The role of the oceans for subseasonal prediction

Insights from eddy-permitting and eddy-rich coupled forecast systems

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Joint CP-TT/DA-TT Ocean Predict Workshop at ECMWF:
Advances in coupled modelling, data assimilation, and predictions

Motivation

The benefits of coupling for initialised predictions are a balance between:

- More realistic air-sea interactions and coupled dynamics.
- Systematic biases that develop at the coupling interface.

Operational S2S systems typically use *eddy-permitting* oceans ($\Delta x \approx 25$ km), which do not fully resolve the ocean mesoscale or sharp SST fronts.

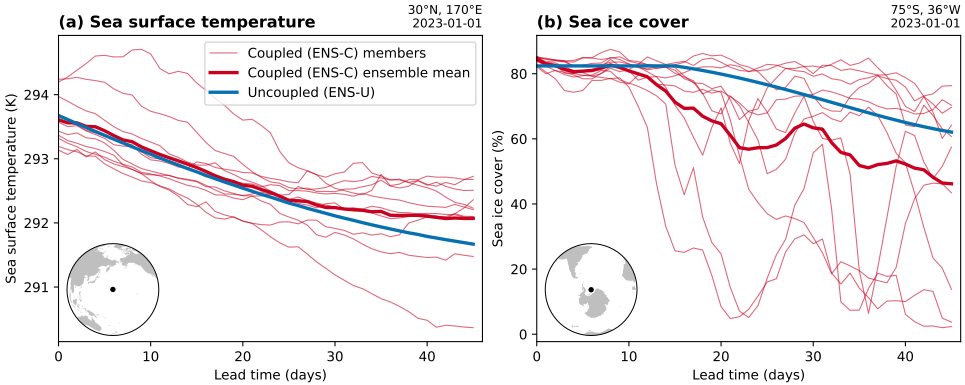
1. What is the role of ocean-atmosphere coupling for atmospheric predictability at lead times of one to six weeks?
2. Is this sensitive to region, lead time, and variable?
3. Does an *eddy-rich* ocean ($\Delta x \approx 8$ km) change these conclusions?
4. Are the impacts of an eddy-rich ocean sensitive to atmospheric resolution?

Subseasonal reforecast experiments

Experiment	Atmosphere	Ocean/ice	Members	Days	Period	ICs
ENS-C	IFS 49r2 (∼35 km)	**NEMO4-SI^3 (∼25 km)**	10	46	2006-2023	ERA5/ORAS6
ENS-U	IFS 49r2 (∼35 km)	**Persistence/climatology**	10	46	2006-2023	ERA5
LRA-EPO	**IFS 48r1 (∼35 km)**	**NEMO4-SI^3 (∼25 km)**	1	32	1995-2016	ERA5/GLORYS12
HRA-EPO	**IFS 48r1 (∼9 km)**	**NEMO4-SI^3 (∼25 km)**	1	32	1995-2016	ERA5/GLORYS12
LRA-ERO	**IFS 48r1 (∼35 km)**	**NEMO4-SI^3 (∼8 km)**	1	32	1995-2016	ERA5/GLORYS12
HRA-ERO	**IFS 48r1 (∼9 km)**	**NEMO4-SI^3 (∼8 km)**	1	32	1995-2016	ERA5/GLORYS12

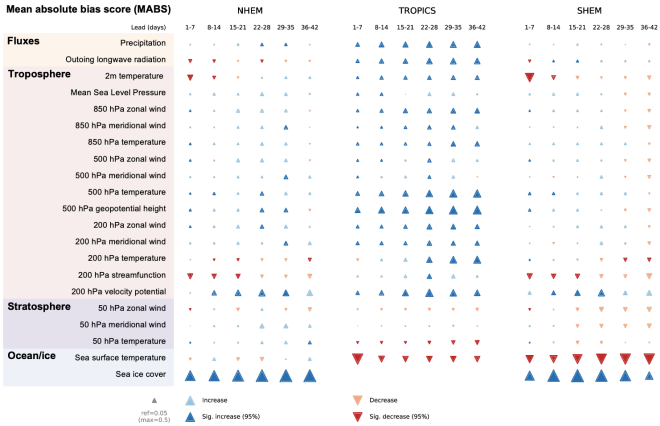
- **Coupling impact:** **coupled** vs **uncoupled** 10-member ensemble reforecasts covering 216 start dates.
- **Ocean resolution impact:** single-member reforecasts covering 264 start dates, with **eddy-permitting** and **eddy-rich** ocean configurations initialised consistently from the same eddy-rich GLORYS12v1 reanalysis.
- Ocean resolution impacts are evaluated at **lower** and **higher** atmosphere resolutions.

