The impacts of increased ocean model resolution in the ECMWF coupled forecast model

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Motivation

- **Increased ocean resolution impacts the atmosphere in two main ways:**
  - Mean state changes (e.g. better representation of the Gulf Stream separation and SST gradients).
  - Variability changes (e.g. increased eddy activity and associated air-sea interaction).

- **Initialized forecasts can aid process understanding**
  - Biases grow with lead time and are mitigated by accurate initialization.
  - Variability effects are present at all lead times.
  - Comparison of initialized forecasts (small biases) and climate integrations (larger biases) can thus help us to disentangle the most important processes within a coupled framework

- **Understanding the processes is important for forecasting strategy**
  - Is the "value" of higher resolution increased at longer lead times?
  - This work emphasizes 1° and 1/4° NEMO v3.4, but same arguments apply for higher resolutions.
  - Will begin testing eddy-resolving NEMO v4.0 configurations in the next year or so.

The ECMWF coupled forecast model

- **Atmosphere-land-wave model.**
  - IFS spectral atmosphere (currently cycle 46R1).
  - Grid-point resolution varies from 9km (HRES) to 36km (SEAS) depending on system.
  - Number of vertical levels varies from 91 (ENS, SEAS) to 137 (HRES).
- **Ocean-sea-ice model:**
  - All ECMWF forecasts are coupled (from day 1 to month 12) to NEMO v3.4 and LIM2.
  - ORCA025 grid (~ 0.25 degrees) with 75 vertical levels.
  - Hourly coupling as single executable (NEMO called as subroutine in IFS).
- **Ongoing work to implement NEMO v4.0 at ECMWF**
  - Led by Kristian Mogensen, Sarah Keely, and Jean Bidlot
  - Collaborating with UKMO on GO8 configuration: includes the multicategory sea ice model (SI3).
  - Integration and re-examination of ECMWF ocean-wave effects.
  - Testing hourly forcing with ERA5 boundary conditions (now available near-real-time).
  - Sea ice model tuning for NWP and bug fixes (e.g. stability issues with advection scheme).

Experiments to evaluate the impact of ocean resolution across timescales

Same modelling system across all timescales.

Ocean initial conditions

Subseasonal: weeks 1-4

Seasonal: months 2-4

Multidecadal historical climate integrations (CMIP6/HighResMIP)

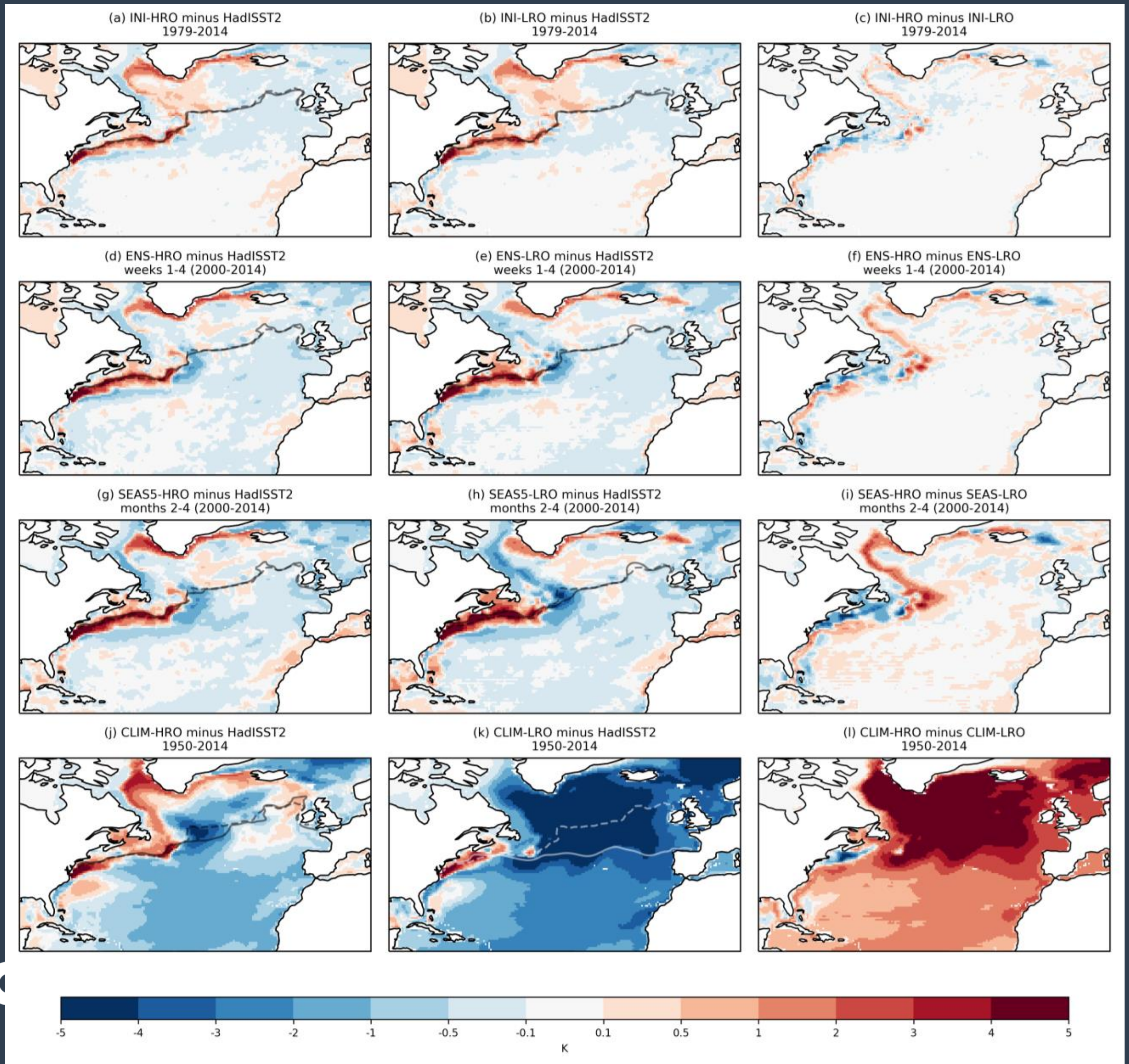
TABLE 1. Model configurations used in this study.

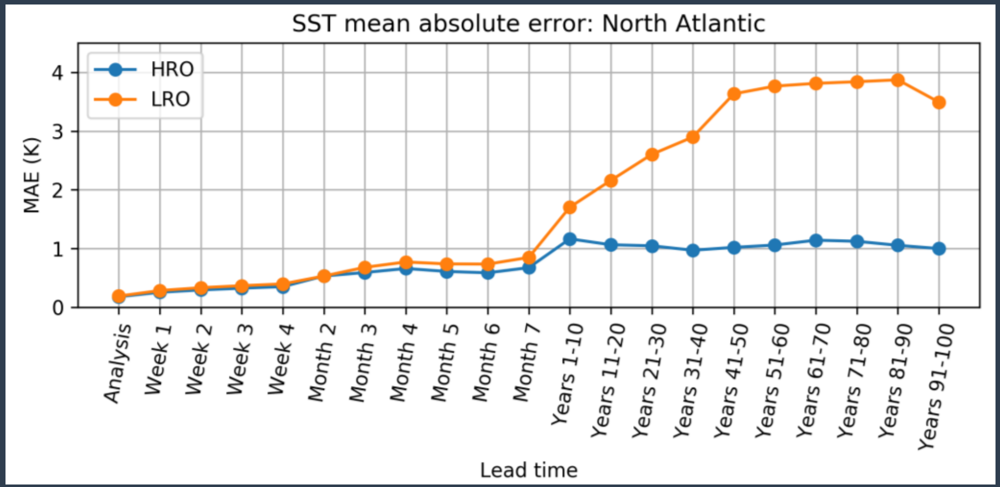
Name	Type	Members	Period	Reforecasts per year	Atm. res.	Ocean res.
INI-LRO	Ocean/sea-ice analysis	5	1979-2016			~100 km
INI-HRO	Ocean/sea-ice analysis	5	1979-2016			~25 km
ENS-LRO	Subseasonal ensemble reforecast	5	1989-2016	12×32 days	~31 km	~100 km
ENS-HRO	Subseasonal ensemble reforecast	5	1989-2016	12×32 days	~31 km	~25 km
SEAS-LRO	Seasonal ensemble reforecast	5	1981-2016	2×7 months	~31 km	~100 km
SEAS-HRO	Seasonal ensemble reforecast	5	1981-2016	2×7 months	~31 km	~25 km
CLIM-LRO	Climate simulation	1	1950-2014		~25 km	~100 km
CLIM-HRO	Climate simulation	1	1950-2014		~25 km	~25 km
CLIM-LRO-LRA	Climate simulation	1	1950-2014		~50 km	~100 km
CLIM-HRO-LRA	Climate simulation	1	1950-2014		~50 km	~25 km

North Atlantic SST biases (DJF)

HRO bias | **LRO bias** | **HRO minus LRO**

Analysis / Weeks 1-4 / Months 2-4 / Climate





- HRO and LRO configurations of ECMWF-IFS have very different climatological biases in North Atlantic

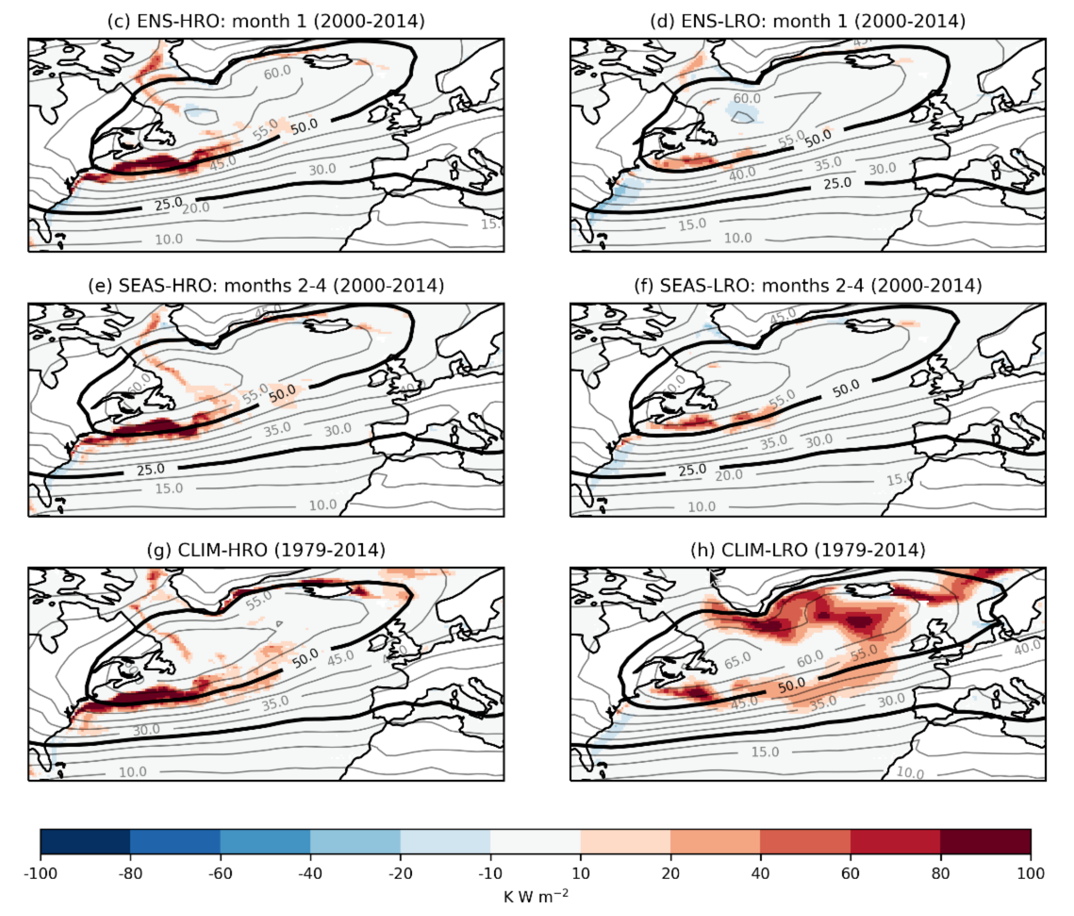
- However, biases in HRO and LRO are similar during weeks 1-4 and partially inherited from initial conditions.

