Coupling of wave, atmosphere & ocean models ...

Fabrice Ardhuin

With the help of many

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Why worry about coupling ?

1. Why couple ?

Wave motion occurs on both side of the air-sea interface …

- **Waves** are influenced by **winds**
- **Waves** are influenced by **currents, water levels, bottom roughness**
- **Waves** are influenced by **sea ice**

… and there is a **feedback**

- The surface roughness (waves) modifies the **wind stress**
- Waves generate **currents** and modify water levels and bottom roughness
- Waves enhance the **upper ocean mixing**
- Waves **break up the ice** and push it around

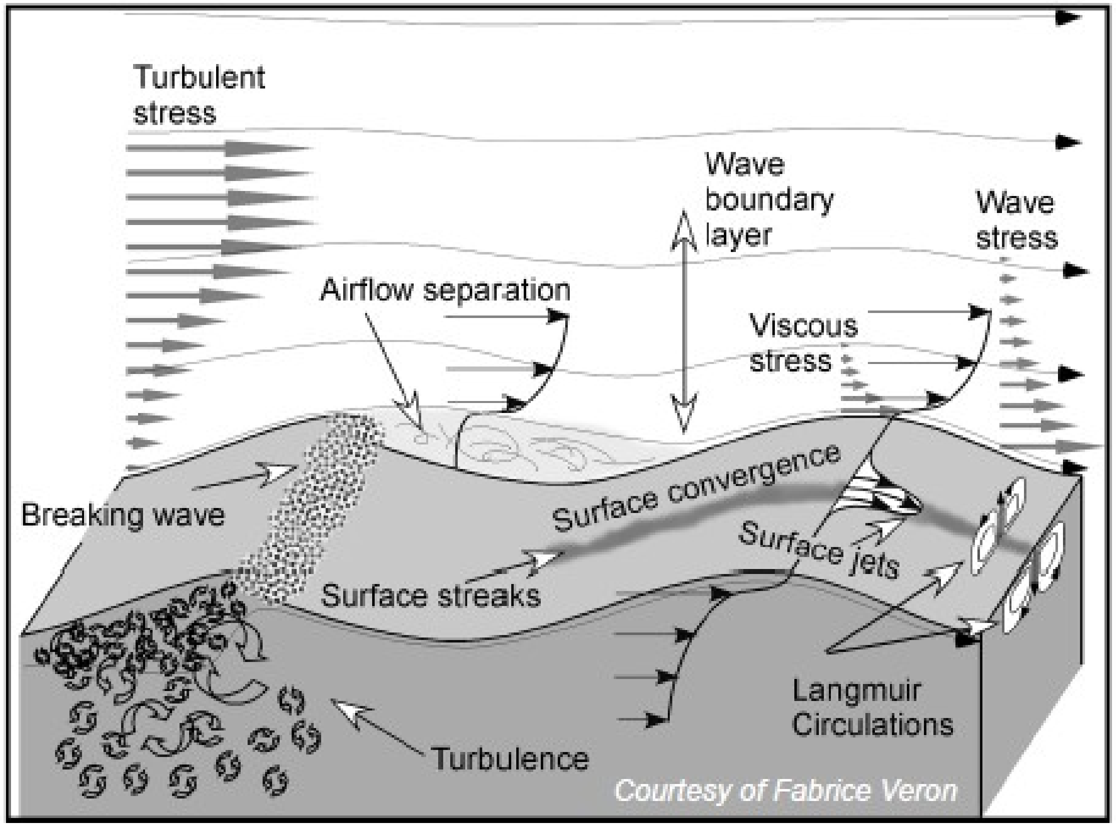
If that feedback has a significant influence on the waves …

… you need to couple the wave model to the other component

1. Why couple ?

Introduction

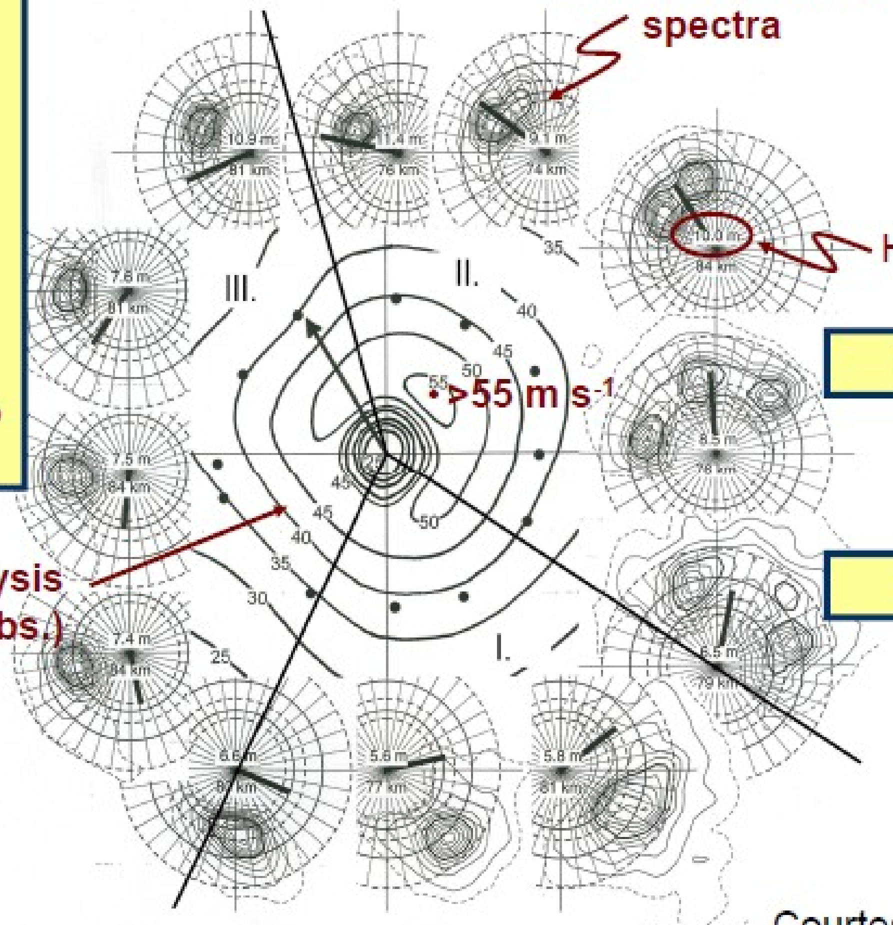
Air-Sea Interaction Processes



1. Why couple ?

Surface Waves Beneath TCs
Scanning Radar Altimeter in Ivan

- Young, steep, and short waves in the right-rear quadrant
- Older, flatter, and longer waves in the right-front and left-front quadrants.
- To the left rear and left front of the eye, the wind and waves are at right angles to each other.

