# Air-Sea Interactions in Earth-System Modelling

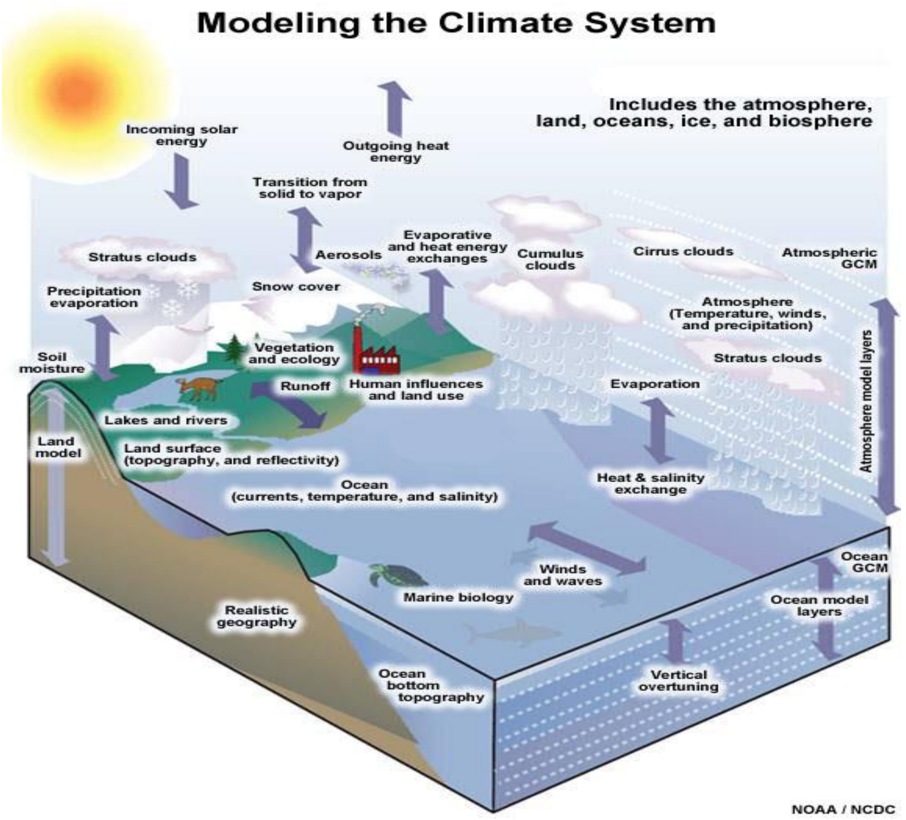
## Role of Ocean Waves in an Earth-System Model.

Jean-Raymond Bidlot
Coupled Processes Team
**ECMWF**
jean.bidlot@ecmwf.int

St Brides Bay, Wales

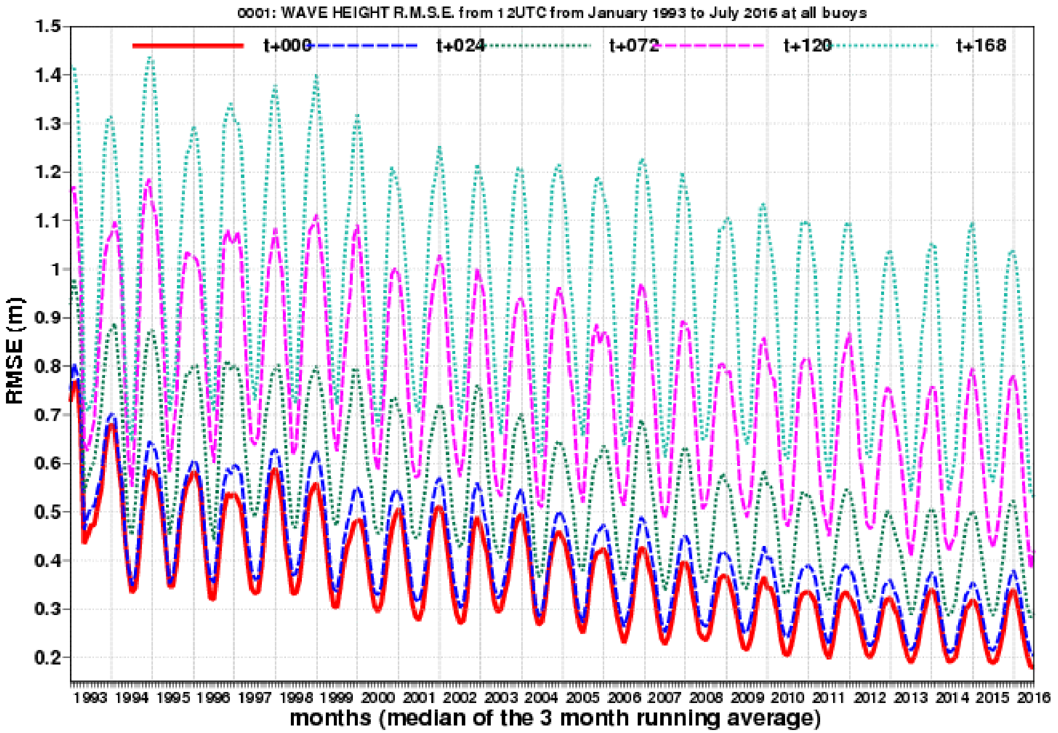
# Outline

- \- Wave modelling and its role in air-sea iteraction.
- \- Towards an Earth-System model at ECMWF.



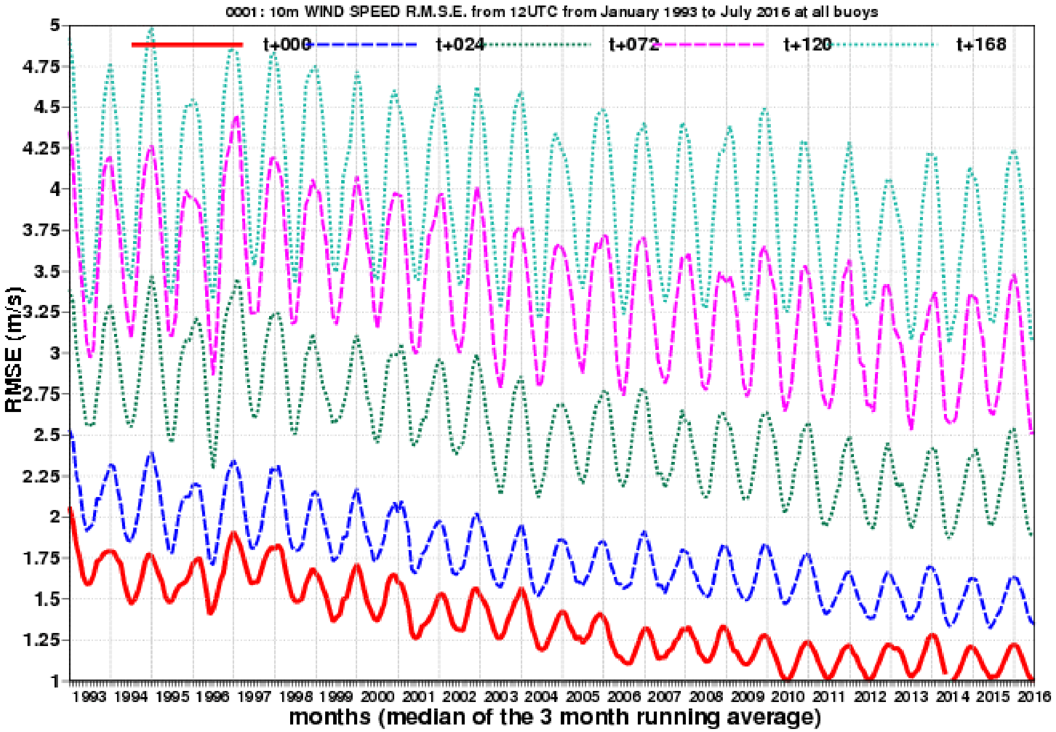
# Introduction:

Comparison of ECMWF analysis and forecasts against buoy data  (RMSE)




Significant wave height (SWH)

7 day FC
5 day FC
3 day FC
1 day FC
analysis

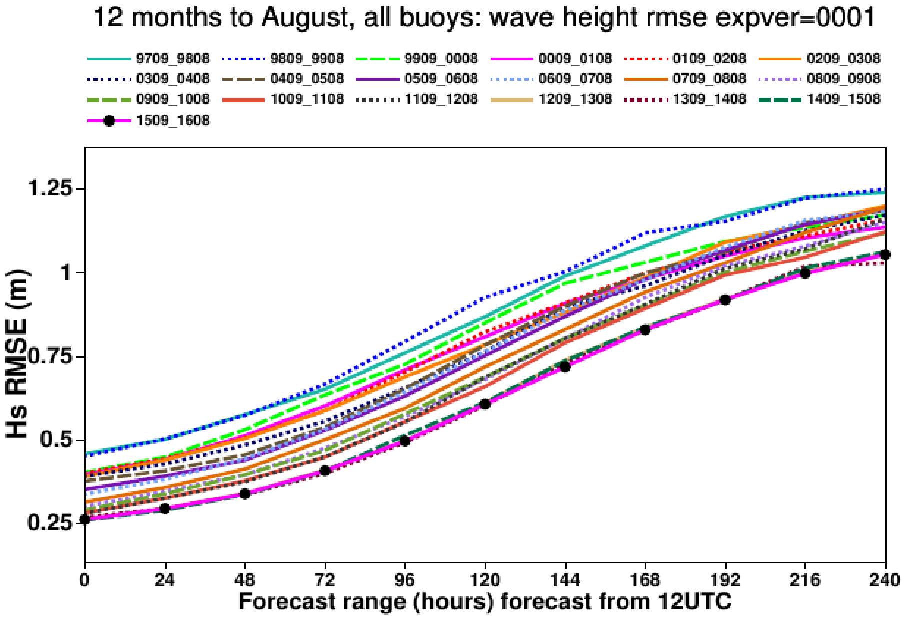



10m wind speed

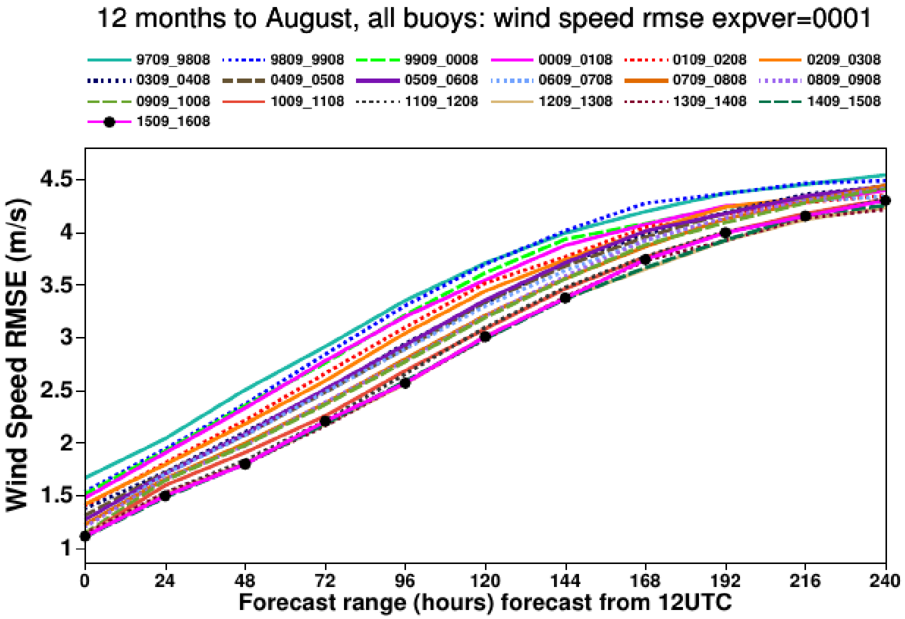
# Can it be maintained?

Significant wave height (SWH)

Comparison against
buoy data
yearly statistics
since 1997




10m wind speed



# ECMWF global forecast models for medium range forecasts

High resolution / Ensemble systems

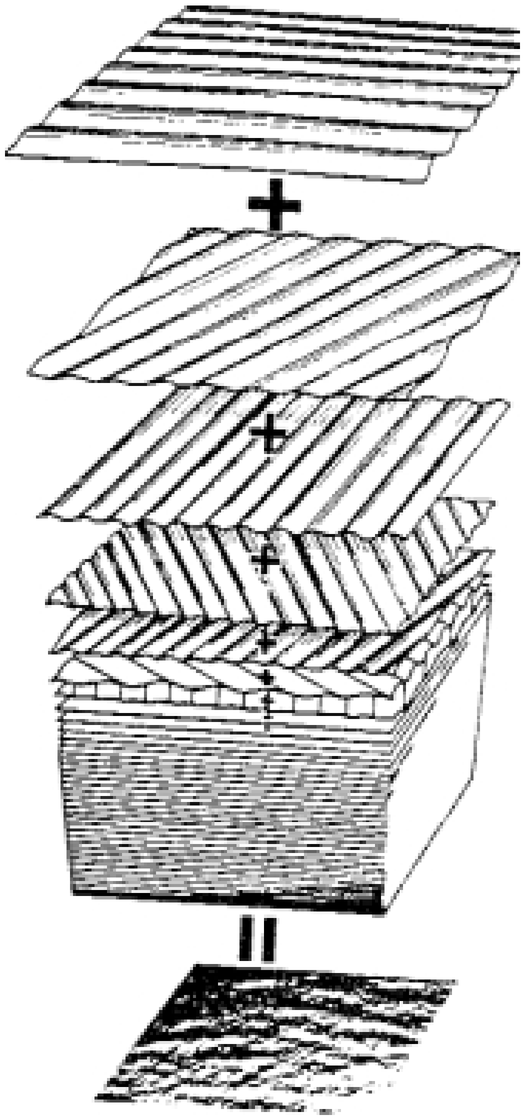
| | |
|---|---|
| **Atmospheric model** | **TCo1279/TCo639*** **~9km/~18km** |
| **Wave model (ECWAM)** | **14km/28km*** |
| **Ocean model (NEMO)** | **Ice model (LIM2)** |

* Resolution as of 8 March 2016

**ORCA1_Z42**
1° in the horizontal
42 vertical levels

Twice per day, ECMWF run a high resolution forecast model up to 10 days ahead. It also runs the lower resolution system (51 forecasts) up to day 15 in order to characterise the forecast uncertainty.

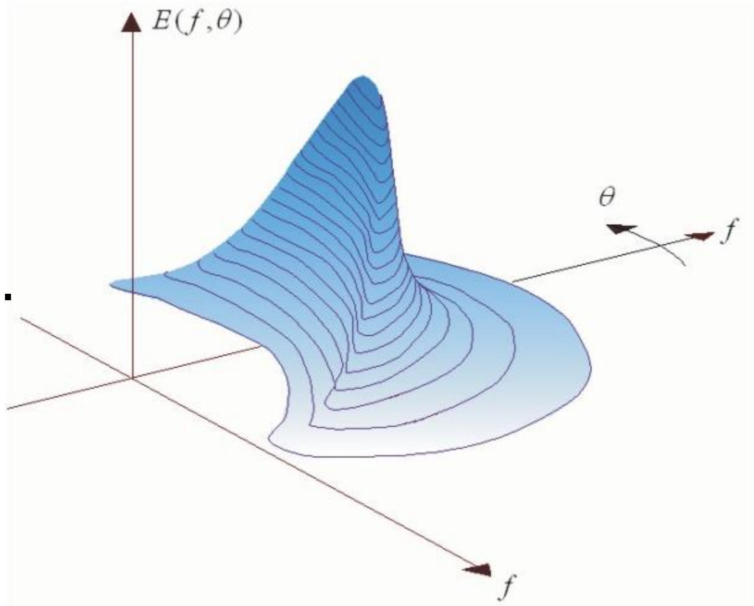
# Ocean Wave Modelling: Wave Spectrum



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

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

water density: $\rho_w$ and gravity: g



# Ocean Wave Model

The 2-D spectrum follows from the energy balance equation
(in its simplest form: deep water case):

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

Where the group velocity $\mathbf{V_g}$ is derived from the dispersion relationship which relates frequency (f) and wave number (k) for a given water depth (D).

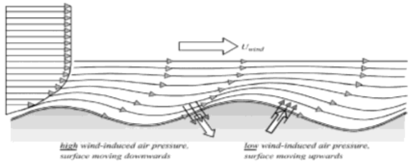



Figure 6.16 The wave-induced wind-pressure variation over a propagating harmonic wave.

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

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

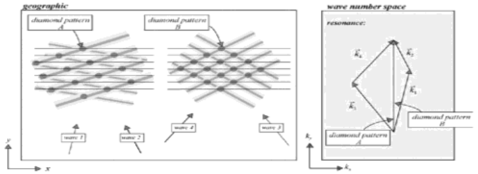



Figure 6.20 *Quadruplet* wave–wave interactions (realisable in deep water). Two pairs of wave components can create two diamond patterns with identical wave lengths and directions and therefore identical wave numbers. When the four waves are superimposed (not shown here), they can thus resonate. The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

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

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

# Wind Input and its interaction

Following Miles (1957), $S_{in}$ depends on the surface stress $\tau = \rho_a \, u_*^2$ and is proportional to the wave spectrum:

$$S_{in} = \gamma F \qquad\qquad \gamma \sim \frac{\rho_a}{\rho_w} \beta(z_0) \left( \frac{u_*}{c} \right)^2$$

with c the phase speed of the waves, $\rho_a$ air density and $\rho_w$ water density, and β is a function of $z_0$ the roughness length experienced by the airflow.

The wave growth by wind implies a momentum loss/drag of the airflow, in such a way that the drag is proportional to the steepness of the waves. As a consequence, for steep waves the roughness length $z_0$ is larger than for gentle waves.

<u>In other words</u>, there is a strong mutual interaction between wind and waves, where the strength of the interaction is determined by the wave-induced stress:

$$\tau_w = \frac{\rho_w}{\rho_a} g \int \mathrm{d}\omega \, d\theta \, \frac{1}{c} S_{in}$$ i.e. the momentum flux due the wind input

# Towards a coupled system

**Atmospheric model** TCo1279/TCo639 9km/18km

**Neutral wind** — Every IFS time step — **Roughness**

**Wave model (ECWAM)** 14km/28km

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

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

Charnock relation

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

**All configurations**

Since **1998**

Single executable

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

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

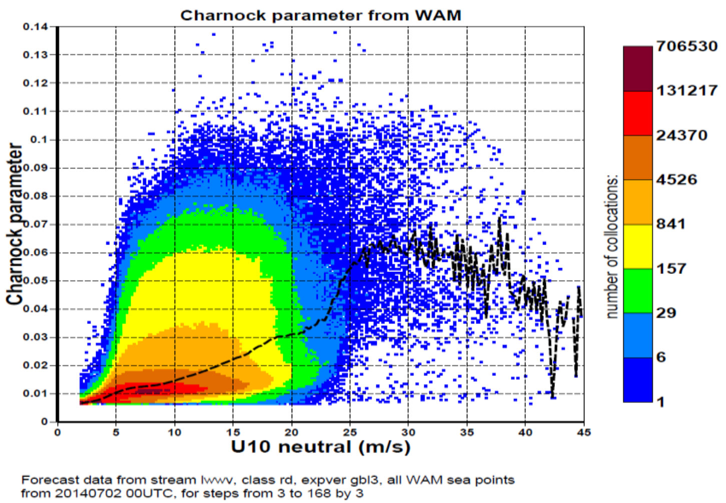
If uncoupled:

$$\alpha = 0.018$$

$\alpha$

0.10

0.02



# Impact of sea state dependent momentum flux

Minimum pressure
952 hPa

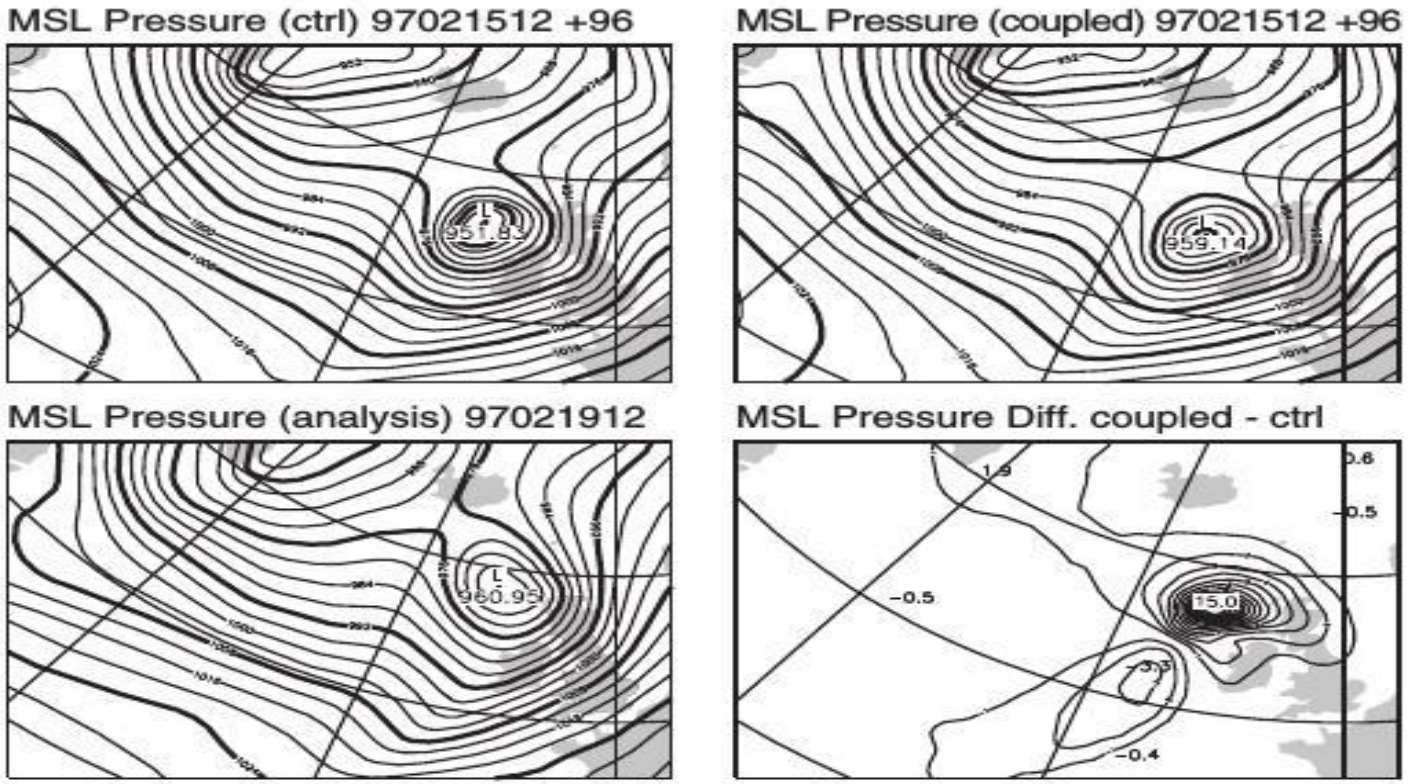
uncoupled

959 hPa

coupled

960 hPa

Verifying analysis



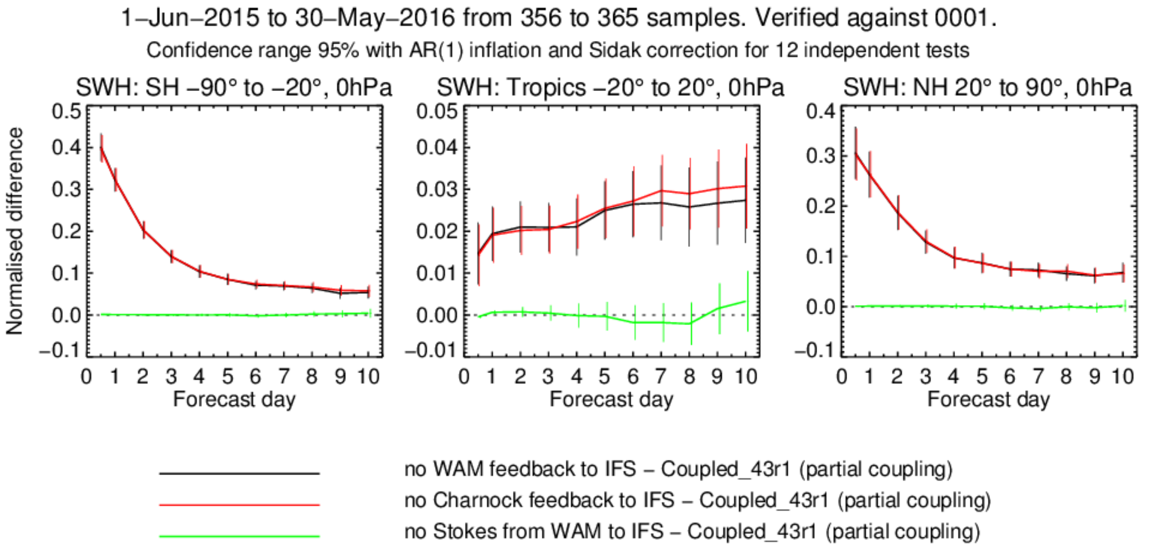

Comparison of 4-day forecast of surface pressure over the North Atlantic, valid for 19 February 1997. Version of coupled model is $T213/L31 - 0.5\,\mathrm{deg}$.

Janssen et al. 2002 and Janssen 2004

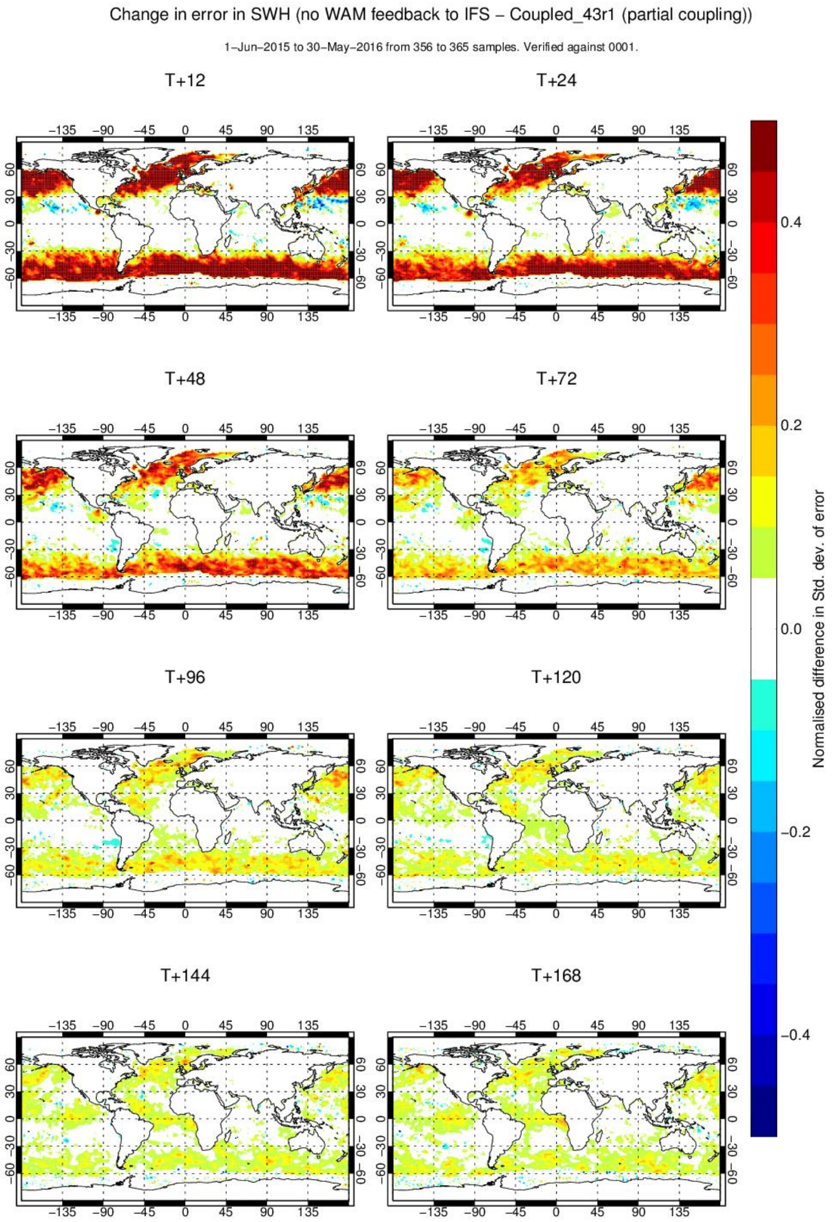
# **Sensitivity study:** Impact of no waves feedback to the atmospheric model

We are currently performing sensitivity studies, running coupled* IFS-ECWAM-NEMO forecasts daily at Tco399 (~40km) resolution, with latest CY43R1, starting from operational analysis, from 1 June 2015 to 31 May 2016, 0 UTC. Scores are against operational analysis

