Air Sea Exchange and wind wave interactions

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Outline:

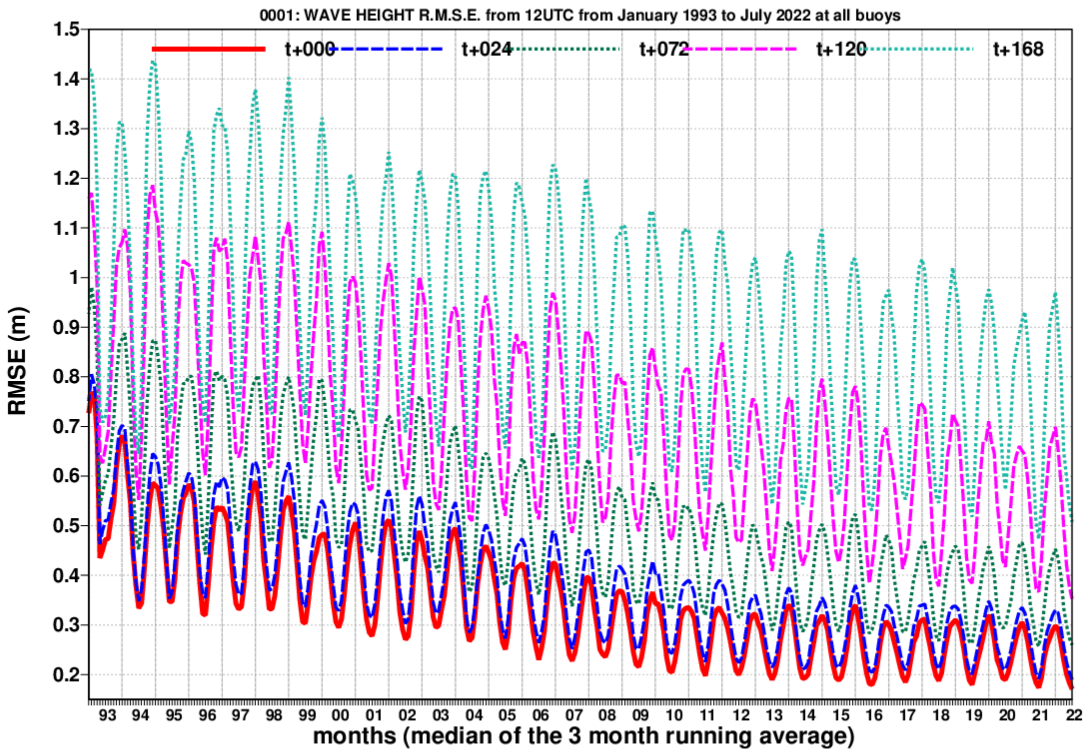
- Ocean Wave modelling at ECMWF.
- Wind – wave interaction for surface momentum exchange.
- Wind – wave interaction for heat and moisture exchanges.
- Possible other interactions involving waves.

Introduction:

- ECMWF has been providing global sea state (waves) forecasts since 21 June 1992.
- The quality of those has steadily improved:
- Obviously, this is more than just improvements in the wave model.
- How have the waves contributed to this progress?

Comparison of ECMWF analysis and forecasts against buoy data (RMSE) from 1993 to present:

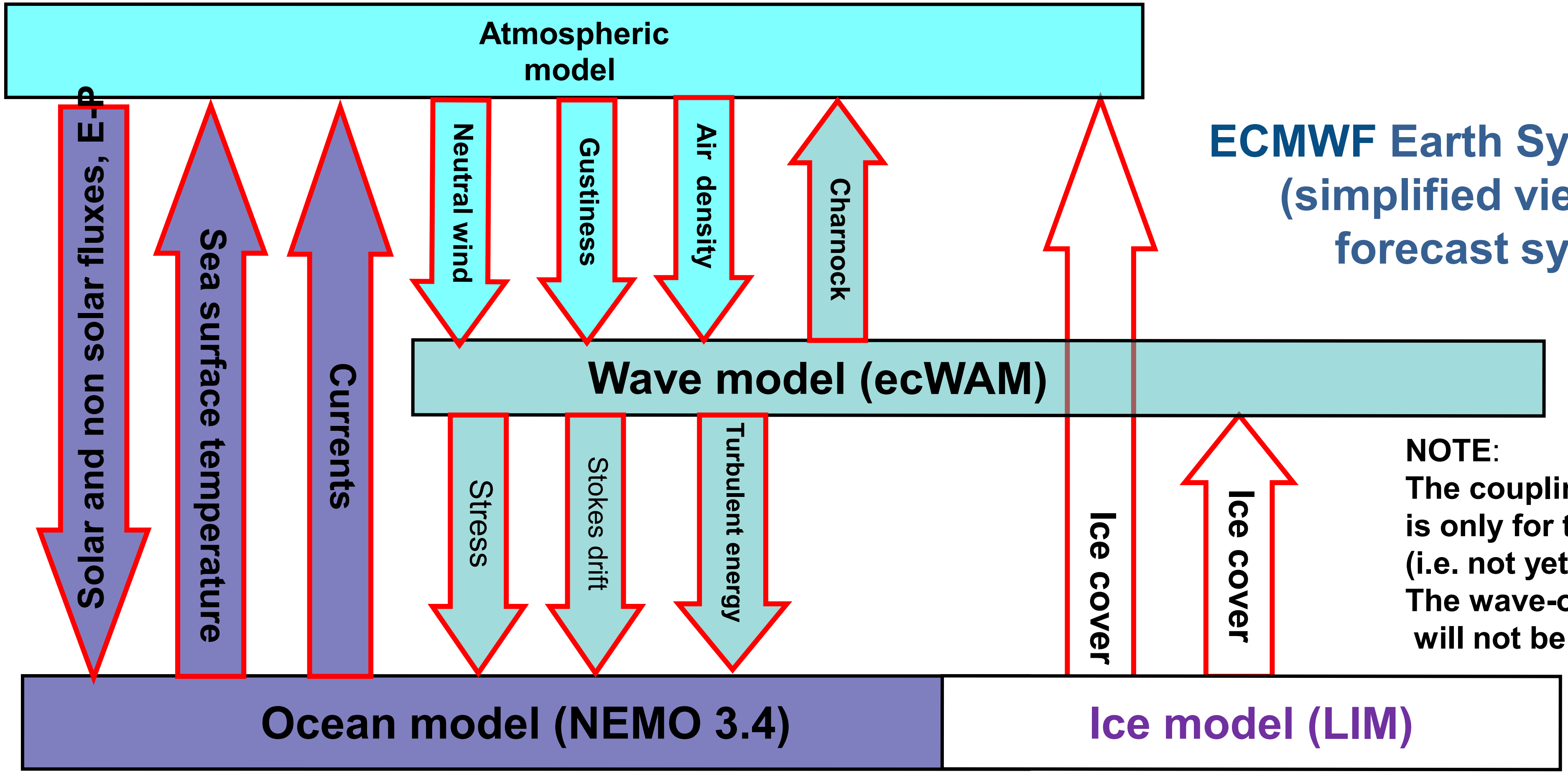
Significant wave height (SWH)



ECMWF

Wave modelling at ECMWF

ECMWF main focus is in the context of its Earth System Model in which the wave model plays an active role in many exchanges between atmosphere and ocean.



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)
The wave-ocean interactions will not be covered in this presentation.

Atmosphere- ocean wave system

Atmospheric model

Neutral wind ↓ **Every IFS time step** ↑ **Charnock**

Wave model (ecWAM)

$$U_{10} = \frac{u_*}{\kappa} \ln\left(\frac{10}{z_0}\right)$$

Charnock relation

$$z_0 = \frac{\alpha \, u_*^2}{g}$$

(there is also a viscous contribution to z_0 in the IFS)

The Charnock coefficient is linked to the amount of momentum that is used to generate waves which varies depending on the sea state evolution:

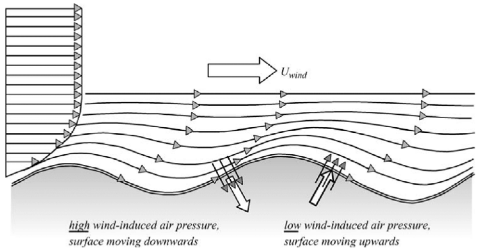
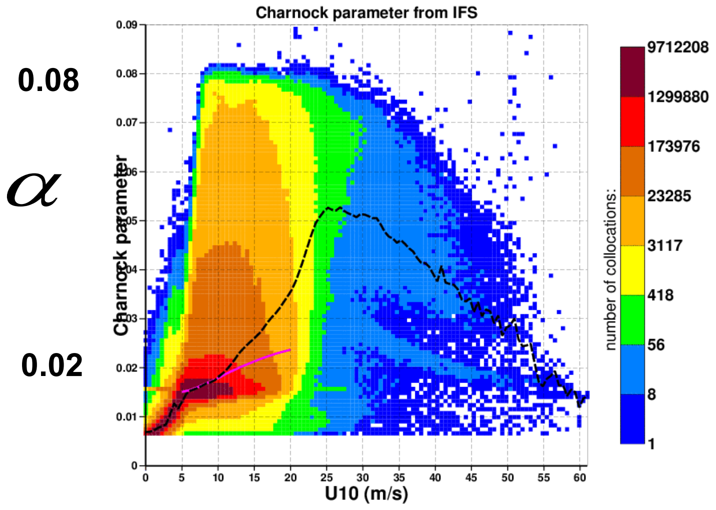


Figure 6.16 The wave-induced wind-pressure variation over a propagating harmonic wave.

the wave grows by this mechanism, the mechanism becomes more effective, so the wave can therefore grow faster, which in turn makes the mechanism even more effective, etc.