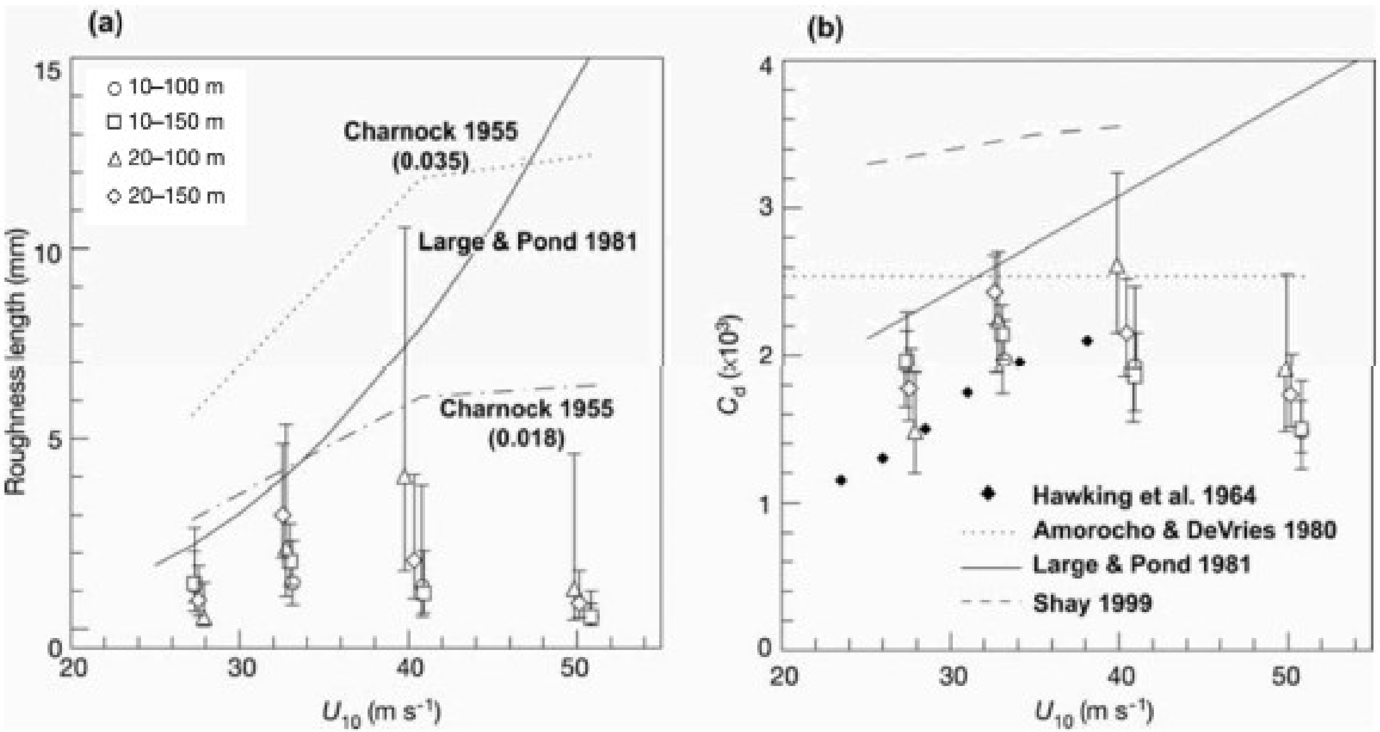


Black et al. (2007)

Courtesy: Ed Walsh 5

Wind-Wave Interaction

Momentum Flux and Drag

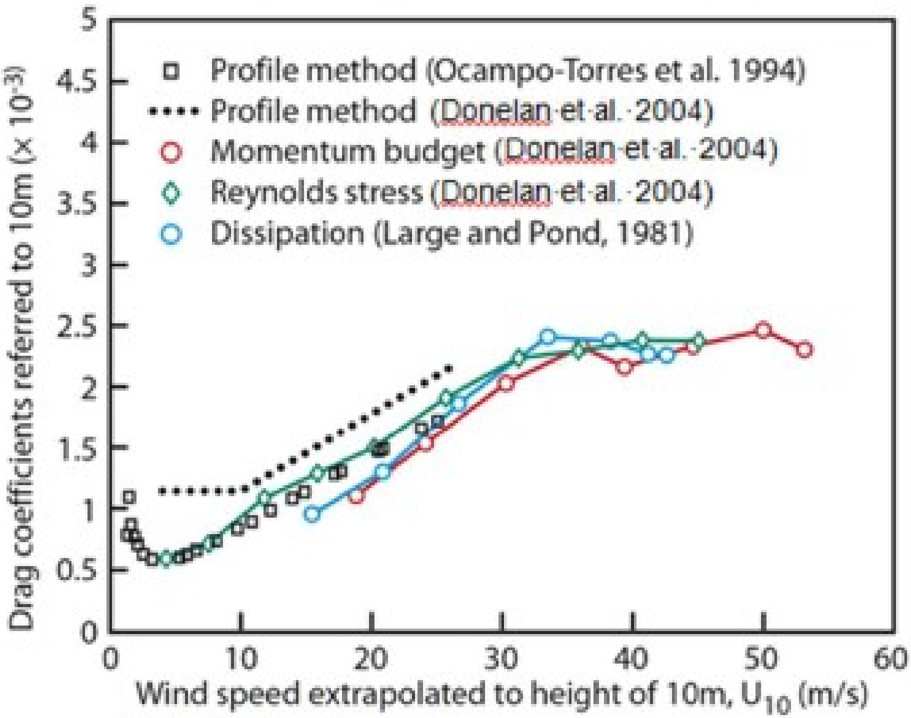


Adapted from Powell et al. (2003)
Modified from Letchford and Zachry (2009)

Powell et al. (2003) breakthrough study on the reduced drag coefficient for high winds in tropical cyclones based on an analysis of over 300 GPS dropsondes in 15 storms (of various intensities).

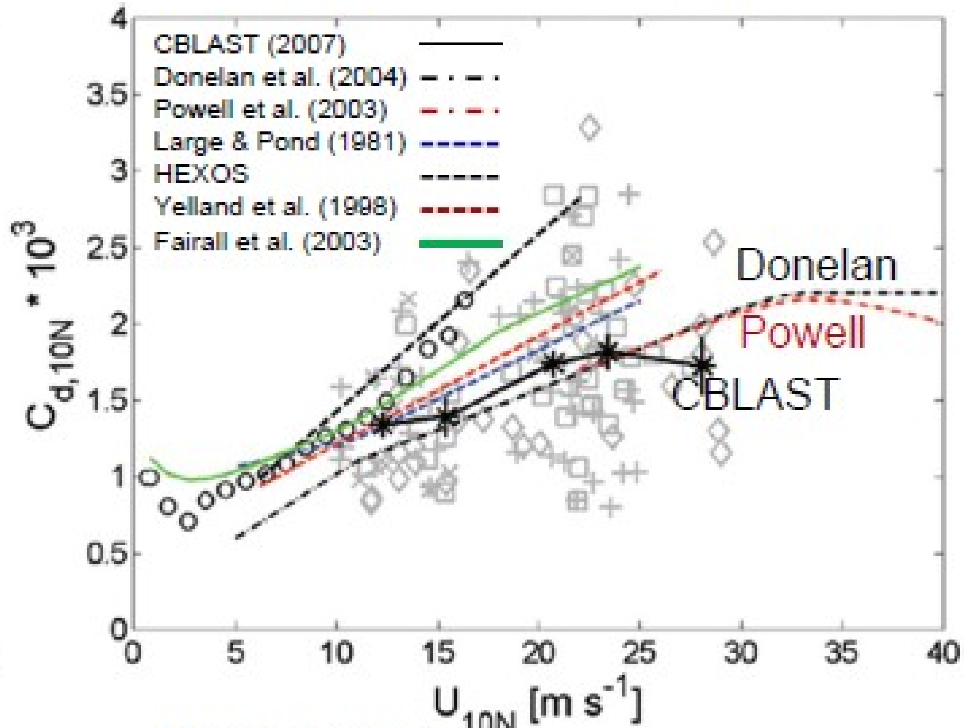
1. Why couple ?

