Recent developments in Air sea exchange and wind wave interactions

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European Centre for Medium-range Weather Forecasts (ECMWF)

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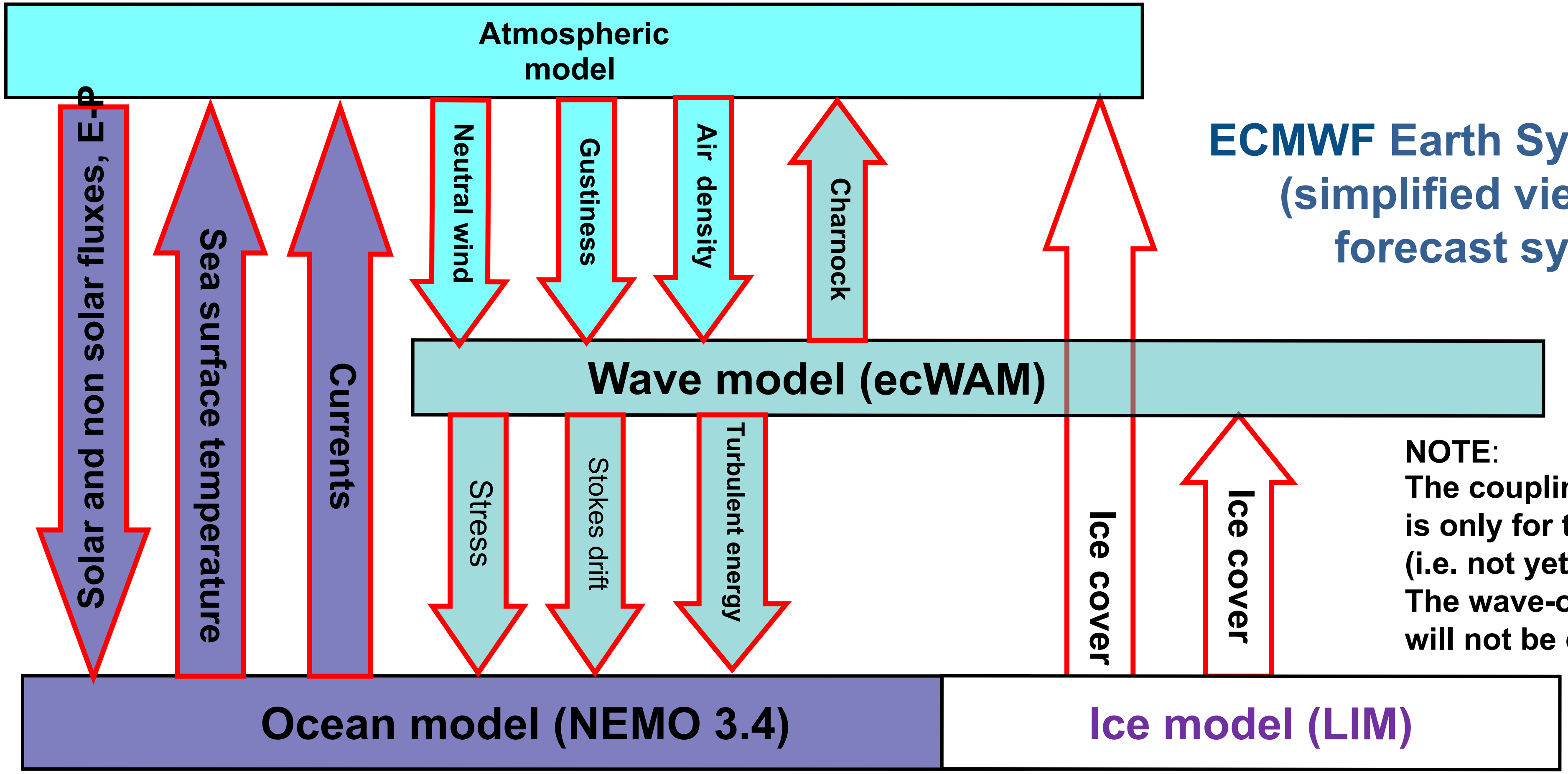
Outline:

1. Ocean Wave modelling at ECMWF.
2. Wind – wave interaction for surface momentum exchange.
3. Wind – wave interaction for heat and moisture exchanges.
4. A glimpse into the next ECMWF/C3S reanalysis (ERA6).

1. 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

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

Neutral wind

Every IFS time step

Charnock

Charnock relation

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

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

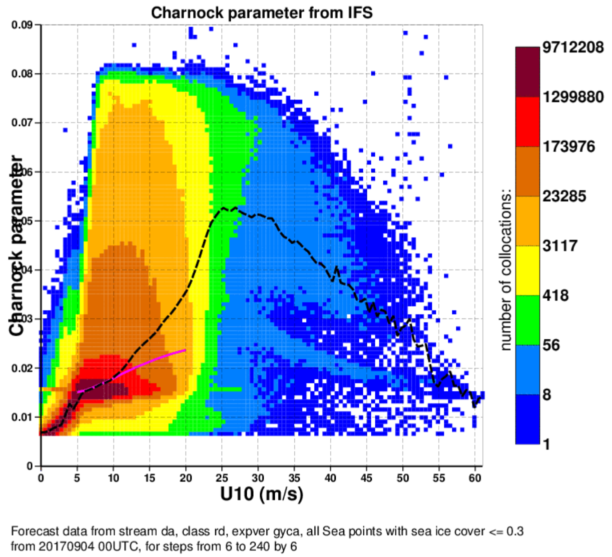
Wave model (ecWAM)

The Charnock coefficient is linked to the amount of momentum that is used to generate waves which varies depending on the sea state evolution (wave induced stress $\boldsymbol{\tau}_w$

0.08

α

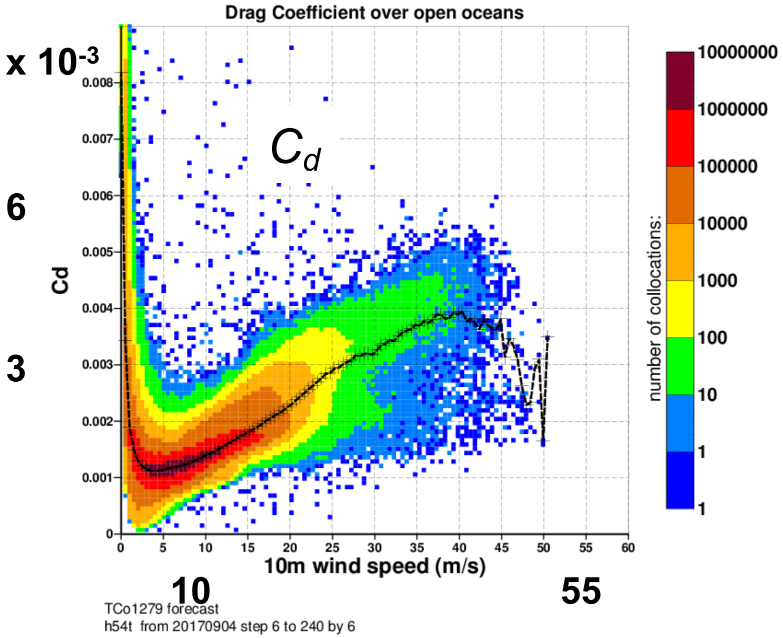
0.02



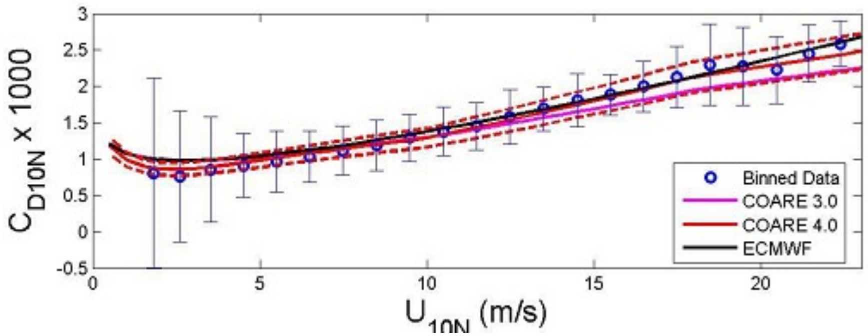
U10

ECMWF

2. Impact of ocean waves on the surface stress



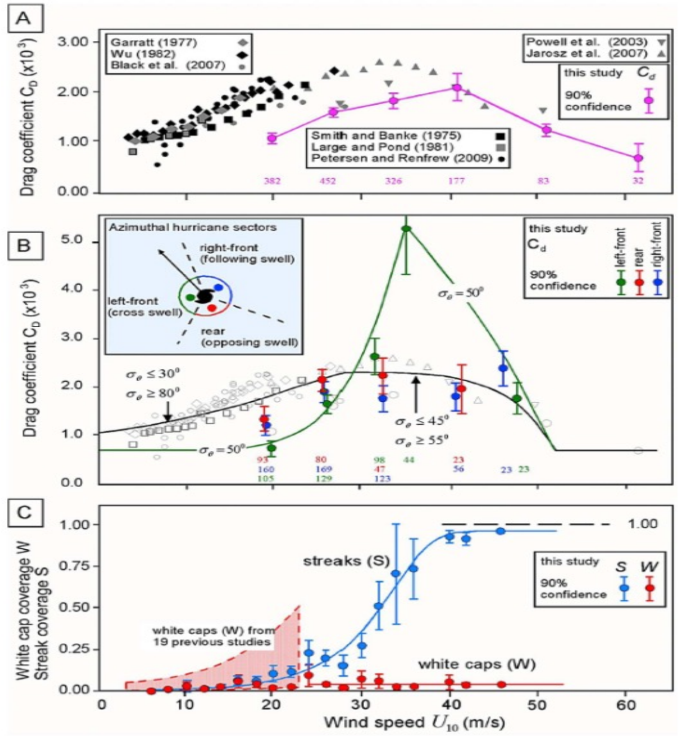
Drag coefficient (C_d)
with respect to wind speed
Operational model (June 2019)



Edson et al., 2013

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.**

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A 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).

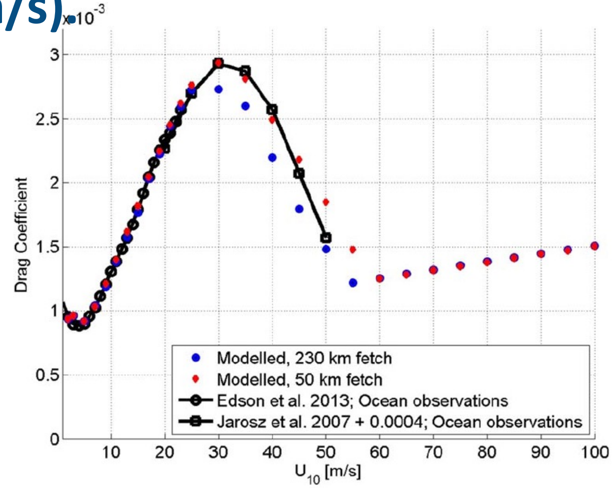


Figure 6. Modeled (with Reynolds number dependent sheltering coefficient, Figure 5, equation (13)) and observed drag coefficients versus wind speed. Note the fetch dependence of the modeled drag coefficient between 30 and 55 m/s.