Normalised difference in standard deviation of error for SWH



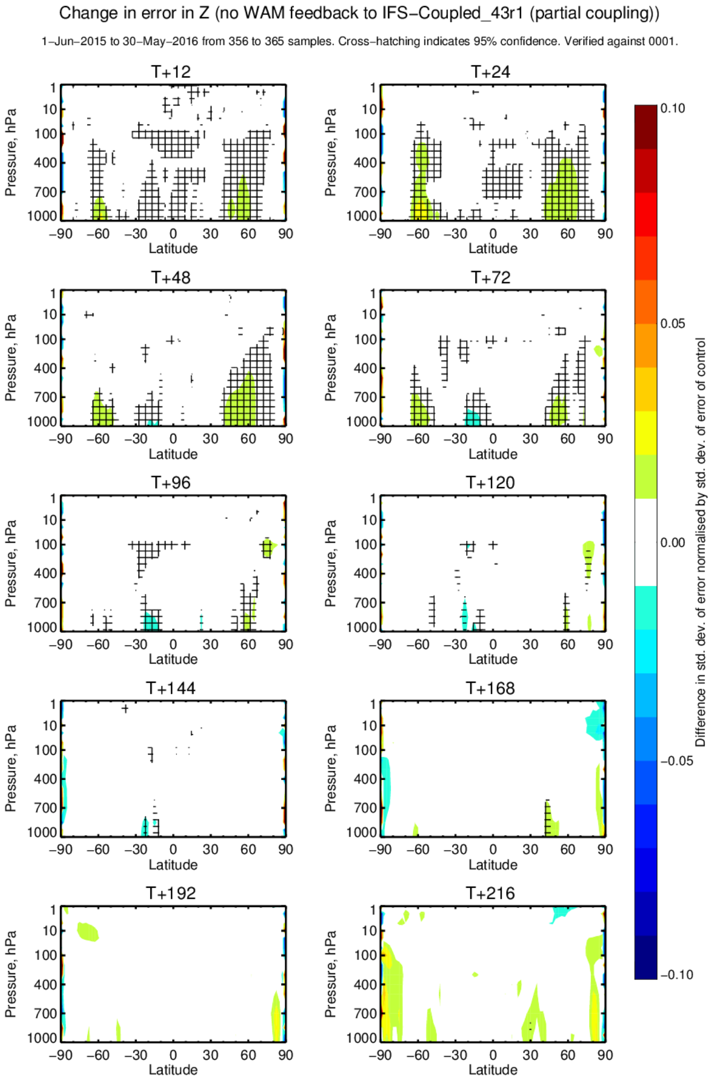

> 0 means worst



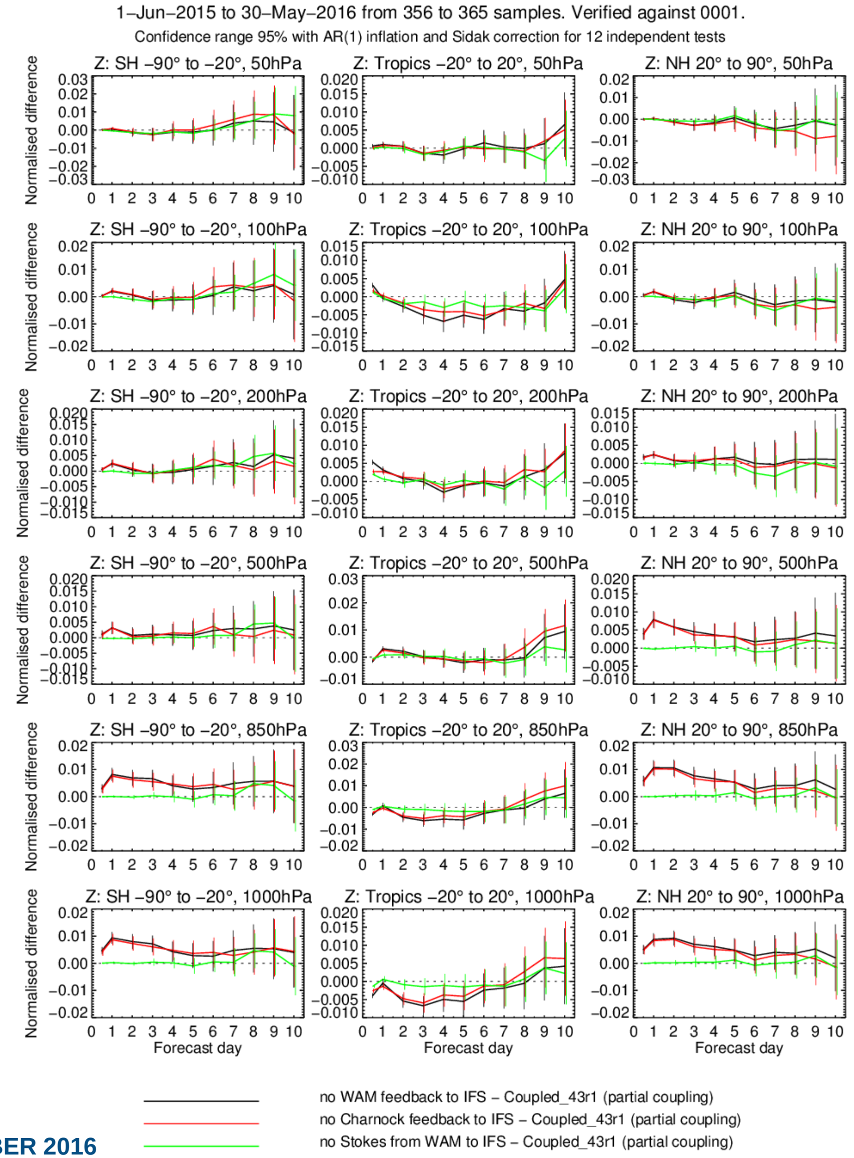

worst

# **Sensitivity study:** Impact of no waves feedback to the atmospheric model

## Normalised difference in standard deviation of error for Z



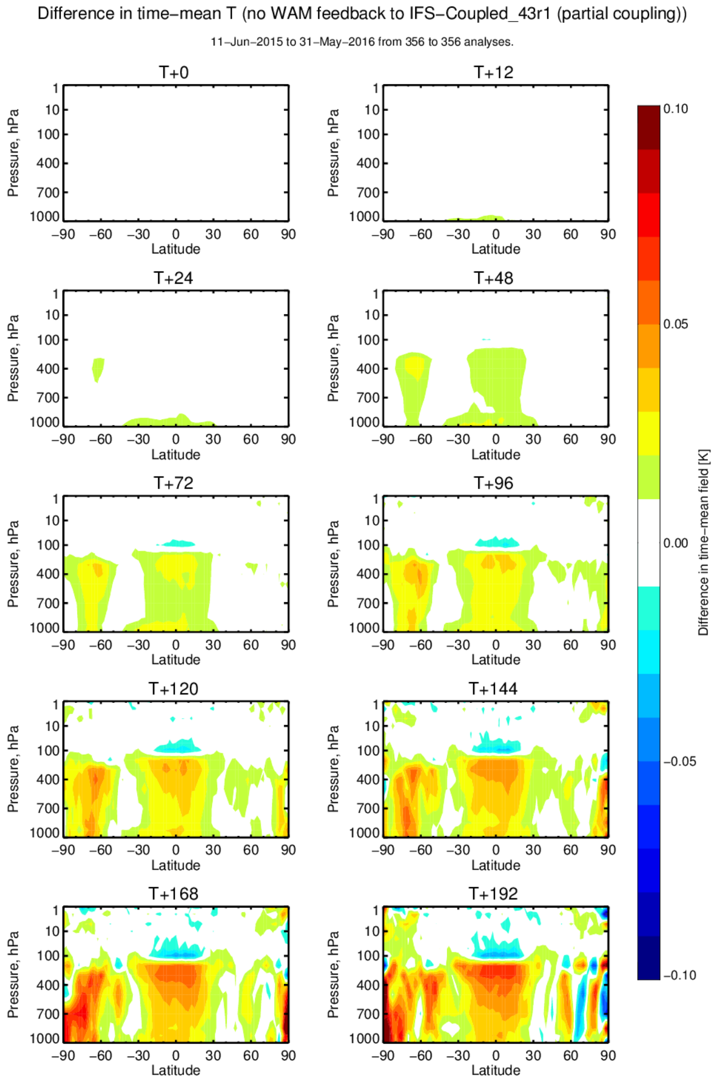

worst



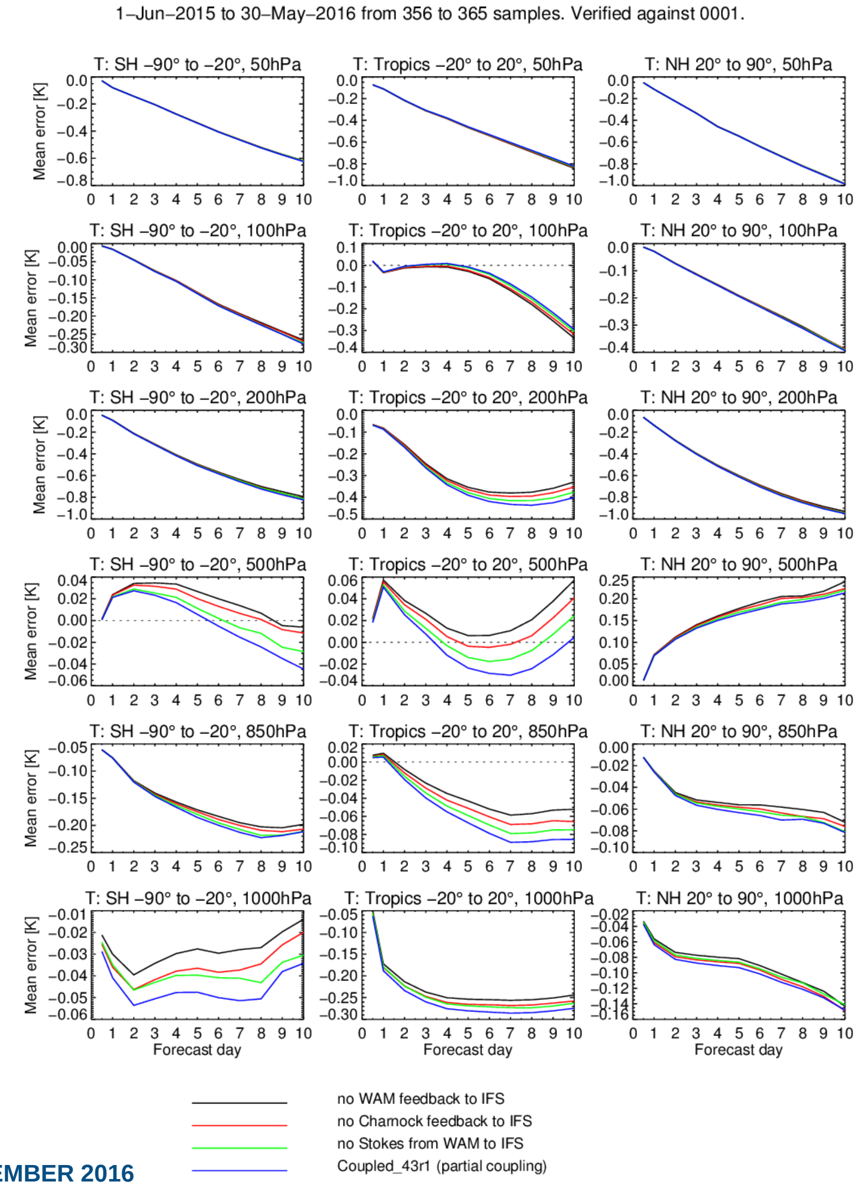

> 0 means worst

# Sensitivity study: Impact of <u>no</u> wave feedback to the atmosphere

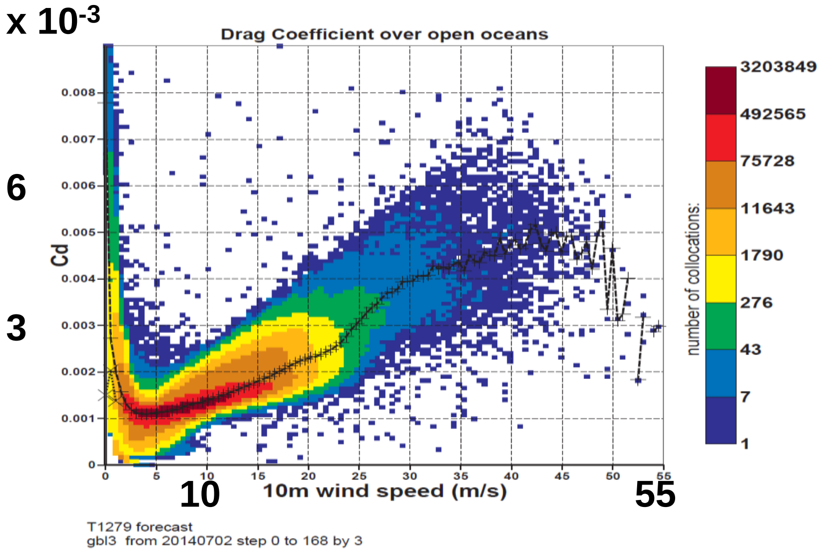
Mean forecast difference in T



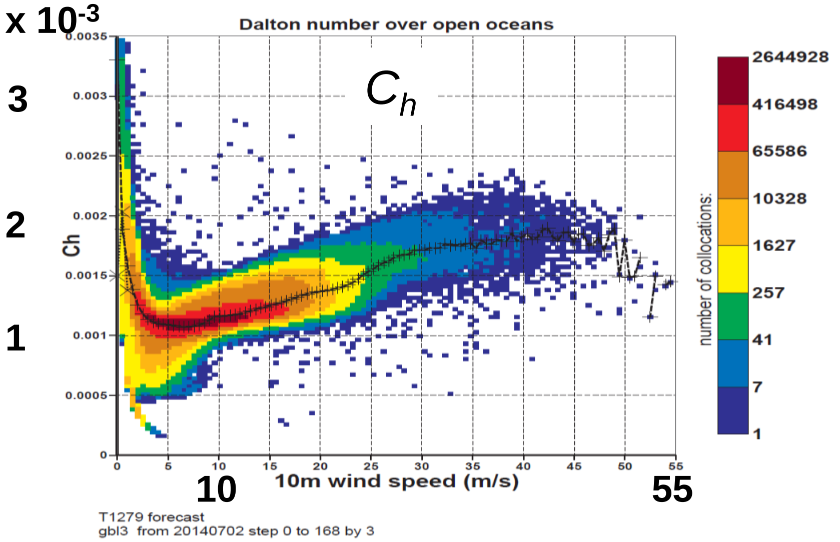

Mean forecast error for T



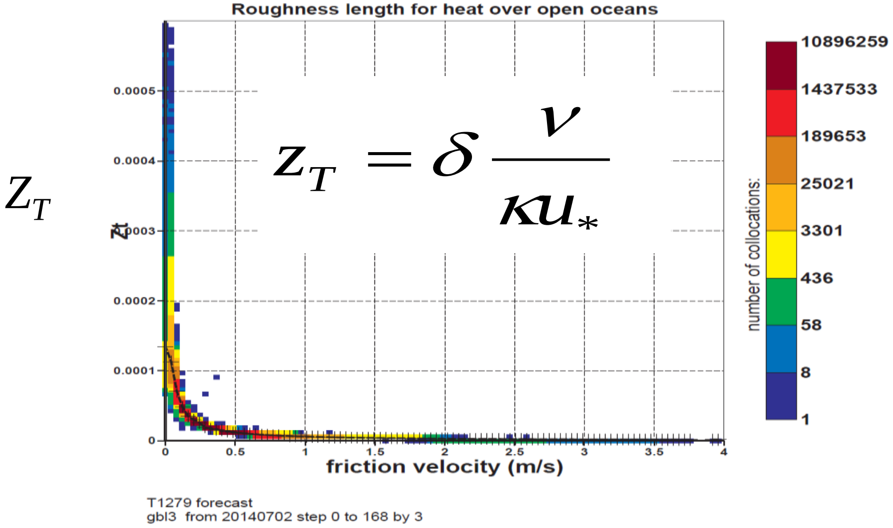
# Sea state dependency on heat flux




Exchange coefficients dependency on wind speed
Left: for momentum (Cd)
Right: for heat (Ch)
Forecast from 20140702
t=0 to 168 by 3
all grid points.




$C_d$ is sea state dependent



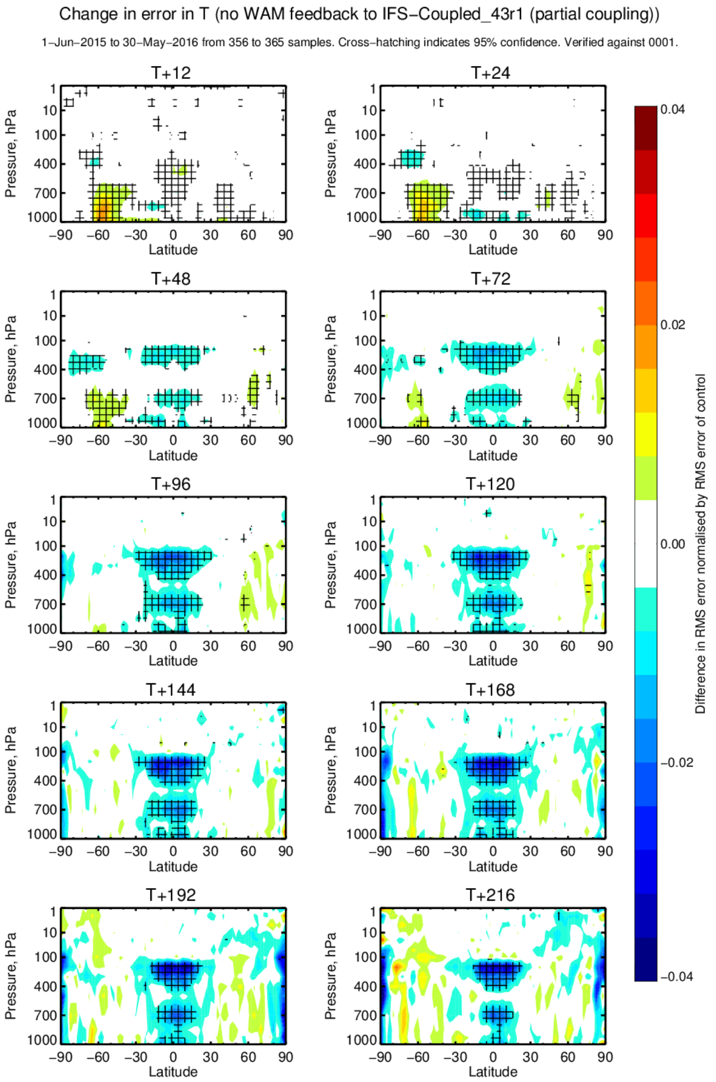

$$z_T = \delta \frac{\nu}{\kappa u_*}$$

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

**Current operational system**

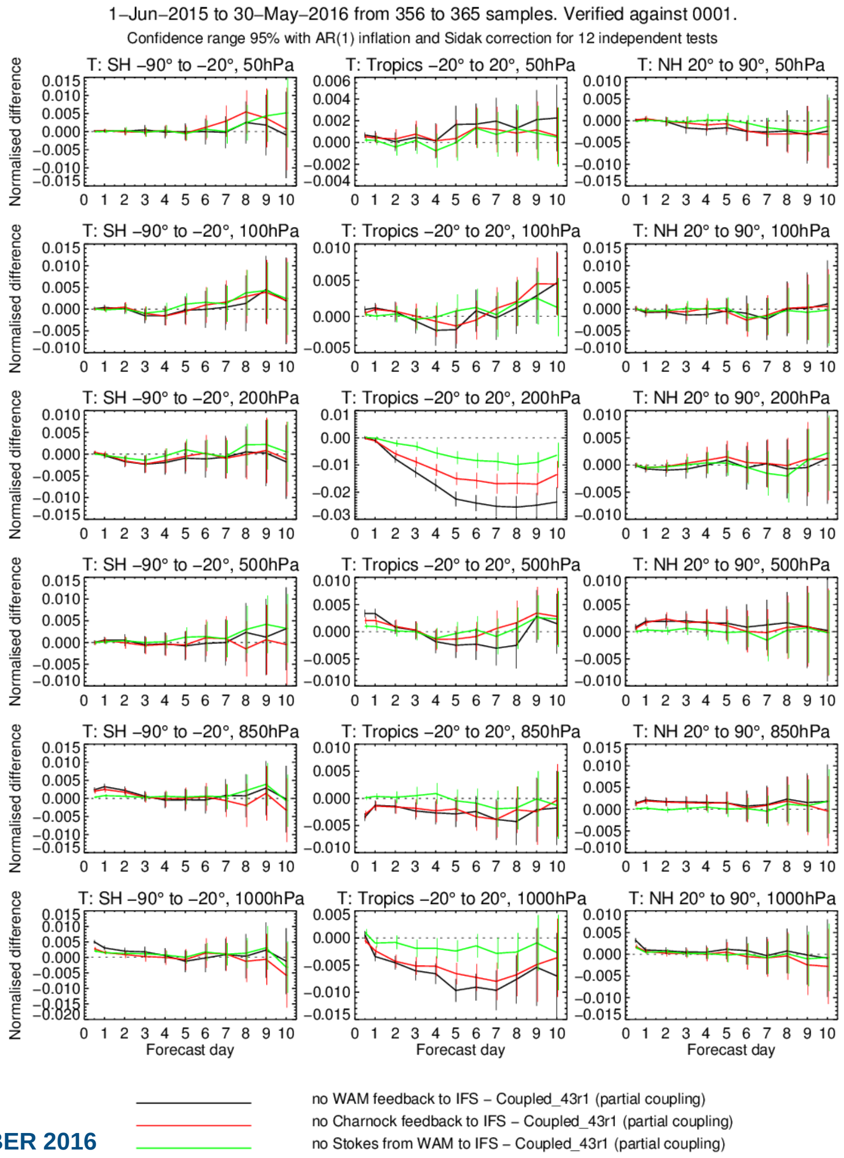
# **Sensitivity study:** Impact of no waves feedback to the atmospheric model

Normalised difference in RMSE for T




worst

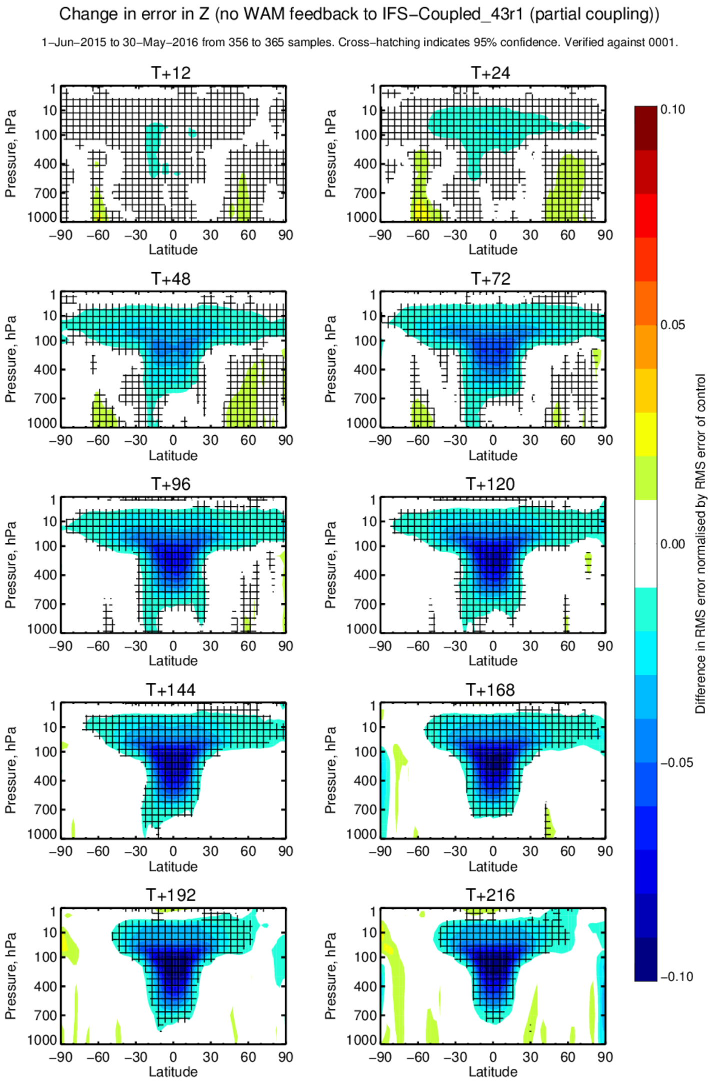
better




> 0 means worst

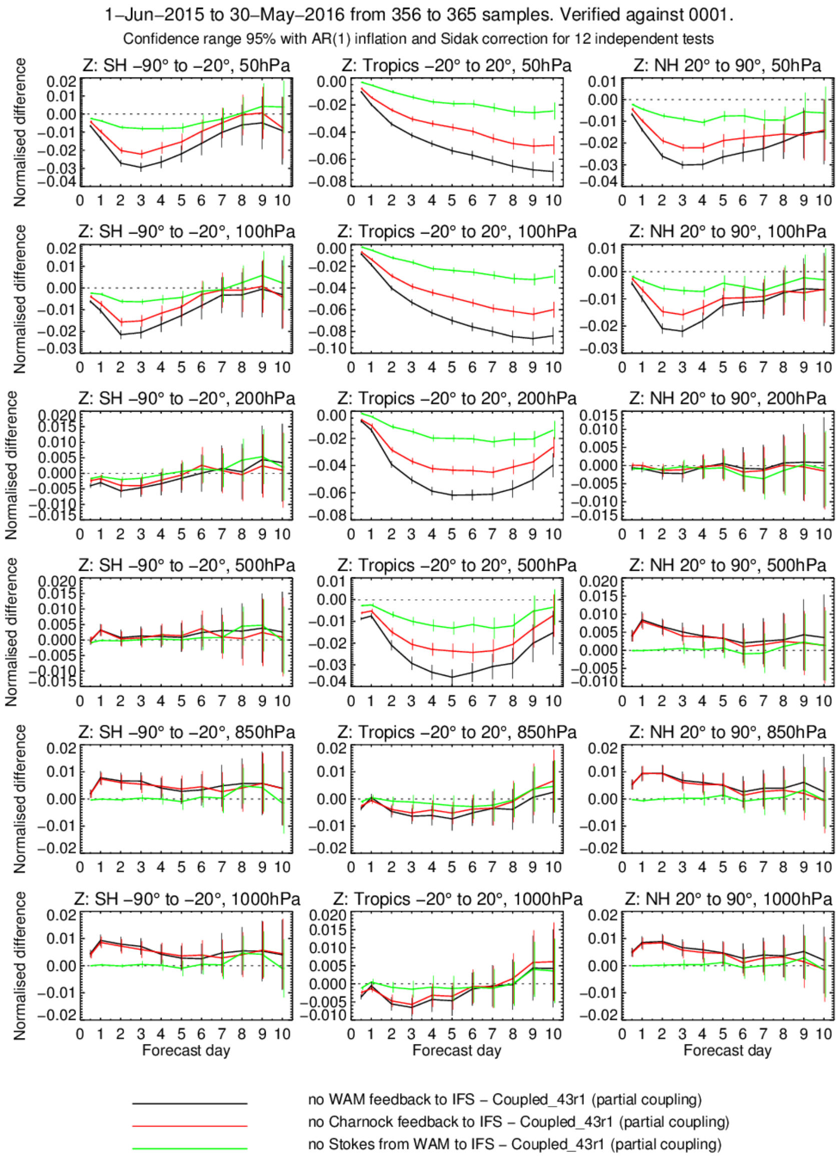
# **Sensitivity study:** Impact of no waves feedback to the atmospheric model

## Normalised difference in RMSE for Z



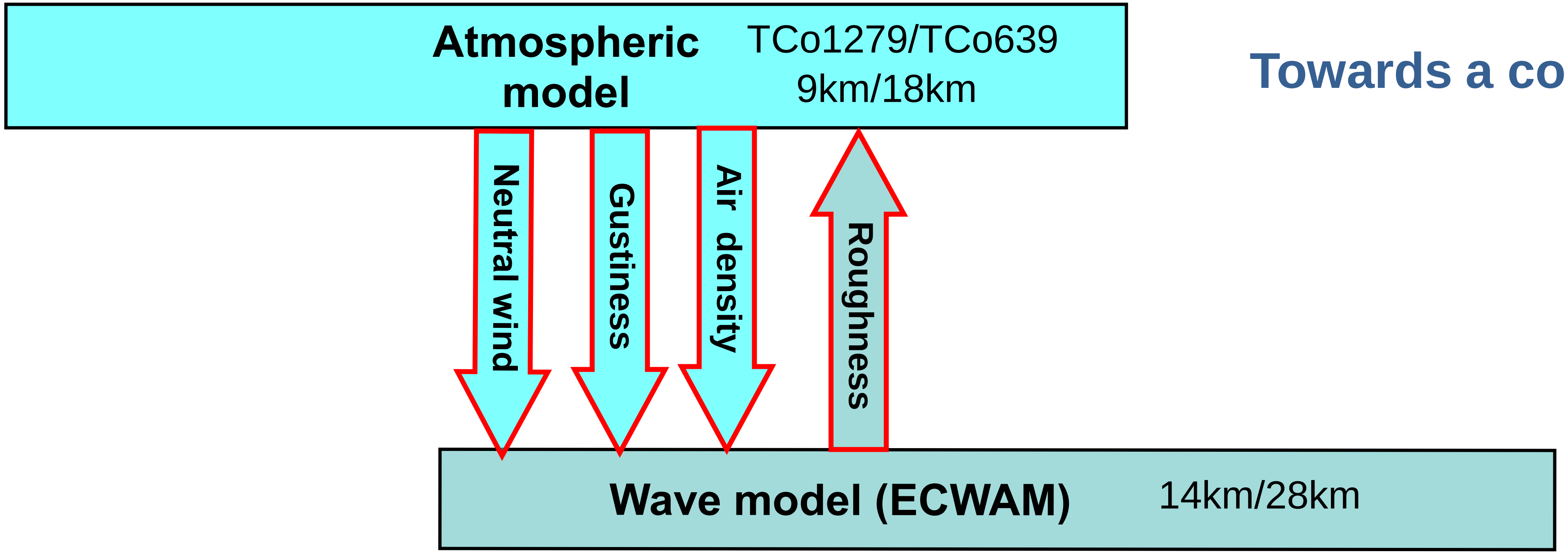

worst

better




> 0 means worst

# Towards a coupled system




All configurations

Since **2002**

Gustiness parameterisation:

$$\gamma(u_*) = 0.5\left(\gamma(\bar{u}_* + \sigma_*) + \gamma(\bar{u}_* - \sigma_*)\right)$$

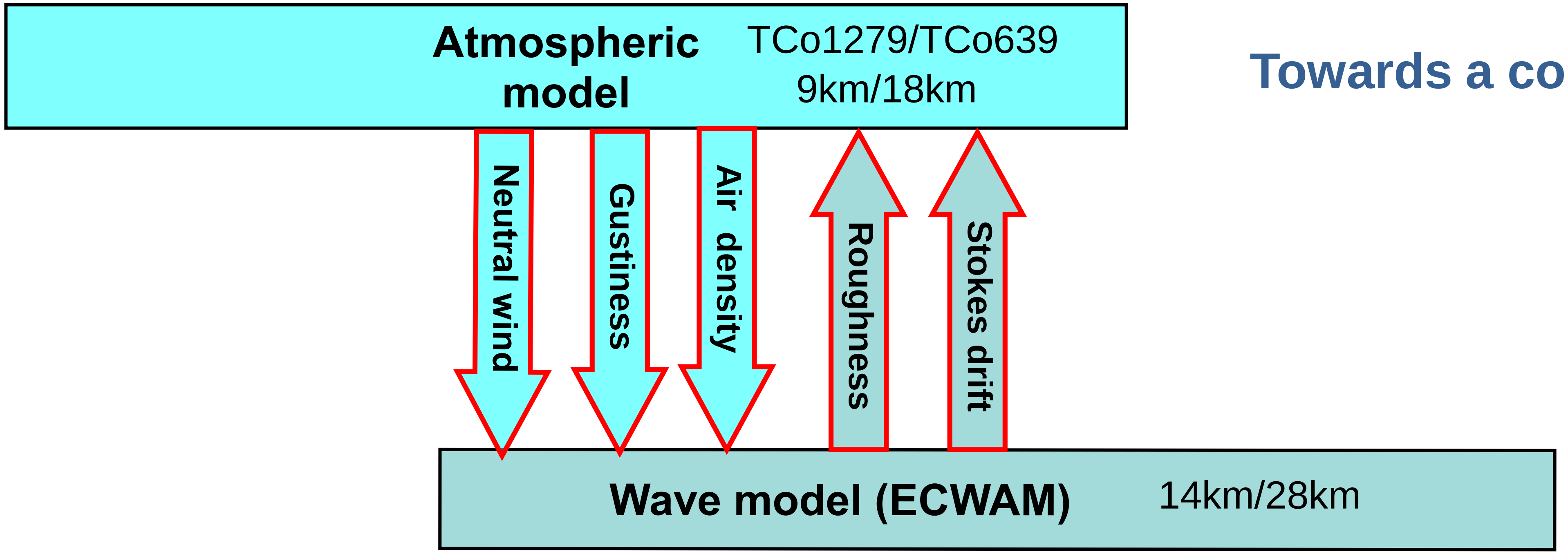
$$\sigma_* = function\left(\bar{u}_* \text{ and } \frac{z_i}{L}\right)$$

$z_i$ is the height of the lowest inversion,
L is the Monin-Obukhov length

Air density effect:

$$\gamma \sim \frac{\rho_a}{\rho_w} \beta(z_0) \left(\frac{u_*}{c}\right)^2$$

# Towards a coupled system




**All configurations**

Since **2010**

The surface Stokes drift is used to parameterise the wave induced mixing in the SST warm layer scheme in the IFS for the representation of the SST diurnal cycle (Takaya et al. 2010)

Stokes drift:

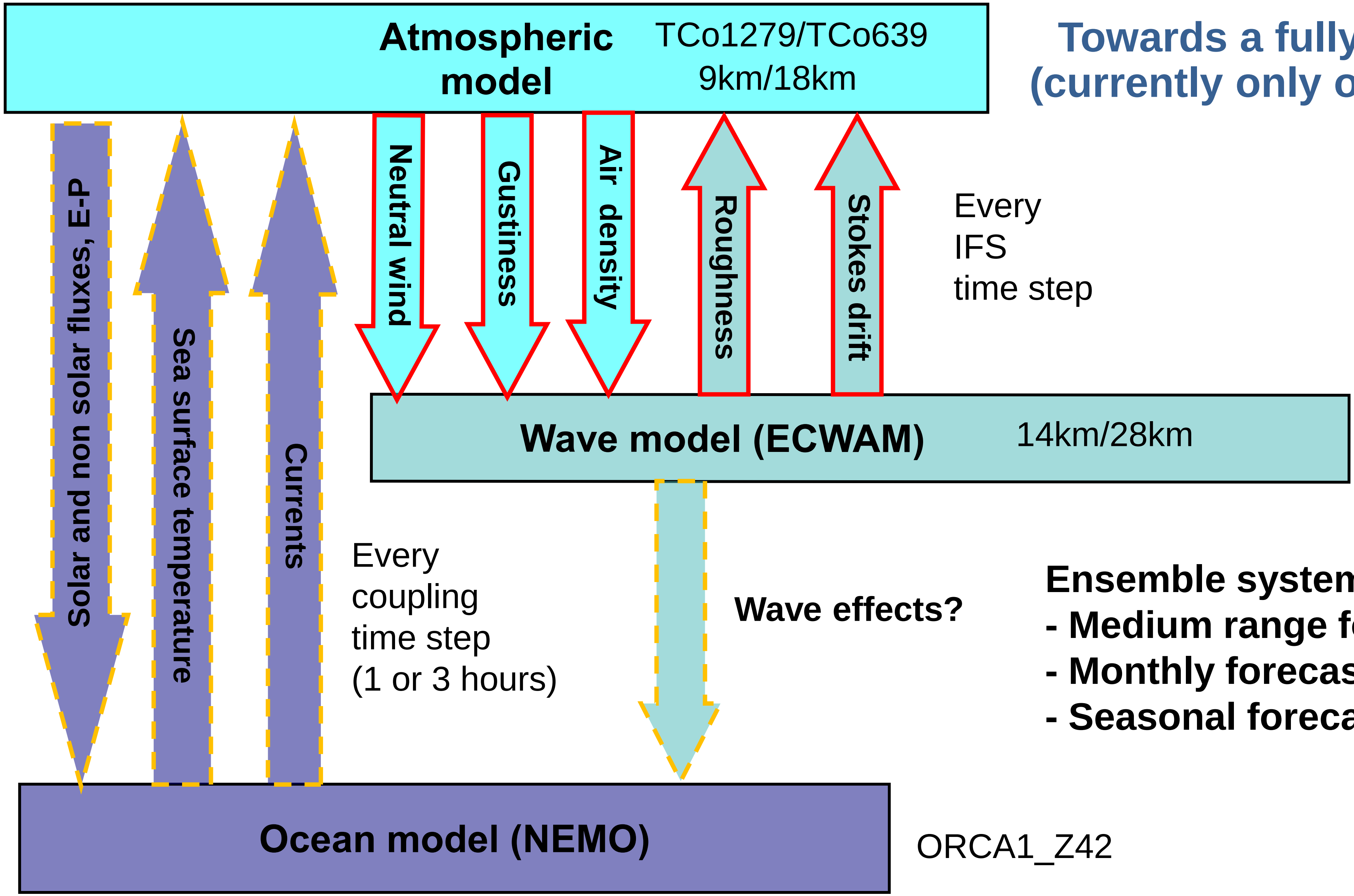
$$\mathbf{u}_s(z) = 4\pi \int_0^{2\pi} \int_0^{\infty} f \mathbf{k} e^{2kz} F(f,\theta)\, df d\theta$$