Laboratory Measurements



Donelan et al. (2004)

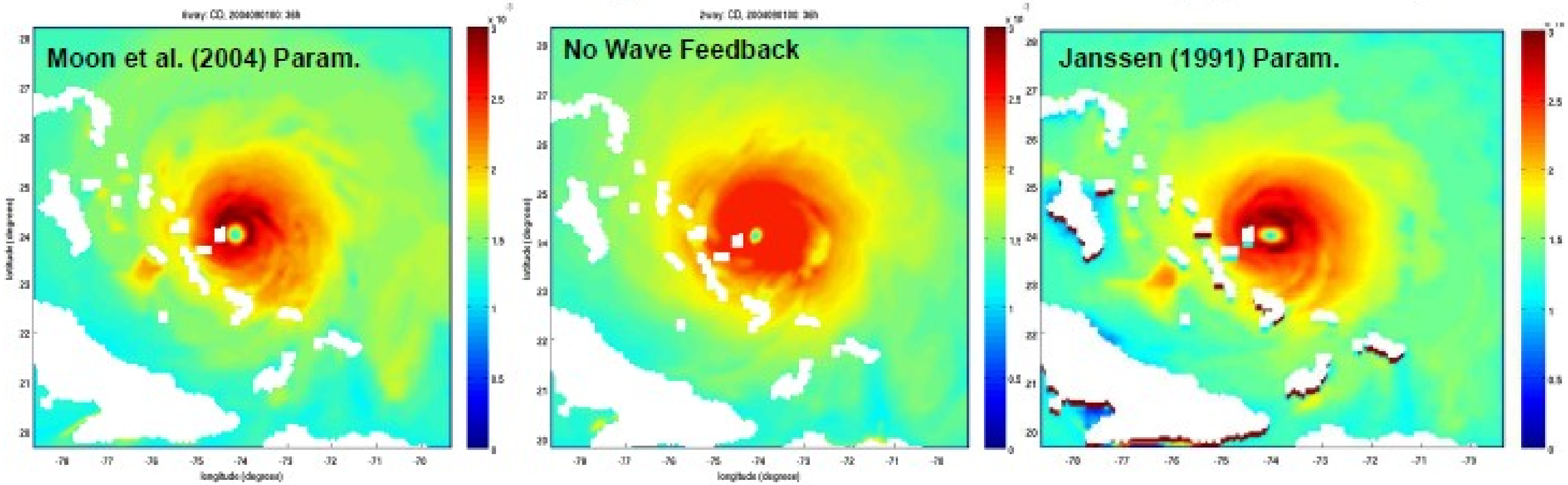
CBLAST Observations



Black et al. (2007)

1. Why couple ?

COAMPS-TC Atmospheric Momentum Drag (Francis)



- **COAMPS-TC is coupled to SWAN and WWIII.**
- **Including the wave feedback to the atmosphere produces stronger drag near the eyewall and changes the storm structure.**

From Doyle 2012

1. Why couple ?

Example with storm surges (Mastenbroek JPO 1993)

→ using a wave-age dependent wind stress

For this North Sea application, « forcing » may be enough (no obvious feedback of surge on waves at that scale … not true for flooding cases → e.g. COAWST applications)

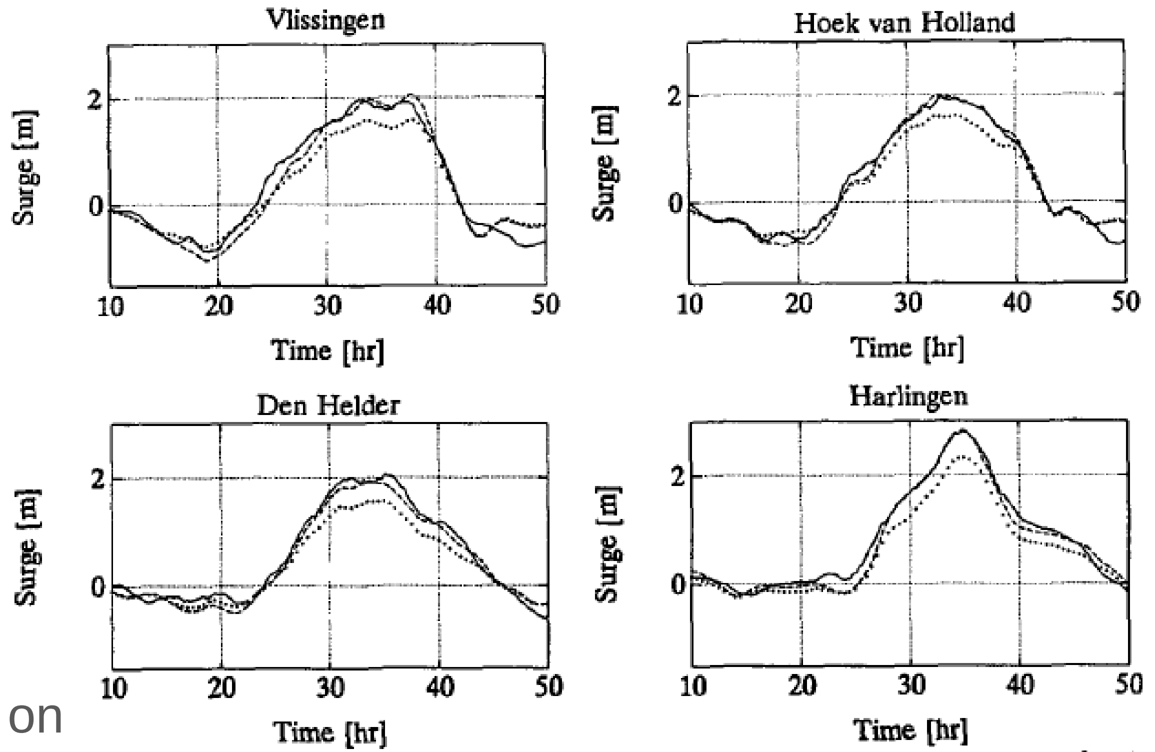


FIG. 3. Residual elevations at several stations along the English and Dutch coasts for the February 1989 storm. The full line represents the observations, the dotted line corresponds to the calculation with the Smith and Banke drag relation, and the dashed line shows the results of the calculation with the wave-dependent drag coefficient. The times on the x axis are given with respect to 0000 UTC 13 February.