- Differences begin to emerge at seasonal lead times, but take several decades to saturate.

Monthly SST-flux covariance and transient eddies in atmosphere (DJF)

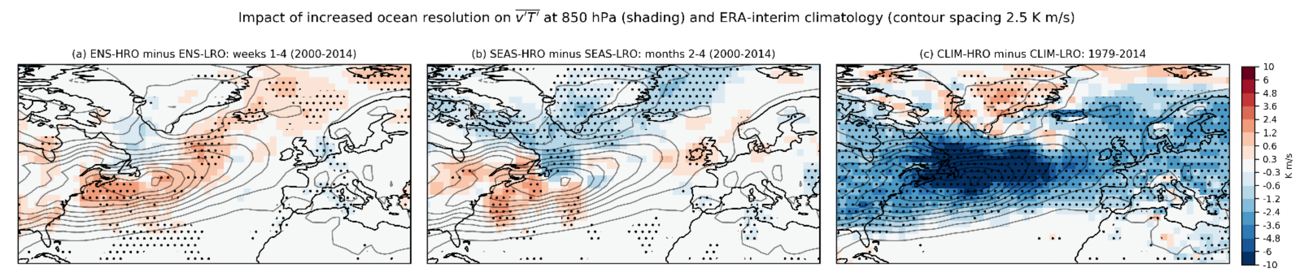
HRO **LRO**

Weeks 1-4 | Months 2-4 | Climate



Filled contours show cov(SST, Q_{turb}). Black contours show the standard deviation of daily (DJF) geopotential height at 850 hPa after application of a 2-6 day band-pass filter, which is a measure of storm track intensity.

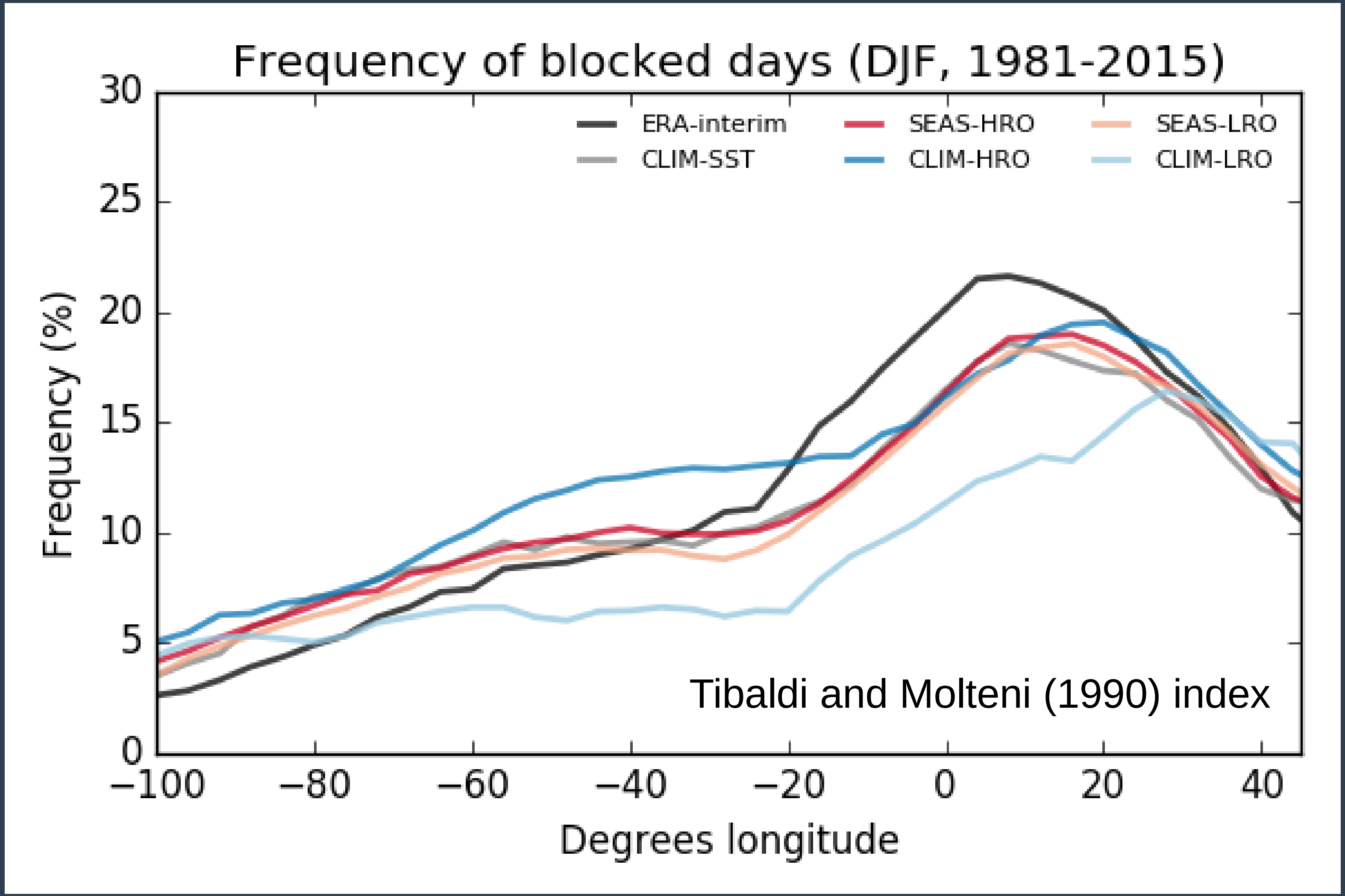
Impact on meridional heat flux by transient eddies at 850 hPa



Weeks 1-4 **Months 2-4** **Climate**

- Intense air-sea interaction over the Gulf Stream is better represented with HRO at all lead times.
- However, climatological storm track variability not particularly sensitive to these large differences in air-sea interaction at short lead times.
- Conclude that the large changes to the storm track and eddy-driven jet in climate runs (much stronger in LRO than HRO) are dominated by the differences in SST biases.

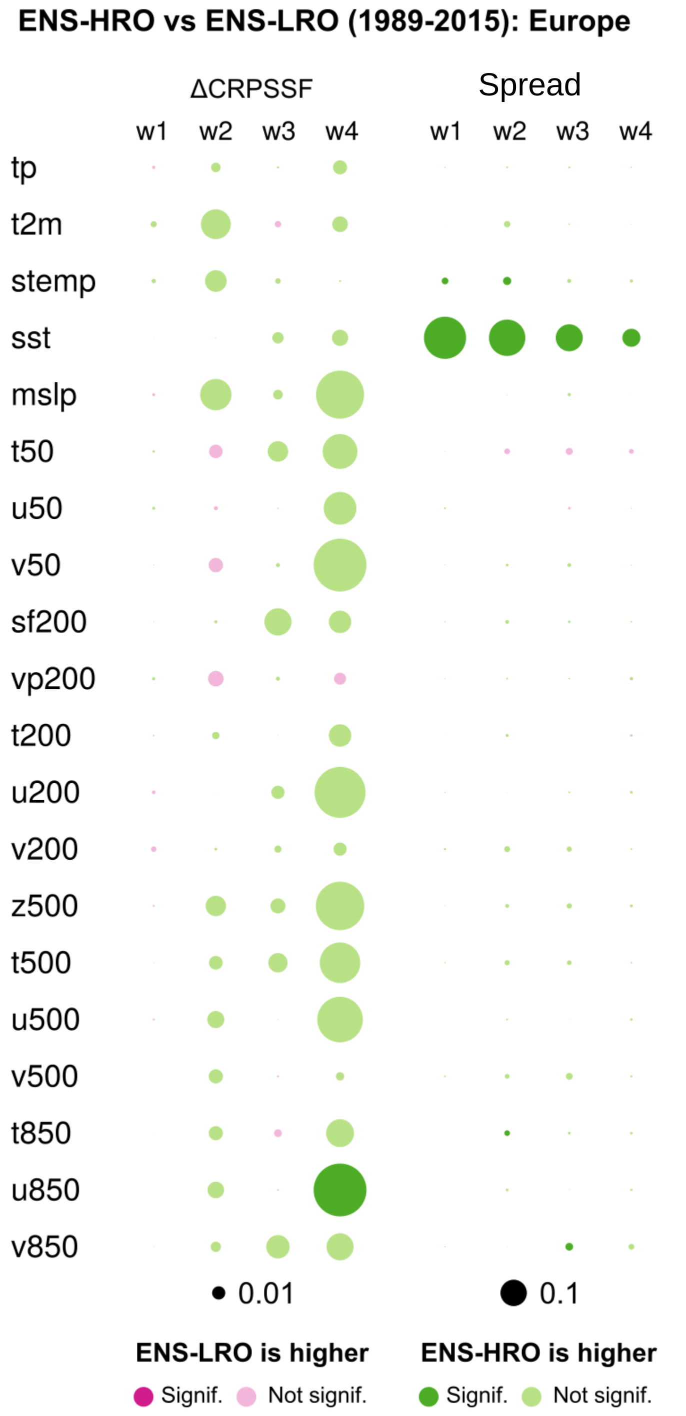
Atmospheric blocking in Euro-Atlantic domain (DJF)



Blocking improved in CLIM-HRO vs CLIM-LRO. Similar impact to the sensitivity reported by Scaife et al. (2011).

However, very little difference at seasonal lead times. In both HRO and LRO blocking is comparable to the same model forced with observed SSTs.

We conclude that blocking is sensitive to ocean resolution in our model, but it depends more on the magnitude of the SST biases than air-sea interaction. Thus there is a larger response at the longer (climate) timescales.



Impact on subseasonal predictions over Europe

Increasing ocean resolution results improves subseasonal predictions. The positive impact is most evident over Europe at longer lead times (week 4).

The probabilistic score (FCRPSS) is a function of the cumulative probability distribution of an ensemble forecast anomalies (i.e. independent of model bias).