# Towards a fully coupled system (currently only operational in EPS)

All configurations

Ensemble FC

Single executable




ORCA1_Z42

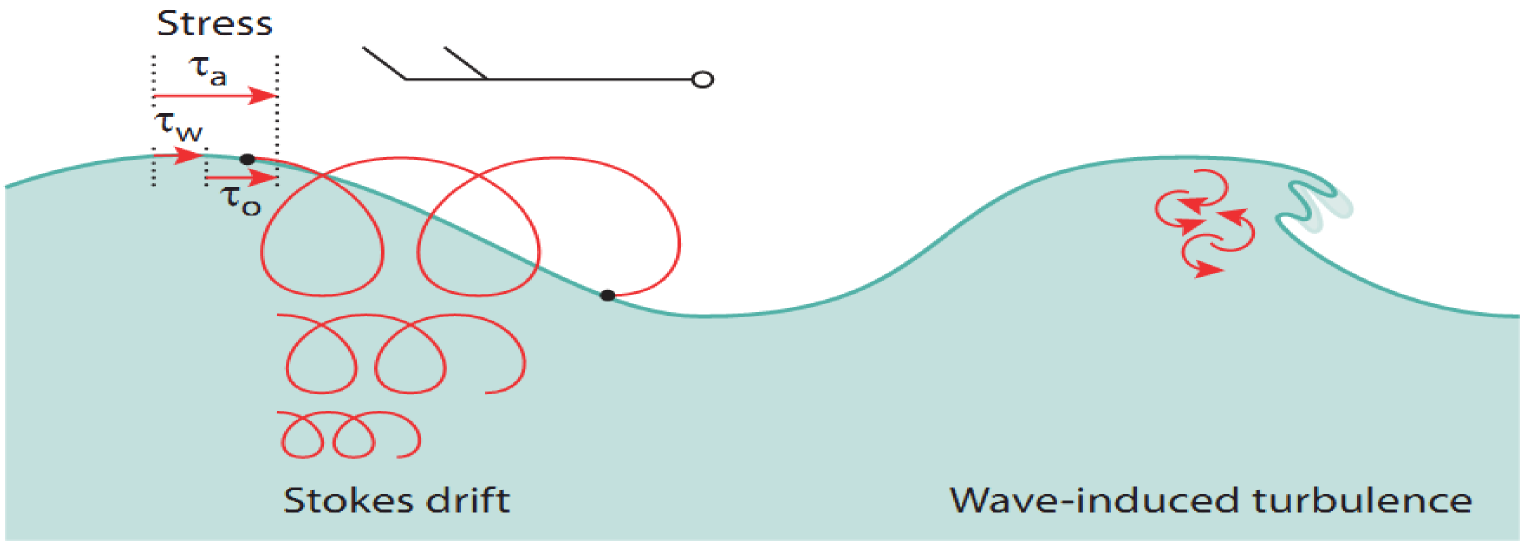
**Ensemble systems only:**
- **Medium range forecast**
- **Monthly forecast**
- **Seasonal forecast**

# Wave effects in NEMO

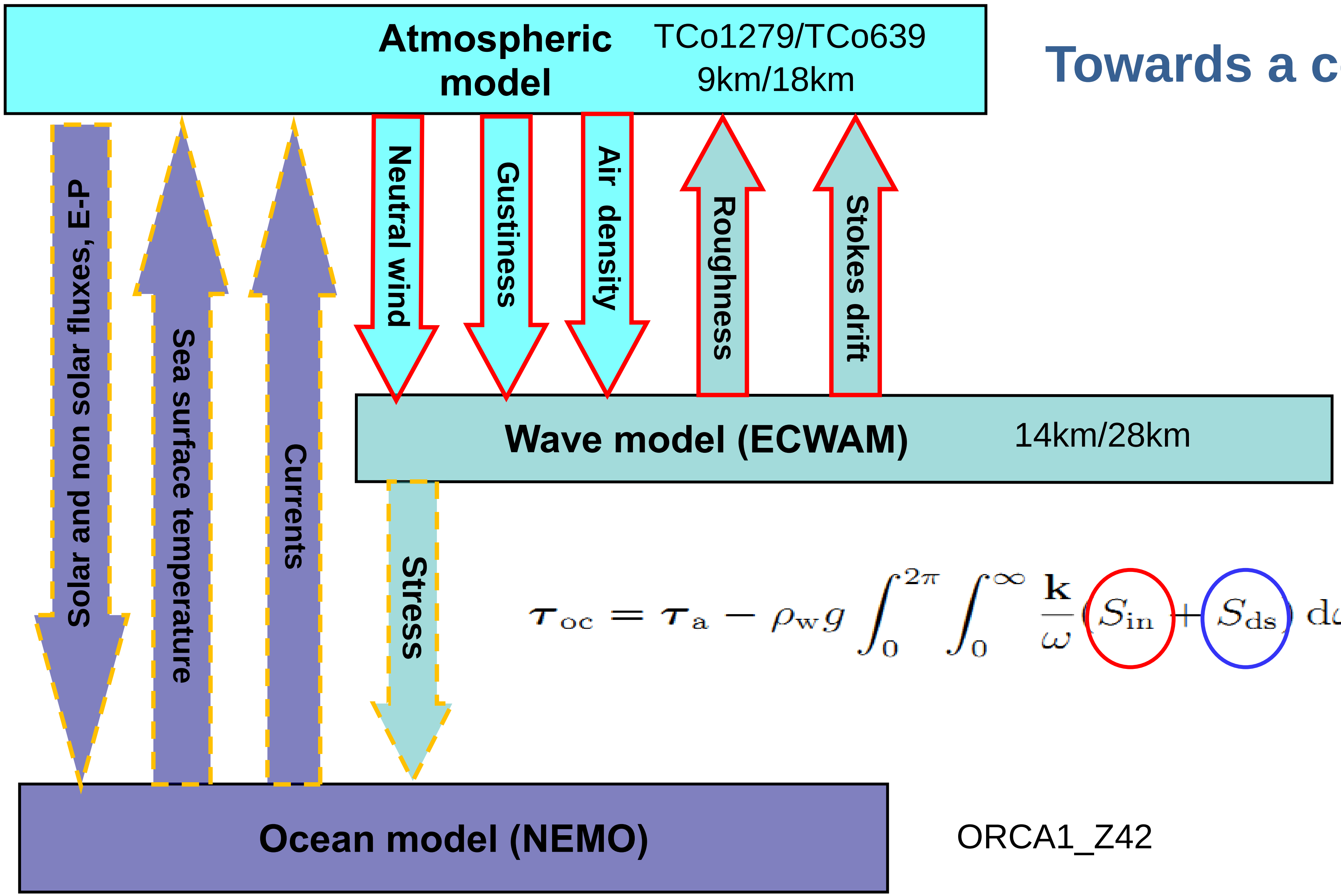
**Stress:** As waves grow under the influence of the wind, the waves absorb momentum ($\tau_w$) which otherwise would have gone directly into the ocean ($\tau_0$) .

**Stokes-Coriolis 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.

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



# Towards a coupled system




All configurations

Ensemble FC

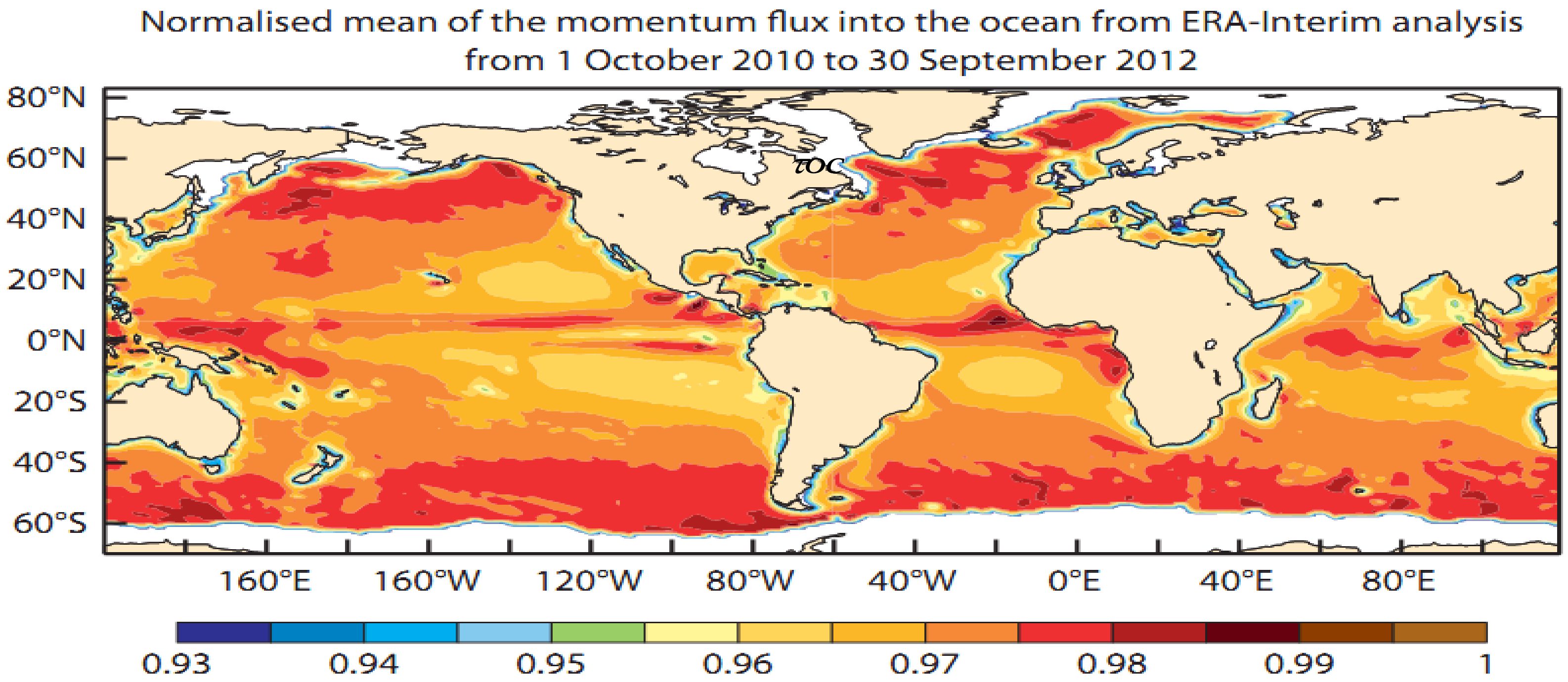
Single executable

$$\boldsymbol{\tau}_{\mathrm{oc}} = \boldsymbol{\tau}_{\mathrm{a}} - \rho_{\mathrm{w}} g \int_0^{2\pi} \int_0^{\infty} \frac{\mathbf{k}}{\omega} (S_{\mathrm{in}} + S_{\mathrm{ds}})\, \mathrm{d}\omega \mathrm{d}\theta .$$

ORCA1_Z42

# Wave effects in NEMO: sea state modulated surface stress

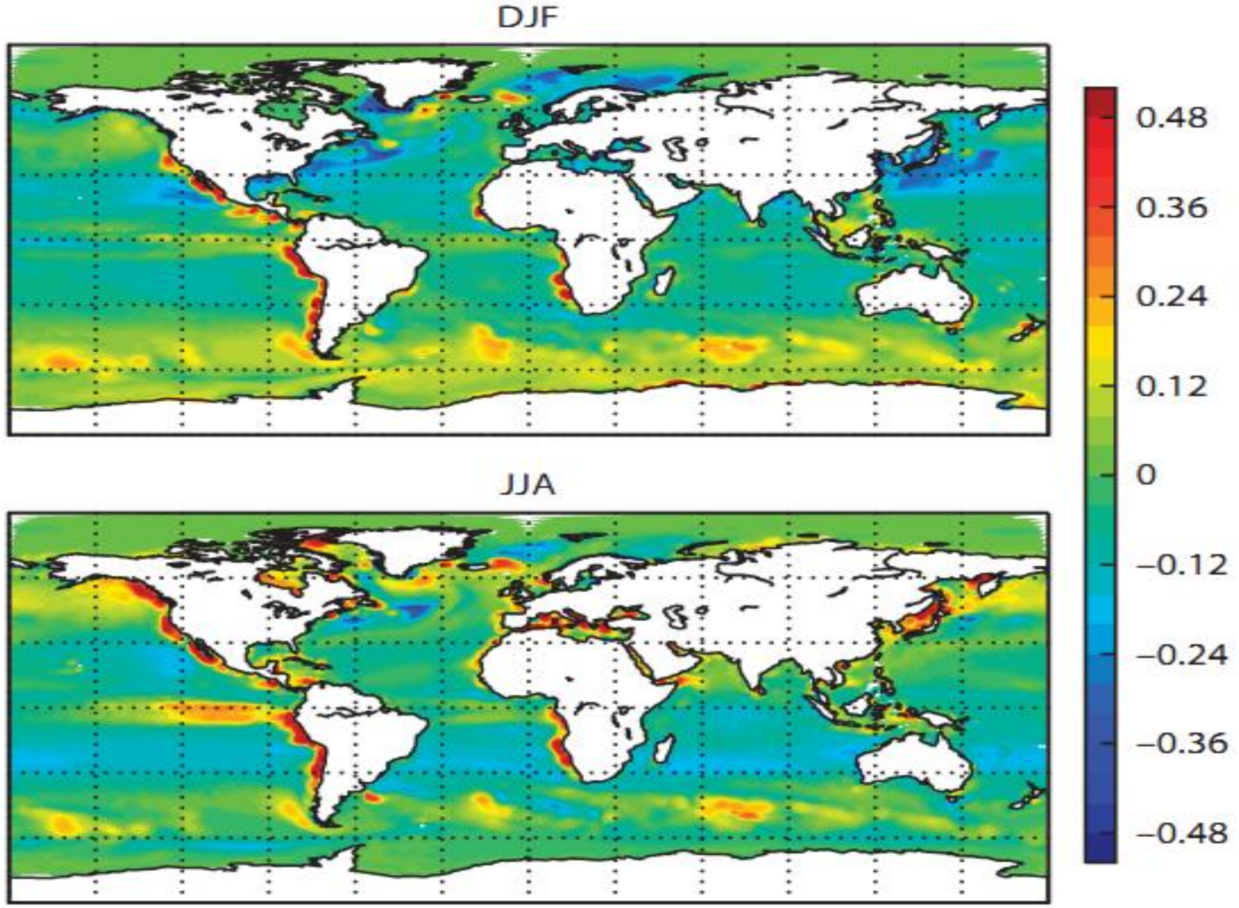
$$\boldsymbol{\tau}_{\mathrm{oc}} = \boldsymbol{\tau}_{\mathrm{a}} - \rho_{\mathrm{w}} g \int_0^{2\pi} \int_0^{\infty} \frac{\mathbf{k}}{\omega} (S_{\mathrm{in}} + S_{\mathrm{ds}}) \, \mathrm{d}\omega \mathrm{d}\theta.$$



# Wave effects in NEMO: sea state modulated surface stress

Boreal winter

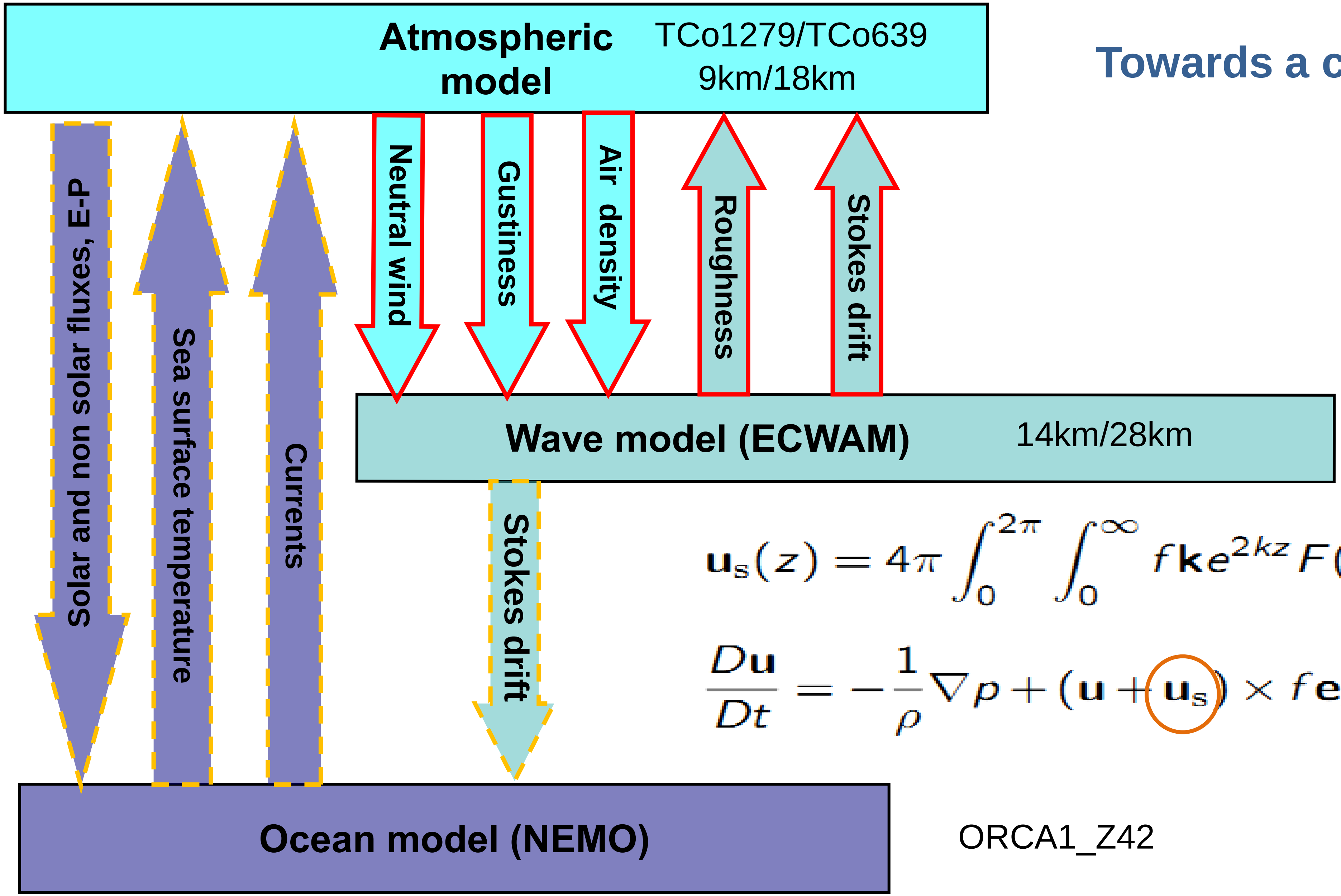
Boreal summer




SST
mean difference

Results from standalone runs, forced by ERA-interim fluxes and sea state.
Averages are over a 20 year period

## Towards a coupled system




**All configurations**

**Ensemble FC**

Single executable

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

$$\frac{D\mathbf{u}}{Dt} = -\frac{1}{\rho}\nabla p + (\mathbf{u} + \mathbf{u}_s) \times f\mathbf{e}_z + \frac{1}{\rho}\frac{\partial \tau}{\partial z}$$

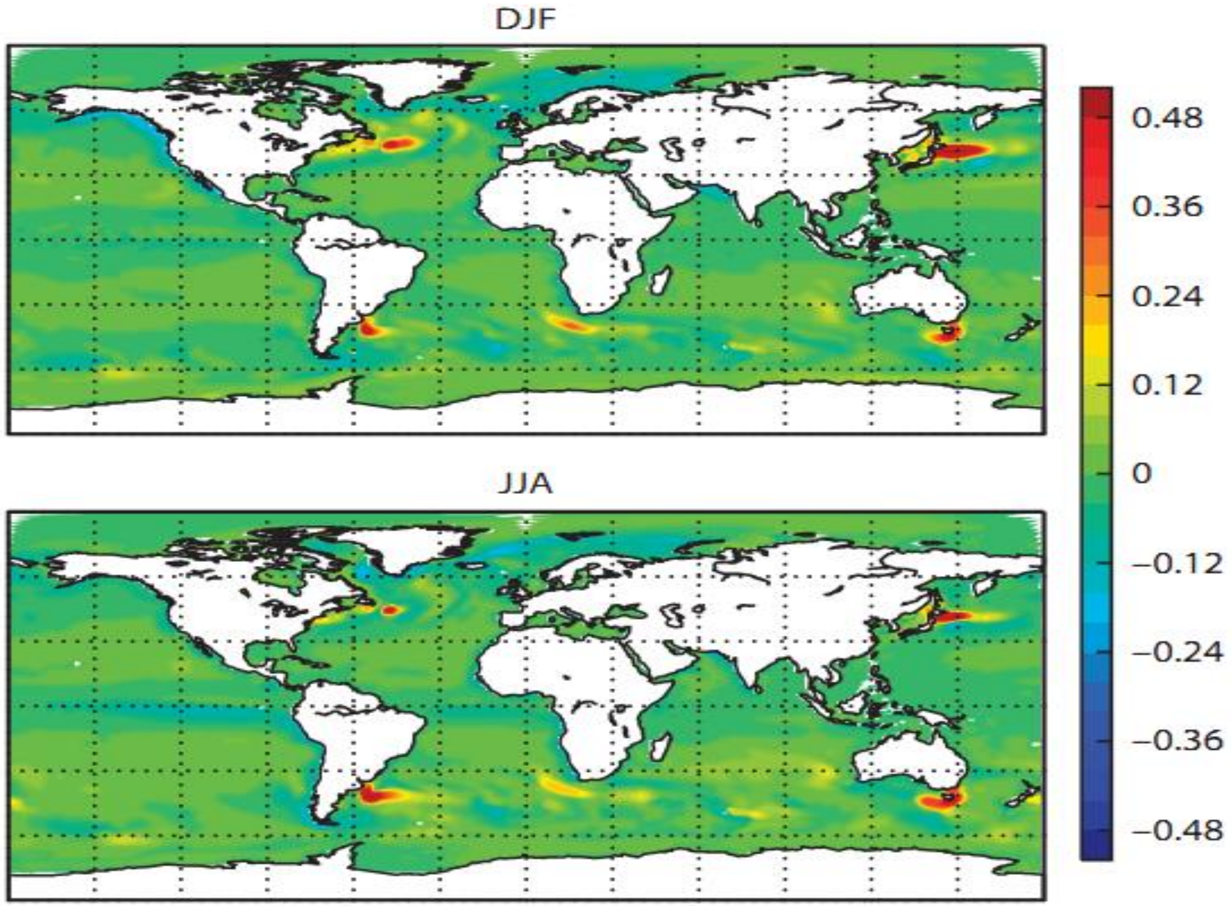
ORCA1_Z42

$U_s(z)$ vertical profile approximated using Breivik et al. 2014

# Wave effects in NEMO: Stokes-Coriolis Forcing

Boreal winter

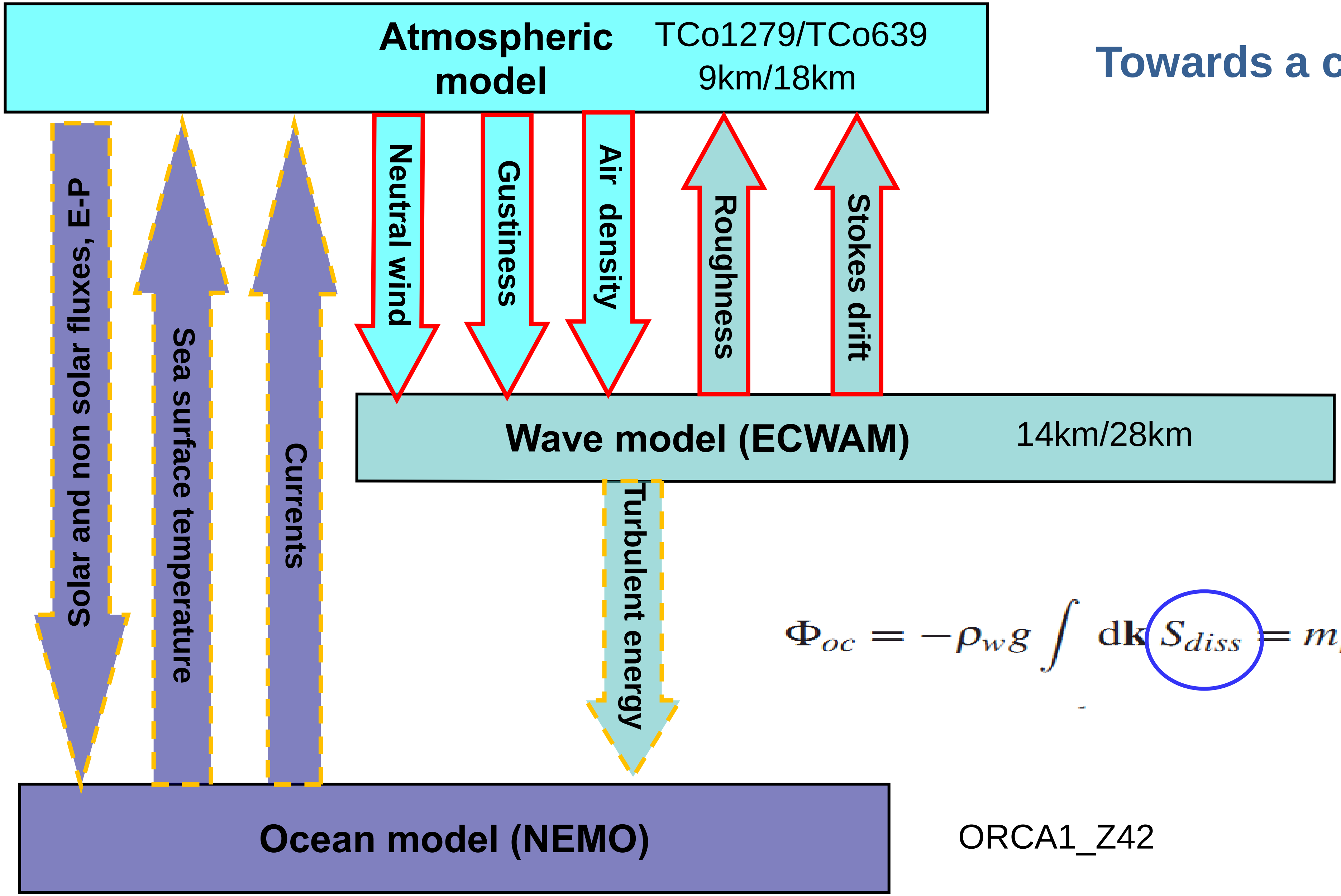
Boreal summer




SST
mean difference

Results from standalone runs, forced by ERA-interim fluxes and sea state.
Averages are over a 20 year period

## Towards a coupled system




ORCA1_Z42

All configurations

Ensemble FC

Single executable

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

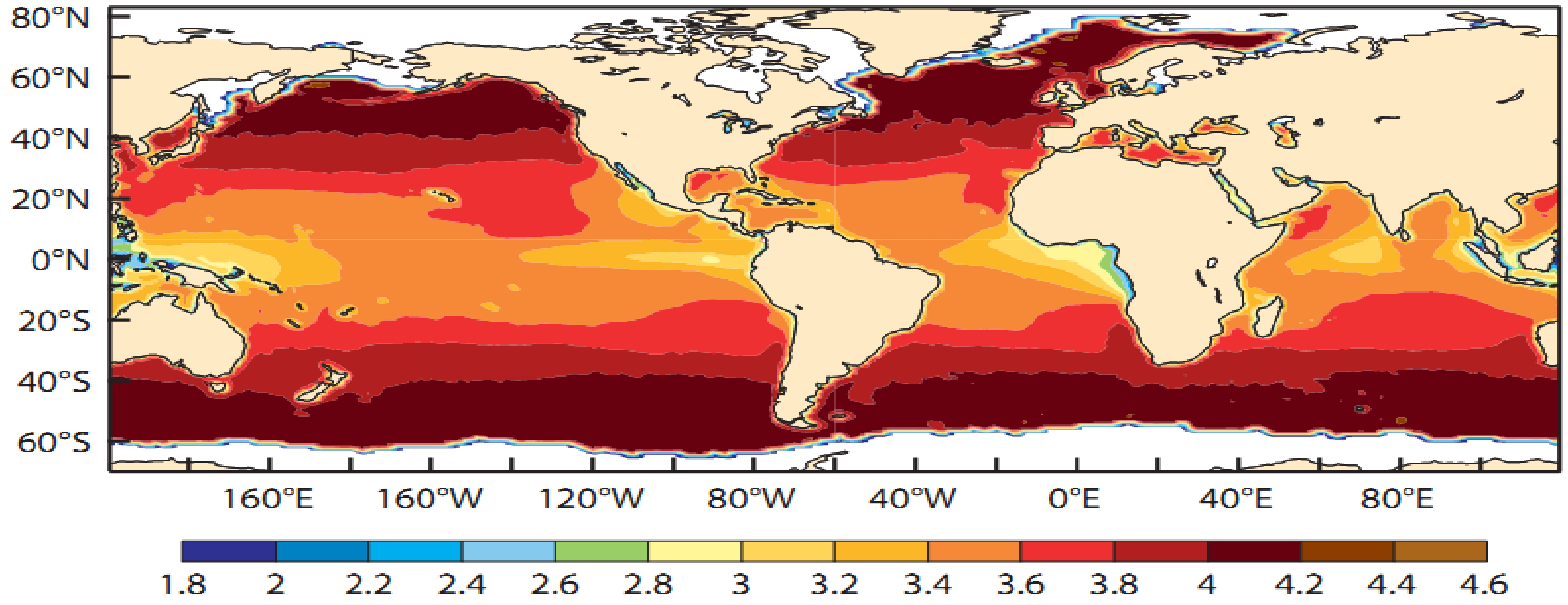
# Wave effects in NEMO: input of turbulent kinetic energy

The turbulence modelling is based on an extension of the **Mellor-Yamada scheme** with sea state effects introduced following Craig and Banner (1994). Here, the turbulence is enhanced by means of the energy flux from waves to ocean column which follows from the dissipation term in the energy balance equation:

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

m: NEMO default m=3.5

Normalised mean of the energy flux into the ocean from ERA-Interim analysis from 1 October 2010 to 30 September 2012



## TKE EQUATION

If effects of advection are ignored, the turbulent kinetic energy (TKE) equation describes the rate of change of turbulent kinetic energy $e$ due to processes such as shear production (including the shear in the Stokes drift), damping by buoyancy, vertical transport of TKE, and turbulent dissipation $\varepsilon$. It reads

$$\frac{\partial e}{\partial t} = \frac{\partial}{\partial z}\left(\nu_q \frac{\partial e}{\partial z}\right) + \nu_m S^2 + \nu_m S \frac{\partial U_S}{\partial z} - \nu_h N^2 - \varepsilon,$$

where $e = q^2/2$, with $q$ the turbulent velocity, $S = \partial U/\partial z$ and $N^2 = g\rho_0^{-1}\partial\rho/\partial z$, with $N$ the Brunt-Väisälä frequency. The eddy viscosities for momentum, heat, and TKE are denoted by $\nu_m$, $\nu_h$ and $\nu_q$. E.g $\nu_m = l(z)q(z)S_M$ where $l(z)$ is the mixing length and $S_M$ depends on stratification.

Wave-induced turbulence is introduced by the boundary condition:

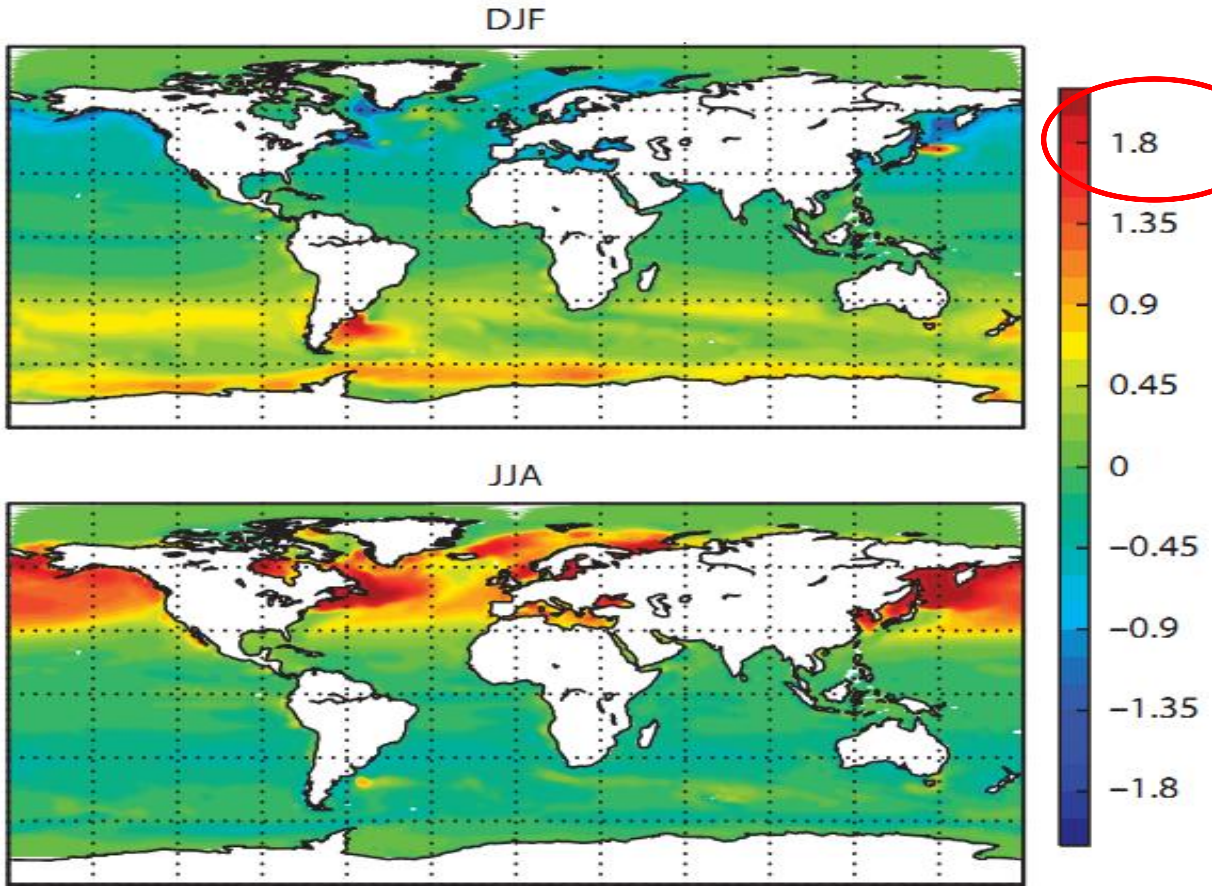
$$\rho_w \nu_q \frac{\partial e}{\partial z} = \Phi_{oc}, \quad z = 0.$$

while effects of Langmuir turbulence are introduced by the term involving the shear in the Stokes-drift profile.