Most of the improvements can be reproduced by assuming an overall increase of the dimensionless roughness parameter. If the Smith and Banke relation is replaced by a Charnock one with a dimensionless constant of $\alpha = 0.032$, the difference in water level between this formulation and the wave-dependent calculation is smaller than the uncertainty in the observations. Different basins would, however, give rise to different choices of α. Therefore, a wave-dependent drag is to be preferred for storm surge modeling.

1. Why couple ?

JEAN-RAYMOND BIDLOT: PRESENT STATUS OF WAVE FORECASTING AT ECMWF ...

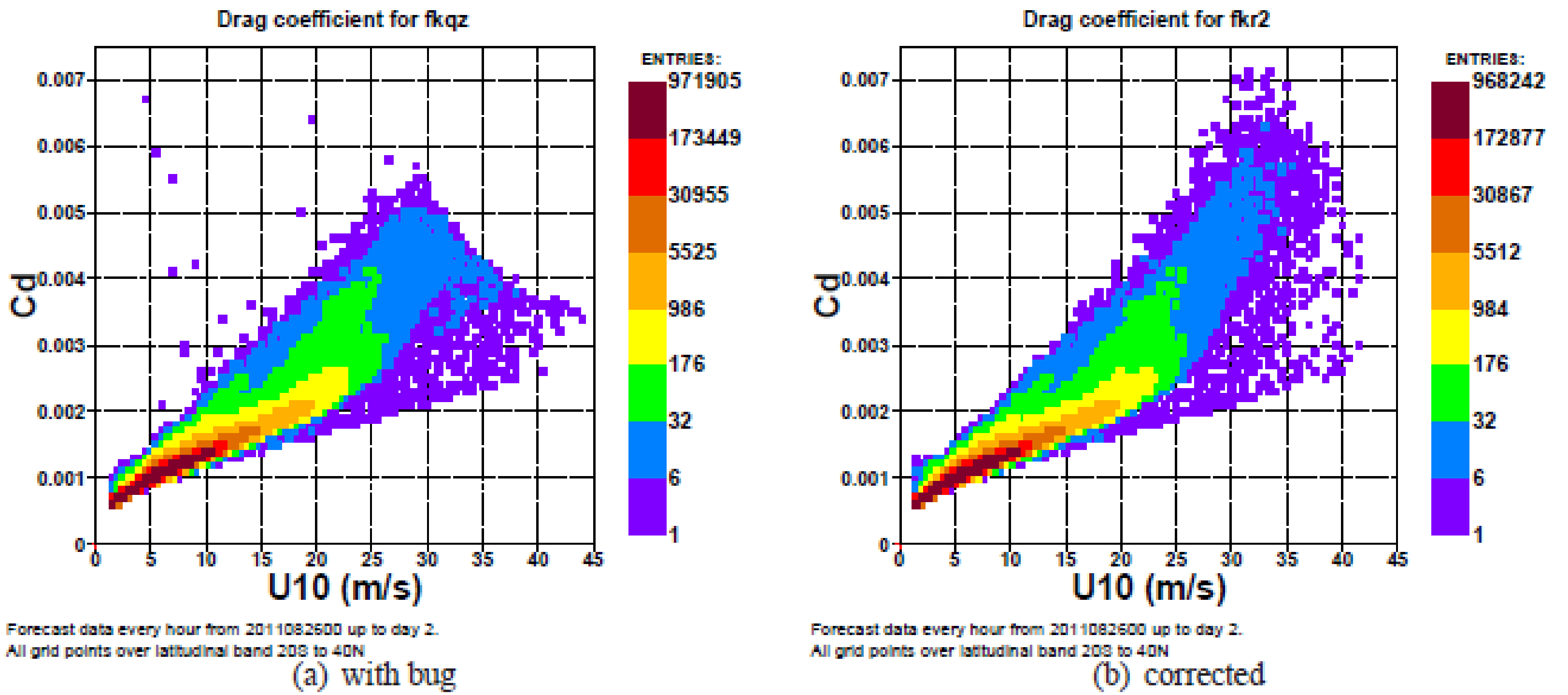


Figure 3: Drag coefficient and corresponding 10m wind speed for all model grid points between 20°S and 40°N for a high resolution coupled atmosphere-ECWAM forecast from 26 August 2011, 0 UTC, output every hour for 2 days. Left pane: the incorrect stress table was used. Right panel: the correct stress table was used.

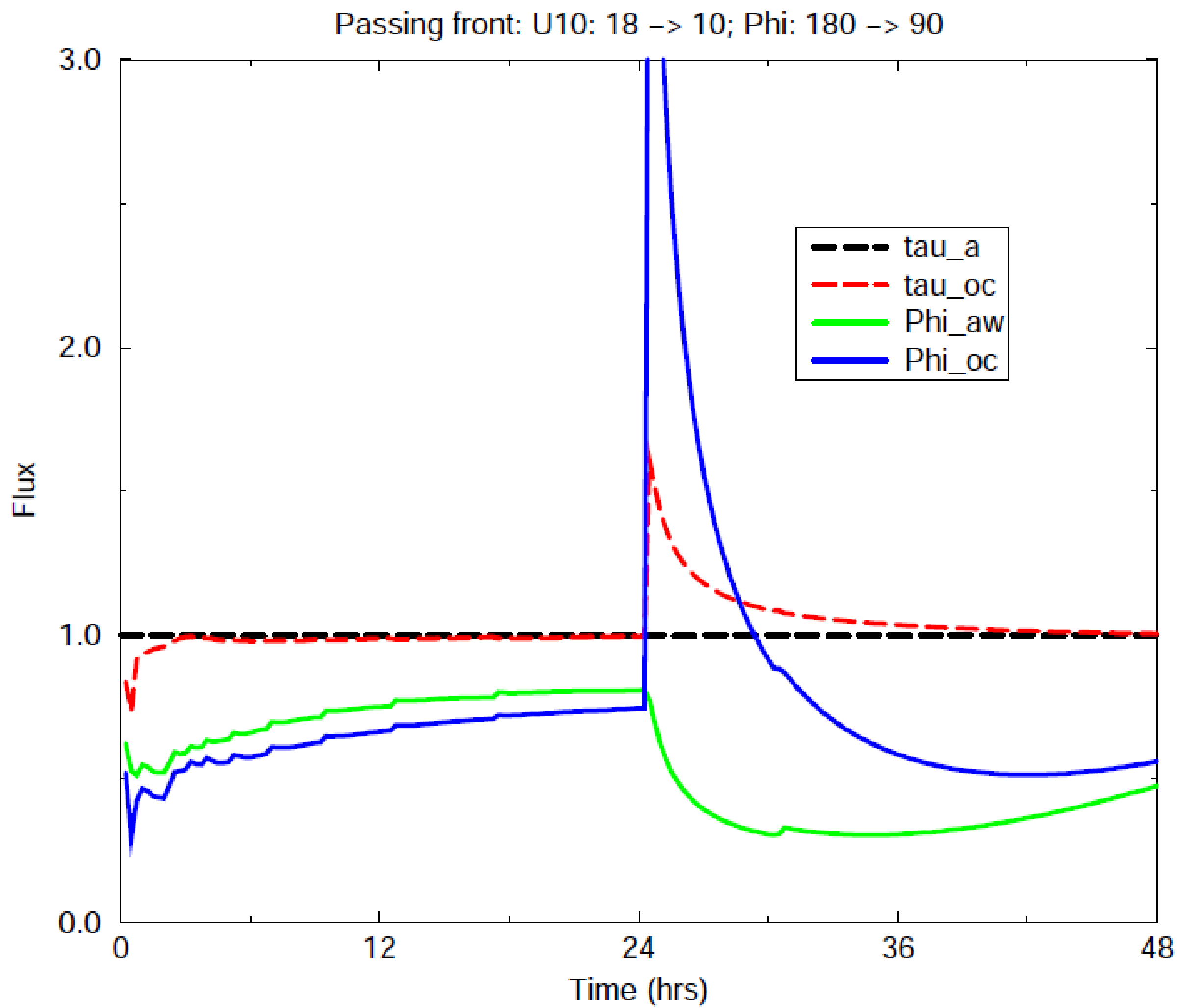
1. Why couple ?