Forecast data from stream da, class rd, expver gyca, all Sea points with sea ice cover <= 0.3 from 20170904 00UTC, for steps from 6 to 240 by 6

U10

Impact of sea state dependent momentum flux

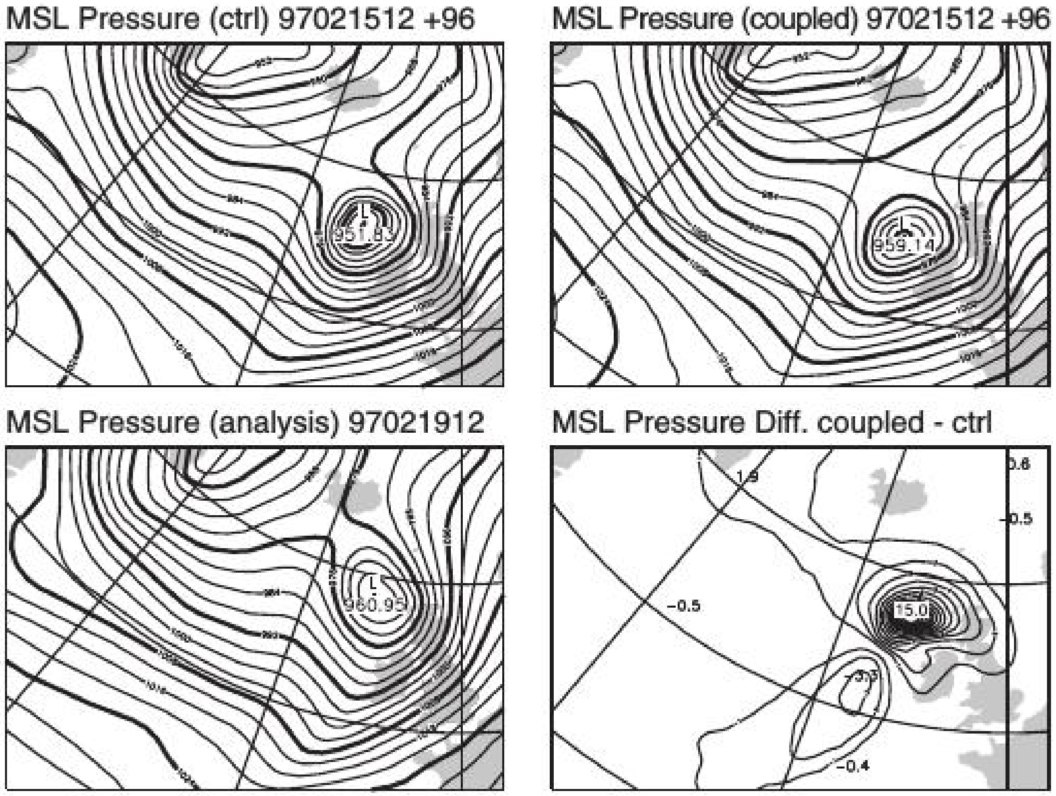
Based on this, the first atmosphere-wave two-way coupled system was introduced in operation in 1998. The example below shows how the tendency to over-depend lows was reduced by the coupling to waves:

Minimum pressure
952 hPa

uncoupled

959 hPa

coupled



960 hPa

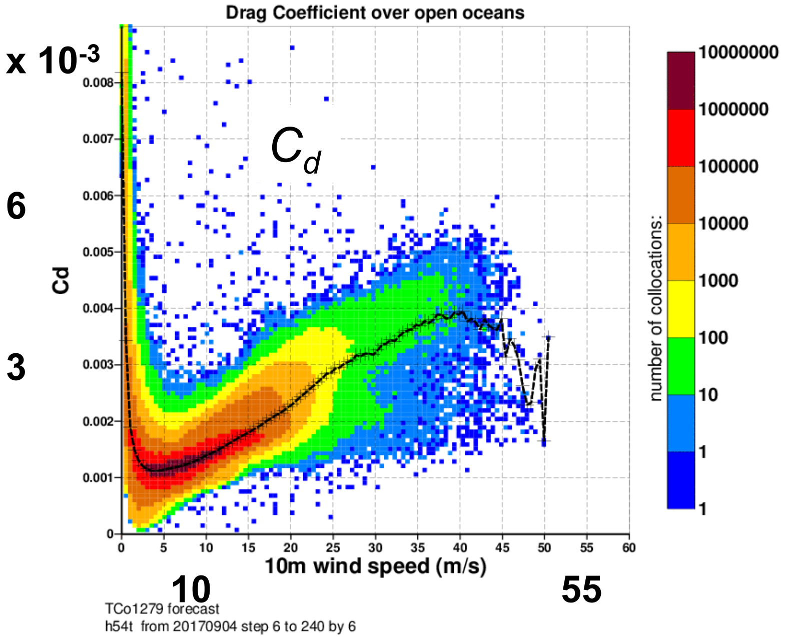
Verifying analysis

Coupled - uncoupled

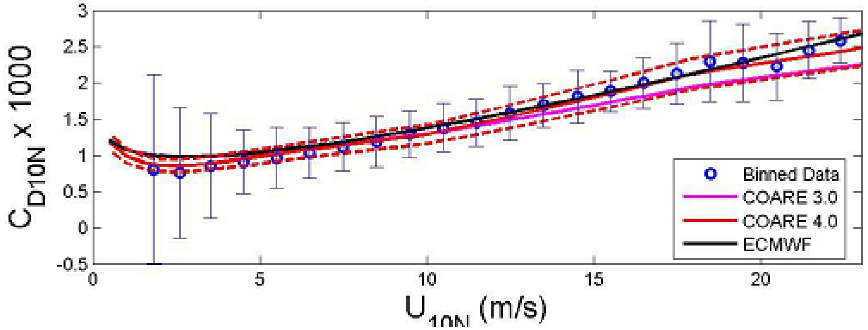
Comparison of 4-day forecast of surface pressure over the North Atlantic, valid for 19 February 1997. Version of coupled model is $T213/L31 - 0.5\,\mathrm{deg}$.

ECMWF

1. Impact of ocean waves on the surface stress



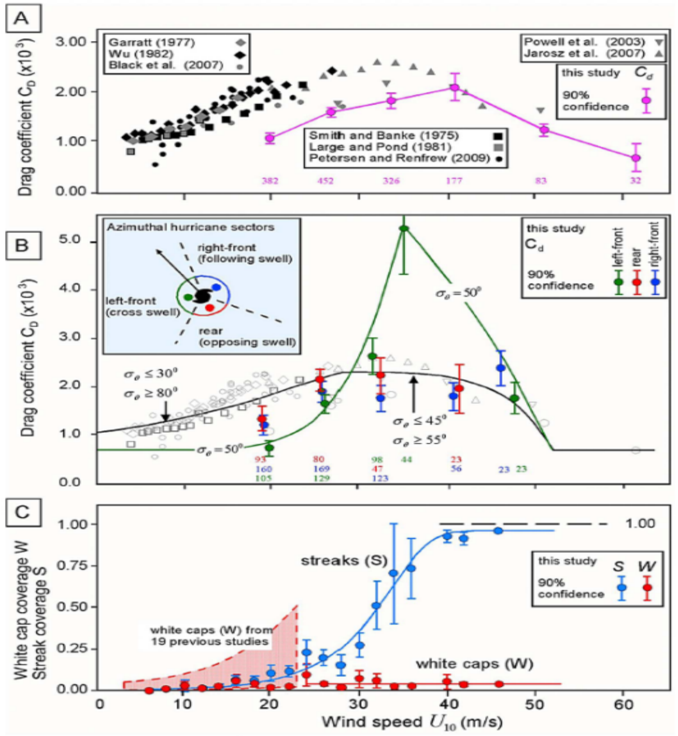
Drag coefficient (C_d)
with respect to wind speed
Operational model (June 2019)



Edson et al., 2013

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 wind storms.**

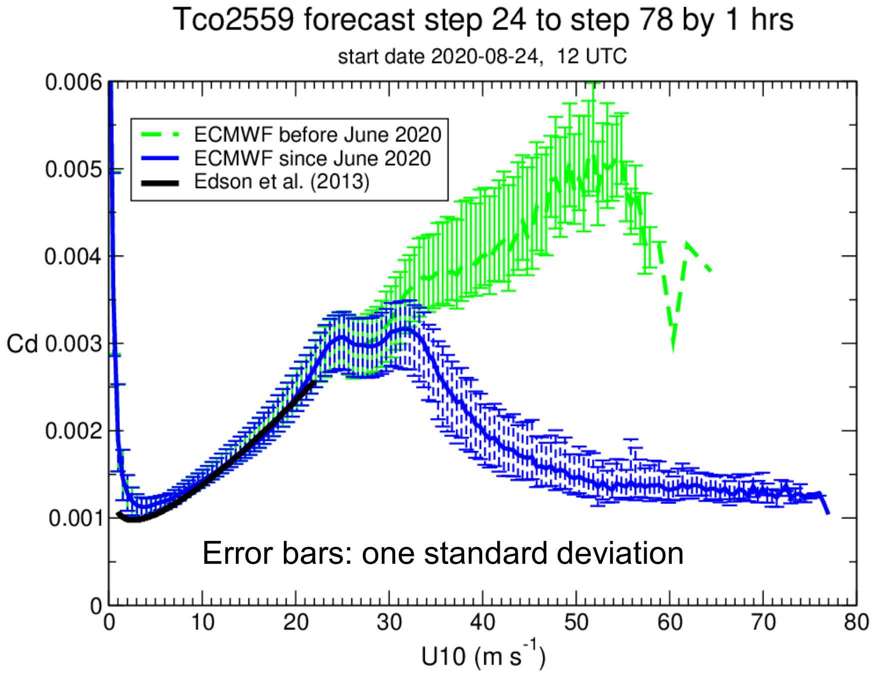
ECMWF

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 4km runs yields better tropical cyclones:

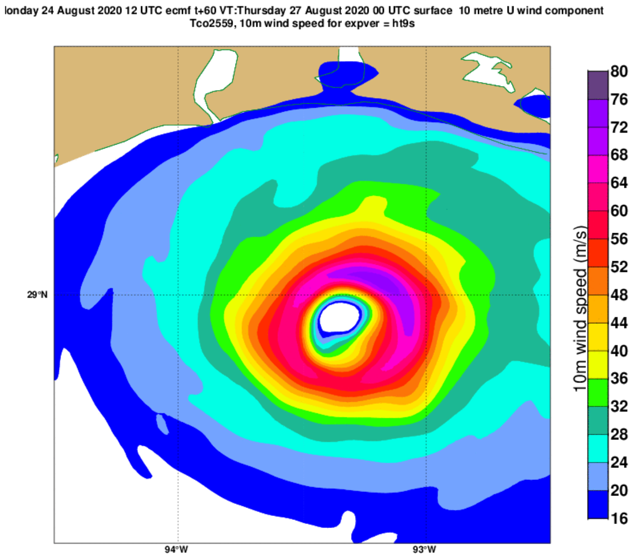
Drag coefficient v 10m wind speed:



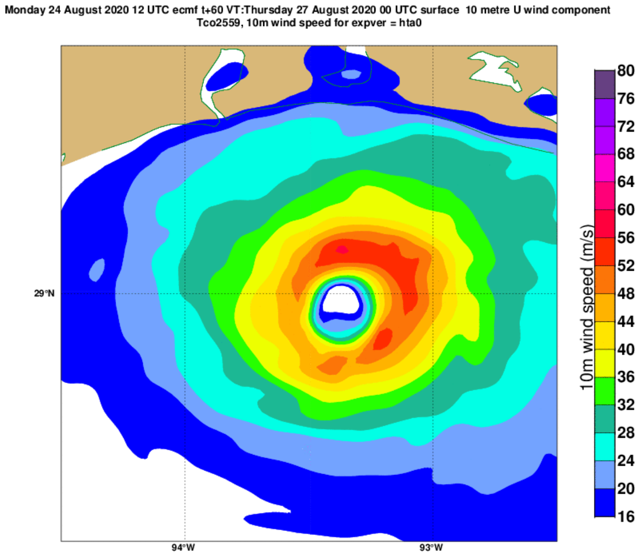
Majumdar et al. (2022)