# Wave effects in NEMO: input of turbulent kinetic energy

Boreal winter

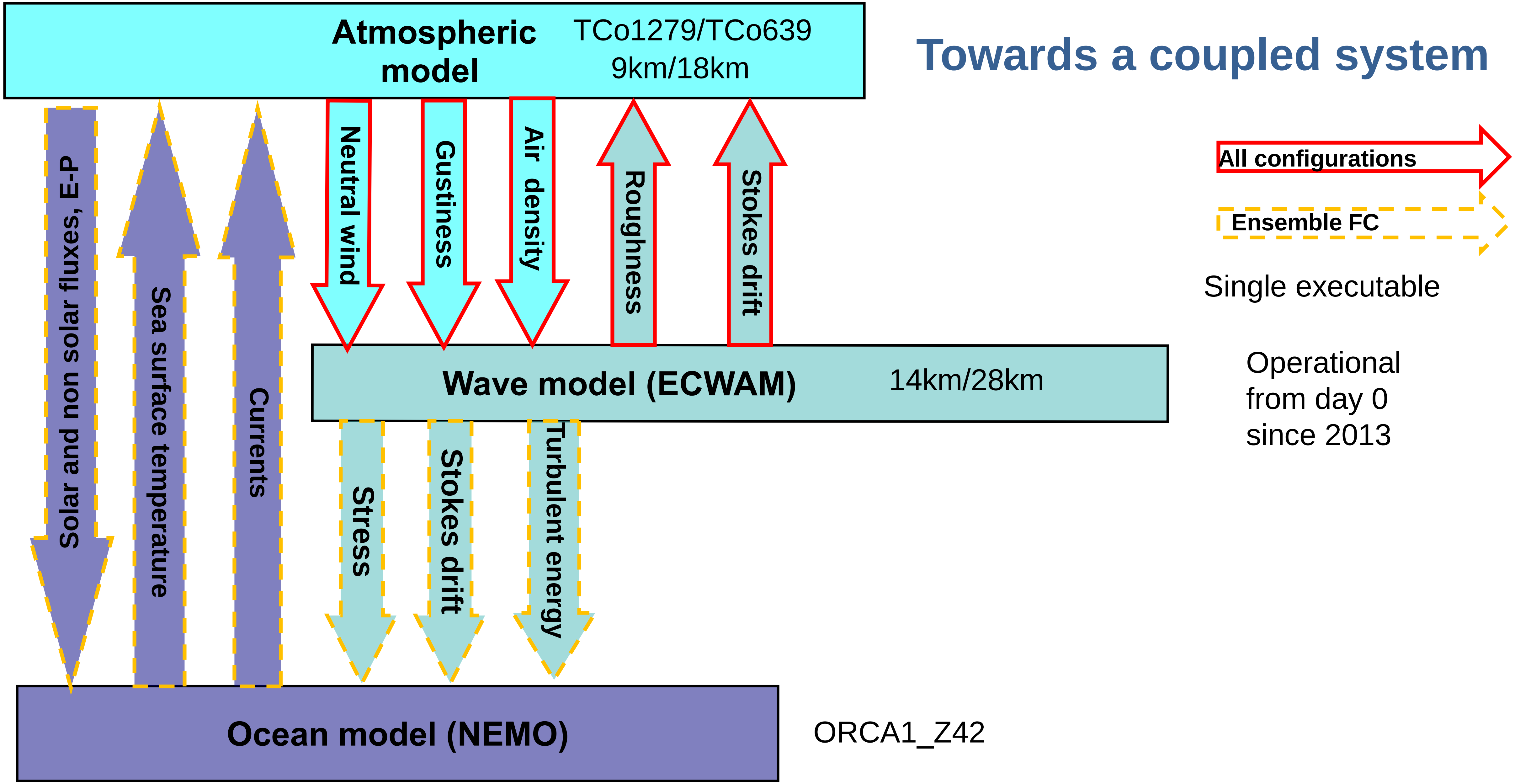
Boreal summer




SST
mean difference

Results from standalone runs, forced by ERA-interim fluxes and sea state.
Averages are over a 20 year period

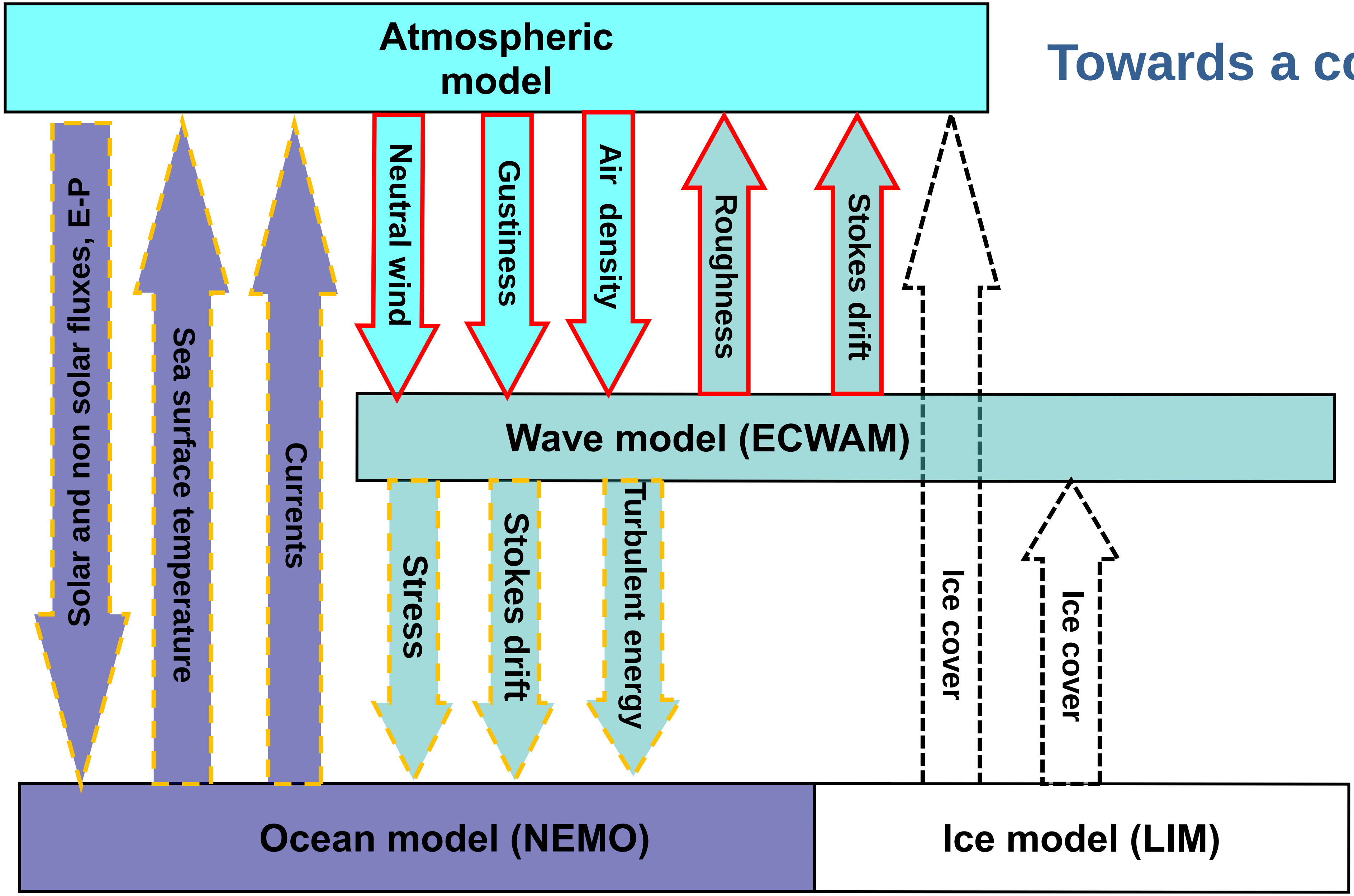
# Towards a coupled system




Single executable

Operational from day 0 since 2013

# Towards a coupled system




All configurations

Ensemble FC

future operational

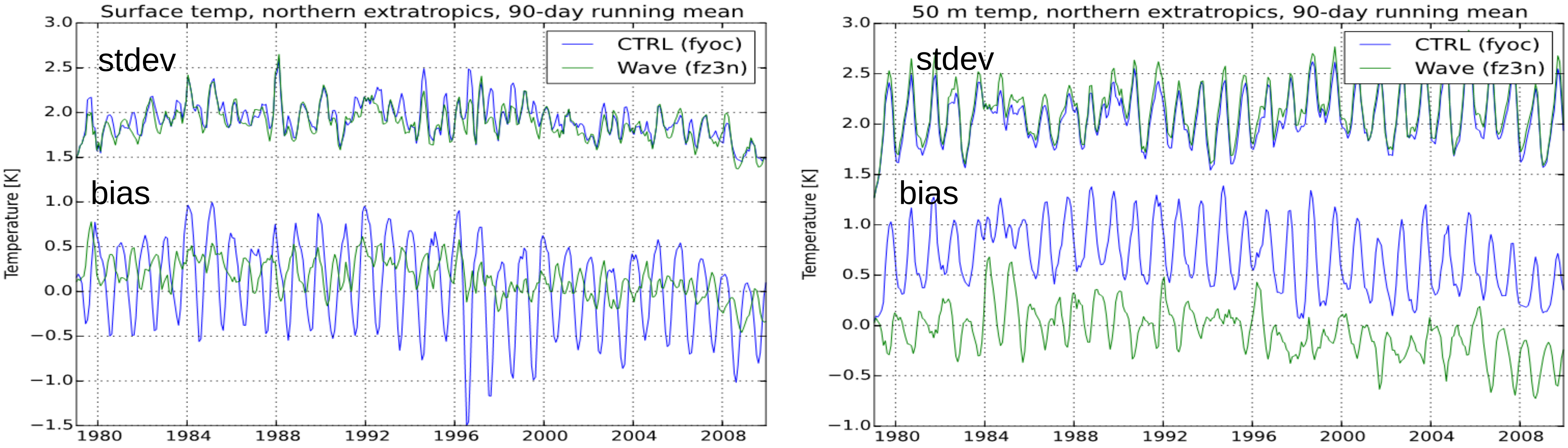
Single executable

**Adding**
**active sea ice model**

**Implementation:**
**CY43R1**
**end 2016.**

**ORCA0.25°_Z75**

# Wave effects in NEMO



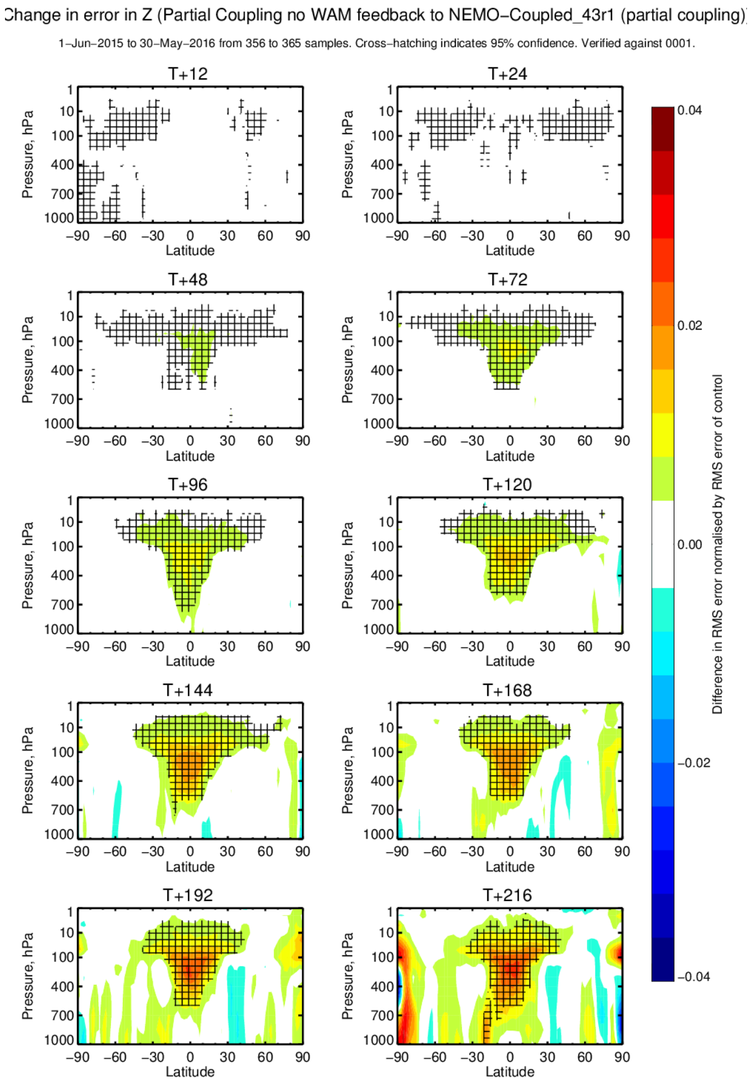

Comparison of surface (left) and 50 m depth (right) EN3 ocean temperature observations (Ingleby and Huddleston, 2007) in the northern extra-tropics in the CTRL run (blue) and a run with all three wave effects switched on (green).

The upper curves show the standard deviation while the lower curves represent the bias.

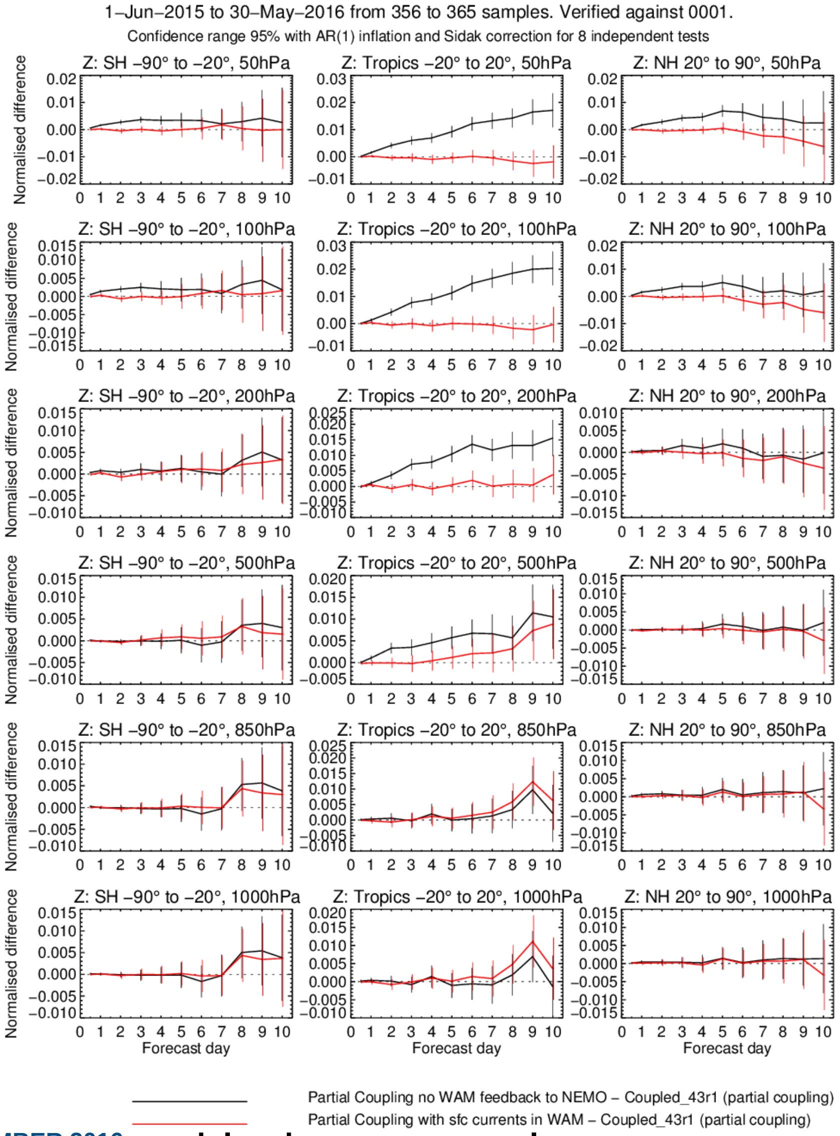
A 90-day running mean is employed.

# Sensitivity study: no wave feedback to NEMO

Normalised difference in RMSE for Z




worst



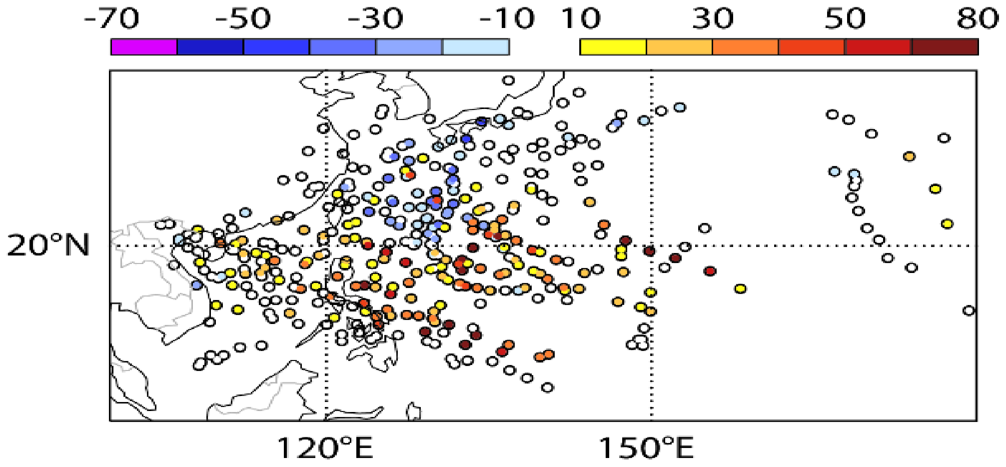

> 0 means worst

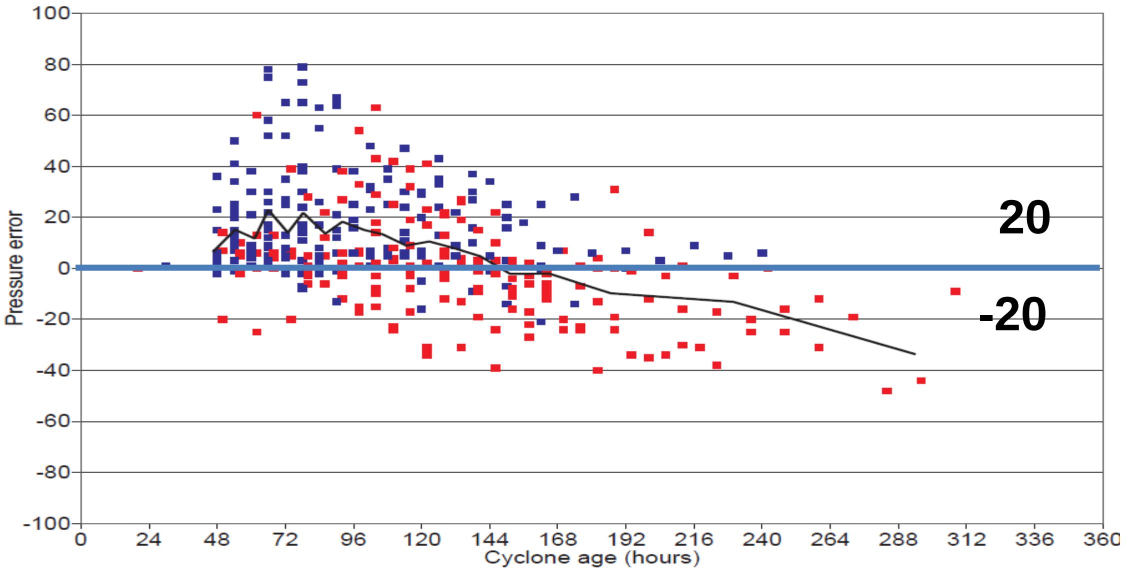
black curves only

# Impact of Coupling on tropical cyclone forecast:

Tropical cyclone **core pressure mean error** in the Western Pacific (hPa) of the <u>operational</u> high resolution system (HRES) in 2013-2014:

**Error (hPa)**




**20**

**-20**

**too weak**

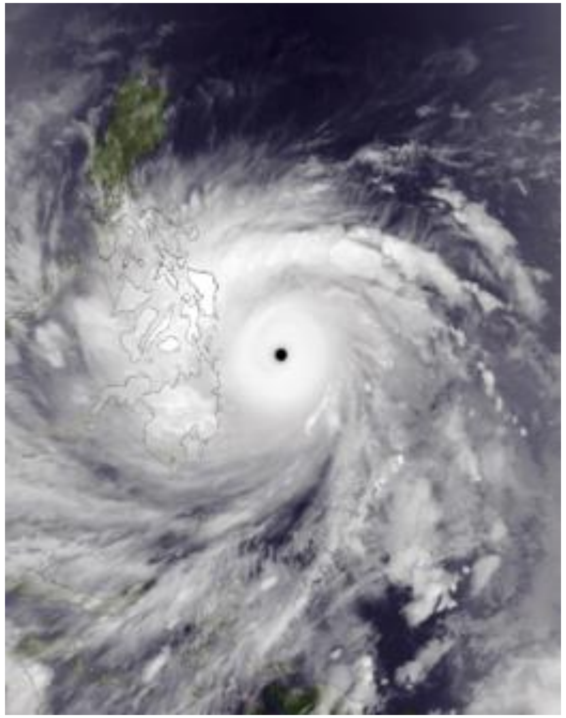
**too strong**

**Cyclone age (hours)**

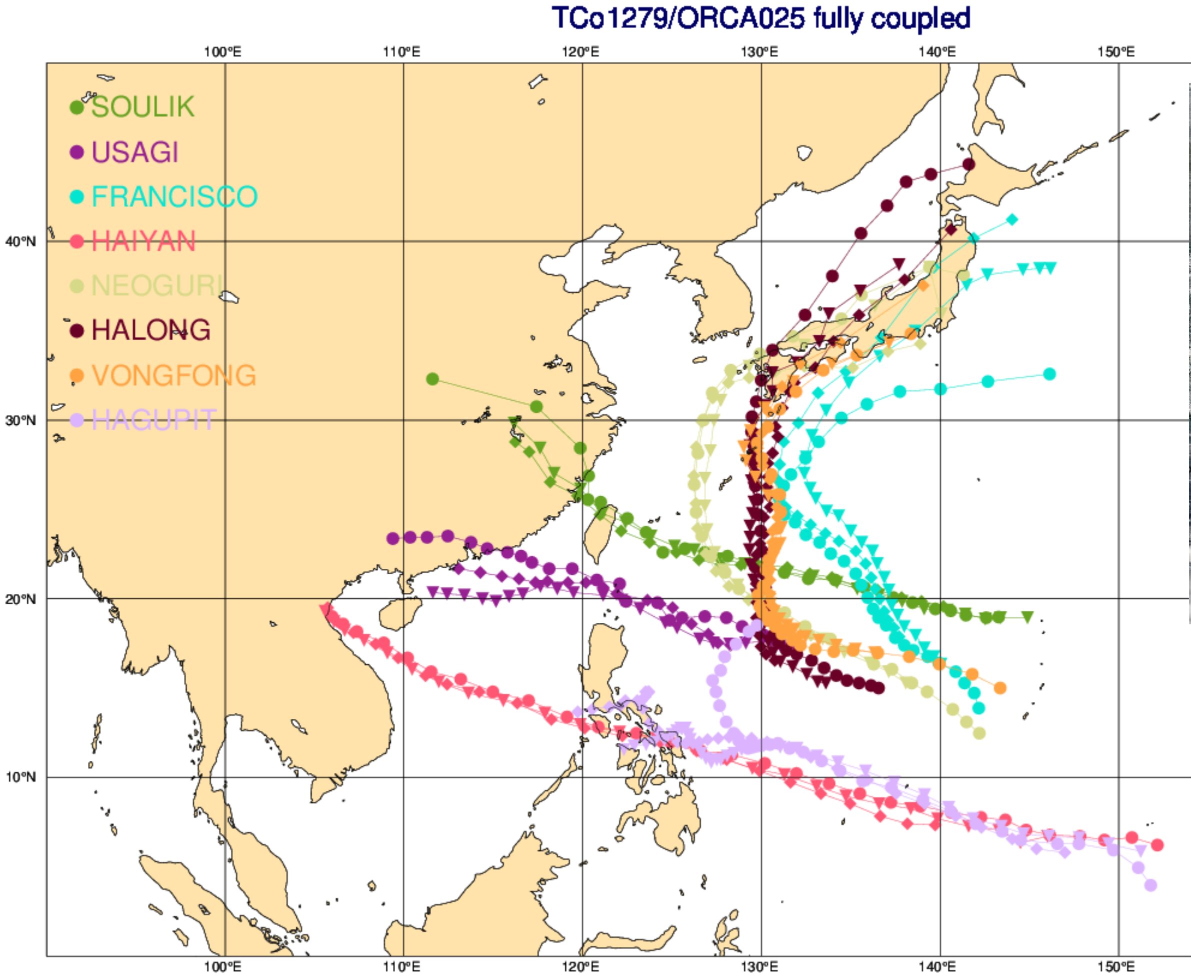
Red dots: north of 20°N
Blue dots: south of 20°N

Rodwell et al., 2015: New Developments in the Diagnosis and Verification of High-Impact Weather Forecasts. ECMWF Technical Memorandum 759. http://www.ecmwf.int/en/elibrary/technical-memoranda

# TCo1279+ORCA025 fully coupled

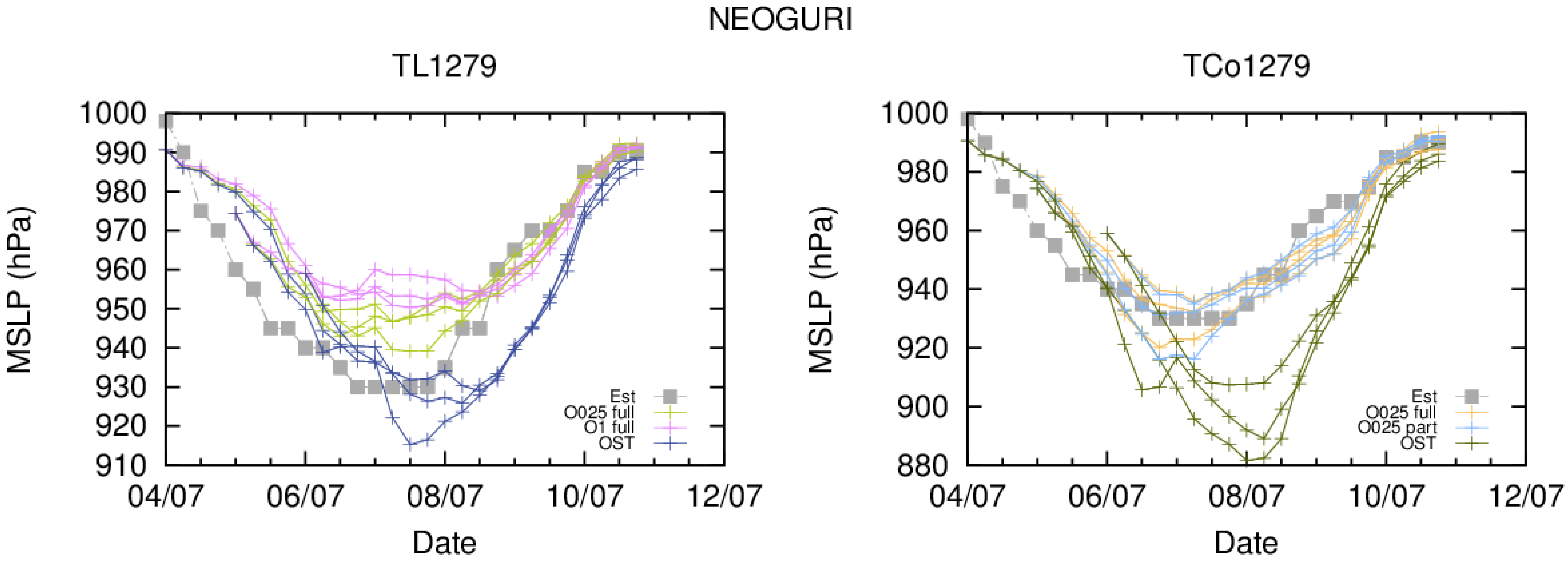


Typhoon Haiyan at peak intensity on November 7, 2013




Neoguri affecting Okinawa on July 8, 2014

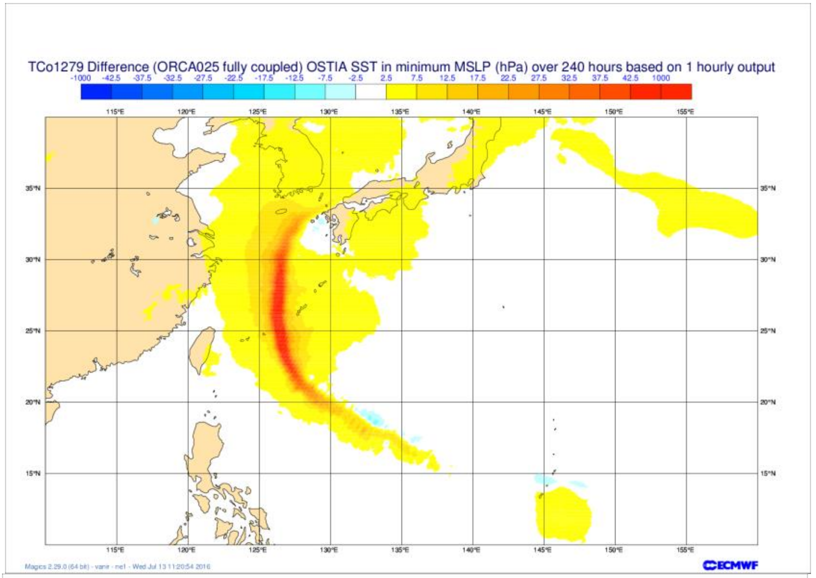
# NEOGURI centre pressure, CY43R1 latest testing

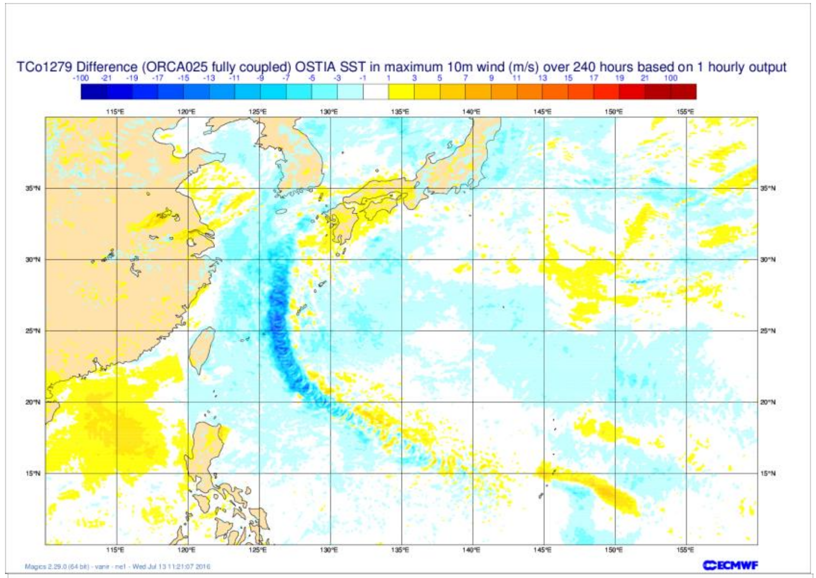



EST : estimated from observations
0025: ORCA0.25°_Z75
01: ORCA1.0°_Z42
OST : prescribed OSTIA SST (uncoupled)

# Differences between coupled and uncoupled for NEOGURI TCo1279 (CY43R1)

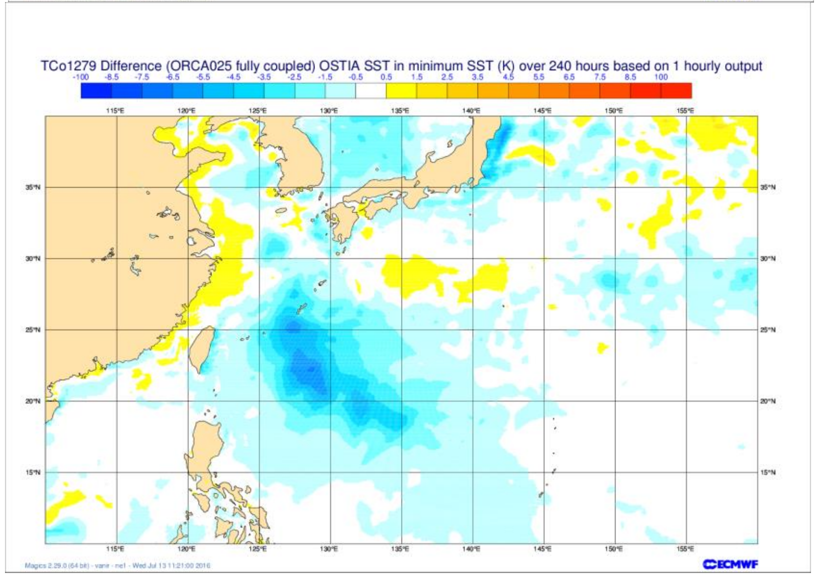
Difference in <u>Minimum</u> MSLP (hPa): Coupled minus operational