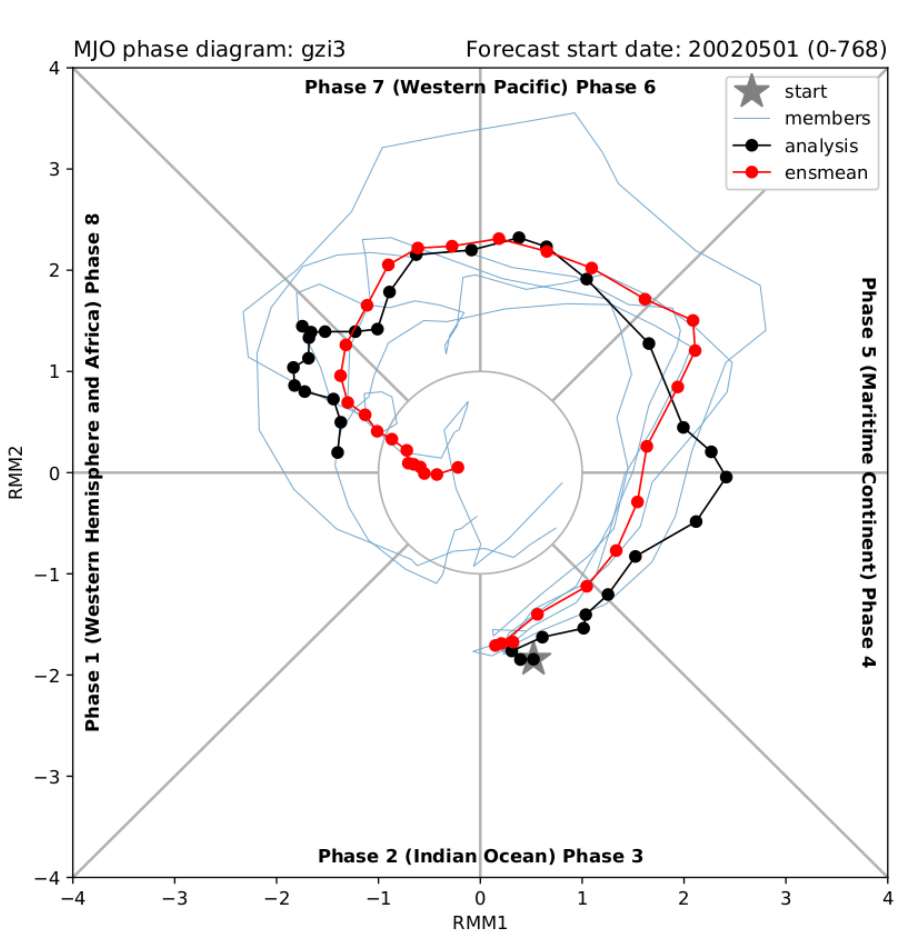
The large signal for increased ensemble spread in local SSTs does not translate to changes in spread for atmospheric variables.

How does ocean resolution improve European skill?
- *changes to North Atlantic mean state/bias?*
- *differences in air-sea interaction over Gulf Stream?*
- *Remote drivers?*

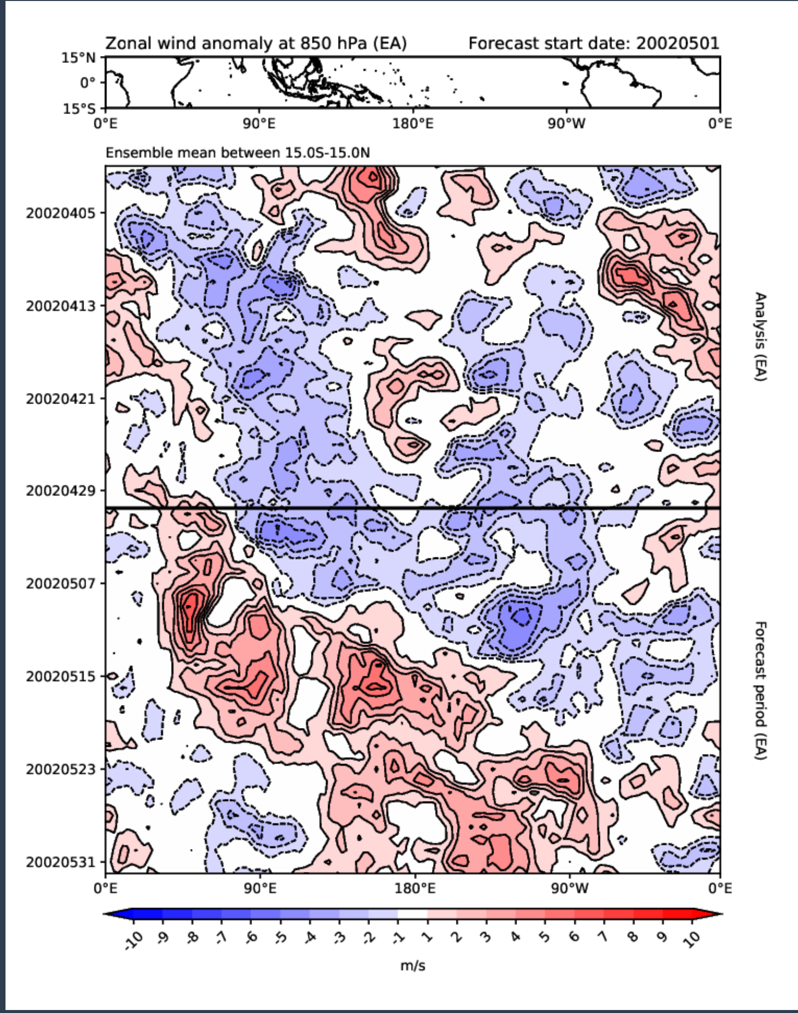
Plausible that mesoscale variability and changes in Gulf Stream air-sea interaction could have a remote response that impacts forecasts (e.g. Ma et al. 2015)

However, the evidence points towards a remote driver associated with improved intraseasonal variability in the tropics.

The Madden-Julien Oscillation (MJO)



The phase and amplitude of the MJO can be characterized by the bivariate Real-time Multivariate MJO index (Wheeler and Hendon, 2004).

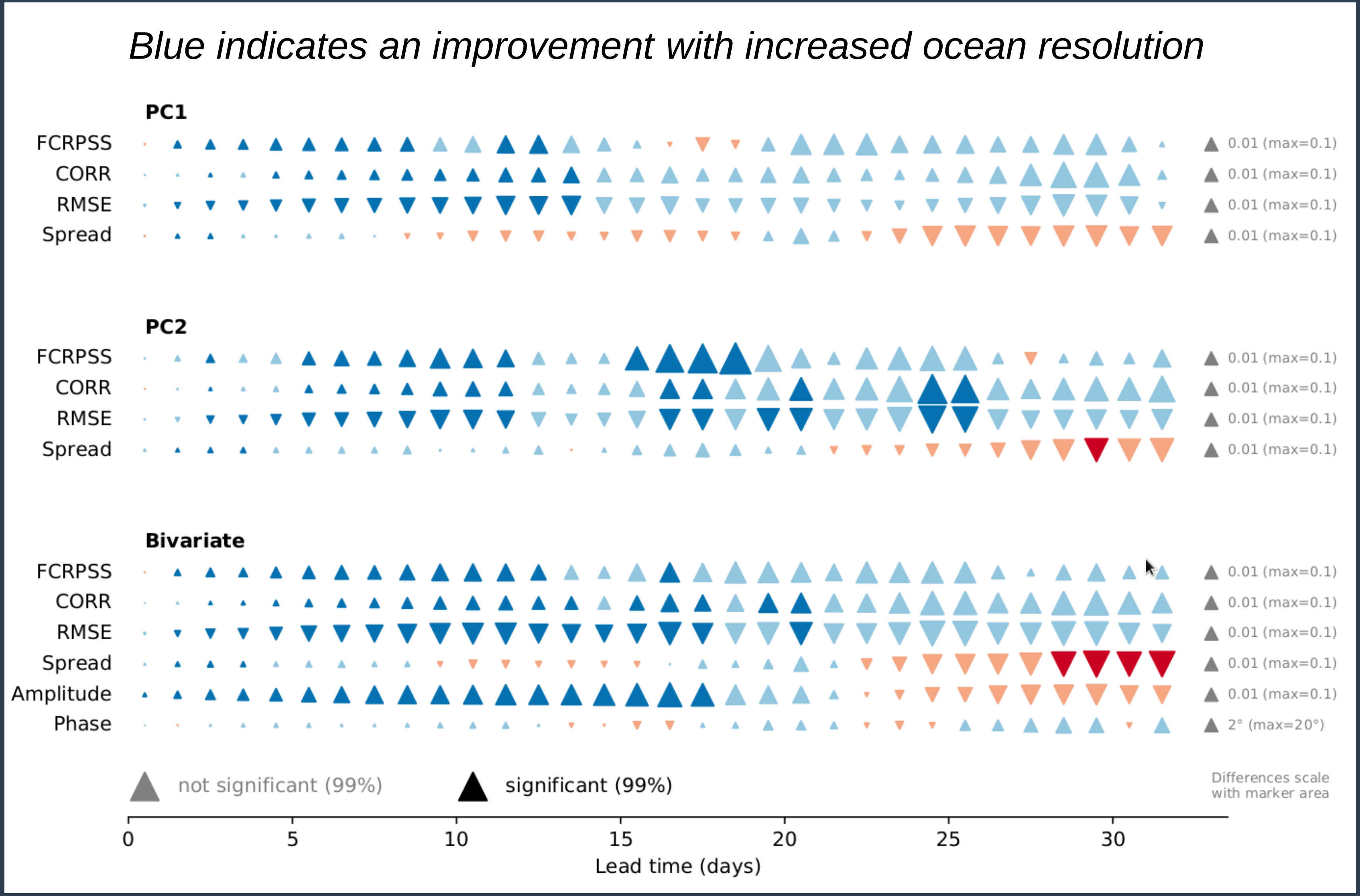


Skill in subseasonal forecasts is often linked to success in predicting the phase and propagation of the MJO its associated tropical-extratropical teleconnections.

Region of active convection is a source of Rossby waves.

Cassou (2008) showed that MJO modulates the probability of weather regimes in North Atlantic with a lag of 5-15 days.

