Ocean circulation and air-sea interaction

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INTRODUCTION

In this talk I would like to discuss air-sea interaction in the context of a **coupled modelling system** (CMS). We have developed a CMS which at the moment consists of three components:

1. atmosphere (IFS)
2. ocean waves (WAM)
3. and the ocean/sea-ice (NEMO)

These three components have been brought together in a single executable.

Today, I discuss briefly the following items:

- **Numerics of the coupling**

  As occasionally there is a strong coupling between the three components of the CMS there is a need to study the numerical scheme involved in such a coupling. For example, if the coupling is strong are there possibilities of numerical instability, do we need to couple in an implicit manner? Do we need an energy/momentum conserving interpolation scheme, etc...

  So far I am not aware of a systematic study of this problem. I will give an example of a serious problem we had in the early part of this Century, namely the generation of **mini vortices** by the coupling between wind and ocean waves, and how this was fixed.

- **Ocean waves and Upper-Ocean Mixing**

  Upper ocean mixing is to a large extent caused by breaking, ocean waves. As a consequence there is an energy flux Φ_{oc} from waves to ocean. It is given by

  $$\Phi_{oc} = m\rho_a u_*^3,$$

  where m depends on the sea state and u_* is the friction velocity. Wave breaking and its associated mixing penetrates into the ocean at a scale of the significant wave height H_S. In addition, Langmuir turbulence penetrates deeper into the ocean with a scale of the typical wavelength of the surface waves.

  In the NEMO model there is a simple scheme to model these effects using the **turbulent kinetic energy** (TKE) equation. However, in the present version of NEMO there are only averaged sea state effects included, hence m is constant. Here, it is shown that when actual sea state effects are included this may have an impact on the mean SST field and even on the temperature field to 400 m depth.

- **Coupling from Day 0**

  Presently, in the operational medium-range/monthly ensemble forecasting system (ENS) the interaction between atmosphere and ocean is only switched on at Day 10 in the forecast. In the autumn a new version of ENS/monthly will be introduced in operations where the coupling starts from Day 0. Also, sea state effects on upper ocean mixing and dynamics will be switched on.

  Coupling from Day 0 has beneficial impacts on hurricane forecasting, the MJO and the statistical properties of ENS.

THE COUPLED MODELLING SYSTEM

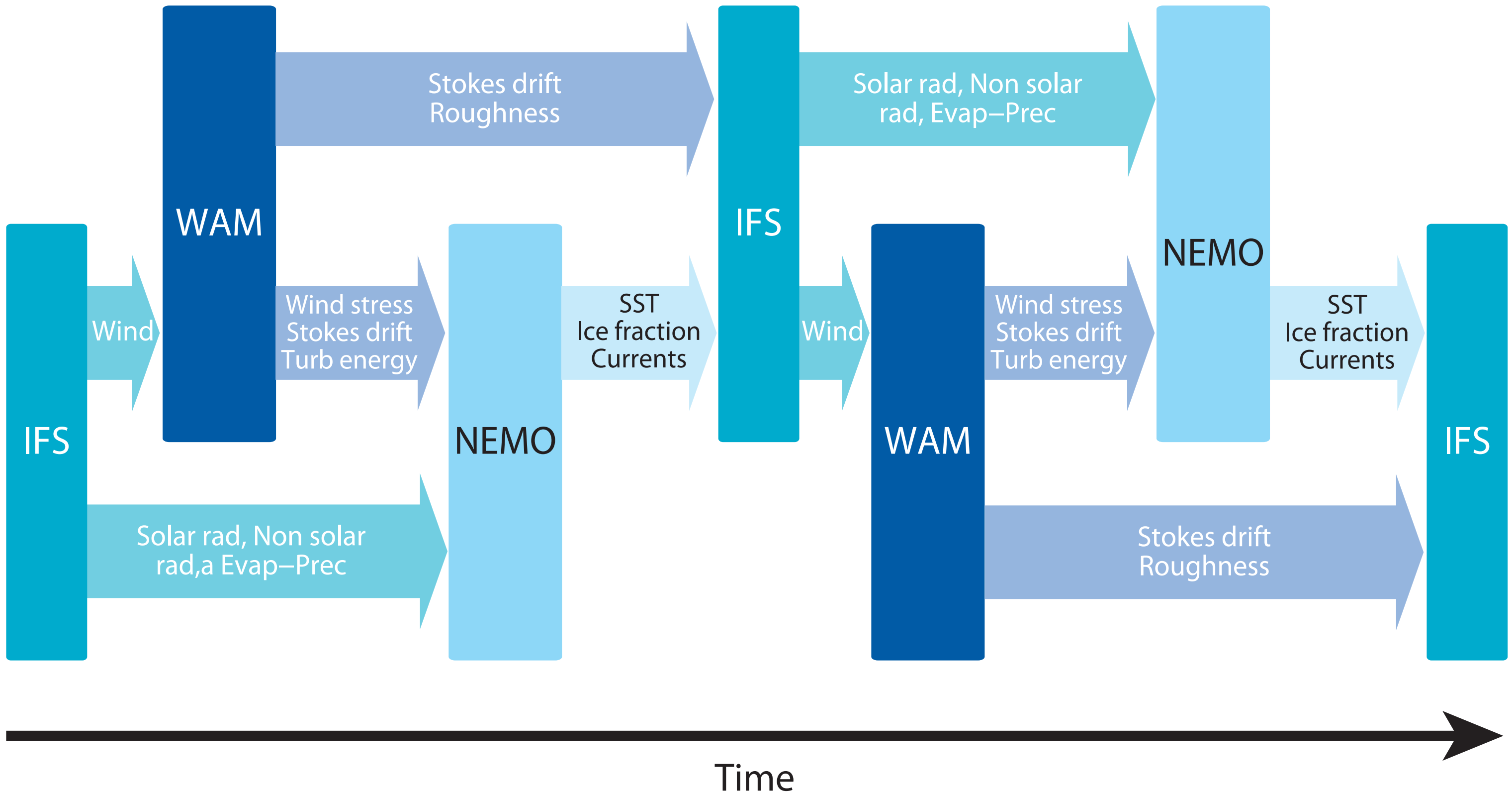


Figure 1: Flow Chart of the coupled model, here two time steps are shown.

Numerics of the coupling

I will give two examples that occasionally there is a strong coupling between the three components of the CMS. One example involves the deepening of a low during IOP17 of FASTEX (atm=ocean-wave) another example involves hurricane Nadine and the cooling of SST by the strong wind circulation.

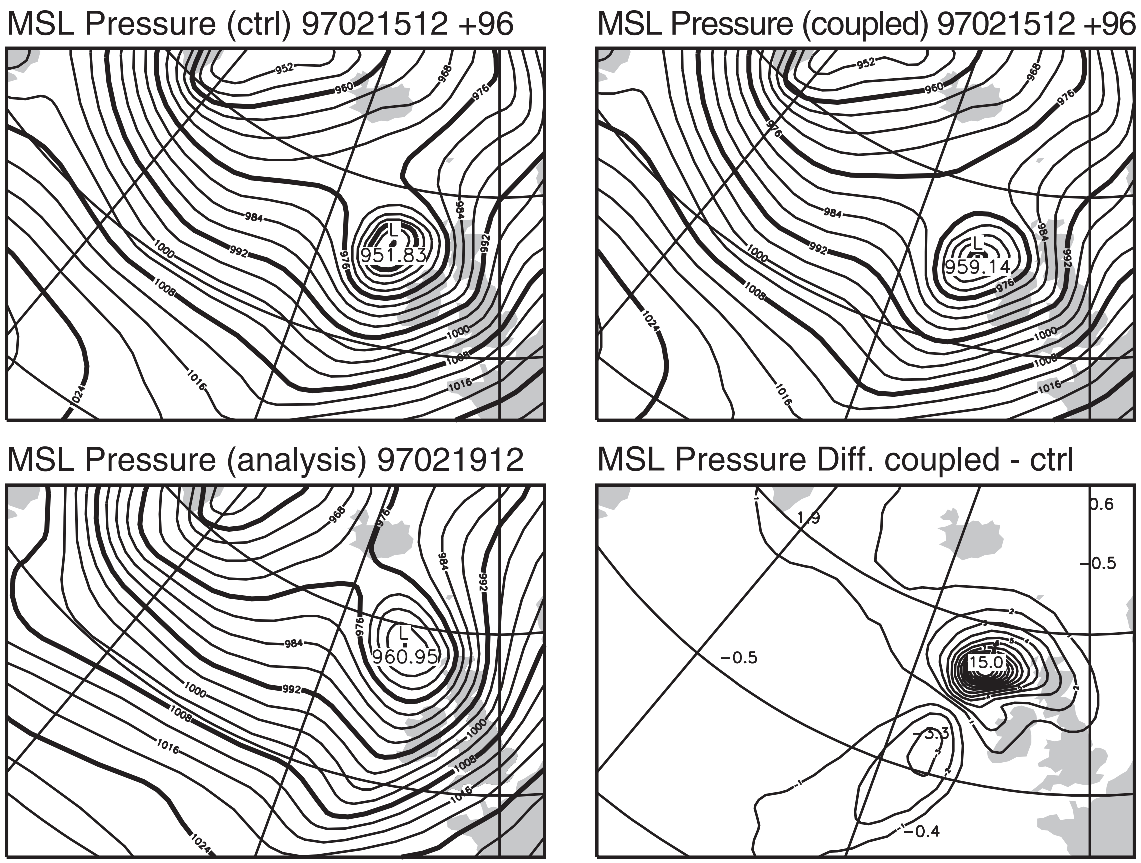


Figure 2: Comparison of 4-day forecast of surface pressure over the North Atlantic, valid for 19 February 1997. Version of coupled model is $T213/L31 - 0.5\,\mathrm{deg}$.