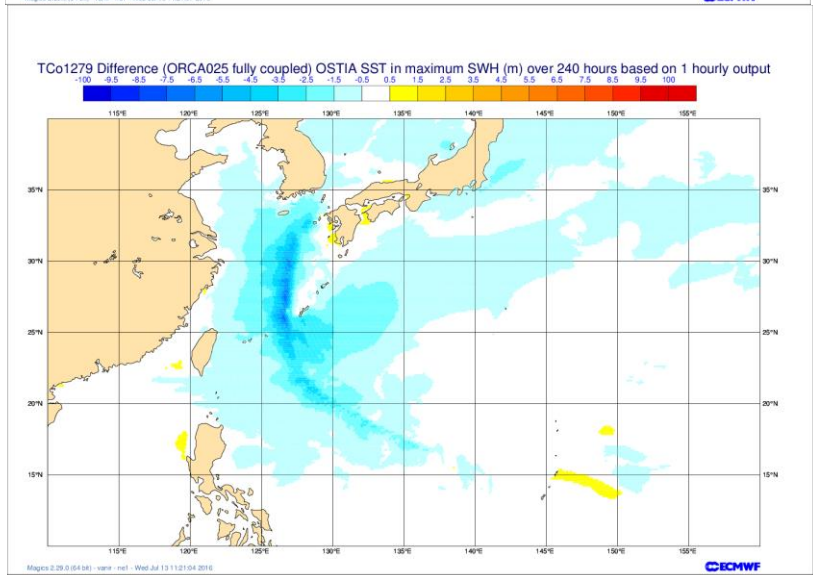



Difference in <u>Maximum</u> Wind speed (m/s): Coupled minus uncoupled

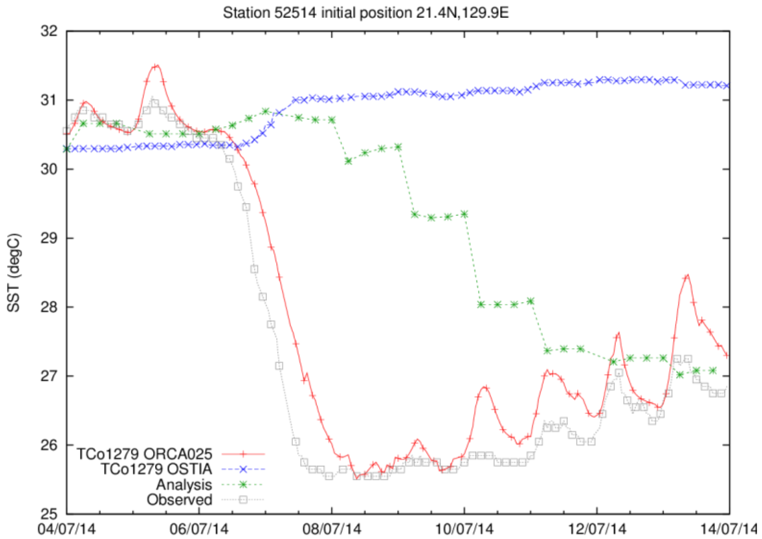
Difference in <u>Minimum</u> SST (K): Coupled minus uncoupled

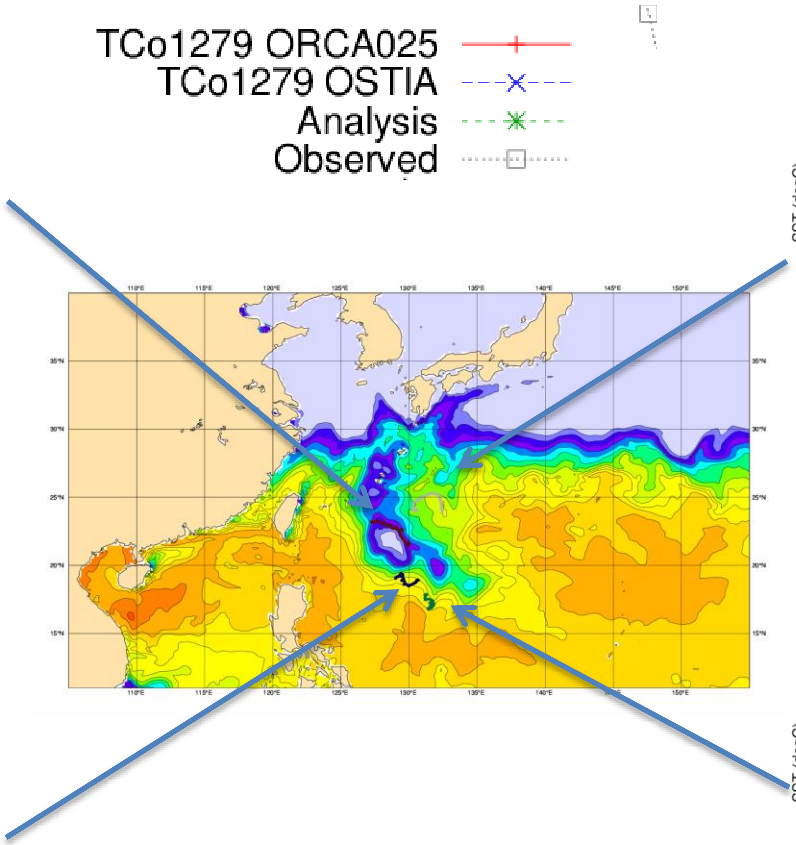


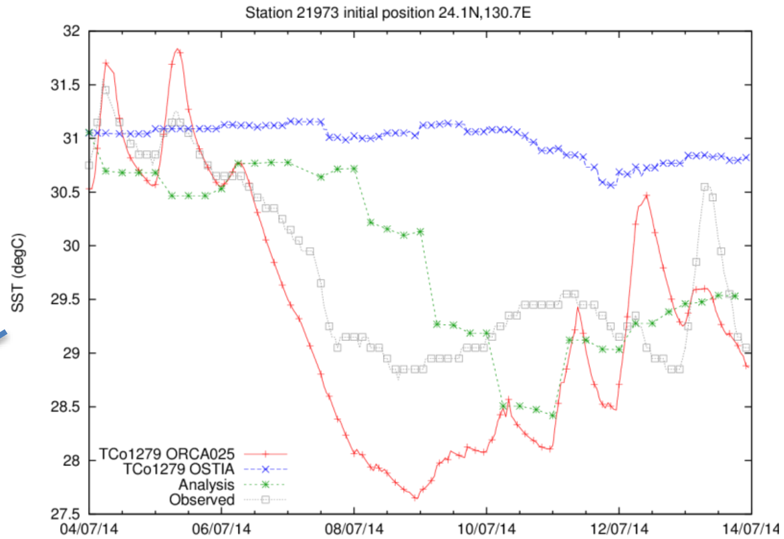



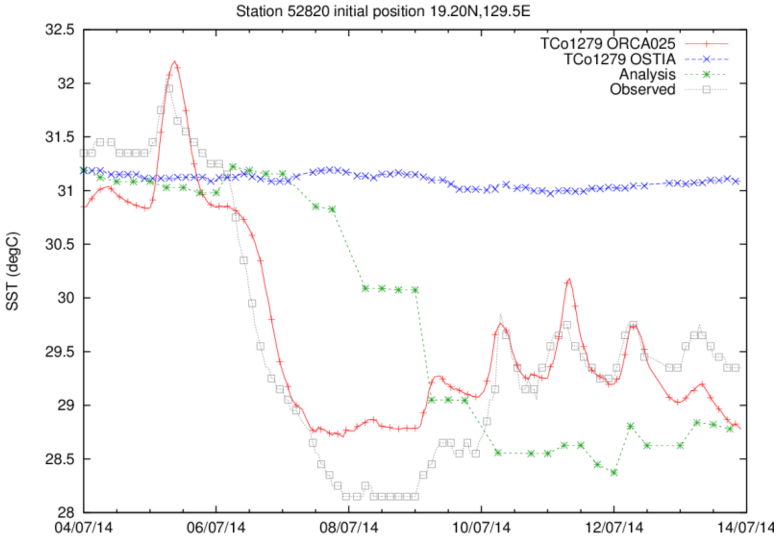

Difference in <u>Maximum</u> SWH (m): Coupled minus operational

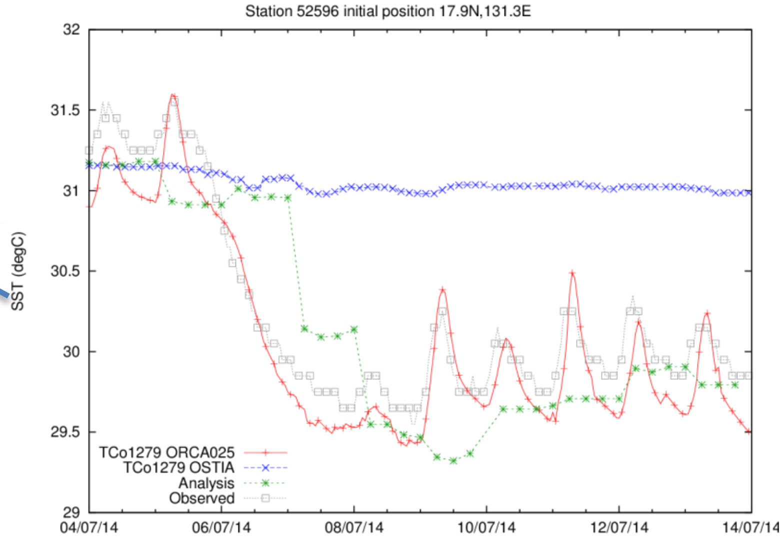
# NEOGURI SST comparison with drifting buoys: TCo1279 full coupling (CY43R1).



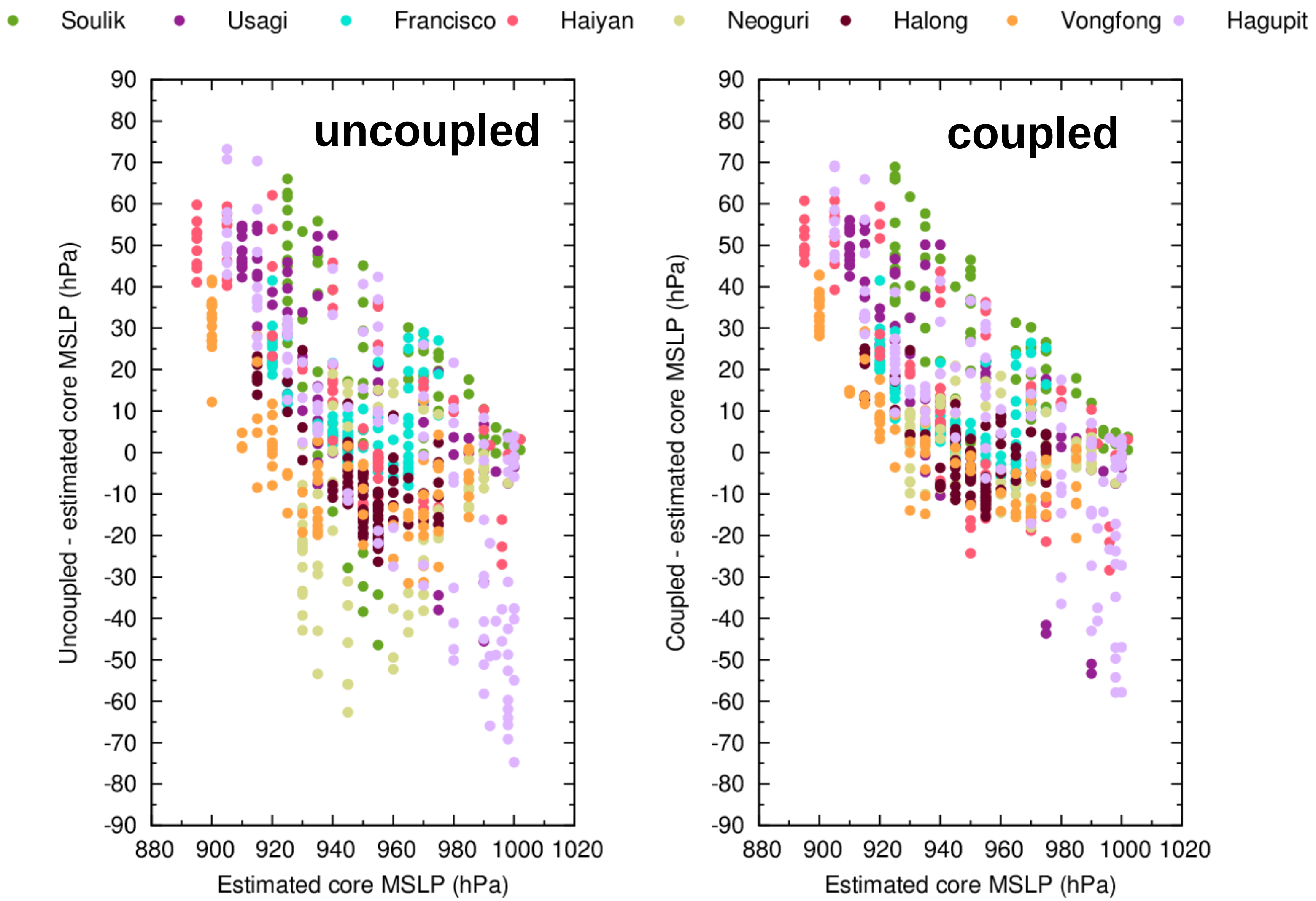



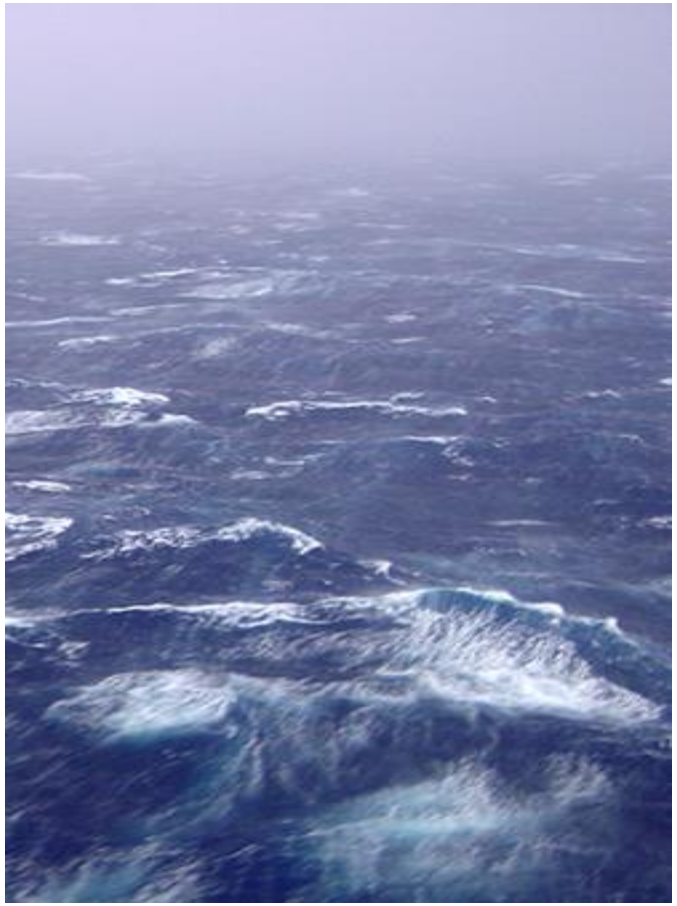



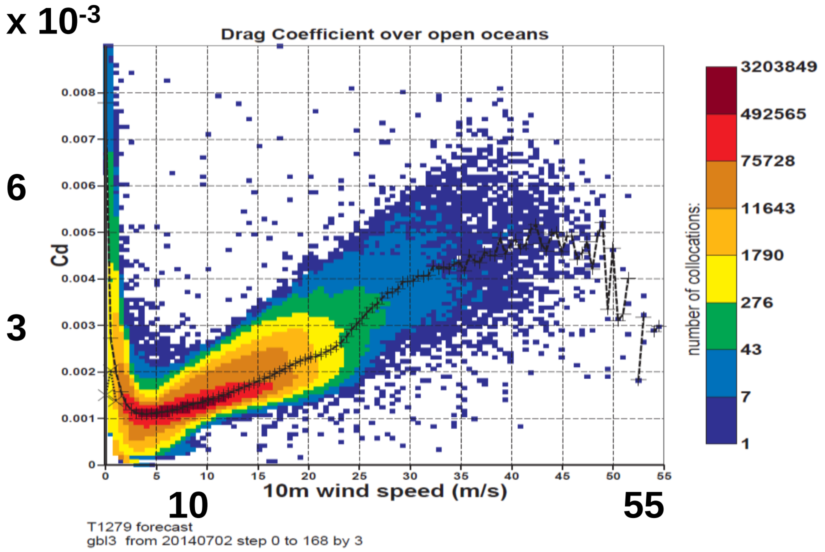
# TCo1279+ORCA025 full coupling relative to uncoupled OSTIA SST



# Future developments:




# Impact of Coupling: revisit parameterisations?



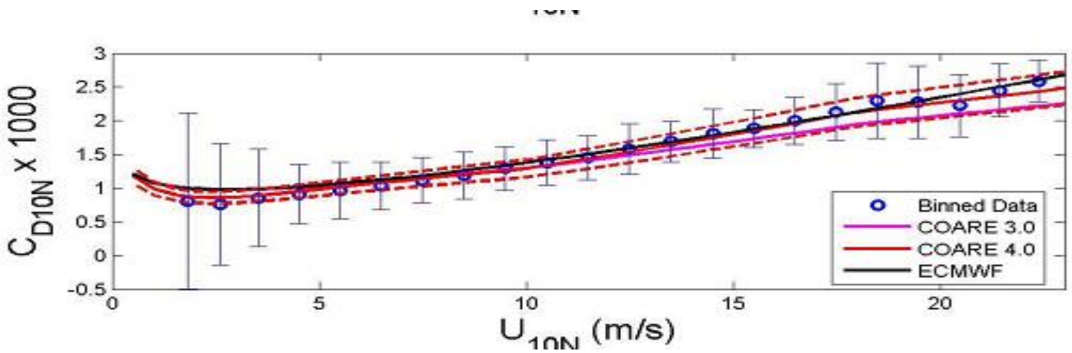

Exchange coefficients dependency on wind speed

Left: for momentum ($C_d$)

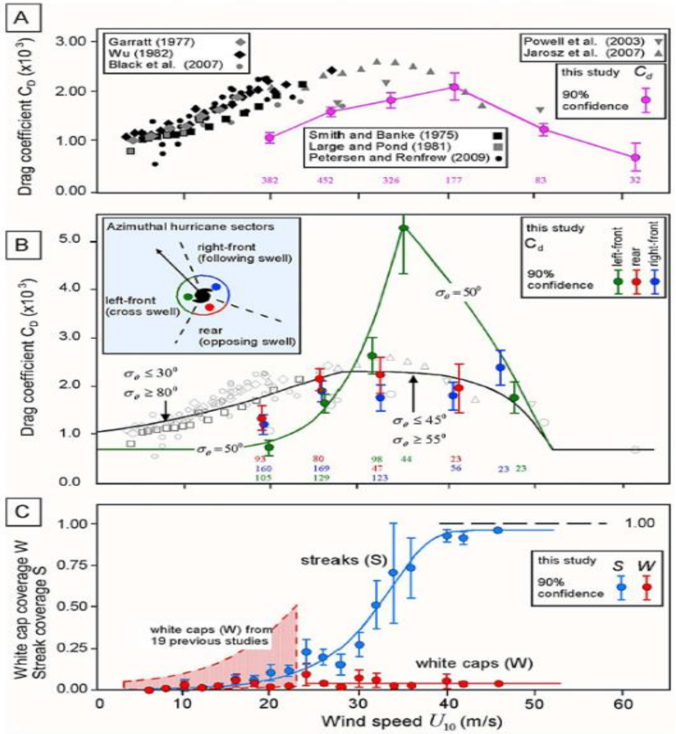
**$C_d$ fits well observations for winds up to 20m/s**

**But it might be too high for large winds**

$C_d$ is sea state dependent

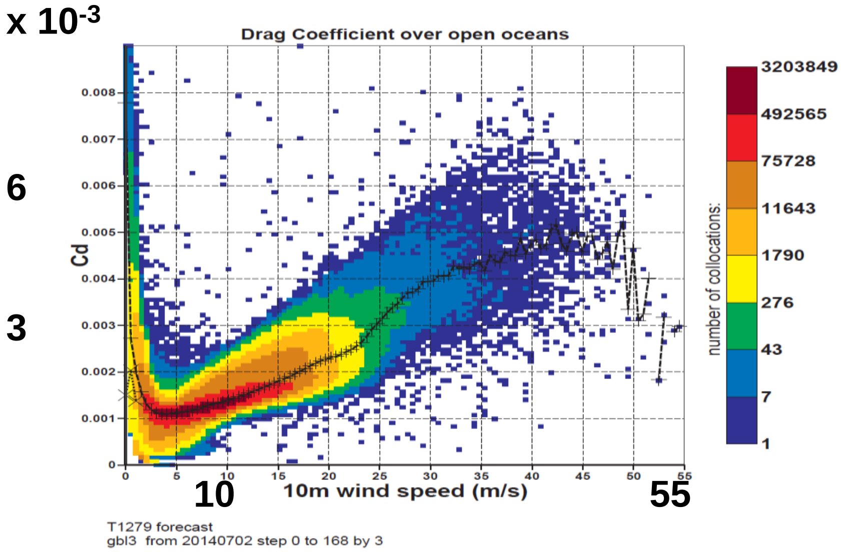



Edson et al., 2013



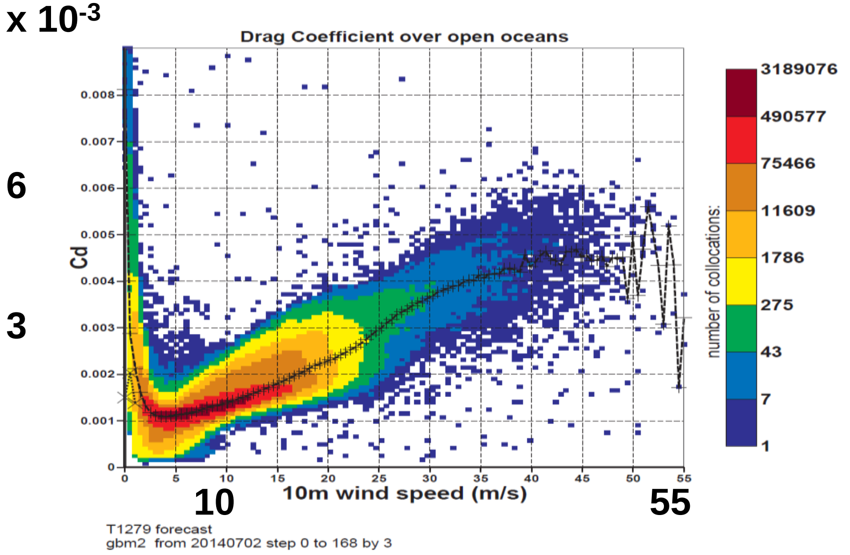

Holthuijsen et al. , 2012

# Impact of Coupling: revisit parameterisations?




In ECWAM, from about 1.3 times the peak frequency the model has an omega−4 spectrum which is caused by the nonlinear interactions pumping energy from the low frequency waves to the high frequency waves. In fact, we have the model spectra take the form of the Toba spectrum in that frequency range.

$$F(\omega) = \alpha_t \, g \, u_* \, \omega^{-4}$$

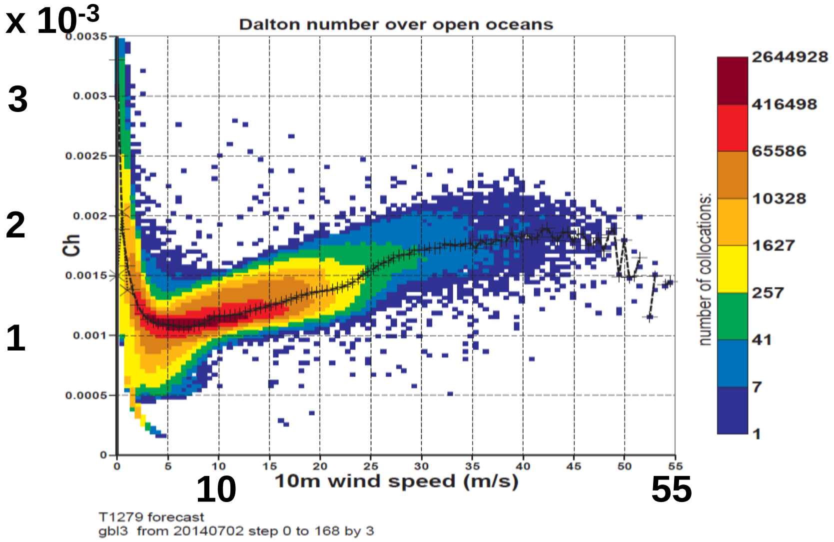



However, clearly for strong winds, hence large u∗, the Toba spectrum cannot hold because the waves in that frequency range become too steep and breaking should happen.
Therefore, we impose a limitation to the high frequency part of the spectrum based on a limiting Phillips spectrum.
This is part of CY43R1.

$$F_{max}(f) = \alpha_{max} \, g^2 \, (2\pi)^{-4} \, f^{-5}$$

# Impact of Coupling: revisit parameterisations?

Exchange coefficients
dependency on wind speed
Right: for heat (Ch)




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

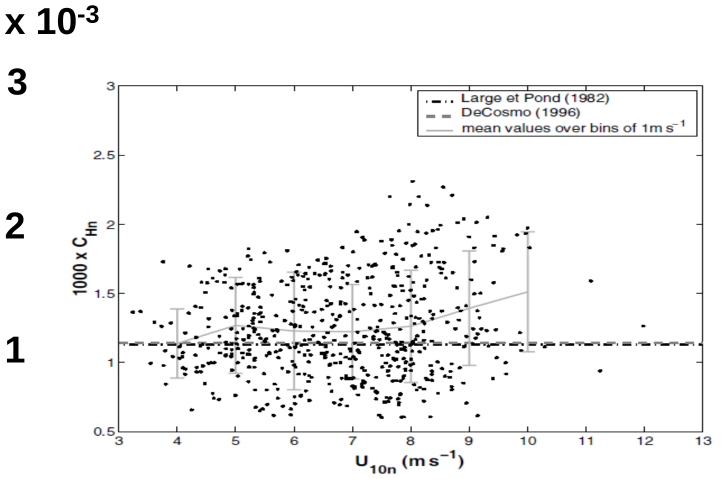


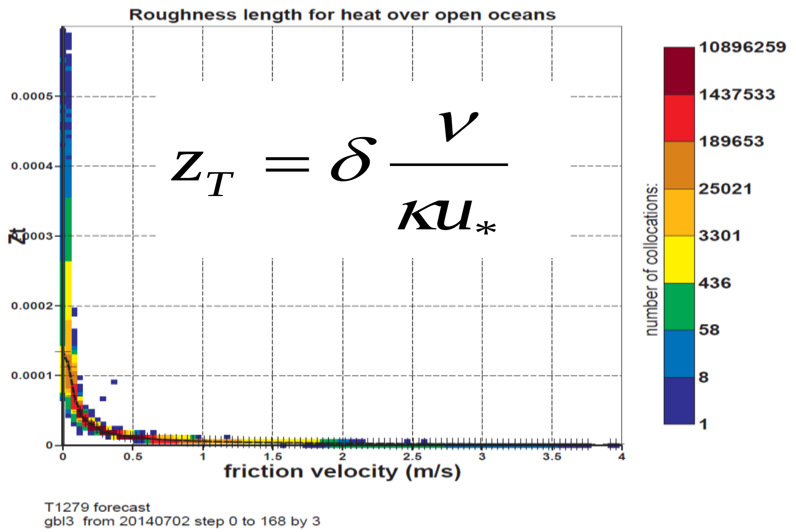

Figure 18. The exchange coefficient for temperature, $C_{Hn}$, as a function of the neutral wind speed at 10 m, $U_{10n}$. The dots correspond to 30-minute samples. The solid line with error-bars represents the values averaged over wind speed bins of 1 m s$^{-1}$. The parametrizations proposed by Large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

Brut et al. 2005

# Effect of waves on heat flux :

Current operational :

$z_T$



# Effect of waves on heat flux :

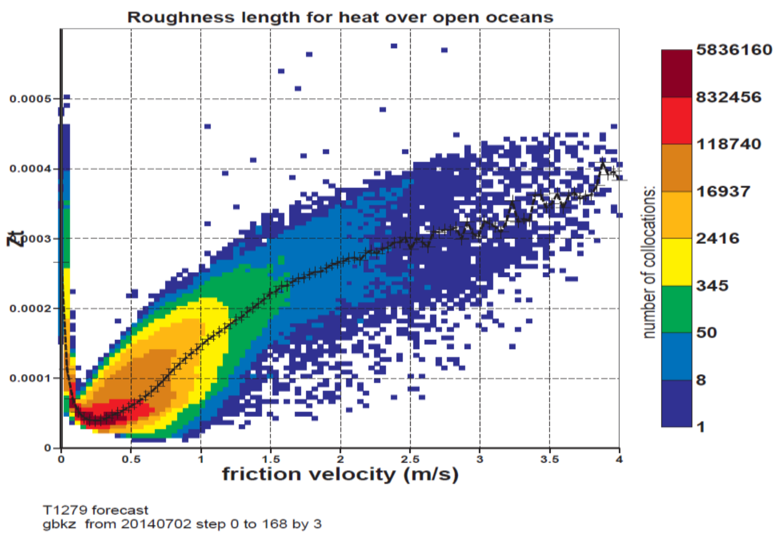
$$z_T = 10\,\frac{\left(\frac{10+x_-}{x_-}\right)^{(z_1-x_-)}}{\left(\frac{10+x_+}{x_+}\right)^{(z_1-x_+)}}$$

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

$$z_1 = \frac{\tilde{\alpha}\,u_*^2}{g}\left(\frac{1}{\{1-\frac{\tau_w}{\tau}\}^{\frac{1}{2}}} - 1\right) \qquad z_\nu = \frac{\delta\,\nu}{\kappa u_*}$$

Enhancing heat transfer:

$Z_T$

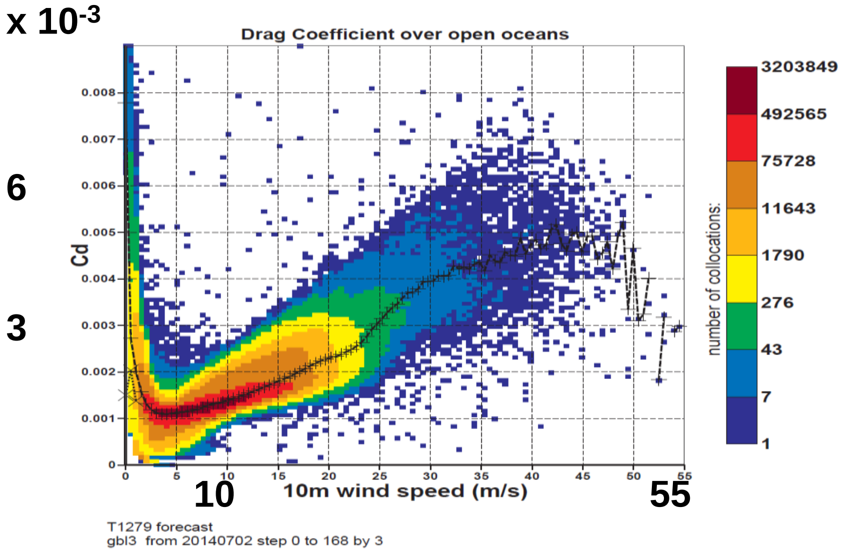


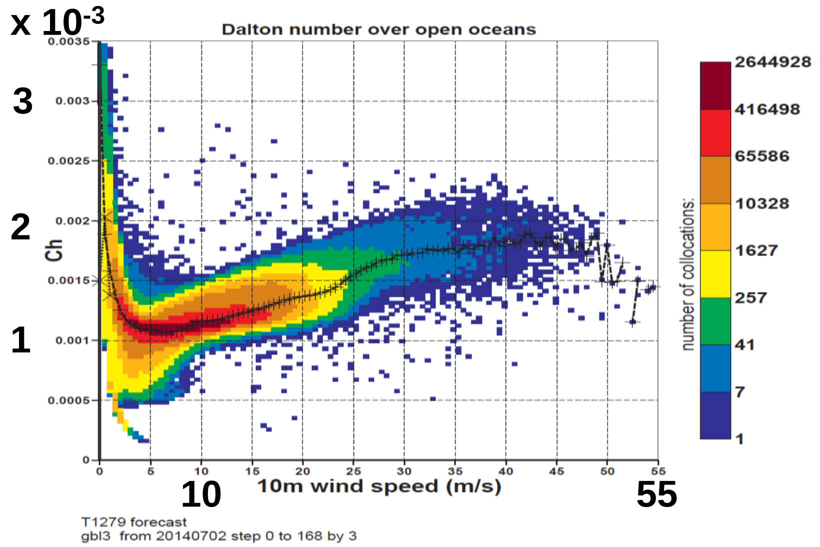

Wave induced stress:

$$\tau = u_*^2 \qquad \tau_w = \int d\omega\, d\theta\, \frac{k}{\omega} S_{wind}$$