Coupled vs uncoupled surface boundary conditions



- Each member of **ENS-C** gets different SST and sea ice boundary conditions.
- **ENS-U** uses observed SST anomalies persisted on a daily climatology, with sea ice persisted for 15 days then relaxed to climatology.

Impact of coupling on the climatological mean state



Positive values of **MABS** indicate that absolute biases aggregated across all locations and seasons are reduced in ENS-C compared to ENS-U.

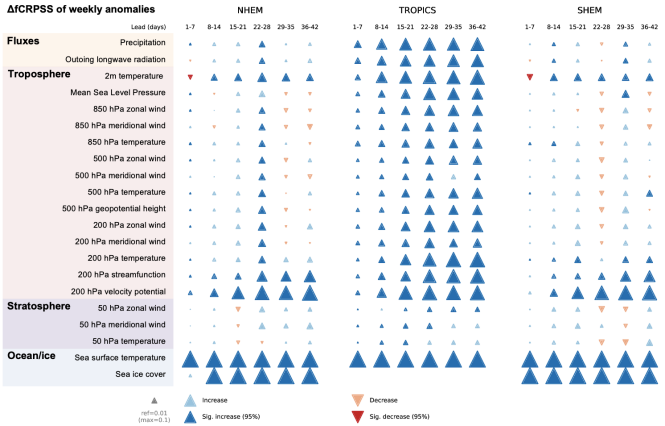
Ocean and sea ice: very small but robust *degradation* of SST climatology in the tropics and SH ($\sim$0.1 K), but improved sea ice cover.

Tropical atmosphere: mean state generally *improved* across most fields and lead times, despite the SST degradation.

Extratropical atmosphere: less sensitive, with slight early degradations to OLR, T_{2m}, and ψ_{200}.

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

Impact of coupling on weekly mean anomaly skill



Ocean and sea ice: large improvements at all lead times, mostly reflecting the crude boundary conditions in ENS-U.

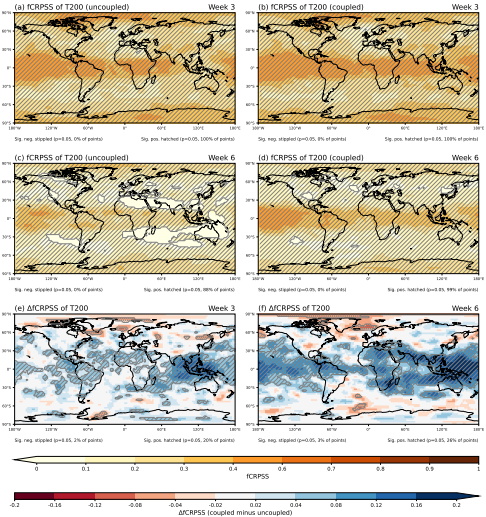
Tropical atmosphere: improved for all fields, most strongly in the troposphere, with benefits growing with lead time.

Extratropical atmosphere: limited impact, except for T_{2m} improvements at weeks 2 to 6, mostly over the oceans.

T_{2m} over sea ice: slightly degraded at week 1 over the Arctic, partly a verification artefact as ERA5 and ENS-U share a fixed 1.5 m ice thickness.