Importance for the ocean

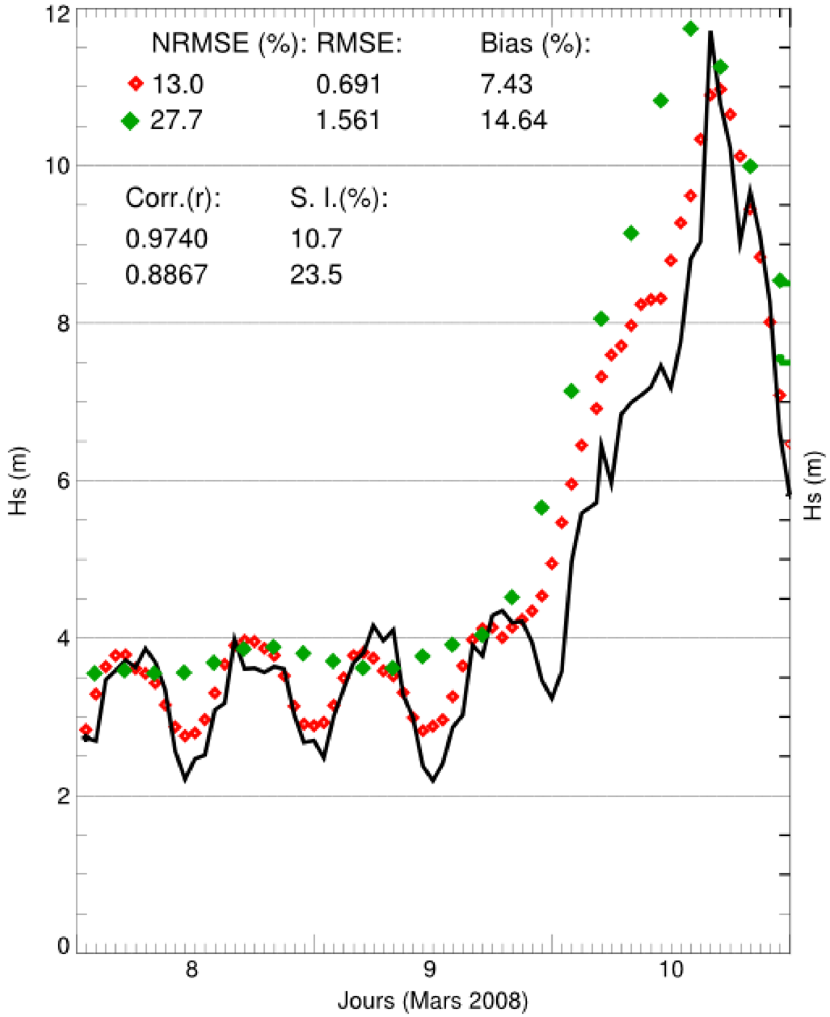
(Janssen 2004)

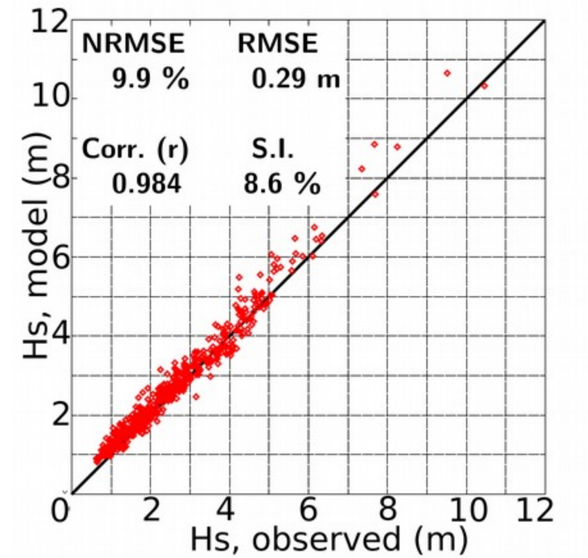
These results are from the ECMWF WAM model

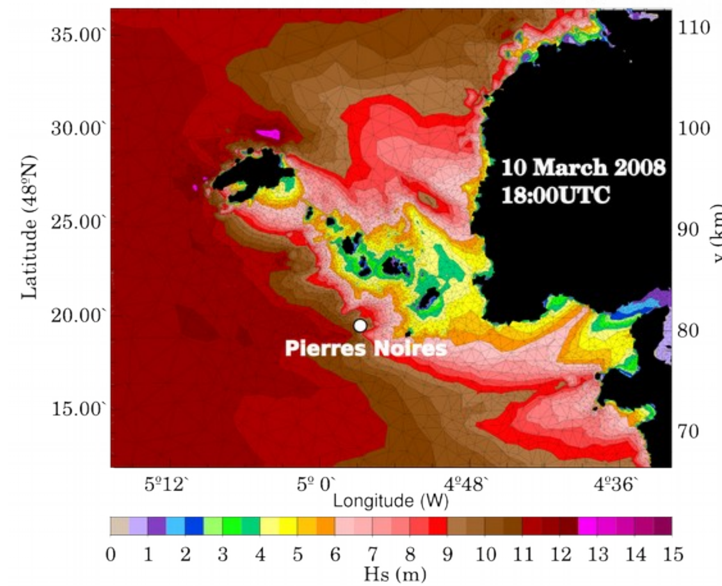
Normalized momentum and energy flux versus time



