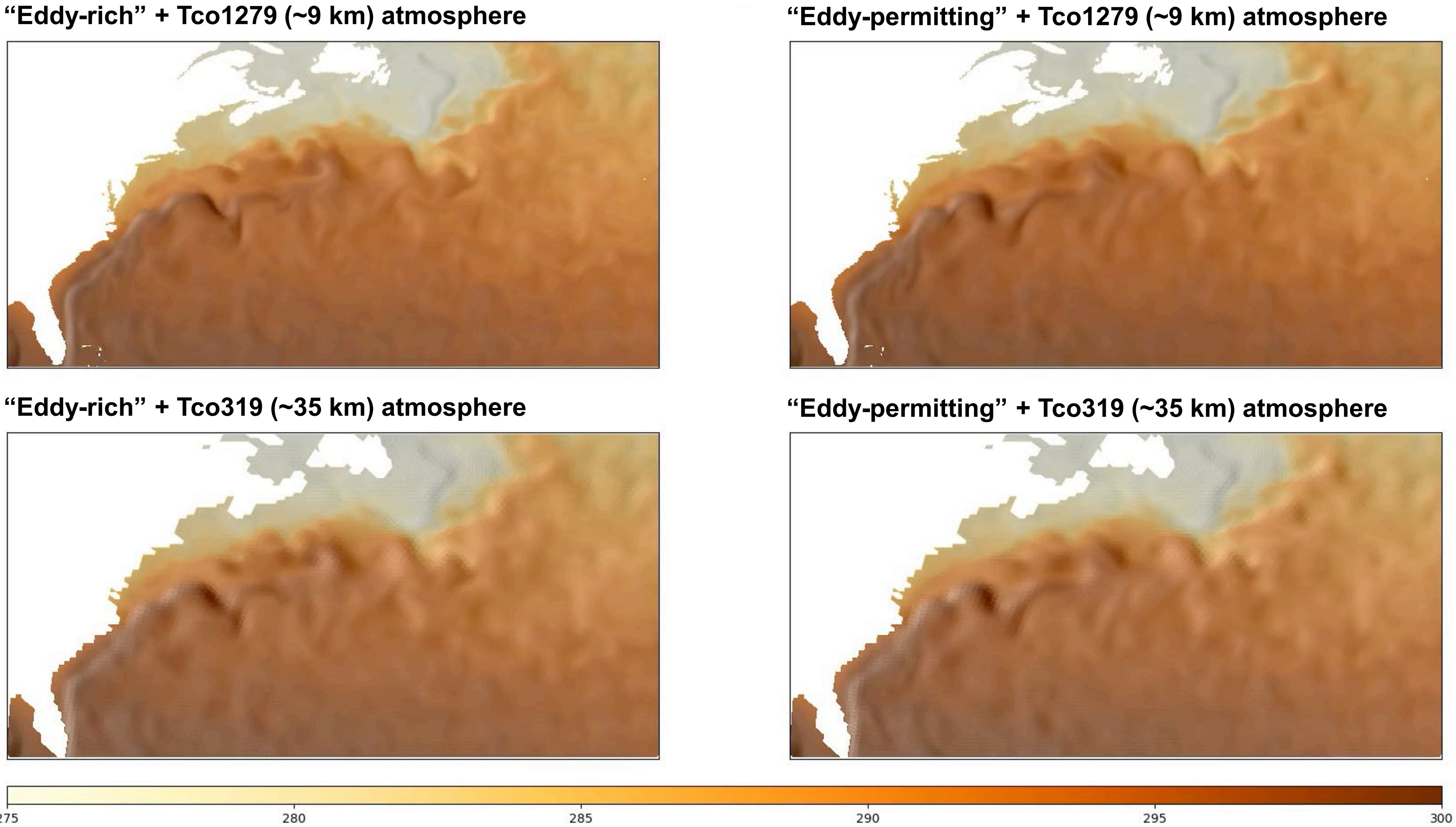


Figure from Frenger et al. (2013). See Seo et al. (2023) for a recent and comprehensive review of this topic.

Preliminary results: an eddy-rich ocean in S2S reforecasts

Reforecast configuration
- CY48R1 + NEMO4/SI3
- GLORYS12-derived initial conditions
- 1 member, 32 day forecasts
- 264 start dates, 1995-2016



SST (K) shaded by meridional currents on IFS octahedral grid in a 32 day coupled forecast

Deficiencies of the eddy-permitting ocean are somewhat mitigated by initializion.