Donelan (2018)

With the wave model, Charnock is expressed as

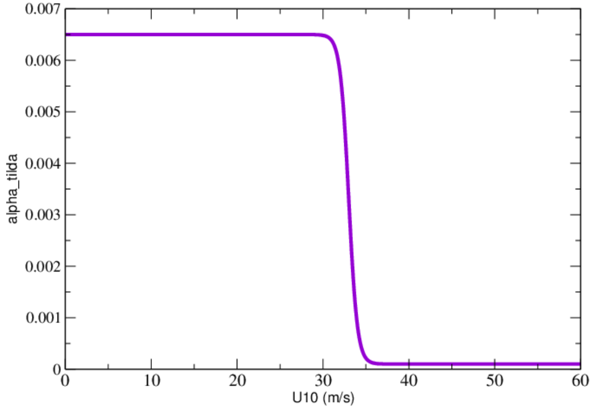
$$\alpha = \frac{\widetilde{\alpha}}{\sqrt{1 - \frac{\tau_w}{u_*^2}}}$$

Originally with

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

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

$\widetilde{\alpha}$



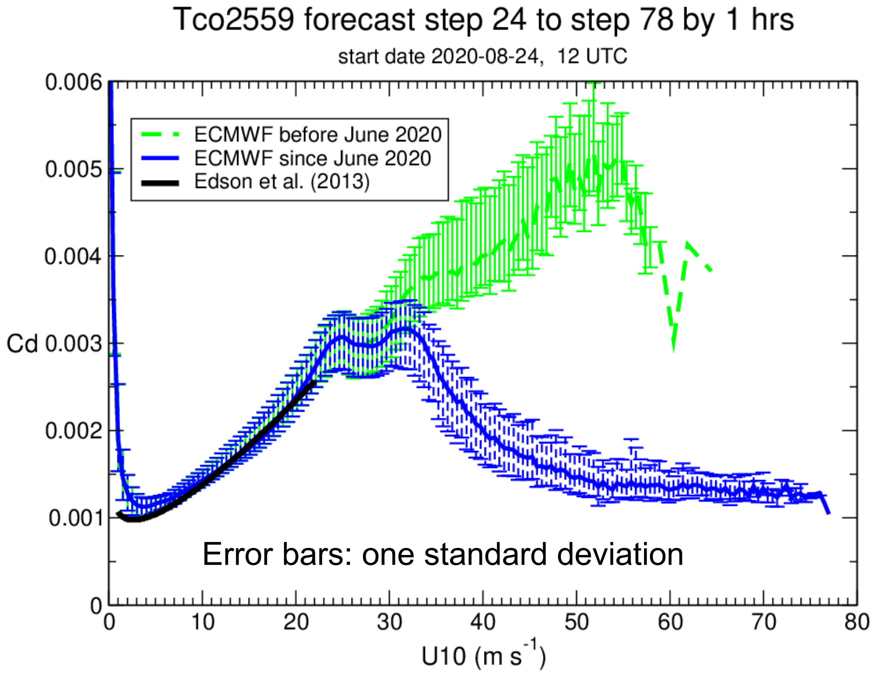
U10

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:

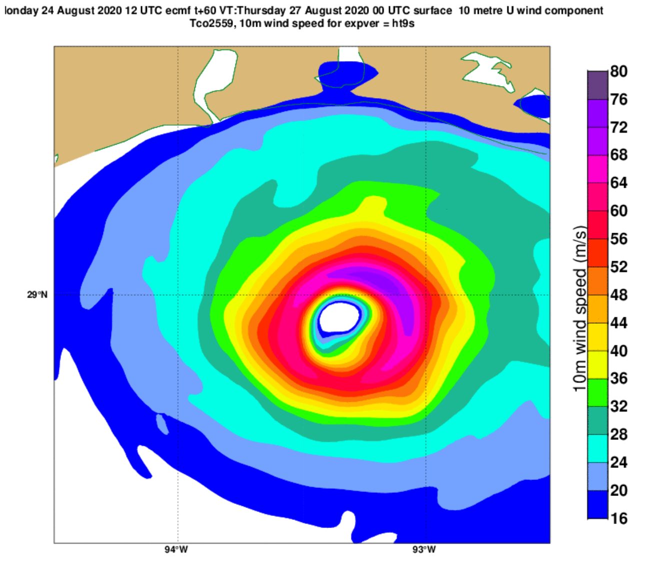
- The latest one was a reduction of the Charnock coefficient for winds above 33 m/s (June 2020).
- This is quite essential now that we can show that 4.4km runs yields better tropical cyclones:

Drag coefficient v 10m wind speed:

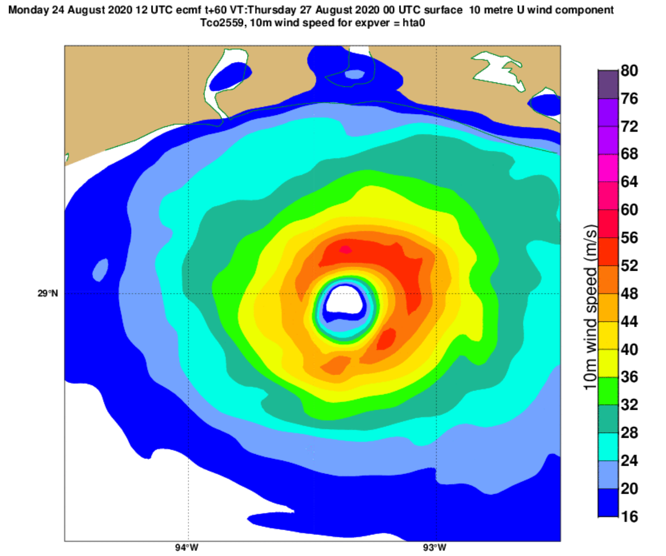


Majumdar et al. (2023)
in review

10m wind speed, Hurricane Laura 27 August 2020



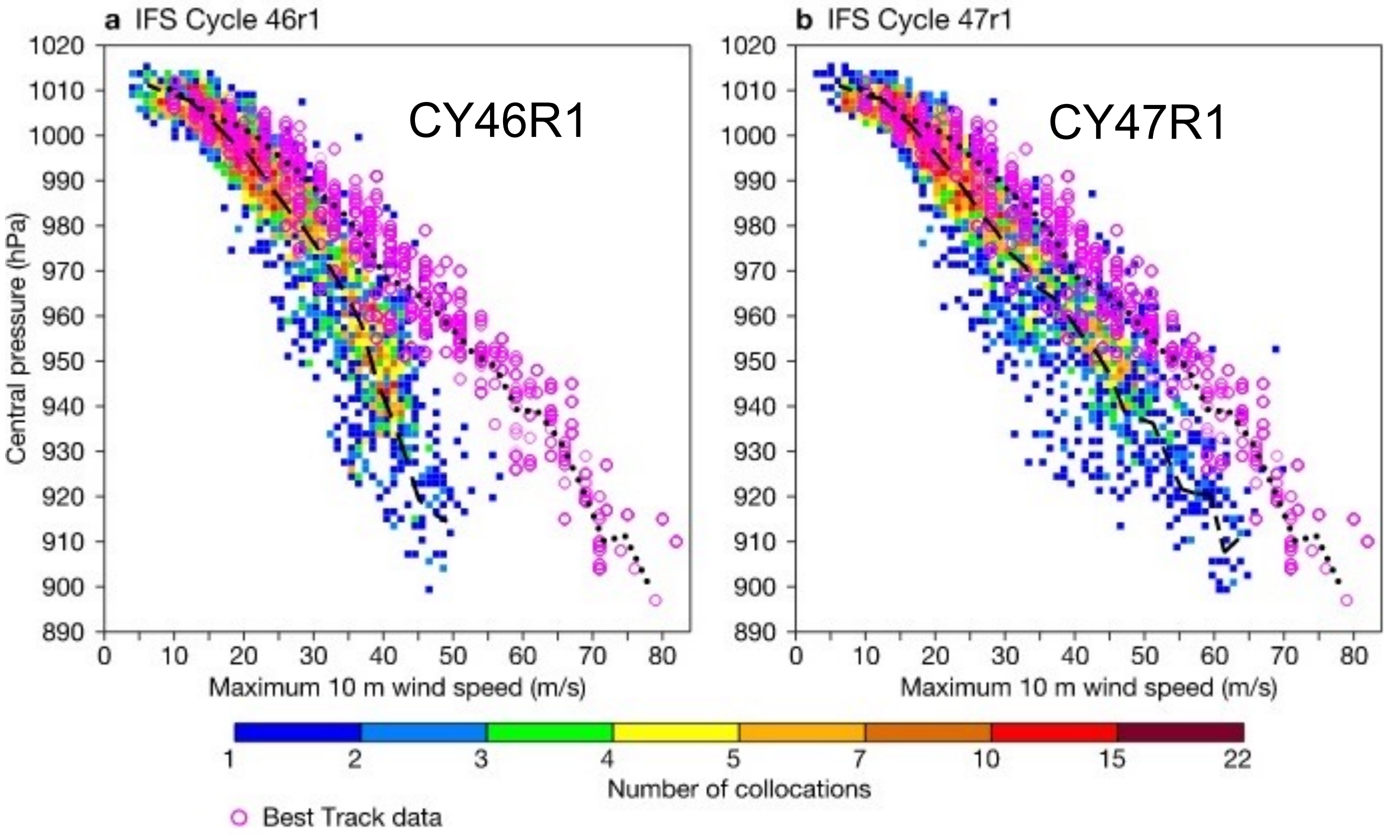
CY48R1



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

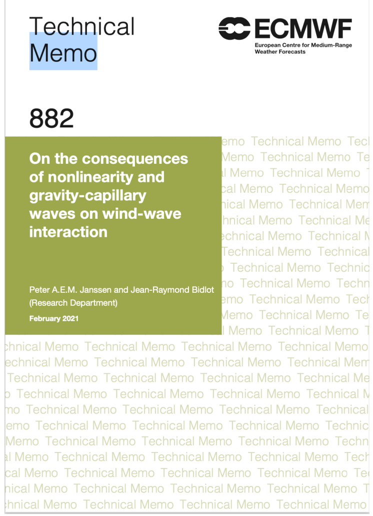
This has resulted in improved Tropical cyclone max wind - min pressure relationship in the operational system:



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.

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


Technical Memo

882

On the consequences of nonlinearity and gravity-capillary waves on wind-wave interaction

Peter A.E.M. Janssen and Jean-Raymond Bidlot (Research Department)

February 2021

Janssen and Bidlot 2023,
Accepted for publication in JPO

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**.

In the original parameterization of Peter Janssen wind input theory, a logarithmic wind profile was assumed:

$$U_0(z) = \frac{u_*}{\kappa} \log\left(1 + \frac{z}{z_0}\right)$$

and the parameterization of the surface roughness z_0 follows

$$z_0 = \frac{z_b}{\sqrt{1 - \tau_w(0)/\tau_a}} \qquad z_B = \alpha_B u_*^2/g,$$

with z_B the background roughness, representing the impact of unresolved short gravity-capillary waves based on a Charnock relation with a fixed tunable parameter $\alpha_B \sim 0.0065$

with the parameterization of the wind input source term

$$S_{in} = \boldsymbol{\gamma}\, F(\omega,\theta)$$

Revised sea state dependent momentum flux: nonlinear wind input growth rate

In the parameterization of Janssen wind input theory, a logarithmic wind profile was assumed:

$$U_0(z) = \frac{u_*}{\kappa} \log\left(1 + \frac{z}{z_0}\right)$$

and the parameterization of the surface roughness z_0 follows

$$z_0 = \frac{z_b}{\sqrt{1 - \tau_w(0)/\tau_a}} \qquad z_B = \alpha_B u_*^2 / g,$$

with z_B the background roughness, representing the impact of <u>unresolved</u> short gravity-capillary waves based on a Charnock relation with a fixed tunable parameter $\alpha_B \sim 0.0065$

with the parameterization of the wind input source term

$$S_{in} = \boldsymbol{\gamma}\, F(\omega,\theta)$$

Revised sea state dependent momentum flux: nonlinear wind input growth rate

But it turns out that because of the strong interaction between wind and waves,
The wind profile will deviate from the log profile.
It can be shown that the growth rate itself depends on the wave spectrum:

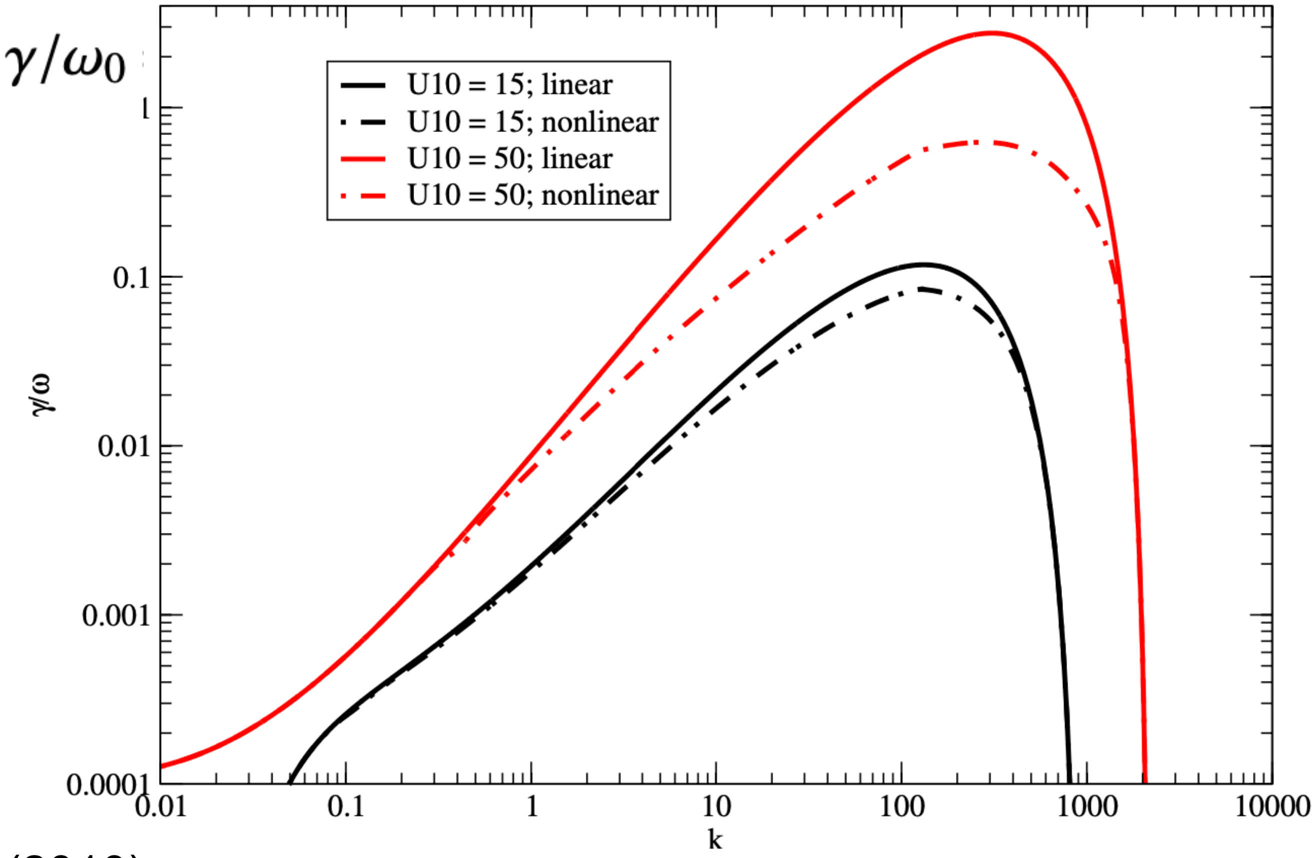
$$\gamma = \gamma_0 \frac{1+N_1}{1+N_2}$$

with γ_0 the growth rate of the logarithmic profile

and the renormalization factors:

$$N_1 = \frac{k^3}{\epsilon \kappa u_*} \int d\theta \, \gamma_0 \, F(k,\theta) \sin^2\theta,$$

$$N_2 = \frac{k^3}{\epsilon \kappa u_*} \int d\theta \, \gamma_0 \, F(k,\theta).$$



Wave number

This will replace the sheltering effect of Ardhuin et al. (2010).

