Atmosphere-ocean interaction through waves

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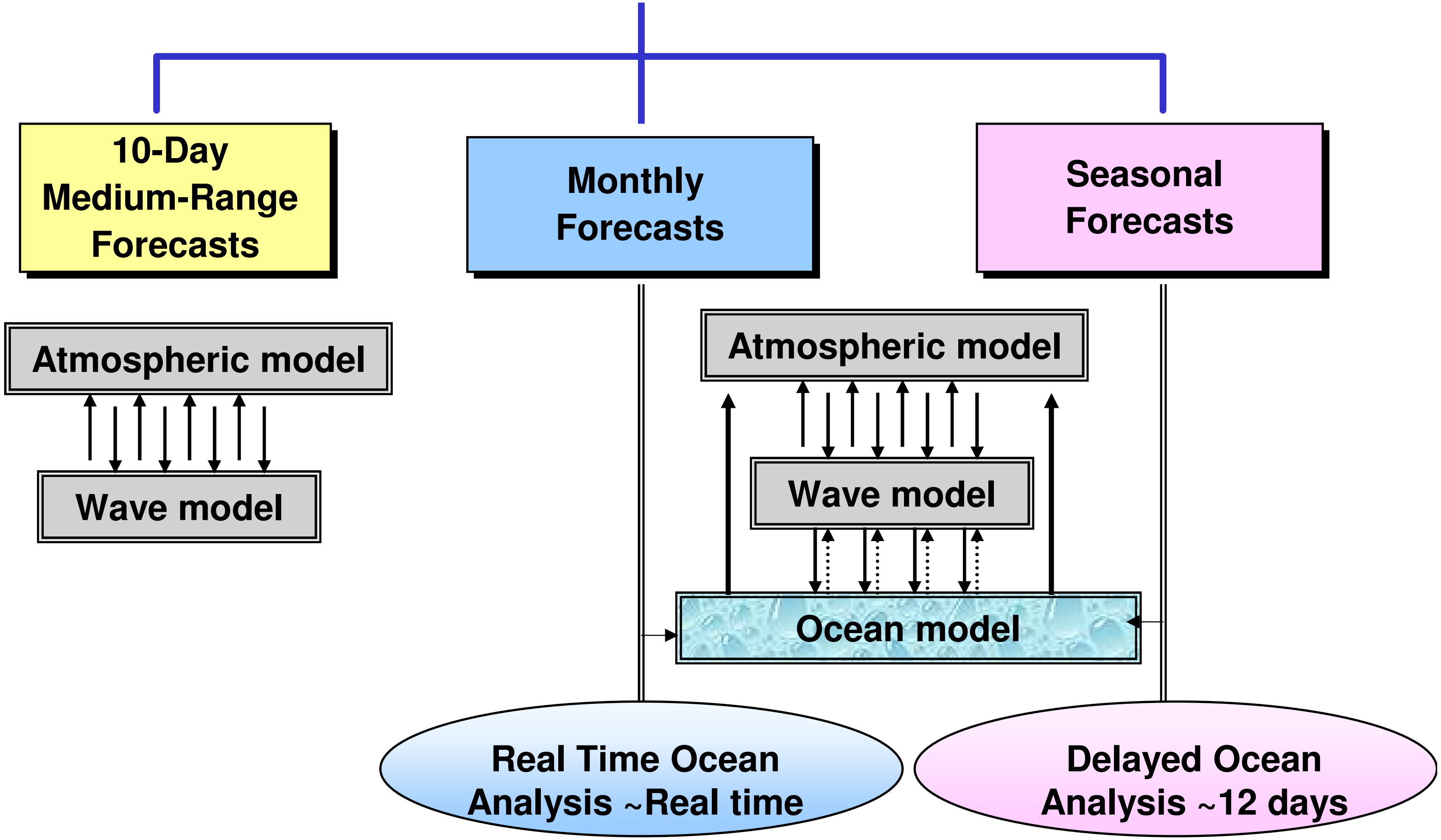
INTRODUCTION

At ECMWF there is slow but steady progress in the development of a fully-coupled **atmosphere, ocean-wave, ocean circulation model**, simply called the Integrated Forecasting System (**IFS**). In June 1998 we introduced the first operational coupled atmosphere, ocean-wave model, which was followed by the first version of the IFS (atm-ocw-oc), used for seasonal forecasting and later for monthly forecasting.

Presently, the interactions between the several components are as follows: Momentum loss and heat exchange from the atmosphere depends on the sea state following the approach of Janssen (1991, 1996, 2004). The ocean circulation is driven by the sea state dependent fluxes and produces surface currents, e.g., which are returned to the atmospheric model needed for the determination of the fluxes.

As a next step, following Saetra's work we are going to test impact of effects such as **Stokes-Coriolis** forcing and it is proposed to drive the ocean circulation model with momentum and energy fluxes directly from the wave model. In addition, effects of ocean-wave, current interaction will be introduced.

ECMWF:
Weather and Climate Dynamical Forecasts



10-Day Medium-Range Forecasts

Monthly Forecasts

Seasonal Forecasts

Atmospheric model

Wave model

Atmospheric model

Wave model

Ocean model

Real Time Ocean Analysis ~Real time

Delayed Ocean Analysis ~12 days

Today, I discuss briefly the following items:

- **MOMENTUM FLUX FOR EXTREME WINDS**

  For extreme winds a maximum in the drag coefficient is found. Illustrated with one example from hurricane Katrina using T_{799} version of the IFS.

- **HEAT FLUXES AND SEA STATE**

  Determine effects of growing ocean waves on heat flux according to critical layer theory. Gives a Dalton and Stanton number which increases with wind speed. This is at variance with the results from HEXOS, but not with recent measurement campaigns. Results in a deepening of hurricane Katrina by 10-15 mb.

- **WAVE BREAKING AND MIXED LAYER**

  Energy flux Φ_{oc} from atmosphere to ocean is controlled by wave breaking. Gives an energy flux of the type $\Phi_{oc} = m\rho_a u_*^3$ where m depends on the sea state.

HURRICANES and the SEA STATE

The problem

Using a simple model for a hurricane, Emanuel argued that central pressure and maximum wind speed depend on the ratio of enthalpy to momentum exchange coefficients, C_k/C_D. This ratio should lie in the range 1.2 – 1.5 in order to get a realistic simulation of a hurricane.

However, according to Hexos, C_k (which is Dalton or Stanton number) is independent of wind speed while C_D increases with wind speed, hence the ratio C_k/C_D decreases with increasing windspeed thereby seriously limiting the maximum wind speed of a hurricane. But these exchange coefficients have only been observed up to a wind speed of 20 m/s, hence extrapolation to extreme cases may be a problem here. There are a few ways out of this. The drag coefficient gets a **maximum** for increasing wind and/or the heat flux **increases** with windspeed.

MOMENTUM FLUX FOR EXTREME WINDS

Before results are discussed I will first give a basic air-sea interaction model. Ocean waves, described by the wave spectrum $F(\mathbf{k};\mathbf{x},t)$, are governed by the

energy balance equation

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

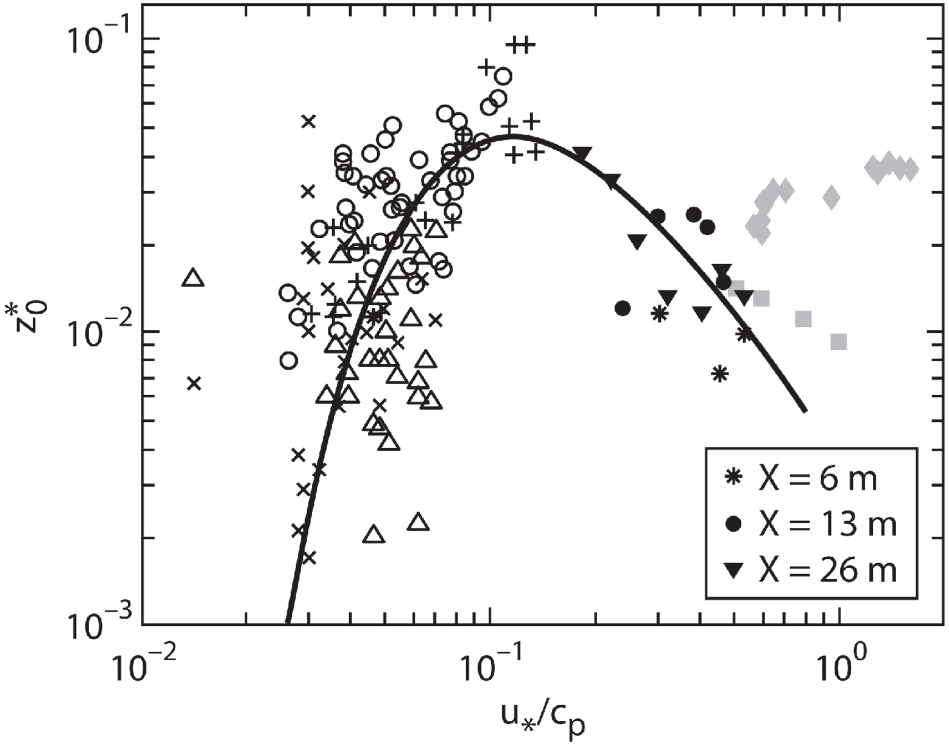
and the source functions S represent the physics of wind input, dissipation by wave breaking and nonlinear four-wave interactions. In my formulation, the roughness length is given by