The higher resolution atmosphere can “see” more ocean detail in both eddy-rich and eddy-permitting configurations.

With thanks to ECMWF colleagues Kristian Mogensen and Charles Pelletier

Impact of an eddy-rich ocean in sub-seasonal reforecasts

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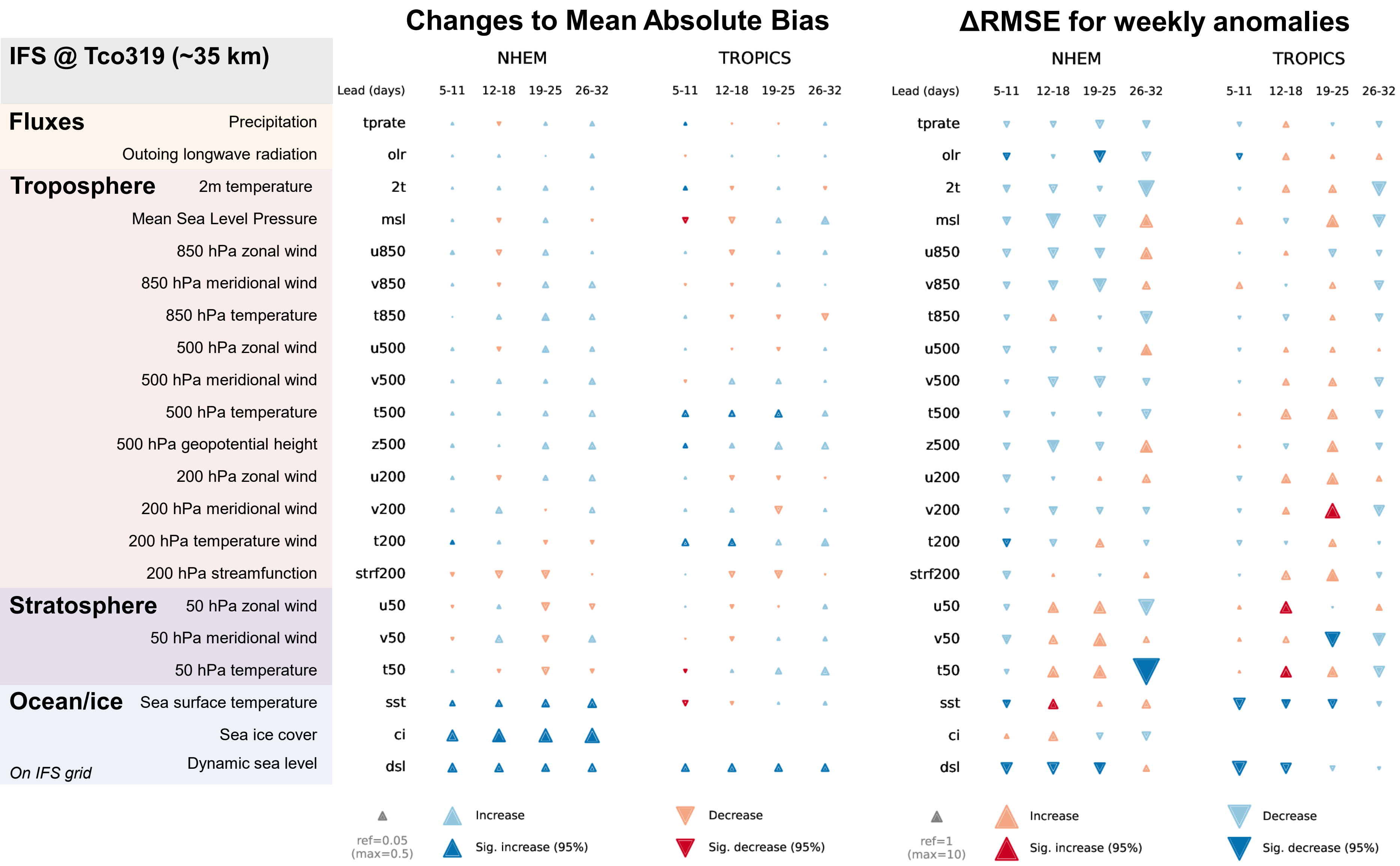