Revised sea state dependent momentum flux: model for the role of gravity-capillary waves

The background roughness z_B was introduced to represent the impact of unresolved short gravity-capillary

$$z_B = \alpha_B u_*^2 / g,$$

With a fixed 'tunable' parameter α_B

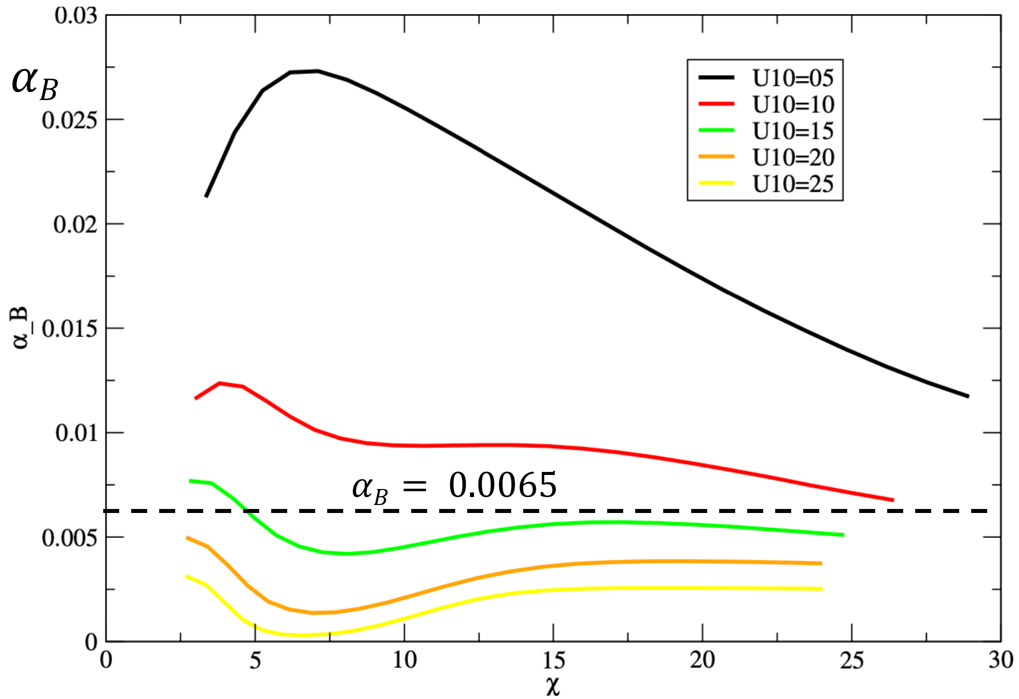
However, based on the VIERS model (Janssen et al. 1998), originally developed for radar backscatter modelling, a model for the spectrum of those short waves was implemented

and is used to update the total surface stress $\boldsymbol{\tau}_a$.

$$\tau_a = \tau_v + \tau_{w,lf} + \tau_{w,hf}$$

since the viscous stress and the wave stress depend in a complicated manner on the surface stress $\boldsymbol{\tau}_a$, the stress balance is solved by iteration.
Hence, a consistent solution for the spectrum of short and long-waves is obtained and at the same time a consistent estimate of the stress over growing wind waves is found

α_B becomes sea state dependent:



Wave age

Single point simulation with constant wind

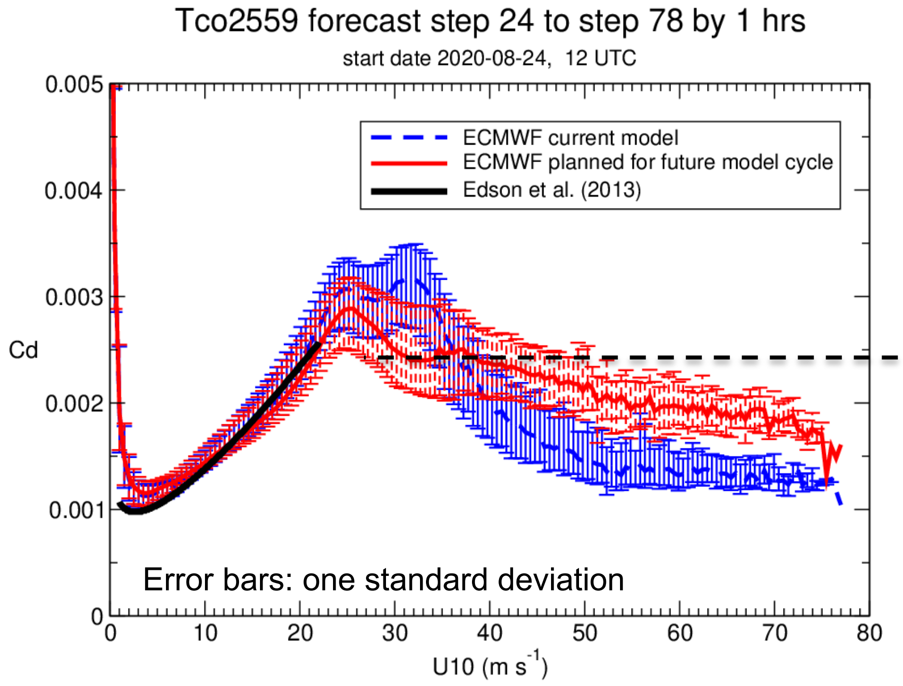
ECMWF

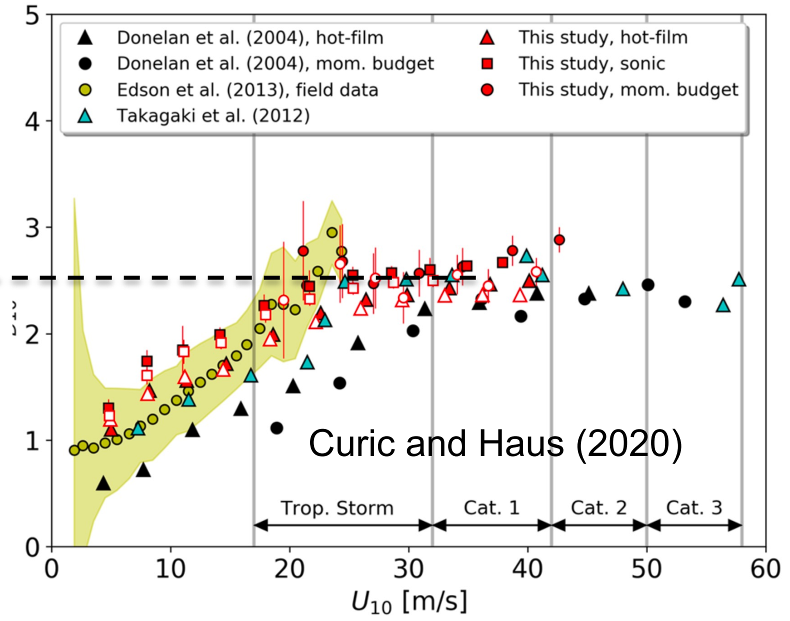
Revised sea state dependent momentum flux: future model change (planned for 2024)

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

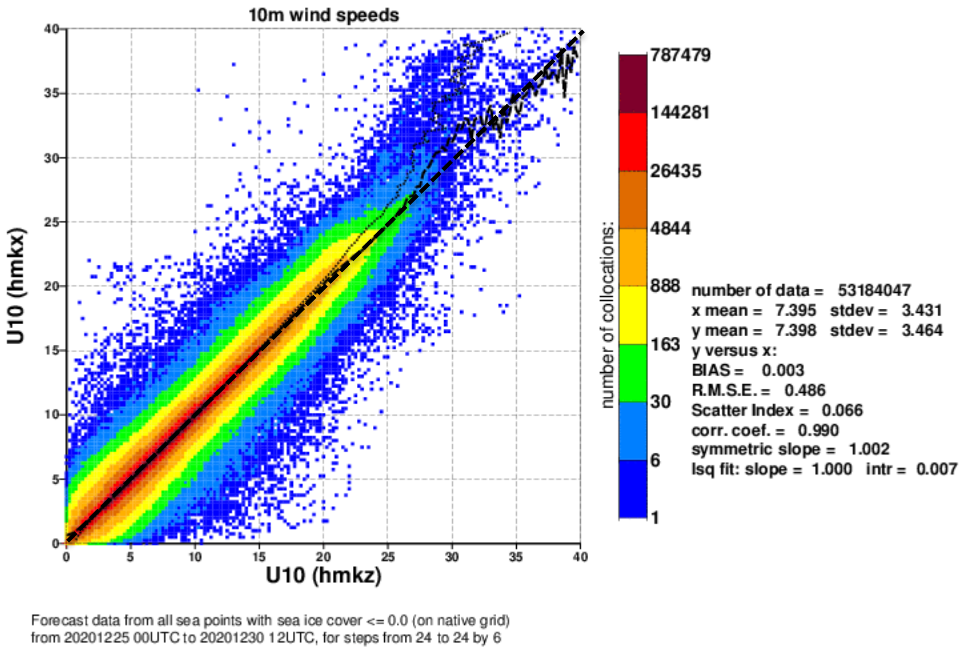




Impact on surface wind speeds

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

new

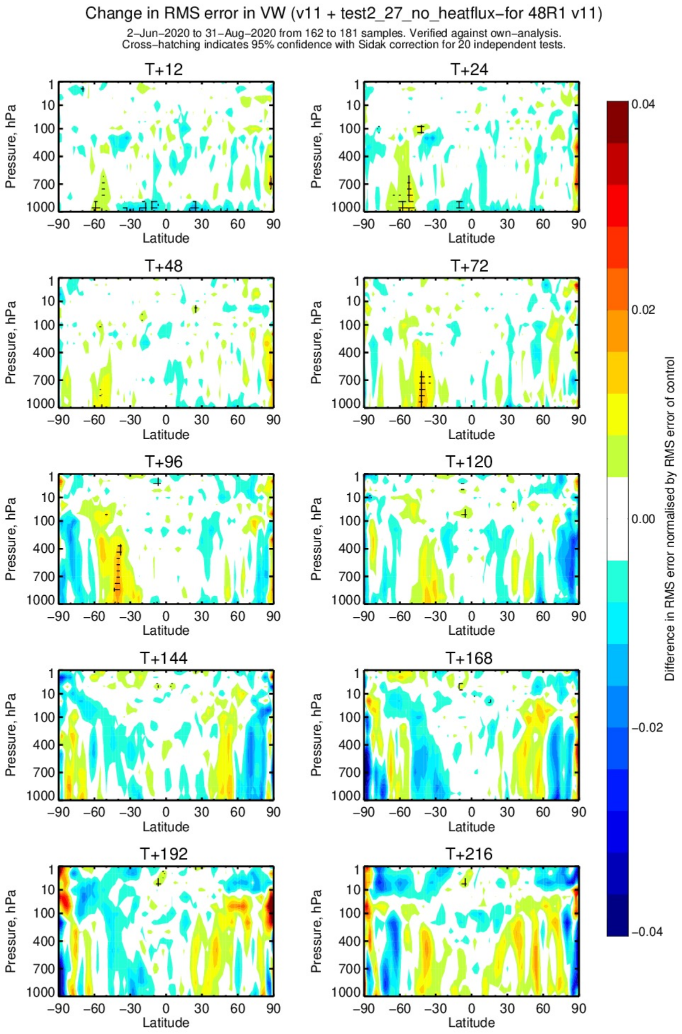


control

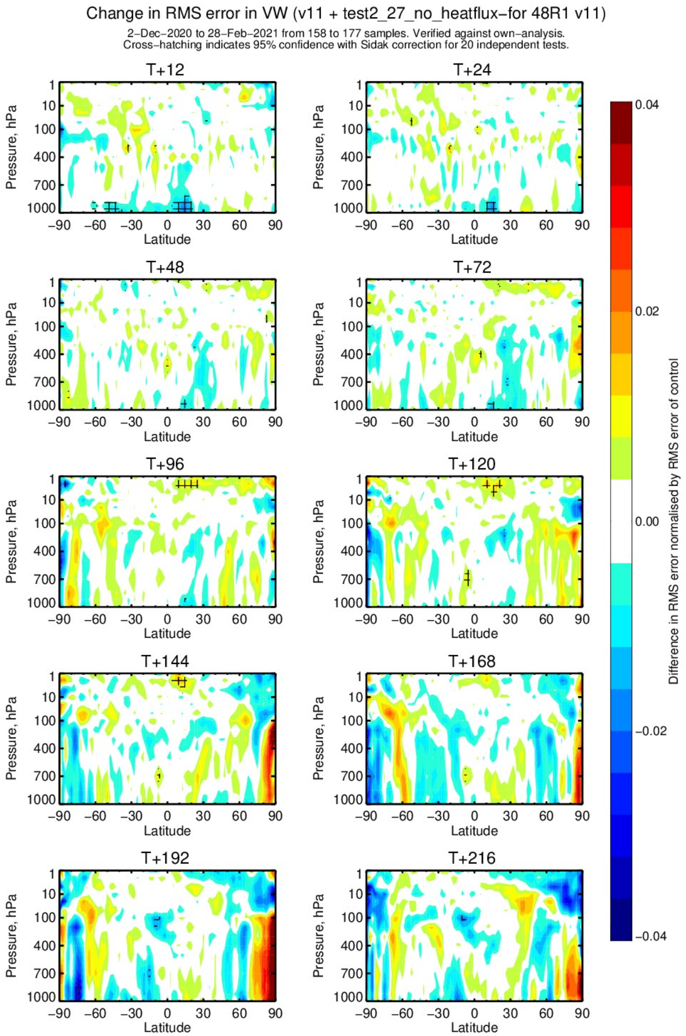
Tco1279 forecasts step 24 with LSM=0 and no sea-ice

