Ocean wave effects in NEMO4

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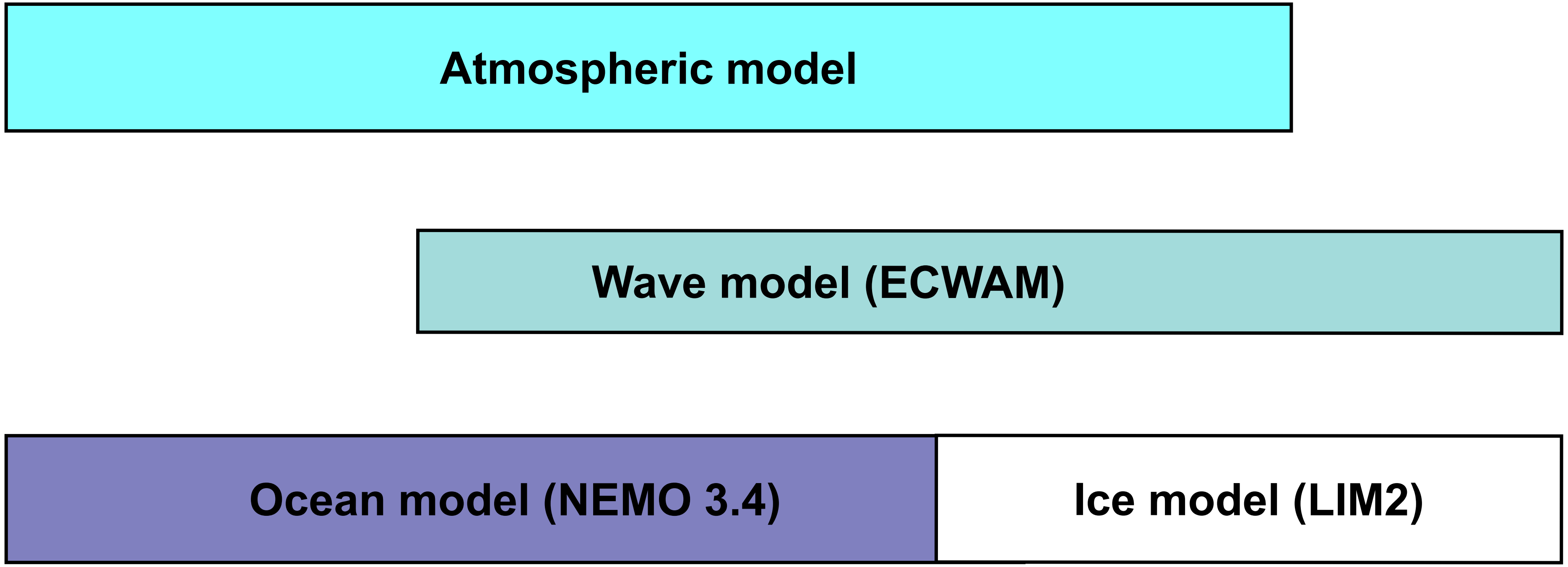
Outline

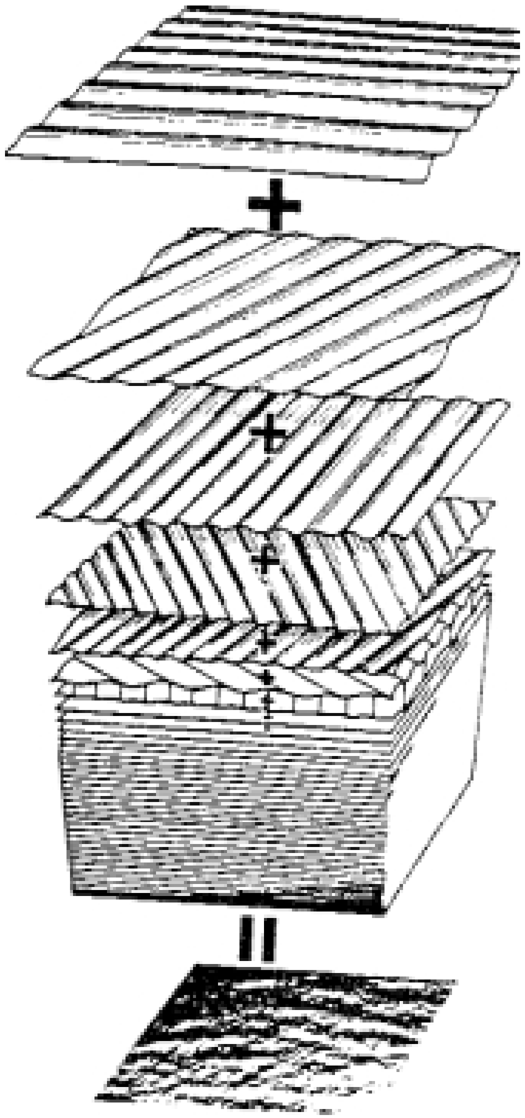
- Introduction.
  - ECMWF Earth System Model.
  - Wave effects in ECMWF Earth System Model.
- Wave effects in forced NEMO4 runs.

ECMWF Earth System Model



Operational system

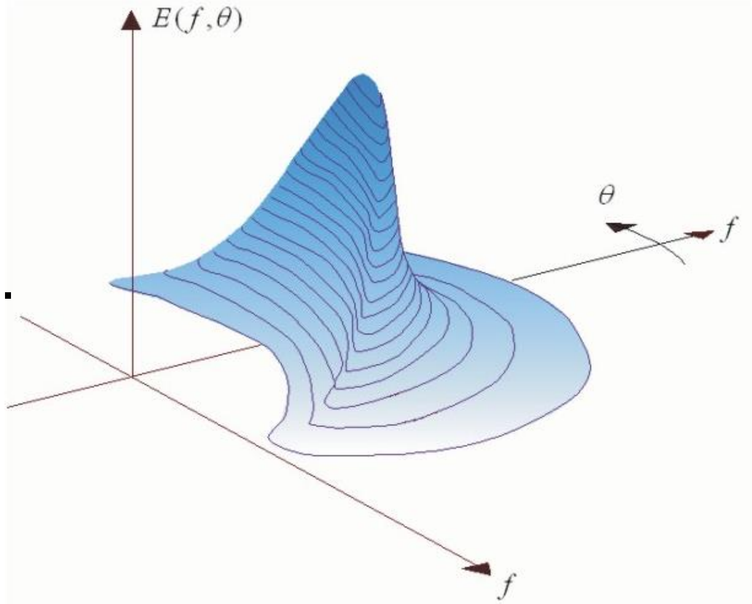
Ocean Wave Modelling: Wave Spectrum



The irregular water surface can be decomposed into a number of simple sinusoidal components with different frequencies (f) and propagation directions (θ).

The distribution of wave energy among those components is called: "wave energy spectrum", $\rho_w\, g\; F(f,\theta)$.

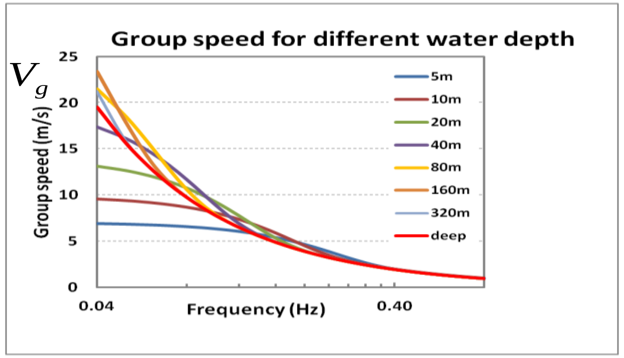
water density: ρ_w and gravity: g



Ocean Wave Model

The 2-D spectrum follows from the energy balance equation (in its simplest form: deep water case, no surface currents):

$$\frac{\partial F}{\partial t} + \vec{V}_g \cdot \nabla F = S_{in} + S_{nl} + S_{diss}$$



where

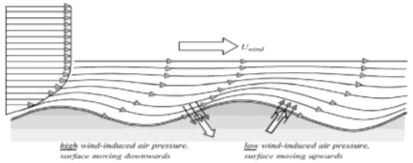


Figure 6.16 The wave-induced wind-pressure variation over a propagating harmonic wave.

the wave grows by this mechanism, the mechanism become
the wave can therefore grow faster, which in turn makes the m
effective, etc.