$$z_0^* = \frac{gz_0}{u_*^2} = \frac{\alpha}{\sqrt{1-\frac{\tau_w}{\tau}}}, \alpha \simeq 0.01$$

and depends on the ratio of wave-induced stress τ_w to total stress τ, where

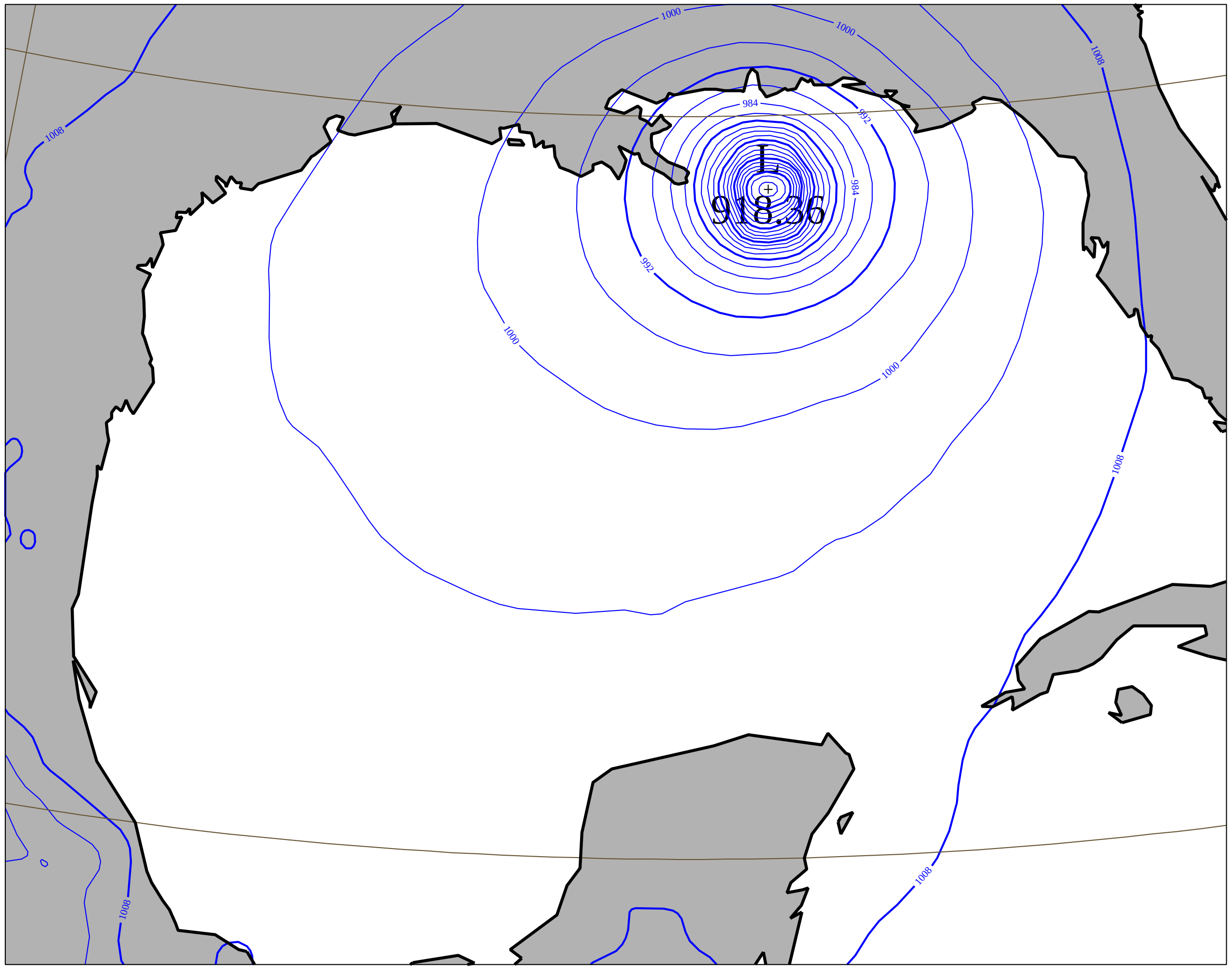
$$\tau_w = \left.\frac{\partial \mathbf{P}}{\partial t}\right|_{wind} = \int d\omega d\theta \, \frac{\mathbf{k}}{\omega} S_{in}.$$

Hurricane winds are highly variable in space and time, and therefore the sea state is extremely young ($c_p/u_* < 5$). In those circumstances there are relatively few waves to exert a stress on the airflow and as a consequence the airflow is smooth. In the course of time more and more waves are generated resulting in an increase in roughness and the drag until the waves get so steep that wave breaking and nonlinear interactions **limit and reduce the roughness** .