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

JJA 2020



DJF 2020-21



improvement

1 hPa

1000 hPa

90S 90N

90S 90N

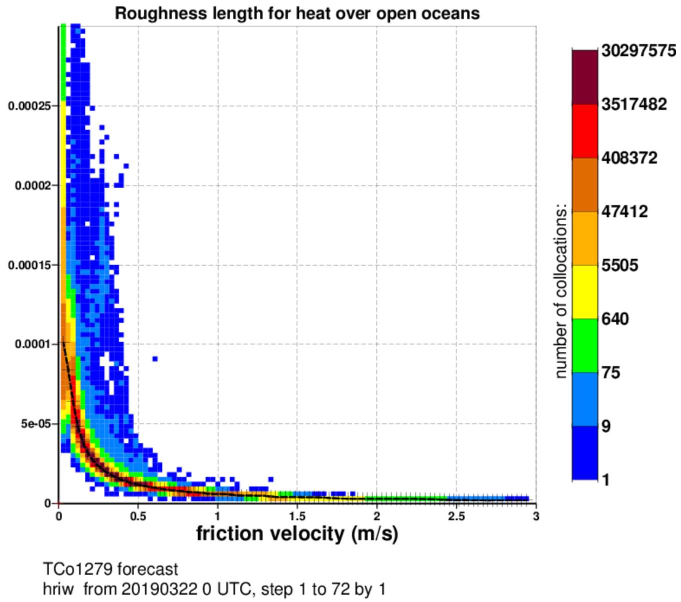
Analysis and forecast experiments at Tco399

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 atmosphere model 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*

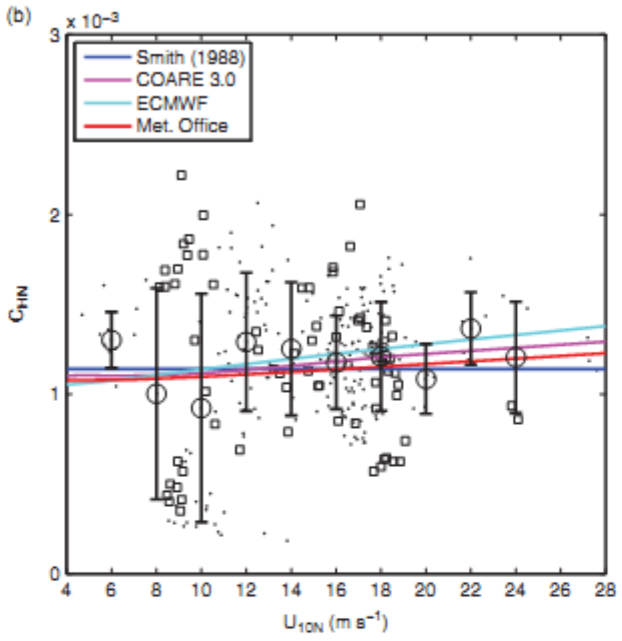
But, for the roughness length scale, We still assume that the exchange is dominated by viscosity:

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

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.**



Cook and Renfrew 2014

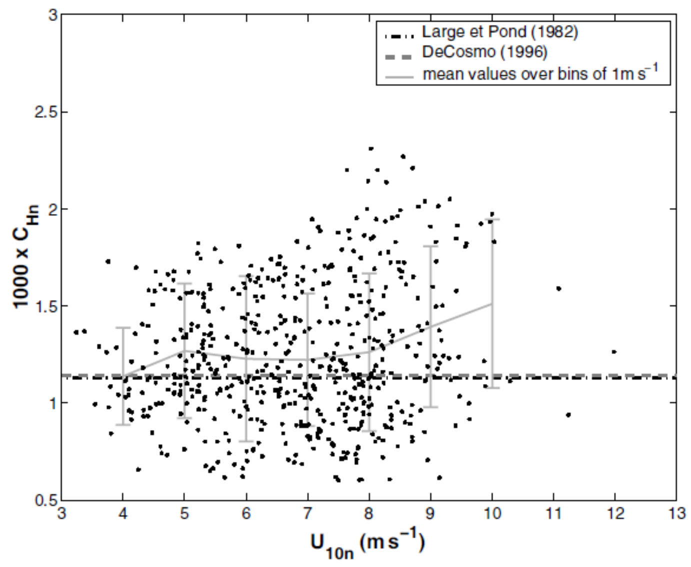
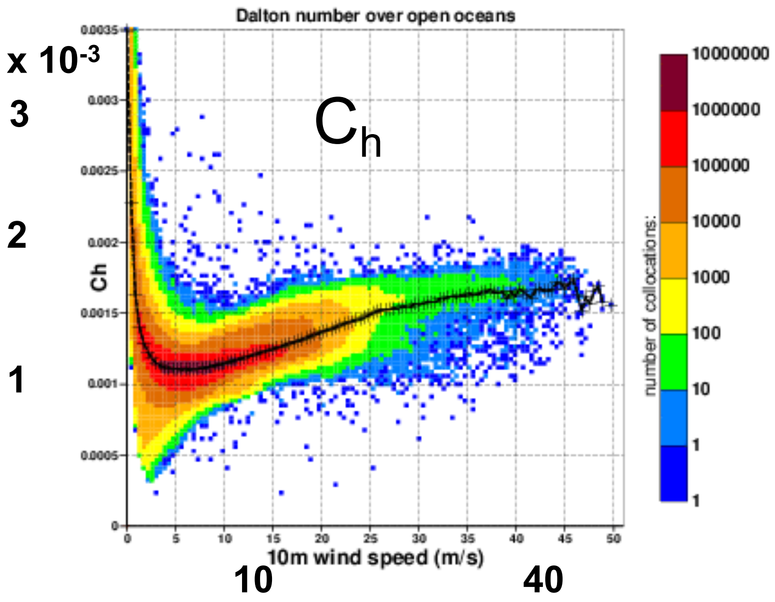


Figure 18. The exchange coefficient for temperature, C_{Hn}, as a function of the neutral wind speed at 10 m, U_{10n}. The dots correspond to 30-minute samples. The solid line with error-bars represents the values averaged over wind speed bins of 1 m s^{-1}. The parametrizations proposed by Large and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

Brut et al. 2005



Heat exchange coefficients dependency on wind speed

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

ECMWF

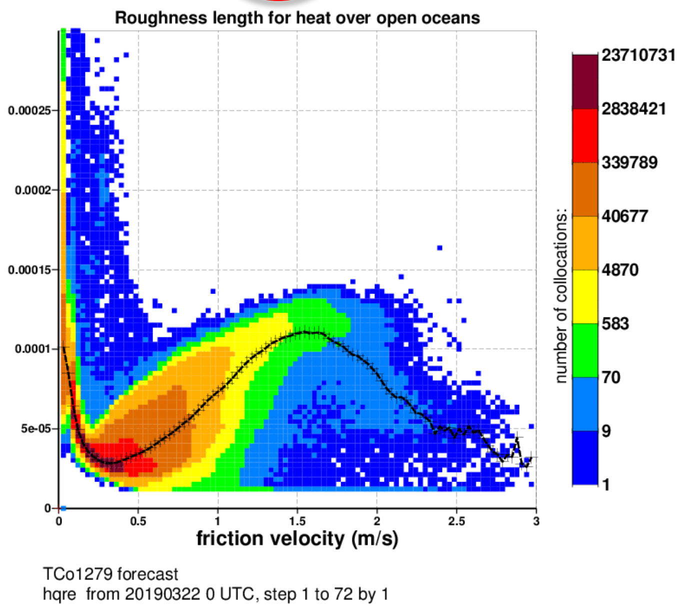
3. Sea state heat and moisture fluxes: future model change (2024)

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.

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

z_T



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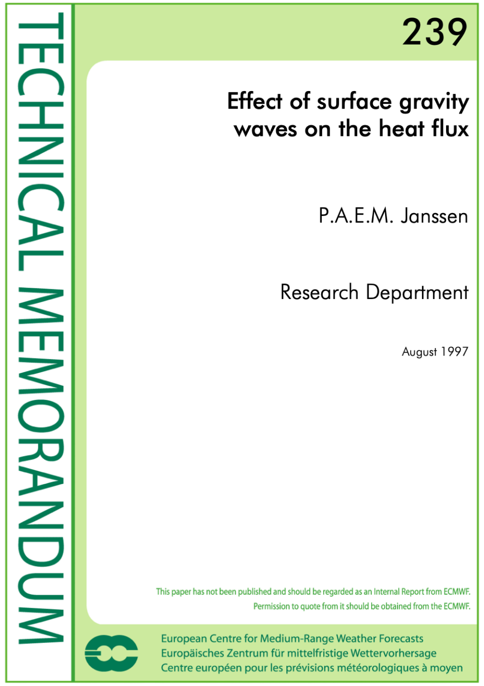
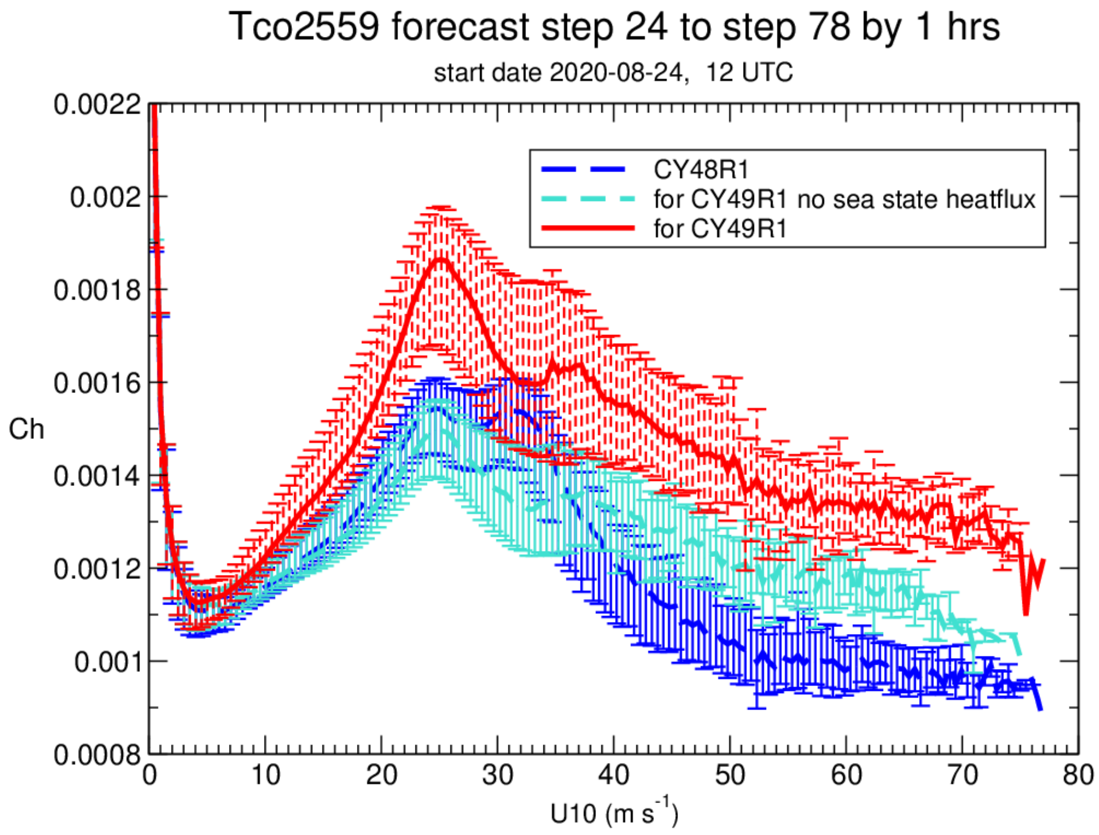