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

Regional impact of coupling: 200 hPa temperature



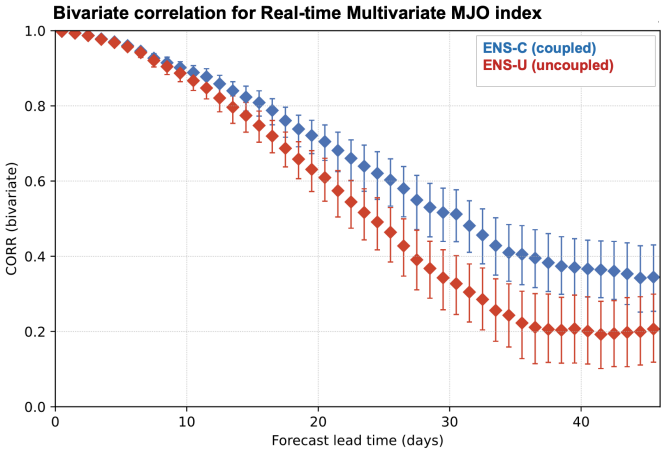
Week 3 fCRPSS (top): Similar patterns of skill exceeding climatology at all locations. Largest improvements over the maritime continent and Indo-Pacific warm pool.

Week 6 fCRPSS (middle): Positive impacts of coupling become more evident. 99% of locations beat climatology in **ENS-C** vs 88% in **ENS-U**.

ΔfCRPSS (bottom): Impacts of coupling are most evident within $\pm 45^\circ$ of the equator.

Similar results for T_{2m}.

Impact of coupling on the Madden-Julian Oscillation



MJO composites and individual RMM trajectories look very similar in coupled and uncoupled systems.

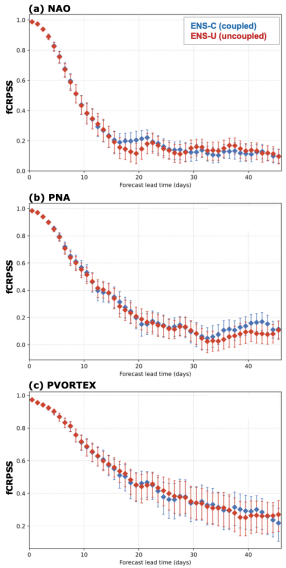
But over all cases, coupling has clear benefits beyond day 7.

MJO skill is extended by $\sim$5 days for Corr=0.6 (21 $\rightarrow$ 26 days).

Improvements are associated with faster propagation and reduced phase bias.

Results are consistent with previous studies [Woolnough et al., 2007, Seo et al., 2009, Shelly et al., 2014].

Impact of coupling on extratropical circulation indices



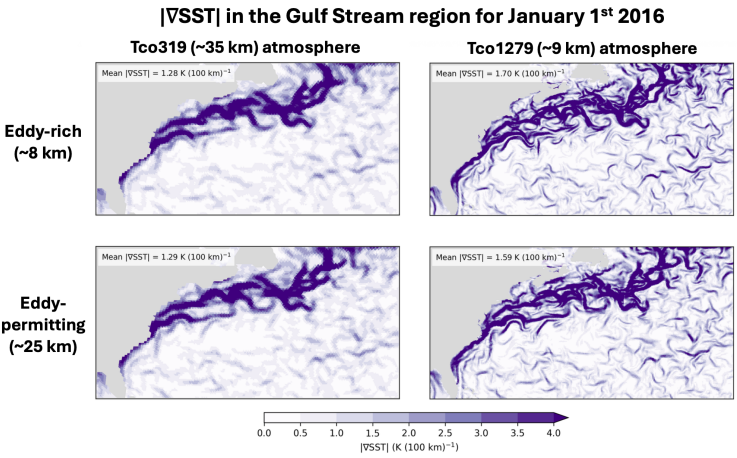
Despite large improvements to extratropical SST and sea ice, coupling has a limited impact on the skill of extratropical circulation indices.

Skill (fCRPSS) of daily mean NAO, PNA, and PVORTEX indices is consistent within 95% confidence intervals at almost all lead times.

Summary: At S2S lead times, coupling matters most in the tropics with limited impacts on the large-scale extratropical atmosphere.

Next slides: *what is the impact of an eddy-rich ocean?*

Gulf Stream SST initial conditions seen by the atmosphere



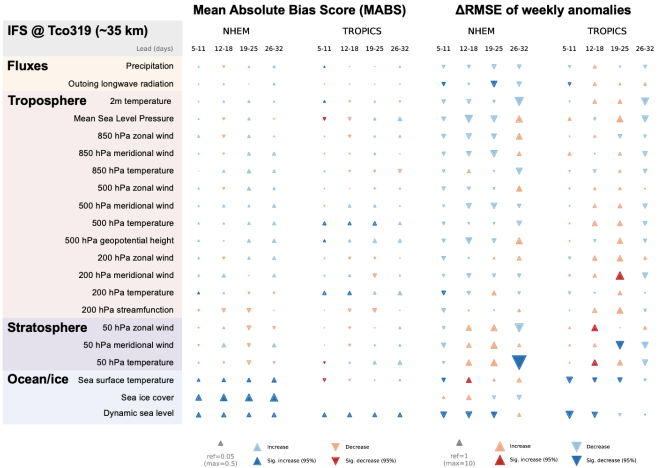
Mesoscale SST features are well constrained in all ocean configurations.