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

# Impact of Coupling: revisit parameterisations?



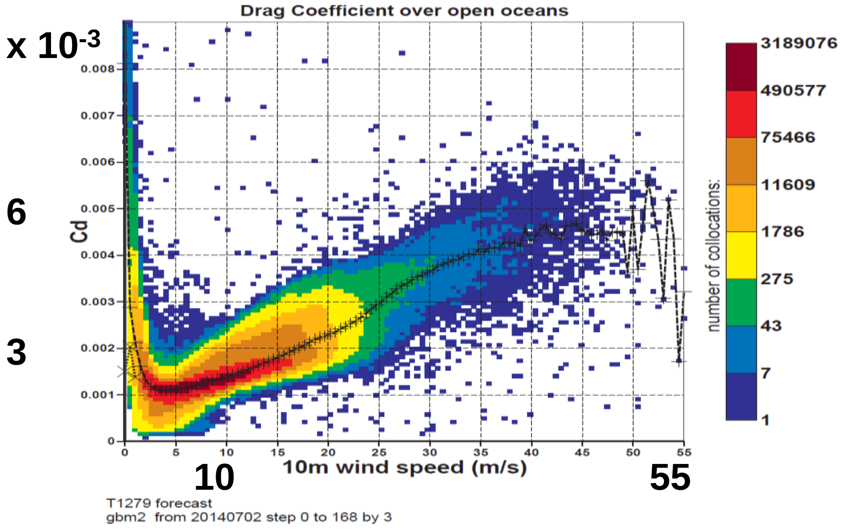



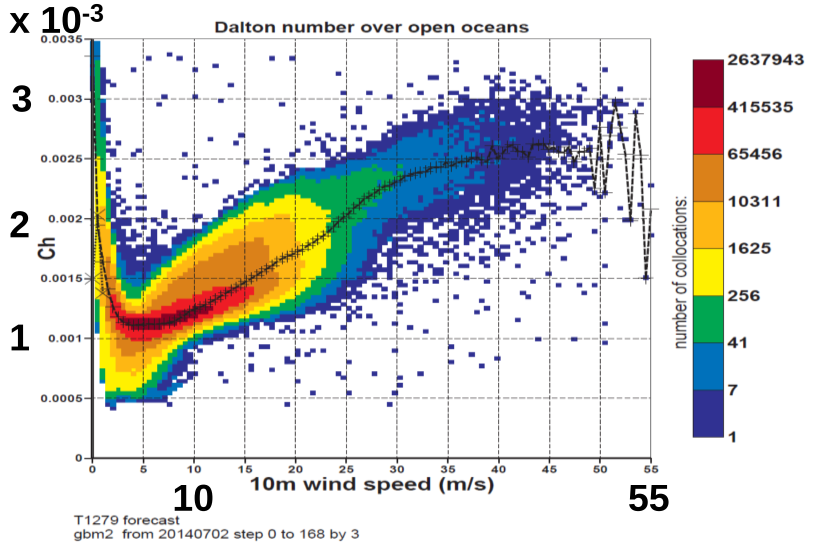

Exchange coefficients dependency on wind speed

Left: for momentum ($C_d$)

Right: for heat ($C_h$)

**Operational version**




**Experimental version**

Sea state depend $C_h$

**and**

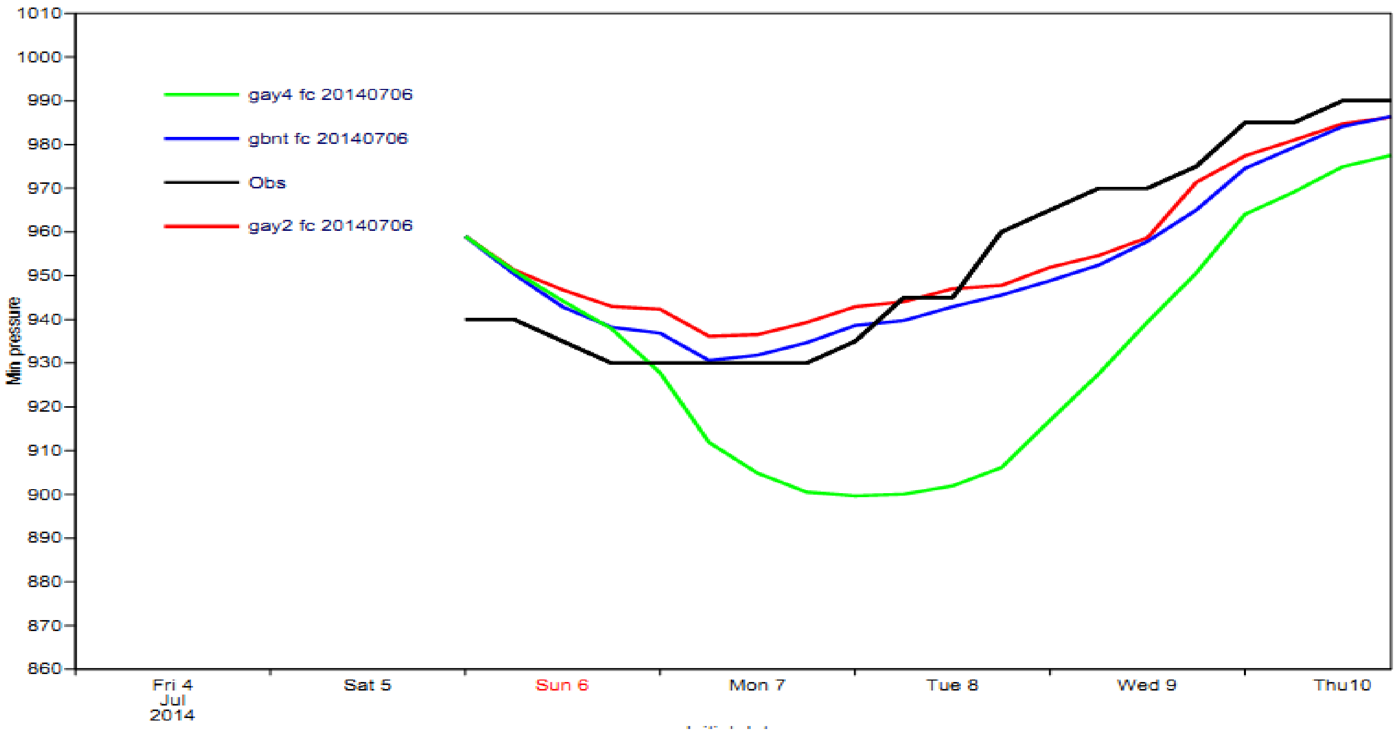
Maximum wave spectral limitation.

# Impact of Coupling on tropical cyclone forecast

min
MSLP (hPa)

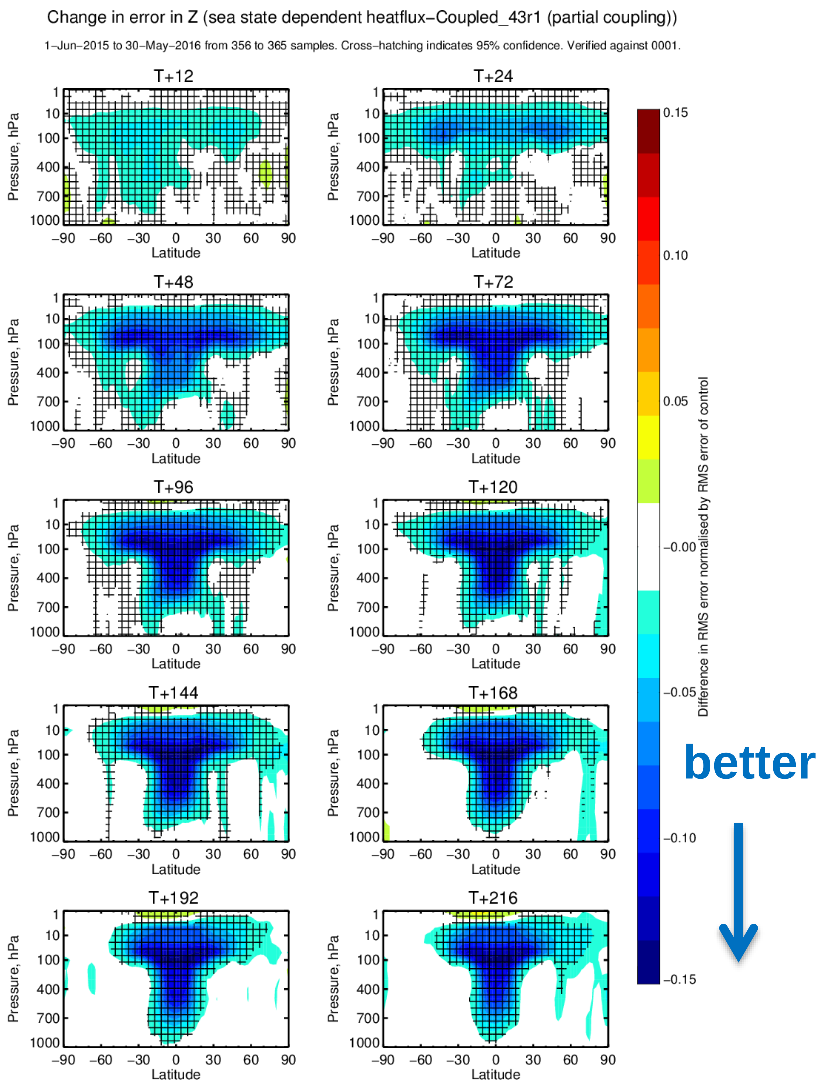
950

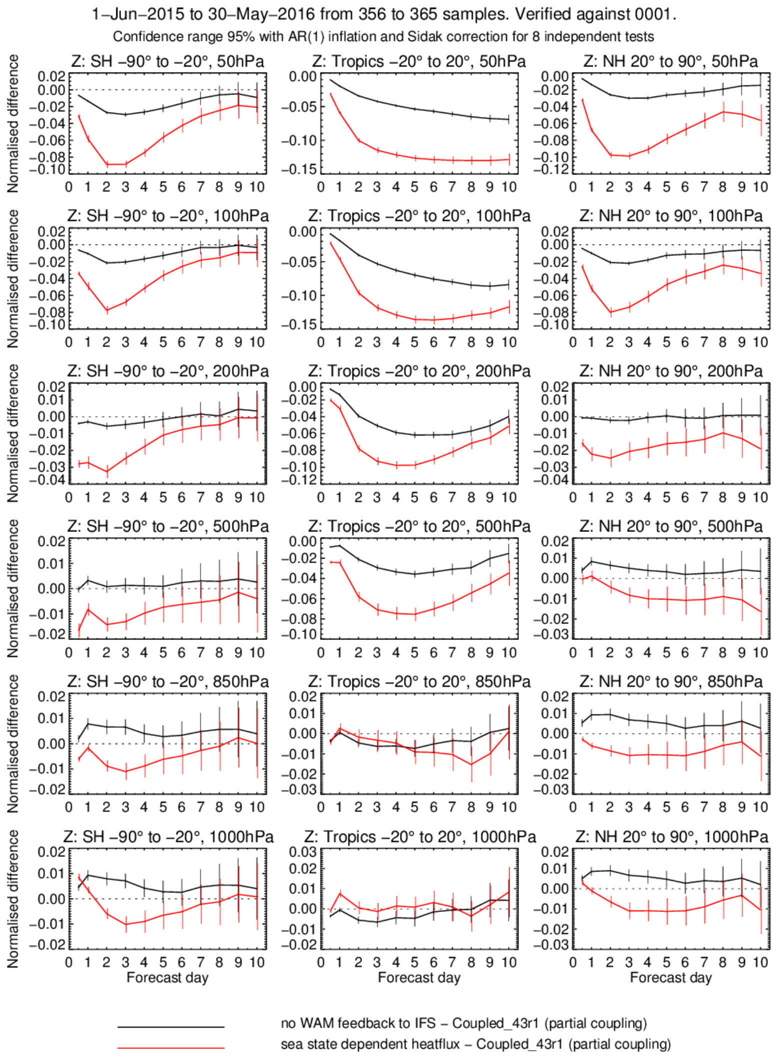
900

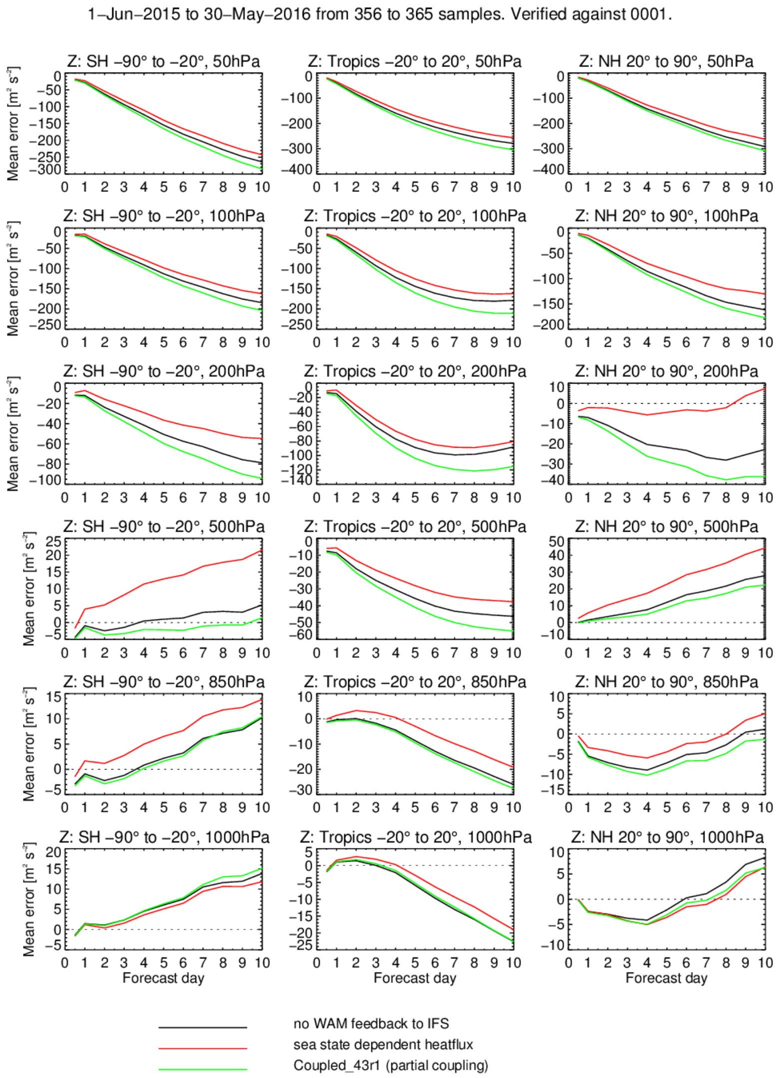



**Black:** estimated from observations
**Green**: operational HRES configuration (**uncoupled**) (16km)
**Red**: 16km **coupled** to NEMO (ORCA025_Z75)
**Blue**: 16km **coupled to NEMO + new sea state dependant heat and moisture fluxes**

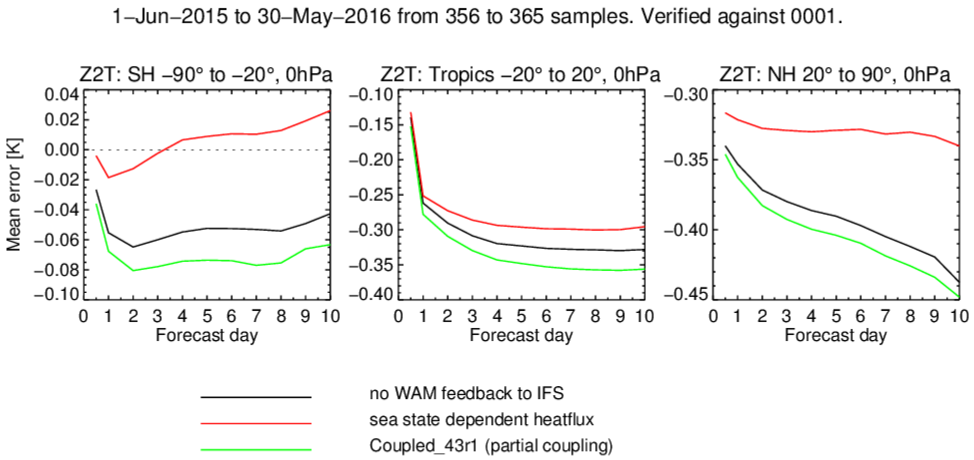
# Sensitivity study: wave dependent heat and moisture fluxes



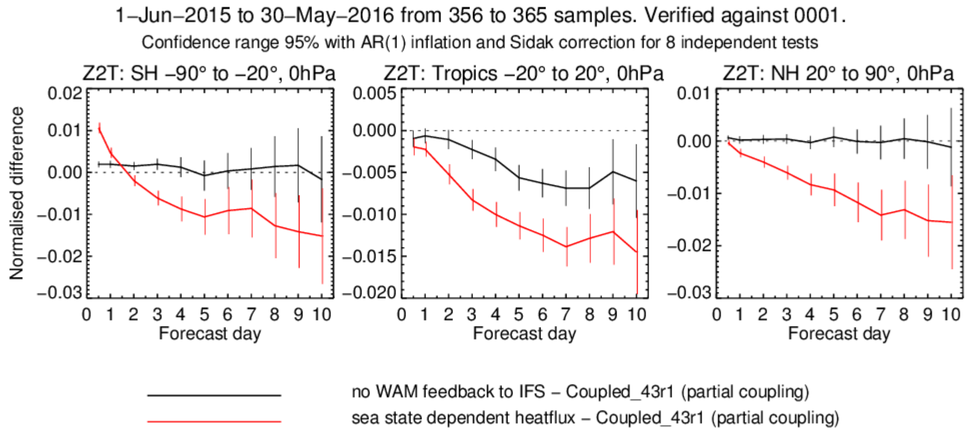



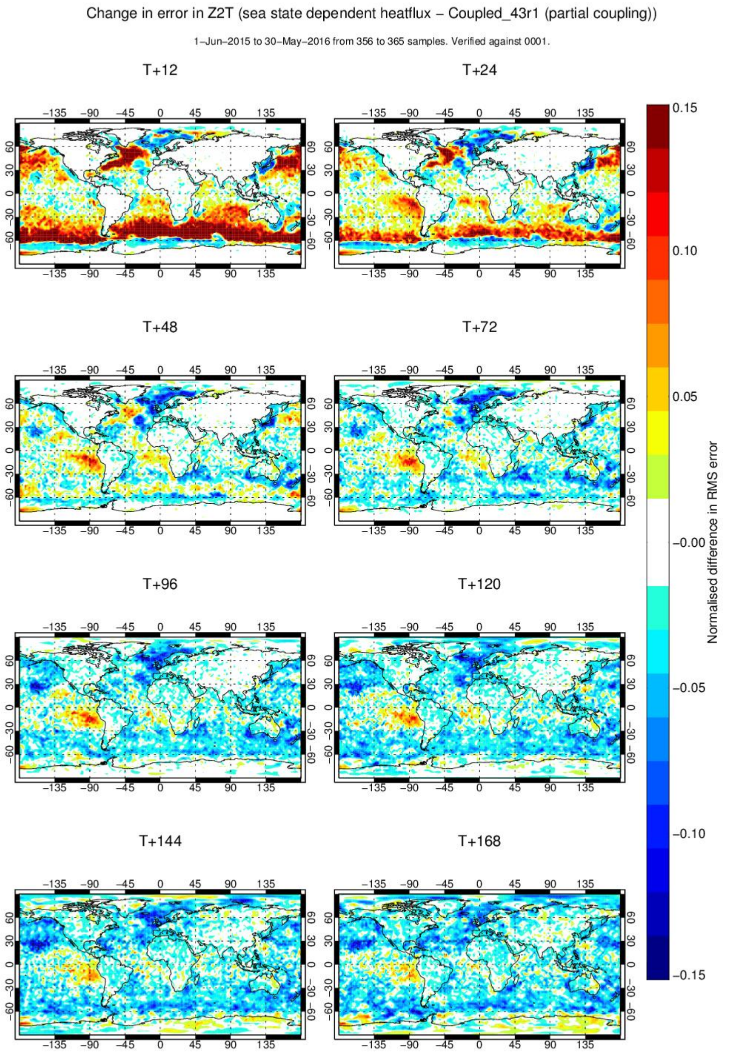
# Sensitivity study: wave dependent heat and moisture fluxes



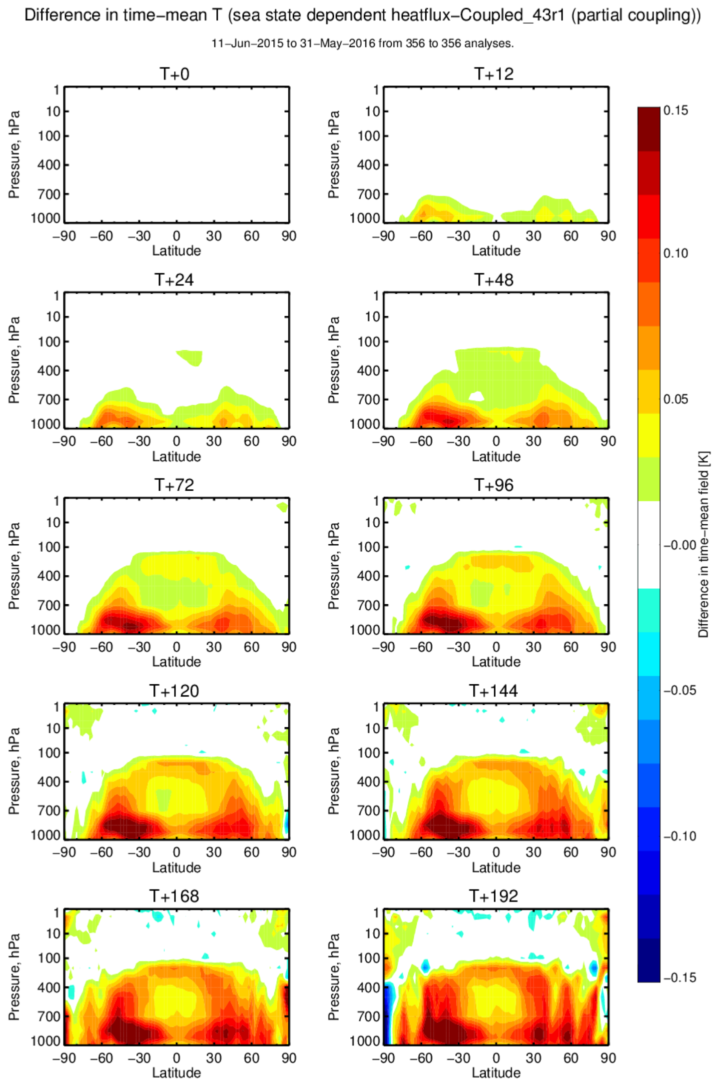

**Mean forecast error for 2mT**




**Normalised difference in RMSE for 2mT**

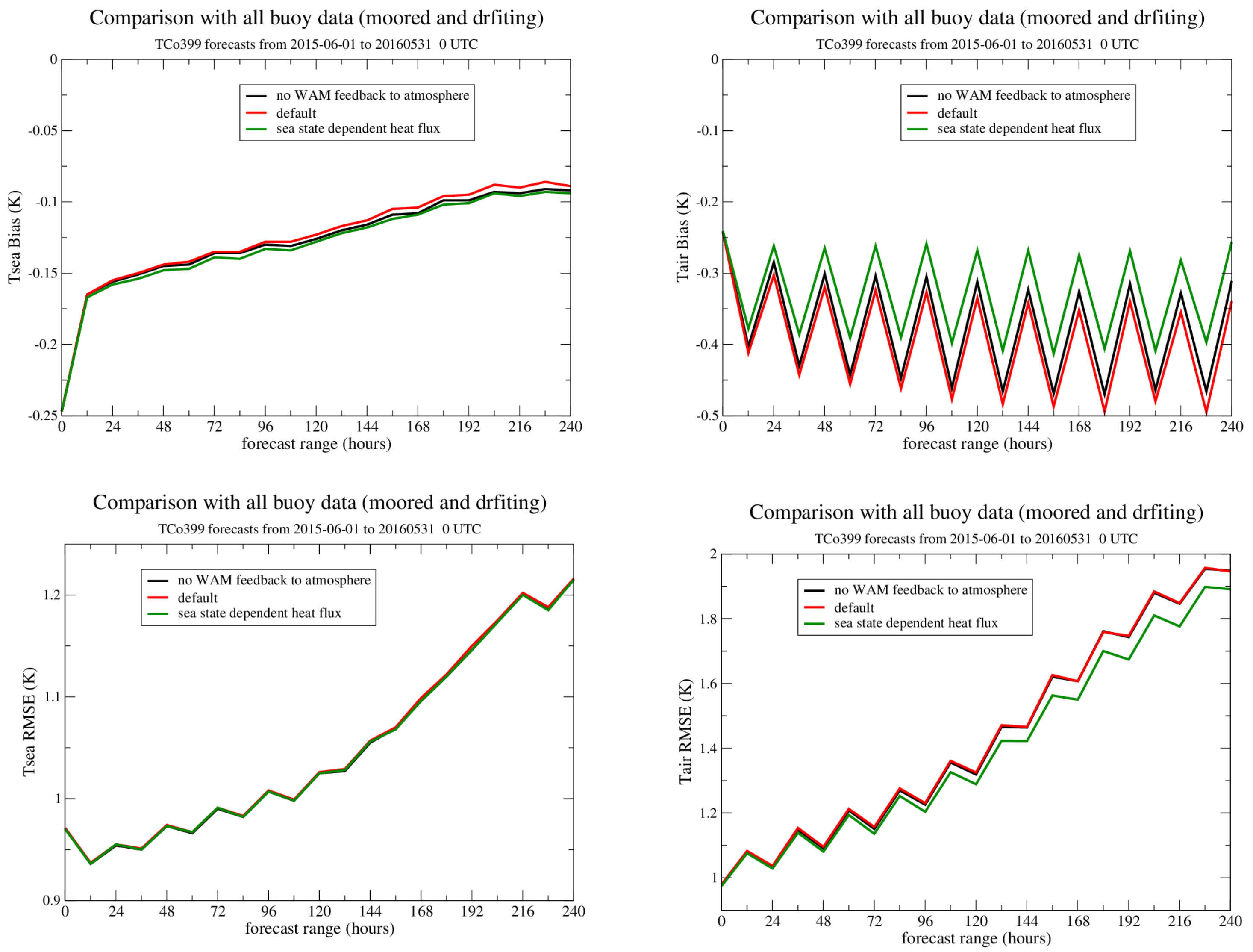



**Normalised difference in RMSE for 2mT**

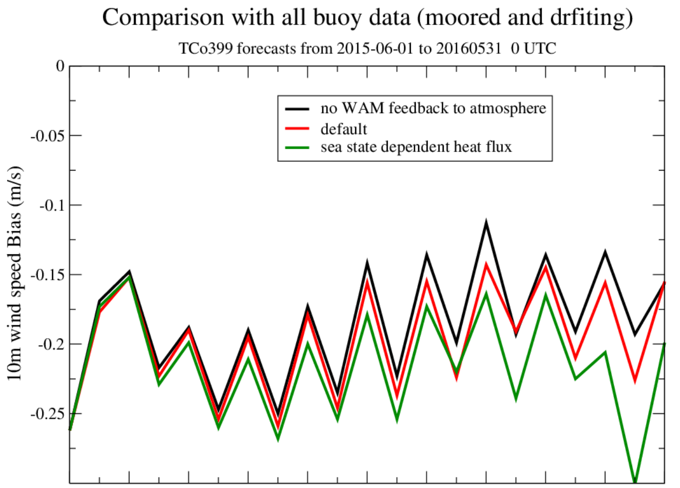


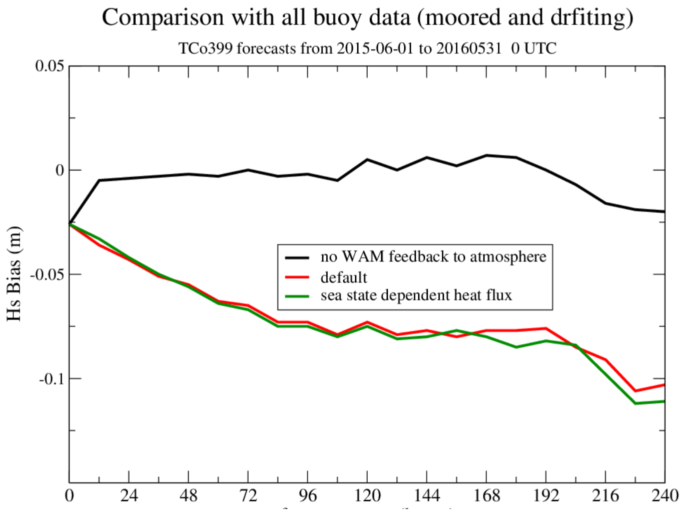

**Mean forecast difference in T**

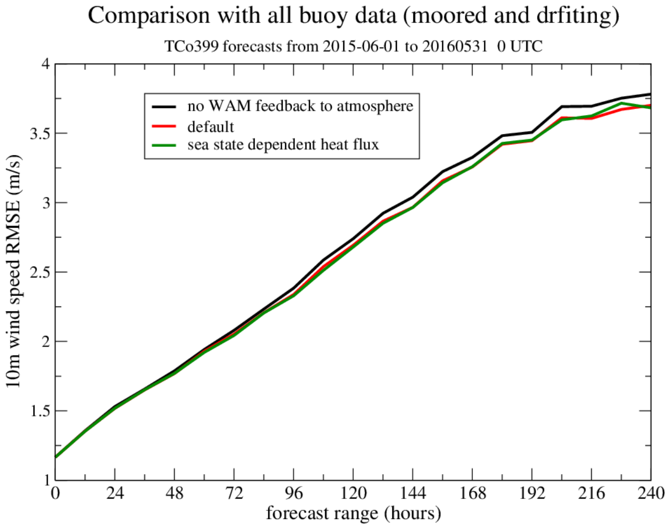
# Sensitivity study: wave dependent heat and moisture fluxes

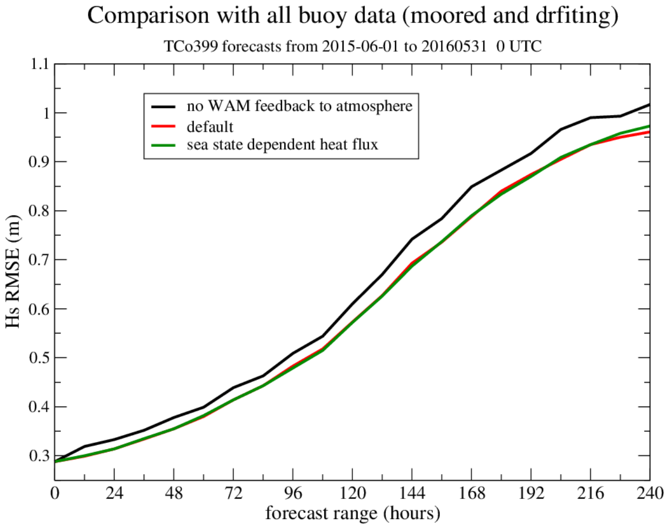


# Sensitivity study: wave dependent heat and moisture fluxes



# Possible future developments: whitecap faction $W_F$

Wave whitecap fraction is used in many parameterisations in air-sea interaction:

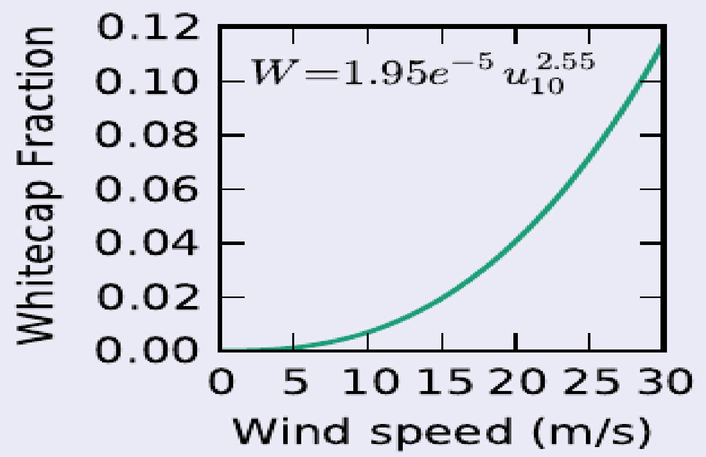
- sea spray production flux
- gas transfer velocity
- bubble production

It is also used to specify sea surface emissivity in satellite temperature radiances retrieval.

$$e = (1 - W)\, e_{foamfree} + W\, e_{foam}$$

Wave whitecap fraction is usually modelled in terms of wind speed:

[Monahan and O'Muircheartaigh, 1986]