ECMWF

10m wind speed, Hurricane Laura 27 August 2020



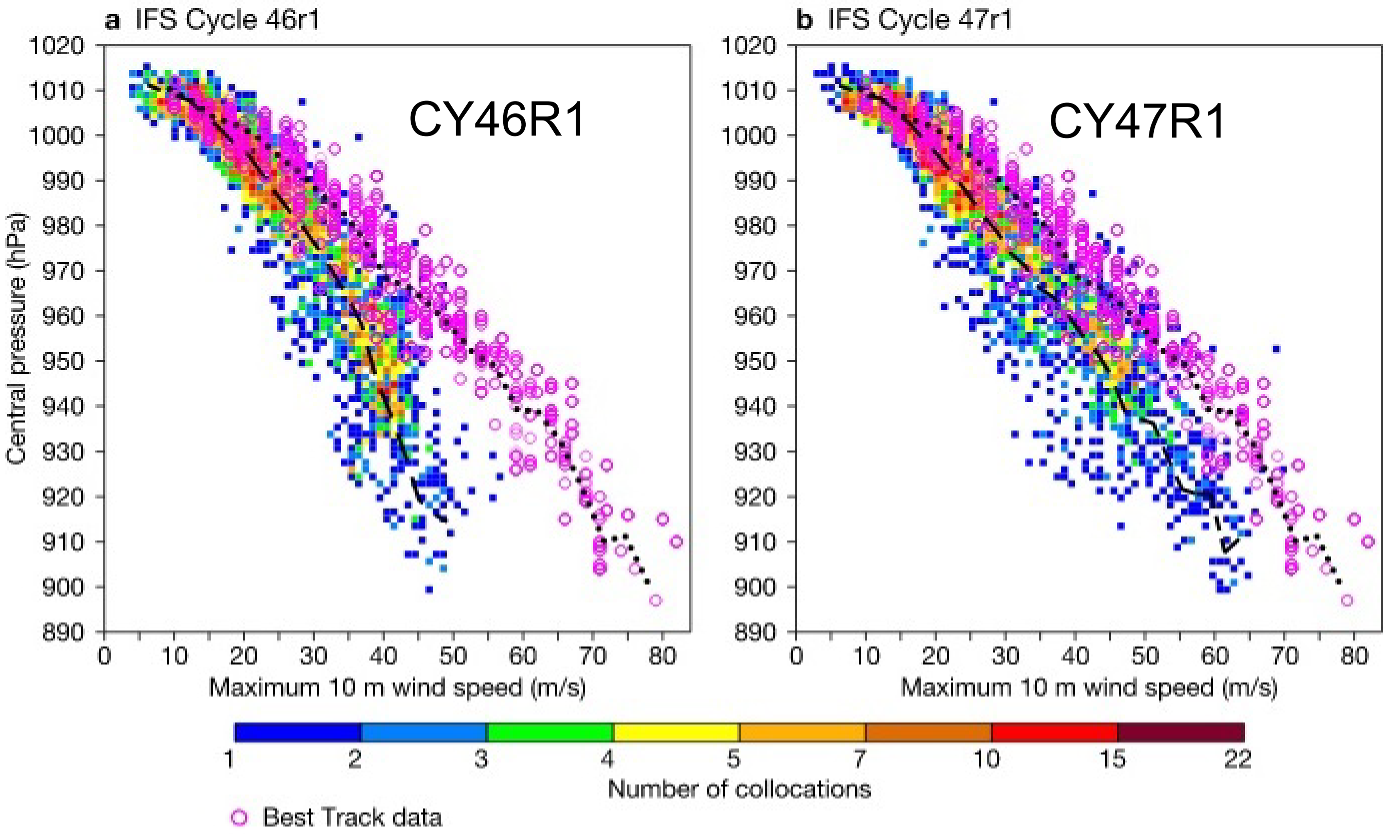
CY48R1



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

Revised sea state dependent momentum flux: recent model change

This has resulted in improved Tropical cyclone max wind - min pressure relationship:



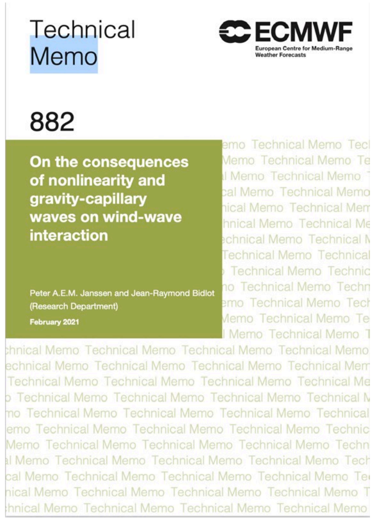
ECMWF Newsletter Bidlot et al. 2020

Tco1279 forecasts from 0 UTC for period 25-08-2019 to 01-01-2020 (coloured shading and dotted line). Reported values (pink symbols and dotted line) for tropical cyclones:Ambali, Belna, Bualoi, Calvinia, Dorian, Faxai, Fengshen, Hagibis, Halong, Humberto, Kammuri, Kyarr, Lingling, Lorenzo, Maha, Matmo, Nakri, Phanfone, Sarai, Sebastien.

ECMWF

Revised sea state dependent momentum flux: future model change (2024)

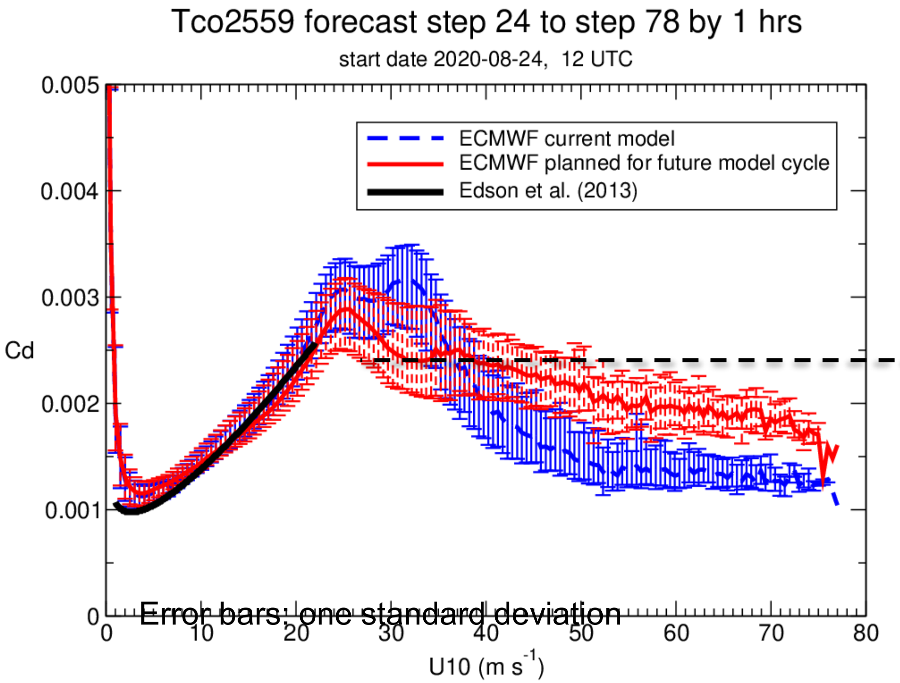
We revisited the problem with the inclusion of a **model for the role of gravity-capillary waves** on the surface stress and the inclusion of a **nonlinear wind input growth rate**.

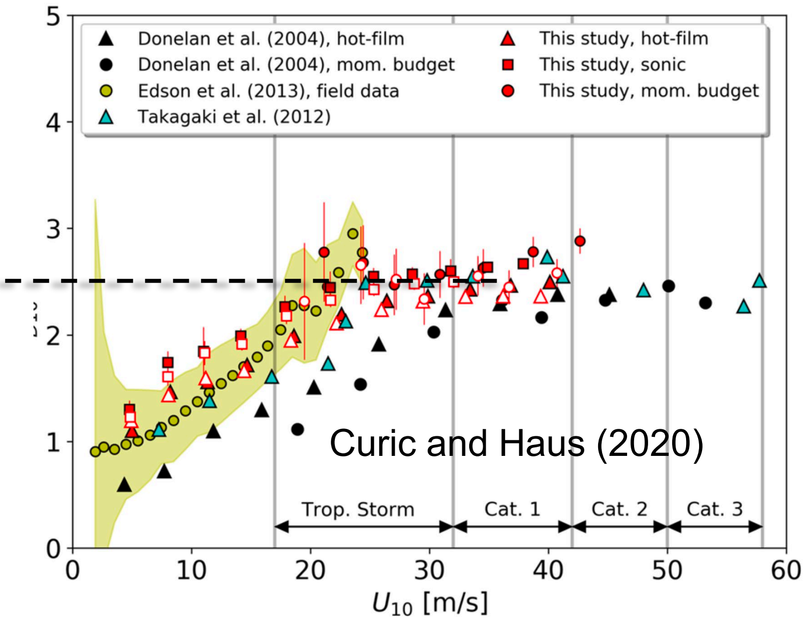


With these new changes, the resulting drag coefficient starts to tail off for storm winds conditions, well before the arbitrary 33 m/s, in accordance with the sea state development. **Note that this will have an impact on mid-latitude storms.**

Recent study by Curic and Haus (2020) found that the decrease in Cd might not be as sharp as postulated in previous studies:

Drag coefficient
v
10m wind speed



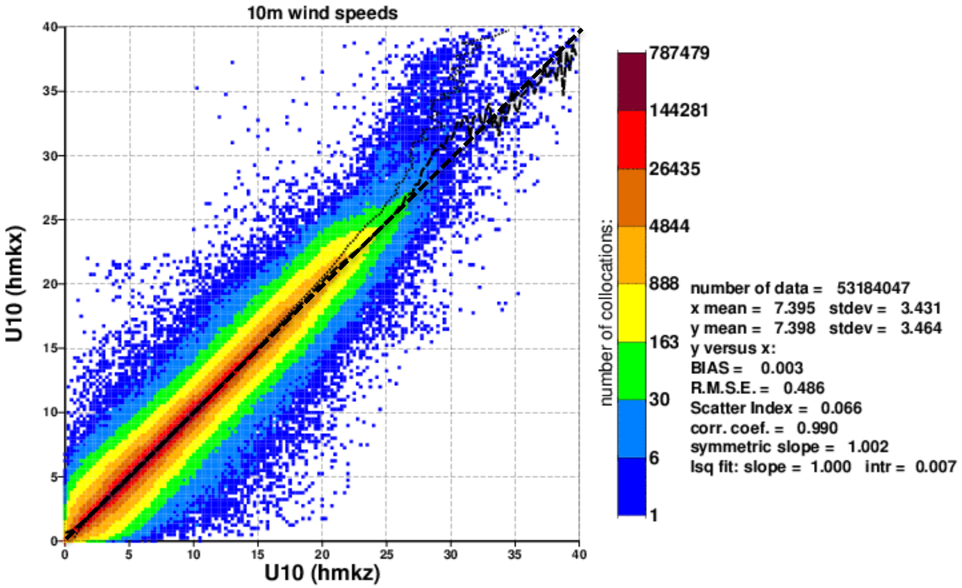


Janssen and Bidlot 2022, JPO, under review

Impact on surface wind speeds

The future model change will help address the known underestimation of extreme ocean winds

new

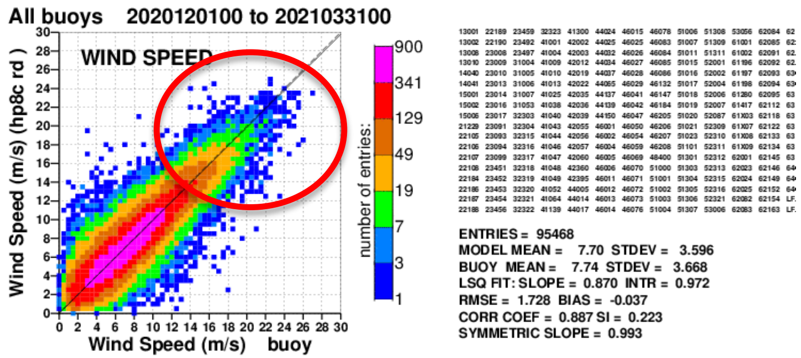


Forecast data from all sea points with sea ice cover <= 0.0 (on native grid)
from 20201225 00UTC to 20201230 12UTC, for steps from 24 to 24 by 6

control

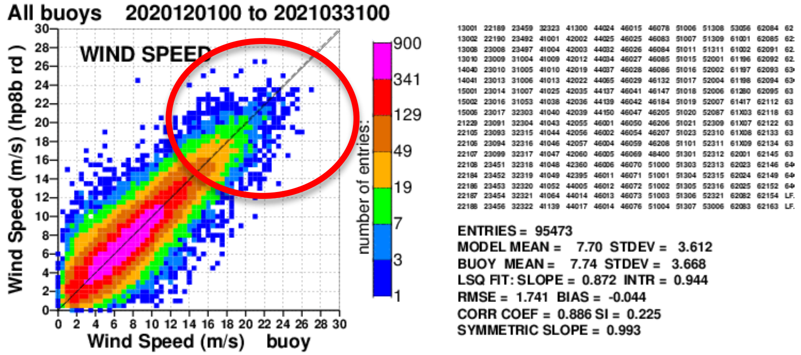
Tco1279 forecasts step 24 with LSM=0 and no sea-ice

control



Comparison of fc steps 24_42_6 ECMWF wind speeds with height corrected averaged buoy data.

new

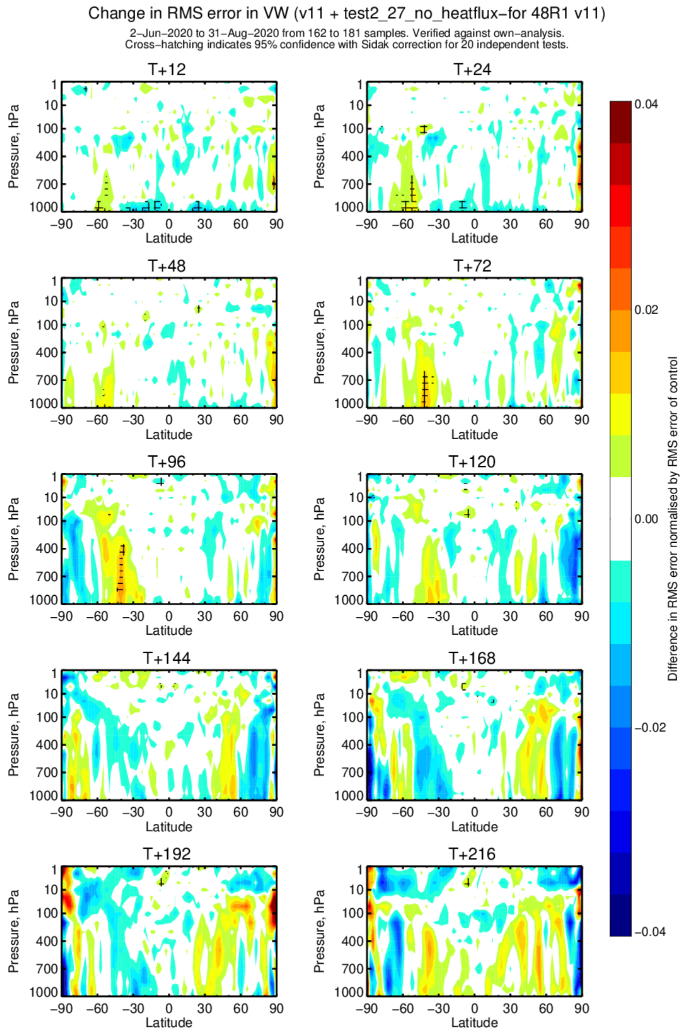


Comparison of fc steps 24_42_6 ECMWF wind speeds with height corrected averaged buoy data.

Better fit for high winds

Change in wind speeds RMSE meridional cross section for different forecast range: fairly neutral

JJA 2020

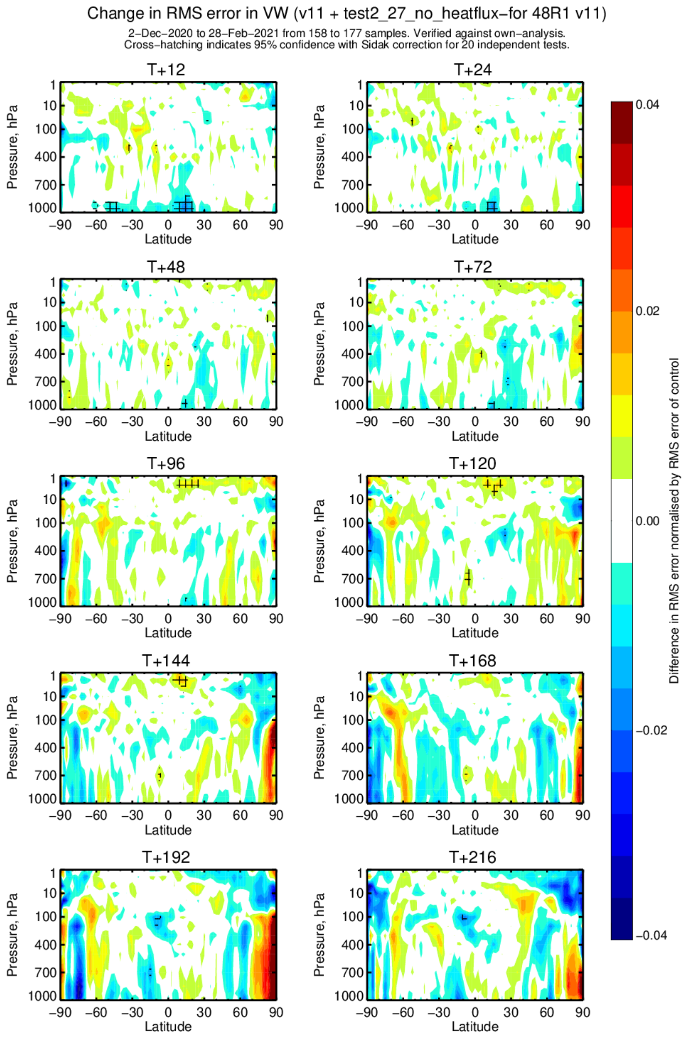


1 hPa

1000 hPa

90S 90N

DJF 2020-21



90S 90N

improvement

ECMWF

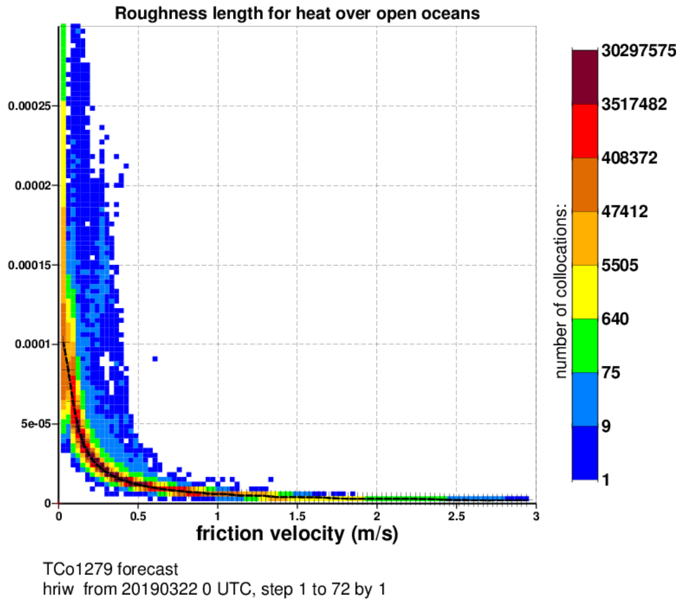
Analysis and forecast experiments at Tco399