Increased ocean resolution improves skill of MJO forecasts

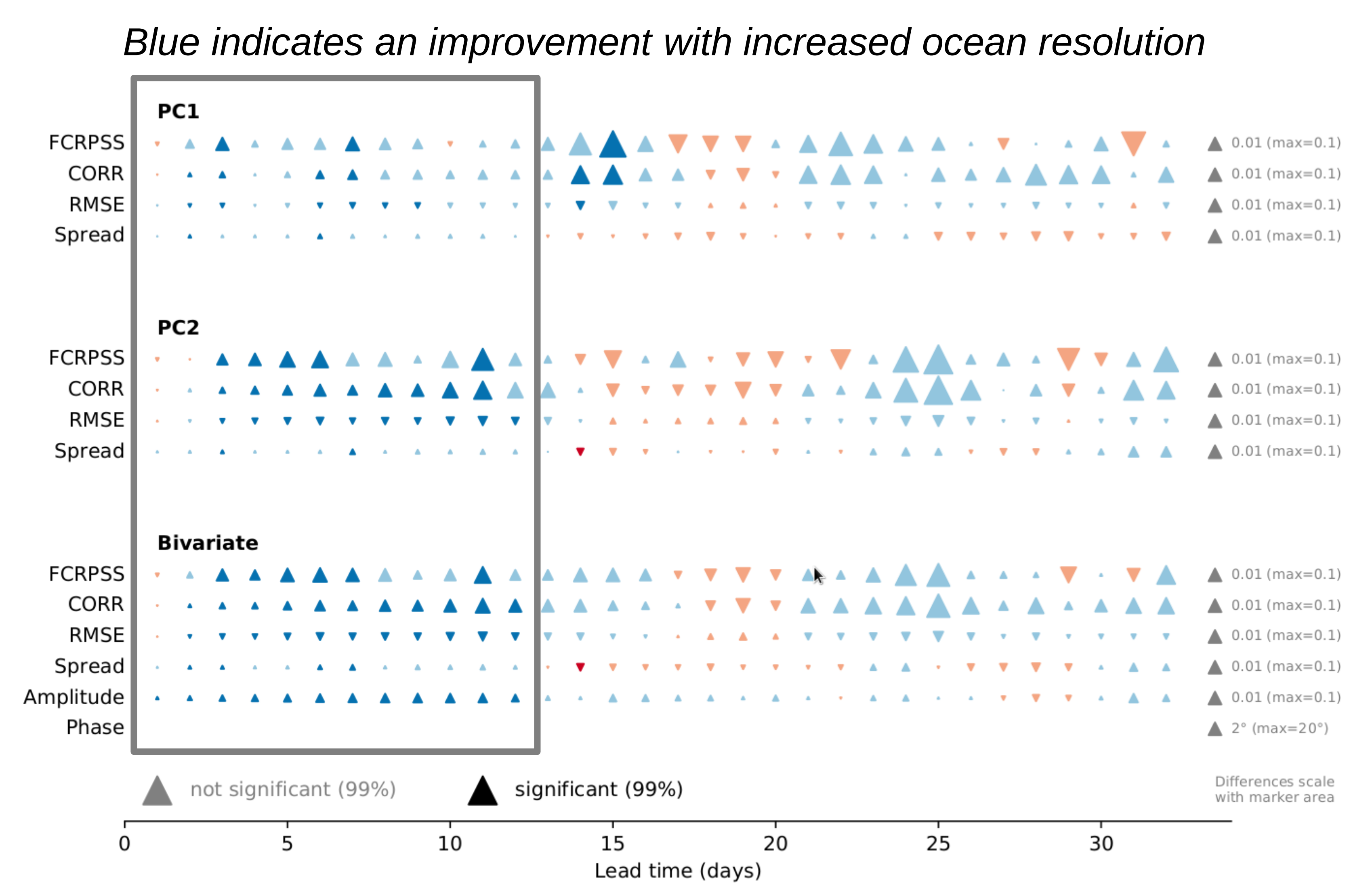


Increasing ocean resolution improves the timing and magnitude of MJO variability in the first ~20 days of subseasonal forecasts.

Propagation speed doesn't change (too slow in both systems).

Skill can be decomposed intro contributions from outgoing longwave radiation (convection) and winds (upper vs lower level).

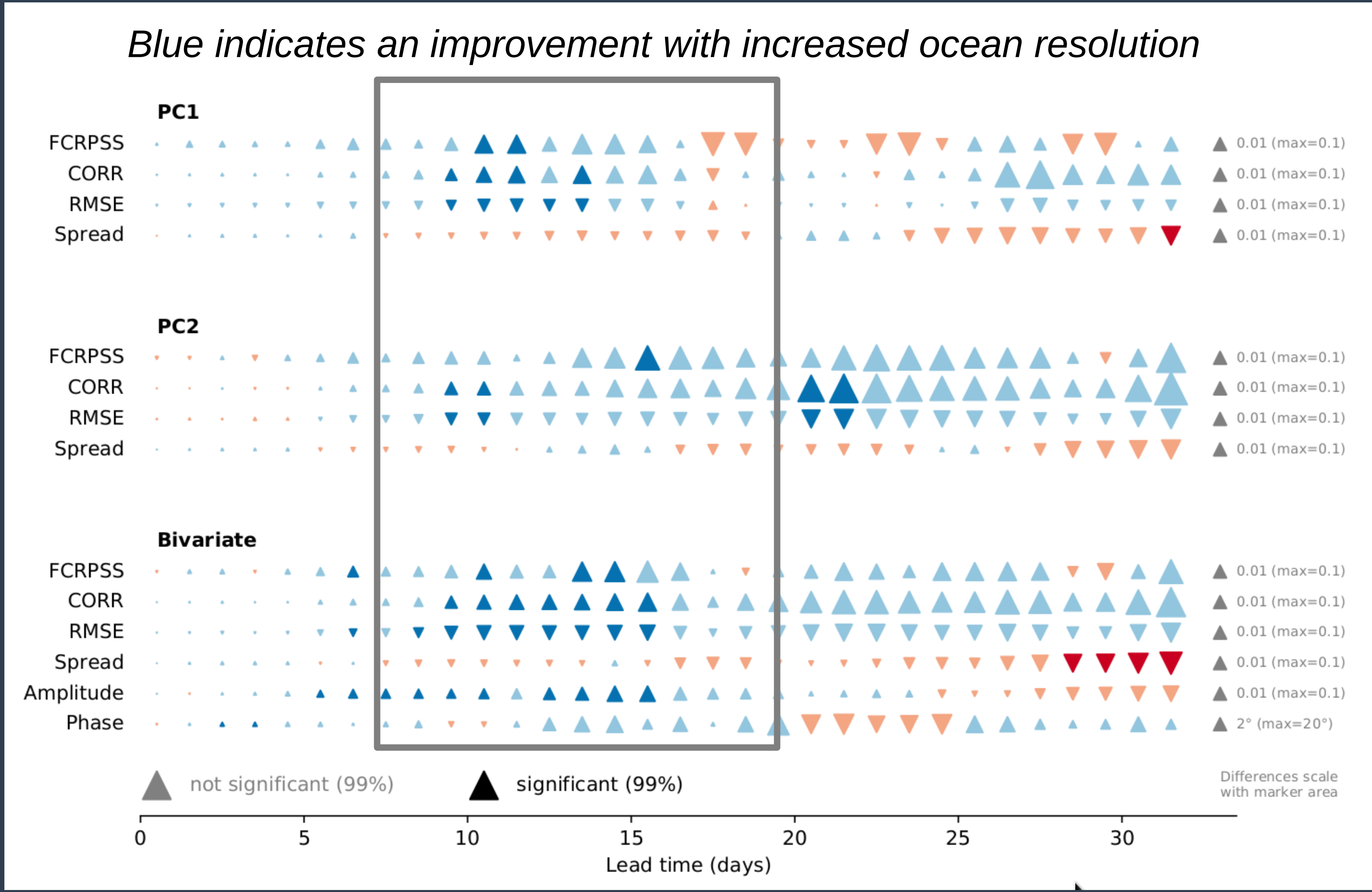
Contribution from outgoing longwave radiation



Initial response to increased ocean resolution is improvements to outgoing longwave radiation (i.e. convection) at days 1-10.

Particularly in PC2, which has centres of action of Indian Ocean and the Maritime Continent.

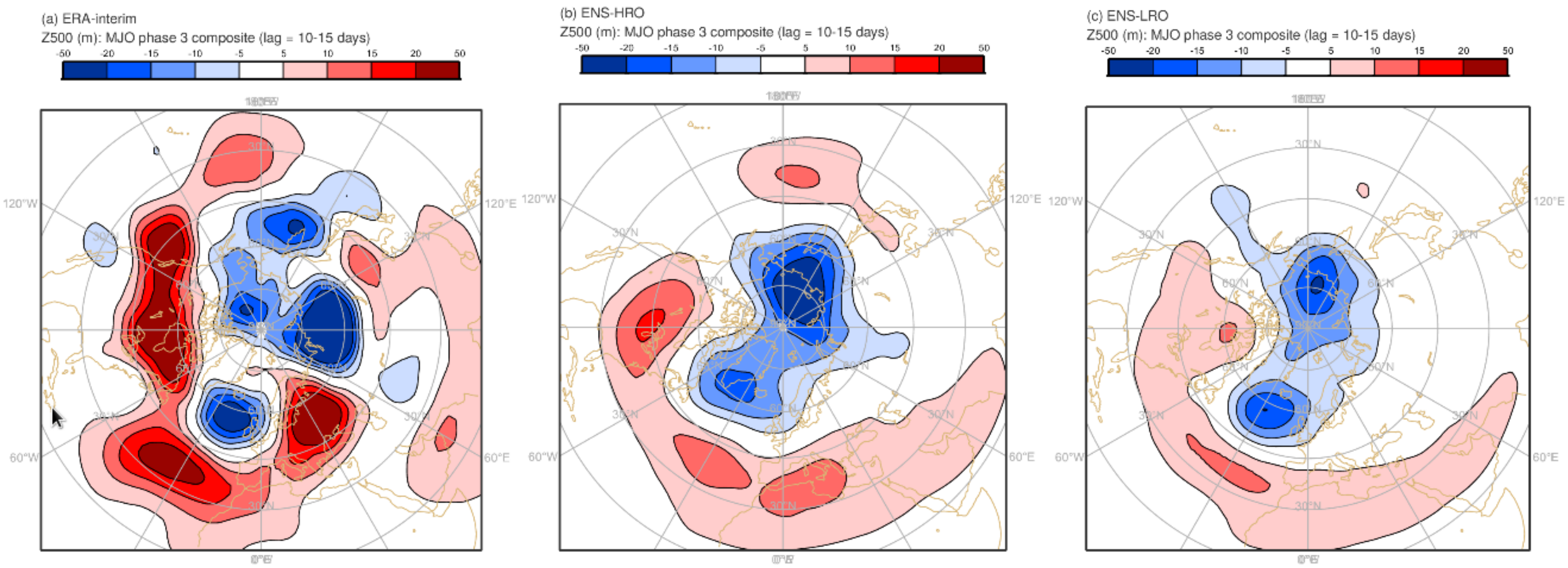
Contribution from zonal winds at 200 hPa



Improvements to upper level winds lag improvements to convection by 5-10 days.

Associated improvements to the divergence will impact the Rossby wave source.

Increased ocean resolution improves the magnitude of MJO teleconnections



ERA-interim **HRO** **LRO**

FIG. 14. Composites of 500 hPa geopotential height (Z500) anomalies for periods 10-15 days after phase 3 of the Madden-Julian Oscillation (MJO), which corresponds to enhanced convective activity in the tropical Indian Ocean , in (a) ERA-interim, (b) ENS-HRO, and (c) ENS-LRO.

Summary and conclusions

- In general, mean biases are reduced with increased ocean resolution and this impact is increased at longer lead times.
- Some aspects of air-sea interaction exhibit a clear improvement with increased ocean resolution at all lead times (weeks to decades).
- However, it is difficult to identify the impact of improved air-sea interaction and increased ocean eddy activity in the variability of the overlying atmosphere.
- Atmospheric blocking and the intensity of the storm track respond more strongly to mean biases than ocean eddy variability and thus have a larger response at longer lead times.
- Increased ocean resolution drives also improvements to subseasonal predictability over Europe. This increase in skill seems to come from improvements to the MJO and its associated teleconnections rather than changes to air-sea interaction in the North Atlantic region.

Future directions and further reading

- Initialized forecasts can be verified against observations and therefore aid process understanding within a coupled framework.