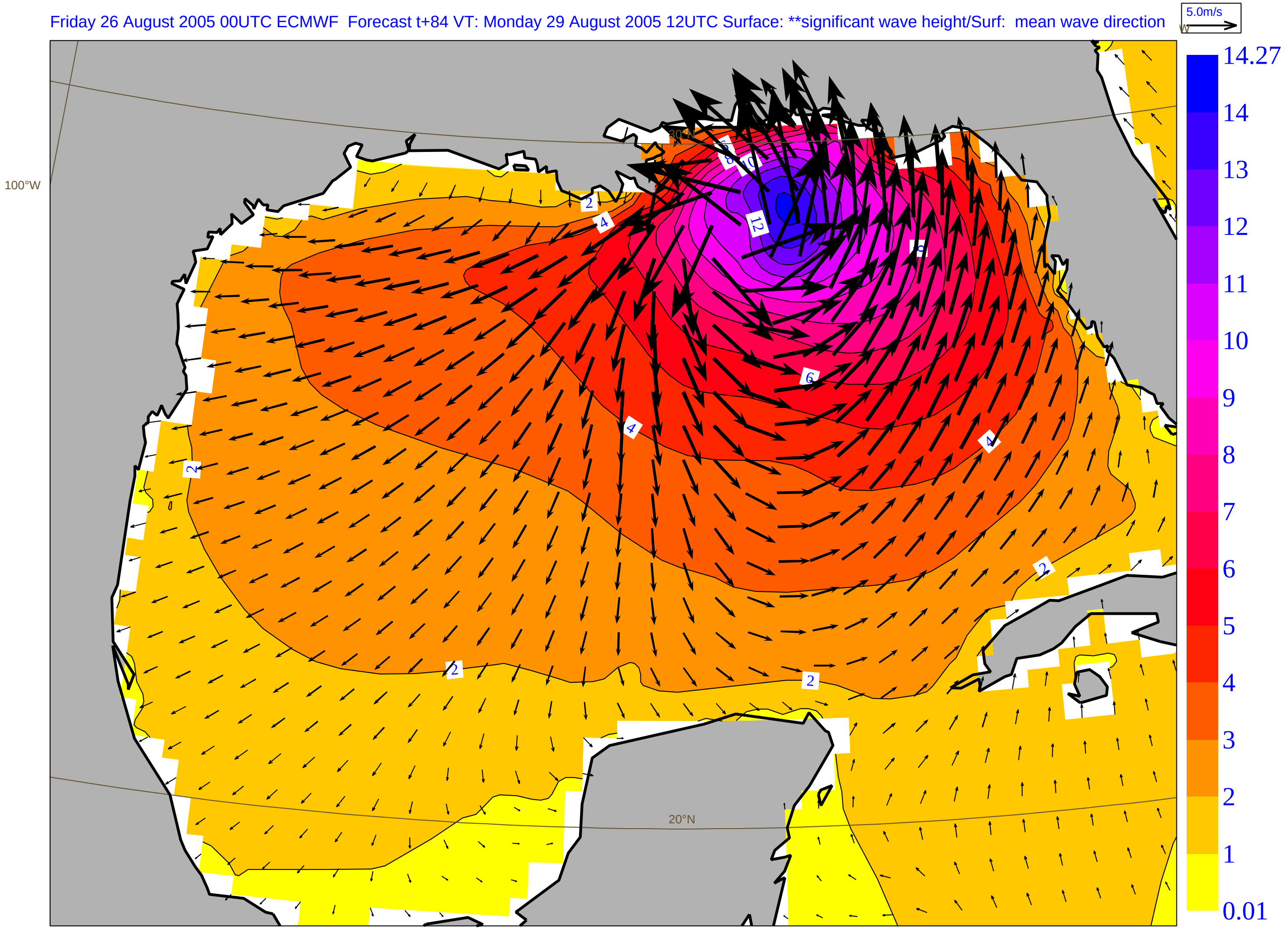


Air-sea interaction and waves

Friday 26 August 2005 00UTC ECMWF Forecast t+84 VT: Monday 29 August 2005 12UTC Surface: Mean sea level pressure

