Wave model driven changes in ECMWF Earth System Model

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ECMWF

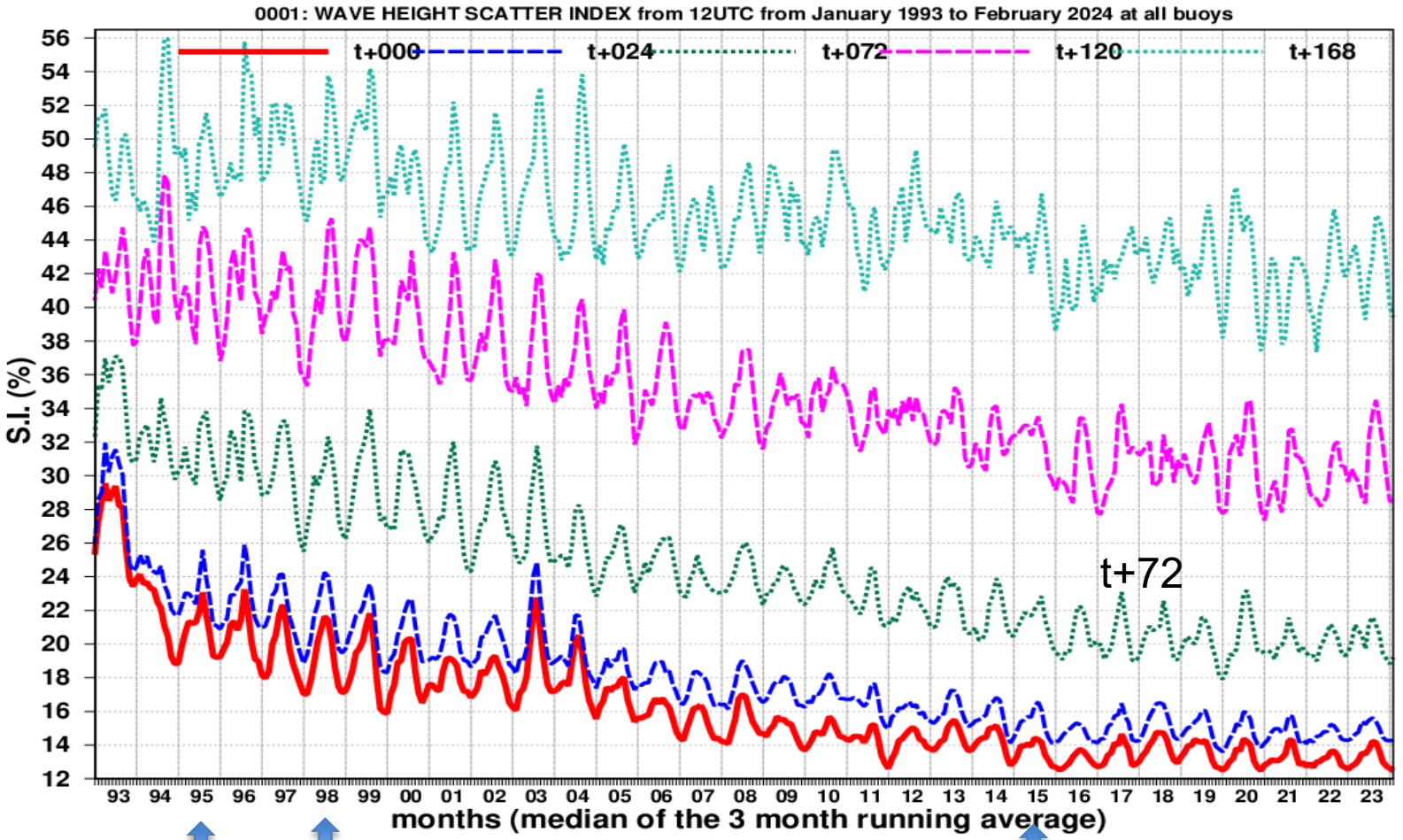
Outline:

1. Ocean Wave modelling at ECMWF.
2. Revision of wind – wave interaction for surface momentum exchange.
3. Revision of wind – wave interaction for heat and moisture exchanges.
4. Overall impacts of waves feedback on ECMWF medium range forecasts.
5. ERA6 preparation.

1. Wave modelling at ECMWF

Comparison with in-situ SWH observations

Scatter Index



Forecast range in hours

Wave forecasting started in June 1992

I joined ECMWF Aug 1995

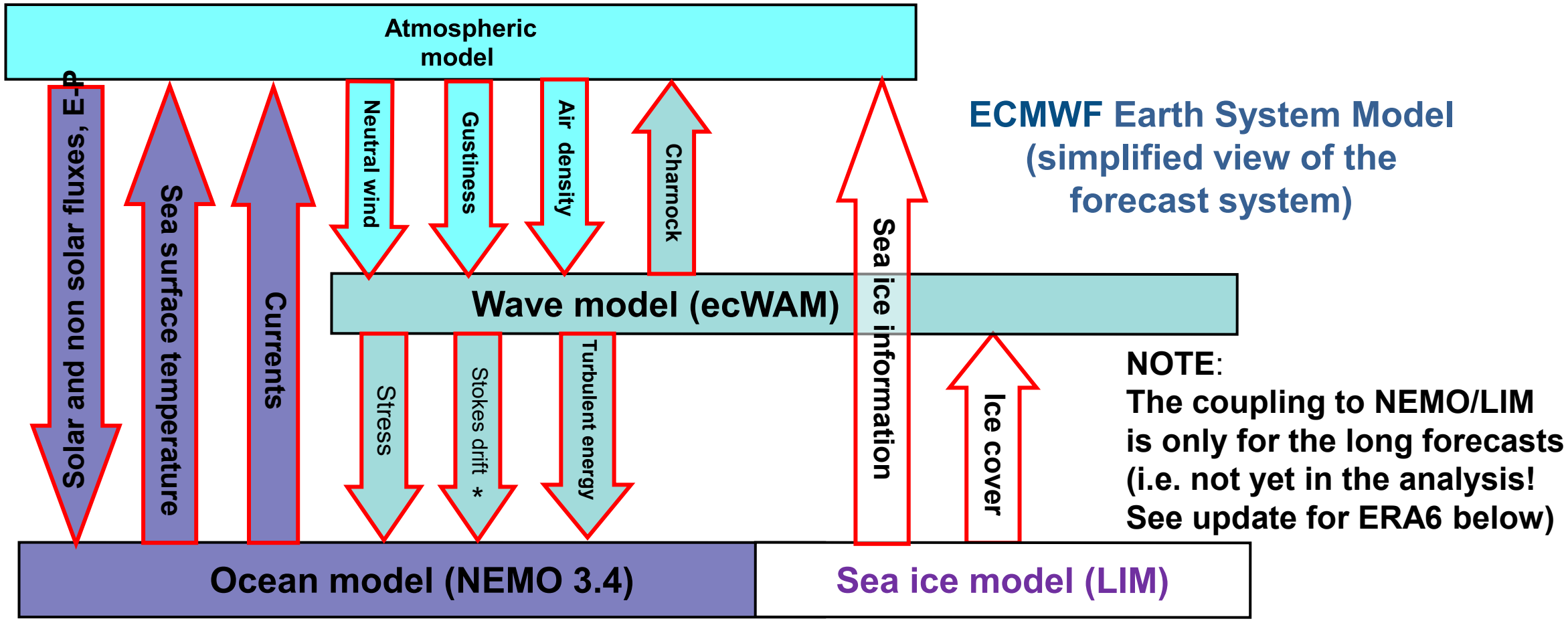
Atm-Wave two-way coupled

Wave effects in ocean for all long forecasts

ECMWF

1. Wave modelling at ECMWF

In the context of its Earth System Model, the wave model plays an active role in many exchanges between atmosphere and ocean in ECMWF Earth System Model.