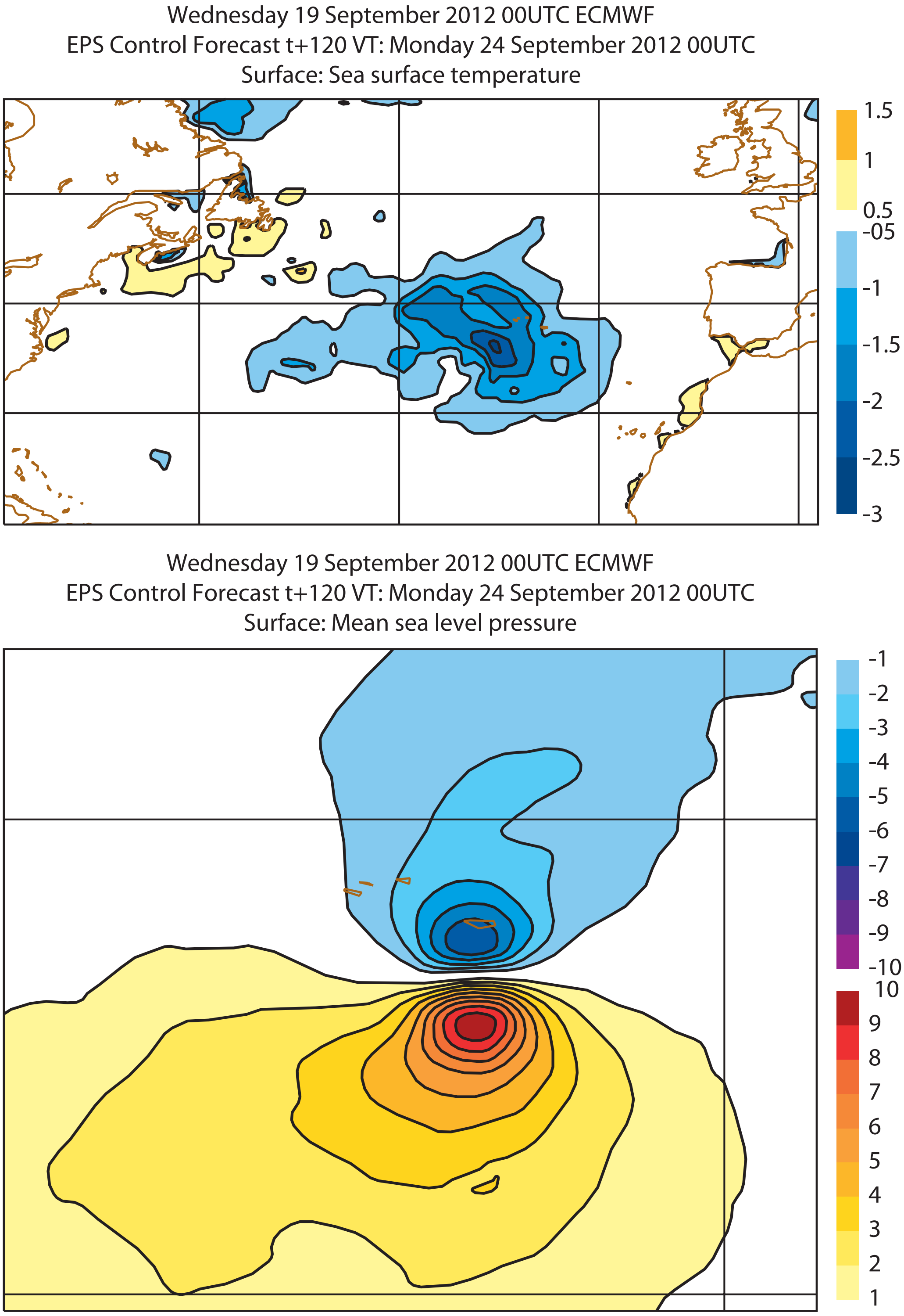


Figure 3: NADINE. Top: ensemble mean sst difference day5-day0. Bottom: ensemble mean pressure difference between coupled and control for day 5 forecast.

Because of this occasional strong interaction between atmosphere and ocean waves there is a need to study the numerical scheme involved in such a coupling. For example, if the coupling is strong are there possibilities of numerical instability, is there a need to couple in an implicit manner, etc.

This might require a systematic study. I will give one example, namely the generation of spurious mini-vortices caused by the coupling between wind and ocean waves.

Generation of spurious mini-vortices

1. Two-way interaction of wind and waves was introduced on June 29 1998. The coupling time step was 4 wave model time steps, hence ample time for the wave model to respond to rapidly varying winds, resulting in realistic values of the roughness length.

2. With the introduction of the T_L511 version of the IFS the coupling time step was reduced to one wave model time step. From the start of the operational introduction occasional small scale, compact features occurred in the surface pressure field that propagated rapidly over the oceans. Called mini-vortices, or even **cannon balls**.

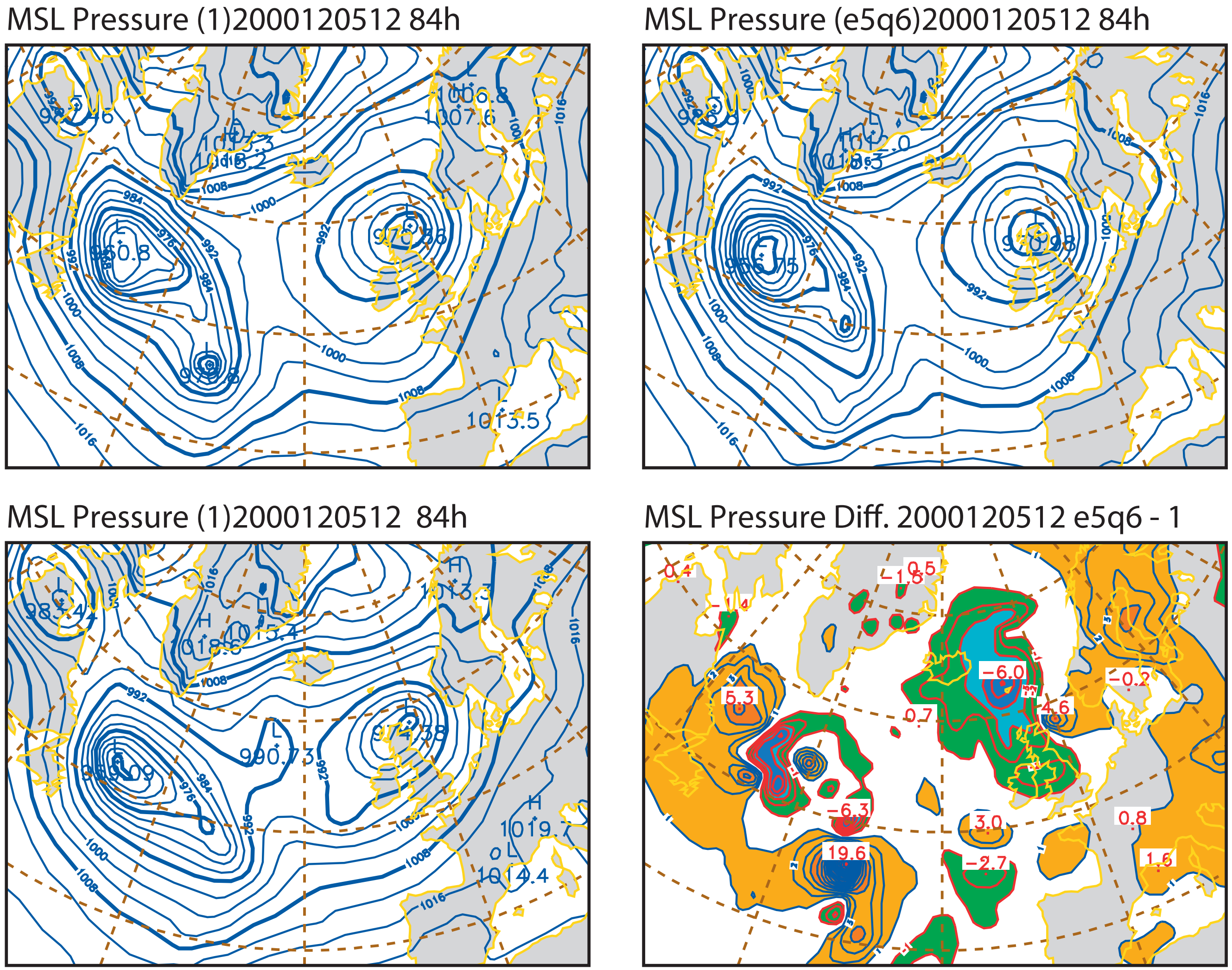


Figure 4: Generation of mini vortices by wind-wave interaction. Top left OPER, Top right EXP, Bottom left ANALYSIS, Bottom right diff between EXP and OPER.