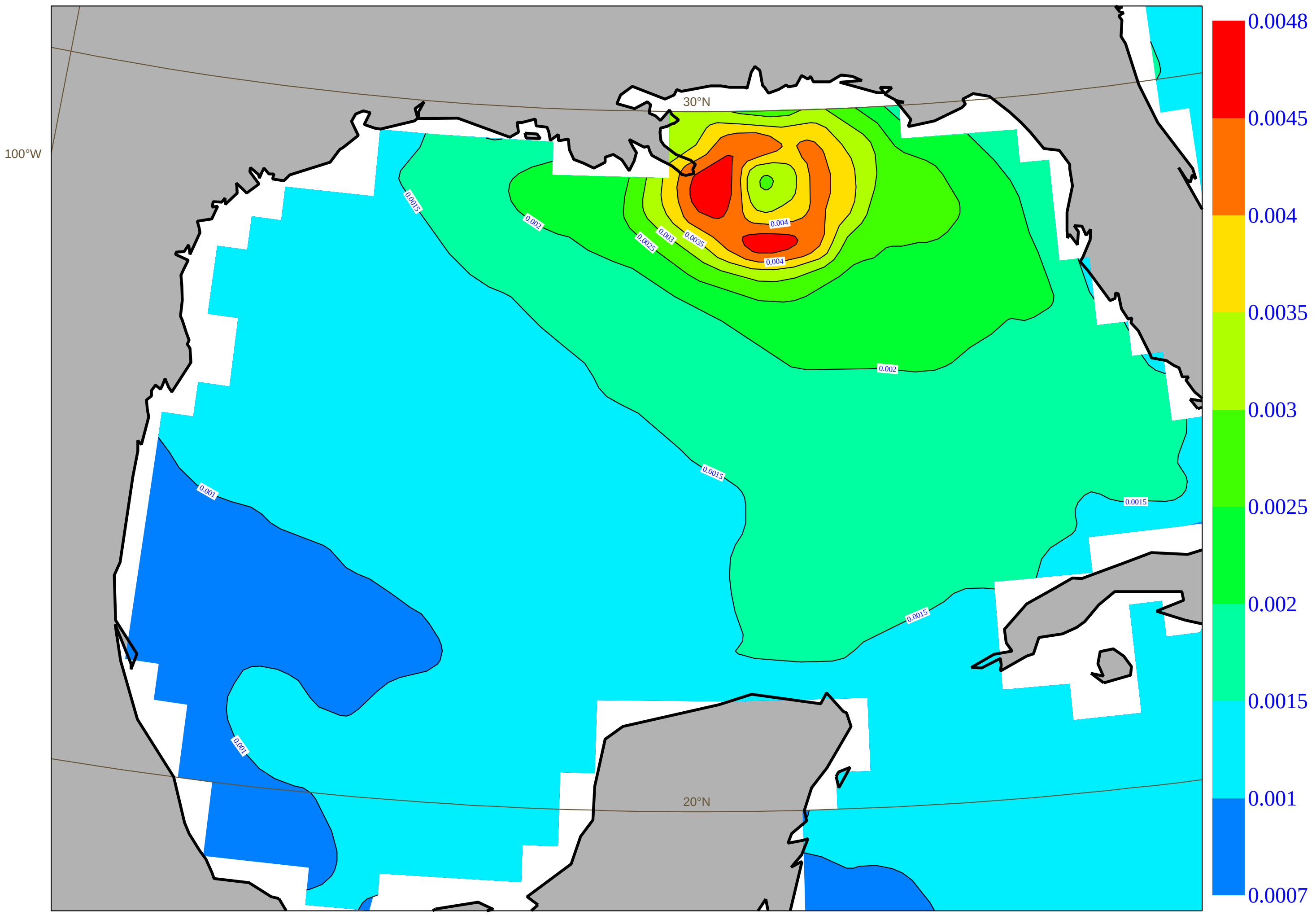


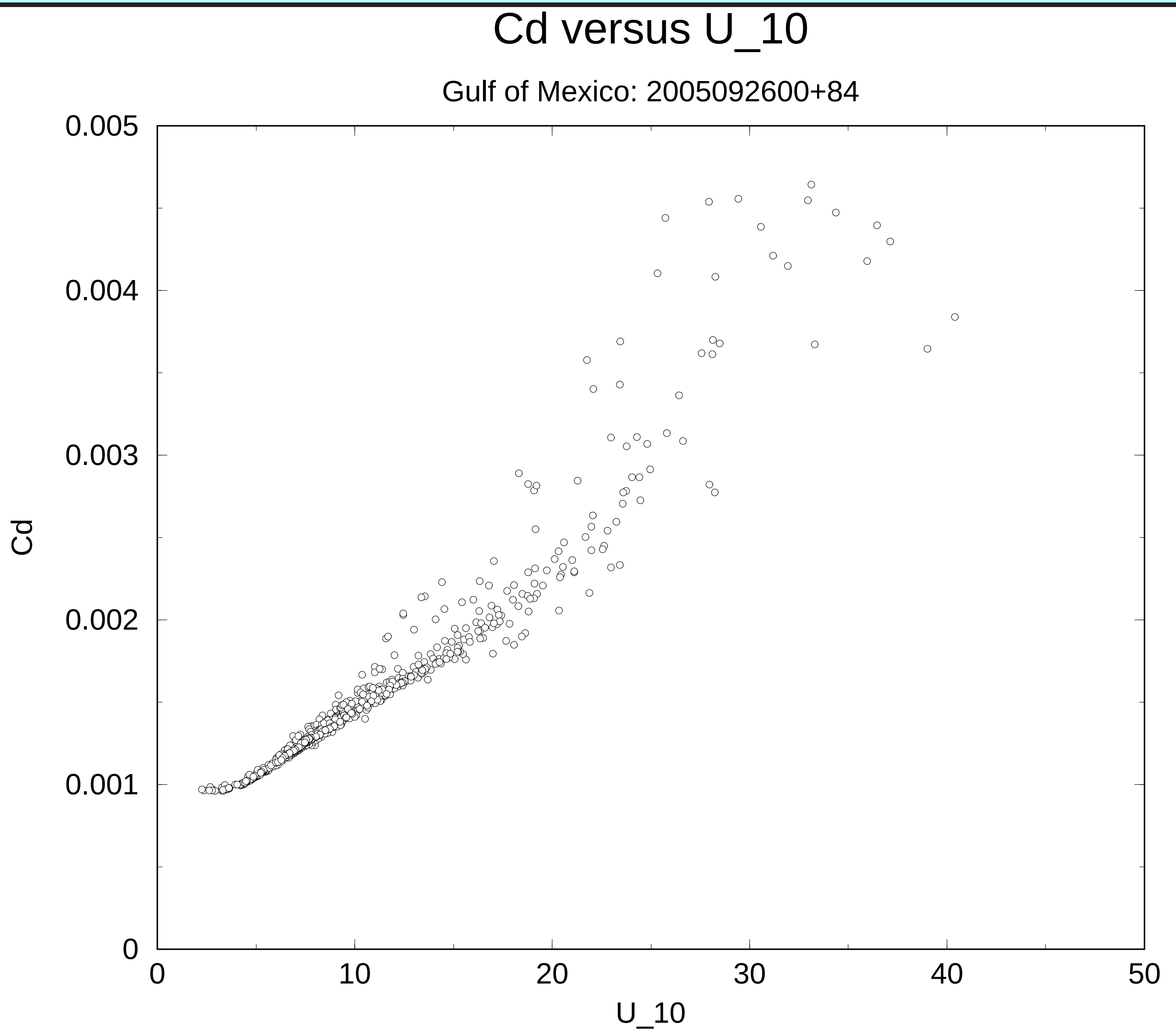
Air-sea interaction and waves



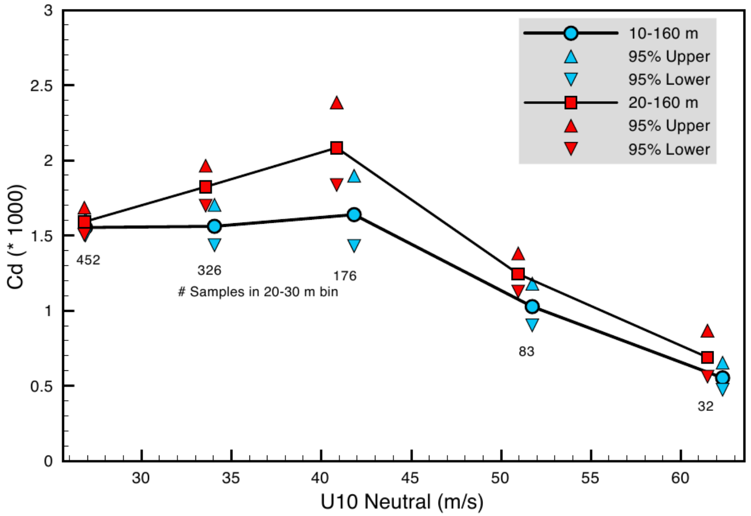
Air-sea interaction and waves

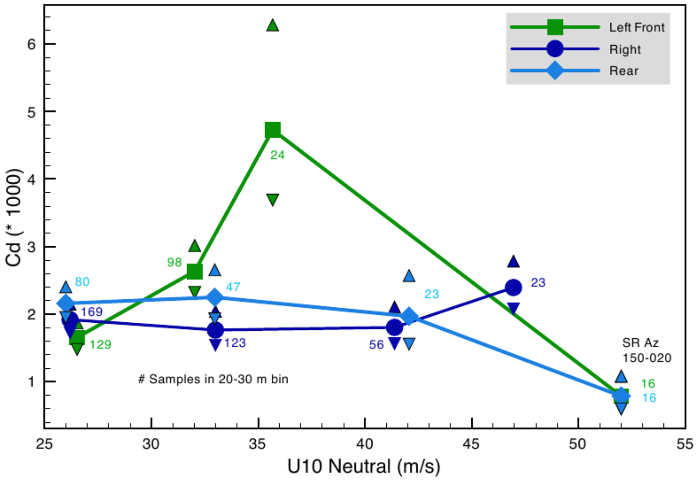
Friday 26 August 2005 00UTC ECMWF Forecast t+84 VT: Monday 29 August 2005 12UTC 10m **drag coeff with waves




Cd versus U_10
Gulf of Mexico: 2005092600+84
Cd
0.005
0.004
0.003
0.002
0.001
0
U_10
0
10
20
30
40
50

This finding is in qualitative agreement with results of Powell (2008)





HEAT FLUXES AND THE SEA STATE

In the rest of my talk I will assume that heat and moisture flux can be treated on an equal footing (and are equal) and we assume the passive scalar approximation, i.e. these quantities do not affect the dynamics of the flow to a significant extent. Denoting by ΔT the air-sea temperature difference, one has

$$\Delta T = \frac{q_*}{\kappa u_*} \log(z/z_T)$$

where z_T is a thermal roughness and $q_* = -\langle w'T' \rangle$. The Dalton number C_q then follows from

$$q_* = C_q U_{10} \Delta T_{10}$$

and, on elimination of ΔT_{10}, one finds

$$C_q = C_D^{1/2} \frac{\kappa}{\log(10/z_T)},$$

where C_D is the drag coefficient which increases with U_{10}. An important question to ask is to what extent z_T depends on sea state and/or wind speed.

Theory

Extend the theory of **wind-wave generation** to include thermal **stratification**. From previous work it is found that the mean flow is affected by the waves through a diffusion term:

$$\frac{\partial}{\partial t}U_0 = \frac{\partial}{\partial z}K(z)\frac{\partial}{\partial z}U_0 + D_w\frac{\partial^2}{\partial z^2}U_0$$

where $K(z)$ denotes a turbulent eddy viscosity and D_w represents the effects of gravity waves (with wave spectrum $F(k)$) on the mean flow,

$$D_w = \frac{\pi\omega^2|\chi|^2}{|c - v_g|}F(k),$$

with $\omega = \sqrt{gk}$, $v_g = \partial\omega/\partial k$ and χ is the normalized vertical component of the wave-induced velocity. In the passive scalar approximation the evolution of **mean temperature** is found to be

$$\frac{\partial}{\partial t}T_0 = \frac{\partial}{\partial z}\left\{(K(z) + D_w)\frac{\partial}{\partial z}T_0\right\}.$$

By parametrizing the wave effect the wind and temperature profile can be obtained and one now immediately finds the expressions for the drag coefficient C_D and the Dalton number C_q:

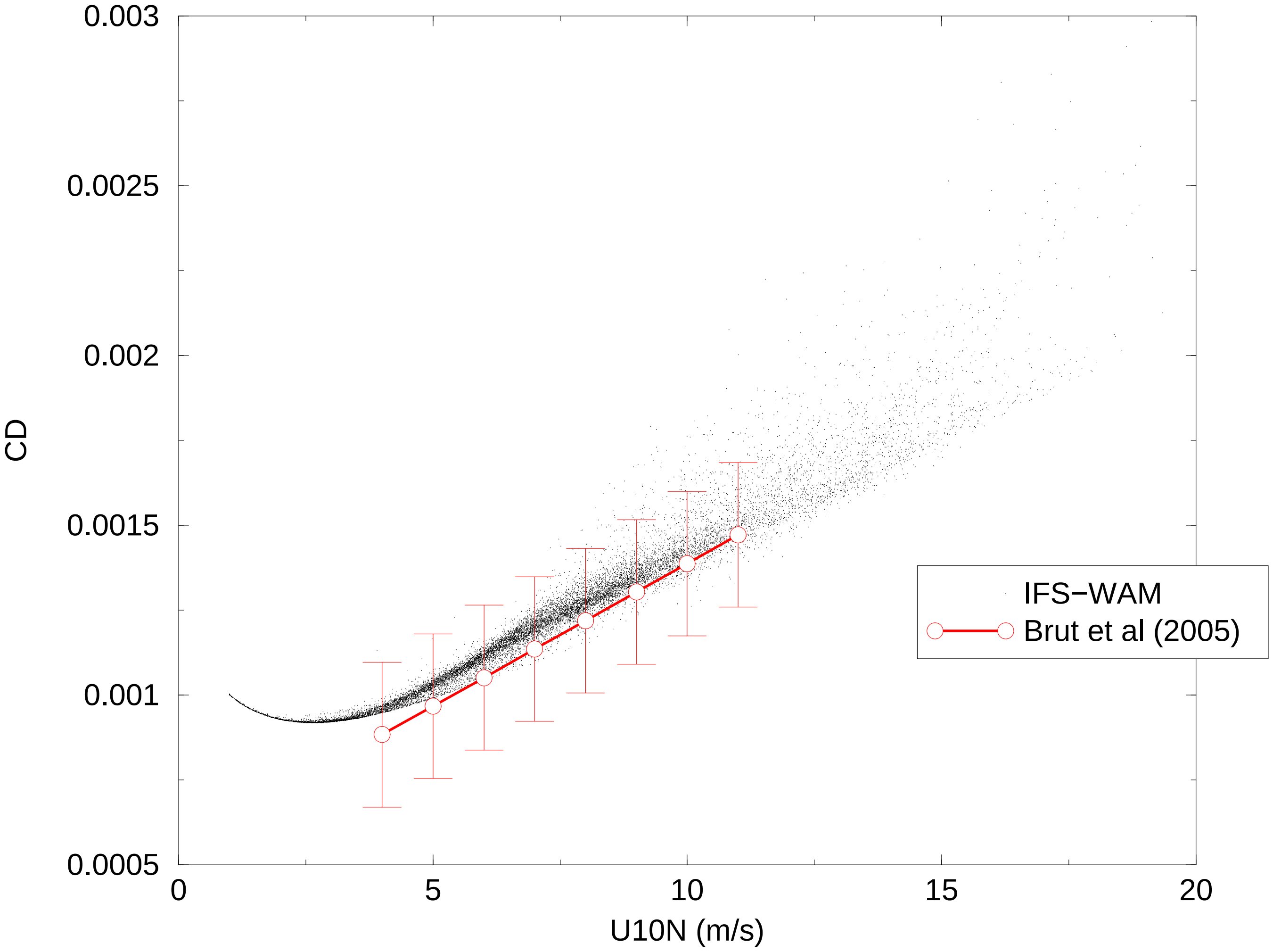
$$C_D(10) = \left\{ \frac{\kappa}{\log\left(10/z_0\right)} \right\}^2, \; C_q(10) = C_D^{1/2} \frac{\kappa}{\log(10/z_T)}.$$