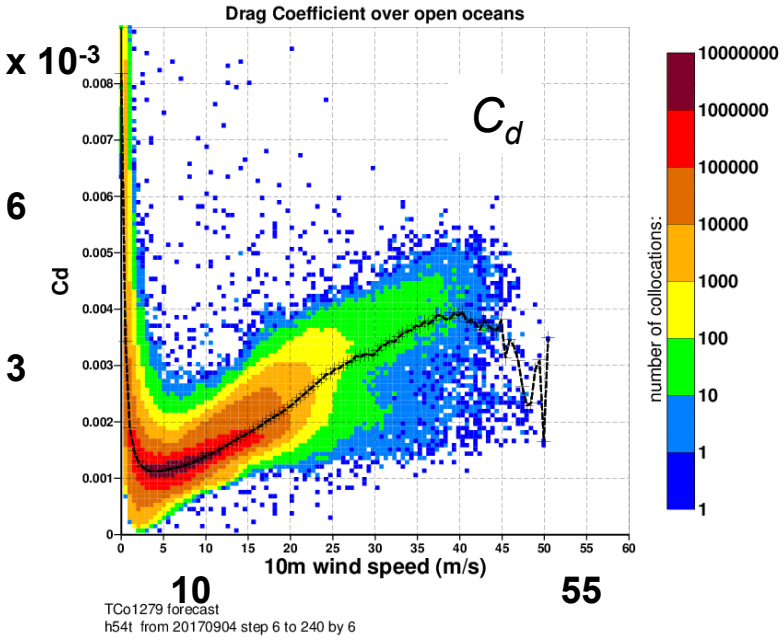
ECMWF Earth System Model (simplified view of the forecast system)

NOTE:
The coupling to NEMO/LIM is only for the long forecasts (i.e. not yet in the analysis! See update for ERA6 below)

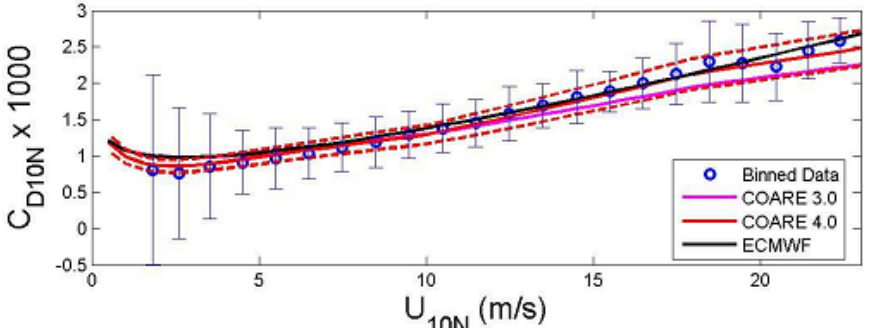
ECMWF

* Stokes drift: surface values + SWH and MWP to estimate profile

2. Impact of ocean waves on the surface stress



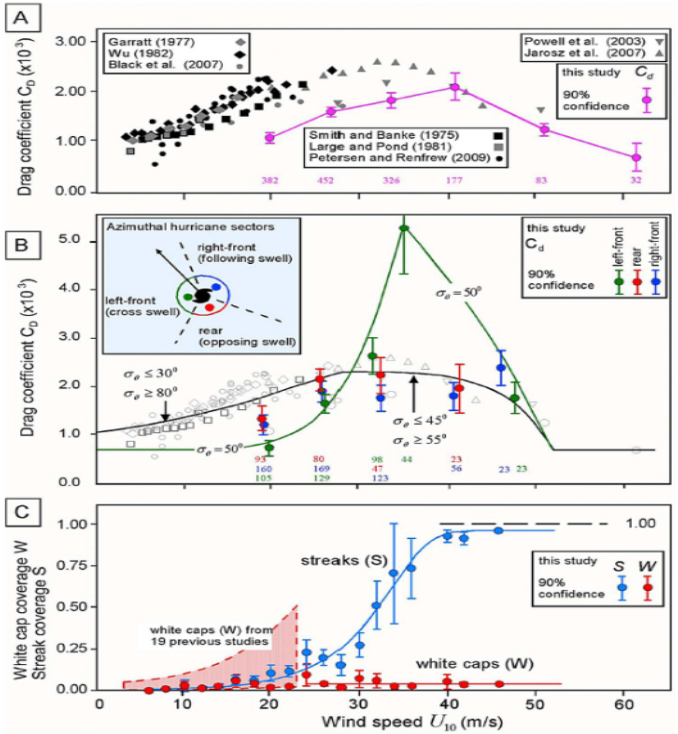
Drag coefficient (C_d)
with respect to wind speed
Operational model (June 2019)



Edson et al., 2013

Model C_d fits well observations for winds up to 20m/s
But it is too high for larger winds

Holthuijsen et al. , 2012



C_d is sea state dependent !

- **It is now accepted that the drag coefficient should generally attained maximum values for storm winds but should level or even decrease for very strong winds, namely in tropical cyclones or intense mid-latitude windstorms.**

ECMWF

An adhoc modification of the wind input source was implemented in CY47R1 (June 2020), whereby the Charnock coefficient estimated by the wave model and therefore the drag coefficient sharply reduce for large winds (> 30 m/s).

With the wave model, Charnock is expressed as

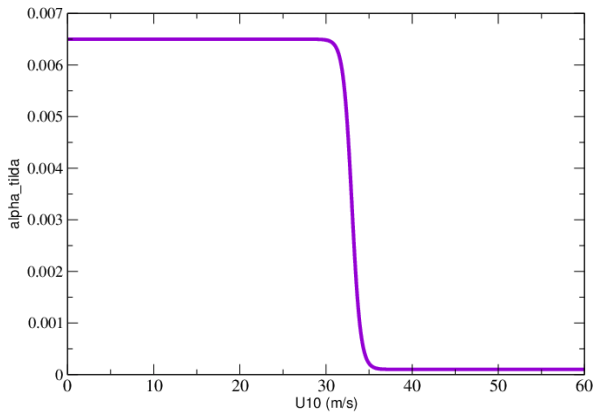
$$\alpha = \frac{\tilde{\alpha}}{\sqrt{1 - \frac{\tau_w}{u_*^2}}}$$

Originally with

$$\tilde{\alpha} = \tilde{\alpha}_0 = 0.0065$$

Charnock has to reduce quite sharply for winds (U_{10}) above 33 m/s and then tails off for very high winds:

$\tilde{\alpha}$



U10

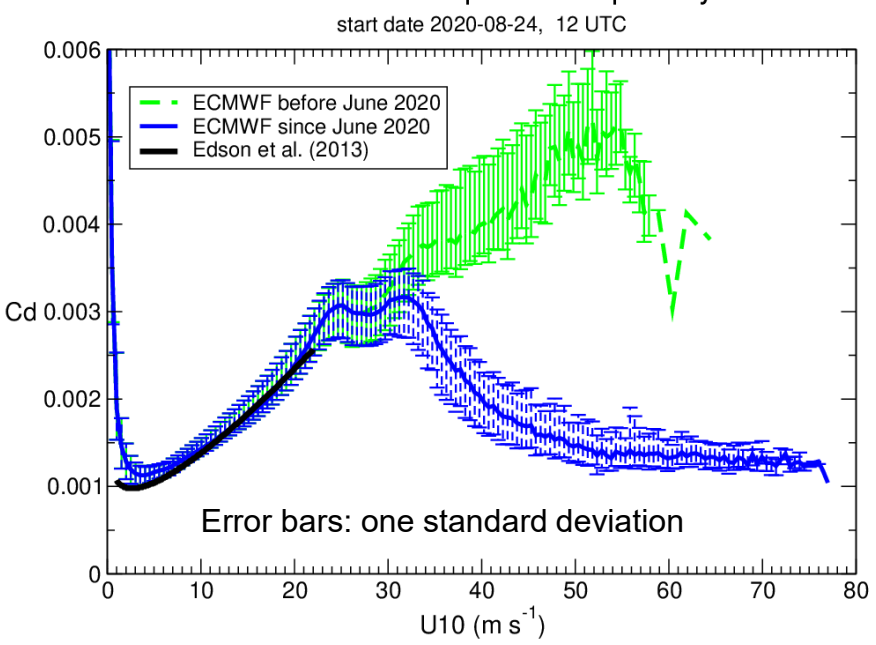
ECMWF (2021)

Revised sea state dependent momentum flux: recent model change

Recent wave model changes have resulted in a better control of the drag for strong winds:

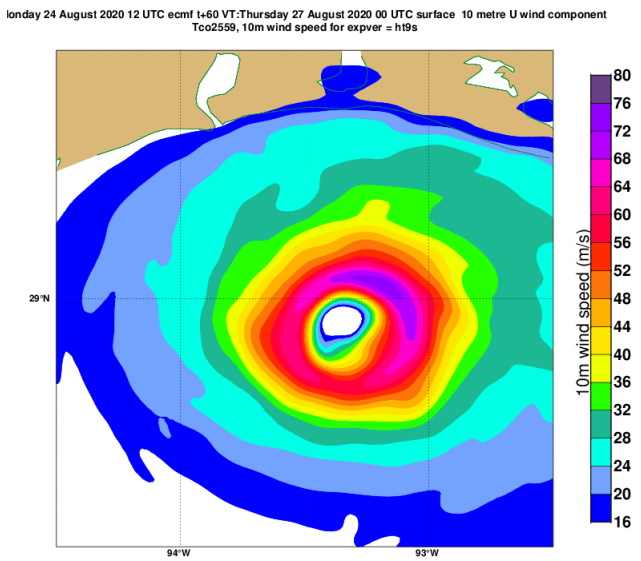
- The latest one was a reduction of the Charnock coefficient for winds above 33 m/s (June 2020).
- This is quite essential now that we can show that 4.4km runs yields much better tropical cyclones:

Drag coefficient v 10m wind speed:

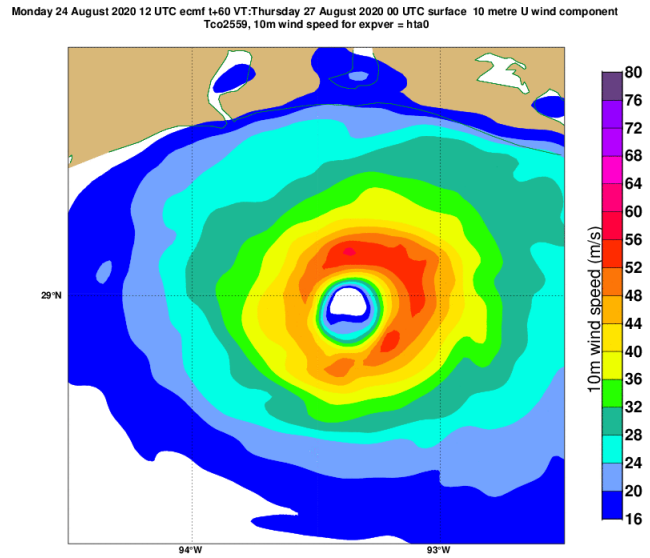


Majumdar et al. (2023)

10m wind speed, Hurricane Laura 27 August 2020



CY48R1



But without the drag reduction introduced in June 2020, it would not have been the case.