Ocean waves

In order to understand how this problem was fixed I need to give a ultra-short course on wave modelling. For given wind (and bathymetry etc.) a wave model calculates at a location of interest the evolution in time of the two-dimensional wave spectrum $F = F(\mathbf{k}, \mathbf{x}, t)$, where $\mathbf{k}$ is the wavenumber vector. The evolution equation for F is called the energy balance equation and is given by

$$\frac{D}{Dt}F = S = S_{in} + S_{nl} + S_{diss},$$

where D/Dt is the advection operator (i.e. gives advection with the group velocity $\mathbf{v}_g$), and the source functions describe the generation of waves by wind (S_{in}), the dissipation of ocean waves by e.g. wave breaking (S_{diss}) and the energy/momentum conserving resonant four-wave interactions (S_{nl}).

The wind input source function S_{in}, which represents the **interaction between wind and waves**, depends on the surface stress $\tau = \rho_a u_*^2$ and is proportional to the wave spectrum! Hence, $S_{in} = S_{in}(F, u_*)$.The **strength of the interaction** is given by the wave-induced stress $\tau_w = \int \mathrm{d}\mathbf{k}\, S_{in}/c$.

In the 1980's there was a considerable European effort to build a wave prediction system based on solving the energy balance equation.

The integration in time was done with a (semi-) implicit scheme as follows.

1. Calculate dimensionless roughness or the Charnock parameter gz_0/u_*^2 from wave-induced stress at $t = t_n$ and wind speed at new time level t_{n+1}. Calculate friction velocity u_*^{n+1}
2. Spectral increments ΔF are obtained from an implicit scheme:

$$\Delta F = \Delta t S_n(u_*^{n+1}) \left[1 - \Delta t \frac{\delta S_n}{\delta F}(u_*^{n+1}) \right]^{-1}$$

Problem is that under rapidly varying winds (e.g. sudden drop in wind) the waves are still steep given a far too large roughness. This results in considerably enhanced heat fluxes that may generate a mini vortex.

Fix: Do the roughness calculation also after the spectral update $F_{n+1} = F_n + \Delta F$.

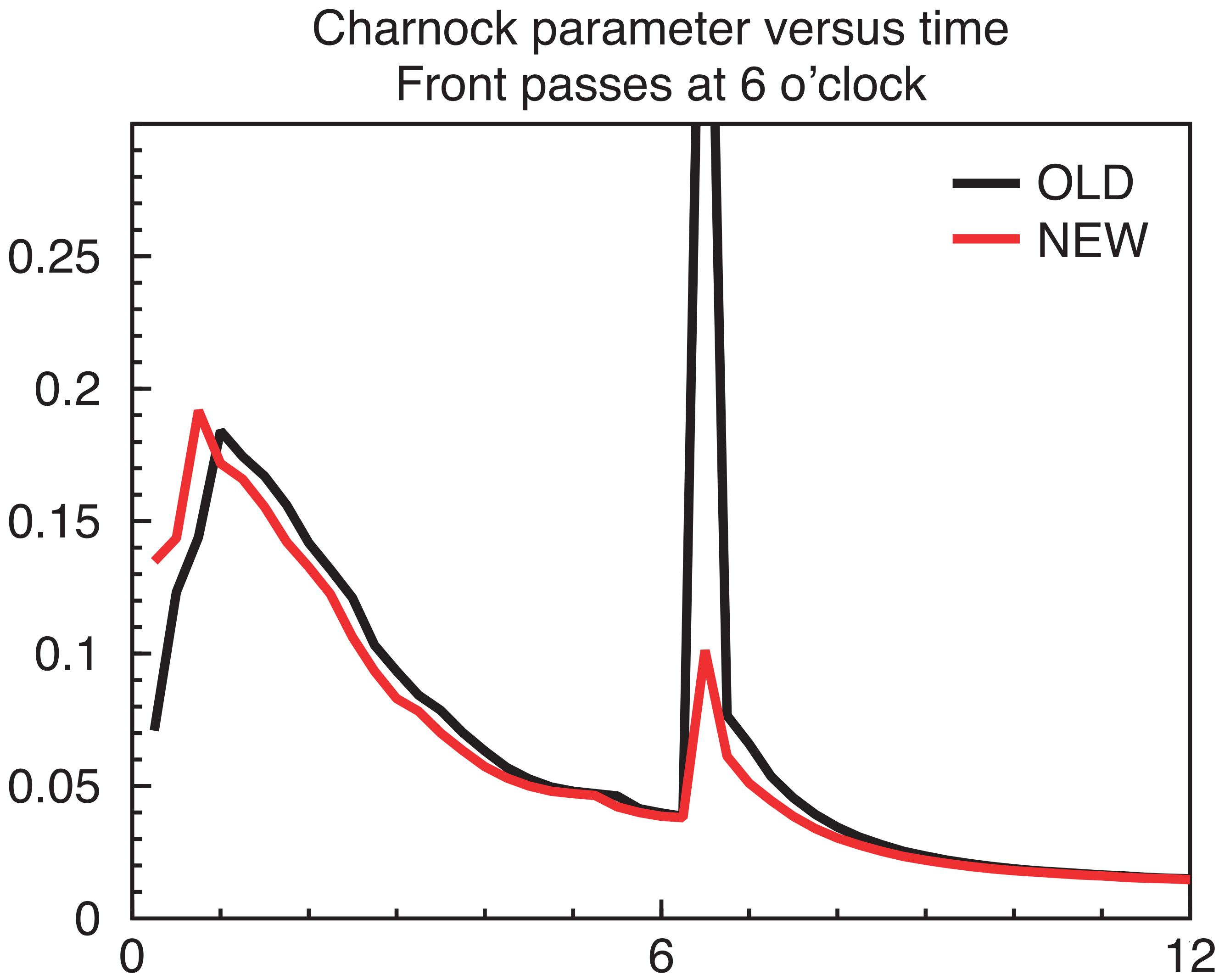


Figure 5: Evolution in time of the Charnock parameter during the passage of a frontal system at $t = 6$ hrs.