2. Impact of ocean waves on heat and moisture fluxes

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

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

z_T



u*

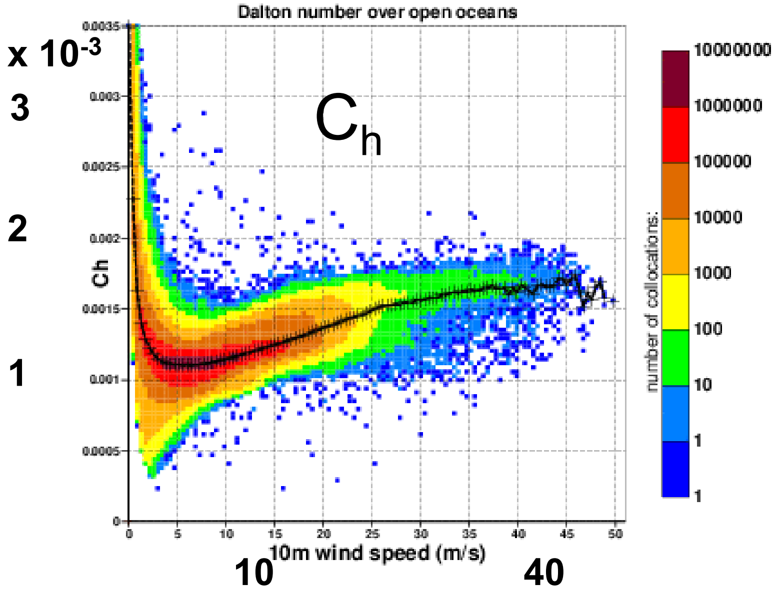
But, for the roughness length scale, We still assume that the exchange is dominated by viscosity

$$z_T = z_\nu = \delta \frac{\nu}{\kappa u_*}$$

δ adjustable parameter

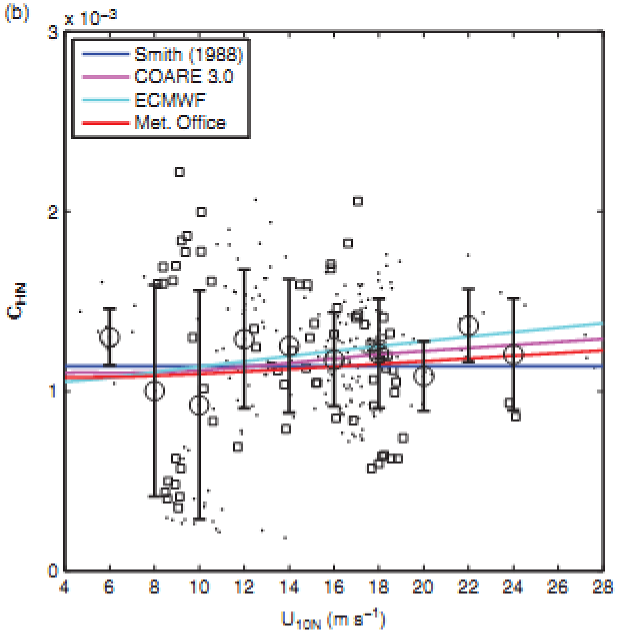
2. Impact of ocean waves on heat and moisture fluxes

➢ **Experimental evidences also point to a sea state/wind dependency of the heat and moisture fluxes.**



Heat exchange coefficients dependency on wind speed

The current model is underestimating a bit the heat transfer from the surface .



Cook and Renfrew 2014

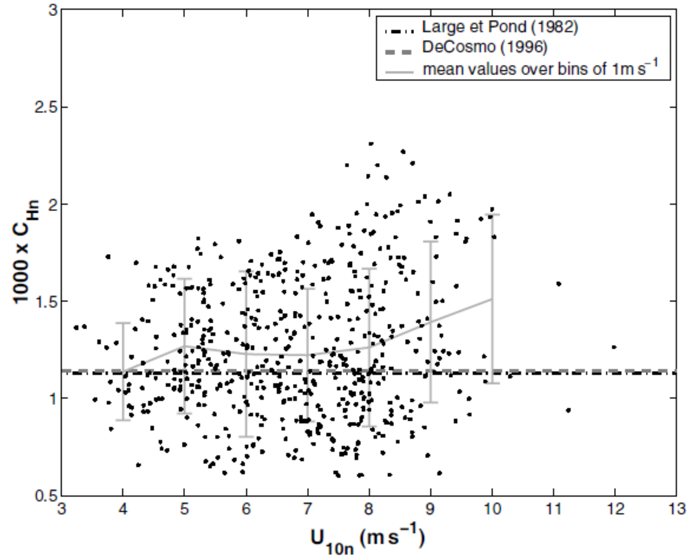


Figure 18. The exchange coefficient for temperature, C_{Hn}, as a function of the neutral wind speed at 10 m, U_{10n}. The dots correspond to 30-minute samples. The solid line with error-bars represents the values averaged over wind speed bins of 1 m s^{-1}. The parametrizations proposed by Large and Pond (1982) and DeCosmo *et al.* (1996) are also plotted.

Brut et al. 2005

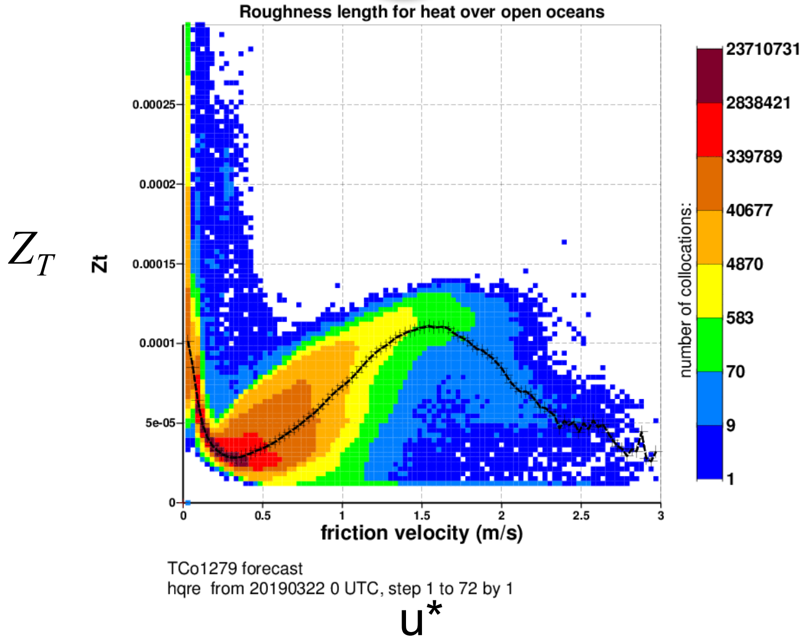
ECMWF

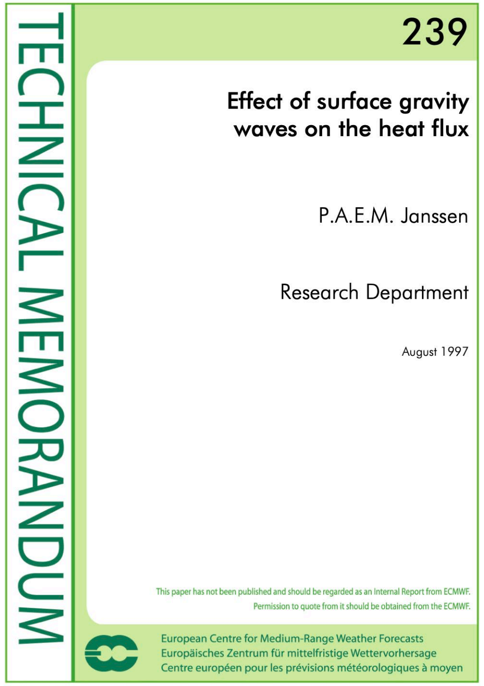
2. Sea state heat and moisture fluxes: future model change (2024)

Following an extension of the wind wave generation theory, a sea state dependent parameterisation for the roughness length scales for heat and humidity has been tested.

It recognises that the waves enhances the transfer from the surface.

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

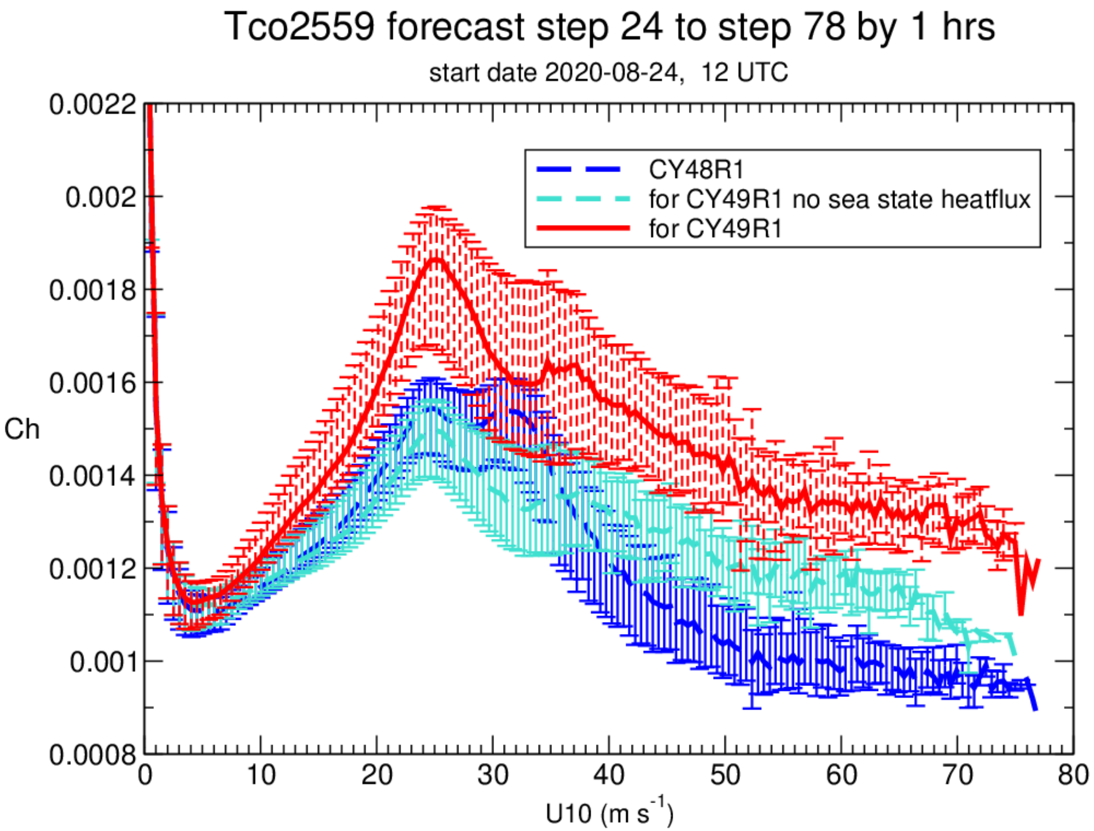




2. Sea state heat and moisture fluxes

Following Janssen (1997, TM239), ocean waves can also have an 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)