Improved with eddy-rich ocean **Degraded with eddy-rich ocean**

Impact of an eddy-rich ocean in sub-seasonal reforecasts

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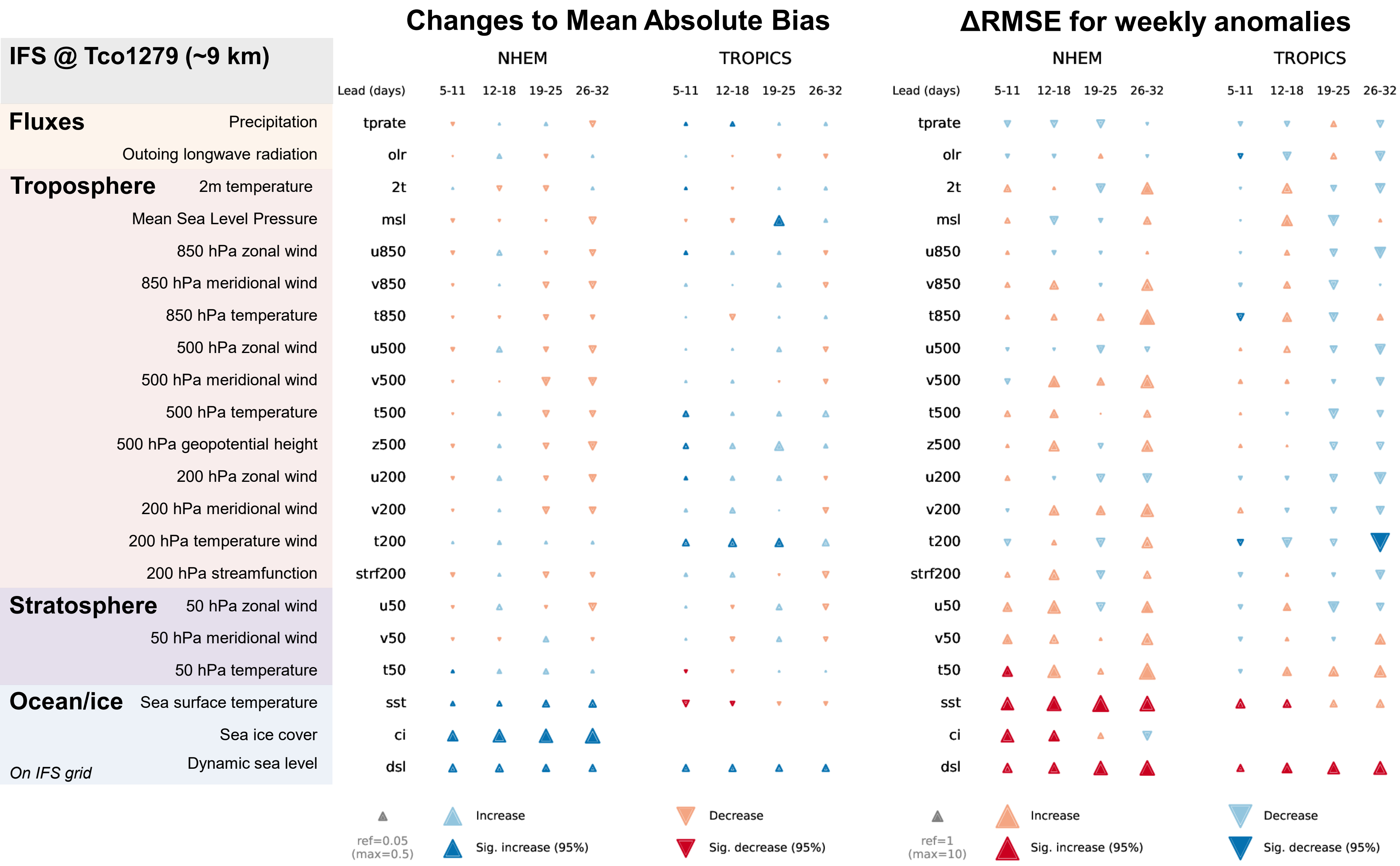


Improved with eddy-rich ocean **Degraded with eddy-rich ocean**

Eddy-rich ocean has very limited impact on atmosphere at S2S lead times.

Some improvements to mean state of ocean fields.