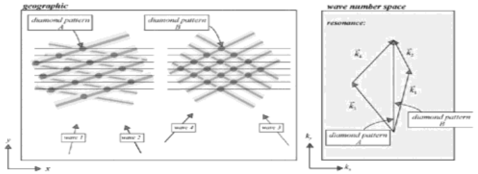


Figure 6.20 *Quadruplet* wave–wave interactions (realisable in deep water). Two pairs of wave components can create two diamond patterns with identical wave lengths and directions and therefore identical wave numbers. When the four waves are superimposed (not shown here), they can thus resonate. The wave-number vectors of the four wave components are shown in the right-hand panel in wave-number space with $\vec{k}_1 + \vec{k}_2 = \vec{k}_3 + \vec{k}_4$.

S_{in}: wind input source term (generation).

S_{nl}: non-linear 4-wave interaction (redistribution).

S_{diss}: dissipation term due to whitecapping (dissipation).

Atmosphere<-> ocean wave system

Simplified view of the operational systems

Atmospheric model

Neutral wind (Every IFS time step)

Roughness

Wave model (ECWAM)

$$\tau = \rho_a u_*^2$$

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

Every
IFS
time step

Charnock relation

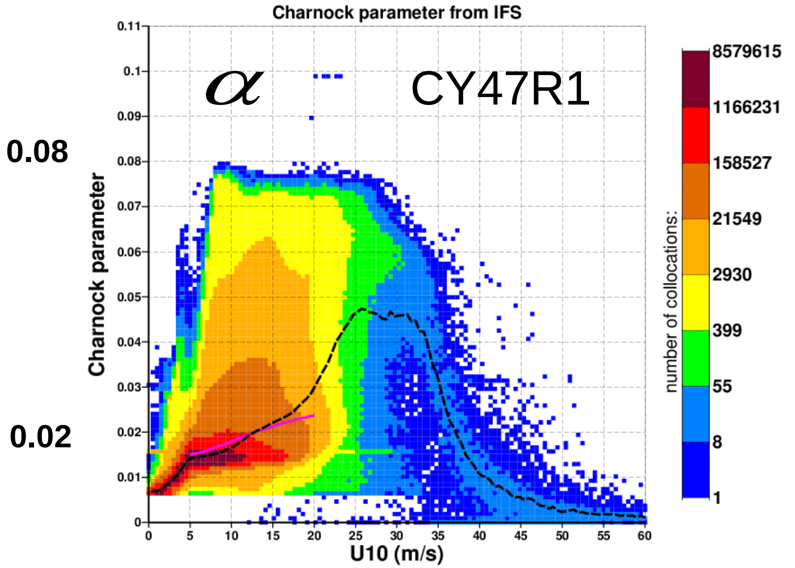
$$z_0 = \frac{\alpha u_*^2}{g}$$

All configurations

Since **1998**

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

$$\tau_w = \frac{\rho_w}{\rho_a} g \int d\omega \, d\theta \, \frac{1}{c} S_{in}$$

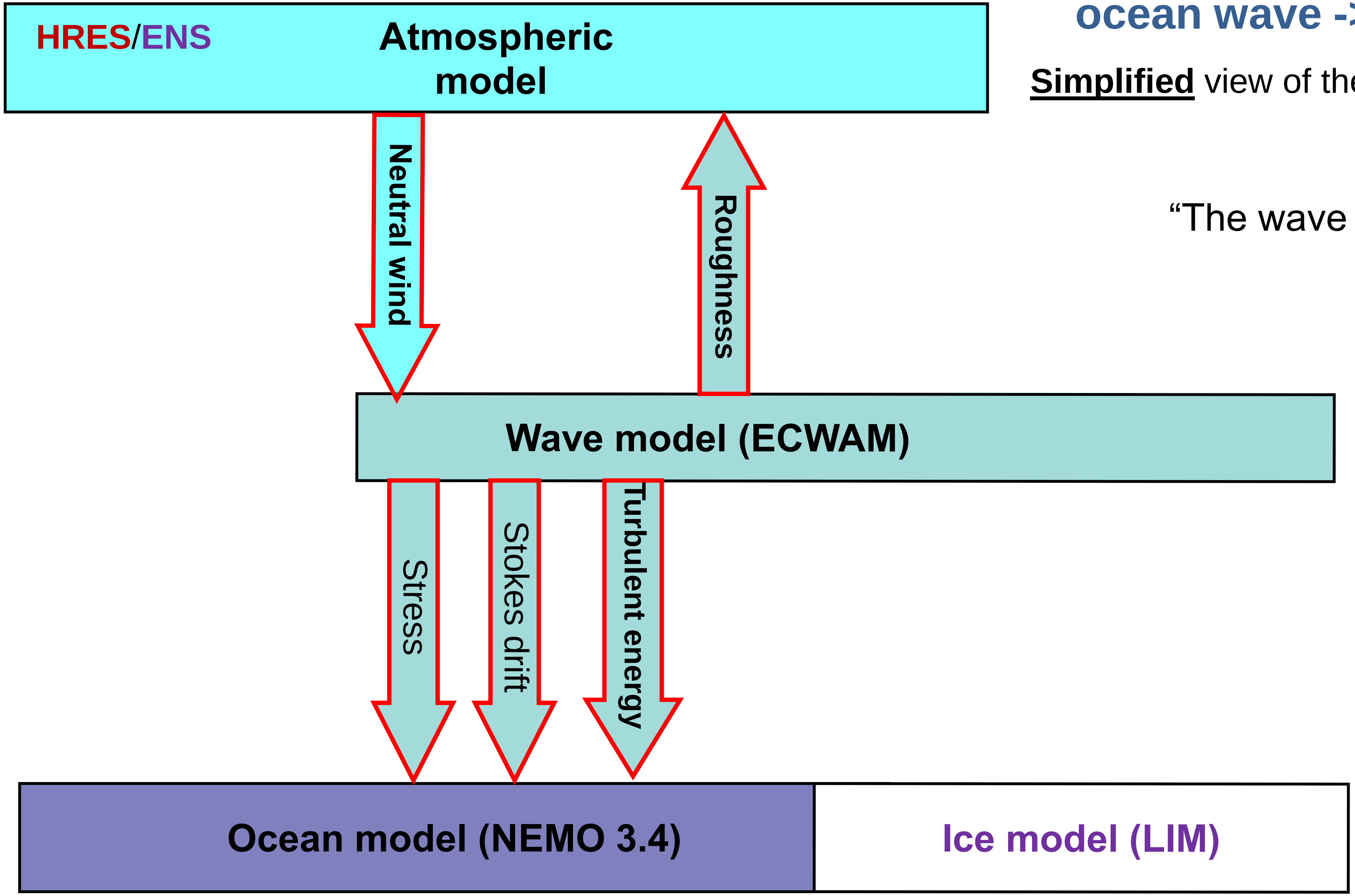


Forecast data from stream da, class rd, expver hex2, all Sea points with sea ice cover <= 0.3
from 20190322 0UTC, for steps from 1 to 72 by 1

ocean wave -> ocean system

Simplified view of the operational systems

“The wave forcing”