# Possible future developments: whitecap faction $W_F$

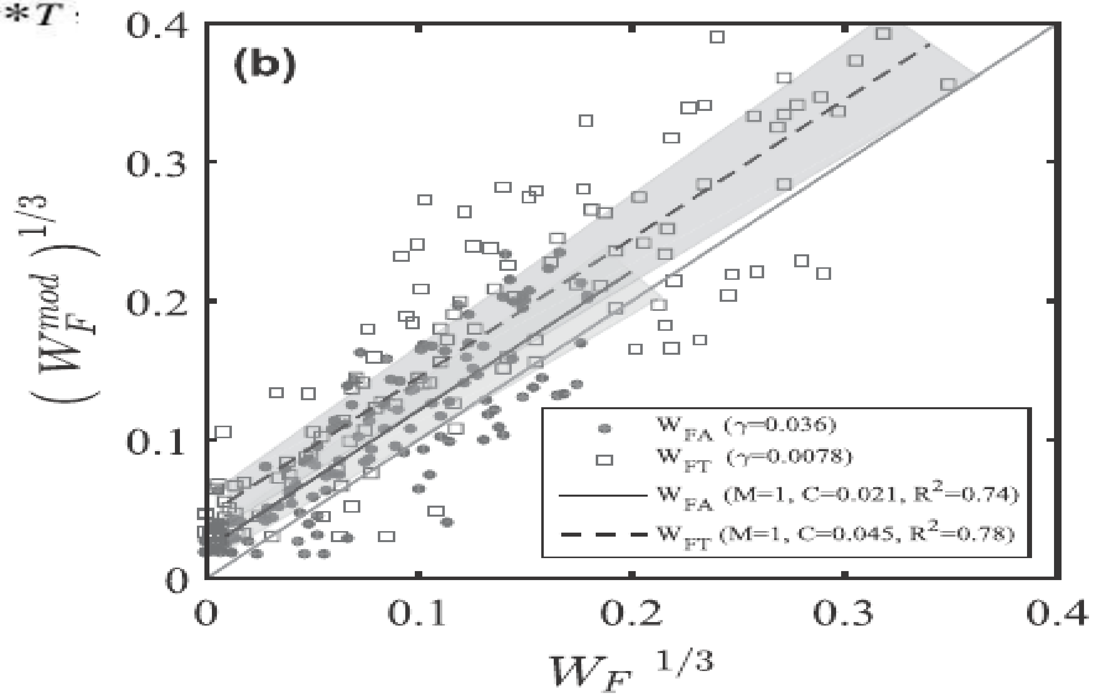
But, following work by Kraan et al. 1996, Scalon et al. (2016) showed that it can be modelled quite well using the wave model whitecap dissipation source term:

$$W_F^{\mathrm{mod}} = \begin{cases} \dfrac{\Phi_{\mathrm{oc}}}{\gamma \rho_w g \overline{\omega} E} \left( \dfrac{u_* - u_{*T}}{u_*} \right)^3 & u_* > u_{*T} \\ 0 & u_* \le u_{*T} \end{cases}$$

$$u_{*T} = 0.065\,\mathrm{m\,s^{-1}}$$

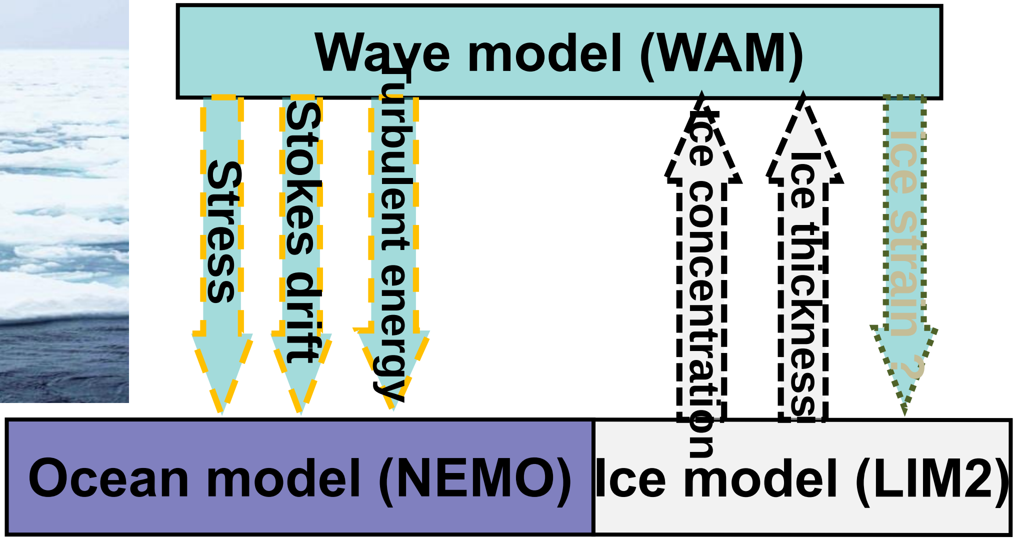
$$E = (H_S/4)^2.$$

$$\Phi_{\mathrm{oc}} = \rho_w g \int_0^{2\pi} \int_0^{\infty} S_{\mathrm{ds}}\, d\omega\, d\theta$$



# Future developments: wave sea-ice interaction


Courtesy: Wendy Pyper





Courtesy: Ben Holt

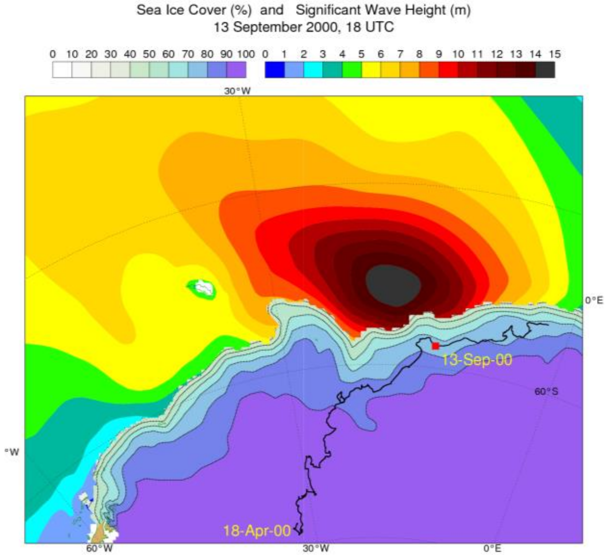
Sea ice attenuates waves,
and waves contribute to sea ice break-up and freeze-up.

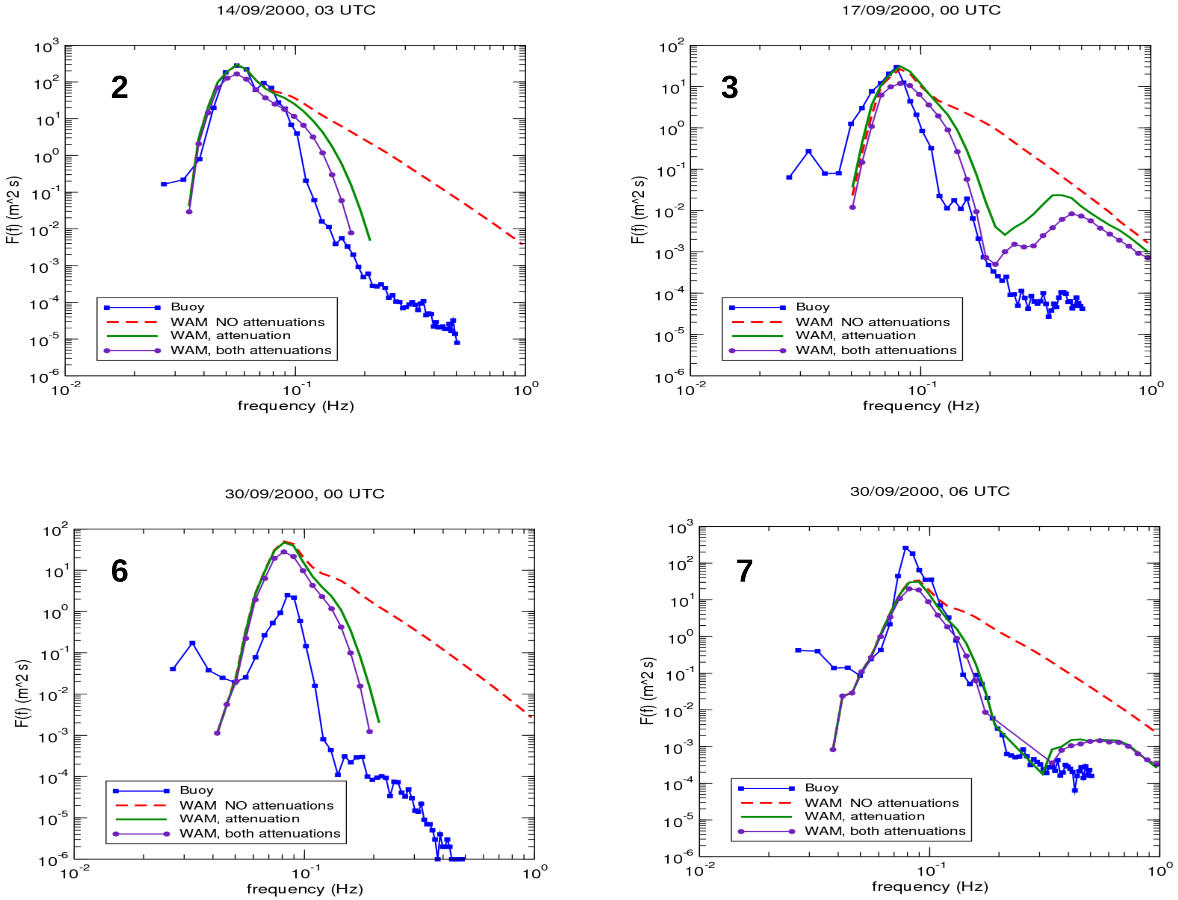
Several parameterisations have been developed to deal with waves attenuation.

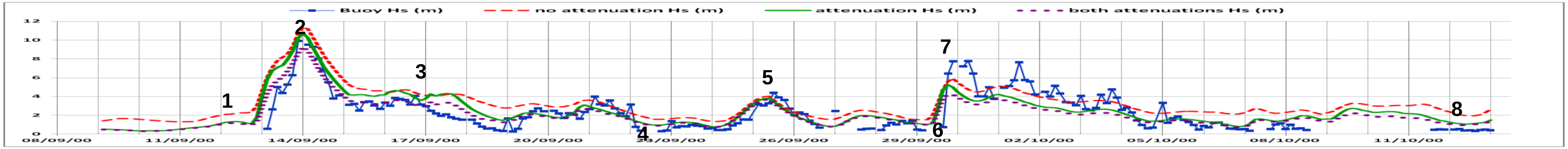
How waves affect sea ice is now an new field of research.

# Sea ice damping modeling: simple scattering model in ECWAM

One buoy survive the winter in sea ice in the Weddell Sea and reported waves after being dislodged by a big storm.



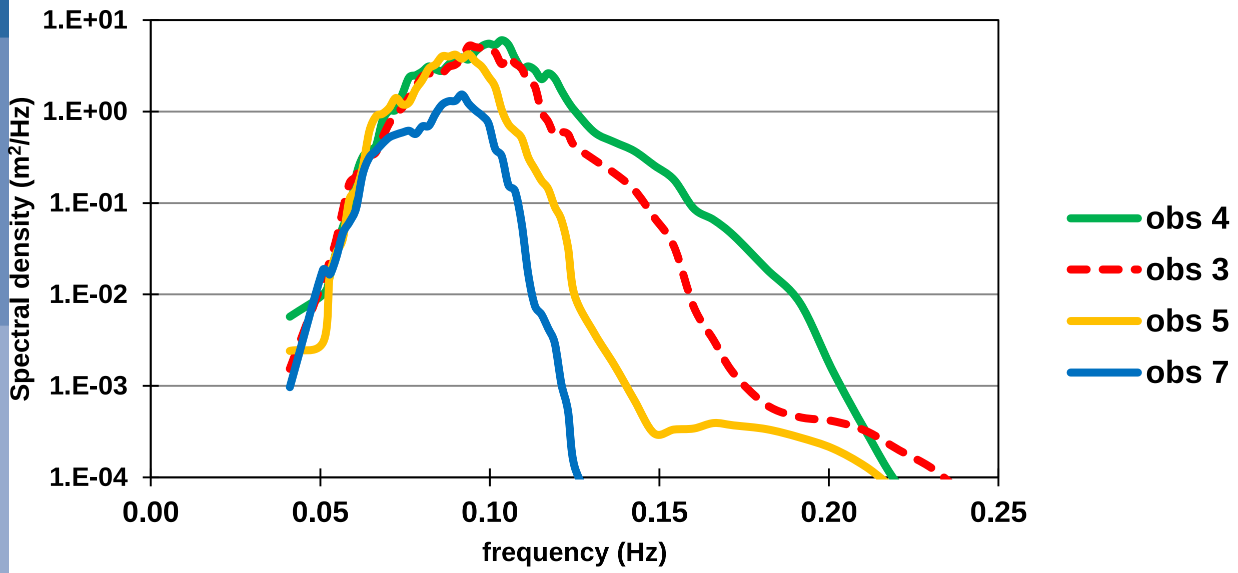



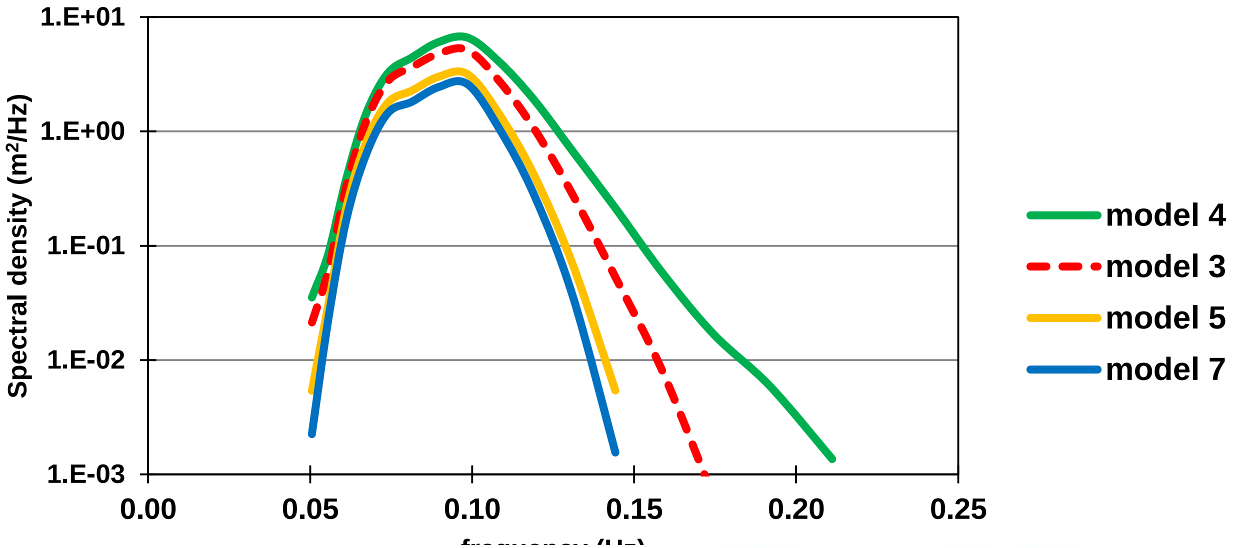

Doble and Bidlot 2013

# Sea ice damping modeling: simple scattering model in ECWAM

in-situ observations on 25/09/2012, 00 UTC




model on 25/09/2012, 00 UTC

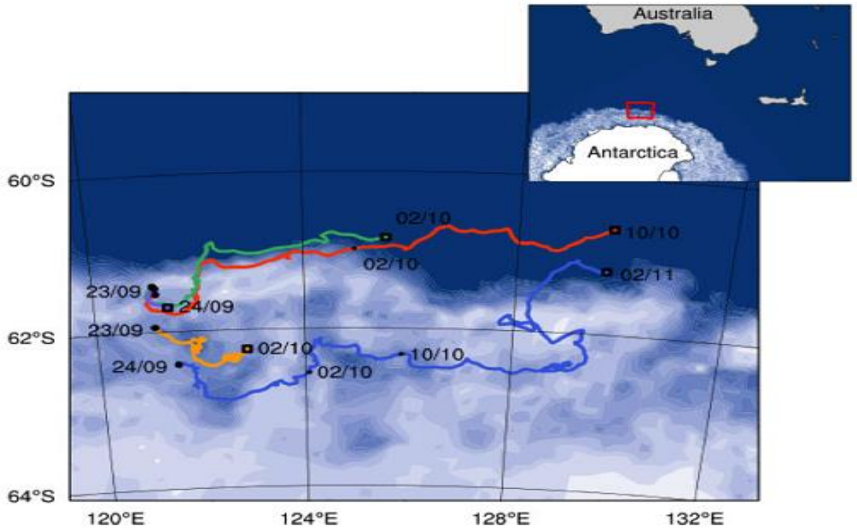



LETTER

doi:10.1038/nature13262

Storm-induced sea-ice breakup and the implications for ice extent

A. L. Kohout[1], M. J. M. Williams[2], S. M. Dean[2] & M. H. Meylan[3]




ECMWF

# Sea ice damping modeling: simple viscoelastic model in WW3

From Rogers et al. 2016.
Data from the Sea State DRI
from the Beaufort Sea

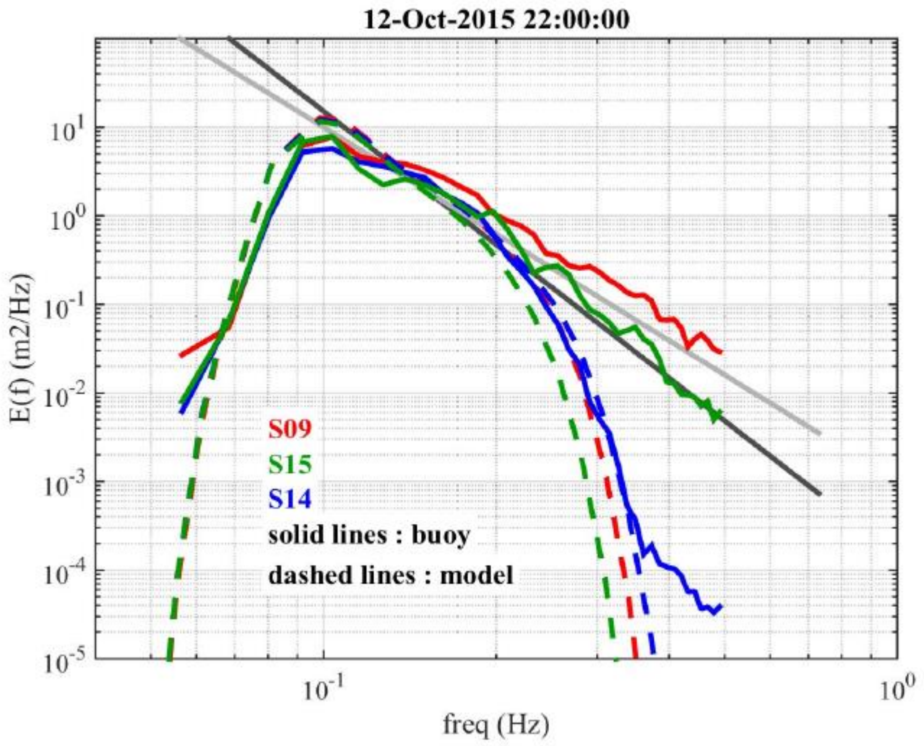



Figure 6. Example comparisons of 1-d spectrum, for three different SWIFT buoys, corresponding to the same time (2200 UTC 12 October). Dark and light gray lines correspond to an $f^{-5}$ and $f^{-4}$ tail slope, respectively. Solid red, dark green, and blue lines are measured spectra. Corresponding dashed lines are from the model hindcast.

All these modelling efforts are currently limited by the lack of detailed sea ice information, particularly affecting the tail of the spectrum

# Conclusions:

ECMWF has a fully coupled atmosphere-wave-ocean circulation forecasting system, currently operational in the Ensemble Prediction System.

Work is ongoing on using a higher resolution ocean components (ORCA025z75) planned for end of 2016 in the Ensemble forecasts and later in the High resolution system.

There is a clear benefit in coupling the different models, but it creates new challenges as model parameterisations will need revisiting and new processes might need to be added.

# 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

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

Rodwell et al., 2015: New Developments in the Diagnosis and Verification of High-Impact Weather Forecasts. ECMWF Technical Memorandum 759.
http://www.ecmwf.int/en/elibrary/technical-memoranda

Brian Scanlon, Øyvind Breivik, Jean-Raymond Bidlot and Peter A. E. M. Janssen, Adrian H. Callaghan, Brian Ward, 2016: Modeling Whitecap Fraction with a Wave Model,
J. Phys. Oceanogr., 46, 887-894. DOI: http://dx.doi.org/10.1175/JPO-D-15-0158.1

# Extra slides

# Partial coupling:

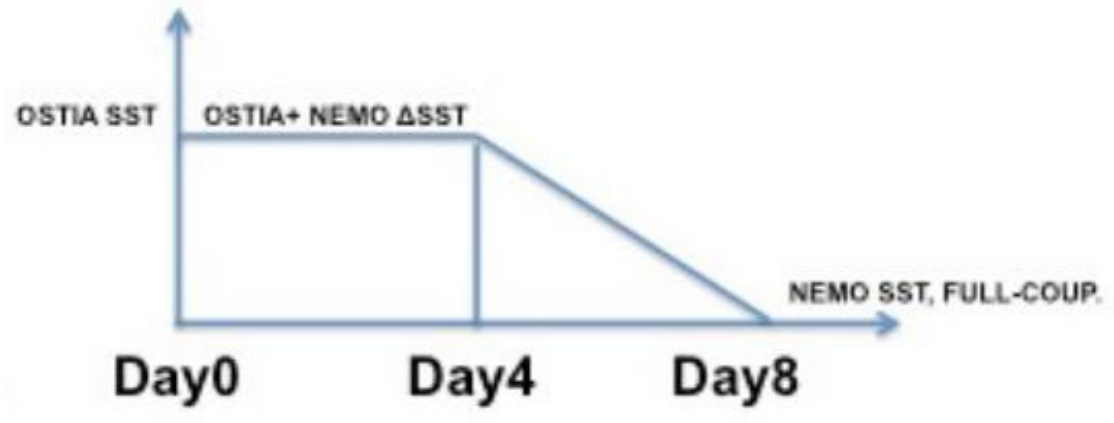
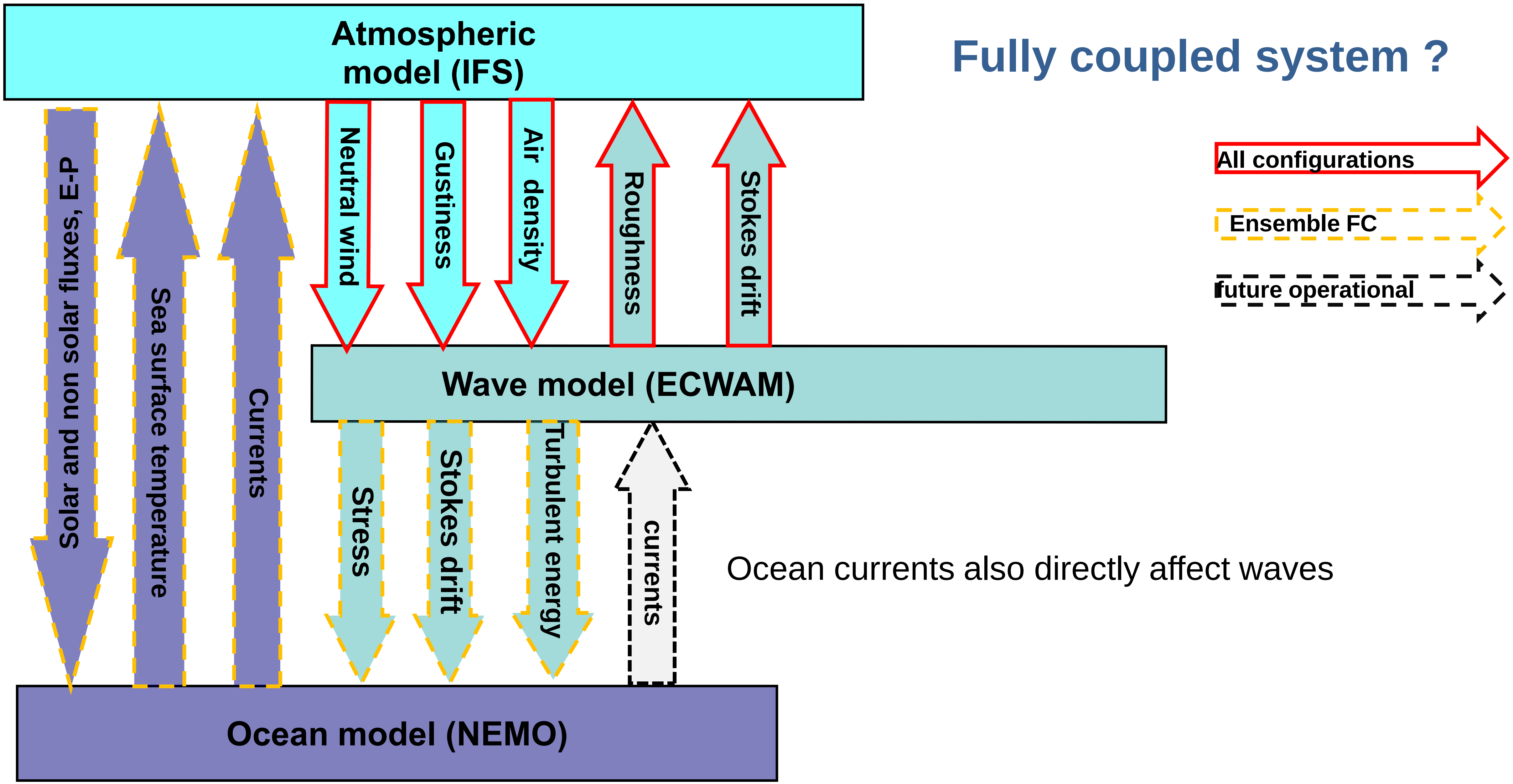


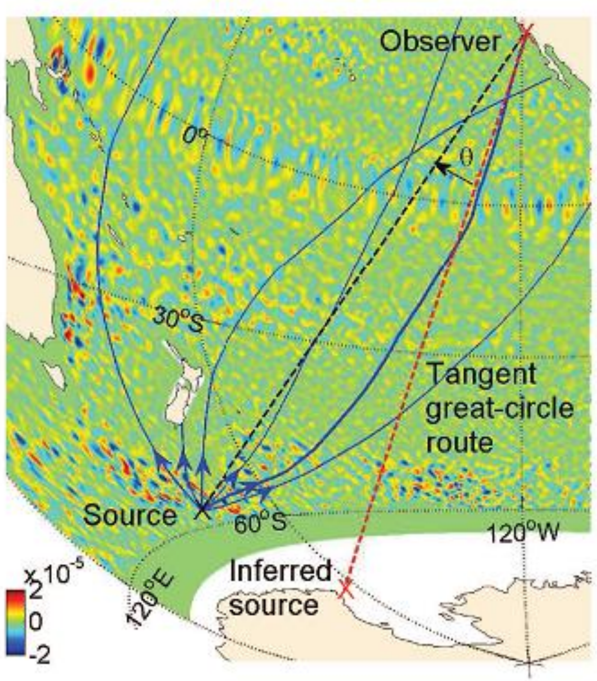

**Figure 2: Partial coupling of the SST: At initial conditions the OSTIA SSTs at high resolution is evolving using the SST tendencies from the NEMO model applying an offset to ORAS SST. After 4-days of forecast integration the offset in temperatures between OSTIA and ORAS5 is progressively reduced towards 0 at day 8 when the SST is fully driven by NEMO model.**

# Fully coupled system ?




Ocean currents also directly affect waves

# Ocean surface current impact on waves:




Gallet B. and Young W.R., 2014, JMR 72

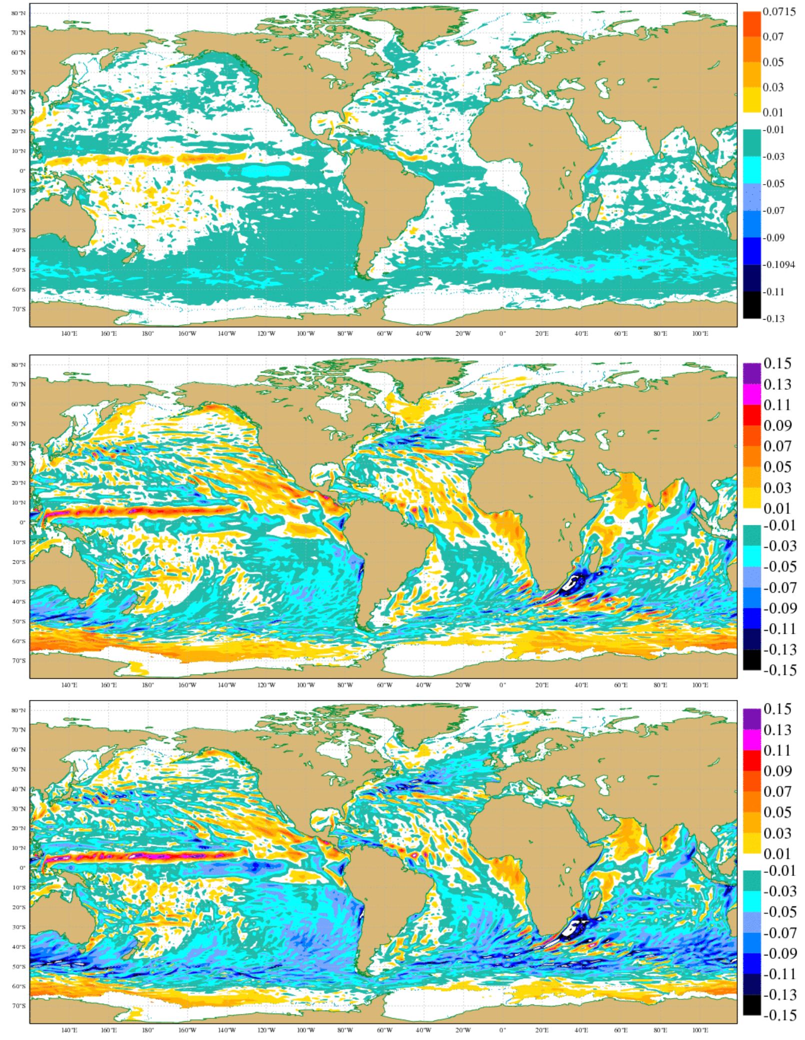
**Currents – no currents**

Mean wave height difference (ffxl wave - ffxd wave)
from 20091228 0Z to 20100228 18Z