1. Why couple ?



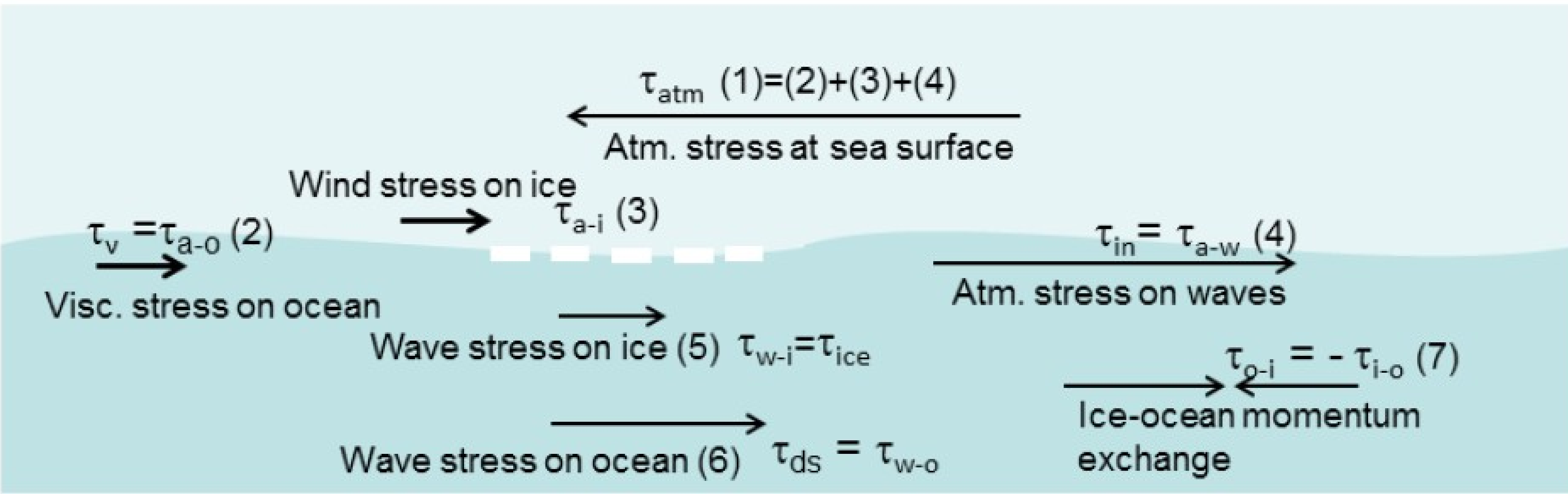




… Here with forcing only …

1. Why couple ?

Waves and sea ice …



Total stress on atm: -2, -3, -4 ; Total stress to ice: +3, +5, +7

Total stress to/from waves: +4, -5, -6 ; Total stress to ocean: +2, +6, -7

2

Parameters for coupling (2.6 in WW3 manual)

2.1 Input for WW3

These can also come from a coupled model ...

2) **CUR** The mean current velocity (vector, m/s).
3) **WND** The mean wind speed (vector, m/s). This wind speed is always the speed as input to the model, i.e., is not corrected for the current speed.
4) **AST** The air-sea temperature difference (°C).
5) **WLV** Water level.
6) **ICE** Ice concentration.
7) **IBG** Wave attenuation due to icebergs: this parameter is the inverse of the e-folding scale associated to the loss of wave energy in a field of small icebergs (Ardhuin et al., 2011b).
8) **D50** Sediment median grain size (D_{50}).
9) **IC1** Ice thickness.
10) **IC5** Ice flow diameter.

2.2 Ouput of WW3

Momentum fluxes

Can be used to force other model, these are 2-component vectors:

TWO Wave to ocean momentum flux

TWI Wave to sea ice stress

TBB Momentum loss in WBBL

TAW Net wave-supported stress (wind to wave momentum flux)

TWA Negative part of the wave-supported stress

Scalars related to momentum flux:

BHD Bernoulli head (m^2/s^2)

$$J = g \iint \frac{k}{\sinh 2kd} F(k,\theta)\, dk d\theta\ ,$$

UST The friction velocity u_* (scalar). Definition depends on selected source term parameterization (m/s). An alternative vector version of the stresses is available for research (requires user intervention in the code).

CHA Charnock parameter for air-sea friction (without dimensions)

3. Energy fluxes (W/m²)

FOC Wave to ocean energy flux (W/m^2)

FAW Wind to wave energy flux

FIC Wave to sea ice energy flux

FBB Energy dissipation in WBBL

3. Bottom boundary layer

ABR Near-bottom rms excursion amplitude

$$a_{b,rms} = \left[2 \iint \frac{1}{\sinh^2 kd} F(k,\theta)\, dk d\theta \right]^{1/2}$$

UBR Near-bottom rms orbital velocity

$$u_{b,rms} = \left[2 \iint \frac{\sigma^2}{\sinh^2 kd} F(k,\theta)\, dk d\theta \right]^{1/2} . \qquad (2.253)$$

BED Bedform parameters: ripple height and directions (NOT TESTED YET)
FBB Energy dissipation in WBBL
TBB Momentum loss in WBBL

3. Ice stuff

IC5 Ice flow diameter.

TWI Wave to sea ice stress

FIC Wave to sea ice energy flux

3. Stokes drift & related stuff

TUS Stokes volume transport (m^2/s)

$$\left(M^w_x, M^w_y\right) = g \iint \frac{(k\cos(\theta), k\sin(\theta))}{\sigma} F(k,\theta)\, dk d\theta\ , \qquad (2.247)$$

USS Stokes drift at the sea surface (m/s)

$$\left(U_{ssx}, U_{ssy}\right) = \iint \sigma \cosh 2kd \frac{(k\cos(\theta), k\sin(\theta))}{\sinh^2 kd} F(k,\theta)\, dk d\theta\ , \qquad (2.248)$$

USF Frequency spectrum of Stokes drift at the sea surface (m/s/Hz)

$$\left(U_{ssx}(f), U_{ssy}(f)\right) = \int \sigma \cosh 2kd \frac{(k\cos(\theta), k\sin(\theta))}{\sinh^2 kd} F(k,\theta) \frac{2\pi}{C_g} d\theta\ , \qquad (2.250)$$

3. Stokes drift & related stuff

BHD Bernoulli head (m^2/s^2)

$$J = g \iint \frac{k}{\sinh 2kd} F(k,\theta)\, dk d\theta \ ,$$

SXY Radiation stresses

$$S_{xx} = \rho_w g \iint \left(n - 0.5 + n \cos^2\theta\right) \ F(k,\theta)\, dk d\theta \ ,$$

$$S_{xy} = \rho_w g \iint n \sin\theta \cos\theta \, F(k,\theta)\, dk d\theta \ ,$$