TECHNICAL MEMORANDUM
239
Effect of surface gravity waves on the heat flux
P.A.E.M. Janssen
Research Department
August 1997
This paper has not been published and should be regarded as an Internal Report from ECMWF.
Permission to quote from it should be obtained from the ECMWF.
European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen

ECMWF

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:

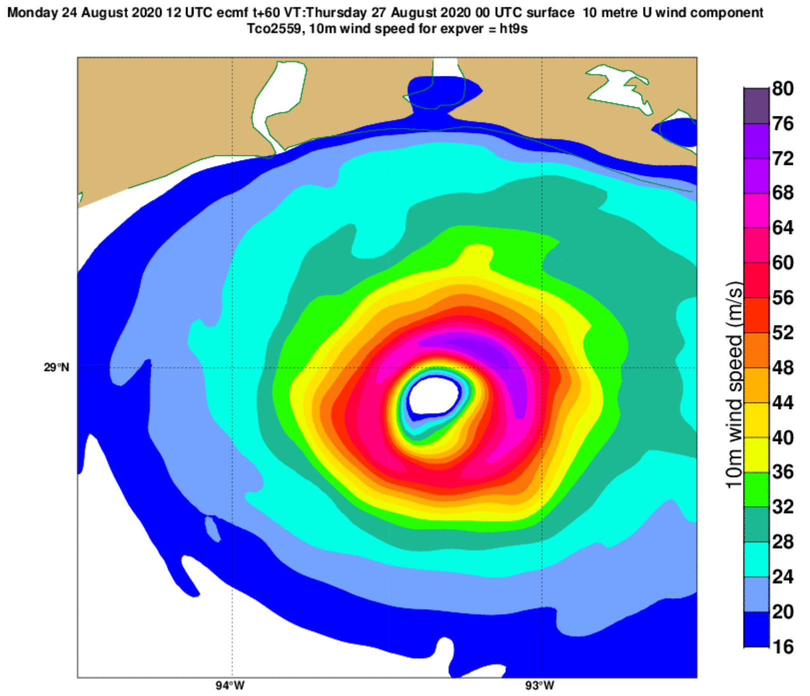
Exchange coefficient dependency on wind speed
for heat (C_h)



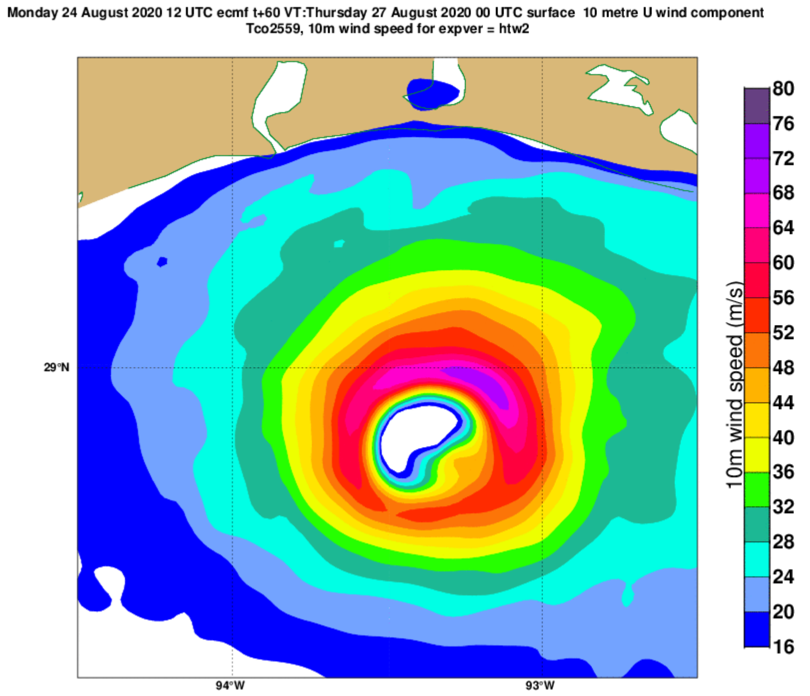
With benefit in tropical cyclone conditions, but also in more normal conditions in the tropics (Janssen and Bidlot 2018).
See also Magnusson et al. 2021, ECMWF Tech Memo 888.

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

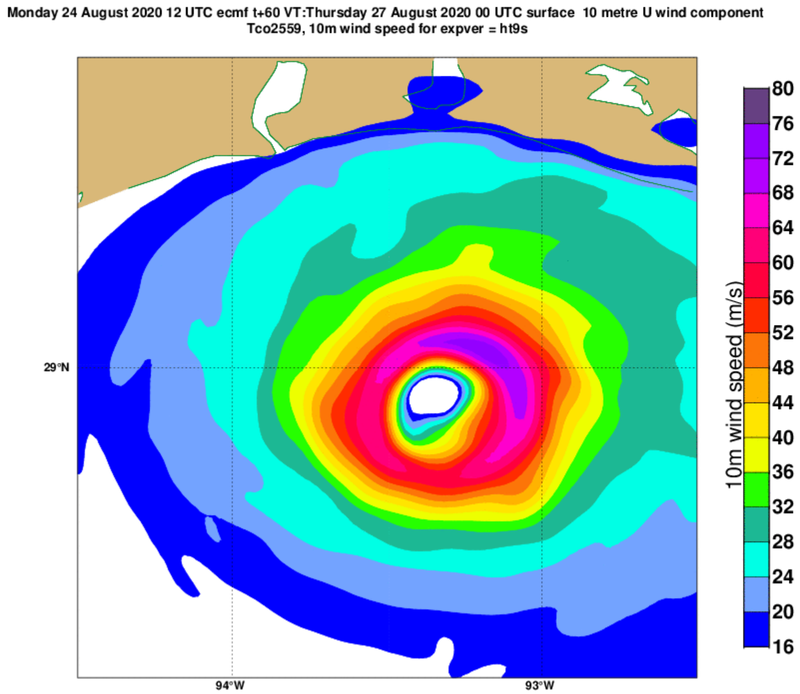


All contributions for CY49R1,
except the sea state heat and moisture

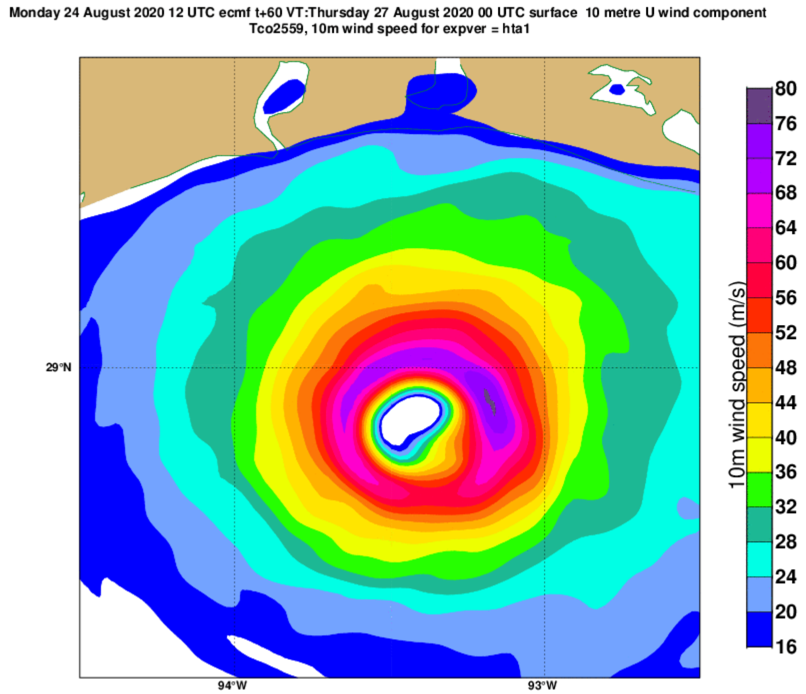
ECMWF

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

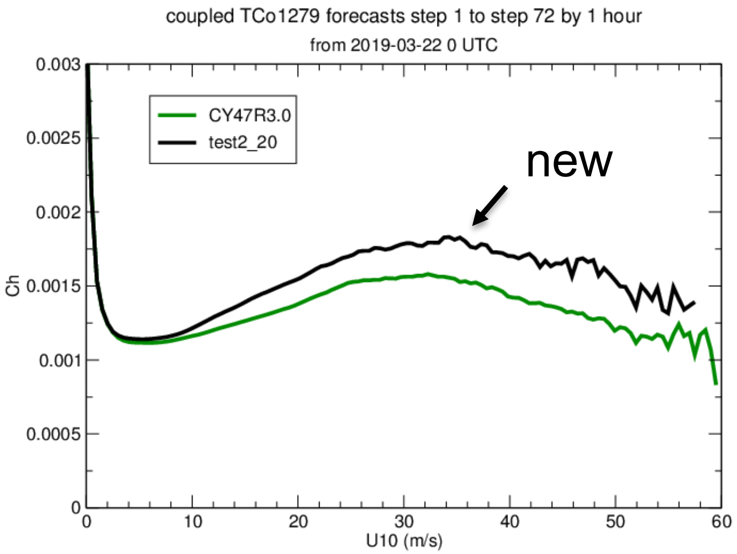
Medium range analysis + forecasts:
Expected impact of the sea state dependent heat and moisture fluxes

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

- 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:

Heat exchange coefficient:

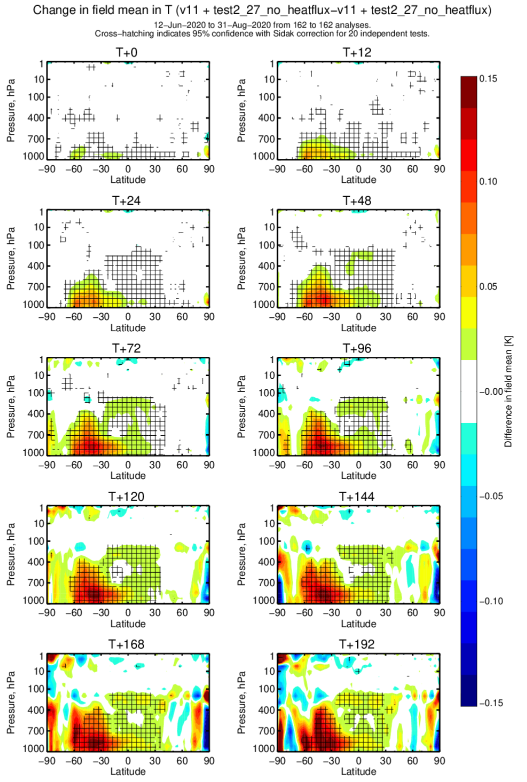
C_h



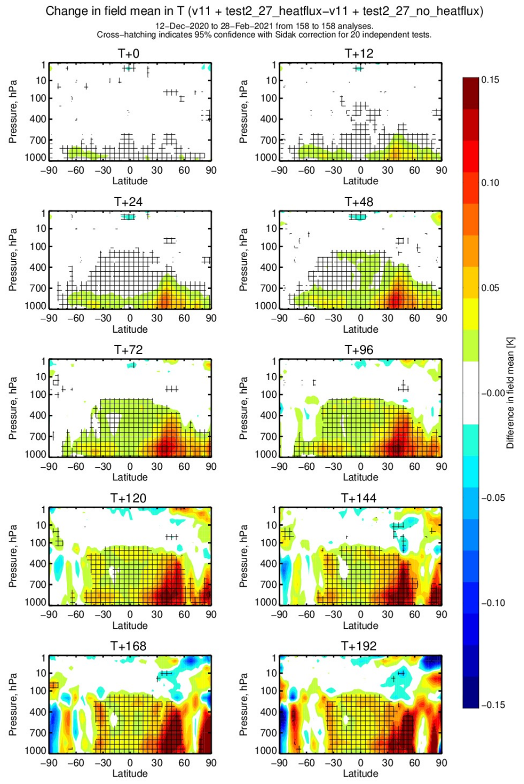
U10 (m/s)