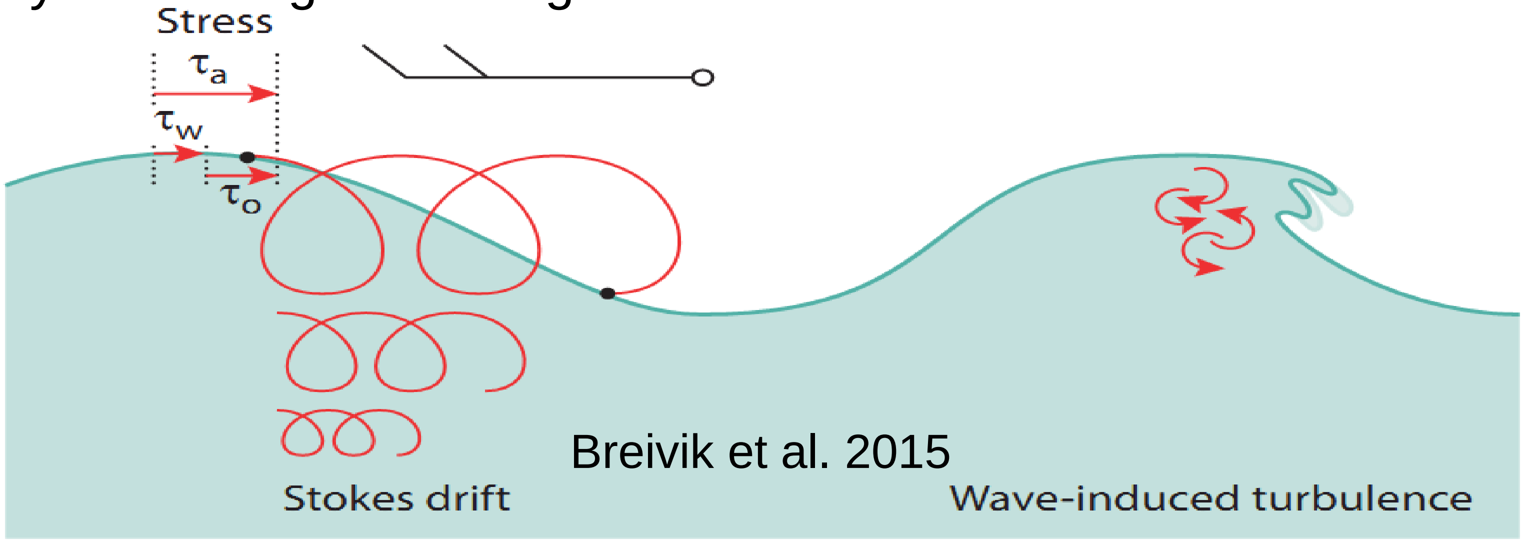
ORCA025_Z75

Direct Wave effects in NEMO

Stress: As waves grow under the influence of the wind, the waves absorb momentum (τ_w) which otherwise would have gone directly into the ocean (τ_o) .

Stokes drift forcing: The Stokes drift sets up a current in the along-wave direction. Near the surface it can be substantial (~1m/s). The Coriolis effect works on the Stokes drift and adds a new term to the momentum equations. Its effect should also be added to the tracer advection and vertical motion via the divergence term (*)

Mixing: As waves break , turbulent kinetic energy is injected into the ocean mixed layer, significantly enhancing the mixing.

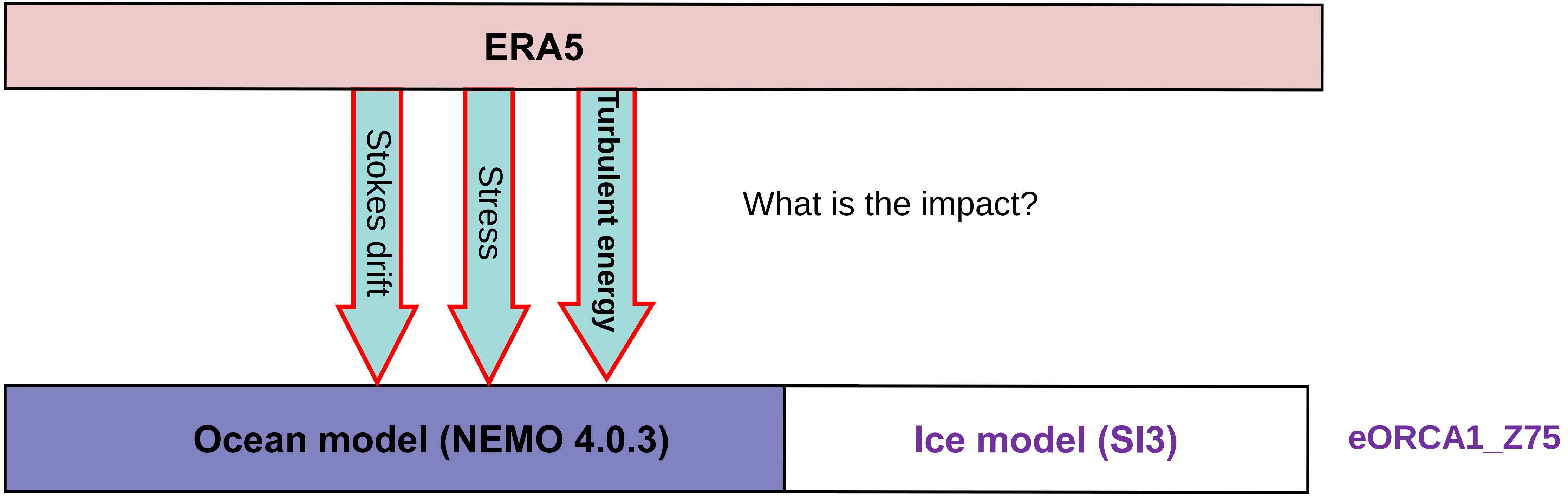


(*) these 2 latter effects were not implemented in the current operational system but are default in NEMO4

ECWMF is working towards using NEMO4

The new NEMO4 has now been available for a while.
ECWMF is committed to replace its old 3.4 version with it.
This is a substantial piece of work!
Before testing it in the fully coupled system, ‘simpler’ experimentations in forced mode have been carried out, to lead the way to further coupled experimentations and ocean analysis/reanalysis developments.

We are reporting here on the impact of the wave forcing on version 4.0.3, with the 1° configuration eORCA1, using hourly ERA5 data from 1979 to 2016. Results shown for 1992-2016.

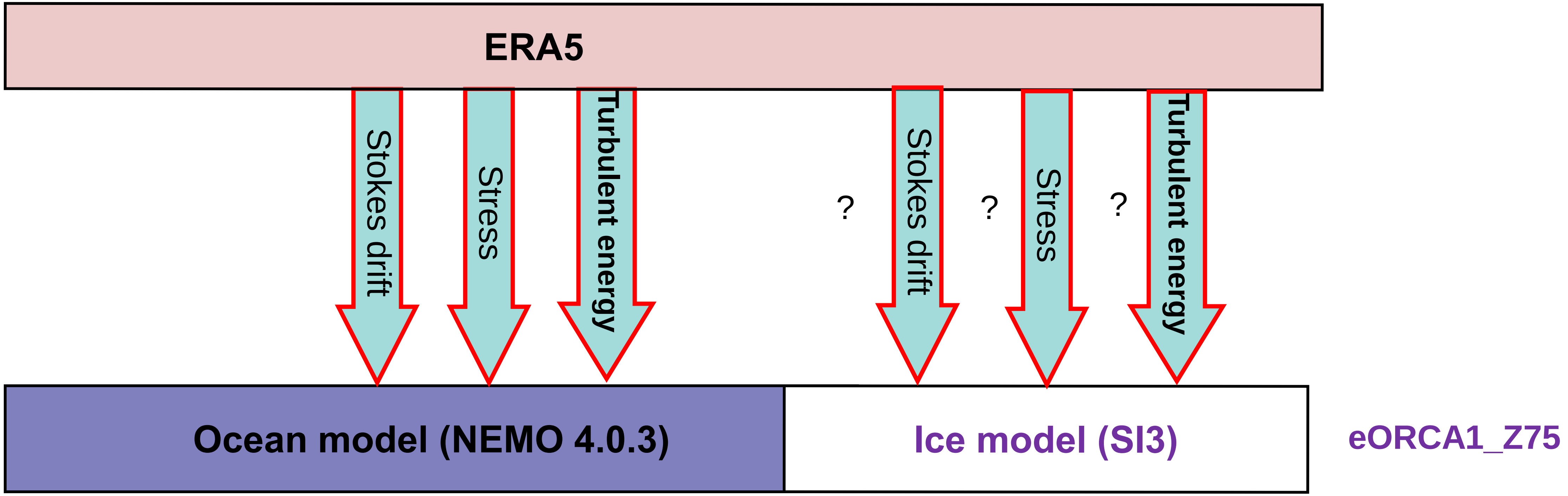


Note: Wave effects over sea ice in forced NEMO4 runs

ERA5, does not have any meaningful wave information over sea ice because all wave fields are set to missing when ERA5 sea ice cover > 30%.