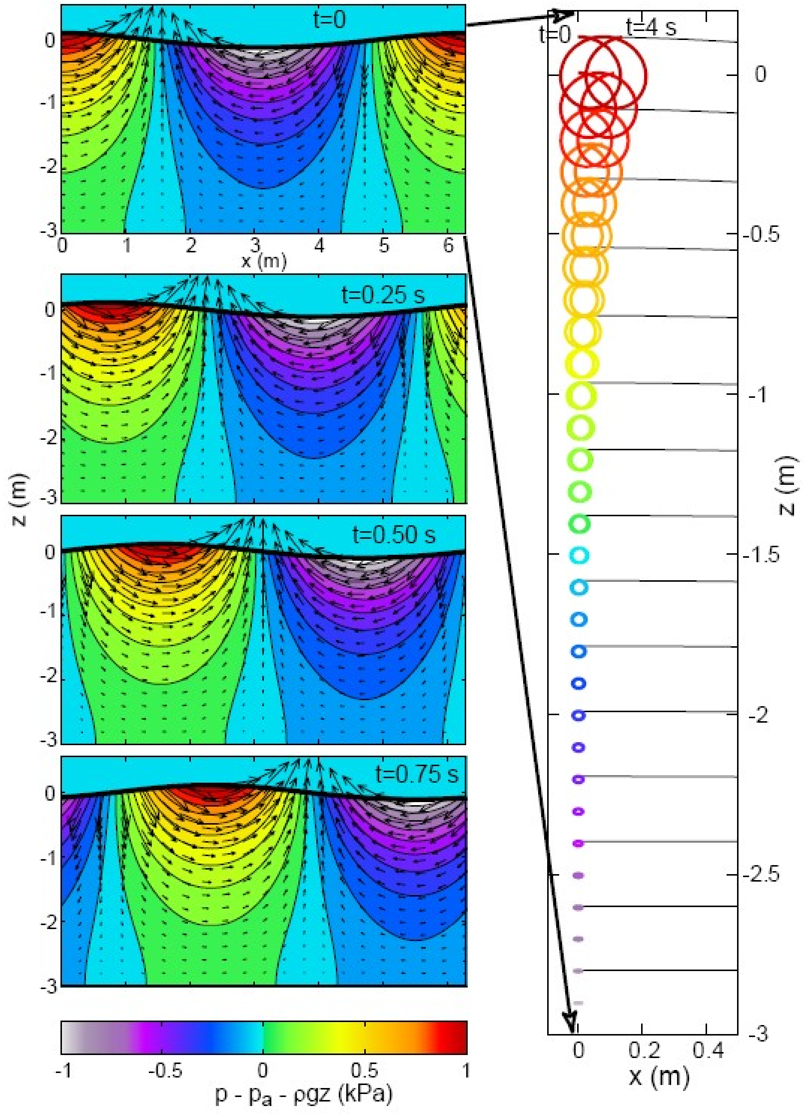
$$S_{yy} = \rho_w g \iint \left(n - 0.5 + n \sin^2\theta\right) \ F(k,\theta)\, dk d\theta \ ,$$

where

$$n = \frac{1}{2} + \frac{kd}{\sinh 2kd} \ .$$

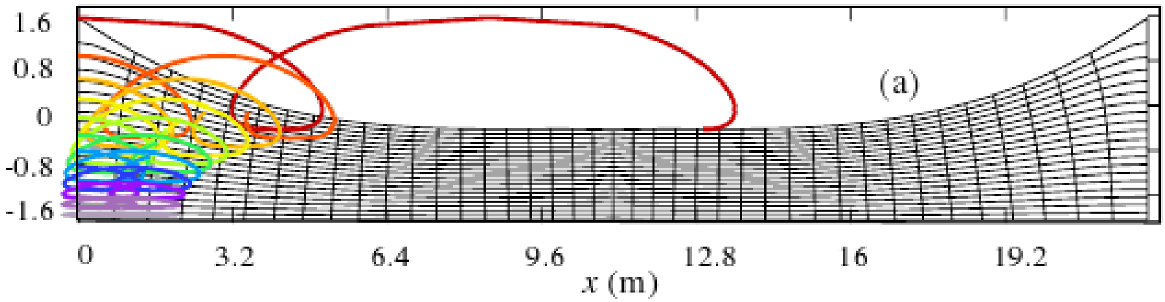
3

Wave-current interactions



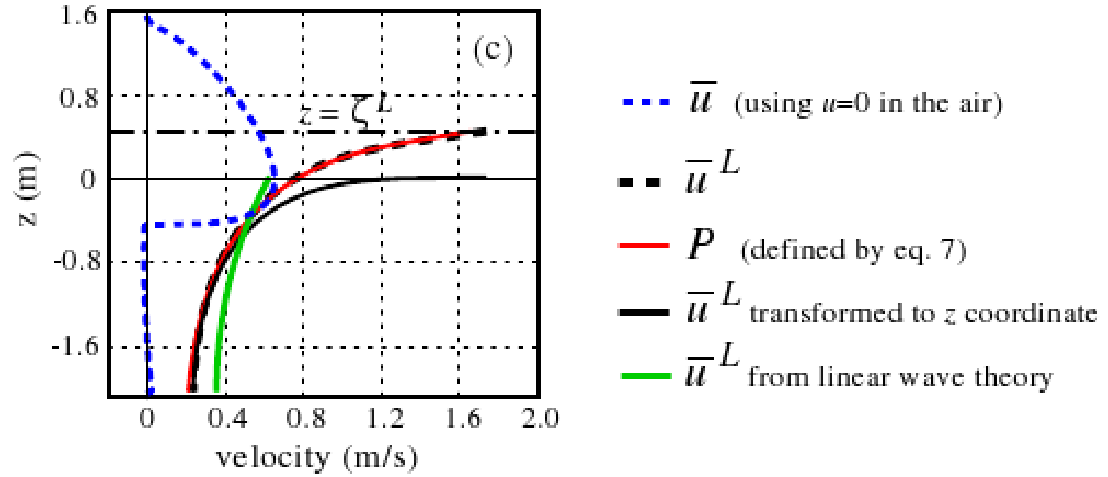
Stokes drift example for monochromatic linear waves

3. Wave-current interaction



Stokes drift in Miche waves

(from Ardhuin et al. Ocean Model. 2008)



3. Wave-current interaction

The 1D model

From the Lagrangian mean velocity U^L we can define a quasi-Eulerian velocity according to Jenkins (1989): $\hat{u} = U^L - U_s$

But how do we get a Lagrangian field ?
Generalized Lagrangian Mean (see later).

Now for a uniform horizontal ocean we have

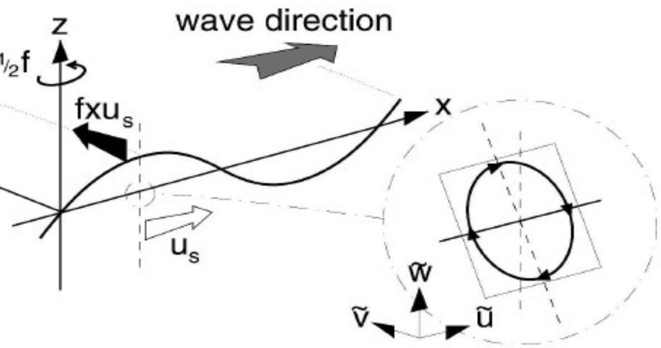
$$\frac{\partial \widehat{\mathbf{u}}}{\partial t} + (\widehat{\mathbf{u}} + \mathbf{u}_S) \times f\mathbf{e}_z = \frac{\partial}{\partial z}\left(K \frac{\partial \widehat{\mathbf{u}}}{\partial z}\right)$$

Us times f is called the « Stokes – Coriolis force »

The eddy viscosity is related to wave breaking (Craig and Banner 1994, Terray & al. 1996 ...).