Mean difference in Temperature

JJA



DJF

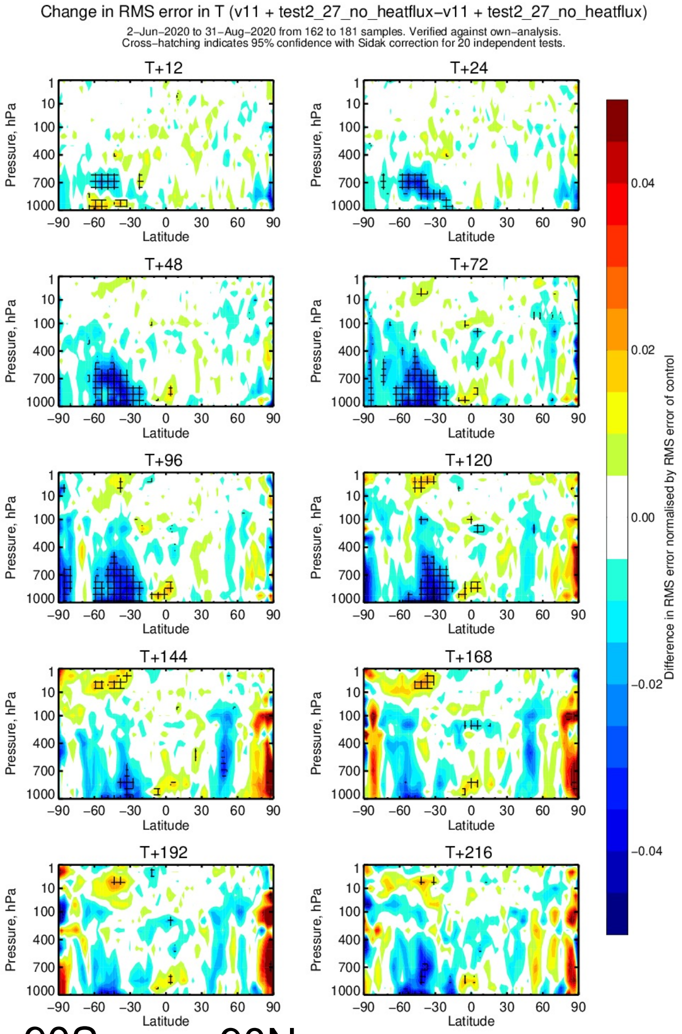


90S 90N

ECMWF

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

JJA 2020

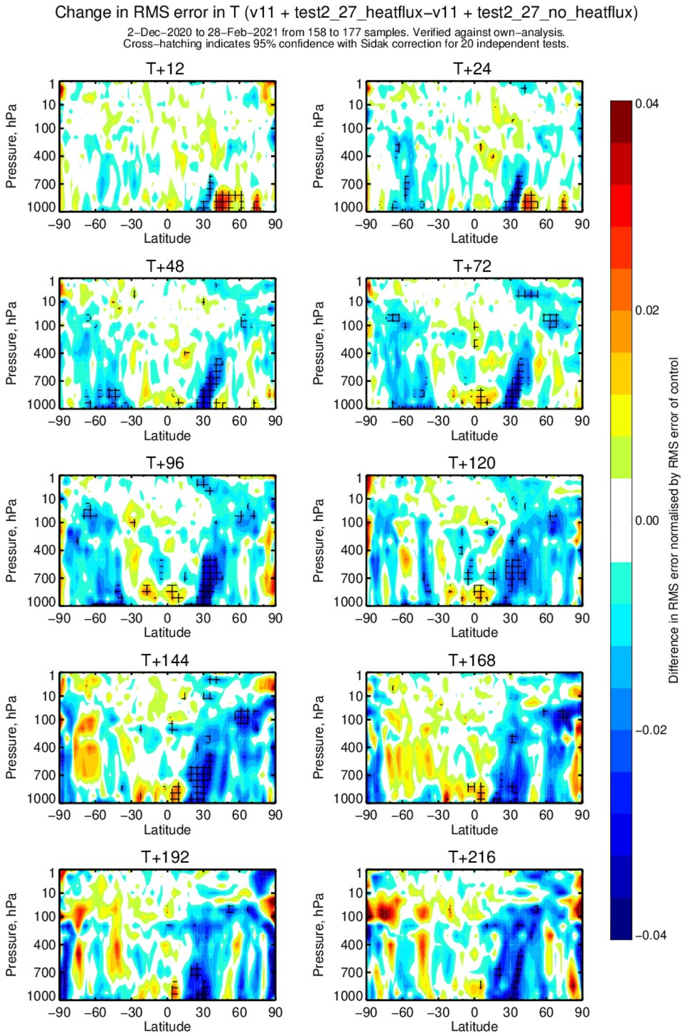


1 hPa

1000 hPa

90S 90N

DJF 2020-21



90S 90N

improvement

ECMWF

Analysis and forecast experiments at Tco399

4. Large waves affecting the southern coast of Victoria, April 2021

I am currently co-author on a paper which focuses on the analysis of a Southern Ocean storm.
The storm is estimated to be a 100-year Extra Tropical cyclone and, as such, it is a demanding test for global wave models under extreme extra-tropical storm conditions.
We carried out a few wave model simulations (hindcasts) forced with ERA5 hourly winds.

All simulations underestimate the extreme sea states from the storm generation phase throughout all of its development.

This is partly due to the negatively biased ERA5 wind speed, as shown by a comparison with the scatterometer and altimeter measurements.

There has been **many** developments since ERA5 and so I was curious to check how a more recent version would compare. It is based latest pre-operational model version soon to be implemented and the changes just described. These are the changes that will form the basis for the next reanalysis (ERA6)

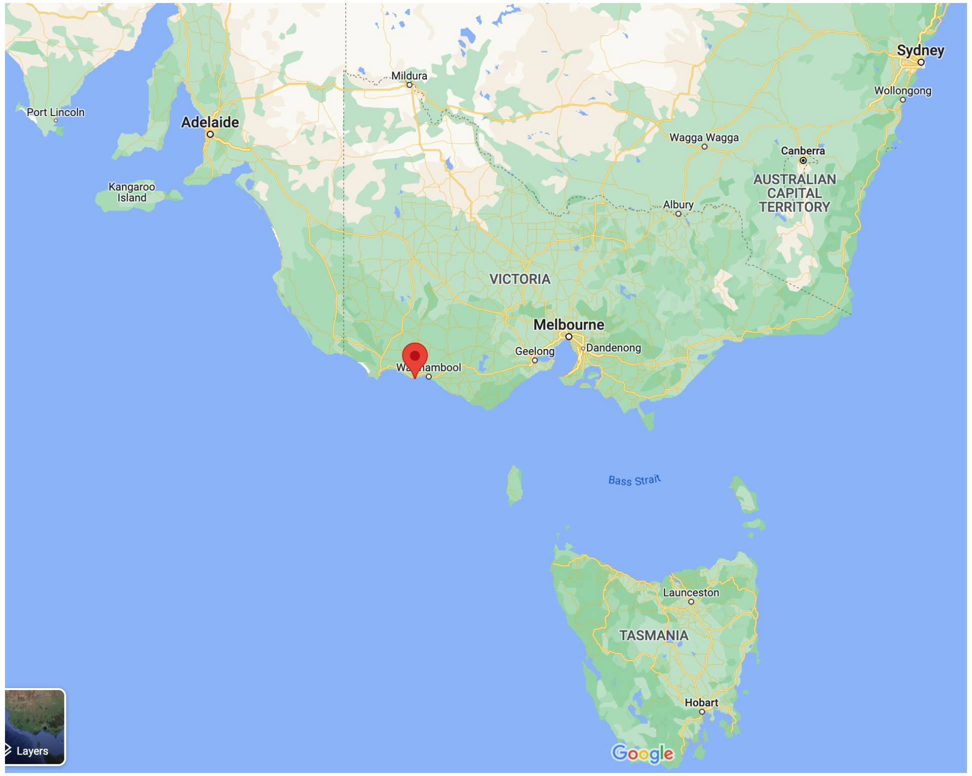
Based on a prototype configuration for ERA6:
I ran a 2-week analysis experiment (1-14 April 2021), at Tco799 (12 km)
The following is a quick analysis for the period of interest (8-10 April 2021)

Large waves affecting the southern coast of Victoria, April 2021

Big surf flips boulders across road in Port Fairy, reigniting climate change, coastal erosion concerns

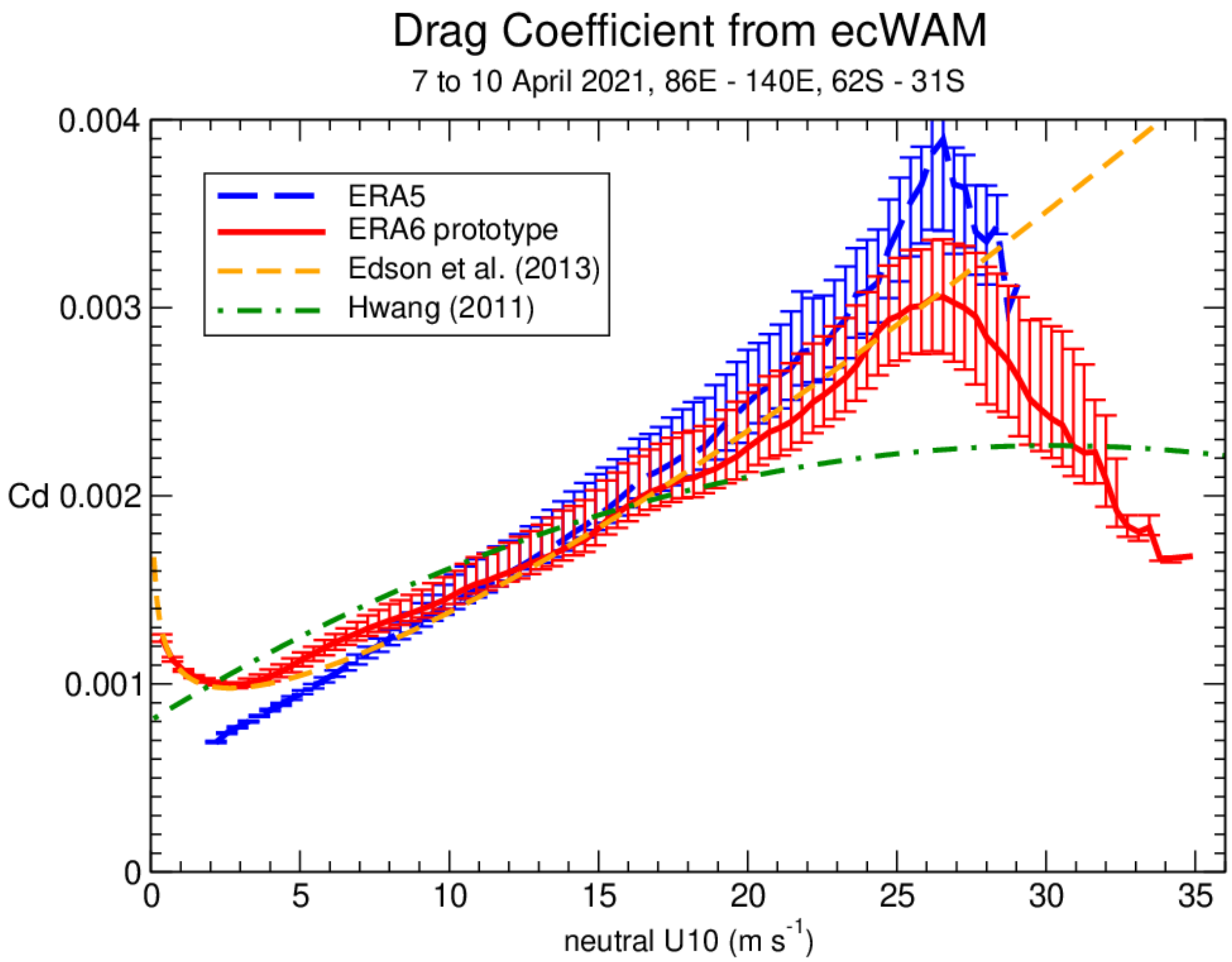
ABC South West Vic

Posted Mon 12 Apr 2021 at 9:20am Monday 12 Apr 2021 at 9:20am



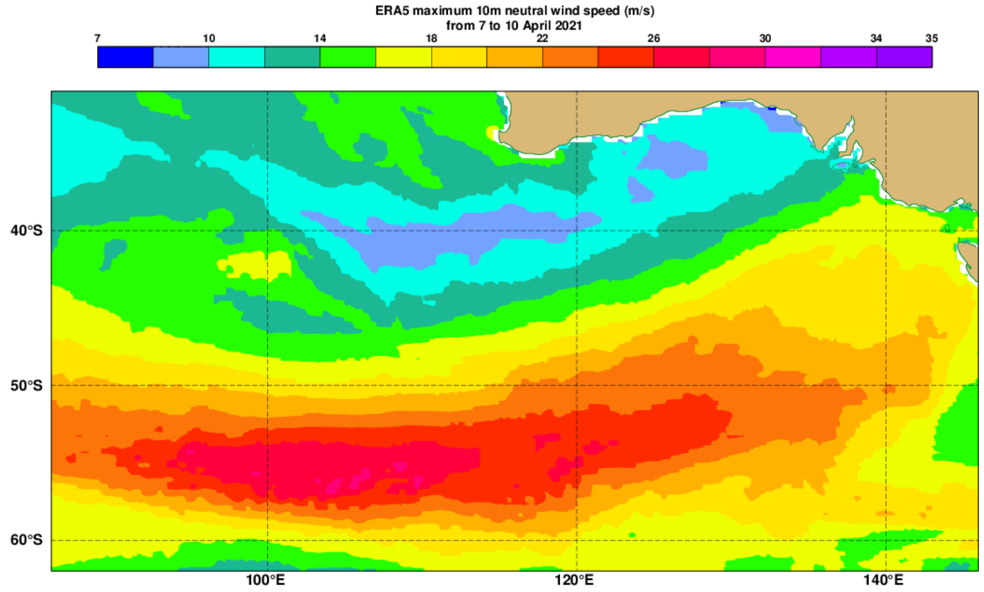
Huge rocks swept up to 30 metres from the seawall.
(Supplied: ABC Radio listener Graham)