The SST gradients felt by the atmosphere can depend more on *atmospheric* than ocean resolution.

At initial time, eddy-rich and eddy-permitting oceans are nearly identical when viewed by a Tco319 atmosphere.

Differences emerge at Tco1279.

Impact of an eddy-rich ocean: Tco319 atmosphere



LRA-ERO vs LRA-EPO (∼35 km atmosphere).

Mean state: small but robust improvements to SST, sea ice, and dynamic sea level (NH).

Ocean anomalies: slightly positive or neutral impact on SST, sea ice, and sea level RMSE.

Atmosphere: no consistent or robust change in anomaly RMSE, or in MJO skill.

Improved with eddy-rich ocean

Degraded with eddy-rich ocean

Impact of an eddy-rich ocean: Tco1279 atmosphere



HRA-ERO vs HRA-EPO (∼9 km atmosphere).

Mean state: same improvements as with Tco319.

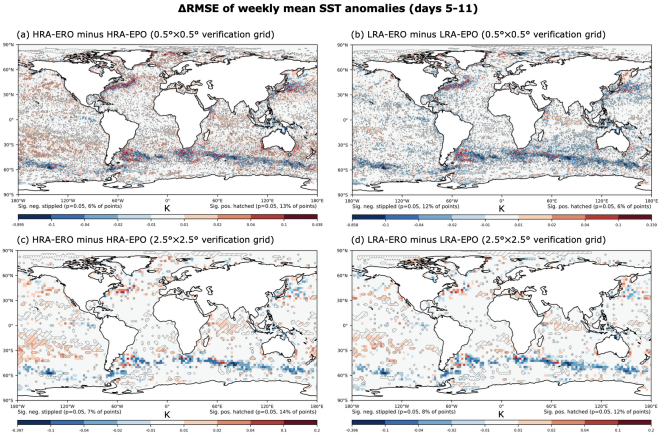
Ocean anomalies: RMSE of SST, sea ice, and sea level *seems to increase*, the opposite sign to Tco319.

Atmosphere: no consistent or robust change in anomaly RMSE, or in MJO skill.

What is the role of the double penalty effect?

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

SST anomaly RMSE using different verification grids



The **double penalty effect** means that sharper features in the wrong place are penalised twice by RMSE.

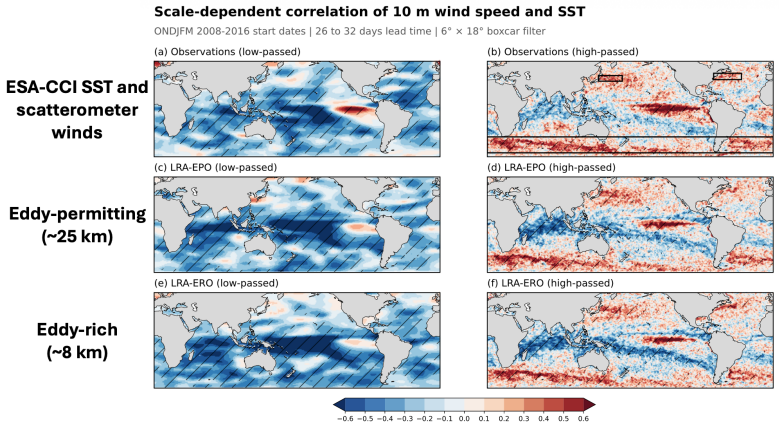
Top: The impacts of an eddy-rich ocean appear more positive at Tco319 ($\sim$35 km) when evaluated on a $0.5^\circ \times 0.5^\circ$ grid.