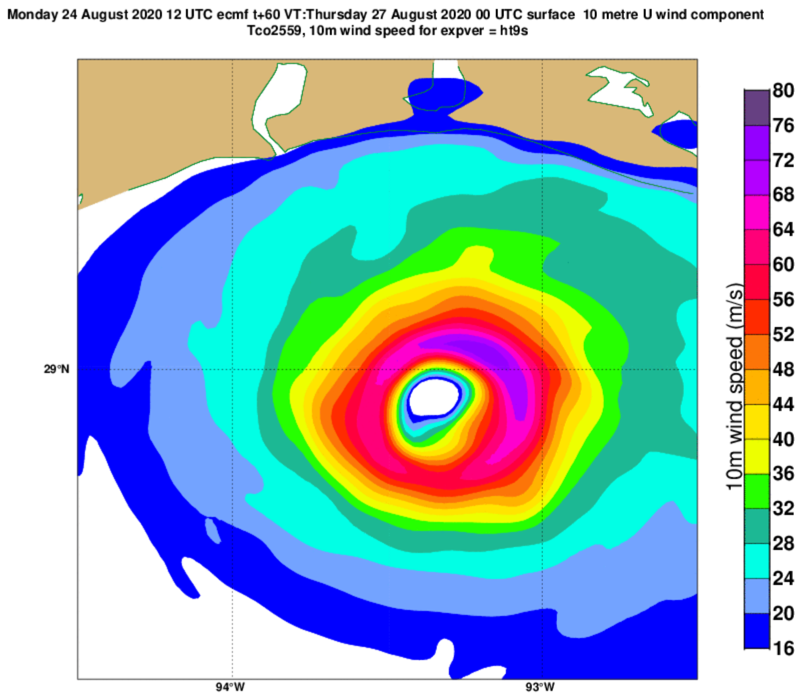


With benefit in tropical cyclone conditions, but also in more normal conditions in the tropics (Janssen and Bidlot 2018). See also SAC paper on tropical cyclones (Magnusson et al. 2021, ECMWF Tech Memo 888)

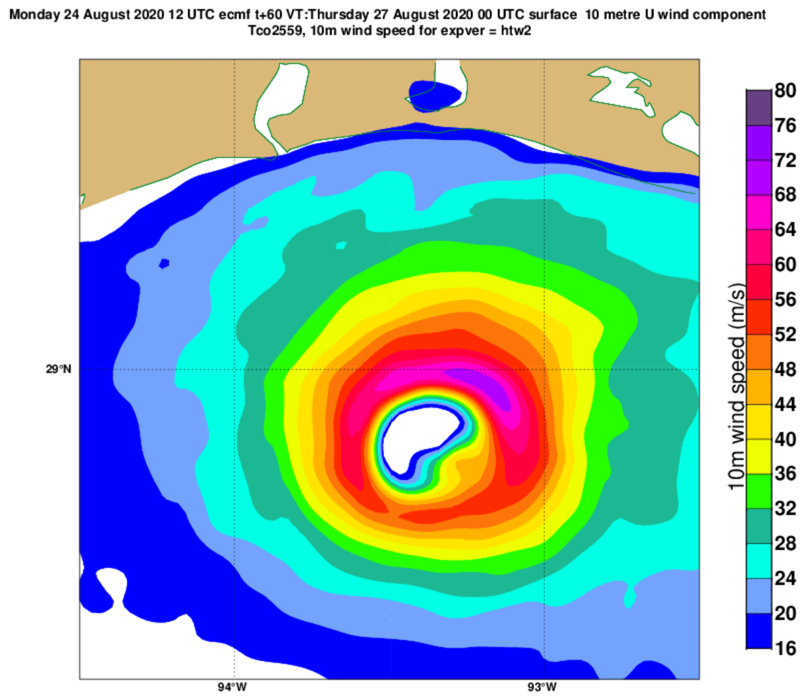
ECMWF

10m wind speed for Hurricane Laura, Tco2559 (4 km), step 60 hours

4km runs yields better tropical cyclones:
S. Majumdar, L. Magnusson, P. Bechtold, J-R Bidlot, J. Doyle, 2022 : Advanced tropical cyclone prediction using the experimental global ECMWF and operational regional COAMPS-TC systems, submitted to MWR.



CY48R1

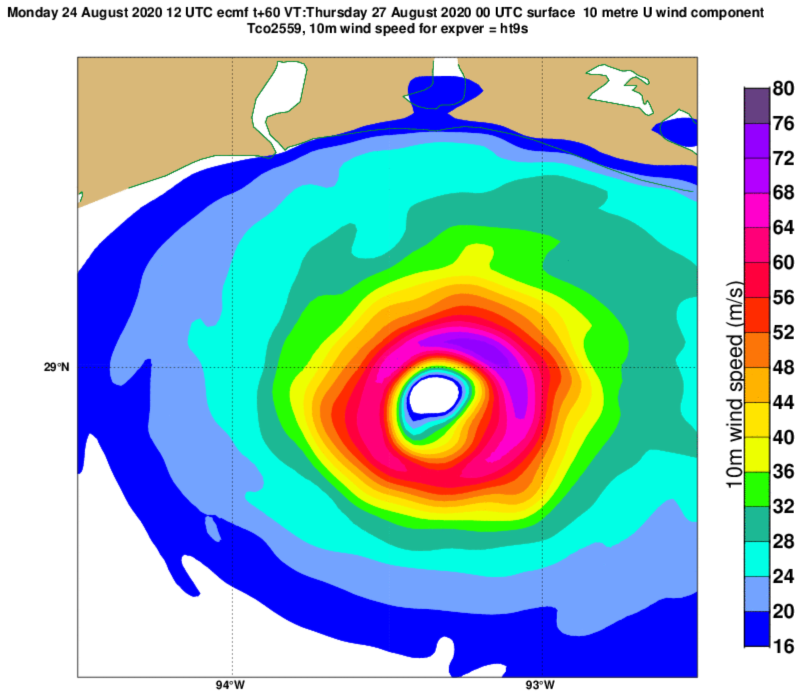


All contributions for CY49R1,
except the sea state heat and moisture

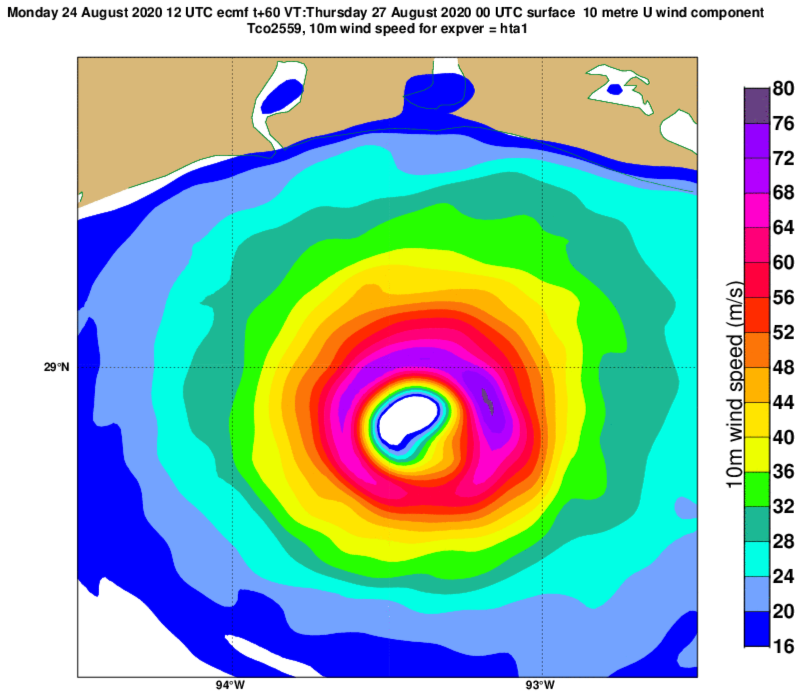
ECMWF

10m wind speed for Hurricane Laura, Tco2559 (4 km), step 60 hours

4km runs yields better tropical cyclones:
S. Majumdar, L. Magnusson, P. Bechtold, J-R Bidlot, J. Doyle, 2022 : Advanced tropical cyclone prediction using the experimental global ECMWF and operational regional COAMPS-TC systems, submitted to MWR.



CY48R1



All contributions for CY49R1

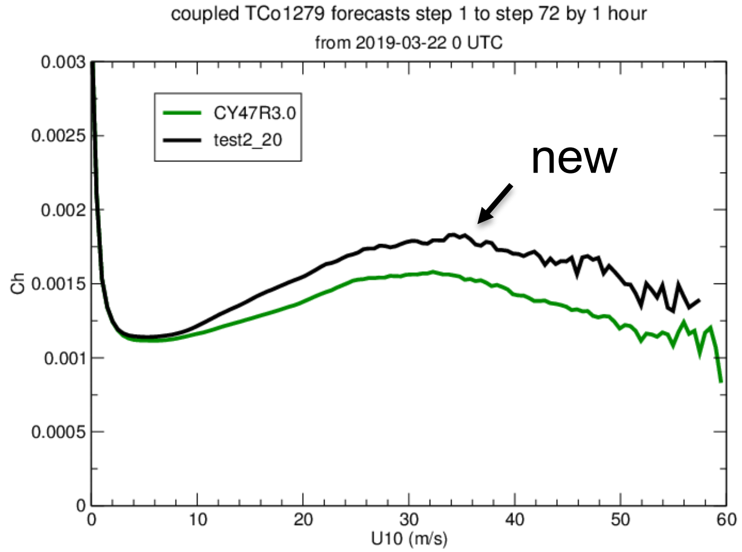
ECMWF

Medium range analysis + forecasts: Expected impact of the sea state dependent heat and moisture fluxes

- With these new changes, the resulting exchange coefficient for heat and moisture increase more rapidly with increasing winds.

Heat exchange coefficient:

C_h

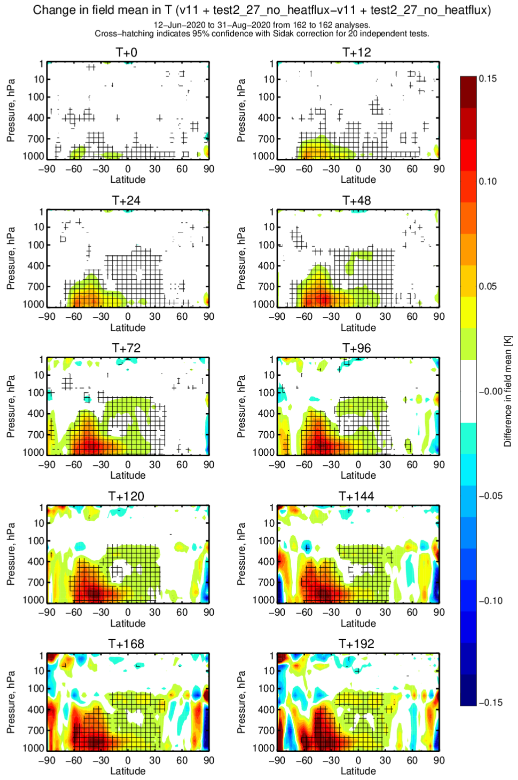


U10 (m/s)

- This has a strong impact on air temperature over the oceans all the way throughout the troposphere, primarily, in the tropics and the winter hemisphere:

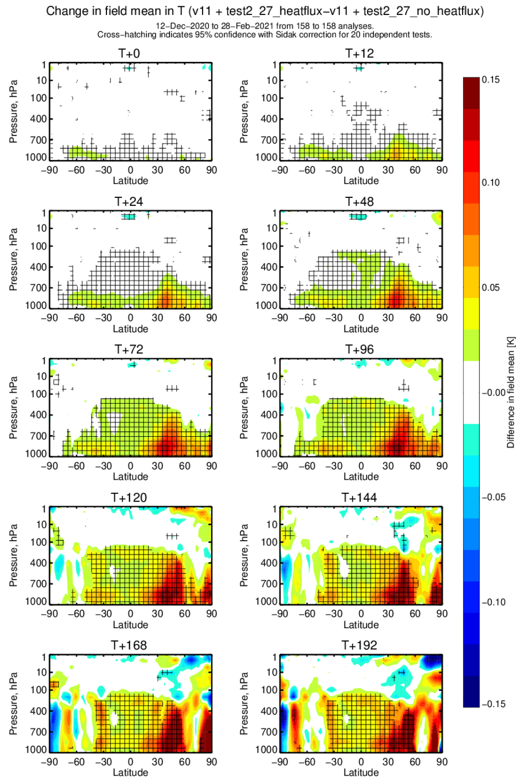
Mean difference in Temperature

JJA



90S 90N

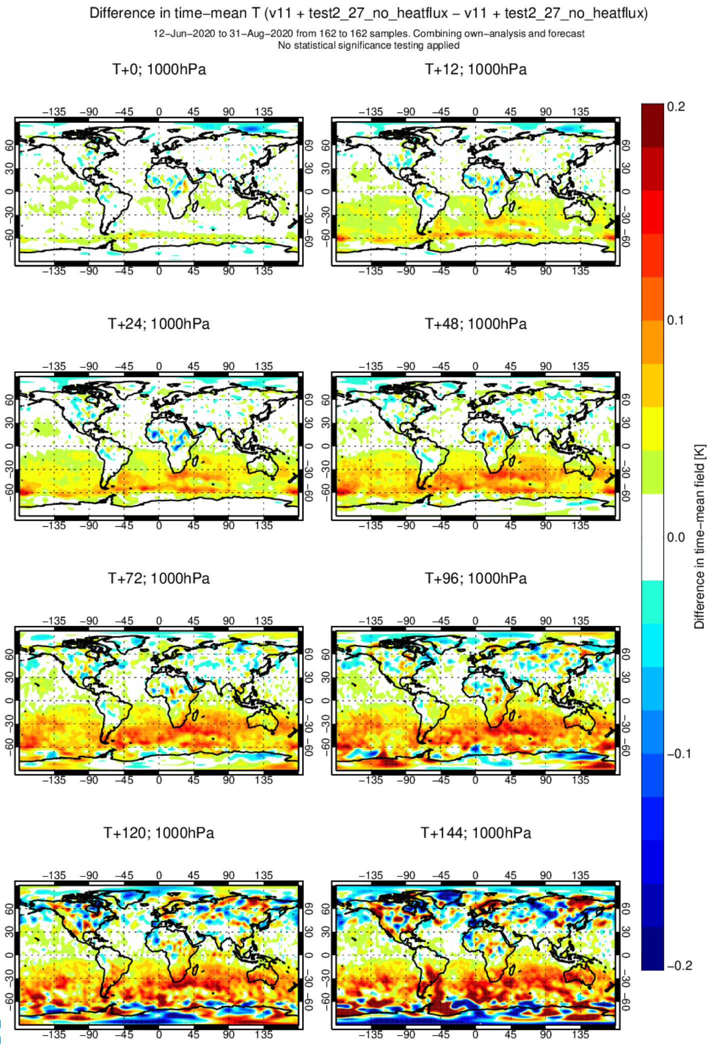
DJF

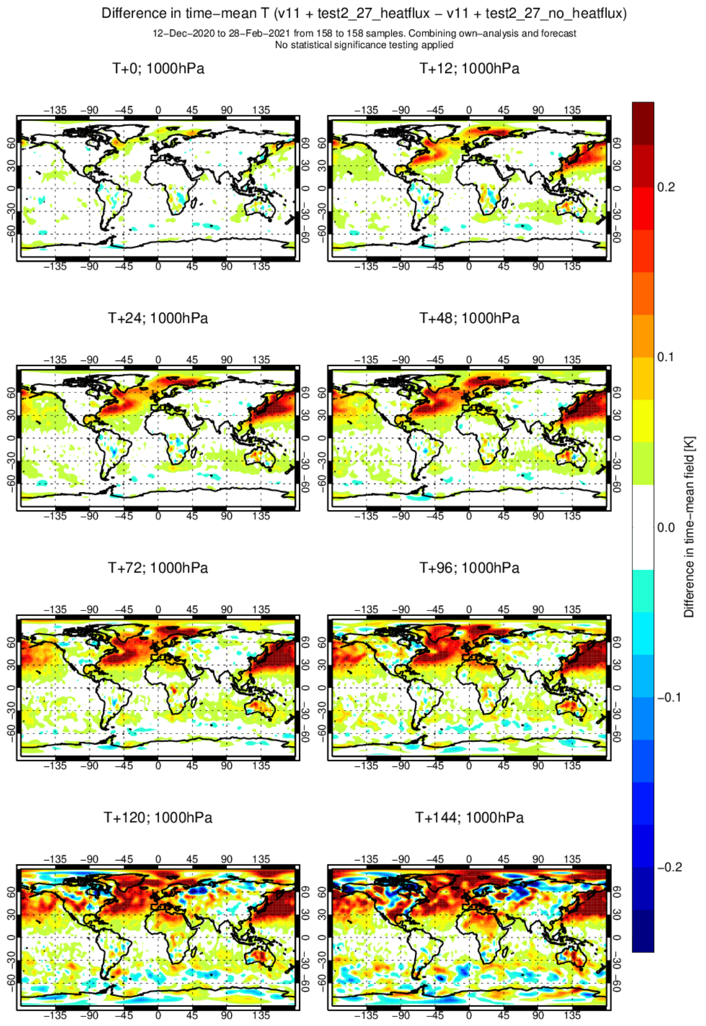


Medium range analysis + forecasts: Expected impact of the sea state dependent heat and moisture fluxes

Mean difference in Temperature at 1000hPa

JJA



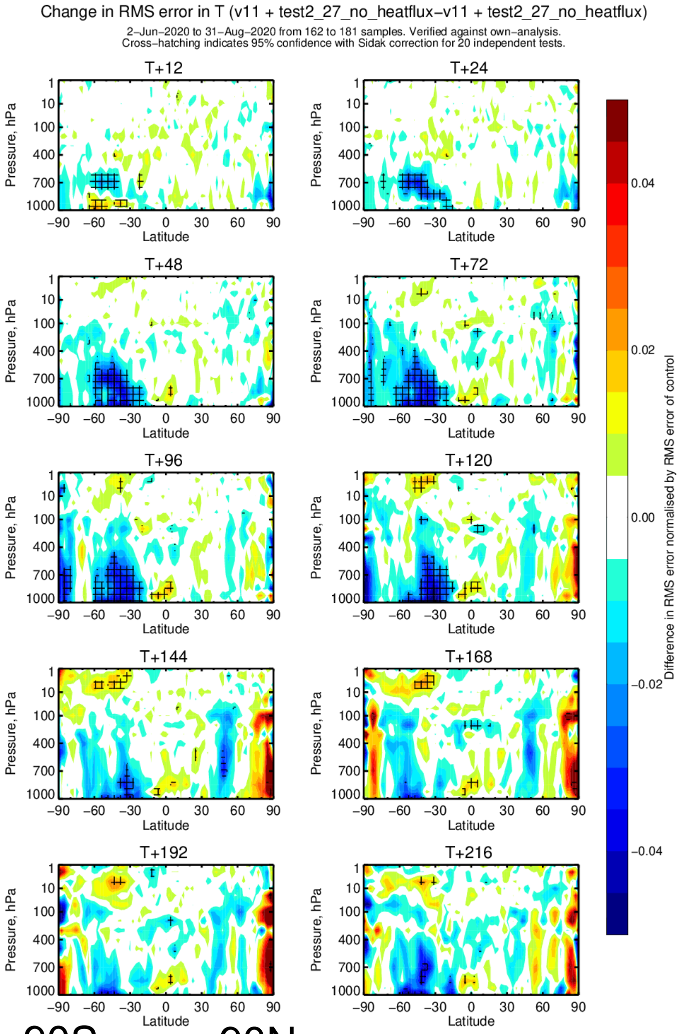


DJF

Analysis and forecast experiments at Tco399

Change in wind speeds RMSE meridional cross section for different forecast range: generally positive