Revised sea state dependent momentum flux: CY49R1 planned for autumn 2024

We revisited the problem with the inclusion of a **model for the role of gravity-capillary waves** on the surface stress and the inclusion of a **nonlinear wind input growth rate (see Peter Janssen's presentation)**

Drag coefficient dependency on wind speed for heat (C_h)

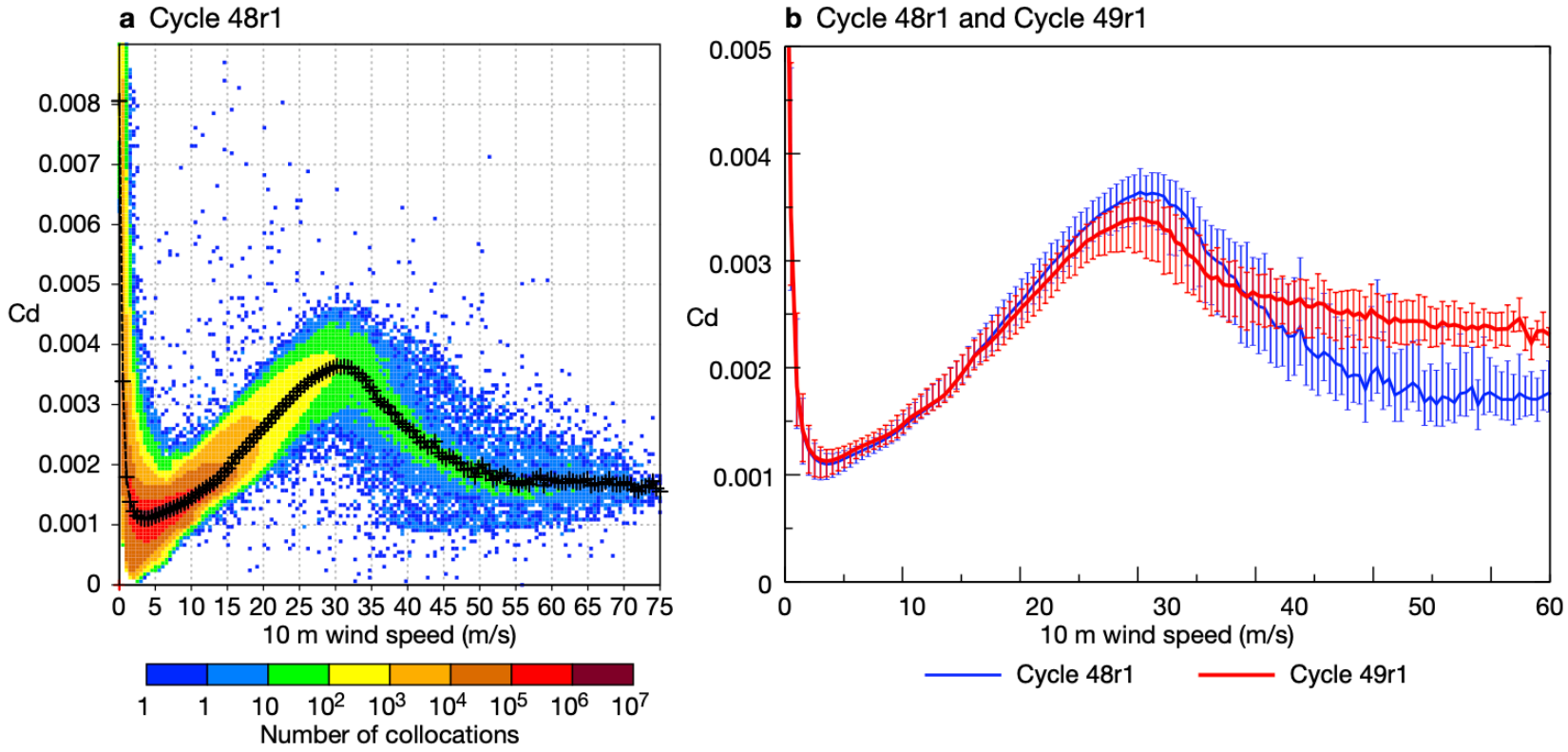
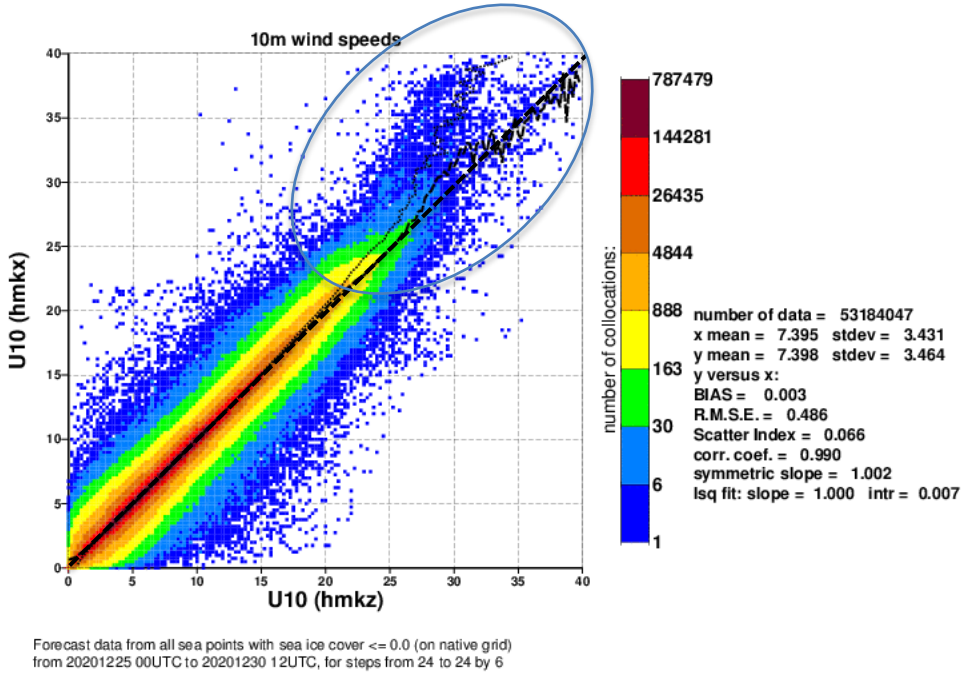


FIGURE 1 Drag coefficient (Cd) over the North Atlantic and corresponding 10 m wind speed during Hurricane Lee. Forecasts from the operational analysis of 8 September 2023, 00 UTC were performed at the experimental TCo2559 resolution (4.4 km). Results are shown aggregating all hourly forecast steps from 12 to 72 hours for (a) Cycle 48r1, with black crosses showing mean Cd values for given wind speeds, and (b) Cycle 48r1 (blue) and Cycle 49r1 (red) for the binned mean values and error bars for one standard deviation on either side of the mean.