- Work will continue as NEMO v4.0 is implemented in ECMWF IFS

- *Roberts, C. D., et al. "The timescale-dependent response of the wintertime North Atlantic to increased ocean model resolution in a coupled forecast model." Journal of Climate (2020), https://doi.org/10.1175/JCLI-D-19-0235.1.*

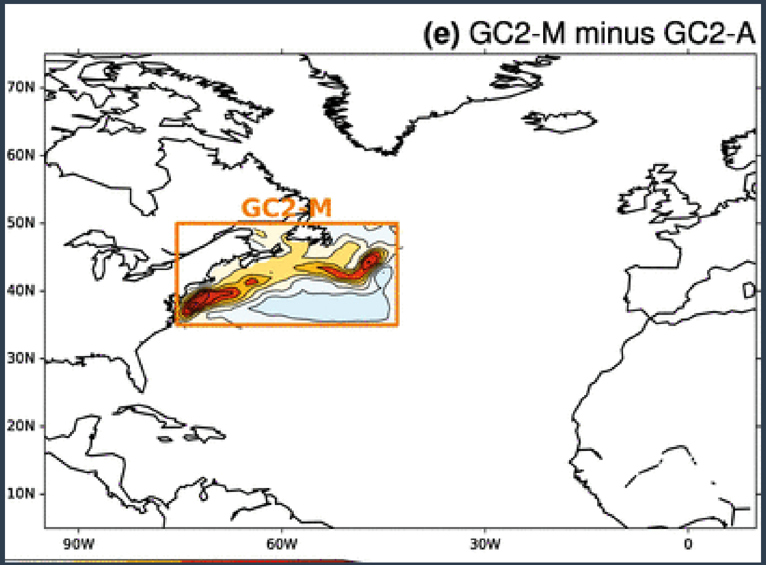
- *Roberts, C. D., et al. "Climate model configurations of the ECMWF Integrated Forecasting System (ECMWF-IFS cycle 43r1) for HighResMIP." Geoscientific model development 11.9 (2018): 3681-3712.*

- *Roberts, C. D., et al. "Reduced-resolution ocean configurations for efficient testing with the ECMWF coupled model", ECMWF Technical Memorandum 858 (2020).*

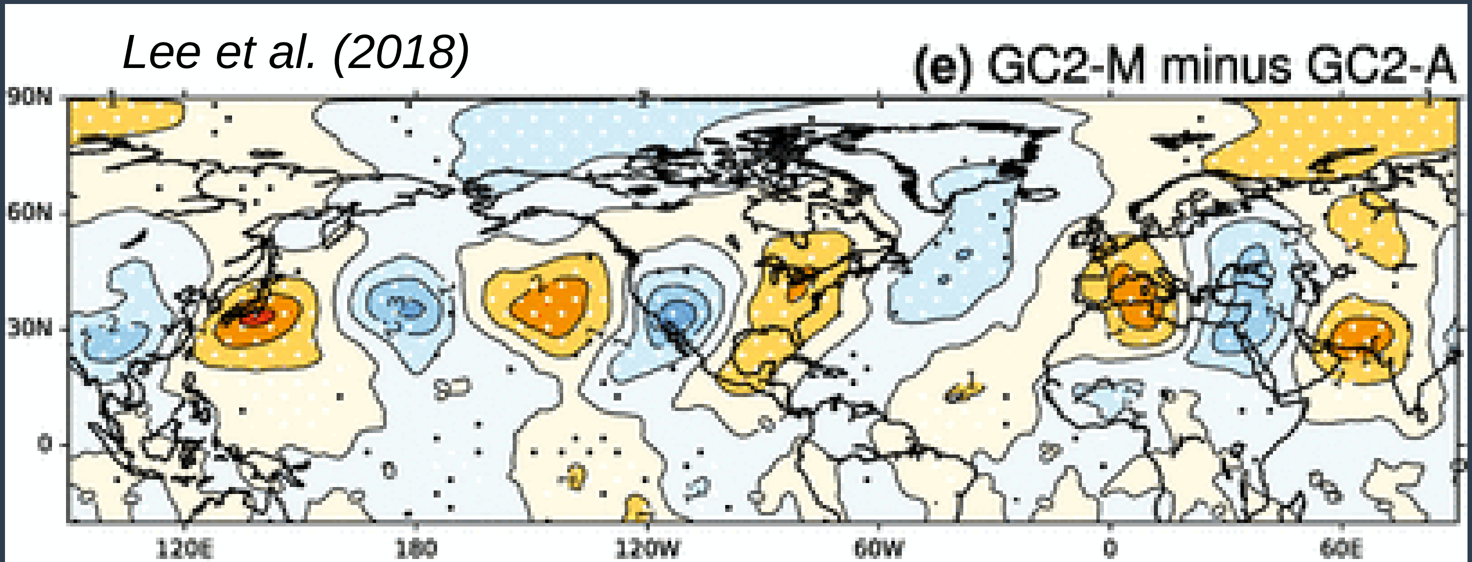
Extra slides

Gulf stream SST biases impact global atmospheric circulation

Imposed SST bias



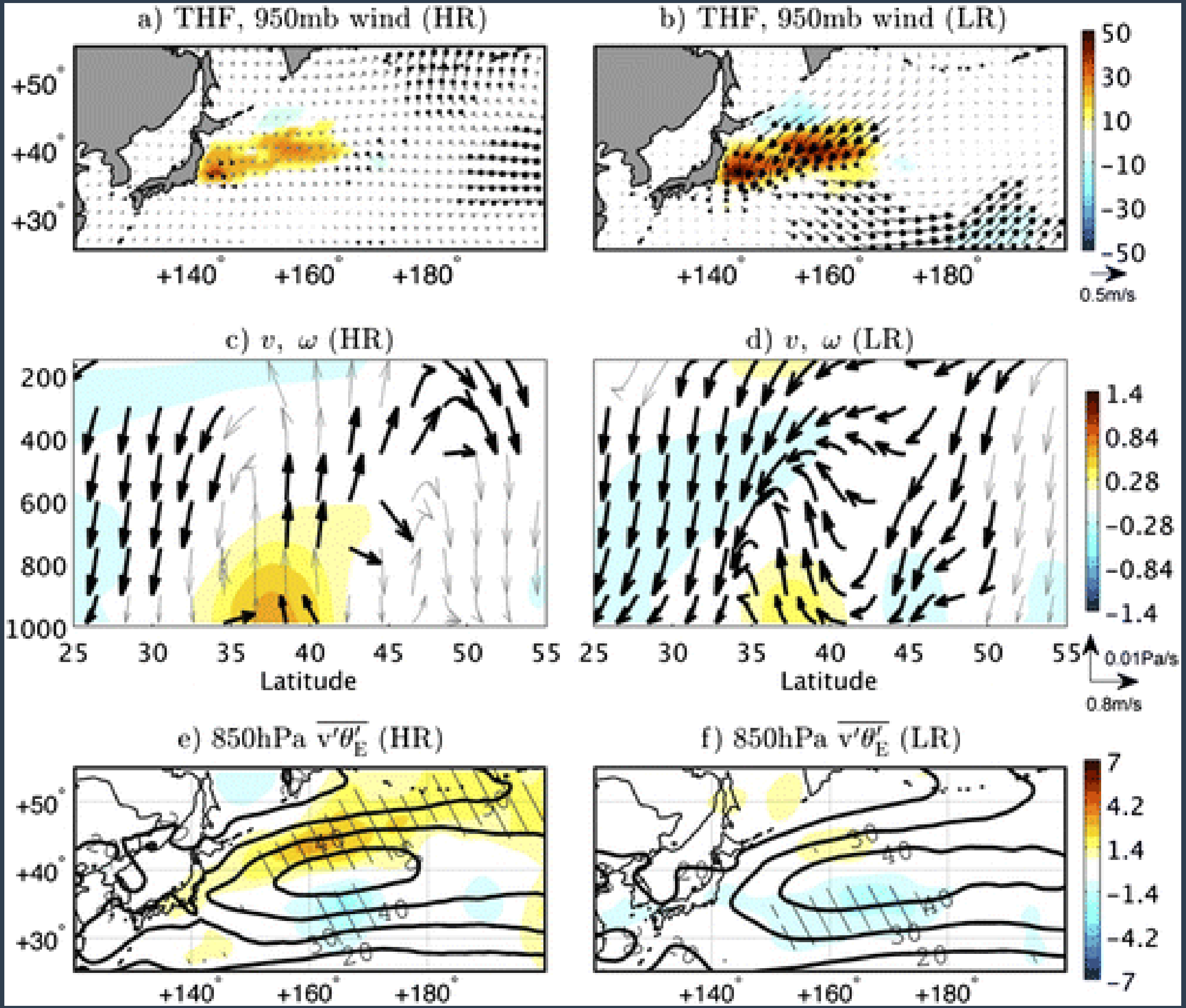
Response of meridional wind at 250 hPa



- Lee et al. (2018) performed idealized atmosphere (~60 km) experiments in which the SST boundary conditions in the Gulf Stream are modified using biases from the equivalent coupled model configuration.
- The anomalous Gulf Stream heating drives enhanced vertical motion in transient eddies and a significant circum-global planetary wave response.

Sensitivity of the response to atmospheric resolution

Smirnov et al. (2015)



Smirnov et al. (2015) performed idealized experiments and evaluated the response to a shift in the Kuroshio current in 25 km (HR) and 100 km (LR) atmospheric models.

HR model response: strong vertical circulation and poleward transient eddy heat and moisture fluxes.

LR model response: equatorward cold air advection, which resembles solutions obtained using linear dynamics.

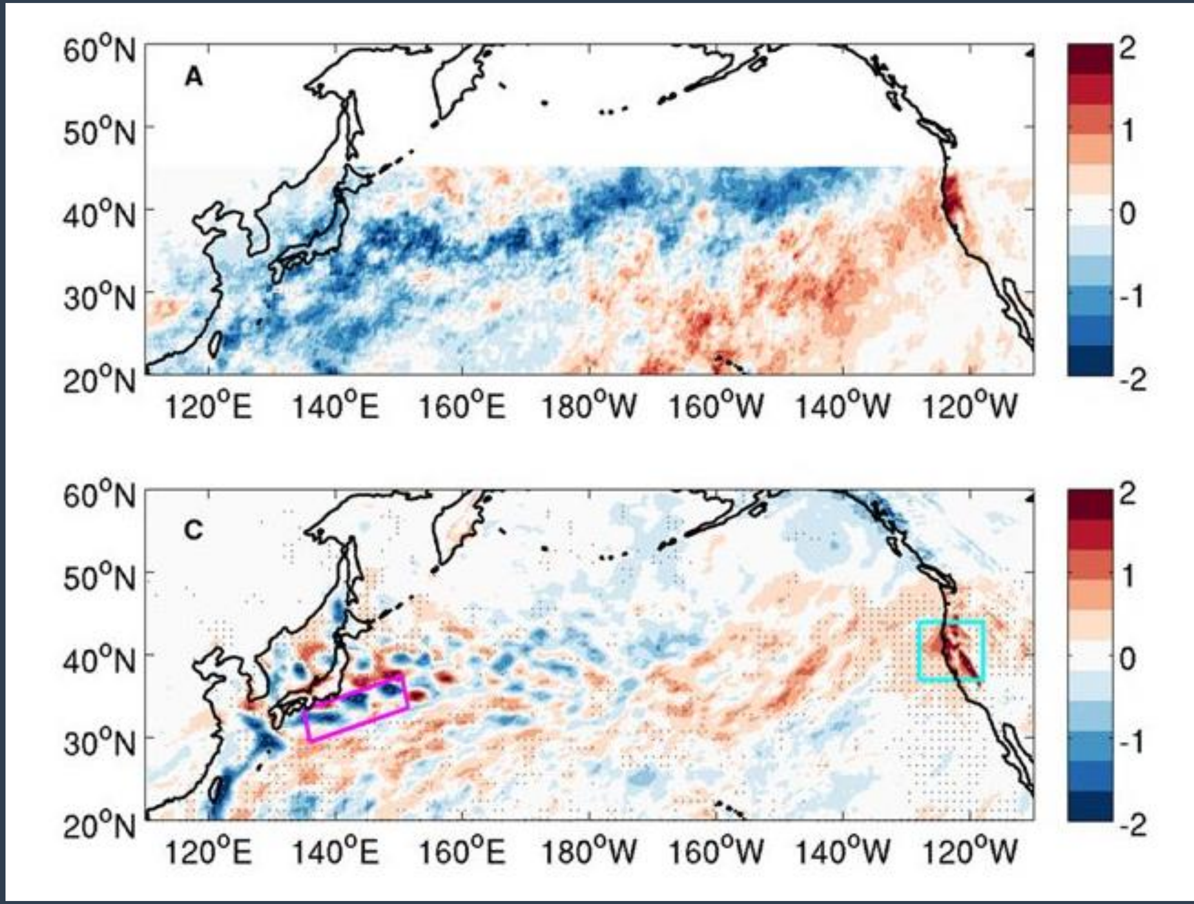
Contrasting responses linked to ability of models to resolve vertical motions in atmospheric fronts (also see Sheldon et al. 2017; Vanniere et al. 2017).