Impact on RMSE of weekly ocean anomalies is sensitive to several factors:
- Variance & double penalty effects
- IFS resolution
- verification grids
- interpolation methods

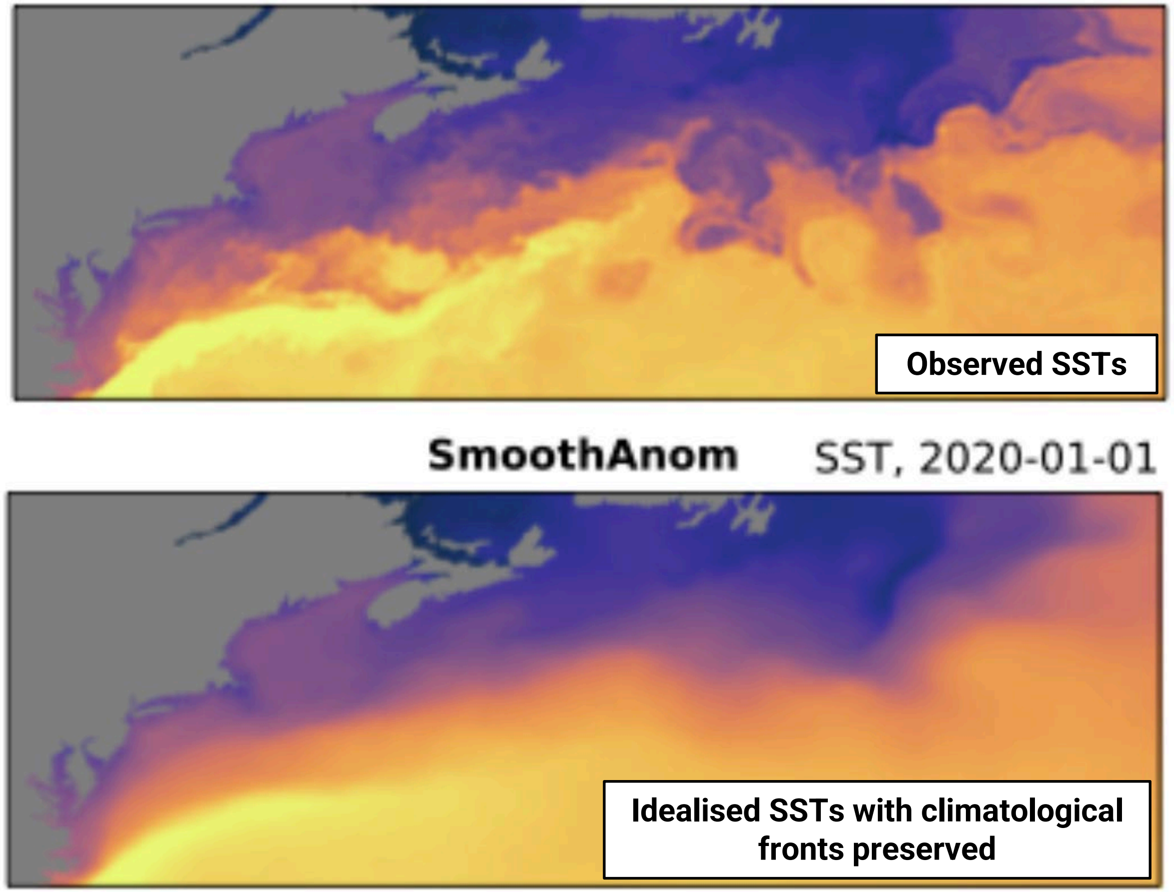
Preliminary results: impact of eddies on the large-scale atmospheric circulation

The EERIE project is running 40-year experiments to isolate the response of the global atmospheric circulation to the direct thermodynamic forcing from extratropical SST anomalies associated with transient eddies.