Adequate choices were made to revert to values of the forcing that would be consistent with the no wave forcing case.

Assessing the impact of wave forcing, first in forced mode, using hourly ERA5 data



Stokes drift in NEMO4

The Stokes drift effects are available by default in NEMO4.

The Coriolis effect works on the Stokes drift and adds a new term to the momentum equations.
Its effect was also added to the tracer advection equation and vertical motion via the divergence term.

ERA5

Wave input fields :

Us(0), Vs(0),
Hs, T_{10}

Stokes drift

$$\mathbf{u}_s(z) = 4\pi \int_0^{2\pi} \int_0^{\infty} f\mathbf{k}e^{2kz} F(f,\theta)\, df d\theta$$

$U_s(z)$ vertical profile approximated using Breivik et al. 2016, using Us(0), Vs(0), the significant wave height Hs, the mean wave period T_{10}

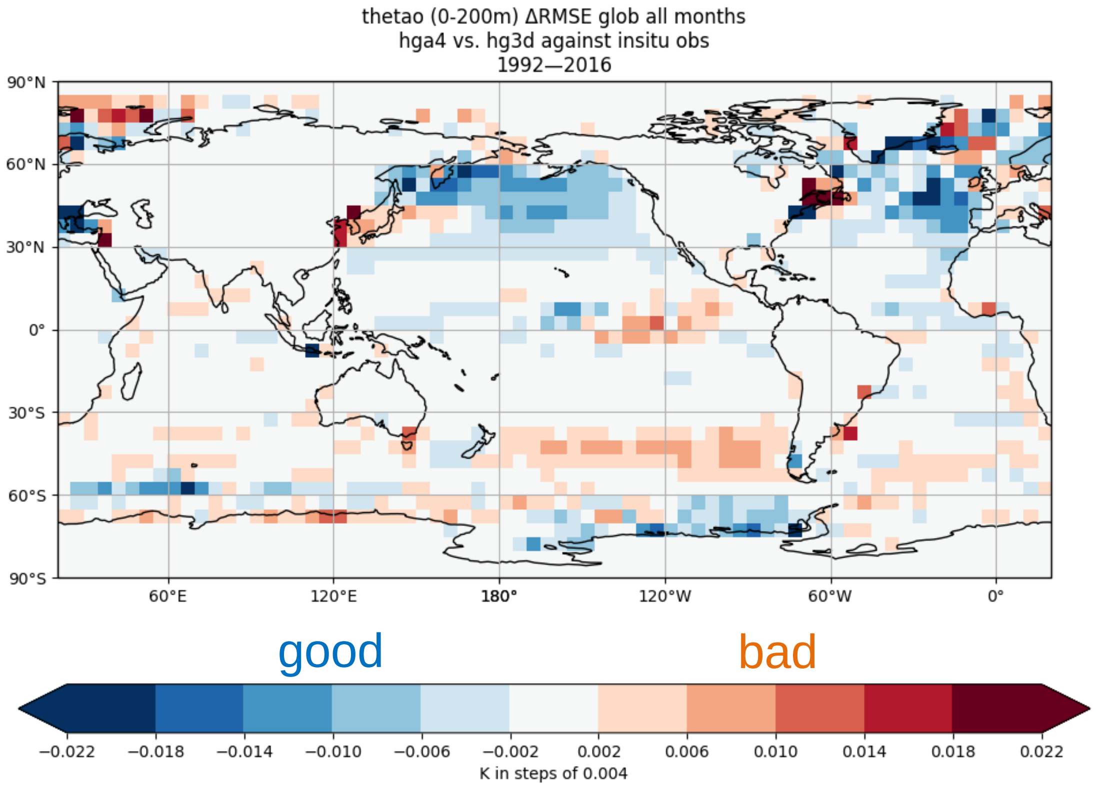
Ocean model (NEMO 4.0.3)

Ice model (SI3)

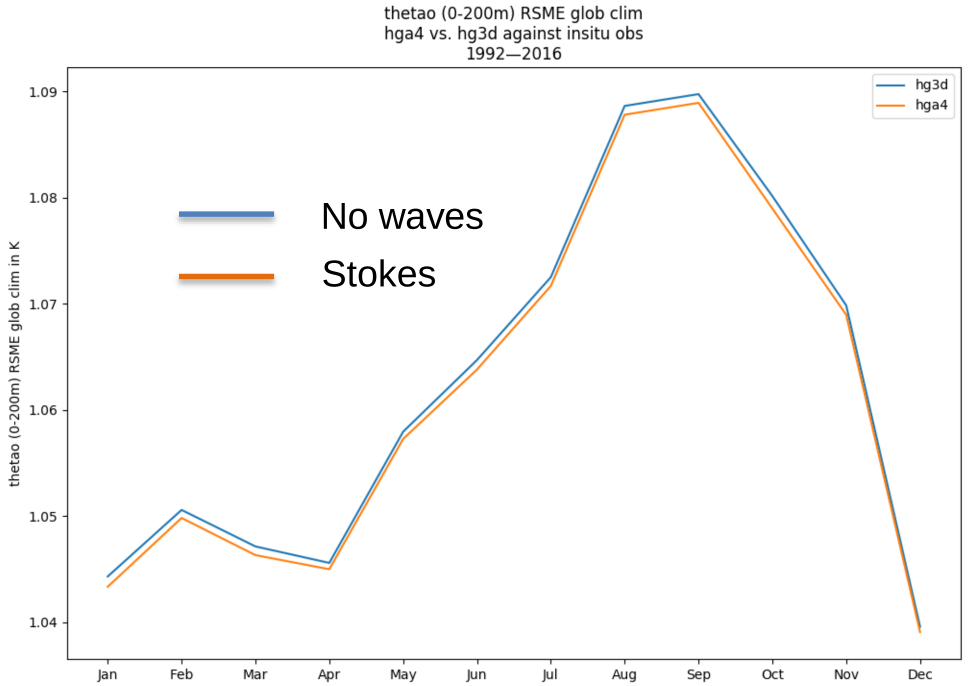
eORCA1_Z75

Stokes drift in NEMO4

Comparison to ocean temperature observations (EN4) in the upper 200m, 1992-2016



Difference in RMSE



RMSE

Momentum, heat and mass fluxes in NEMO4

With NEMO4, we use the new AeroBulk parameterisation for the prescription of fluxes for momentum, heat and moisture. This parameterisation is based on the one used by ECMWF.
As implemented in NEMO4, it uses a fixed Charnock coefficient in an iterative process to find the atmospheric surface stress in the presence of surface current (*).
We have modified NEMO4 to use the wave dependent Charnock coefficient that can be recover from ERA5 data.
Using a frozen drag coefficient from the wave model is not consistent with the bulk formula !
The atmospheric stress Ta is then modulated by the balance between the momentum flux into the wave and and the flux back into the ocean due to wave breaking to yield Toc

ERA5

Wave input fields :