Bottom: Averaging over eddies on a $2.5^\circ \times 2.5^\circ$ grid improves consistency between atmospheric resolutions.

All differences are tiny and typically less than the ESA-CCI SST grid-point uncertainty ($\sim$0.18 K).

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

All configurations capture scale-dependent coupling



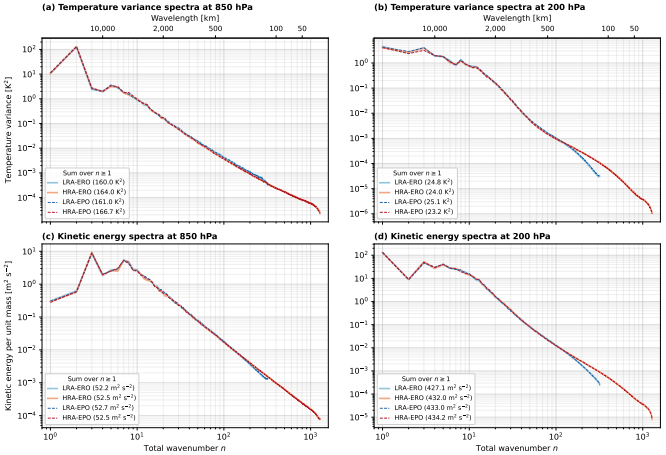
Basin scale: atmosphere drives ocean (**negative correlation**).

Mesoscale: ocean drives atmosphere (**positive correlation**).

[Small et al., 2008, Bryan et al., 2010]

Forecasts also capture the magnitudes of mesoscale regression slopes in mid-latitudes.

Atmospheric temperature variance and kinetic energy spectra



Atmospheric spectra from eddy-permitting and eddy-rich configurations are statistically indistinguishable at all resolved scales.

Results are consistent with skill evaluations that find limited impact on large-scale tropospheric variability at subseasonal lead times.

In contrast, atmospheric resolution has a clear impact on spectra at small scales.

Summary

Ocean-atmosphere coupling

- The benefits of coupling for initialised predictions depend on the balance between improvements from more realistic air-sea interactions and the impact of systematic errors (e.g. SST biases).
- The importance of the ocean is unequivocal for predictions at seasonal, decadal, and climate timescales.
- At S2S lead times, the largest benefits from ocean coupling are in the tropics (e.g. MJO skill extended by $\sim$5 days), with only marginal impacts on extratropical circulation.

Eddy-rich ocean ($\sim$25 km $\rightarrow$ $\sim$8 km)

- In free-running models, mesoscale eddies must be resolved or adequately parameterised for realistic ocean budgets, feedbacks, and air-sea interactions.
- At S2S lead times, many deficiencies of eddy-permitting oceans are mitigated by accurate (eddy-rich) initialisation [Roberts et al., 2022].
- In ECMWF-IFS, eddy-rich oceans give small improvements to ocean and sea ice mean state, but no detectable improvement to large-scale atmospheric skill or variability at subseasonal lead times.

However, other factors may still justify an eddy-rich ocean, including regional/coastal ocean and sea ice products, coupled data assimilation, and extreme events.

Questions?

Roberts et al. (2026), arXiv:2605.00621, https://arxiv.org/abs/2605.00621

Accepted in *QJRMS*.

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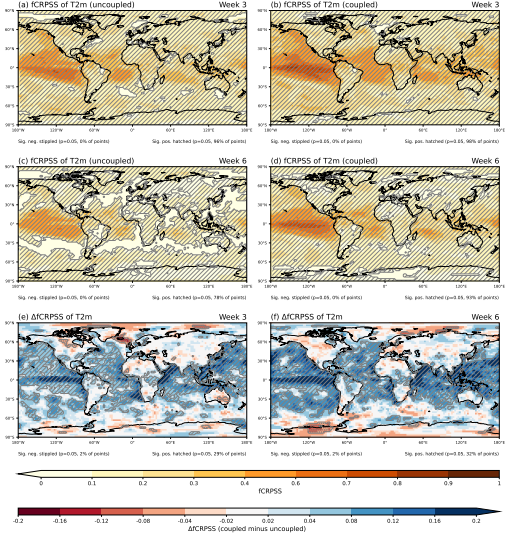
K.-H. Seo et al. (2009) Evaluation of MJO forecast skill from several statistical and dynamical forecast models. *Journal of Climate*, 22(9), pp. 2372-2388.