Impact on surface wind speeds

CY49R1 will help address the known underestimation of extreme ocean winds

new



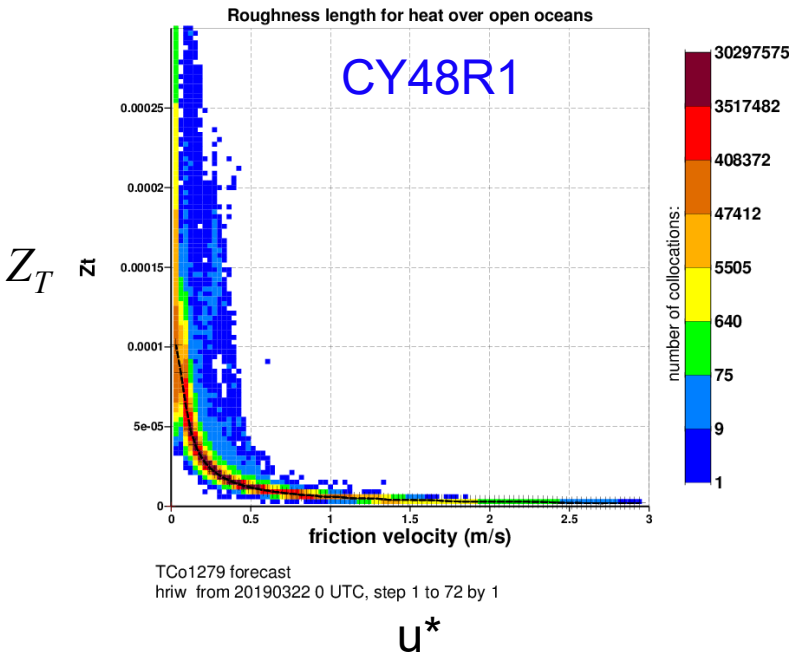
old

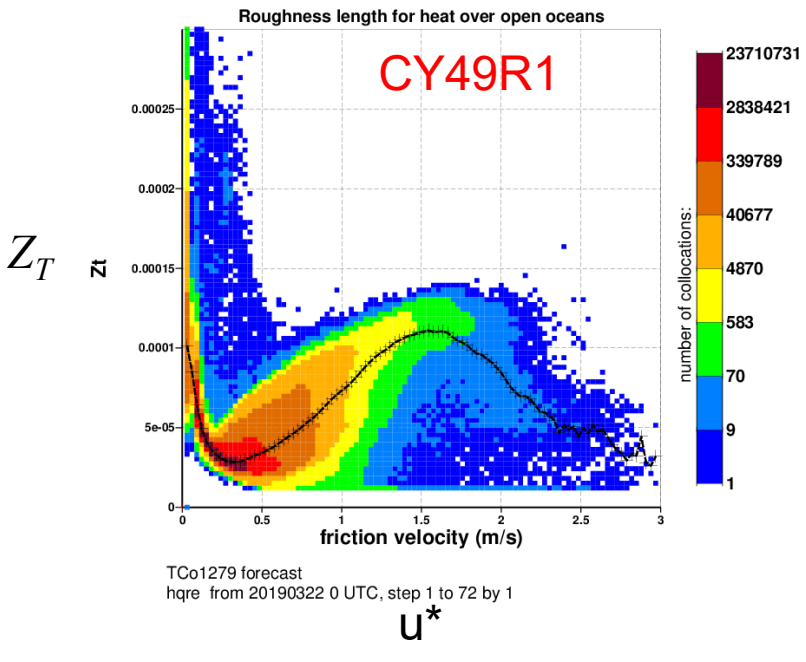
Tco1279 forecasts step 24 hours

3. Impact of ocean waves on heat and moisture fluxes

Sea state dependency on momentum is also affecting heat and moisture fluxes because in the atmosphere model those transfer coefficients depend on the squared root of Cd

$$C_h = C_d^{1/2} \frac{\kappa}{\ln(\frac{10}{Z_T})}$$





3. Sea state heat and moisture fluxes

Following Janssen (1997, TM239), ocean waves can also have a direct impact of the exchange of heat and moisture, enhancing their exchange for windy (i.e. wavy) conditions:

Exchange coefficient dependency on wind speed for heat (C_h)

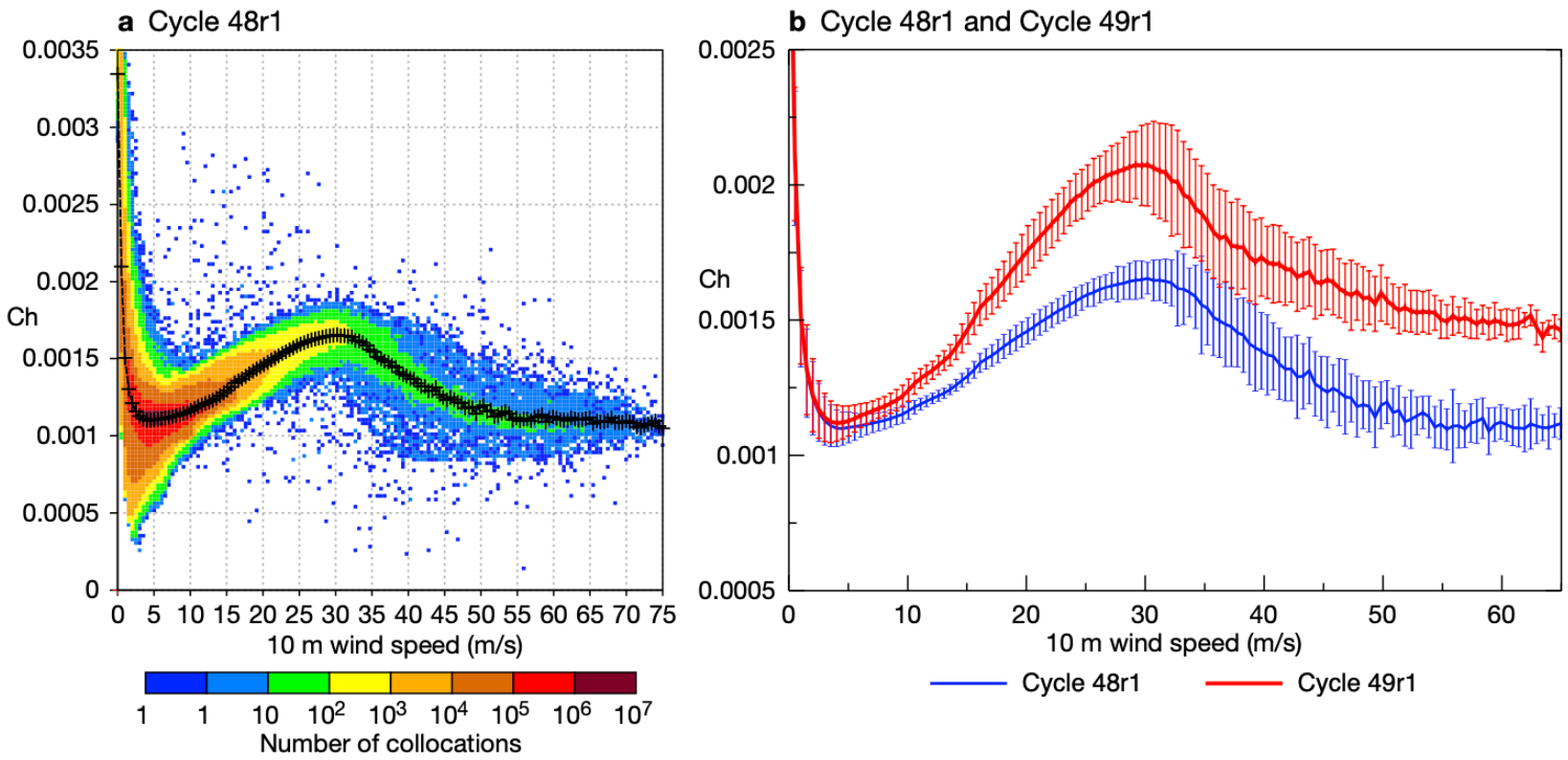


FIGURE 2 The same as Figure 1, but for the heat exchange coefficient Ch.

Change in temperature RMSE meridional cross section for different forecast ranges: generally positive