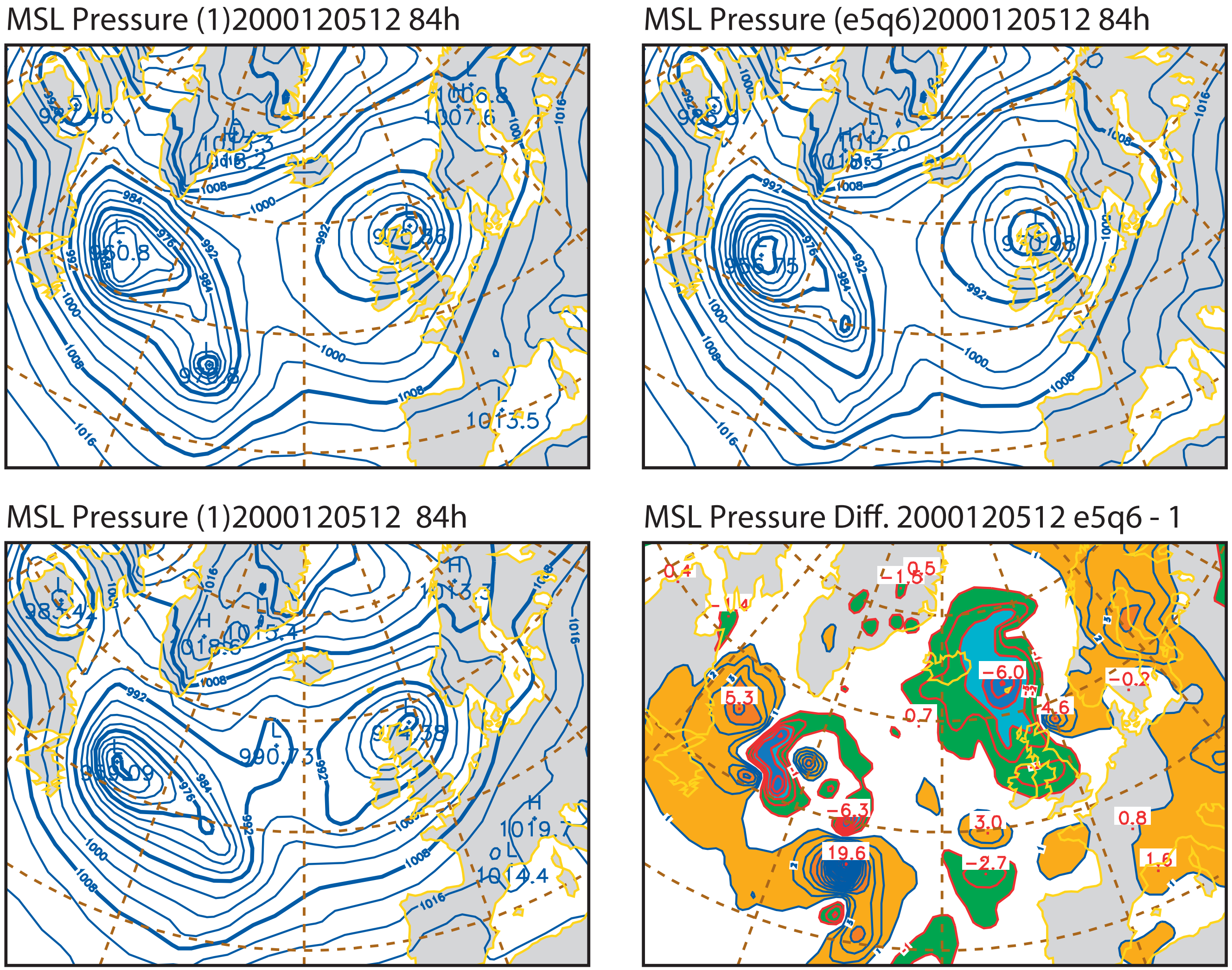
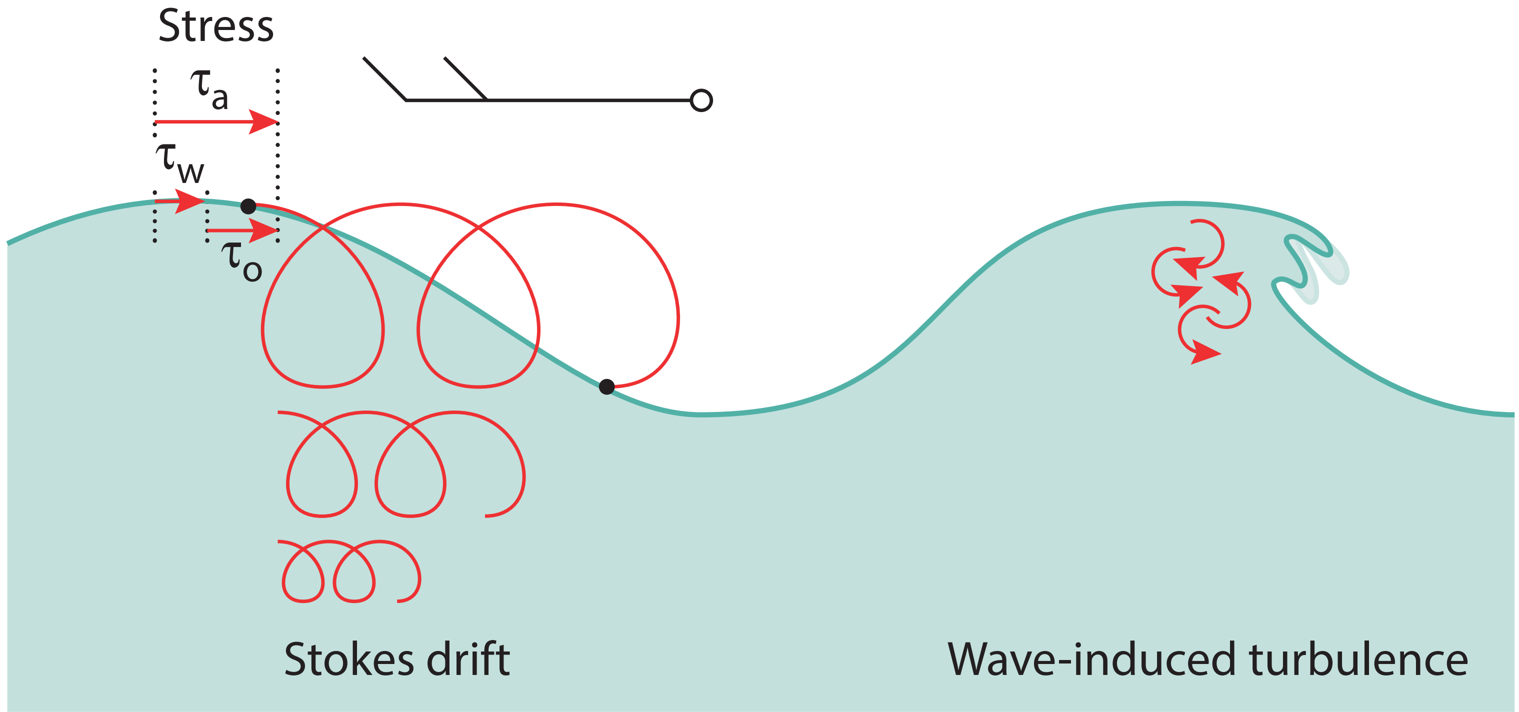


Figure 6: Generation of mini vortices by wind-wave interaction. Top left OPER, Top right EXP, Bottom left ANALYSIS, Bottom right diff between EXP and OPER.

COUPLING OF WAM AND NEMO



WAVE BREAKING and UPPER OCEAN MIXING

In the past 15 years observational evidence has been presented about the role of wave breaking and Langmuir turbulence in the upper ocean mixing.

Wave breaking generates turbulence near the surface, in a layer of the order of the wave height H_S, which enhances the turbulent velocity by a factor of 2-3, while, in agreement with observations there is an enhanced turbulent dissipation. This deviates from the 'law-of-the-wall'.

The turbulence modelling is based on an extension of the **Mellor-Yamada scheme** with sea state effects. 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:

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

and in general m is not a constant, as shown next.