Impact on surface drag coefficient used by ecWAM

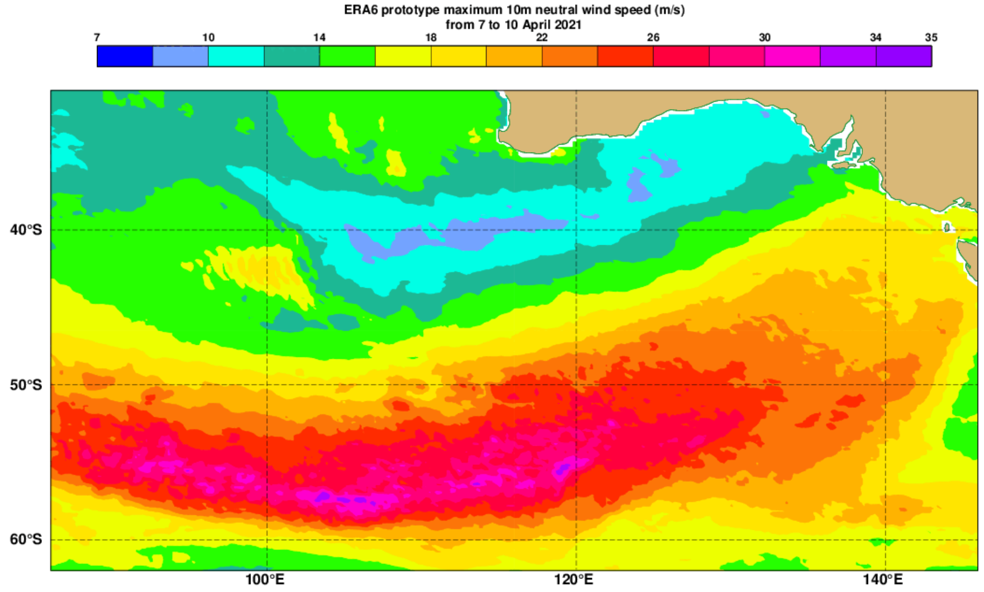


Impact on maximum surface wind speeds

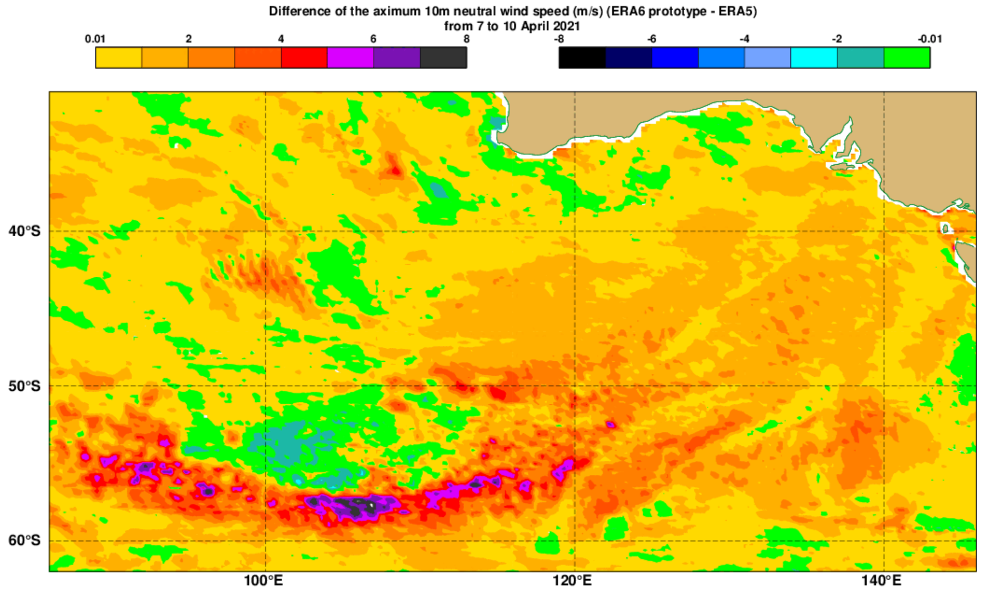
ERA5



ERA6P

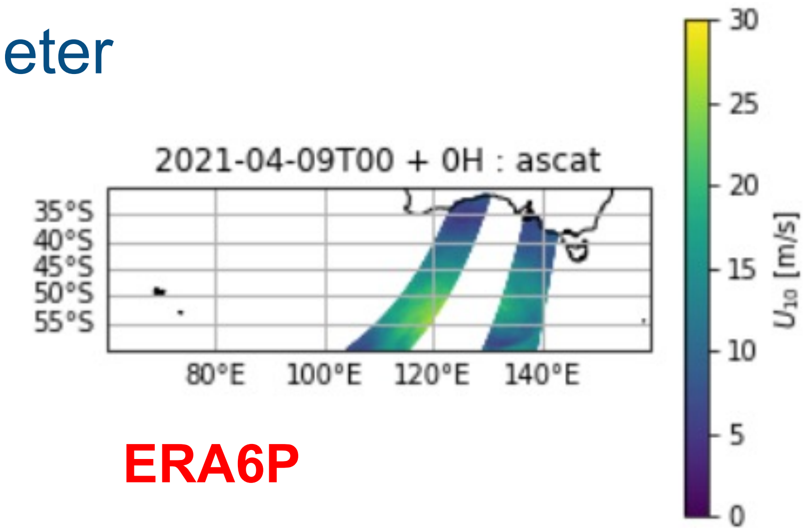


ERA6P - ERA5

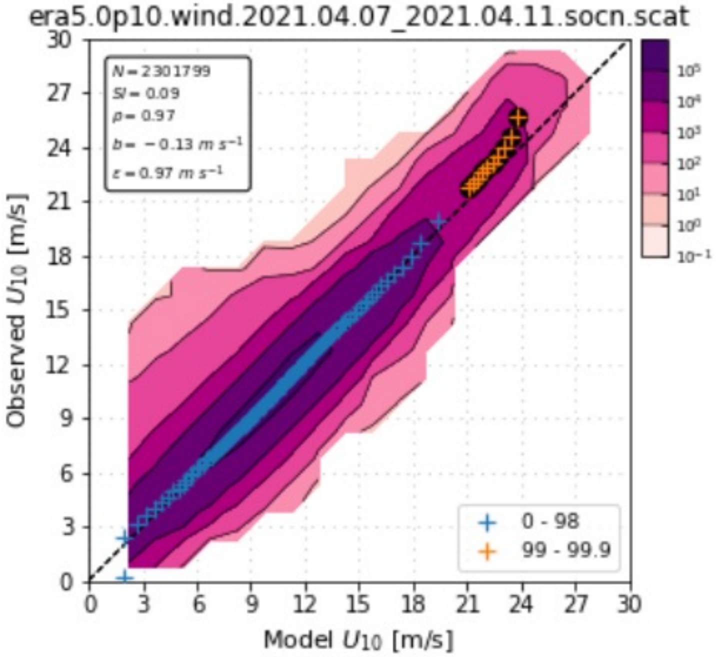


Comparison to scatterometer

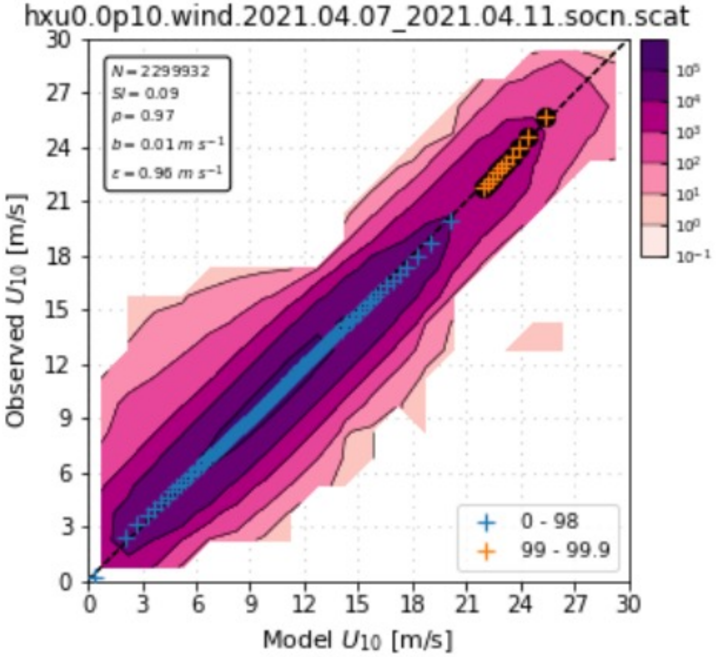
Hourly stepping from 2021-04-07T00:00 to 2021-04-12T00:00 for area :



ERA5



ERA6P

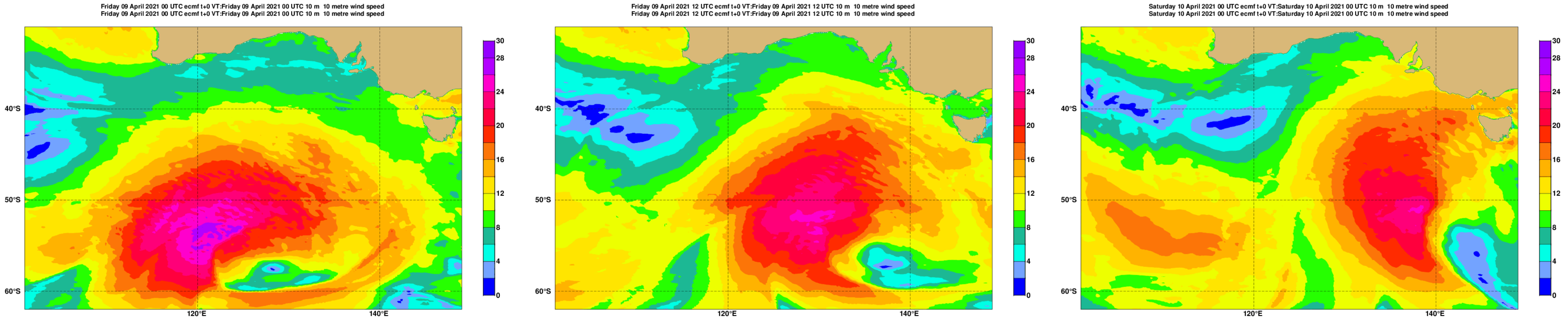


ECMWF

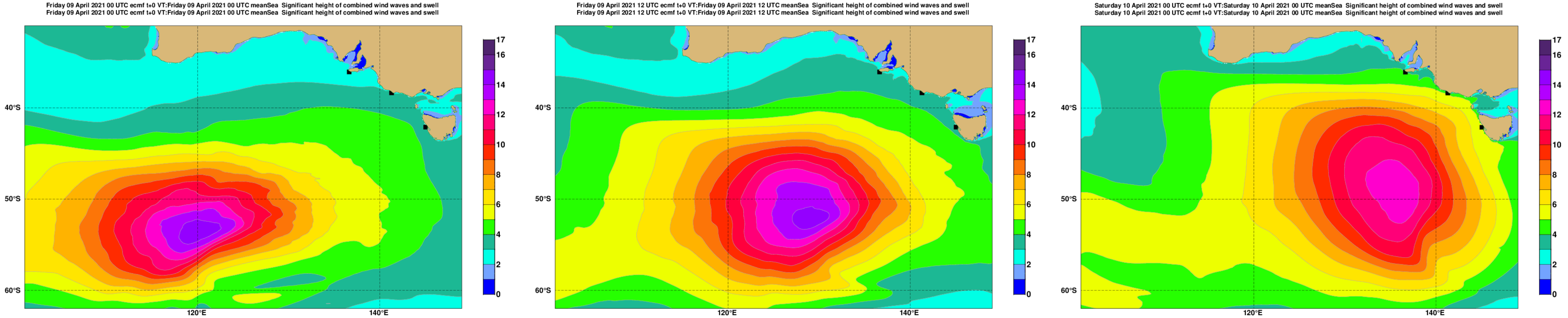
Effectively eliminated the negative wind bias for this extreme event
Extremes (Q99-99.9) notably better

Large waves affecting the southern coast of Victoria, April 2021

ERA6 prototype 10m wind speed(m/s)



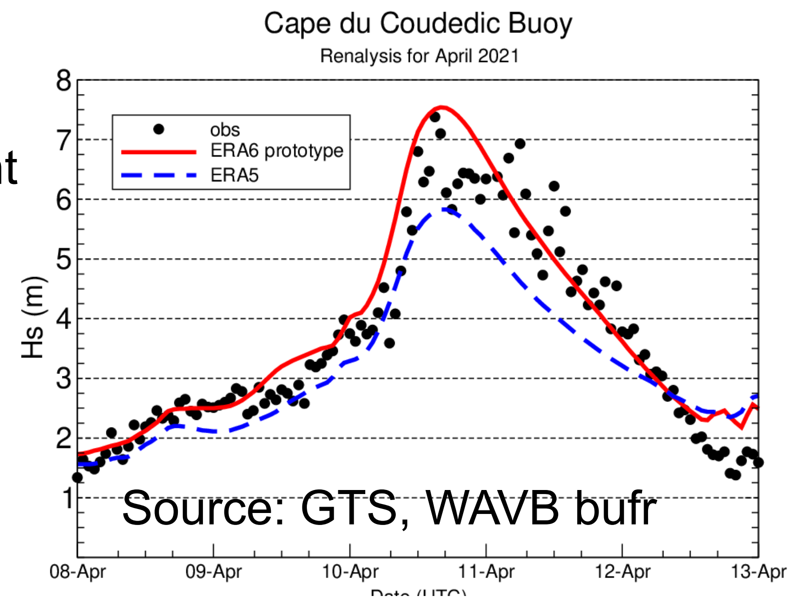
ERA6 prototype Significant wave height(m)