Charnock

$\frac{\tau_{oc}}{\tau_a}$

Stress

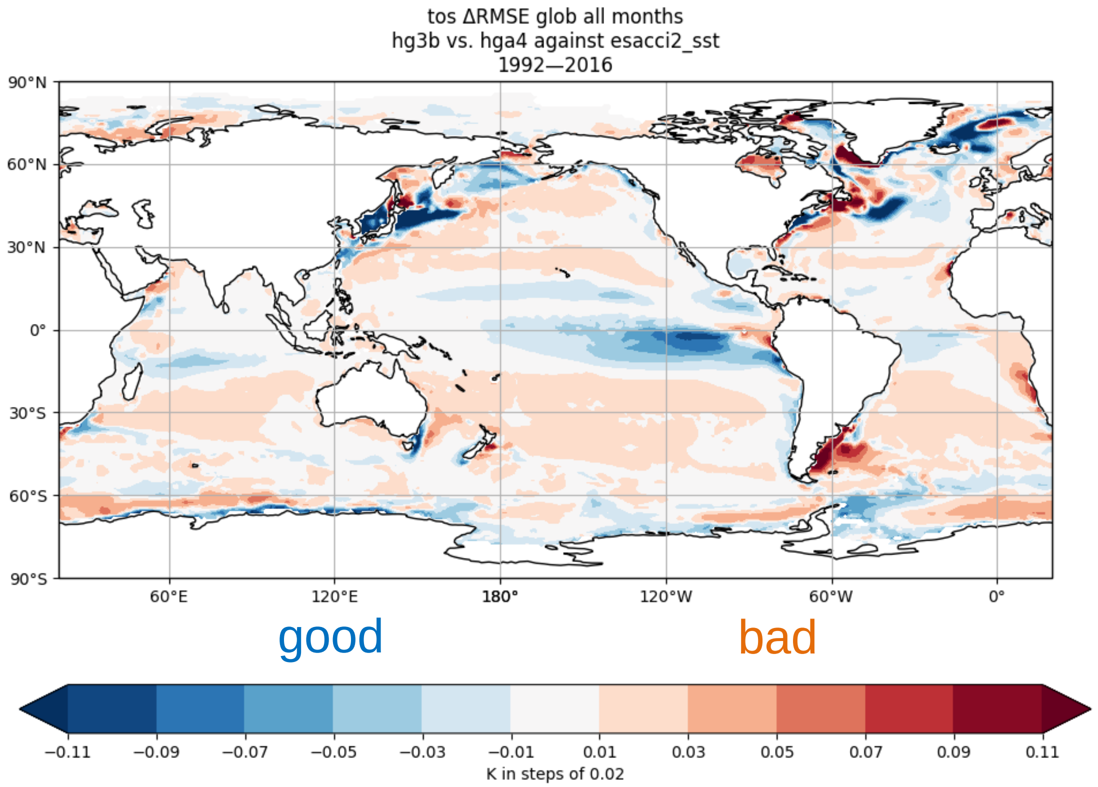
$$\tau_{oc} = \tau_a - \rho_w g \int_0^{2\pi} \int_0^{\infty} \frac{\mathbf{k}}{\omega} (S_{in} + S_{ds}) \, d\omega \, d\theta.$$

(*) we currently use ½ of the surface current for the relative winds

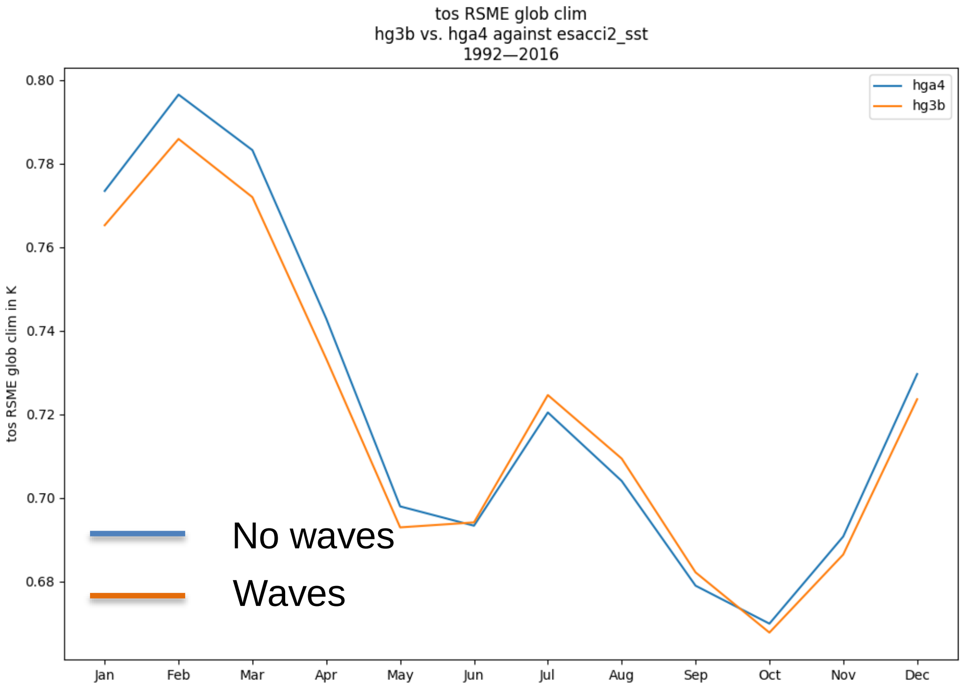
Ocean model (NEMO 4.0.3) | **Ice model (SI3)** | **eORCA1_Z75**