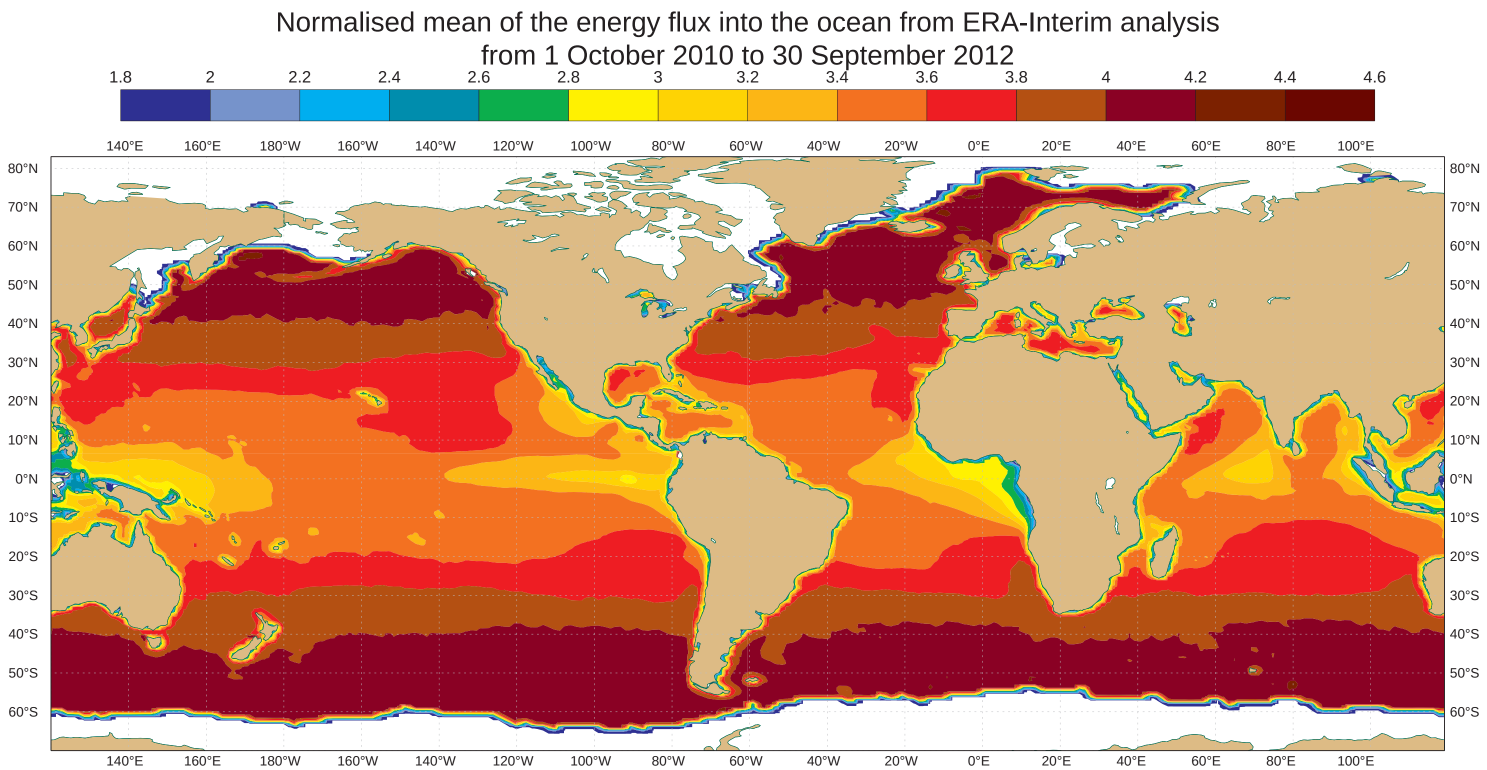


Figure 7: Mean of energy flux into the ocean, normalized with the mean of $\rho_a u_*^3$. Averaging period is two years.

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 ε. 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 ν_m, ν_h and ν_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:

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

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

In the next Figure we show an approximate solution to the TKE equation which illustrates that wave breaking enhances turbulence up to a depth of a few wave heights, while Langmuir turbulence acts in the deeper parts of the ocean. For comparison, results for Monin-Obukhov similarity (from balance of turbulent shear production and turbulent dissipation) are shown as well.

The following Figure shows a comparison between the profile of modelled dissipation and a fit to observations of turbulence dissipation. The law-of-the wall follows from

$$\varepsilon = \nu_m S^2,$$

which for a constant stress, i.e. $\nu_m S = \text{const}$, gives an inverse dependence on the distance from the surface.

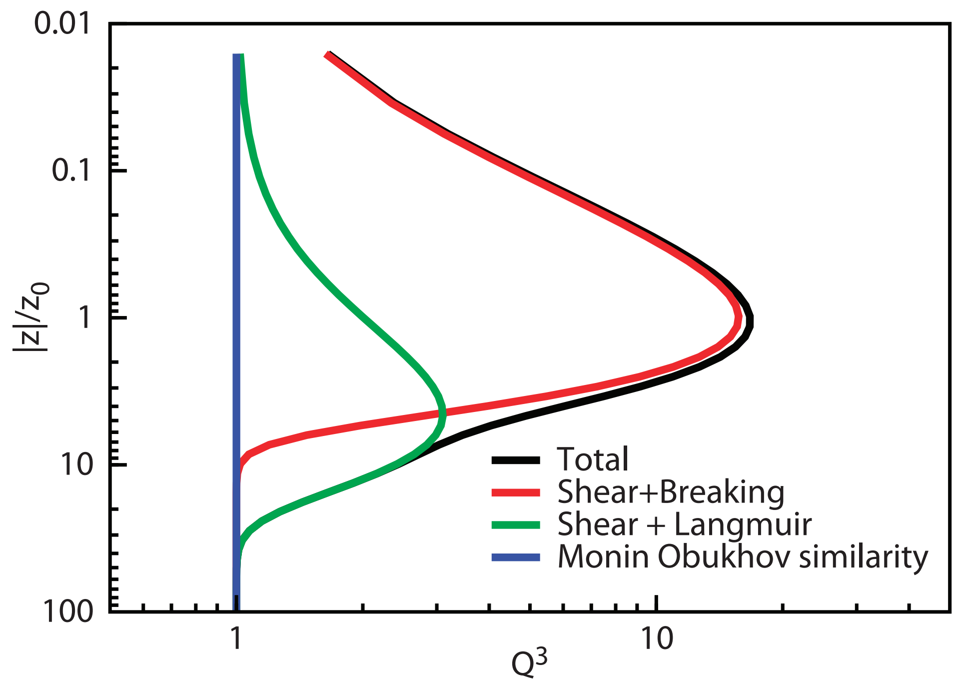


Figure 8: Profile of Q^3 in the ocean column near the surface, with Q a dimensionless turbulent velocity. The contributions by wave dissipation (red line) and Langmuir turbulence (green line) are shown as well. Finally, the profile according to Monin-Obukhov similarity, which is basically the balance between shear production and dissipation, is shown as the blue line and is constant because of the constant stress assumption.

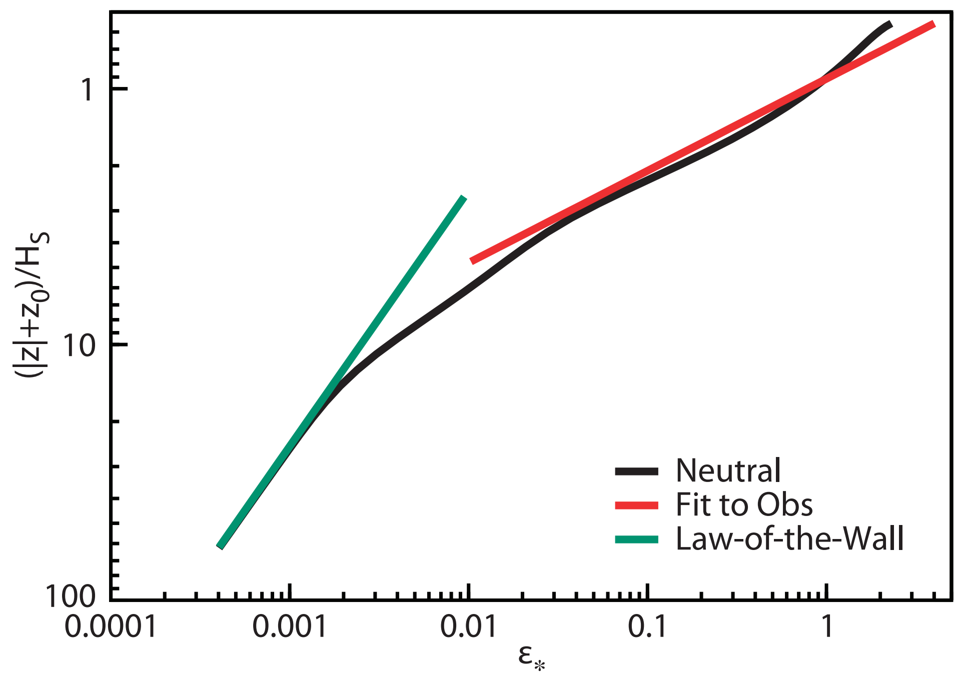


Figure 9: Dimensionless dissipation $\varepsilon_* = \varepsilon H_S/\Phi_{oc}$ versus $(z+z_0)/H_S$

IMPACT ON MEAN SST FIELD

We introduced the sea state dependent upper ocean mixing in the NEMO model.

The ocean circulation equations are very similar to the hydrostatic equations for the atmosphere, except, of course no clouds, but rather salinity.

A number of methods are used to advance these equations (discretized on an Arakawa C grid) in time. The non-diffusive parts are treated by a leap frog scheme, while for the diffusive parts a forward/backward time differencing scheme is used. By introducing a semi-implicit computation of the hydrostatic pressure gradient term the stability range of the leap frog scheme can be extended by a factor of two.

Show results from standalone runs, forced by ERA-interim fluxes and seastate. Averages are over a 20 year period. The control run is one where the dimensionless energy flux is a constant, given by $m = 3.5$.