A. Shelly et al. (2014) Coupled versus uncoupled hindcast simulations of the Madden-Julian Oscillation in the Year of Tropical Convection. *Geophysical Research Letters*, 41(15), pp. 5670-5677.

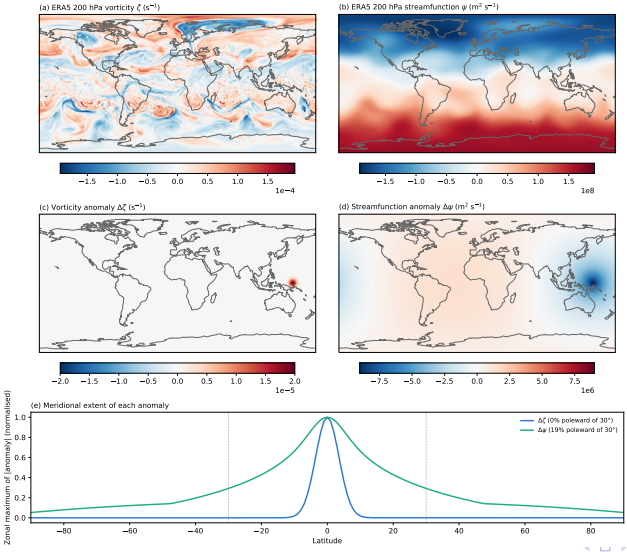
R. J. Small et al. (2008) Air-sea interaction over ocean fronts and eddies. *Dynamics of Atmospheres and Oceans*, 45(3-4), pp. 274-319.

S. J. Woolnough, F. Vitart, and M. A. Balmaseda (2007) The role of the ocean in the Madden-Julian Oscillation: implications for MJO prediction. *QJRMS*, 133(622), pp. 117-128.

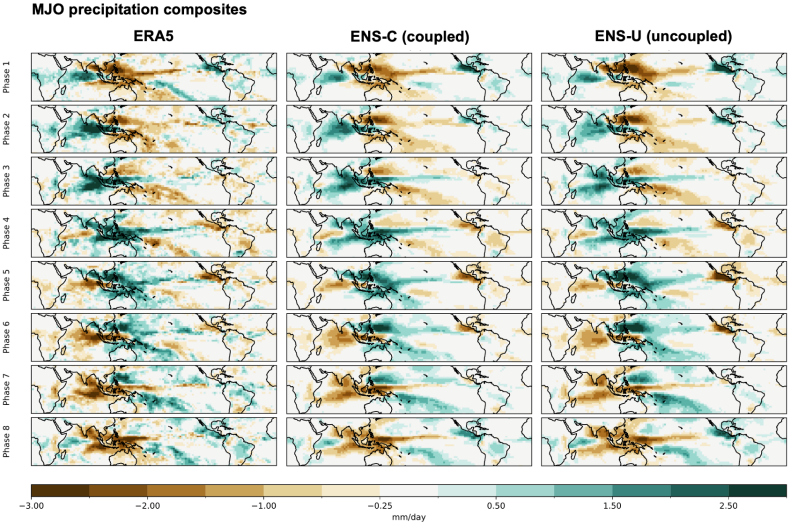
Backup: regional impact of coupling on T_{2m}



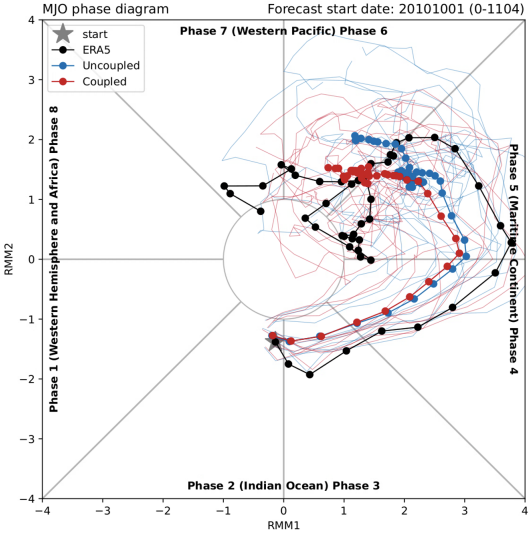
Backup: non-local streamfunction response