Remote response to mesoscale SST variability in Kuroshio current

Change in winter (NDJFM) rainfall (with eddies minus without eddies)

Observational composite

Simulated



Ma et al. (2015)

Ma et al. (2015) performed idealized experiments with a regional atmospheric model to isolate impact of mesoscale features in prescribed SST boundary conditions.

They found that Kuroshio eddies can influence winter rainfall variability along U.S. North Pacific coast.

Mechanism: mesoscale SST anomalies intensify winter cyclogenesis, which in turn drives anticyclonic SLP anomaly in eastern Pacific.

Impact of Gulf Stream SST gradients on the troposphere

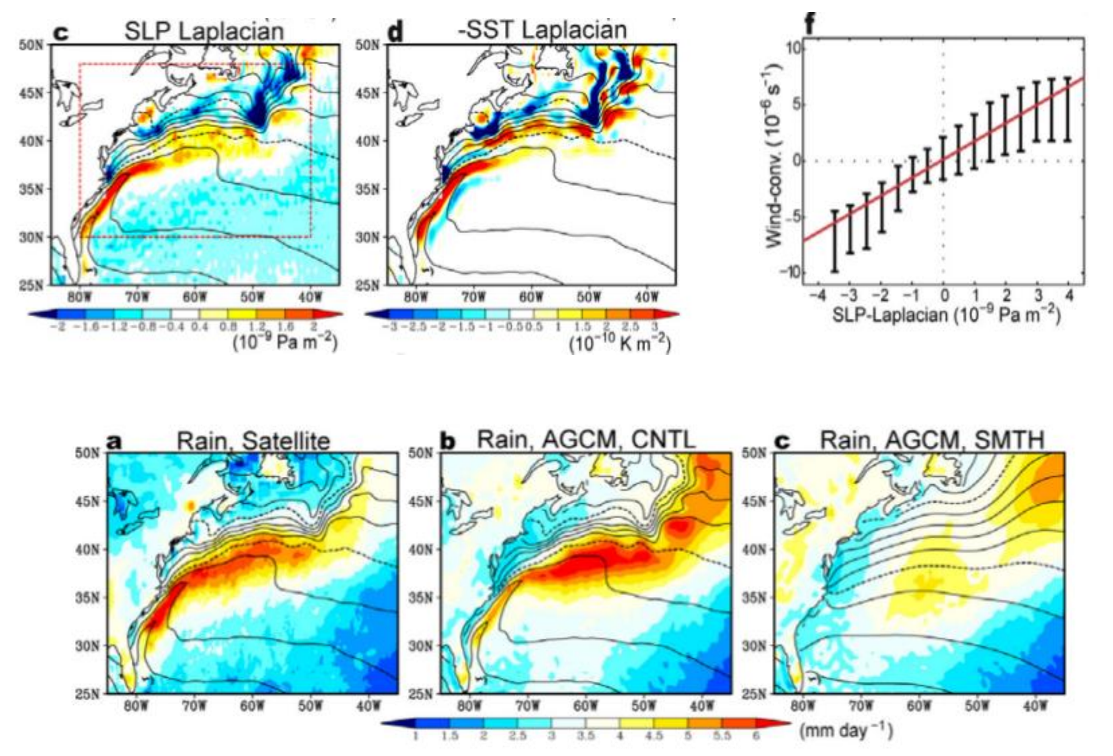


Figure 2. Annual climatology of rain rate: (a) observed by satellites, and in the AGCM with (b) observed and (c) smoothed SSTs. Contours are for SST as in Fig. 1.

Minobe et al. (2008)

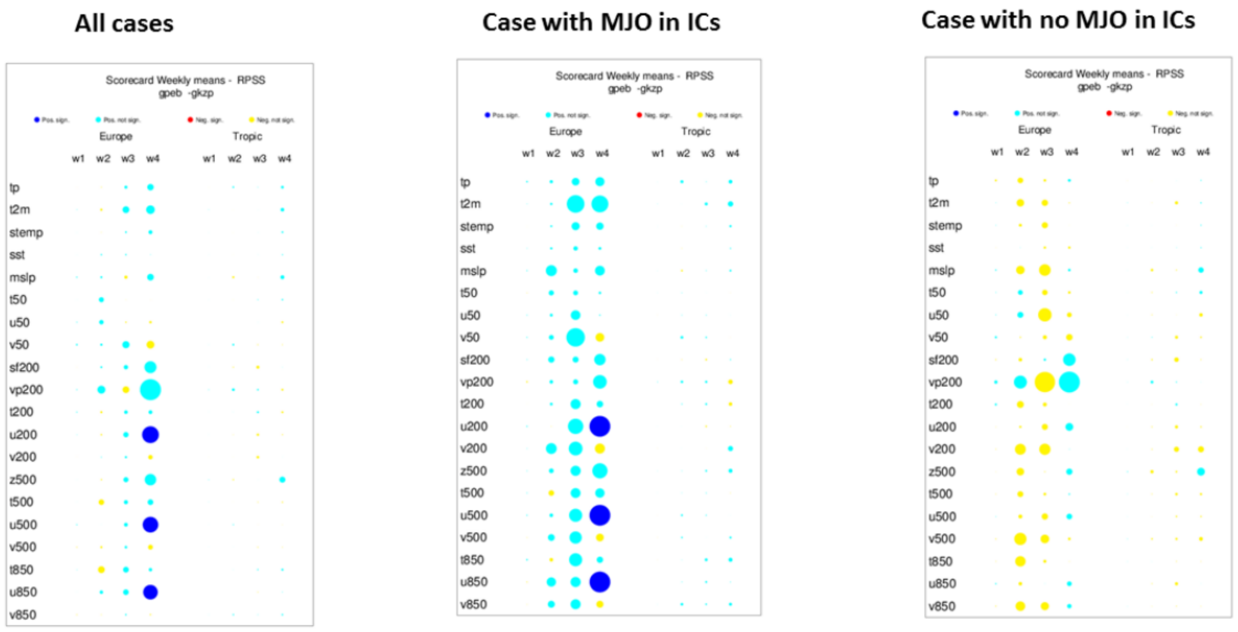
Gulf Stream SST gradients induce an atmospheric response that extends into the free troposphere.

Minobe et al. (2008) linked response to hydrostatic pressure adjustment mechanism (PAM; Lindzen and Nigam 1987) that relates the Laplacian of SST to convergence in the MABL and upward motion into the troposphere.

Results in rain band that is “anchored” to warm side of front, which is lost when SSTs are smoothed artificially.

Although relationships manifest in the time-mean, they are consequence of the accumulated effect of near-surface convergence and upward motion within individual synoptic systems (Parfitt and Czaja 2016; ONeill et al. 2017).

North Atlantic SST biases degrade ECMWF extended range forecasts



Vitart & Balmaseda (2018)

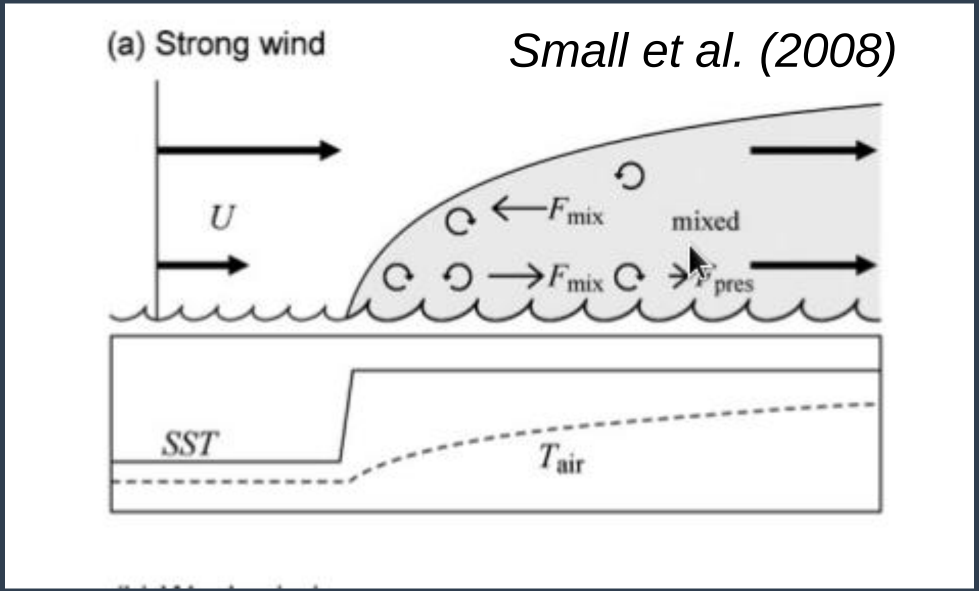
Figure 15: Scorecards of BC_ET CRPSS over Europe relative to Control when all the forecasts are included (left panel), only cases with a strong MJO in the initial conditions (middle panel) and when there is no MJO in the initial conditions (right panel).

- North Atlantic SST biases also impact skill in ECMWF extended range forecasts.
- Reducing North Atlantic SST biases with online correction scheme improves extended range forecast skill over Europe.
- Increased skill linked to improved MJO teleconnection magnitude.