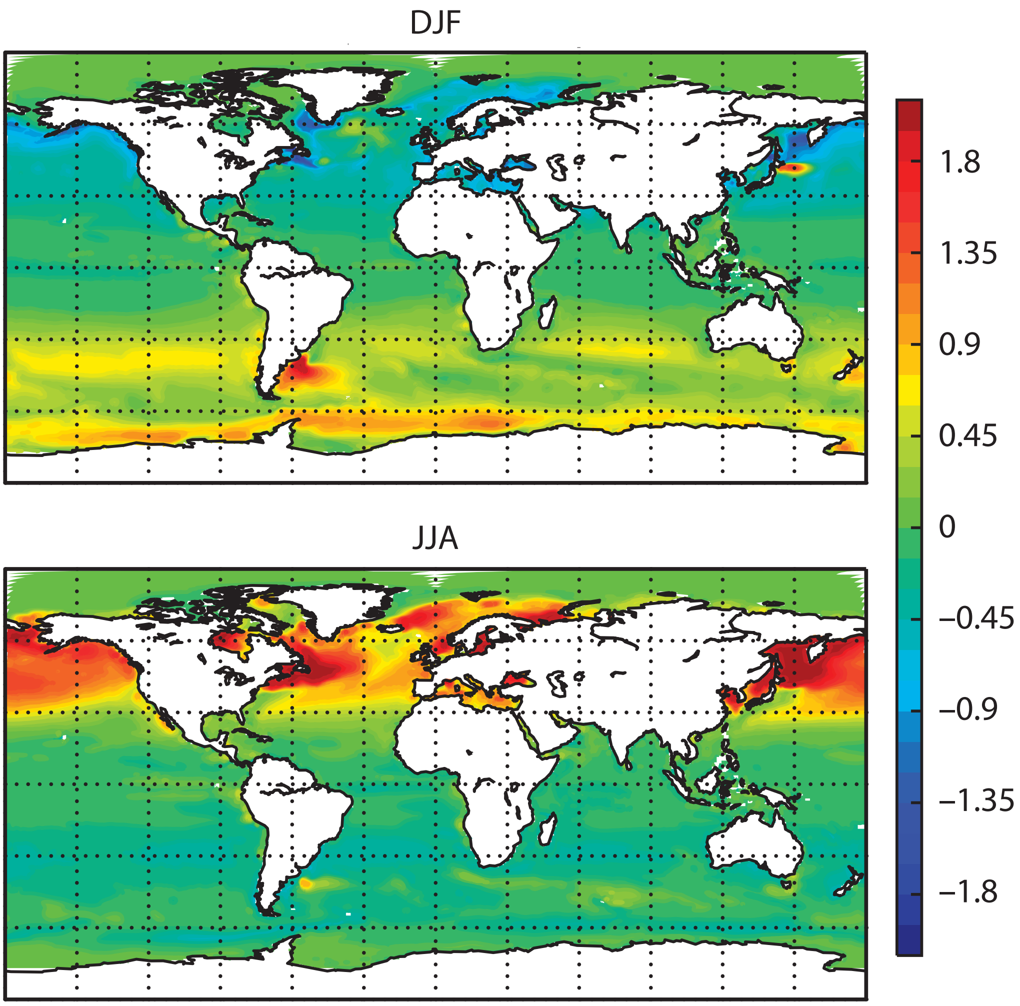


Figure 10: 20-yr average SST difference between CTRL (fsei) and a run with TKE mixing dictated by the energy flux from the ERA-Interim WAM model plus the other wave effects (fxl2). The differences are most pronounced in the summer hemisphere, where the mixing is reduced, leading to higher SST. The colour scale is ± 2 K.

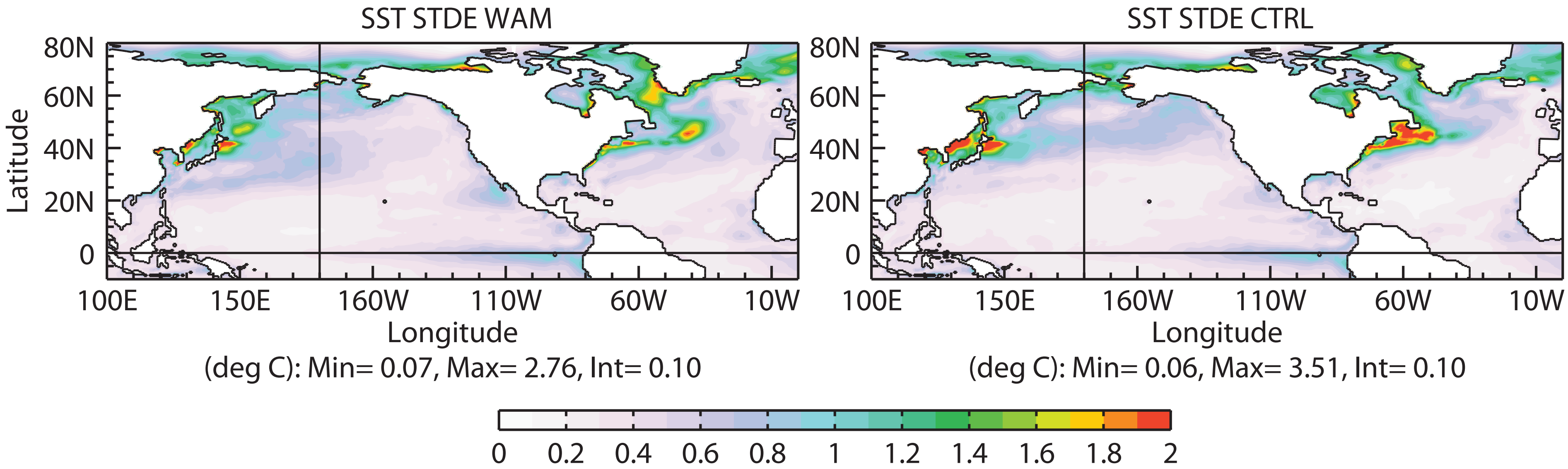


Figure 11: Standard deviation of errors in modelled SST, obtained from a comparison with OIv2 SST analyses.The left panel, labeled WAM, shows the STD errors when all sea state effects are switched on, while the right panel shows the STD errors obtained from CTRL.

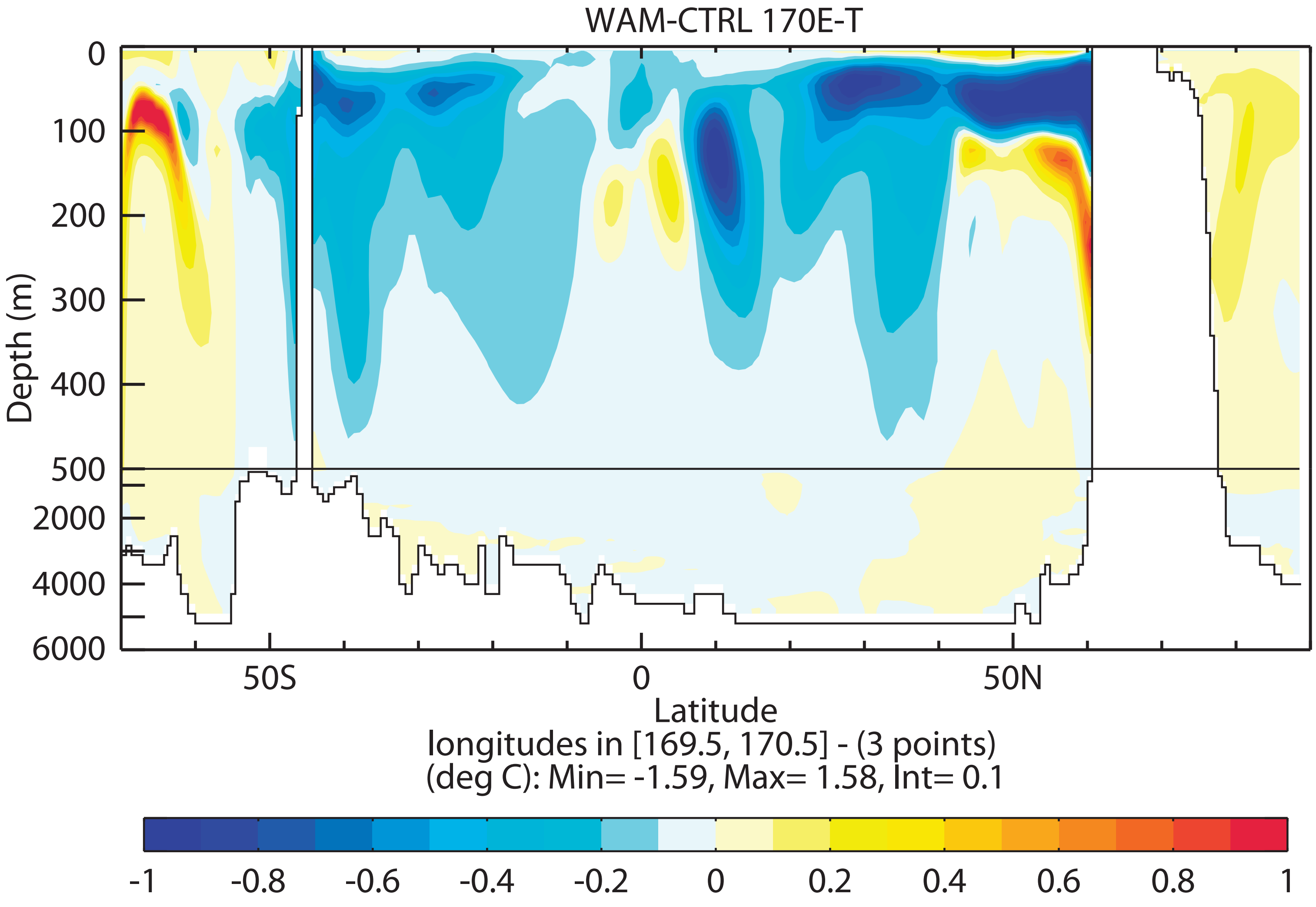


Figure 12: Panel a: Cross section at 170 E of the difference between temperature of WAM and CTRL. Impact of sea state dependent mixing is seen down to 400 m depth.