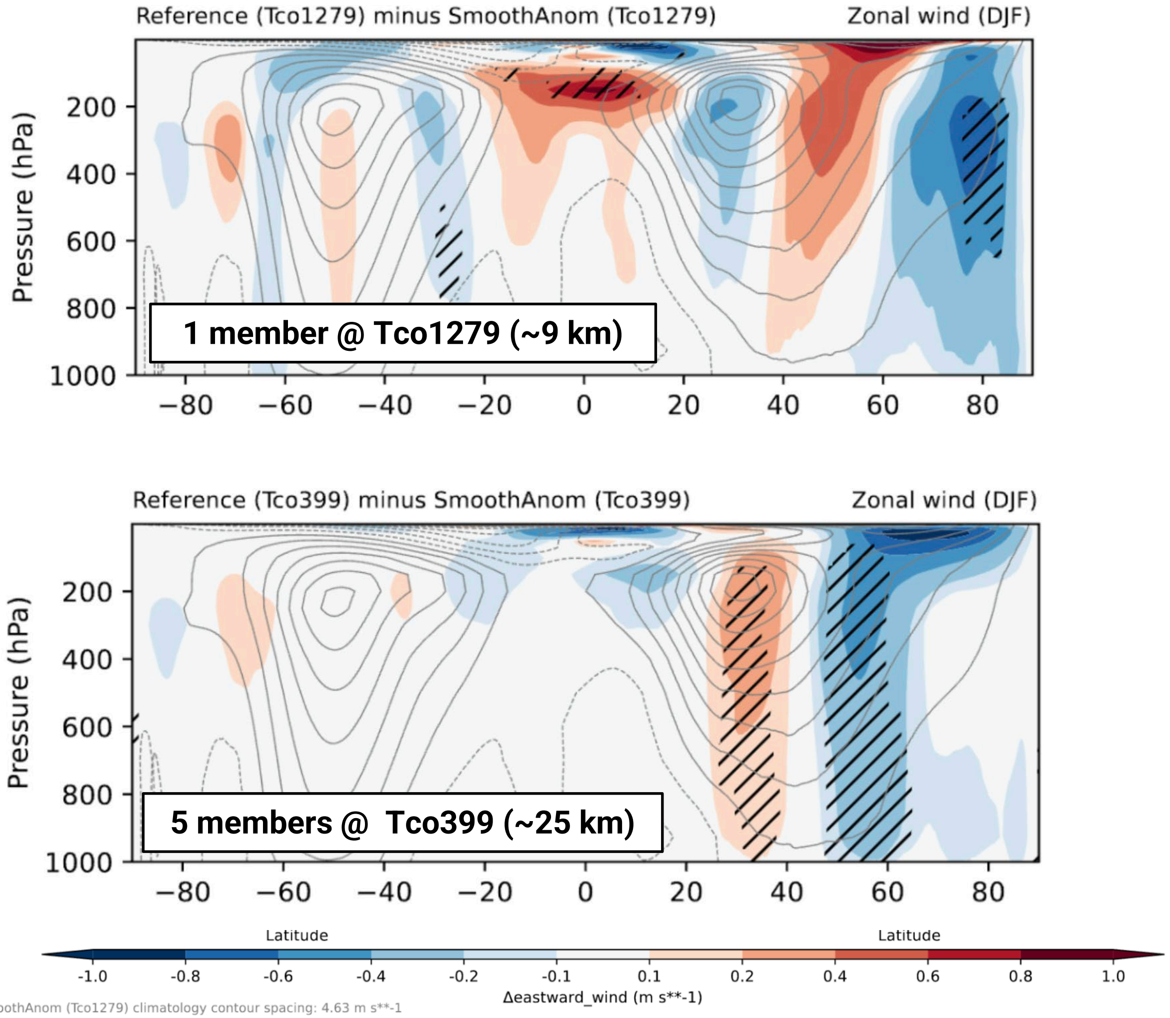
Funded by the European Union

ETH Zürich's contribution to EERIE is funded by the Swiss State Secretariat for Education, Research and Innovation (SERI) under contract #22.00366.

All UK Partners in EERIE are funded by UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding guarantee (grant numbers 10057890, 10049639, 10040510, 10040984).



DJF zonal mean zonal wind response to ocean eddy forcing



With thanks to Matthias Aengenheyster

Summary

1. The benefits of coupling for initialised predictions depends on the balance between improvements from more realistic air-sea interactions and the impact of systematic errors (e.g. SST biases).

2. The importance of the ocean is unequivocal for predictions at seasonal, decadal, and climate timescales.

3. At sub-seasonal and shorter lead times, the biggest impacts from ocean coupling are in the tropics.

4. It is crucial to resolve ocean eddies for credible climate projections (e.g. for realistic mass, heat, and salt transports and associated feedbacks).

5. However, for medium-range and sub-seasonal timescales, many of the deficiencies of eddy-permitting models can be mitigated by accurate initialization.

6. Preliminary work indicates that eddy-rich ocean configurations have a limited impact on the atmosphere at S2S lead times. This is consistent with idealised experimentation within the EERIE project.

7. Other factors may be important when considering the case for an eddy-rich ocean in the coupled IFS:
    - Impacts on weather extremes that are not captured in standard verification.
    - Higher-resolution (and more accurate) ocean and sea ice forecast products.
    - Impacts on data assimilation (e.g. reduced representativity errors for observation comparisons).

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Zuo et al. (2024), ECMWF's next ensemble reanalysis system for ocean and sea ice: ORAS6.

Outline

- The role of the oceans across climate and weather timescales.
- When and where is ocean coupling important for ECMWF S2S forecasts?
- Where do ECMWF coupled predictions have room for improvement?
- Preliminary results:
  - Eddy-rich ocean configurations for S2S forecasts.
  - Impact of eddies on the large-scale atmospheric circulation (EERIE project).