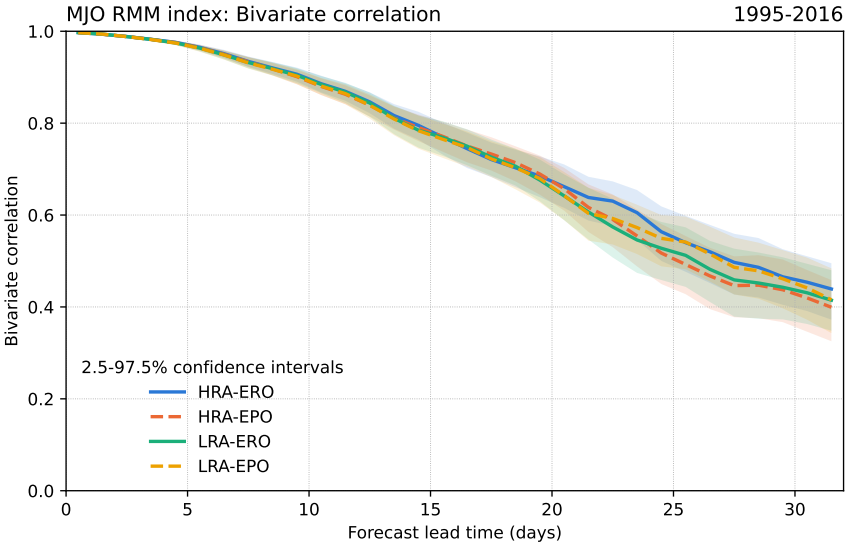
Backup: MJO precipitation composites



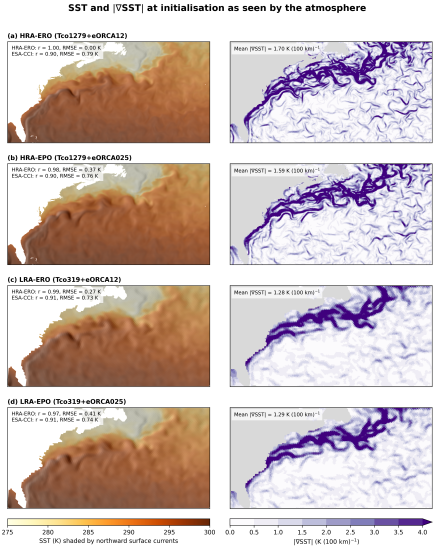
Backup: MJO phase diagram for 1 October 2010



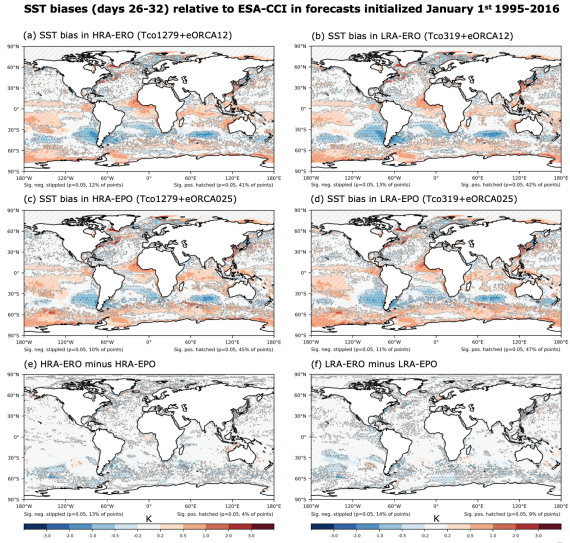
Backup: MJO skill vs ocean resolution



Backup: Gulf Stream SST initial conditions



Backup: week $4\frac{1}{2}$ SST biases (1 January start dates)