IMPACT ON COUPLED RUNS

Next, we study results from coupled seasonal forecast runs. Again, the control run is one where the dimensionless energy flux is a constant, given by $m = 3.5$.

As the control gave substantial biases, and seasonal forecasting skill is very sensitive to systematic errors we used an additional control run with a reduced value of m, $m = 0.56$, which had very similar systematic errors as the experiment with seastate effects included. Surprisingly, in certain areas this had a negative impact on forecasts skill. At the moment, we are at a loss how to properly interpret the skill scores of the seasonal forecasting system.

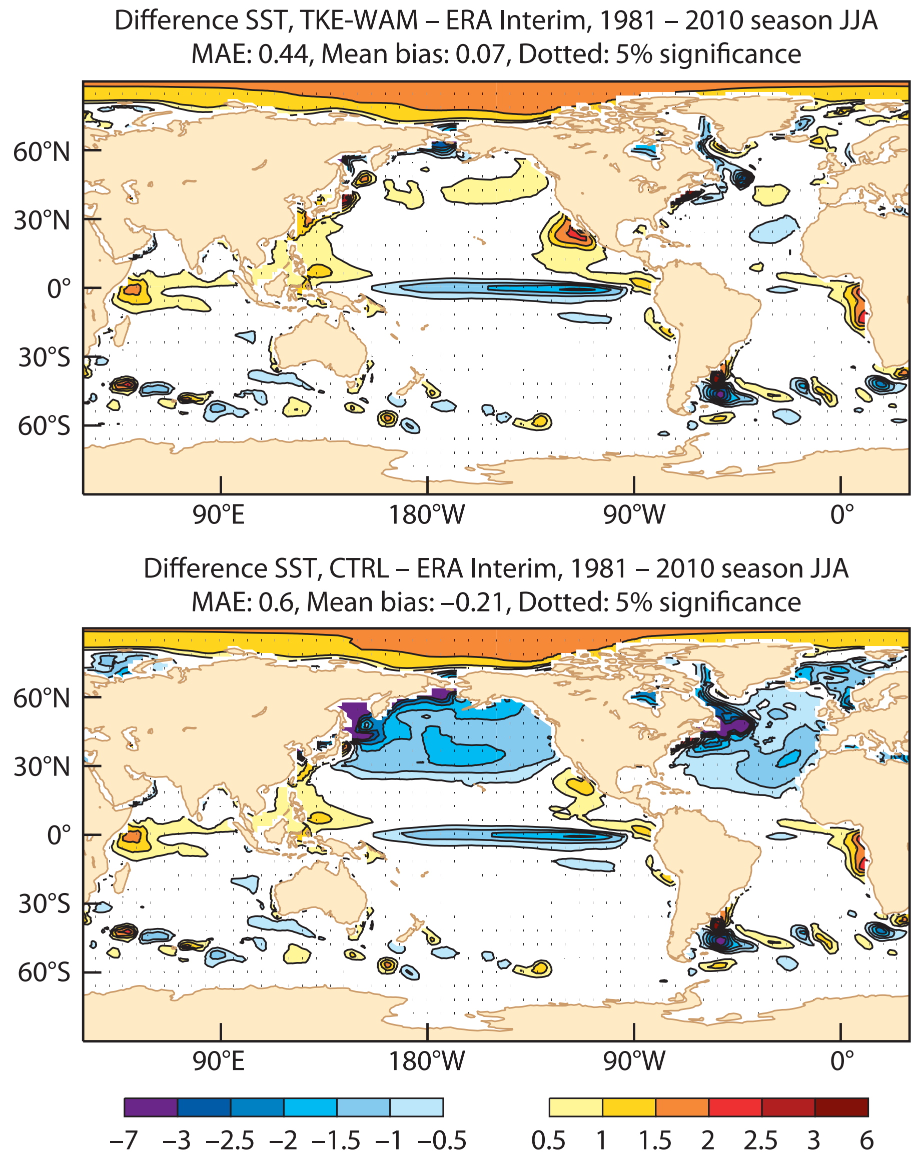


Figure 13: Systematic differences in SST with respect to the OIv2 analysis for JJA with start dates in May. Top panel the experiment TKE-WAM, bottom panel the CTRL experiment.

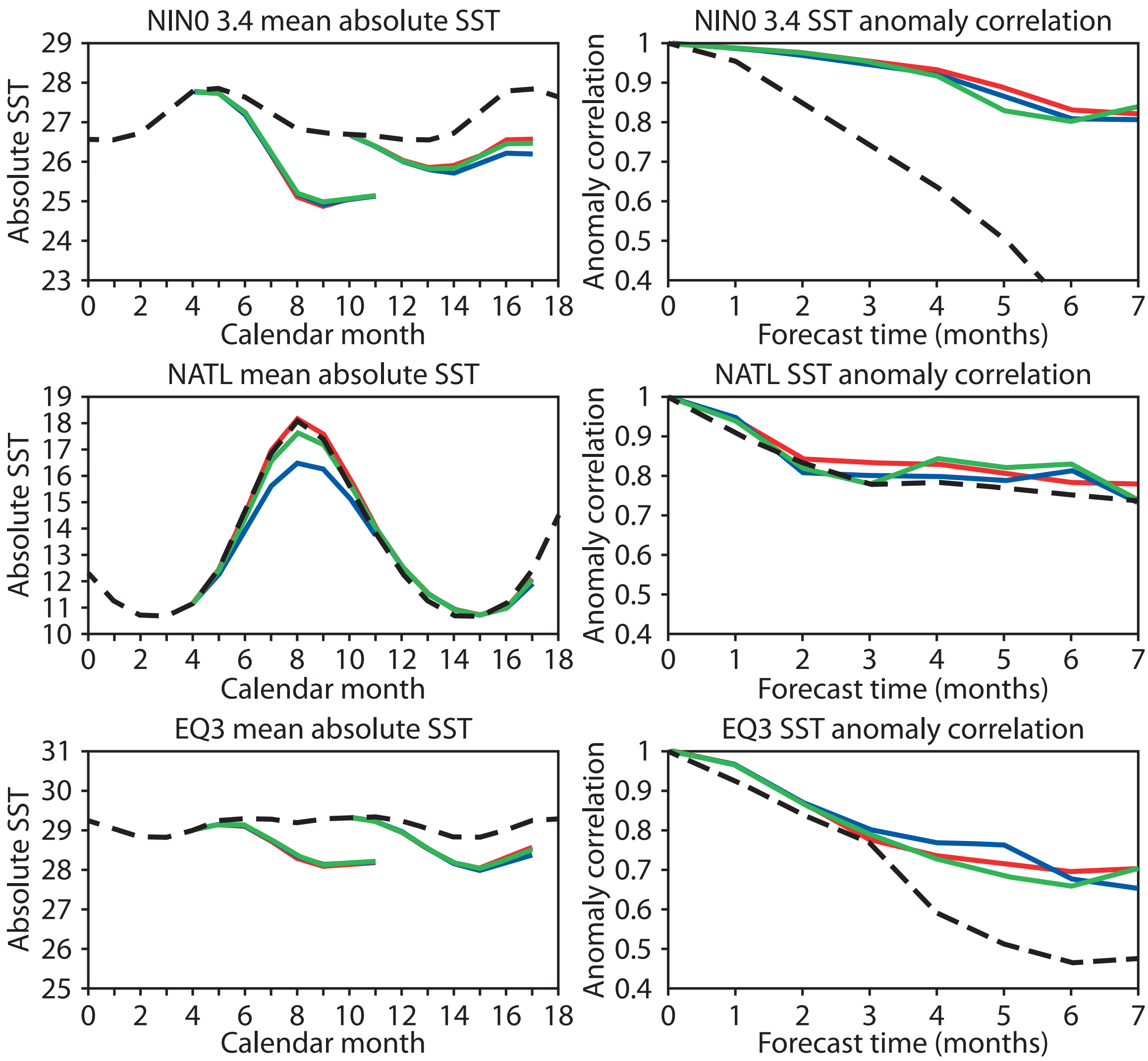


Figure 14: Absolute SST (left column) and correlation (right column) for the seasonal forecasts with CTRL ($m = 3.5$) (blue), TKE-WAM (red) and TKE-20 ($m = 0.56$, green) in selected areas.