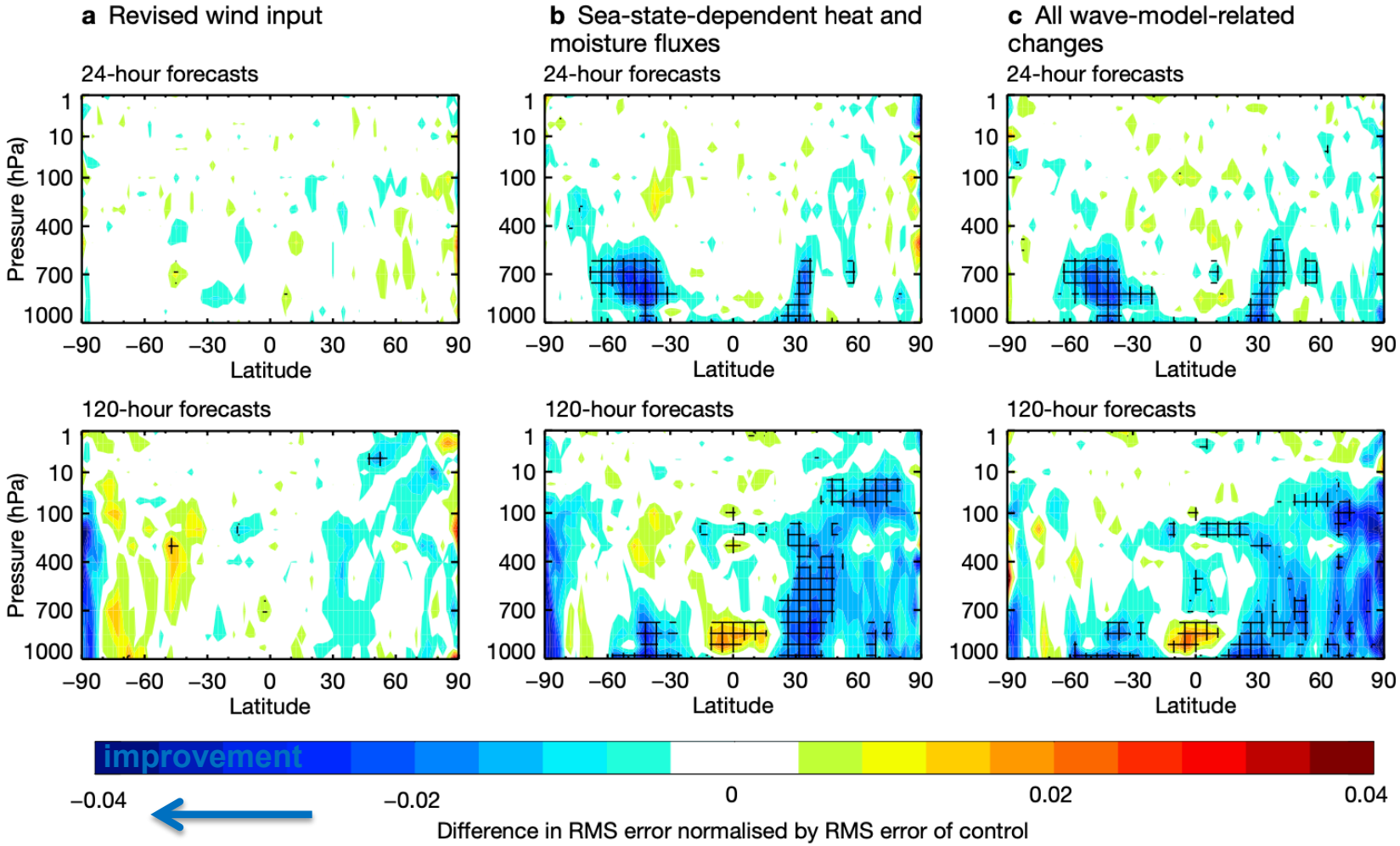


FIGURE 3 Normalised change in temperature forecast root-mean-square (RMS) error, measured against own analysis, showing the impact of (a) the revised wind input, (b) sea-state-dependent heat and moisture fluxes, and (c) all wave-model-related changes, for combined winter and summer seasons. Cross-hatching indicates statistical significance at a confidence level of 95%. Blue areas indicate a reduction in RMS and hence a beneficial impact from the contributions.

Change in 2m Temperature RMSE for different forecast ranges: generally positive

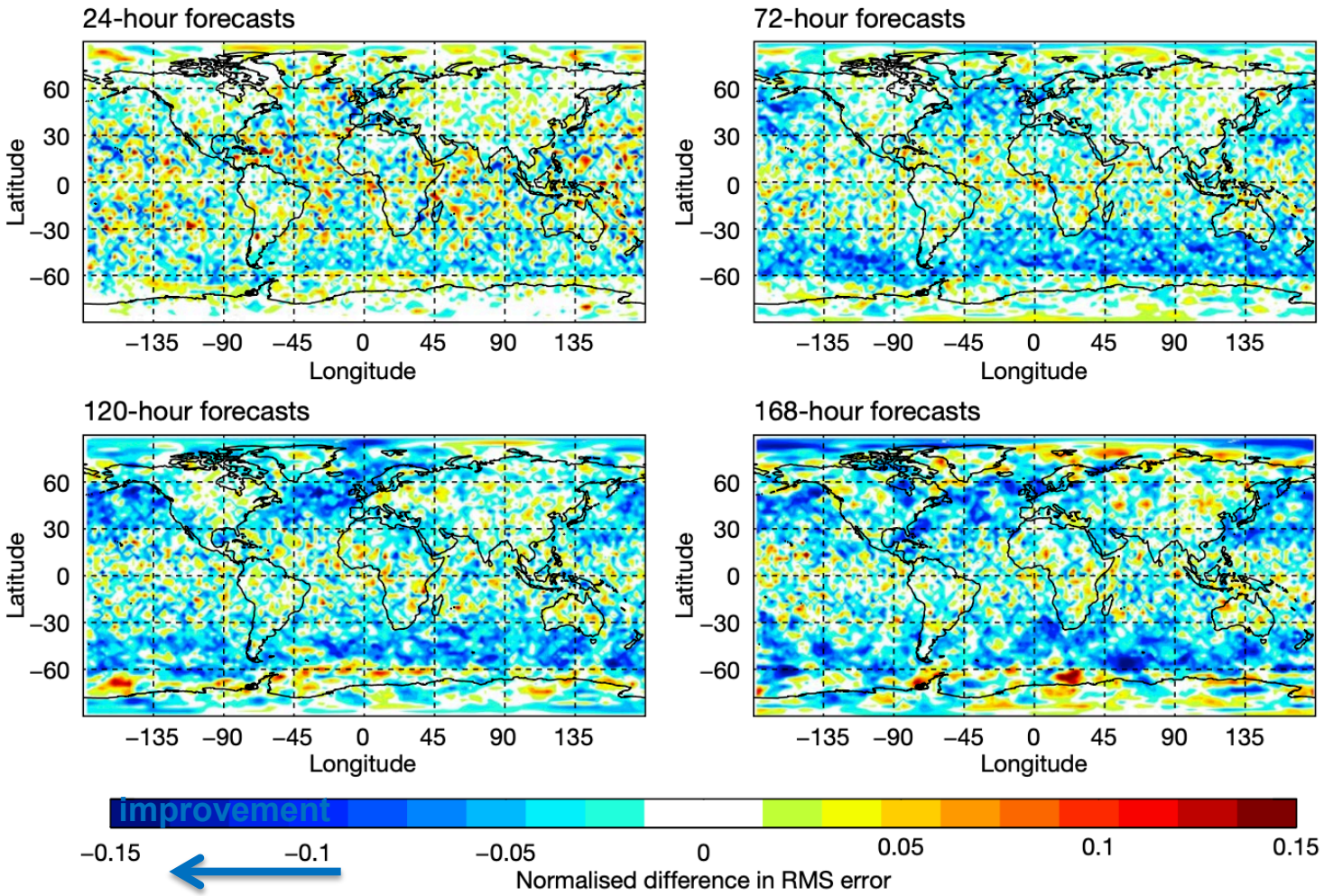
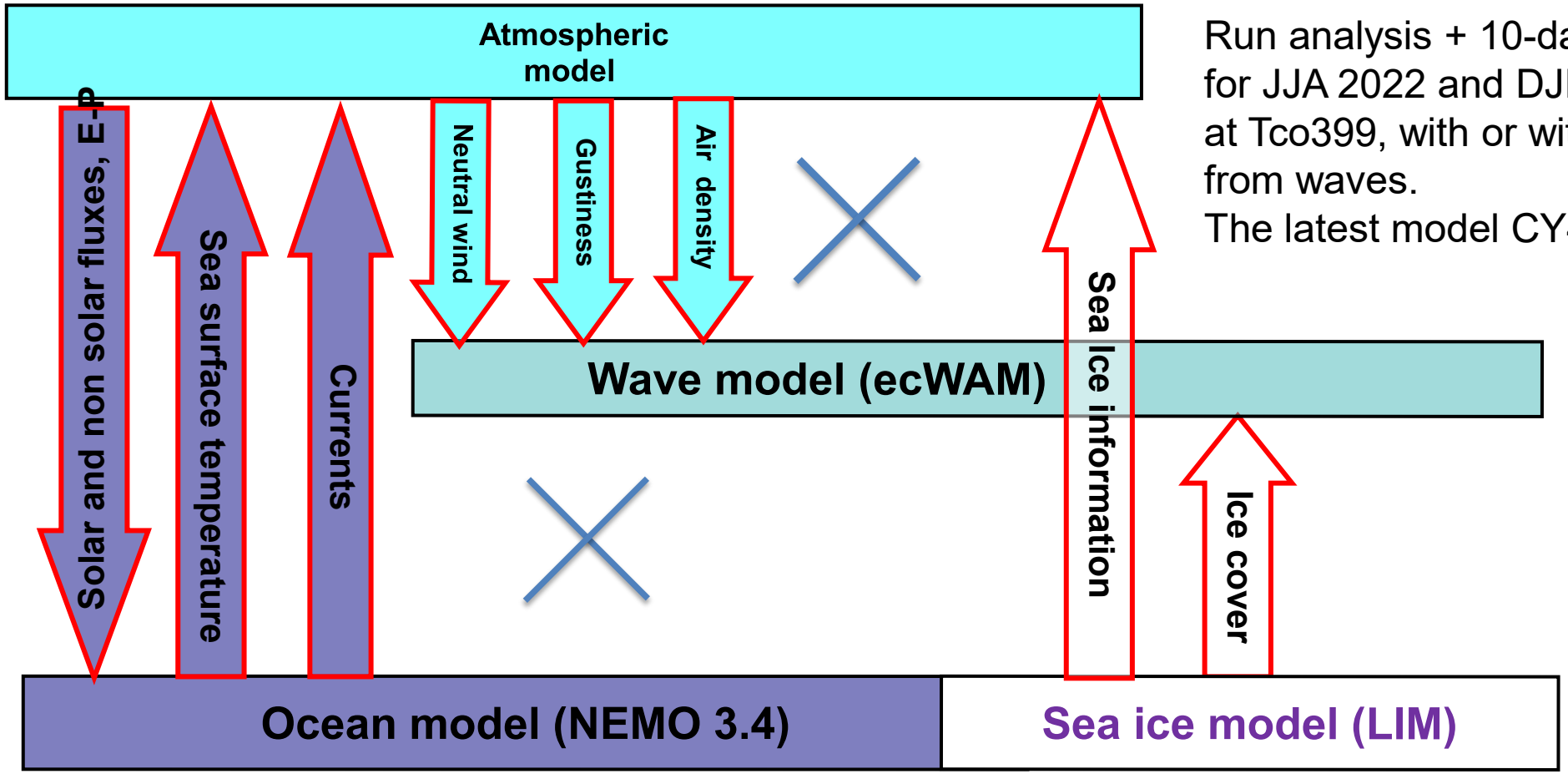