Backup: ocean and sea ice initial conditions

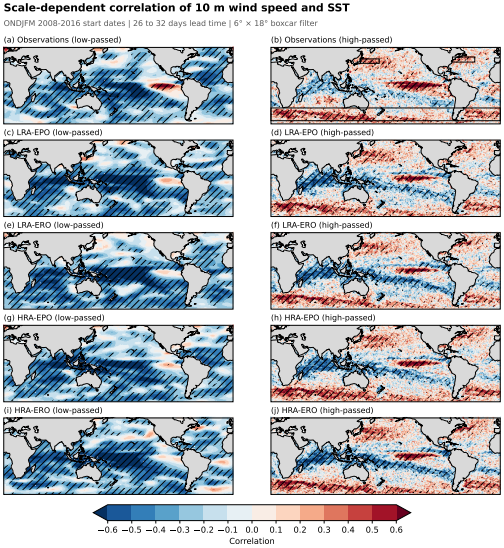
Eddy-permitting (eORCA025) and eddy-rich (eORCA12) initial conditions come from ERA5-forced NEMO4-SI^3 runs relaxed towards daily GLORYS12v1:

- 3D temperature and salinity relaxed over the full water column with a 5-day timescale.
- Sea ice concentration and thickness relaxed with a 10-day timescale, distributed across five SI^3 categories.
- Conservative remapping to eORCA025, bilinear interpolation to eORCA12.

Both configurations therefore start from the same realistic eddy-rich ocean state. The experiments measure the added value of higher ocean resolution *during* the 32-day forecast, which is limited by how quickly the two ocean states diverge.

This differs from idealised studies that replace realistic SST fronts and eddies with heavily smoothed boundary conditions.

Backup: wind speed and SST correlations



Backup: regression slopes of mesoscale wind speed on SST

Regional mean slopes (m s^{-1} K^{-1}) of high-passed weekly mean 10 m wind speed on high-passed SST anomalies, days 26 to 32, 2008-2016 start dates.

	Gulf Stream		**Southern Ocean**		**Kuroshio**	
	ONDJFM	AMJJAS	ONDJFM	AMJJAS	ONDJFM	AMJJAS
Observations	0.15	0.07	0.18	0.29	0.20	0.13
LRA-EPO	0.15	0.03	0.12	0.26	0.18	0.10
LRA-ERO	0.17	0.09	0.12	0.26	0.19	0.12
HRA-EPO	0.17	0.11	0.18	0.28	0.20	0.14
HRA-ERO	0.16	0.10	0.17	0.29	0.19	0.12

Backup: impact of ocean resolution on atmospheric spectra

Eddy-rich minus eddy-permitting global temperature variance and kinetic energy (% of eddy-permitting) at day 32, 1 January start dates 1995-2016. Square brackets give bootstrap 95% confidence intervals.

All scales ($n \geq 1$)

Atmosphere	Level (hPa)	T (%)	KE (%)	KE_{div} (%)	KE_{rot} (%)
Tco319	200	−1.0 [−7.7, 6.6]	−1.4 [−3.7, 1.2]	3.7 [−4.2, 12.8]	−1.5 [−3.8, 1.0]
Tco319	850	−0.6 [−2.7, 1.7]	−1.0 [−4.3, 2.3]	1.9 [−2.6, 6.6]	−1.2 [−4.4, 2.2]
Tco1279	200	3.6 [−1.5, 9.7]	−0.5 [−2.8, 1.7]	2.1 [−5.3, 8.0]	−0.6 [−2.8, 1.6]
Tco1279	850	−1.6 [−3.7, 0.6]	0.1 [−3.0, 3.7]	0.2 [−4.0, 4.2]	0.1 [−3.2, 3.8]

Small scales ($n \geq 100$, wavelengths $\lesssim$400 km)

Atmosphere	Level (hPa)	T (%)	KE (%)	KE_{div} (%)	KE_{rot} (%)
Tco319	200	−4.5 [−10.6, 2.7]	−1.8 [−5.7, 2.5]	−1.1 [−5.2, 3.3]	−2.5 [−6.7, 2.3]
Tco319	850	−1.2 [−4.7, 2.9]	−0.7 [−4.1, 2.3]	−2.7 [−5.8, 0.0]	0.1 [−3.7, 3.5]
Tco1279	200	0.3 [−4.6, 5.9]	2.0 [−1.2, 5.2]	0.5 [−2.4, 3.7]	3.6 [−0.6, 7.5]
Tco1279	850	−0.1 [−3.1, 3.1]	−0.6 [−2.5, 1.6]	−0.2 [−2.0, 2.0]	−0.7 [−2.8, 1.7]