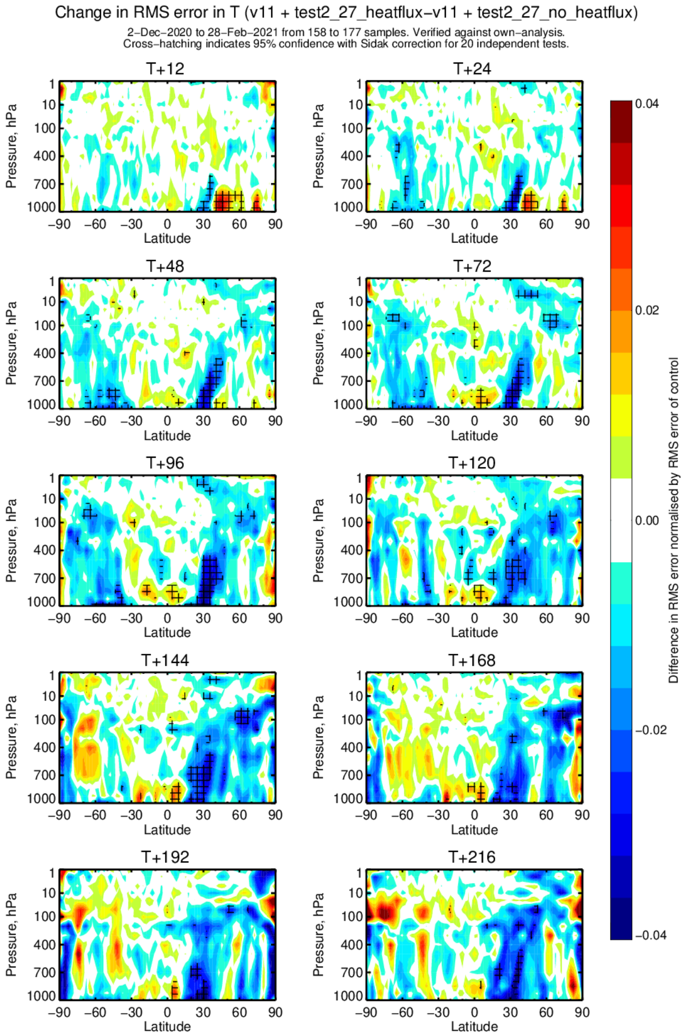
JJA 2020



1 hPa

1000 hPa

90S 90N



90S 90N

DJF 2020-21

improvement

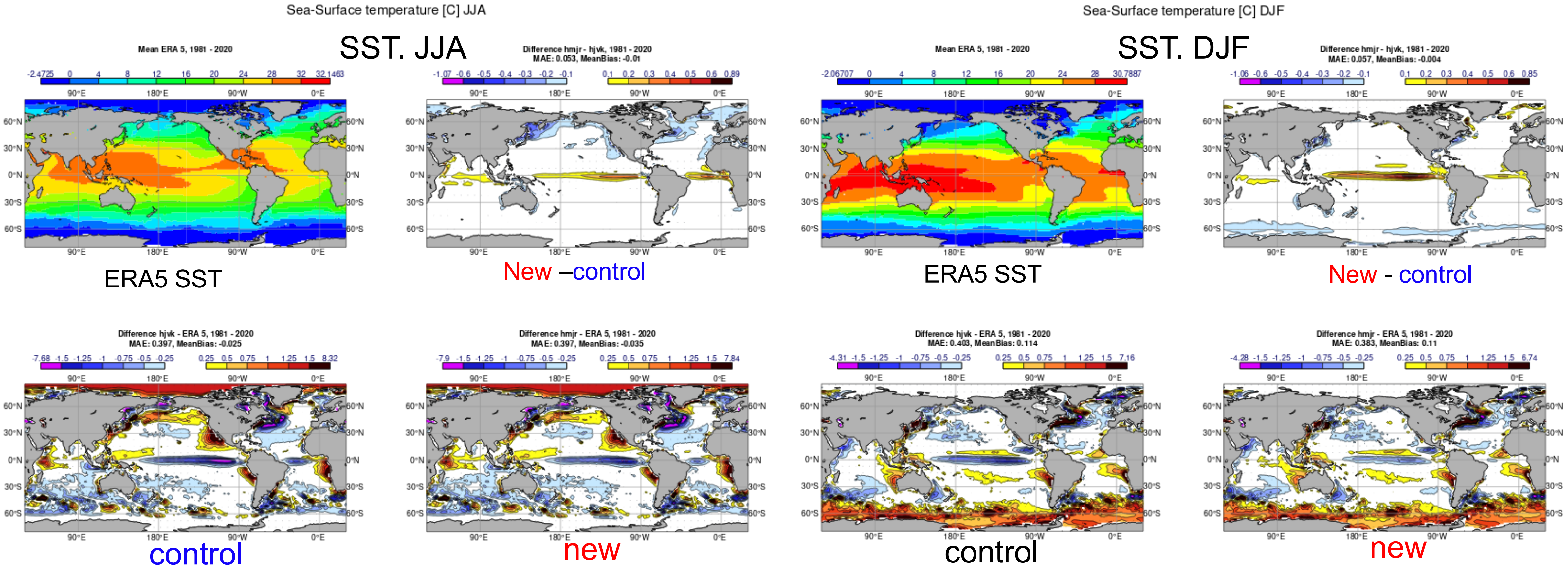
ECMWF

Analysis and forecast experiments at Tco399

3. Relative 10m winds

When both atmosphere and the wave models are also coupled to the ocean model, the surface ocean currents are now used as boundary condition in the surface flux calculation in both models (until now, it was only done in the atmospheric model).

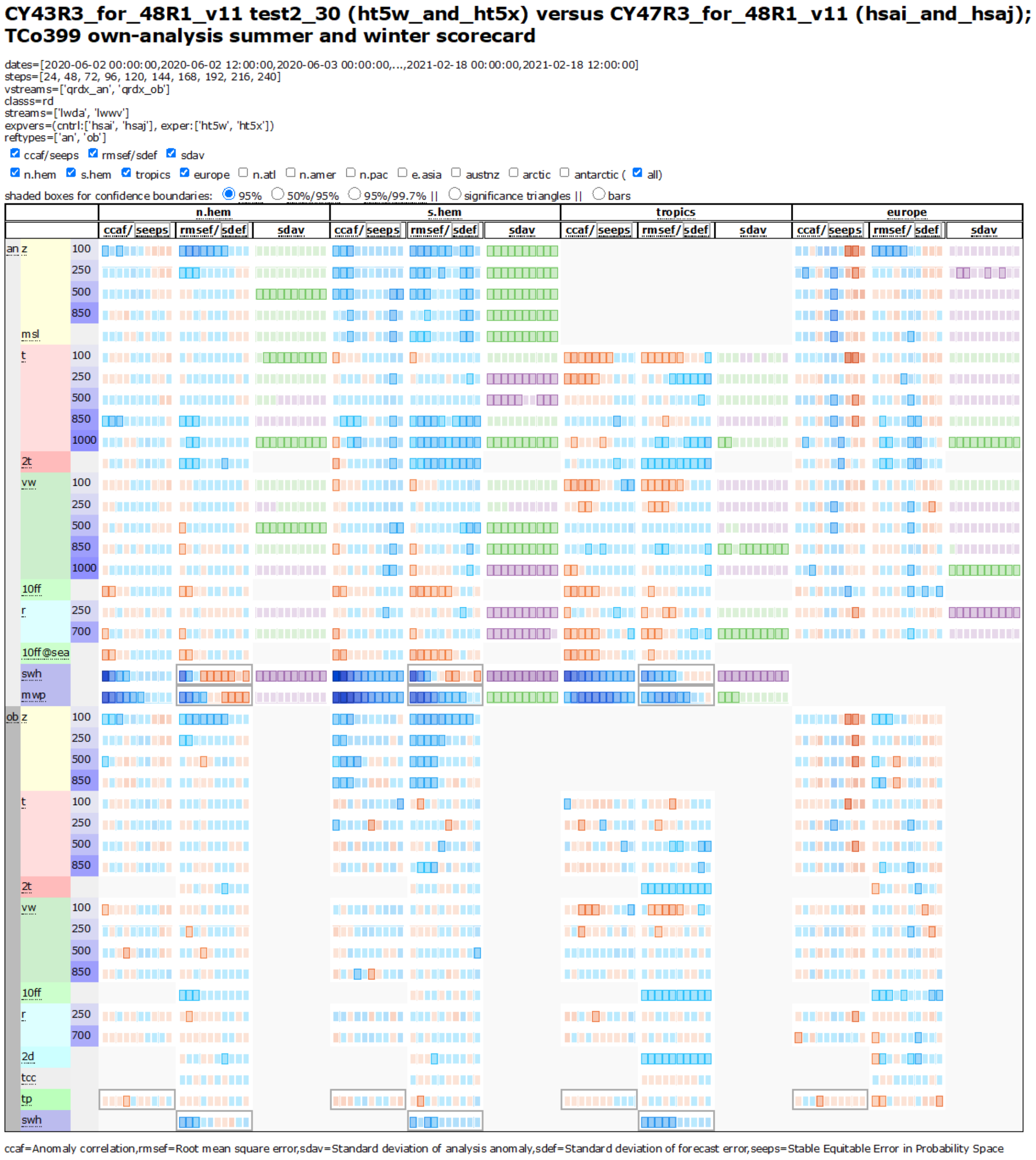
Seasonal range forecasts: Impact on Sea Surface Temperatures:



ECMWF

Combined score cards (Tco399) for all contributions

Analysis exp



Future work

- There have been quite recent a few developments on wave-sea ice interactions. These will be incorporated and tested in ECMWF Earth System Model.

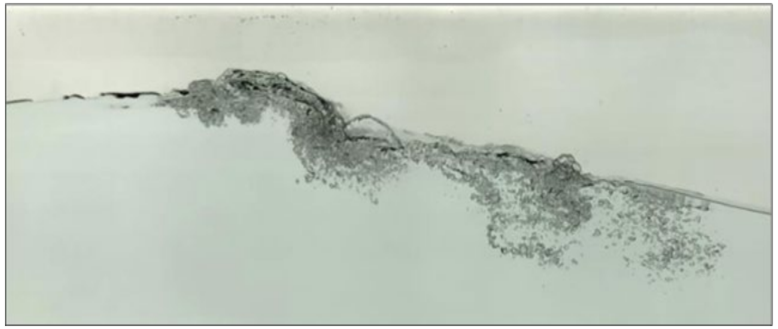
- Collaborations to study the use of wave information on developing and implementing new parameterization for gas exchange, sea salt aerosol production or more generally bubble mediated fluxes (see Adrian Callaghan's talk).

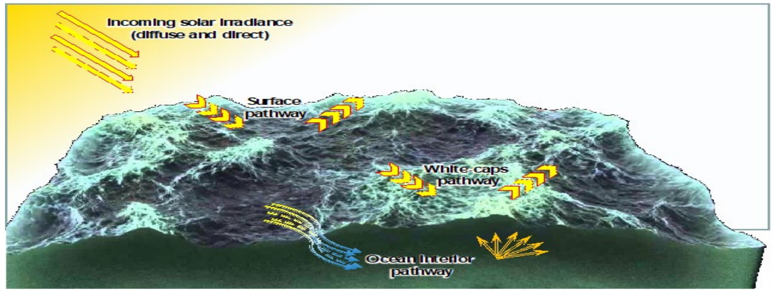
- Study the impact of sea spray for very strong winds

- The role of ocean waves in controlling ocean albedo.

- …

ECMWF





Conclusions

- Ocean waves are an active components of the Earth system.
- ECMWF has using sea state information for momentum exchange over the ocean for years
- Extension to other surface fluxes is under consideration for future model cycles.

ECMWF

Questions ?

Sunset on St Joseph Peninsula, Windmark, Florida

References

ECMWF (2021). “Part VII: ECMWF wave model,” in IFS Documentation CY47R3, (Reading: Shinfield Park). https://www.ecmwf.int/en/elibrary/20201-ifs-documentation-cy47r3-part-vii-ecmwf-wave-model

Janssen, P.A.E.M., 1997: Effect of surface gravity waves on the heat flux. ECMWF Technical Memorandum 239. http://www.ecmwf.int/en/elibrary/technical-memoranda

Peter A.E.M.Janssen and Jean-Raymond Bidlot, 2018: Progress in Operational Wave Forecasting, Procedia IUTAM Volume 26, 2018, Pages 14-29. https://www.sciencedirect.com/science/article/pii/S2210983818300038

Peter A.E.M.Janssen and Jean-Raymond Bidlot, 2021. ECMWF Technical Memorandum 882. https://www.ecmwf.int/en/elibrary/19943-consequences-nonlinearity-and-gravity-capillary-waves-wind-wave-interaction
A paper is under review in JPO.

S. Majumdar, L. Magnusson, P. Bechtold, J-R Bidlot, J. Doyle, 2022 : Advanced tropical cyclone prediction using the experimental global ECMWF and operational regional COAMPS-TC systems, submitted to MWR.