FIGURE 4 Normalised change in 2 m temperature forecast root-mean-square (RMS) error, measured against own analysis, showing the impact of sea-state-dependent heat and moisture fluxes for the combined winter and summer seasons. Blue areas indicate a reduction in RMS and hence a beneficial impact.

4. After all those years, what is the impact of waves feedbacks …



Run analysis + 10-day forecast experiments for JJA 2022 and DJF 2022-23 at Tco399, with or without any feedback from waves.
The latest model CY49R1 was used.

4. Score cards

Blue = better

Red = worse

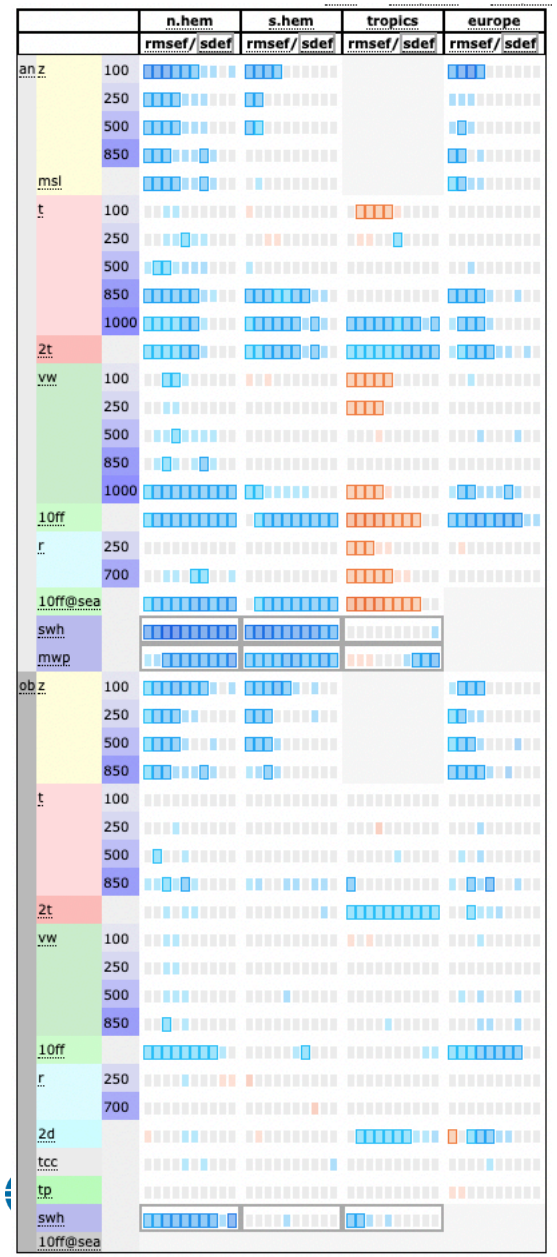