COUPLING FROM DAY 0

Presently, in the operational medium-range/monthly ensemble forecasting system (ENS) the interaction between atmosphere and ocean is only switched on at Day 10 in the forecast. In the autumn a new version of ENS will be introduced in operations where the coupling starts from Day 0. Also, sea state effects on upper ocean mixing and dynamics will be switched on.

Coupling from Day 0 has beneficial impacts on

- hurricane forecasting (already shown)
- the MJO
- and the statistical properties of ENS.

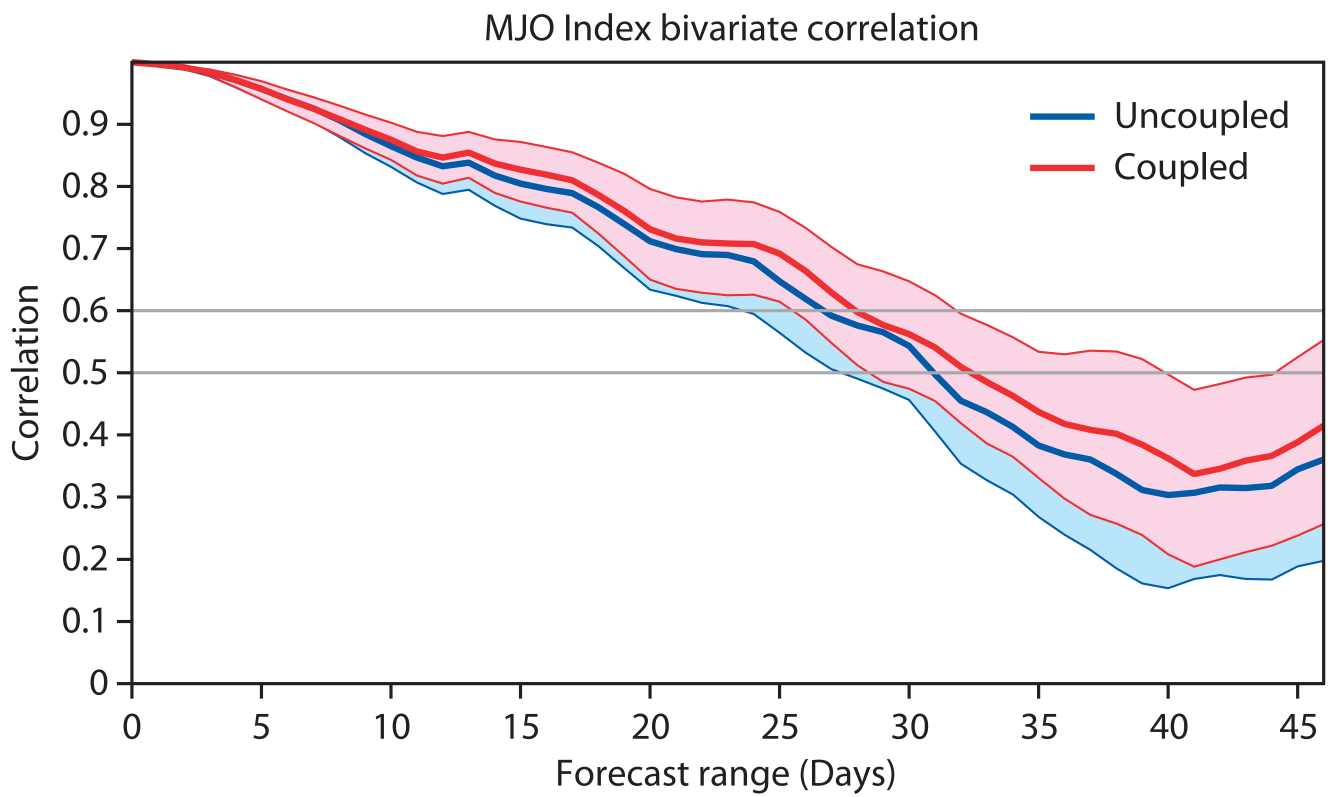


Figure 15: MJO Bivariate correlation for the control runs (legA uncoupled, blue curve) and coupled from day 0 integrations (leg A coupled, red curve). The shaded areas represent the 5% level of confidence using a 10,000 re-sampling bootstrap procedure.

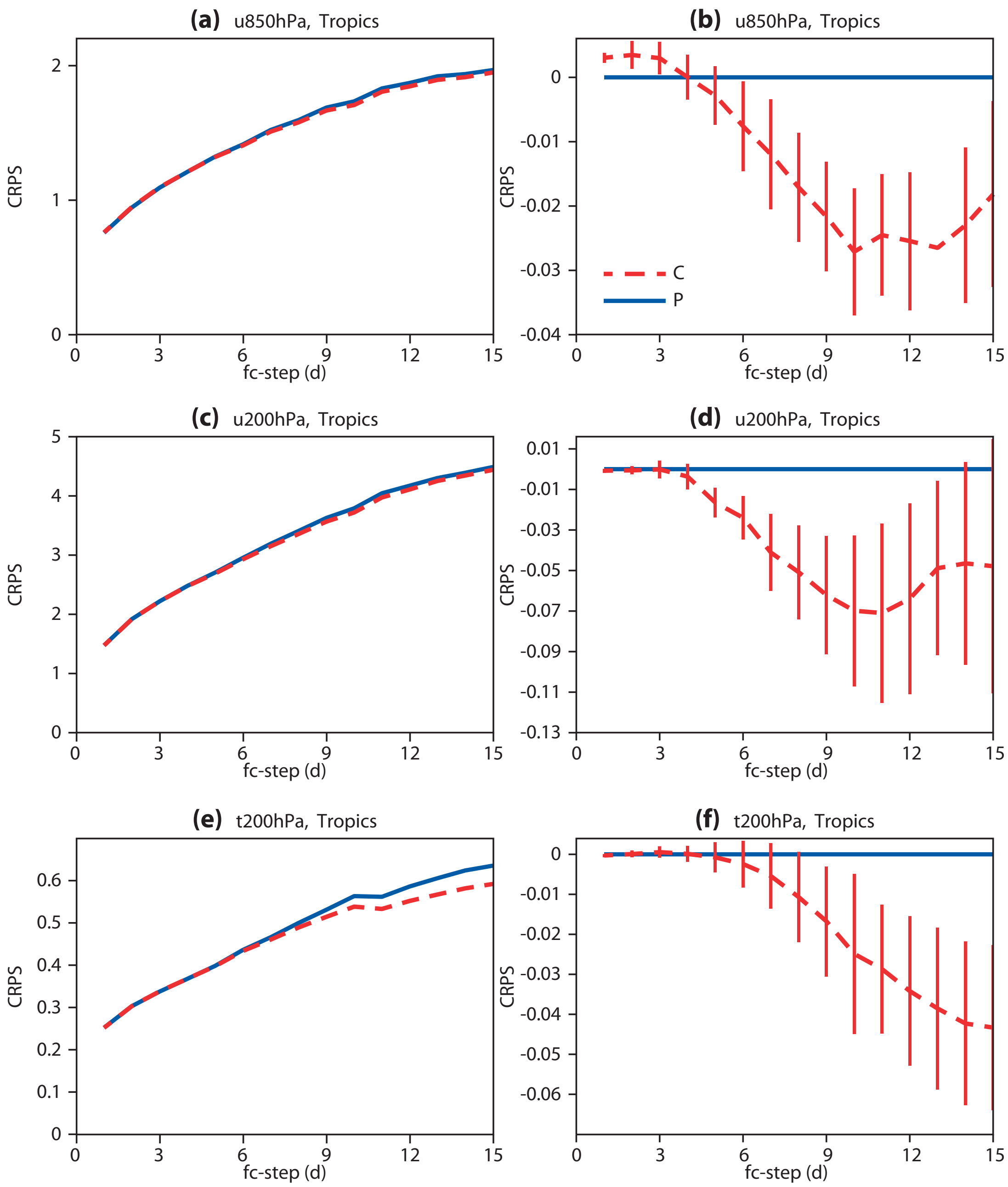


Figure 16: Impact of coupling on CRPS for tropics: (a,b) zonal wind at 850 hPa, (c,d) zonal wind at 200 hPa and (e,f) temperature at 200 hPa.

CONCLUSIONS

- There might be a need to have a systematic study on numerics of coupled systems.
- Wave breaking enhances the upper ocean mixing and even affects the average SST field over a 20 year period, while there is a hint that it might have impact on predictability.
- There is a trend towards the introduction of more complicated CMS's. Not only forecasting but also data assimilation needs to be done in the context of a coupled system.
- Work on the development of a weakly coupled data assimilation system is in progress.