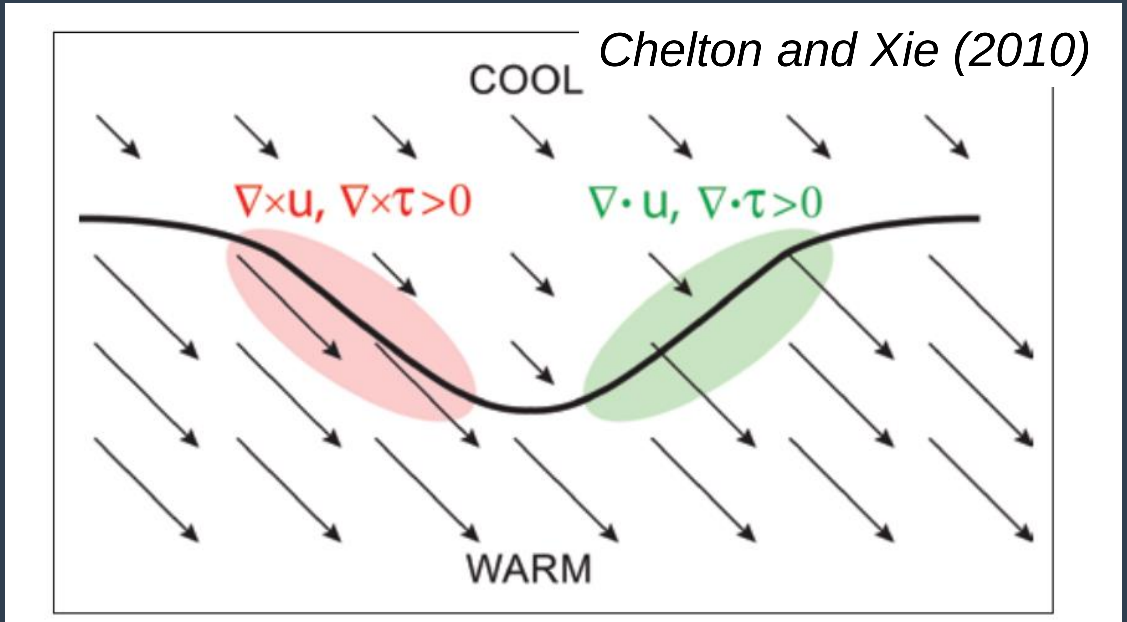
Character of air-sea interaction is scale-dependent

At scale basin of ocean basins, there is negative or zero correlation between SST and wind speed/heat fluxes out of the ocean. ***Stronger winds → ocean heat loss → SST cooling → atmosphere driving ocean.***

At scale of ocean fronts and eddies, there is positive correlation between SST and wind speed/heat fluxes out of the ocean: ***Warmer SSTs → ocean heat loss → stronger winds → ocean driving atmosphere.***



A case where air flowing over an SST front experiences enhanced mixing and downward transfer of momentum.



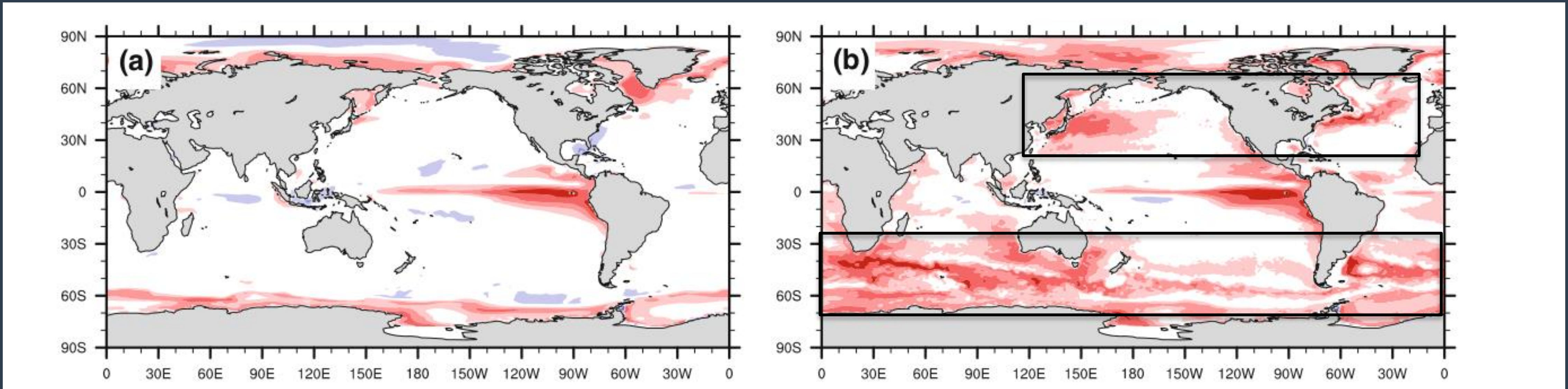
Relative orientation of prevailing winds and SST gradients can impact wind stress curl and dirvergence (Chelton and Xie, 2010)

Character of air-sea interaction is scale-dependent

Eddy-permitting or eddy-resolving ocean models are thus required to correctly simulate positive correlations between SST and heat flux anomalies in regions of intense eddy activity such as western boundary current and the Antarctic circumpolar current.

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

CCSM – 1 degree ocean *CCSM – 0.1 degree ocean*



Kirtman et al. (2012)

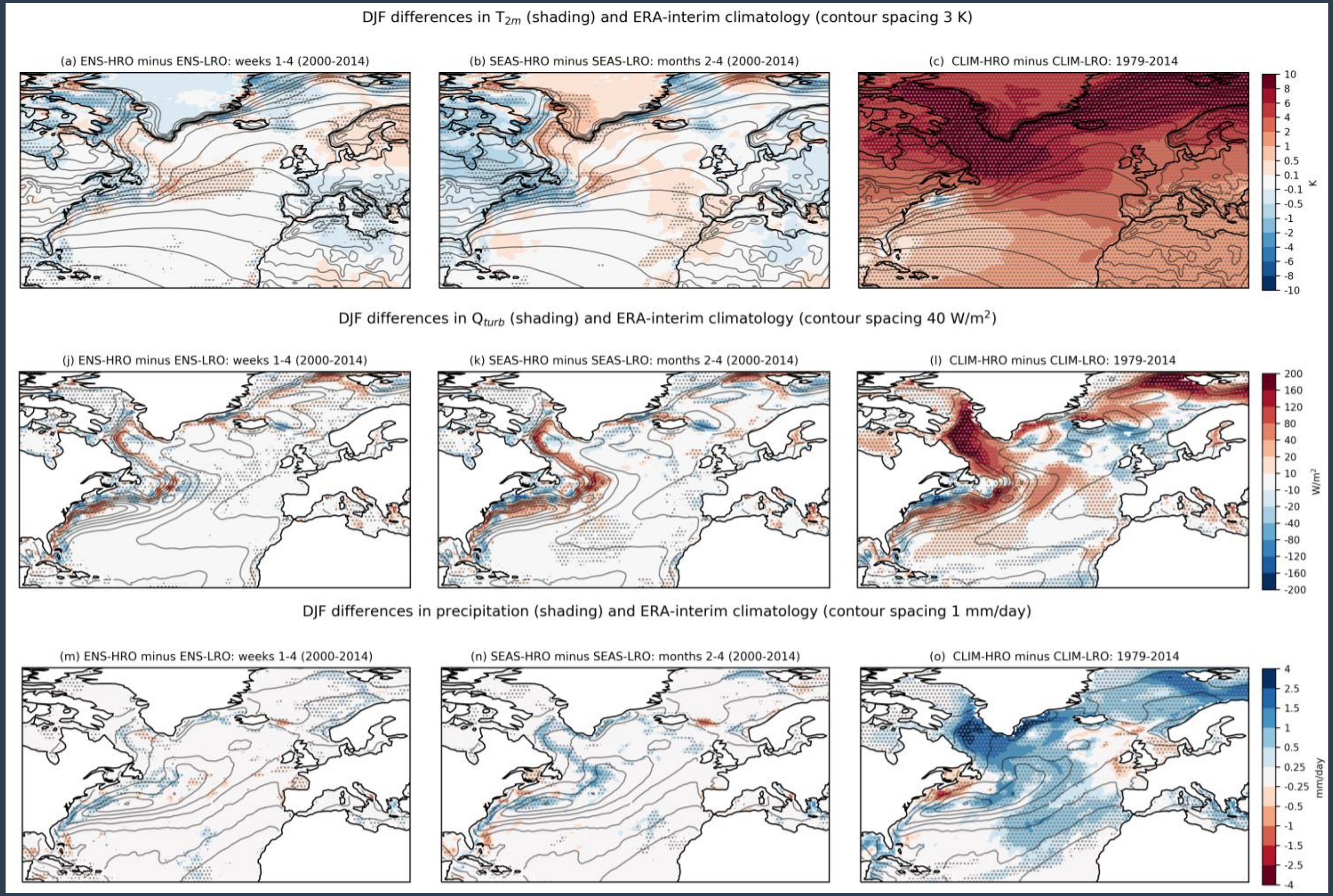
Mean atmospheric response (DJF): HRO minus LRO

Weeks 1-4 | **Months 2-4** | **Climate**

T_{2m}

Q_{turb}

Precip



Changes in T_{2m}, $Q_{turb,}$ and precip reflect changes in SST.

Differences correspond to reduced biases in HRO.

Higher SSTs in HRO (e.g. Labrador Sea, Gulf Stream extension) associated with higher T_{2m}, increased Q_{turb} (atm -> ocean), and increased precipitation.

Lower SSTs in HRO (e.g. north of Gulf Stream separation) associated with lower T_{2m}, reduced Q_{turb}, and reduced precipitation.

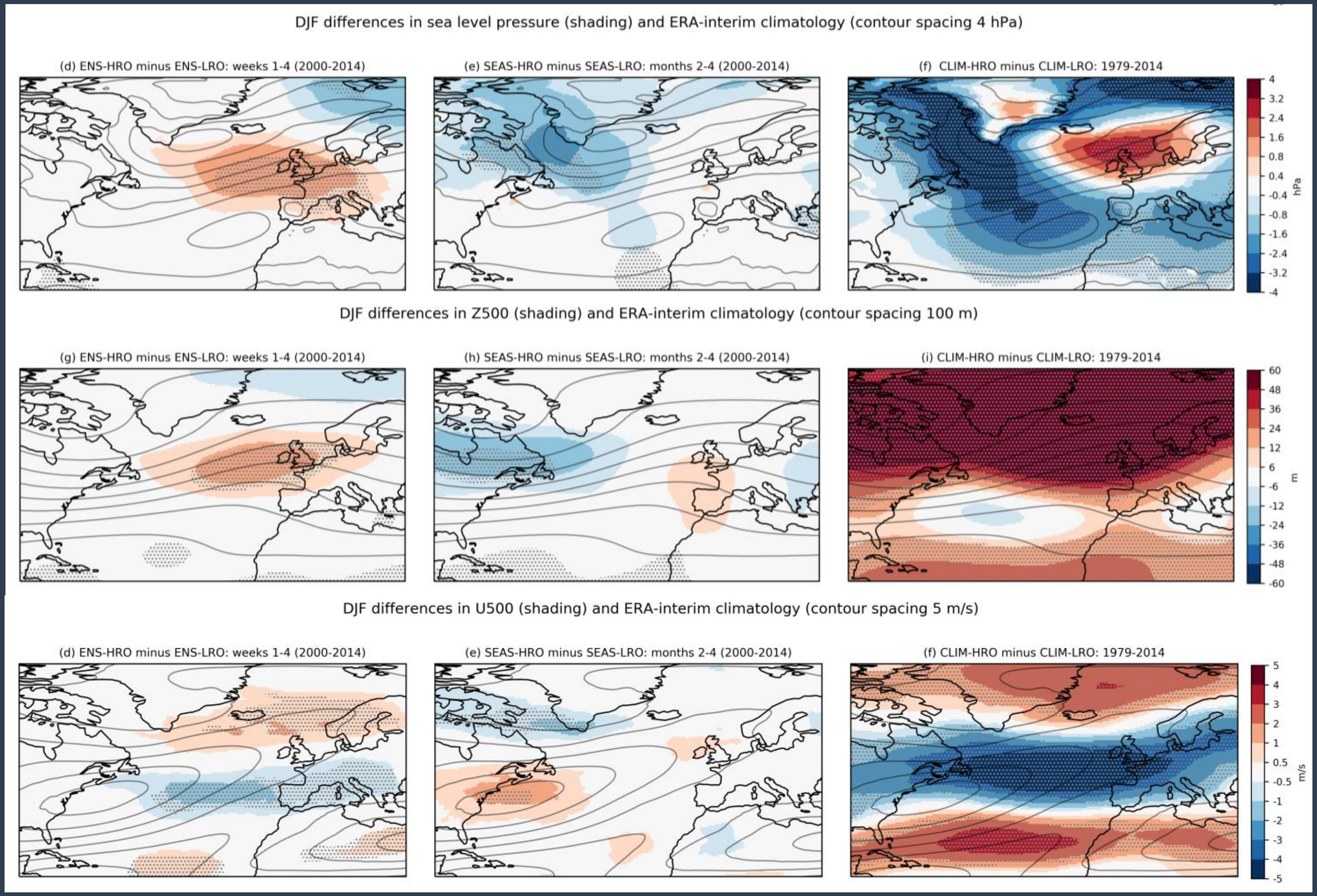
Mean atmospheric response (DJF): HRO minus LRO

Weeks 1-4 **Months 2-4** **Climate**

MSLP

Z500

U500



Dynamic response is more complex: non-linear feedbacks are sensitive to sign/magnitude/location of SST changes.