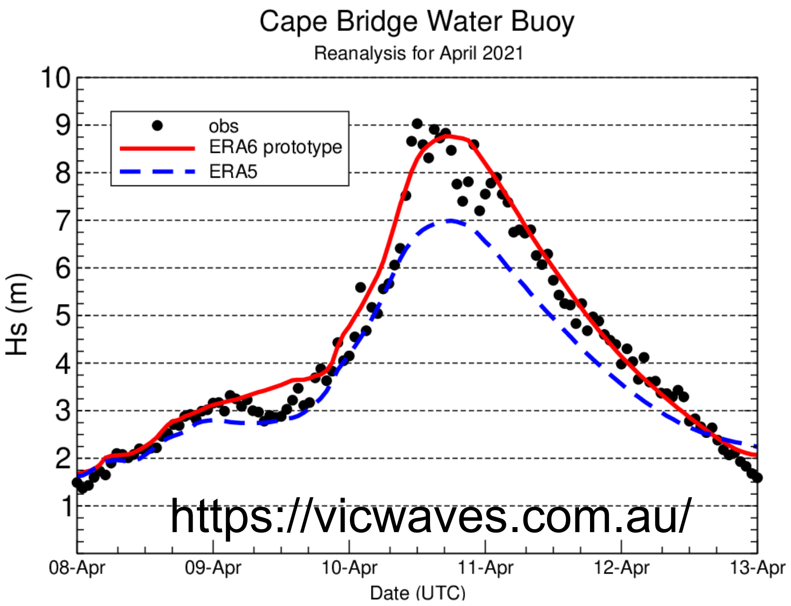


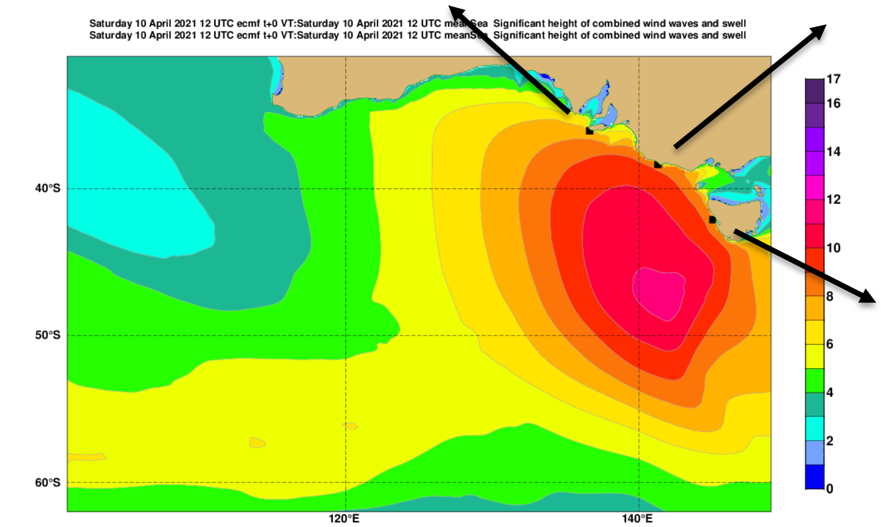
9 April 2021, 0 UTC | 9 April 2021, 12 UTC | 10 April 2021, 0 UTC

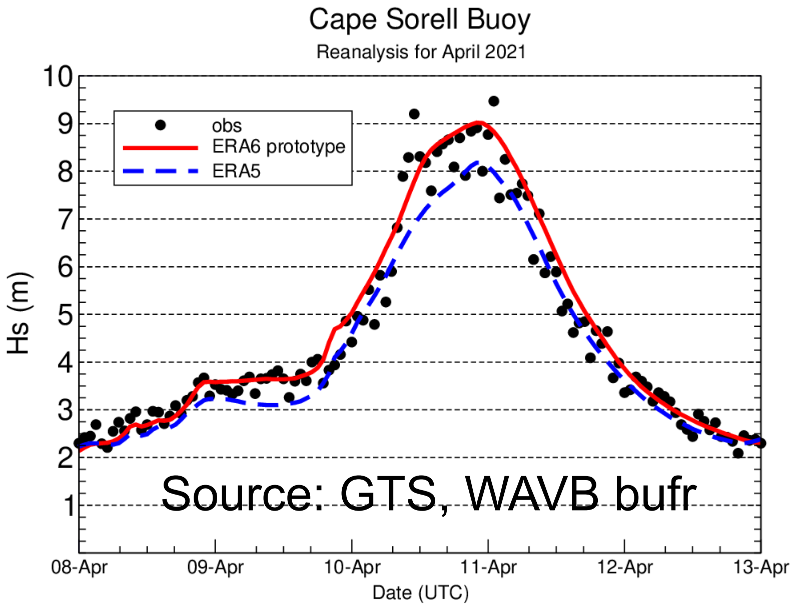
Large waves affecting the southern coast of Victoria, April 2021

Significant wave height from buoys









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.
- ERA6 should have better surface winds than ERA5.

Questions ?

- **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.**

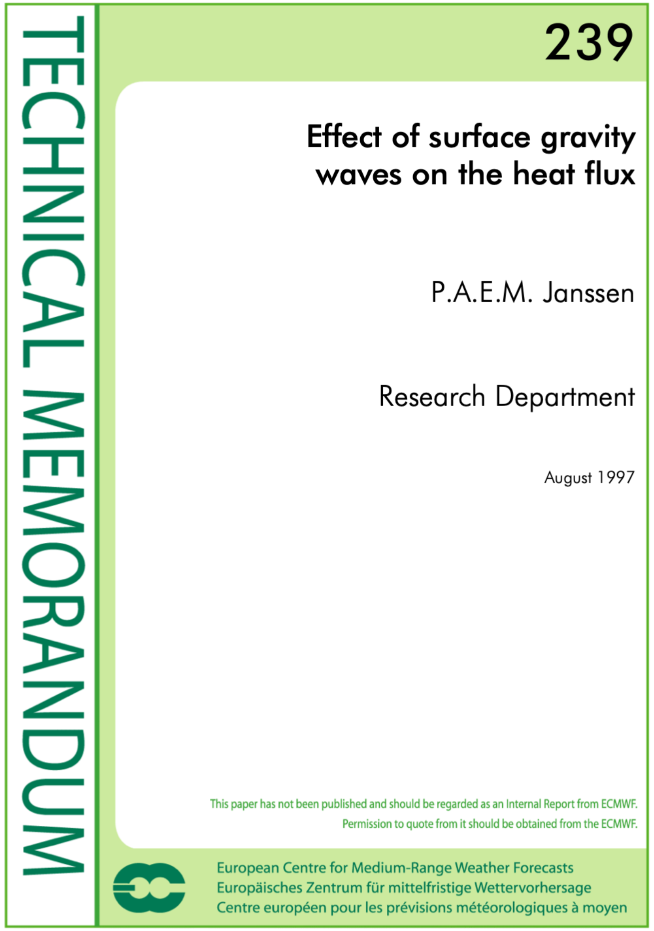
$$z_T = 10\,\frac{\left(\frac{10+x_-}{x_-}\right)^{(z_1-x_-)}}{\left(\frac{10+x_+}{x_+}\right)^{(z_1-x_+)}}$$

$$x_\pm = (z_1 + \tfrac{1}{2} z_\nu) \mp \{z_1^2 + (\tfrac{1}{2} z_\nu)^2\}^{1/2}$$

$$z_1 = \frac{u_*^2}{g}(\alpha - \tilde{\alpha}) \qquad z_\nu = \frac{\delta\nu}{\kappa u_*}$$

α Sea State dependent Charnock

$\tilde{\alpha}$ Background roughness Charnock



TECHNICAL MEMORANDUM

239

Effect of surface gravity waves on the heat flux

P.A.E.M. Janssen

Research Department

August 1997

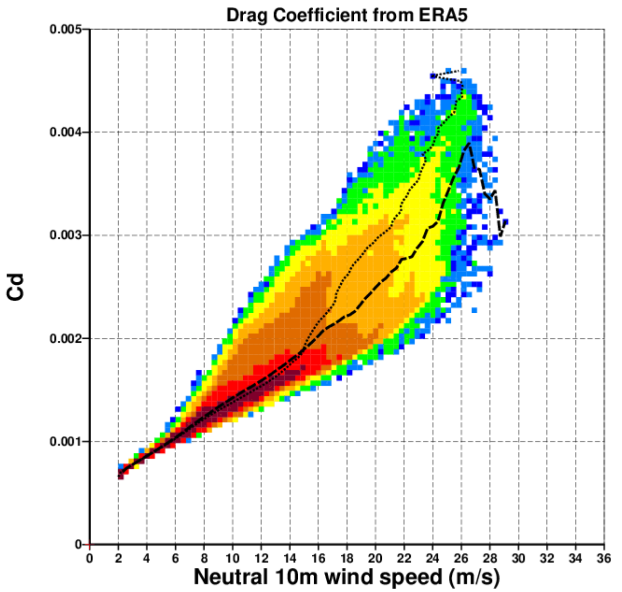
This paper has not been published and should be regarded as an Internal Report from ECMWF.
Permission to quote from it should be obtained from the ECMWF.

European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen

See also :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

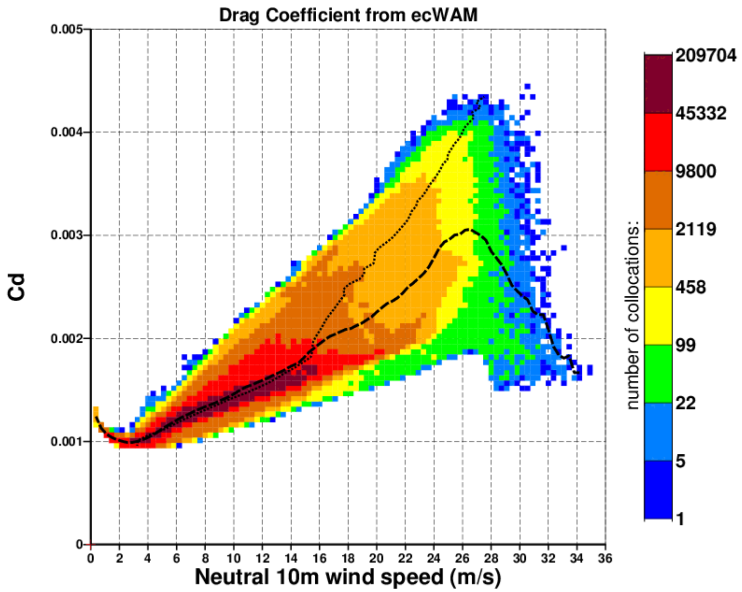
Impact on surface drag coefficient used by ecWAM

ERA5



Analysis data from stream wave, class ea, expver 0001, all ecWAM sea points
from 20210407 to 20210410 for subarea -31/86/-62/140

ERA6P



Analysis data from stream wave, class rd, expver hxu0, all ecWAM sea points
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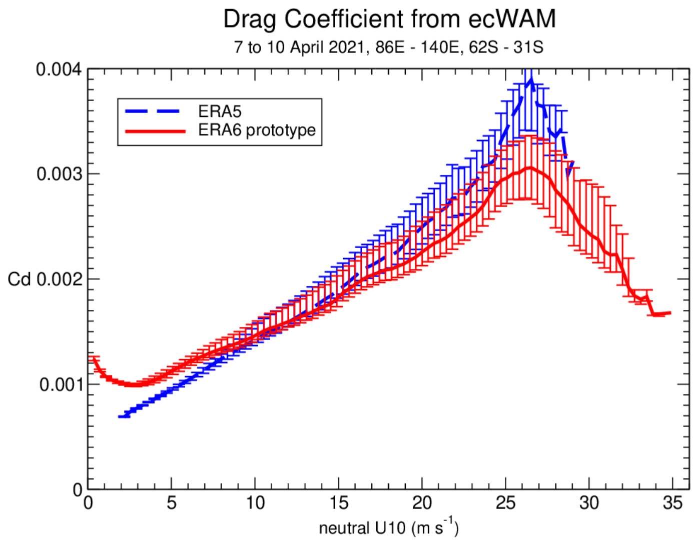

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Peter A.E.M.Janssen and Jean-Raymond Bidlot, 2021. ECMWF Technical Memorandum 882.
https://www.ecmwf.int/en/elibrary/19943-consequences-nonlinearity-and-gravity-capillary-waves-wind-wave-interaction
A paper has been accepted for publication JPO (proofs are back with the editor).

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.