It is straightforward to evaluate these coefficients from ECMWF’s IFS. Results show, in agreement with Brut *et al.* (2005), an increase of C_D with wind while C_q also increases with wind but to a lesser extent. However, result for C_q is in sharp contrast with HEXOS which gives a constant for the Dalton number.

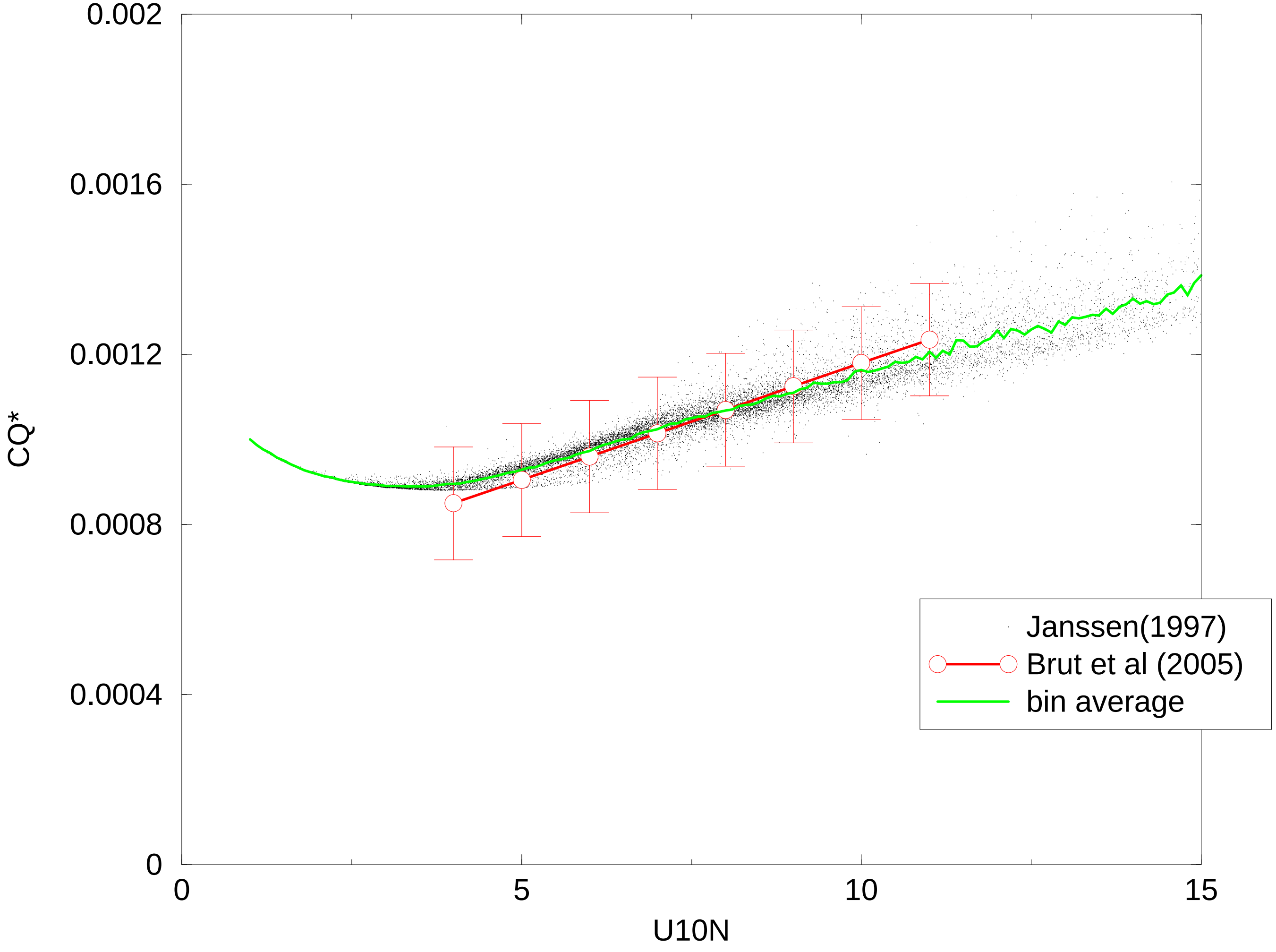
Smedman *et al.* (2007) (and also Oost *et al.* (2000)) had another look at the heat exchange problem and they also found that C_q increases with wind speed.

Is there now ’conclusive’ evidence that Dalton/Stanton number increase with wind?

CD versus neutral wind



CQ* versus U10N



IMPACT ON HURRICANE KATRINA

I have performed a number of sensitivity experiments on hurricane Katrina to test sensitivity to the formulation of the heat and moisture flux. The control experiment is the operational IFS which uses the following representation of the thermal roughness

$$z_T = \delta \frac{\nu}{u_*}, \ \delta = 0.4, 0.6.$$

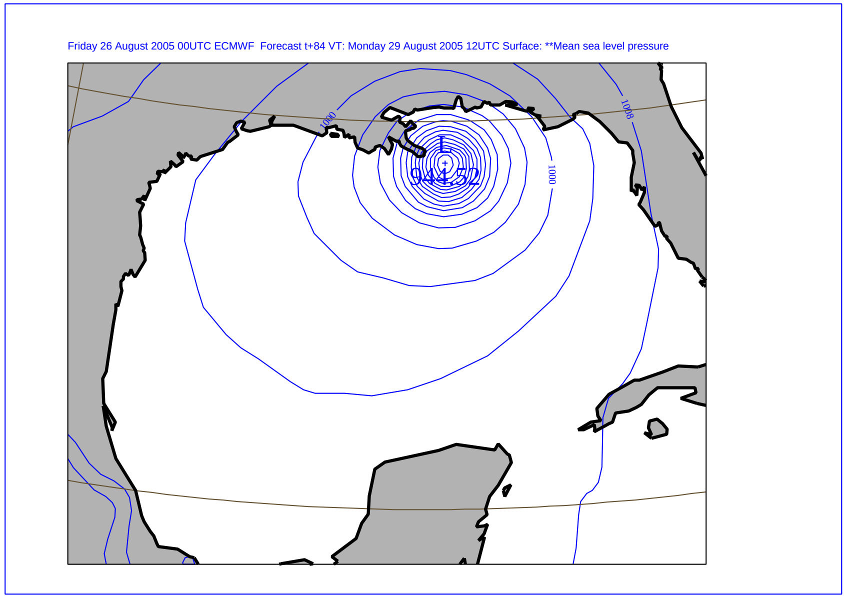
When substituted in the expression of the Dalton/Stanton number,