Momentum, heat and mass fluxes in NEMO4

Comparison to Sea Surface Temperature observations (ESACCI2), 1992-2016



Difference in RMSE

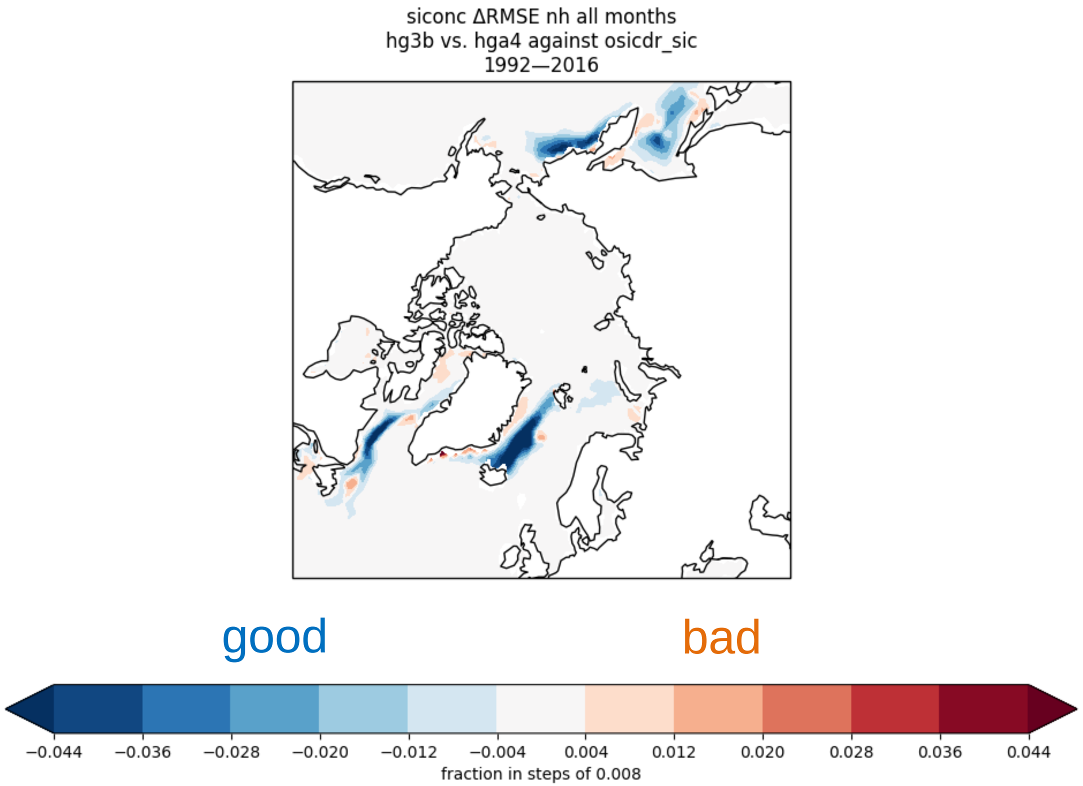


RMSE

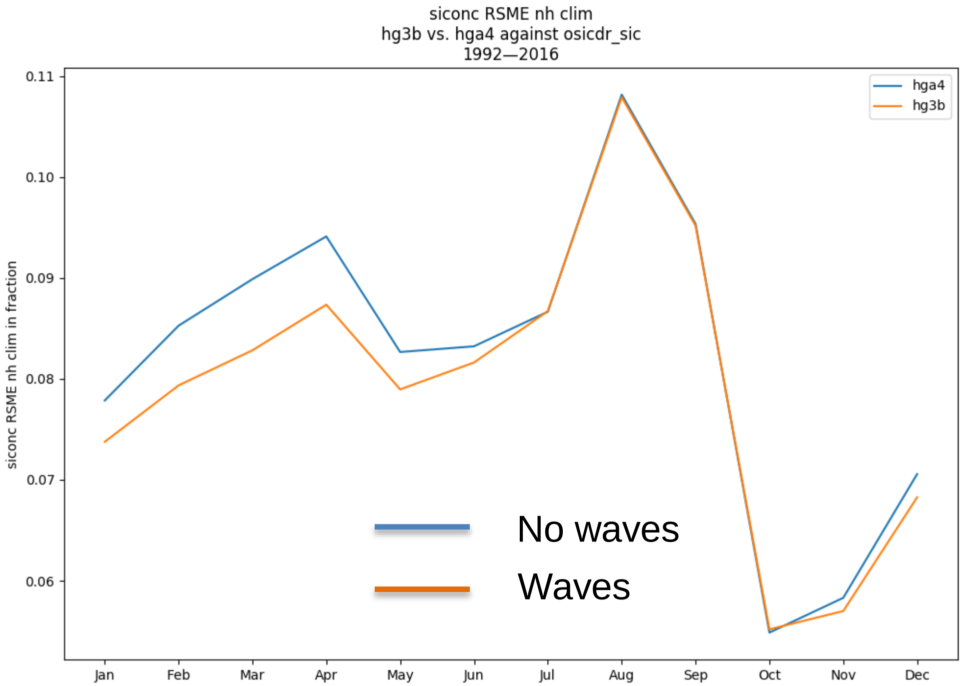
ECMWF

Momentum, heat and mass fluxes in NEMO4

Comparison to Sea Ice Cover observations (OSICDR), 1992-2016



Difference in RMSE

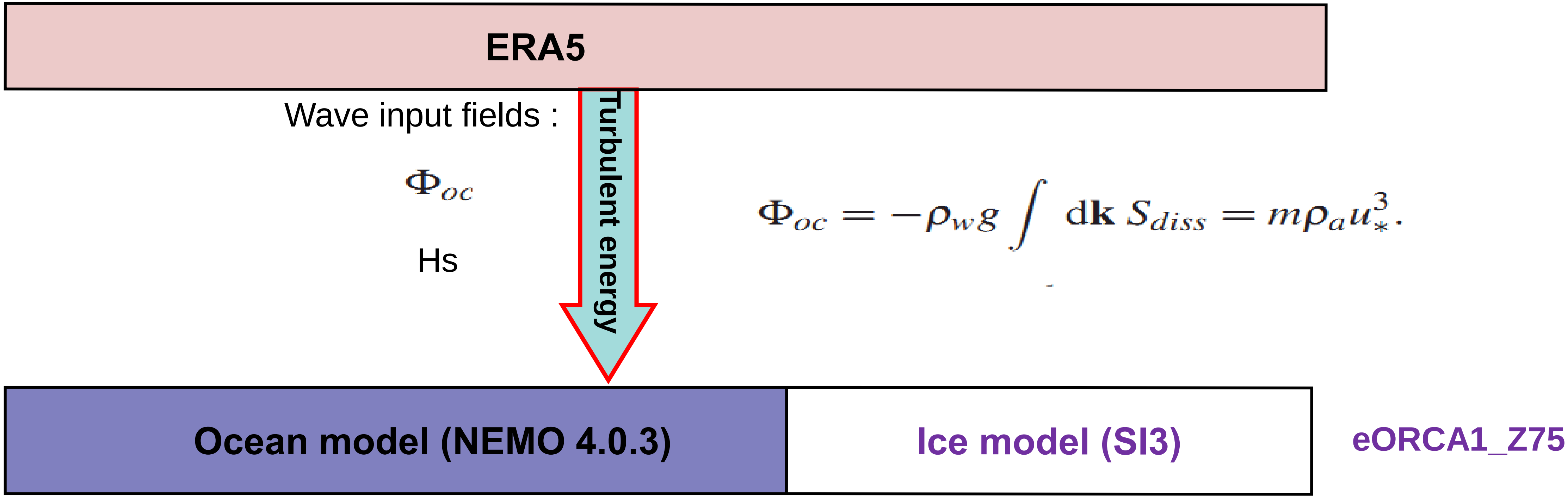


RMSE

ECMWF

TKE flux in NEMO4

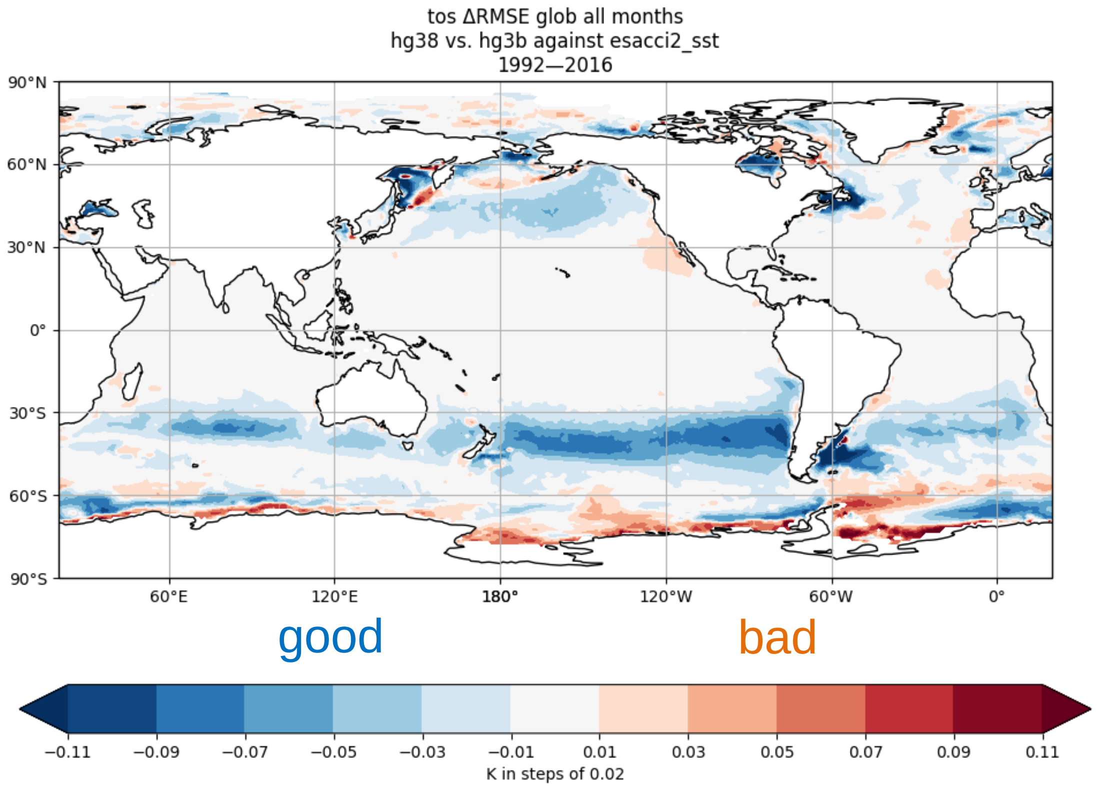
The upper ocean mixing is modelled using the TKE scheme in which the impact of breaking waves is implicitly represented with a surface flux of TKE.
We have reactivated in NEMO4 what has been used in our NEMO3.4, whereby this flux of TKE is connected to the wave breaking source term from the wave model.
Note that the impact of this surface flux is again averaged over the first model layer as proposed by Breivik et al. (2015), with a vertical length scale that scales with the significant wave height (Hs).