JJA + DJF Seasons

95%-99.7% confidence

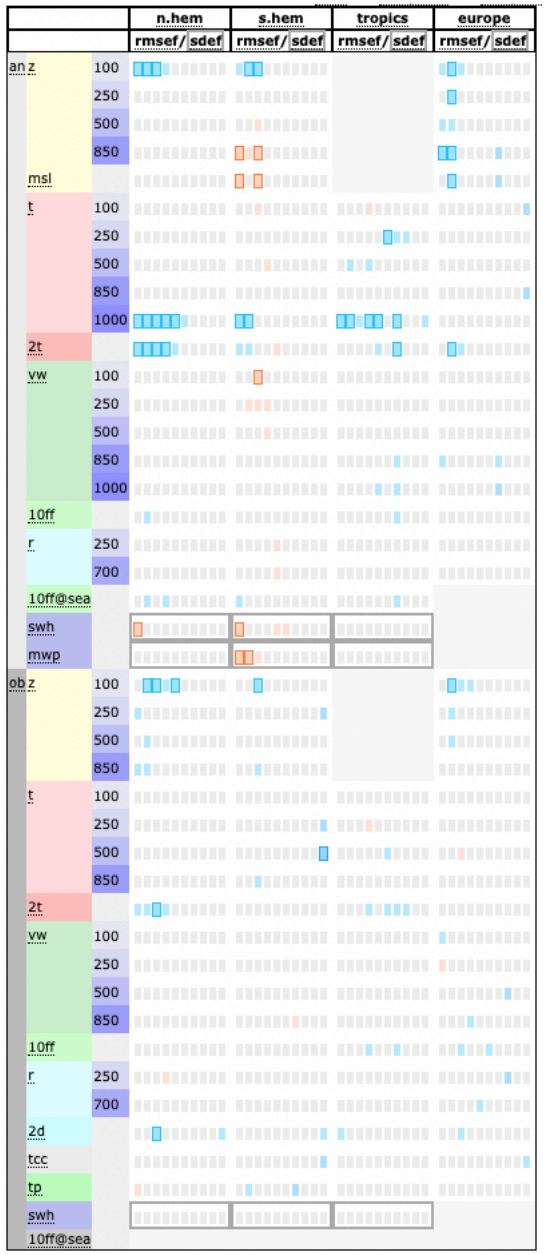
Comparison with own analysis

Comparison with observations

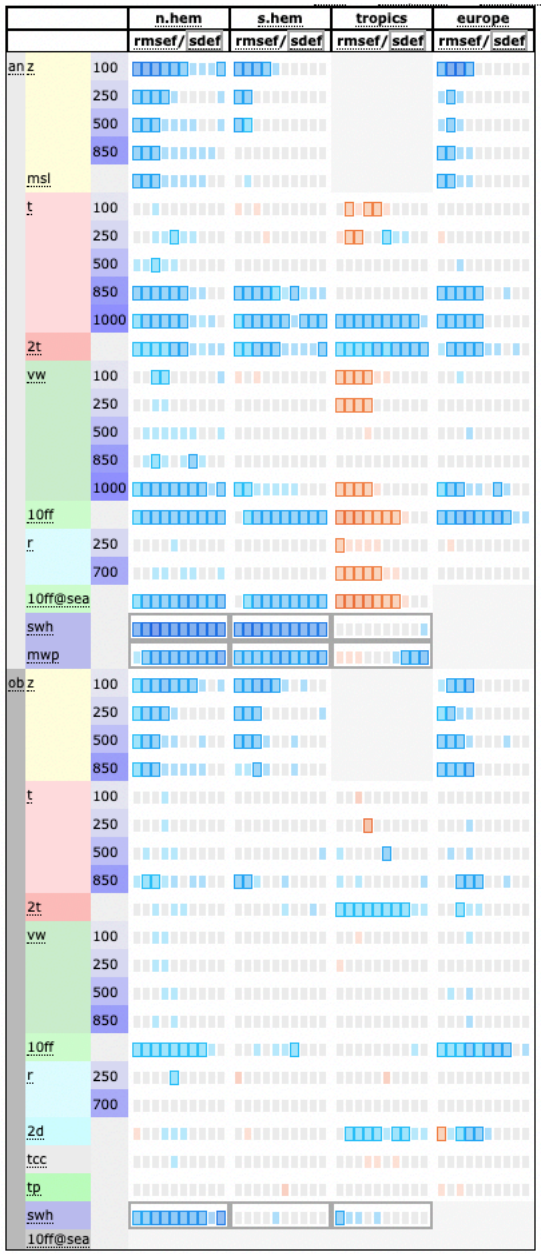
Impact of waves feedback to atmosphere



Impact of waves feedback to ocean



Impact of waves feedback to atmosphere and ocean



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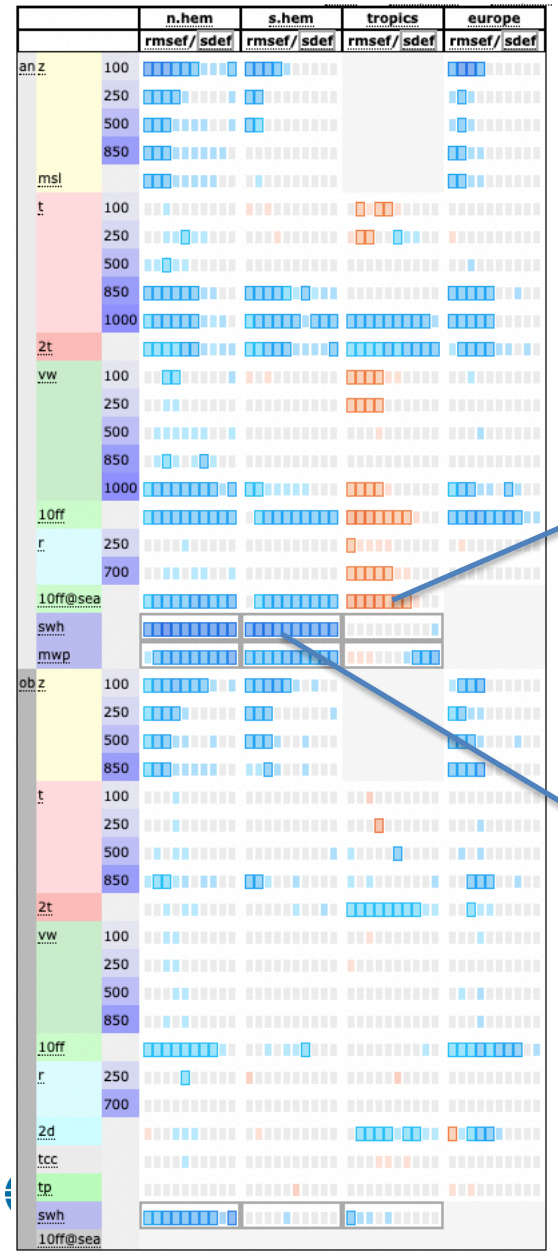
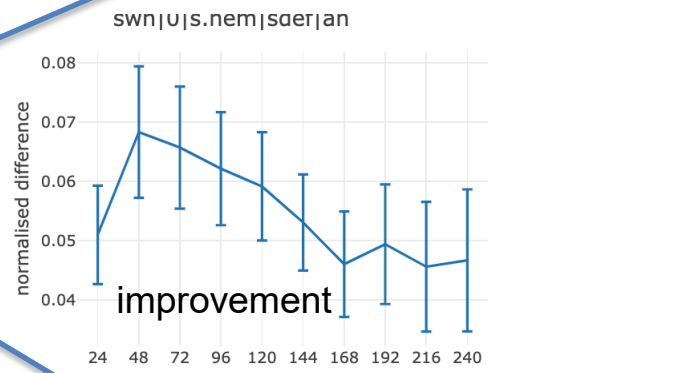
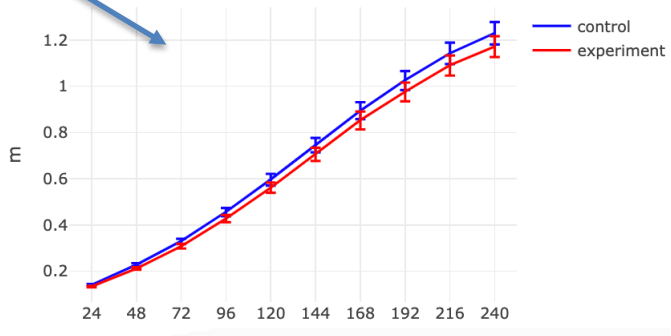
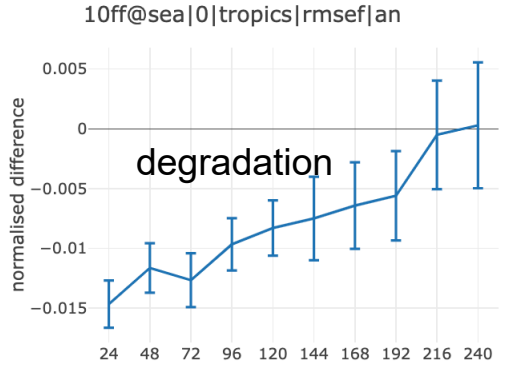
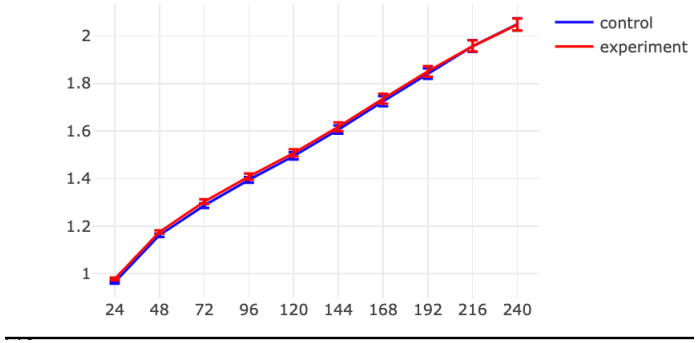