**Impact of modified winds due to currents on waves**

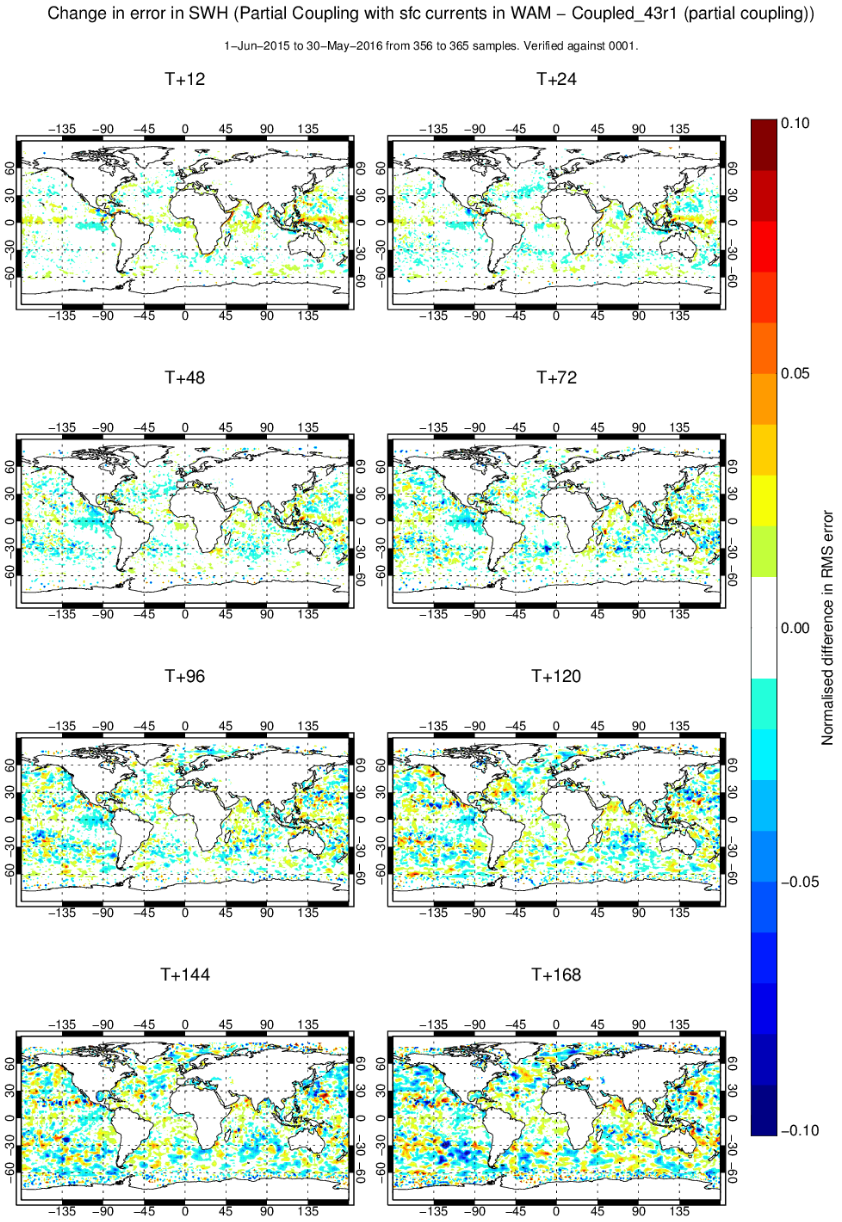
**Direct impact of currents on waves**

**Combined impact of currents on waves**




Bidlot J, 2012, ECMWF research memo

# Sensitivity study:



# Ocean Wave Modelling

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

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

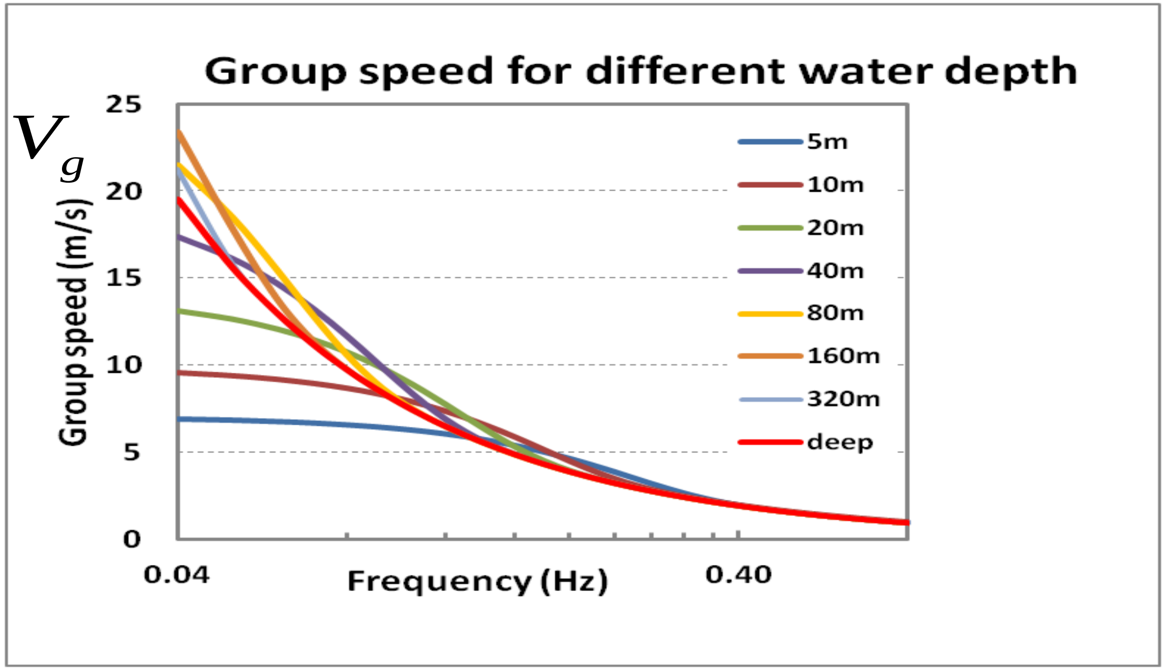
Where the group velocity $\mathbf{V_g}$ is derived from the dispersion relationship which relates frequency (f) and wave number (k) for a given water depth (D).

$$\omega^2 = g\,k\,\tanh(k\,D)$$

$$V_g = \frac{\partial \omega}{\partial k}$$

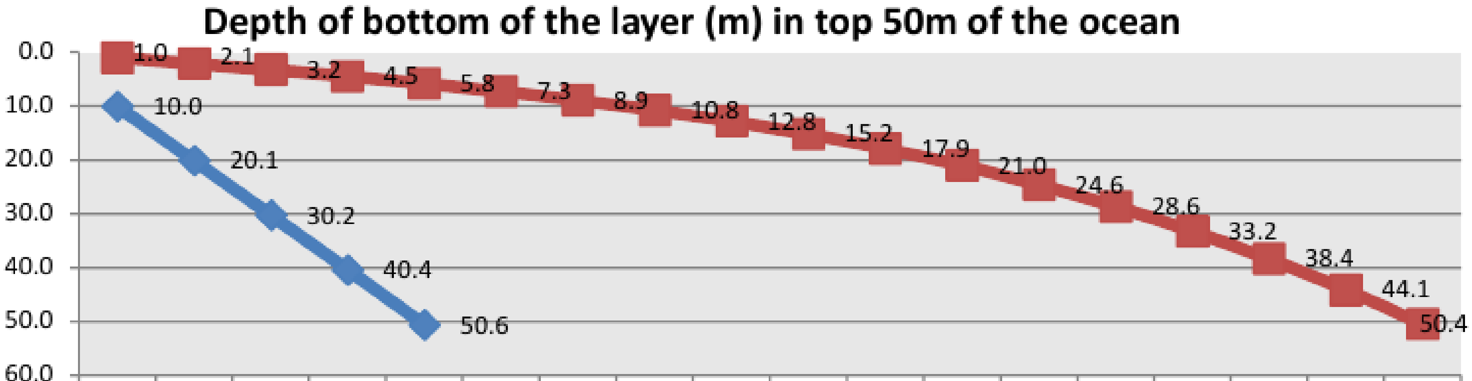
$$\omega = 2\pi\, f$$

D: water depth



# Sensitivity study: Stokes to IFS (double counting)?

ORCA025_Z75 has a much finer vertical resolution than ORCA1_Z42



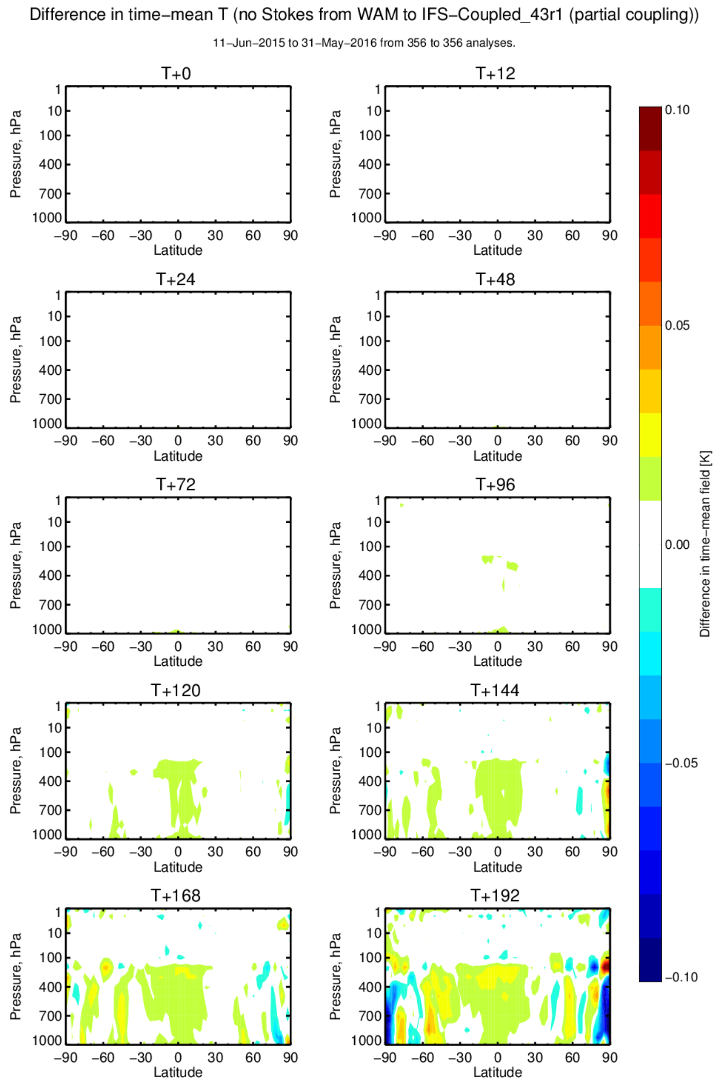

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ORCA1_Z42 | 10.0 | 20.1 | 30.2 | 40.4 | 50.6 | | | | | | | | | | | | | |
| ORCA025_Z75 | 1.0 | 2.1 | 3.2 | 4.5 | 5.8 | 7.3 | 8.9 | 10.8 | 12.8 | 15.2 | 17.9 | 21.0 | 24.6 | 28.6 | 33.2 | 38.4 | 44.1 | 50.4 |

**Figure 1: Vertical discretisation of the ocean layers in the top 50m below the surface in ORCA1_Z42 (blue) and ORCA025_Z75 (red).**

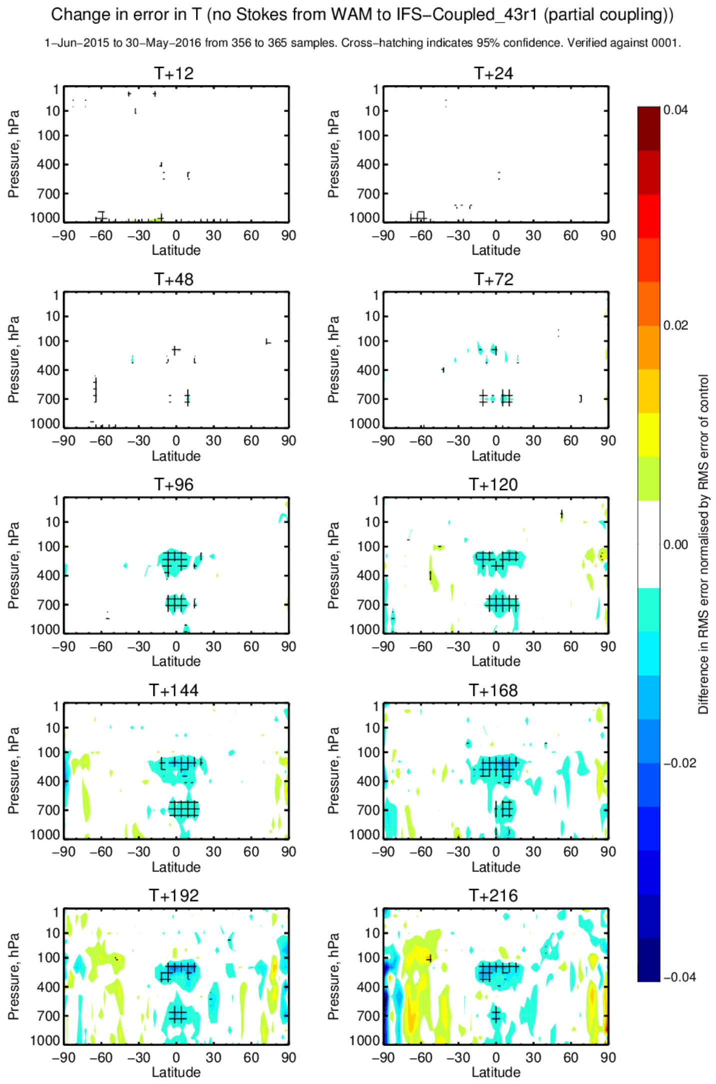
Wave effect on the upper ocean mixing is both passed to NEMO, but also to the atmospheric model.
The SST from NEMO is modified by the waves, there shouldn't be any need to also modify again (?)

# Sensitivity study: No Stokes to IFS

Mean forecast difference in T

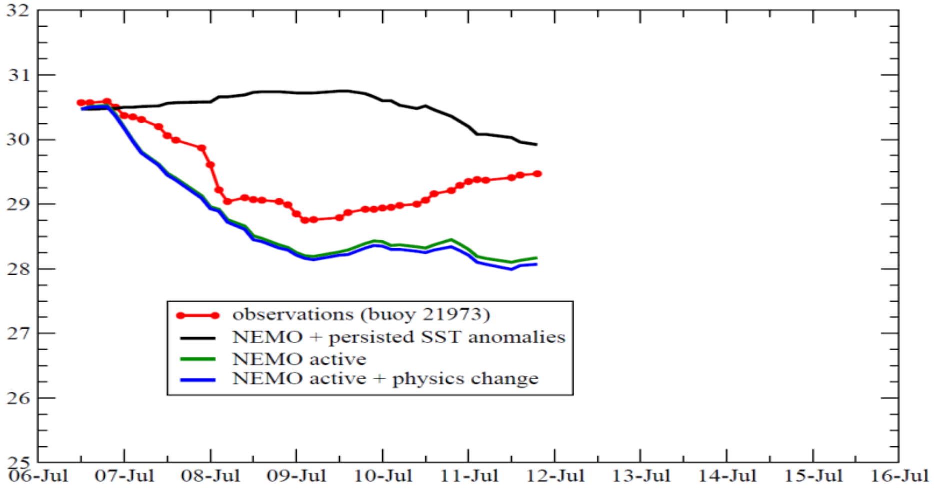


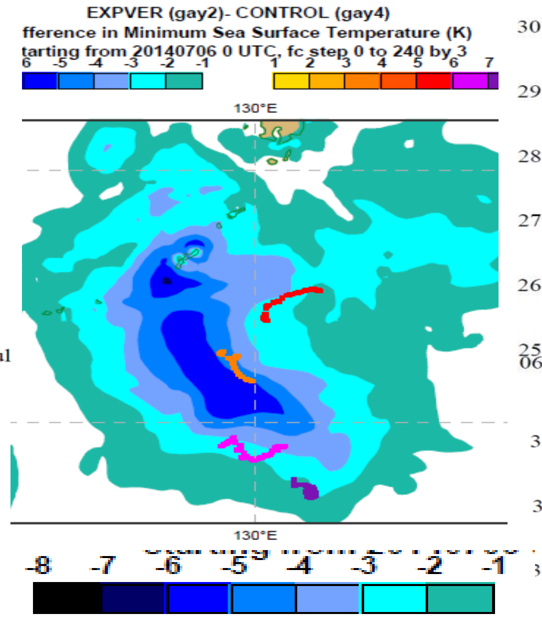

Normalised difference in RMSE for T

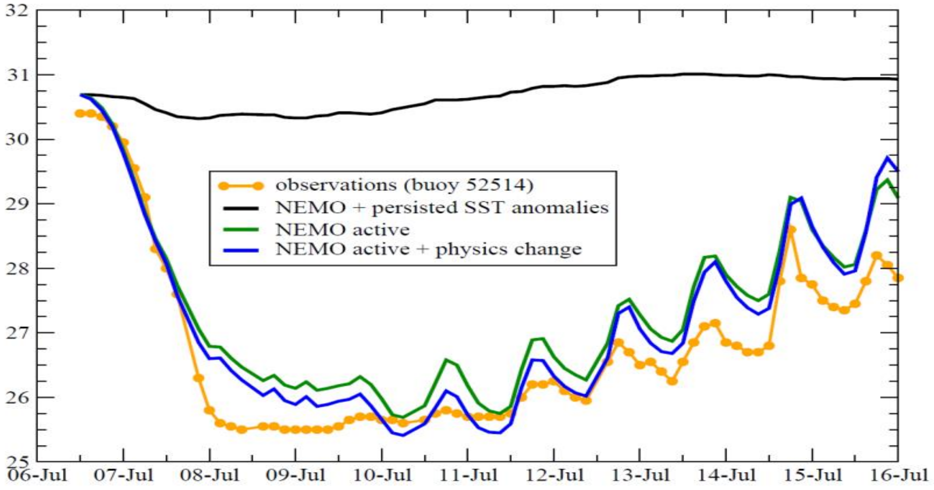


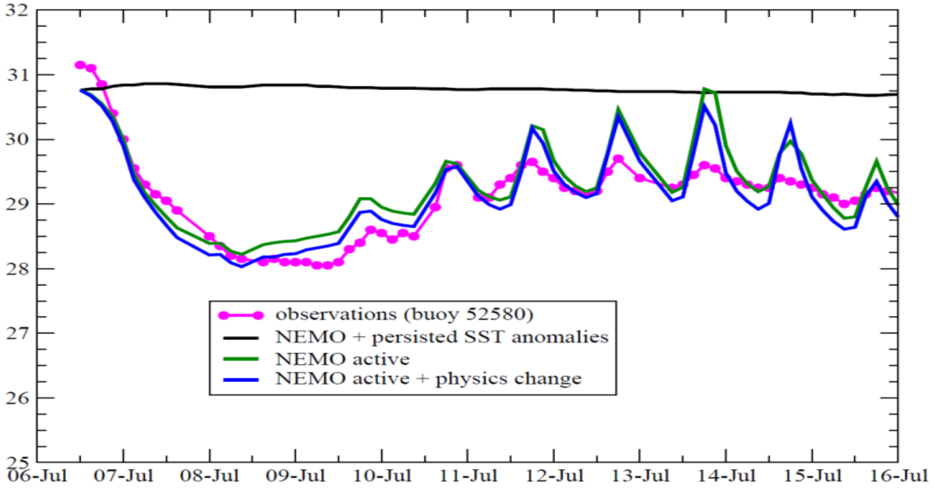

**better**

# Impact of **Coupling** on tropical cyclone forecast

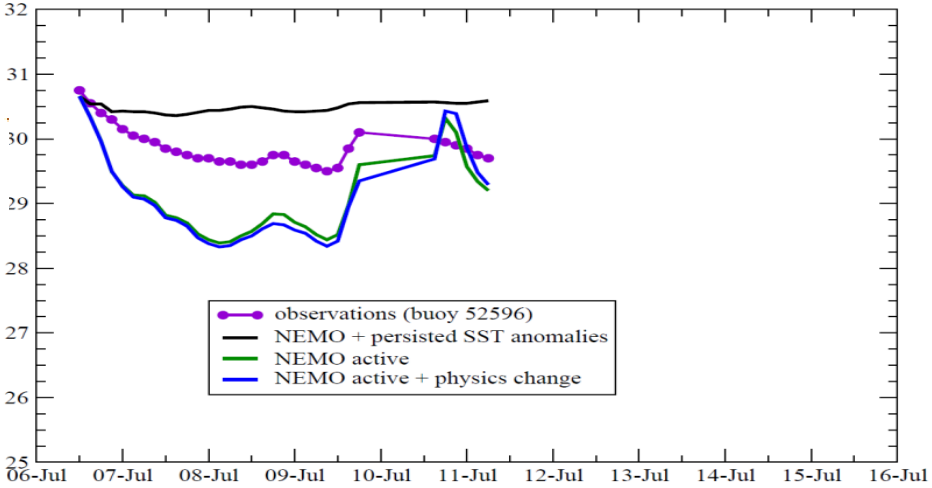



Data from
drifting buoys



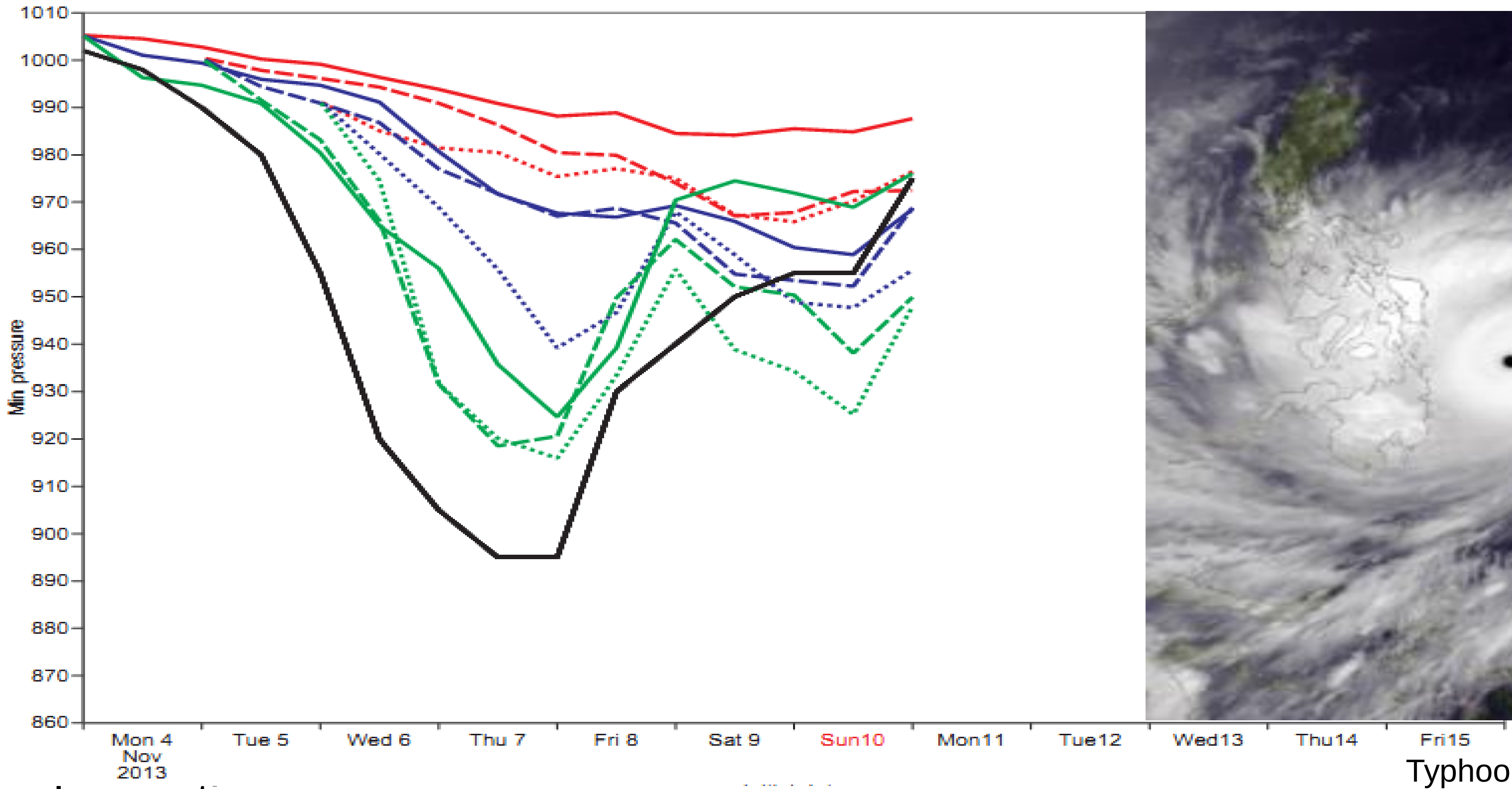
# Impact of **Resolution** on tropical cyclone forecast

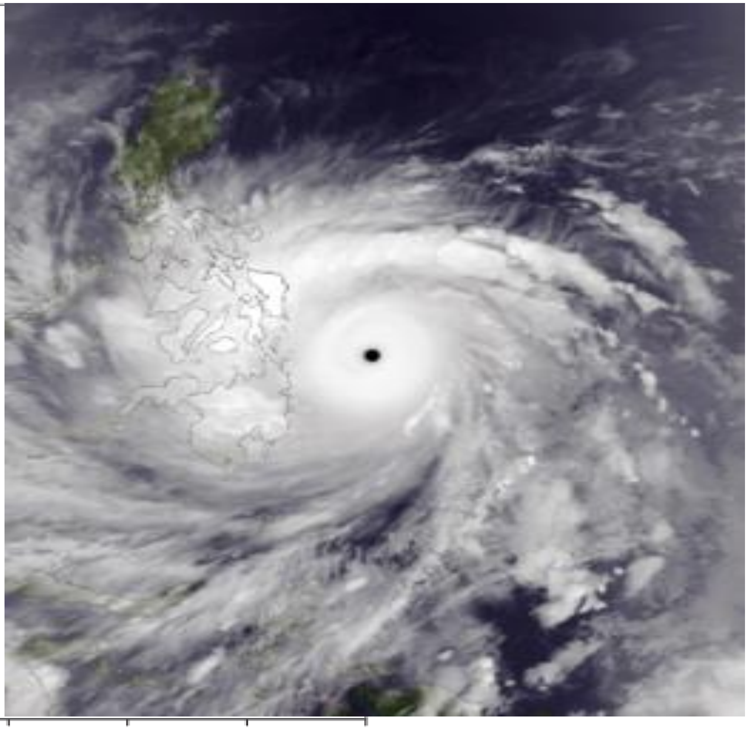
For instance Typhoon Haiyan: forecasts from 4th, 5th and 6th November 2013, 0 UTC
all from <u>operational</u> analysis.

min
MSLP (hPa)

950

900



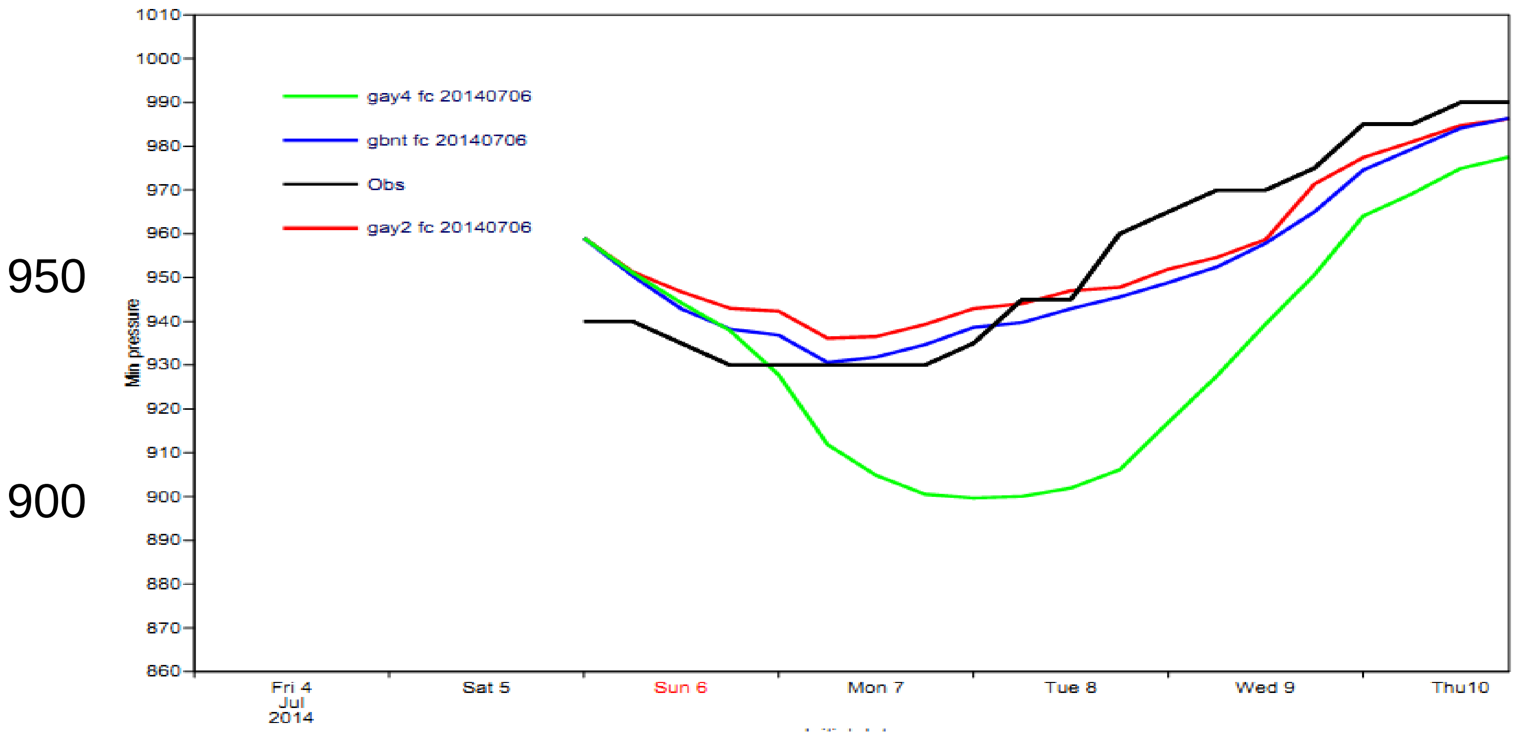
Typhoon Haiyan at peak intensity on November 7, 2013

**Black:** estimated from observations
**Red**: old operational Ensemble resolution (**32 km**)
**Blue**: old operational HRES configuration (**16 km**)
**Green**: new HRES configuration (**10km**) (CY41R2)

# Impact of **Coupling** on tropical cyclone forecast

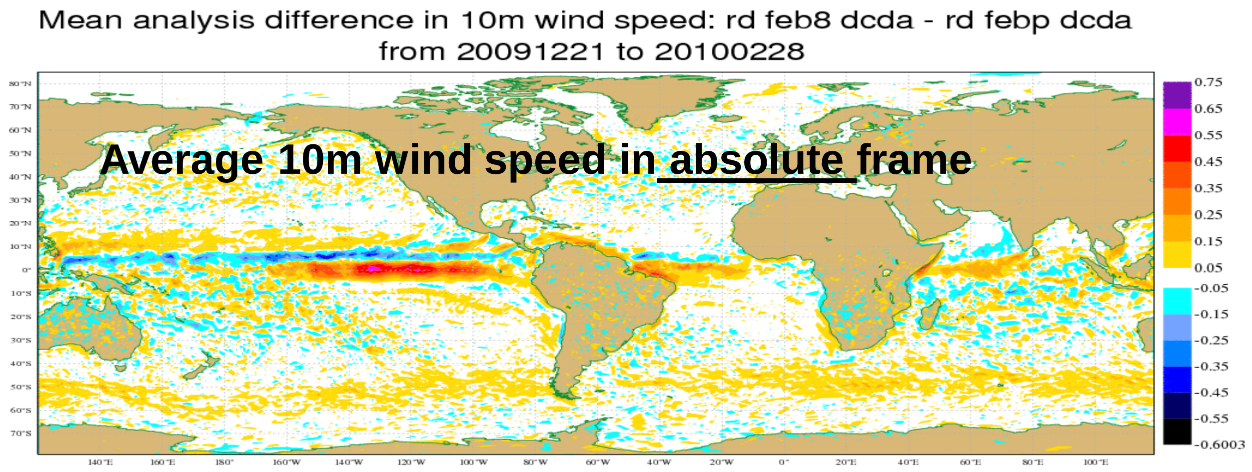
For instance Typhoon Neoguri: forecasts from 6 July 2014, 0 UTC

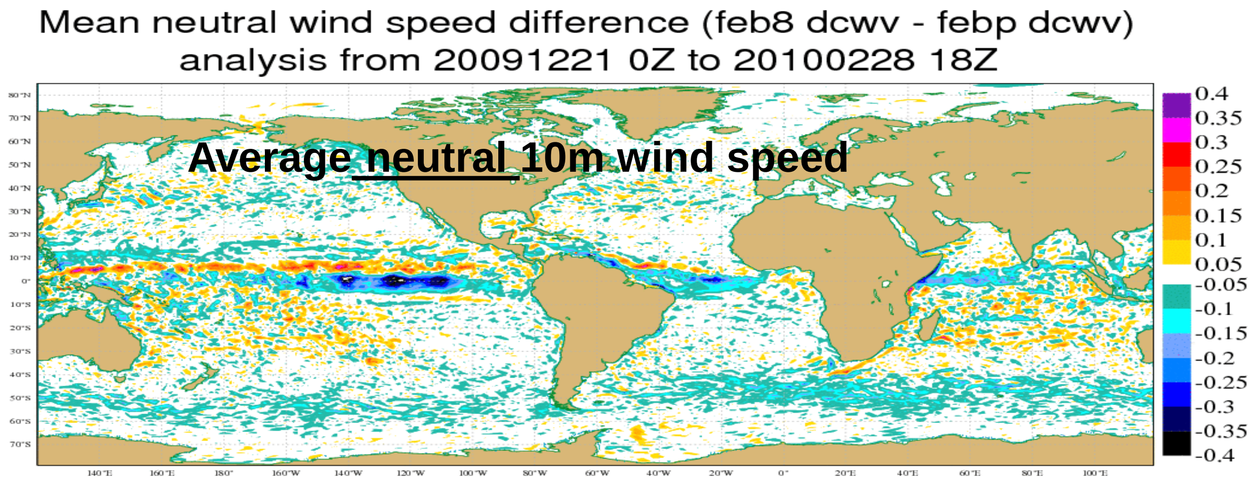
min
MSLP (hPa)



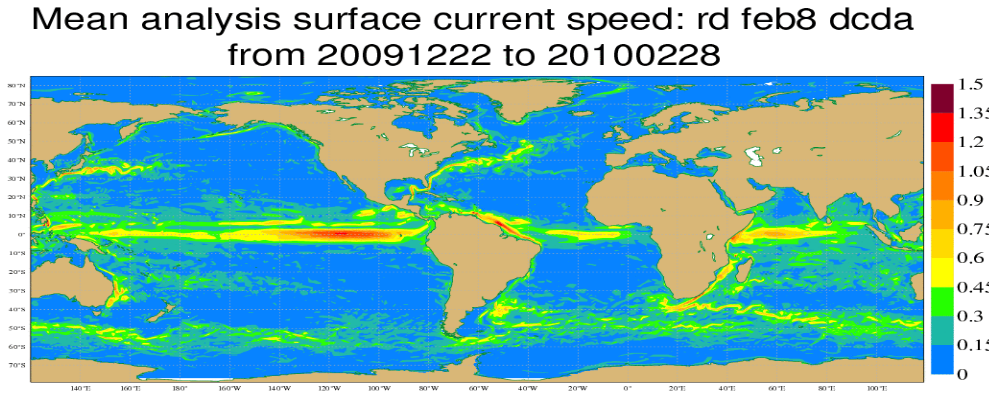

**Black:** estimated from observations
**Green**: old operational HRES configuration (**uncoupled**) (prescribed OSTIA SST) (16km)
**Red**: experimental: 16km **fully coupled** to NEMO (ORCA025_Z75)
**Blue**: 16km coupled to NEMO + new physics

# Surface current feedback on atmosphere




**Currents – no currents**




- **Absolute winds receive about 50% from ocean currents**