$$C_q = C_D^{1/2} \frac{\kappa}{\log(10/z_T)},$$

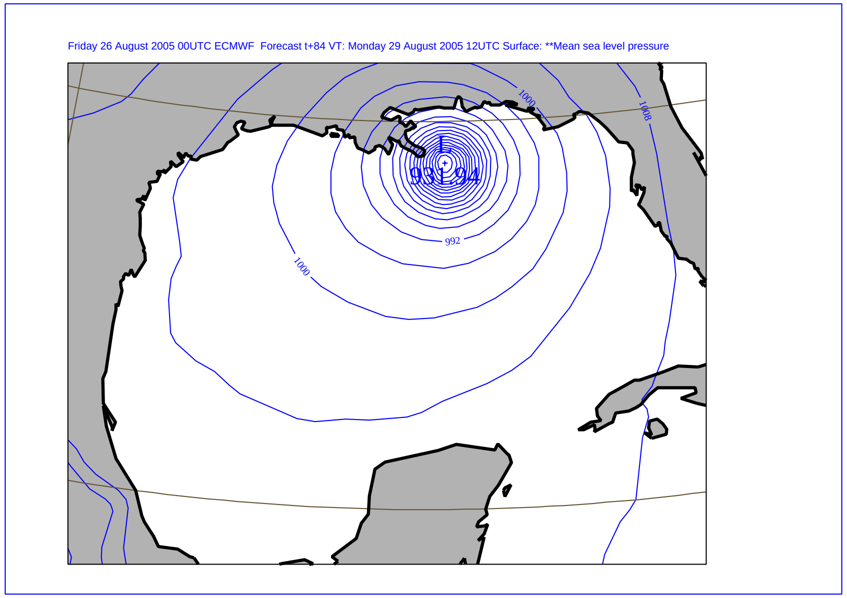
this choice of thermal roughness results in a Dalton/Stanton number that is almost independent of wind speed (which agrees with HEXOS).

The next viewgraphs show results of a T_{511} simulation with the IFS for surface pressure and significant wave height and the differences between the experiment (with seastate dependent thermal roughness) and control. Impact is quite substantial.

Air-sea interaction and waves



Friday 26 August 2005 00UTC ECMWF Forecast t+84 VT: Monday 29 August 2005 12UTC Surface: **Mean sea level pressure



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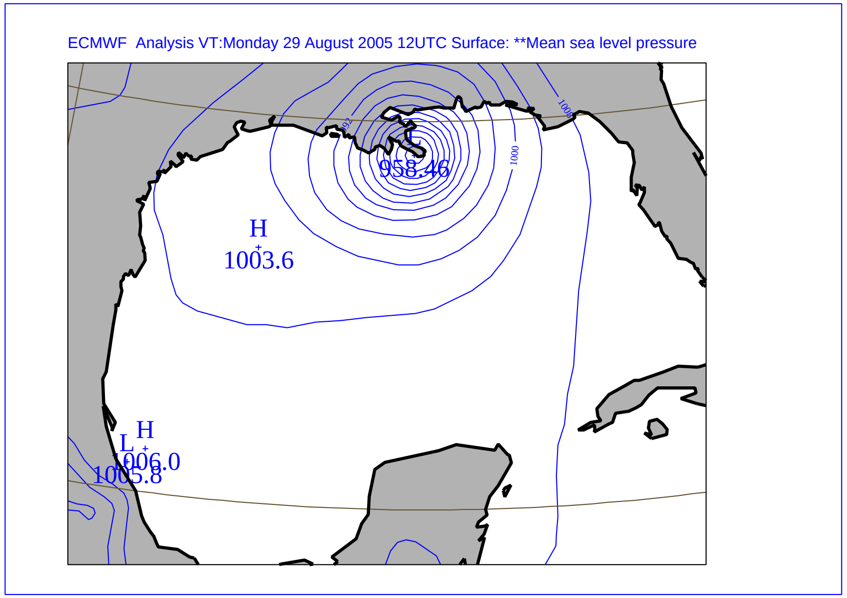
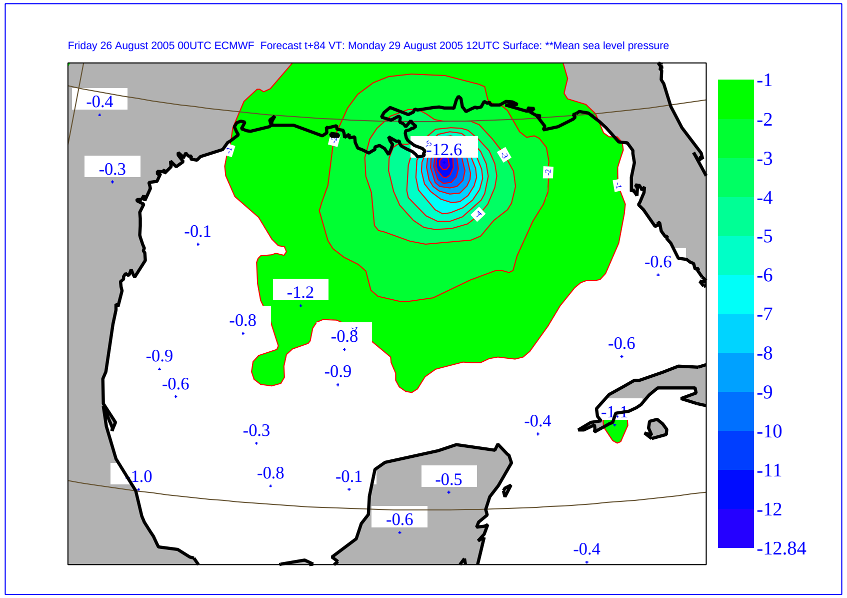
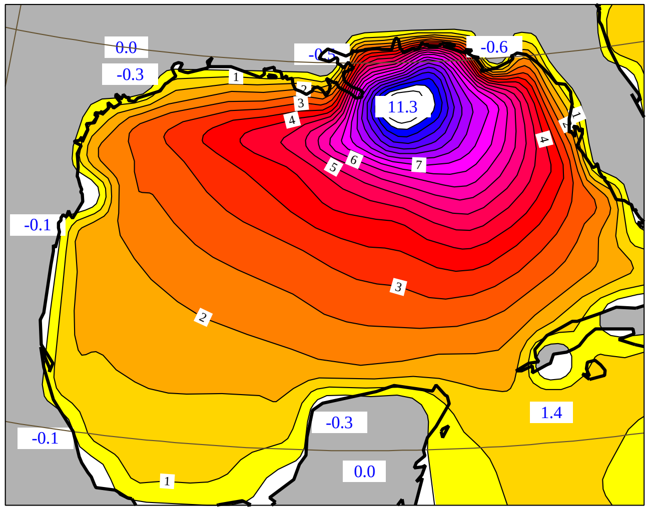


ECMWF Analysis VT:Monday 29 August 2005 12UTC Surface: **Mean sea level pressure

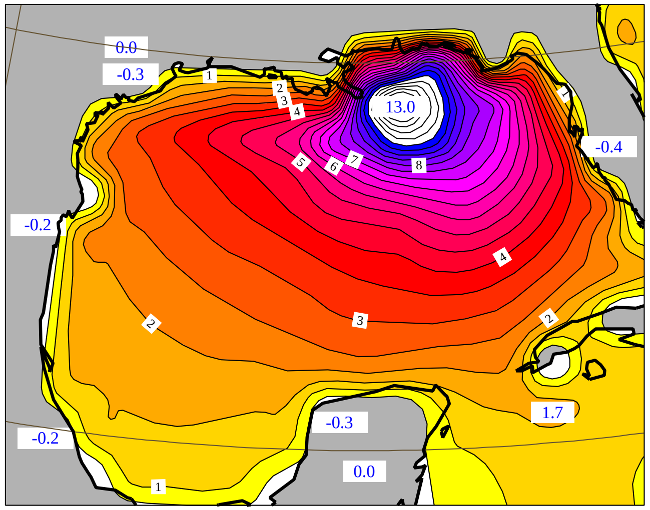


Friday 26 August 2005 00UTC ECMWF Forecast t+84 VT: Monday 29 August 2005 12UTC Surface: **Mean sea level pressure