Weeks 1-4: Equivalent barotropic, increase of Z500/MSLP in north-east Atlantic, northward shift of jet.

Months 2-4: Equivalent barotropic, decrease of Z500/MSLP in north-west Atlantic, intensification of jet.

Climate: Baroclinic, direct thermal response dominates. Cooling of SPG in CLIM-LRO increases meridional temperature gradient and polar jet.

SST gradient magnitude and precipitation (DJF)

HRO

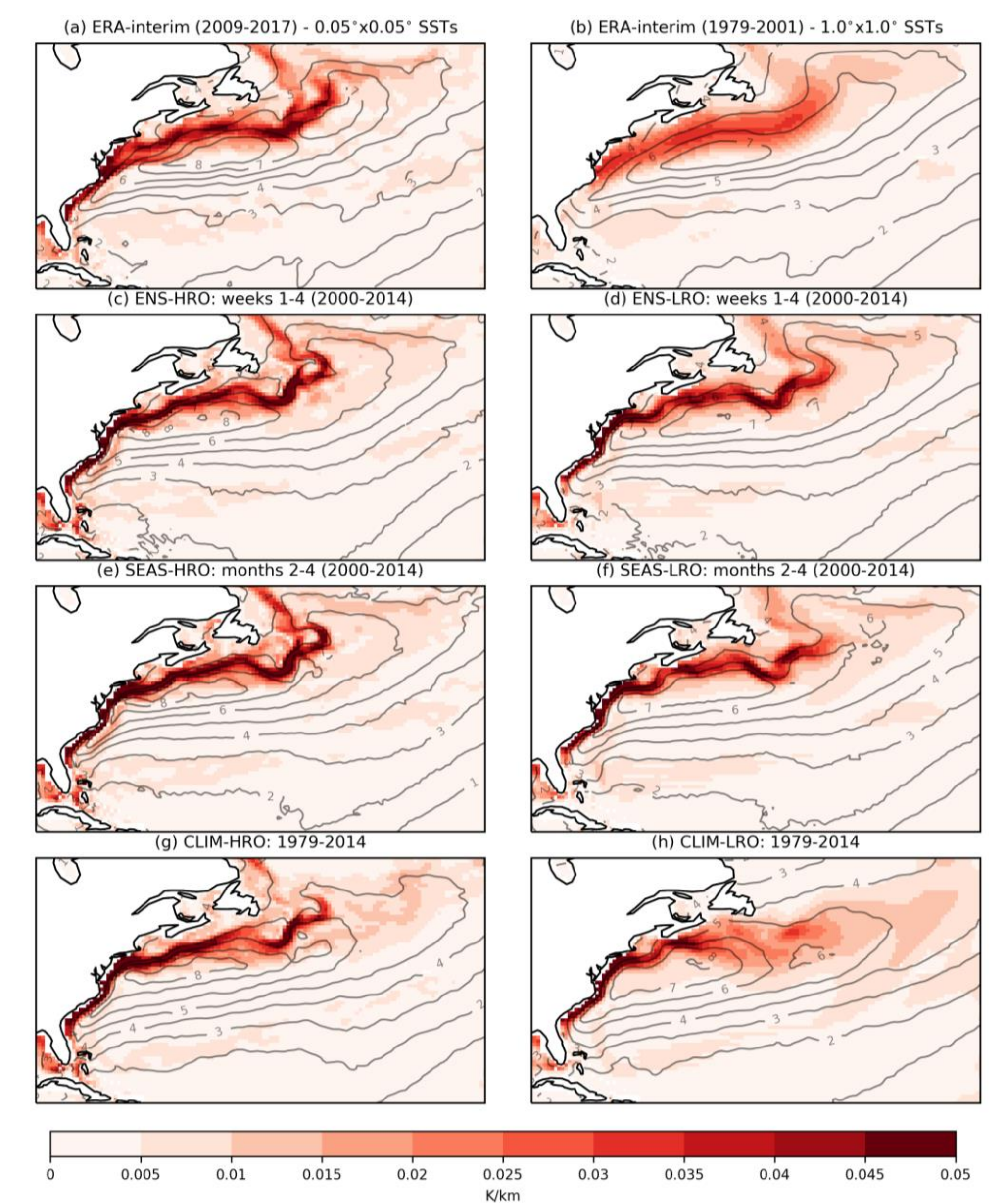
LRO

ERA-int

Weeks 1-4

Months 2-4

Climate



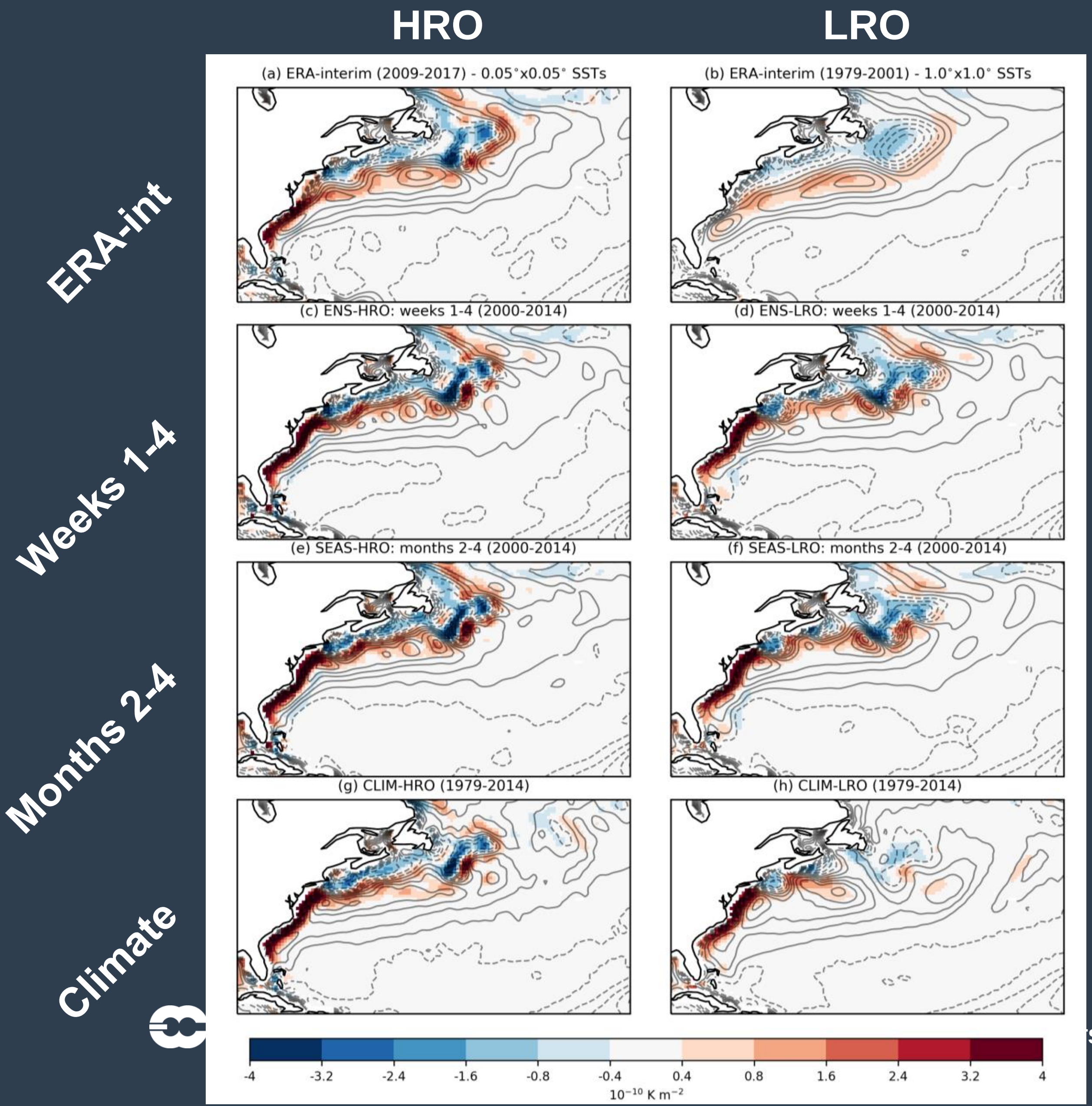
Sharp SST gradients anchor precip south of Gulf stream. ERA-int is sensitive to resolution of SST boundary conditions (see Parfitt et al. 2017).

Mean SST gradients are qualitatively reproduced in both ENS-LRO and ENS-HRO. Large gradients along coast inherited from initial conditions and drive westward expansion of peak rainfall.

SST gradients and rain band begin to weaken in SEAS-LRO.

SST gradients maintained in CLIM-HRO but show weakening and southward shift in CLIM-LRO.

∇^2SST and 10 m wind convergence



Similar story for ∇^2SST and convergence in marine atmospheric boundary layer.

Structure reasonably well constrained in ENS-LRO and ENS-HRO by initialization.

Deterioration of LRO becomes more evident at seasonal lead times.

Eventually CLIM-LRO exhibits breakdown in pattern of ∇^2SST and associated convergence and precipitation patterns.

PRIMAVERA: Multi-decadal climate simulations with the IFS

Atmosphere-only and coupled climate model configurations of IFS (CY43R1) for different combinations of ocean and atmosphere resolution.

Multi-decadal ensemble experiments follow the protocols of the High Resolution Model Intercomparison Project (HighResMIP) and phase 6 of the Coupled Model Intercomparison Project (CMIP6).

Evaluation of experiments is ongoing as part of multi-model analysis in PRIMAVERA project. Data to be available through ESGF.

Further details available in description paper:

Roberts et al. (2018), "Climate model configurations of the ECMWF Integrated Forecasting System (ECMWF-IFS cycle 43r1) for HighResMIP", Geosci. Model Dev., 11, 3681-3712.