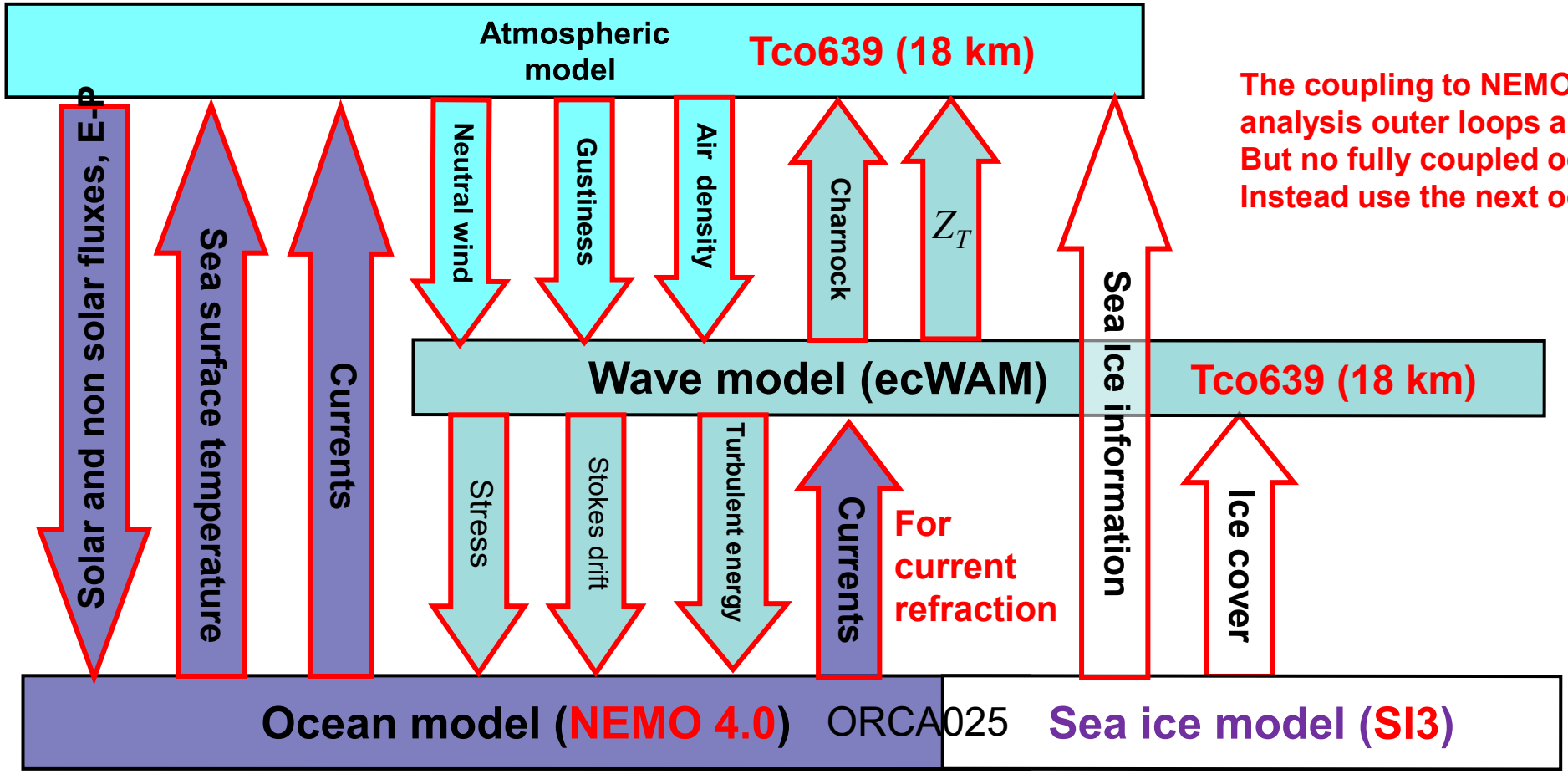






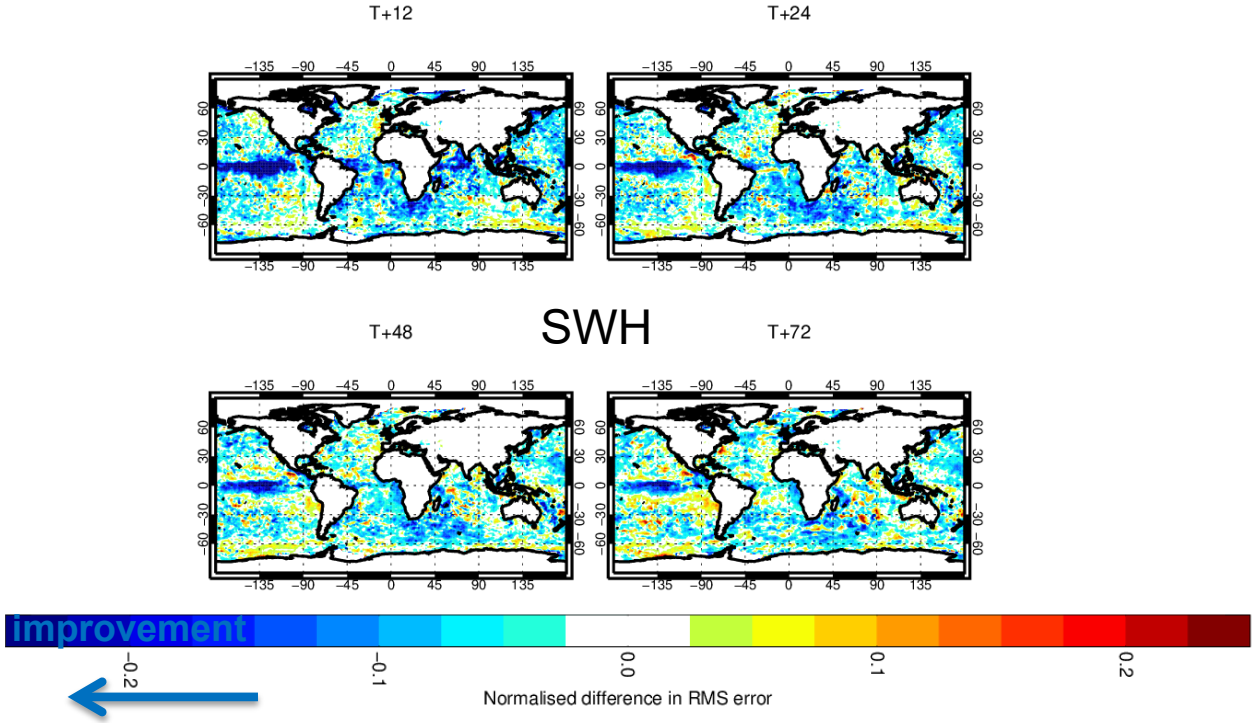
5. Plans for next global reanalysis (ERA6)

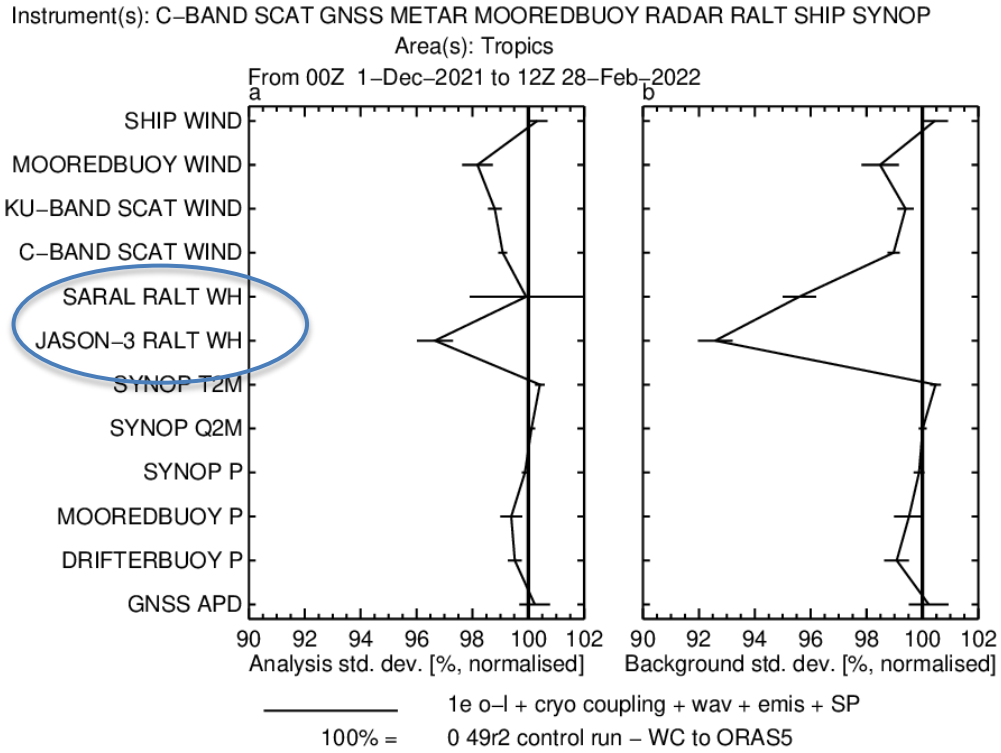
ERA6 will be based on CY49R2. Production is due to start in 2025.

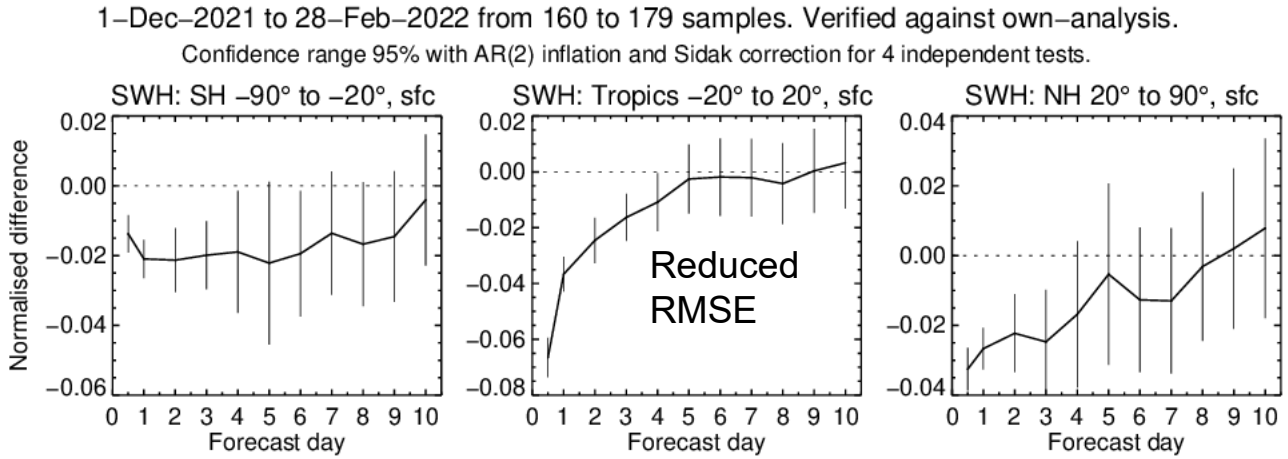


The coupling to NEMO/SI3 will also be done in analysis outer loops and short-range forecasts
But no fully coupled ocean data assimilation.
Instead use the next ocean re-analysis (ORAS6)

5. Very beneficial impact of outer loop coupling and current refraction on the significant wave height scores







Conclusions

- Ocean waves are an active components of the ECMWF Earth System Model.
- ECMWF has been using sea state information for momentum exchange for years.
- Extension to heat and moisture fluxes will be implemented in next model cycles (CY49R1).
- Direct impact of sea spray on air-sea exchange not yet included.
- Coupling to waves is generally beneficial but there is still room for some improvements (tropics).
- ERA6 should have better surface winds and waves than ERA5.

- ecWAM is now open source:

  https://github.com/ecmwf-ifs/ecwam

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A paper has been accepted for publication JPO (proofs are back with the editor).

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