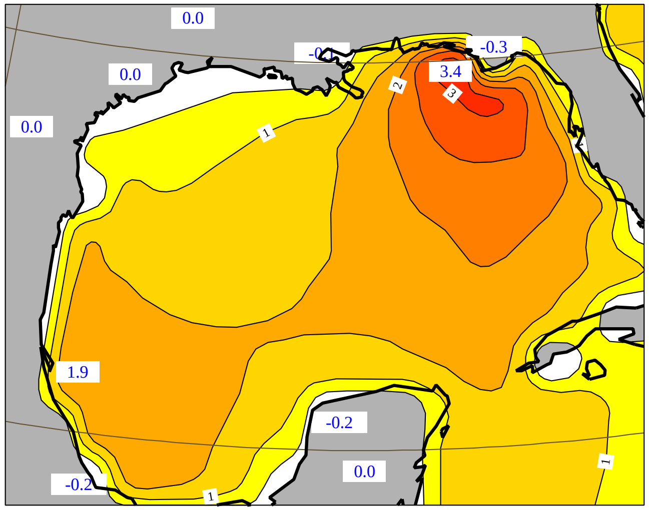
Air-sea interaction and waves



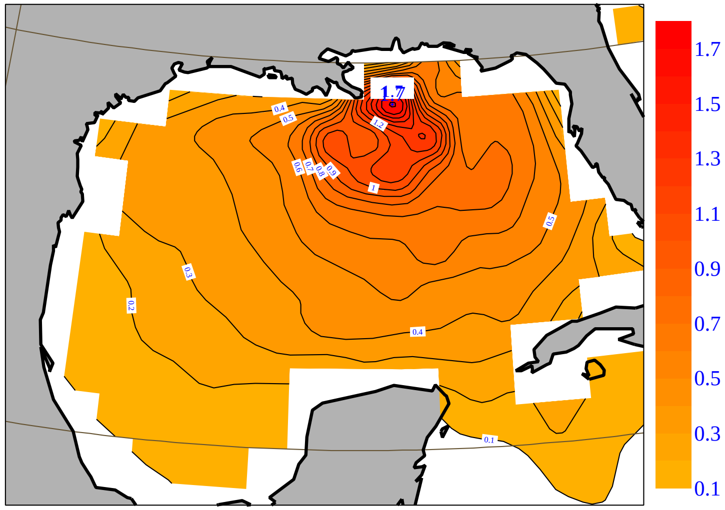
Friday 26 August 2005 00UTC ECMWF Forecast t+84 VT: Monday 29 August 2005 12UTC Surface: **significant wave height



Friday 26 August 2005 00UTC ECMWF Forecast t+84 VT: Monday 29 August 2005 12UTC Surface: **significant wave height



ECMWF Analysis VT:Tuesday 30 August 2005 12UTC Surface: **significant wave height



Friday 26 August 2005 00UTC ECMWF Forecast t+84 VT: Monday 29 August 2005 12UTC Surface: **significant wave height

WAVE BREAKING AND THE MIXED LAYER

Nowadays the role of breaking ocean waves and its contribution to the surface current and mixing is well-understood (Craig and Banner, 1994; Terray *et al.*, 1999). Near surface dissipation is closely related to the sea state. It are the breaking waves that dump energy in the ocean column and there is no direct correspondence between surface wind and breaking, hence there is no direct relation between energy flux and local wind.

In the context of ocean waves the energy flux Φ_{oc} and the momentum flux τ_{oc} into the ocean are given by

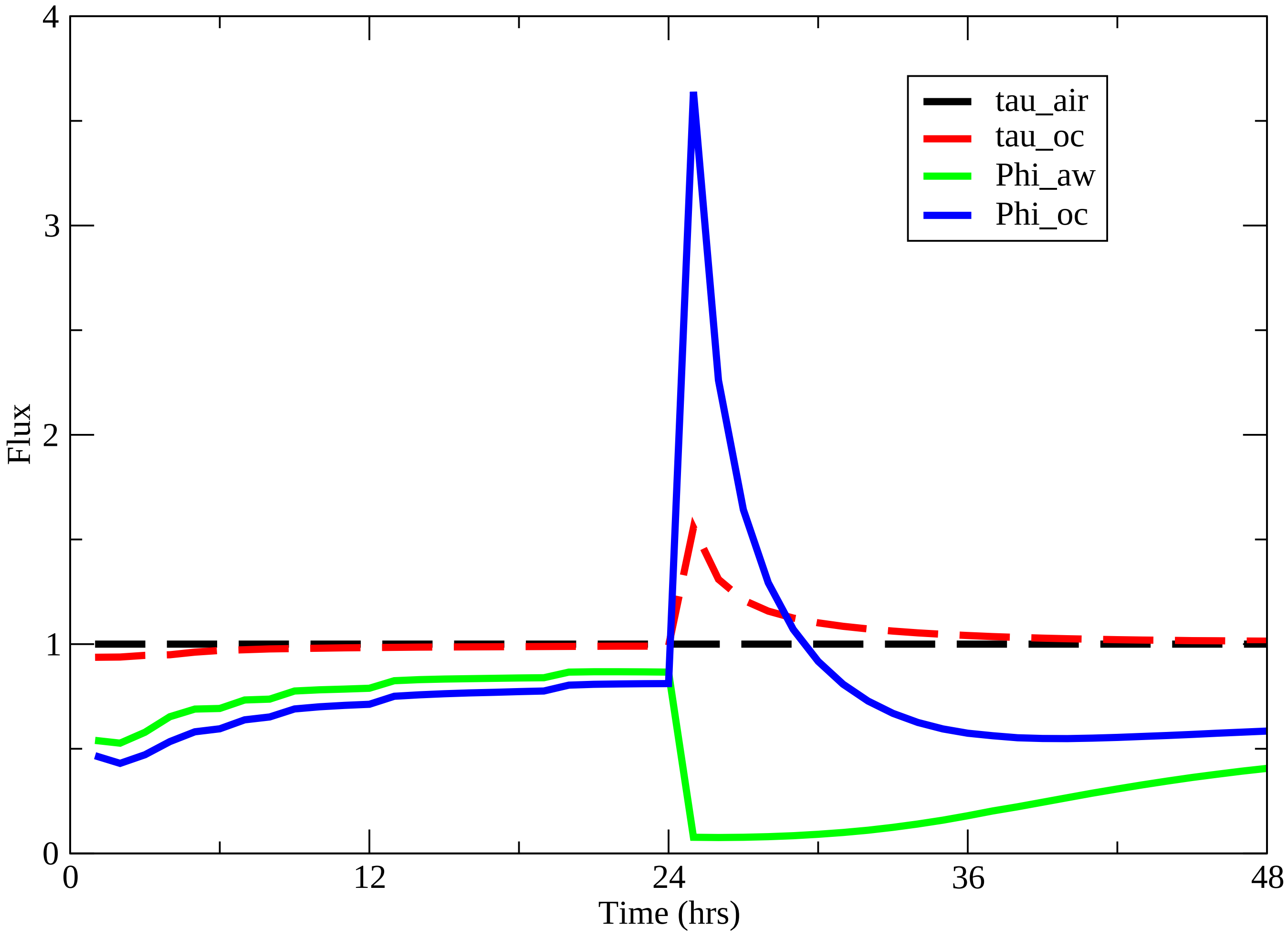
$$\tau_{oc} = \left.\frac{\partial \mathbf{P}}{\partial t}\right|_{diss} = \int \mathrm{d}\omega \mathrm{d}\theta \, \frac{\mathbf{k}}{\omega} S_{ds}, \quad \Phi_{oc} = \left.\frac{\partial E}{\partial t}\right|_{diss} = \int \mathrm{d}\omega \mathrm{d}\theta \, S_{ds}.$$

Since the dissipation term scales like $\omega^2 F(\omega)$ the integrals are mainly determined by the high-frequency part of the spectrum. But, because of the extra factor k/ω, the momentum flux is, compared to the energy flux, to a larger extent determined by the high frequencies.