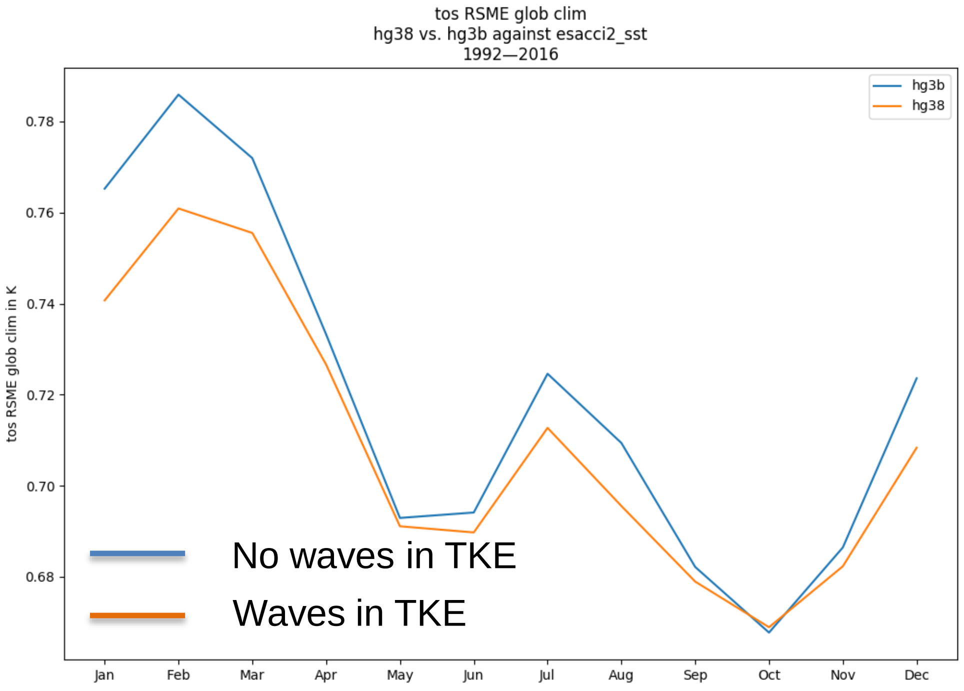
$$\Phi_{oc} = -\rho_w g \int \mathrm{d}\mathbf{k}\, S_{diss} = m \rho_a u_*^3 .$$

TKE flux in NEMO4

Comparison to Sea Surface Temperature observations (ESACCI2), 1992-2016



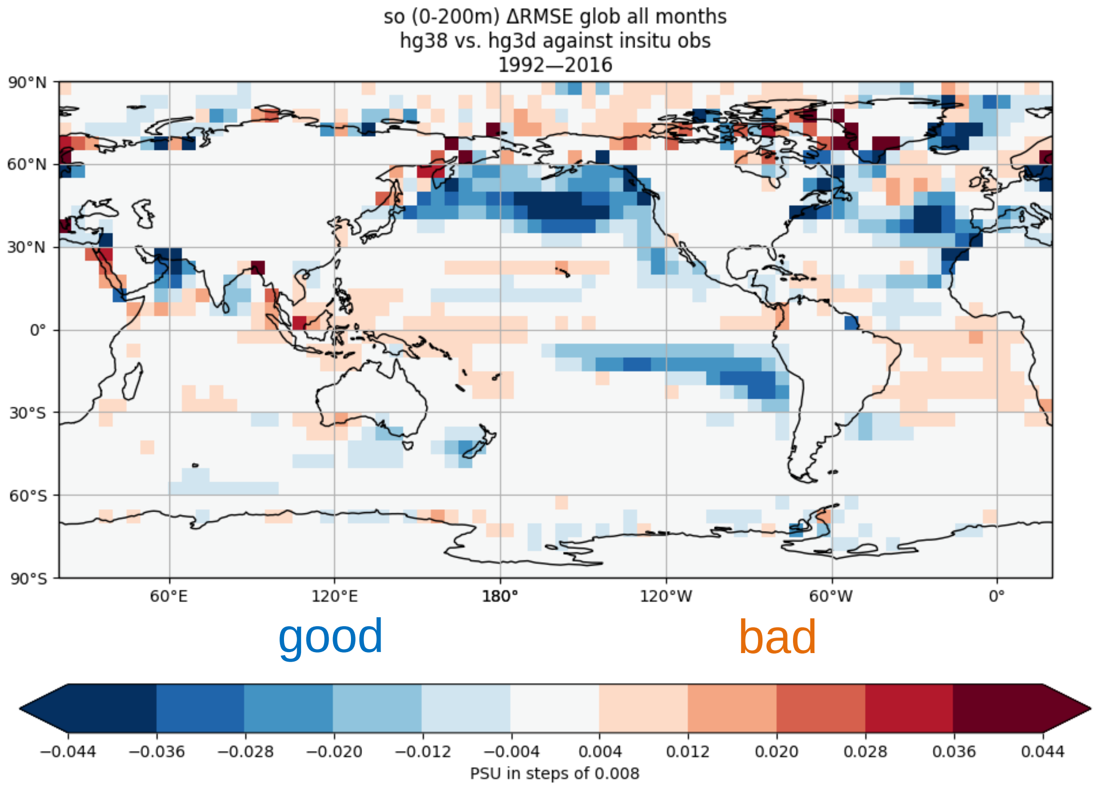
Difference in RMSE



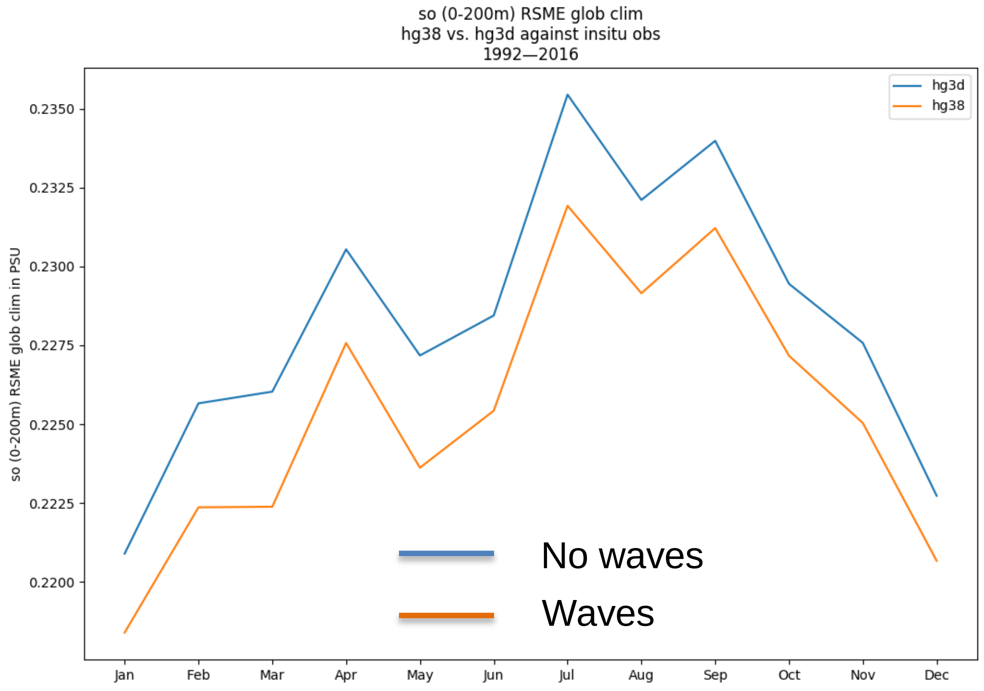
RMSE

Finally: All wave effects in NEMO4

Comparison to ocean salinity observations (EN4) in the upper 200m, 1992-2016



Difference in RMSE



RMSE

ECMWF

Conclusions:

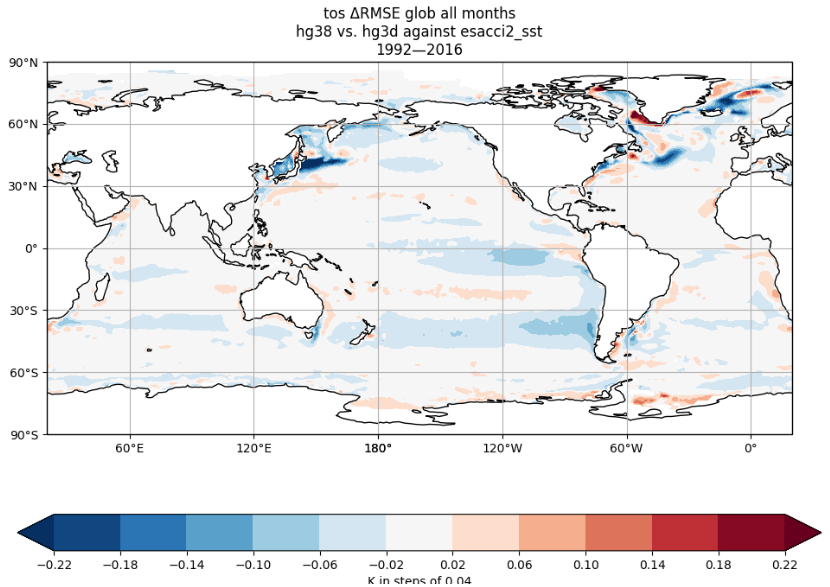
ECMWF has revisited the use of wave forcing in NEMO4.
These are now (new and existing ones):

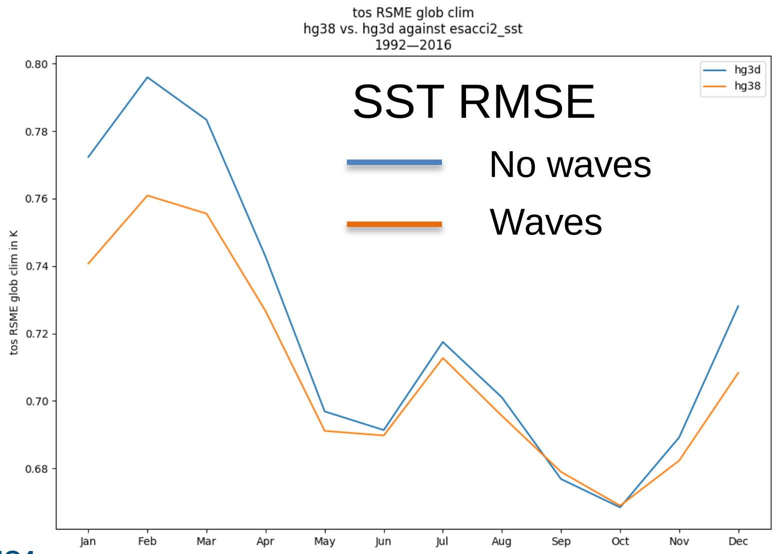
- Wave dependent Charnock coefficient*.
- Modified ocean side stress.
- Stokes drift.
- Turbulent kinetic energy flux in the TKE.

Results are for the eORCA1 configuration, with no SST relaxation, with ERA5 hourly forcing.

*ECMWF AeroBulk formulation was selected. It allows to be consistent with ERA5 so that the wave dependent Charnock coefficient can be used. Using a frozen drag coefficient from the wave model is not consistent with the bulk formula !

Impact is generally beneficial. Work is still ongoing.



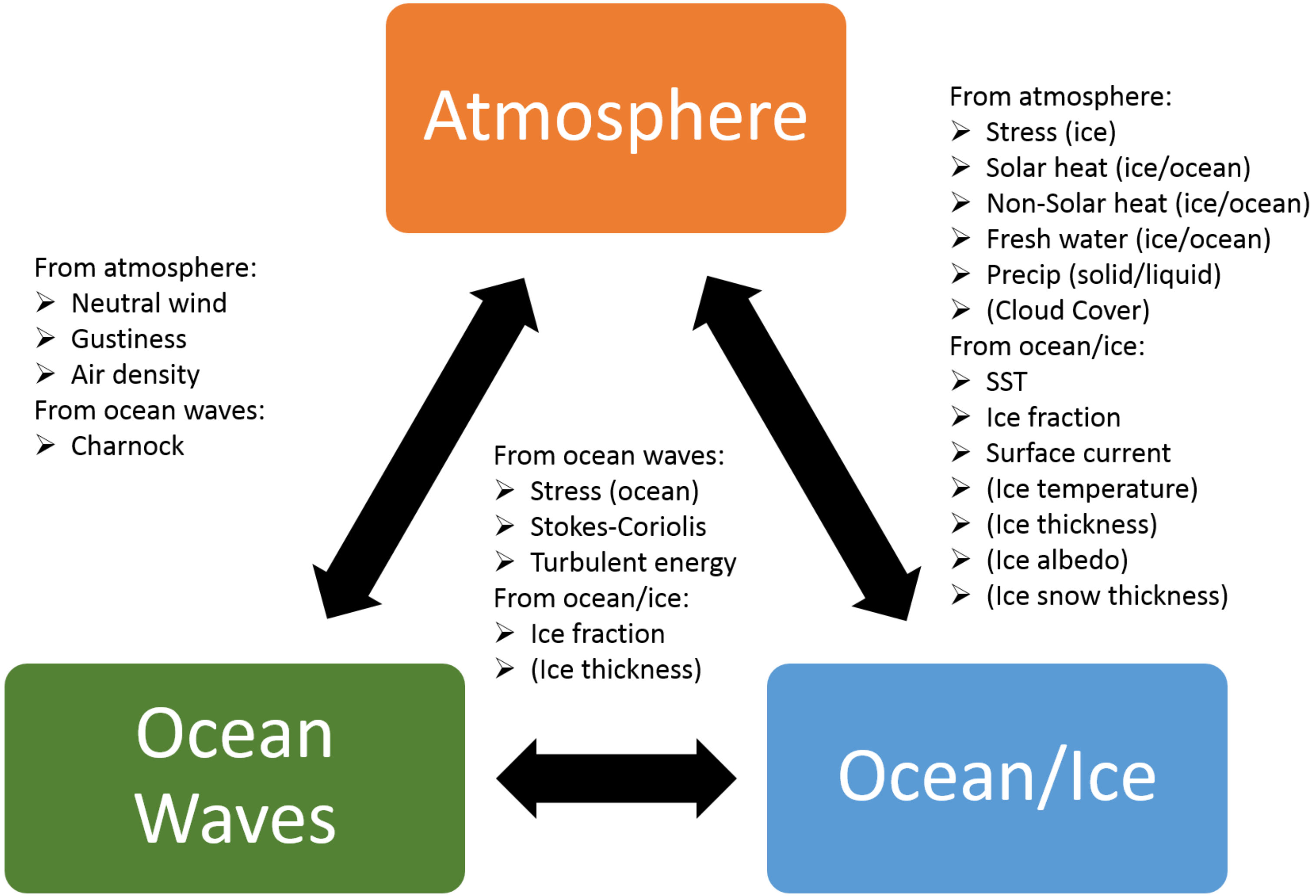


Thank you for your attention …

Øyvind Breivik, Kristian Mogensen, Jean-Raymond Bidlot, Magdalena Alonso Balmaseda, and Peter A.E.M. Janssen, 2015: Surface Wave Effects in the NEMO Ocean Model: Forced and Coupled Experiments. JGR, doi: 10.1002/2014JC010565

Breivik, O., J.-R. Bidlot, P.A.E.M. Janssen, 2016: A Stokes drift approximation based on the Phillips spectrum, Ocean Modelling, doi:10.1016/j.ocemod.2016.01.005

Data exchanges in the ECMWF coupled model



Fields in () are not currently used in operations