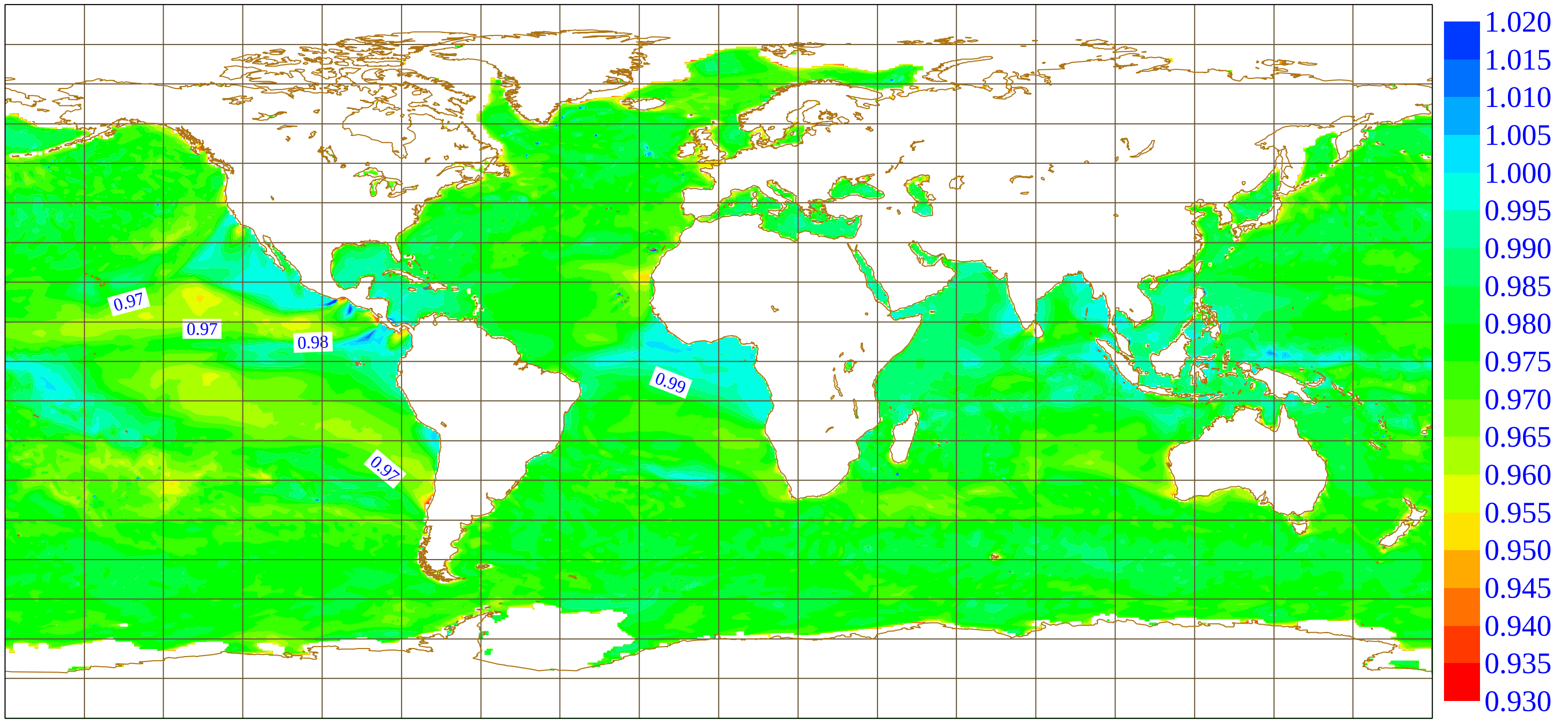
In practice the high frequency part of the spectrum is in **equilibrium** with the wind which means that **wind input and dissipation balance** for these high frequencies. As a consequence, on average, it is a fair approximation to parametrize the momentum flux into the ocean by means of the local stress, but this does not hold for the energy flux (as they are to some extent determined by the longer waves which are not in equilibrium with the wind).

This is illustrated by two examples: The first one is a single grid-point run which mimics the passage of a frontal system. Hence, after one day of a constant wind of 18 m/s, the wind turns by 90° and drops to 10 m/s. In the second example we calculated the fluxes from an actual wave model run for the month of January 2003 and determined the monthly mean.

Here the momentum fluxes are scaled with the local stress $\rho_a u_*^2$, while the energy flux is scaled by $m \rho_a u_*^3$ where $m = 5.2$ which is the mean value from the monthly run.

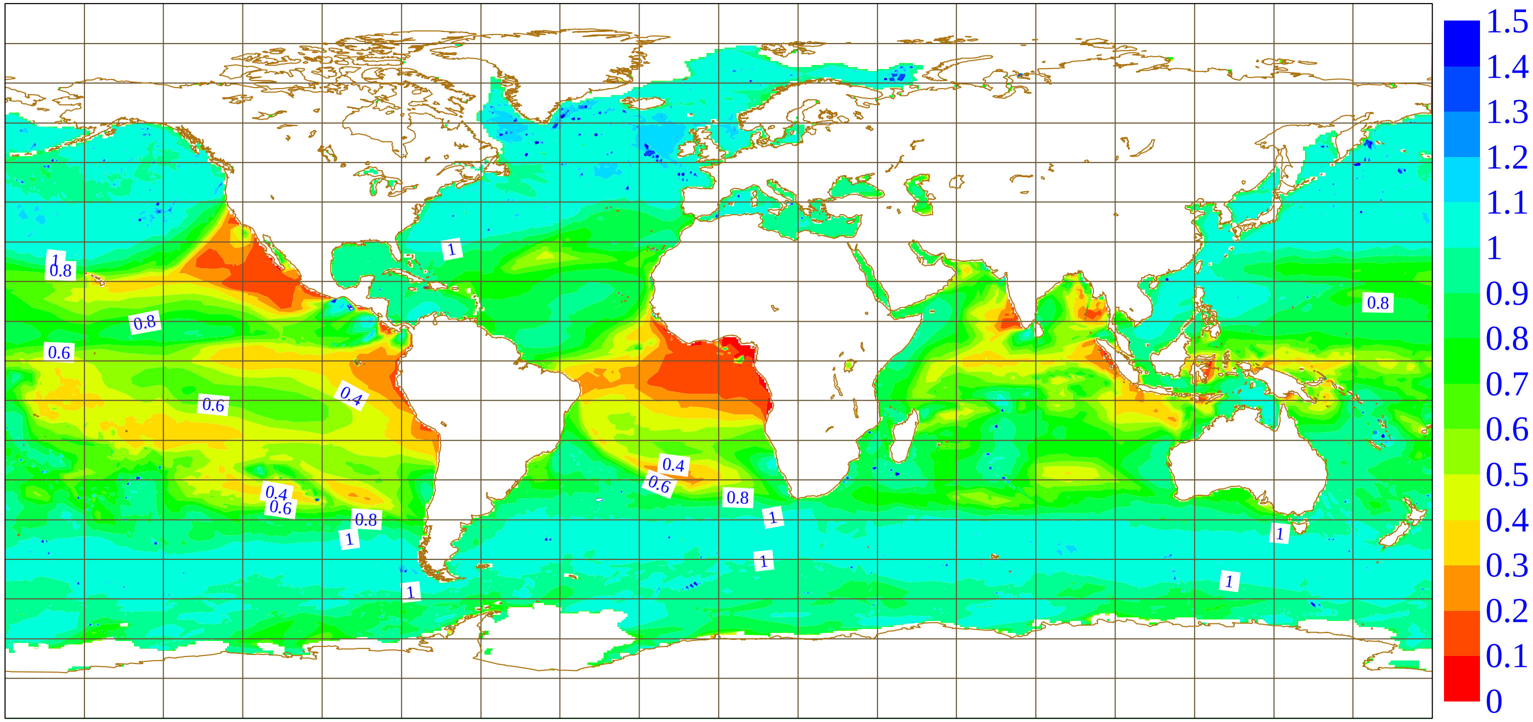

tau_air
tau_oc
Phi_aw
Phi_oc
Flux
0
1
2
3
4
0
12
24
36
48
Time (hrs)

Air-sea interaction and waves



ECMWF Monthly mean relative momentum flux (Tau/Ustar**2) for January 2003

ECMWF Monthly mean relative energy flux (E/5.2Ustar**3) for January 2003



CONCLUSIONS

- Two-way interaction of winds and waves results in a realistic distribution of the drag for a hurricane. A maximum in the drag is automatically generated because for extremely young sea state there are relatively few waves to exert a drag on the airflow.

- The ratio of the enthalpy (heat and moisture) to the momentum transfer coefficient plays an important role in the development of a hurricane. Wave dynamics affects the heat and moisture transfer and the resulting Dalton and Stanton number show a good agreement with present day parametrizations of observations (e.g. Brut *et al.* (2005)).The wave effect on heat and moisture flux plays an important role in the evolution of extreme events, but overall impact on forecasts (although positive) is fairly small.

- Parametrisation of the energy flux into the ocean is not really feasible using the local friction velocity. An estimate based on wave breaking dissipation seems to be more appropriate.