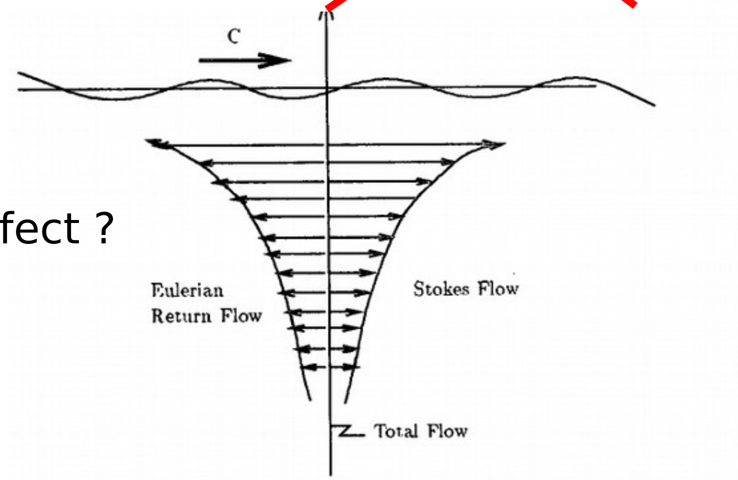
û is expected to be almost uniform near the surface due to a strong mixing

How does that square with Stokes' theory?
The transversal wave component (v) is in phase with u, so that d<uv>/dz is f*us this « Hasselmann stress » sets up a current that opposes the Stokes drift (Hasselmann 1970). (see also Xu and Bowen JPO 1994).



In steady state without mixing we have

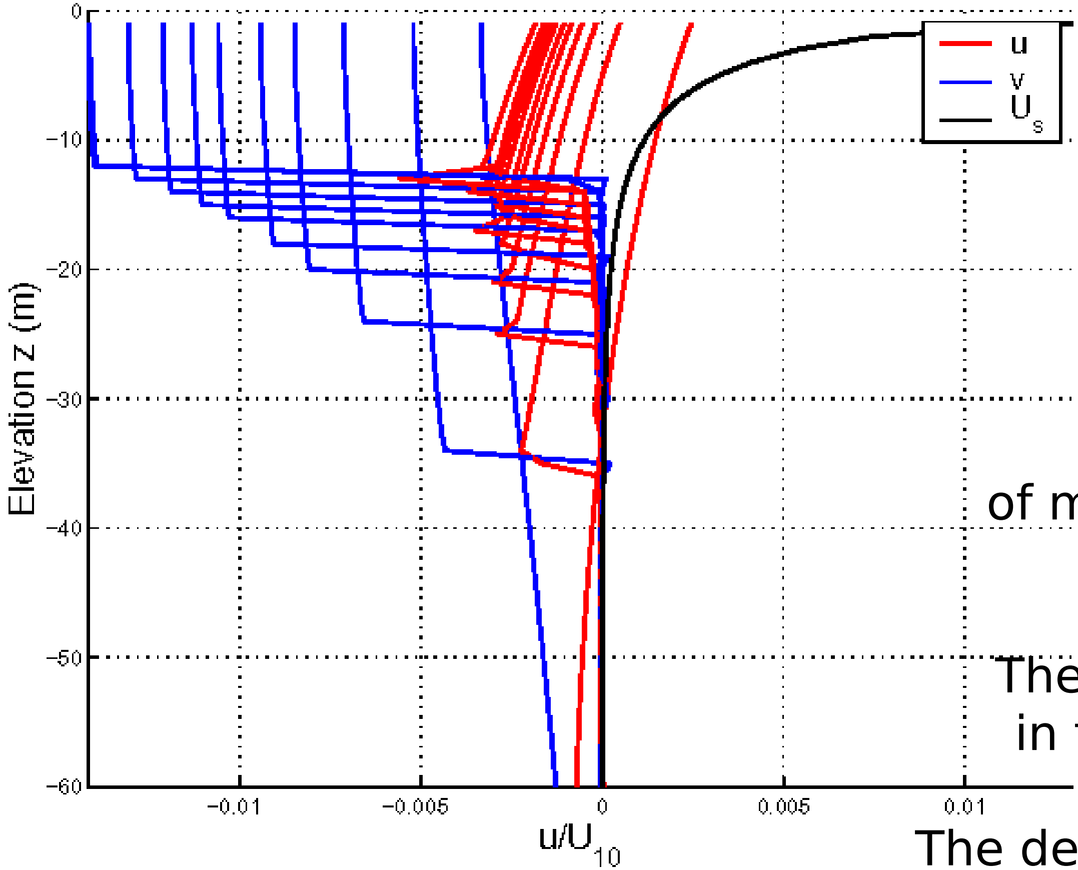
$$(\hat{\mathbf{u}} + \mathbf{u}_S) \times f\mathbf{e}_z = \frac{\partial}{\partial z}\left(K \frac{\partial \hat{\mathbf{u}}}{\partial z}\right)$$



Can we measure this Hasselmann / Sokes-Coriolis effect ?

Polton et al. (JPO 2005) argued yes ...

The 1D model



Academic case
with deepening
of mixed layer: current response
is a function of stratification

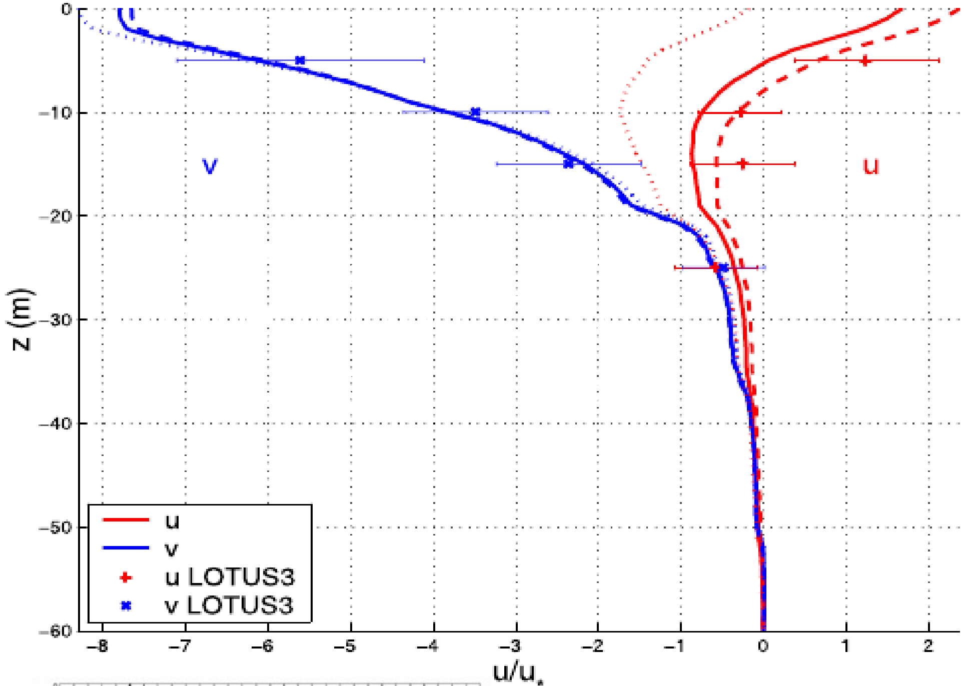
The “counter-drift” is contained
in the red quasi-Eulerian profile

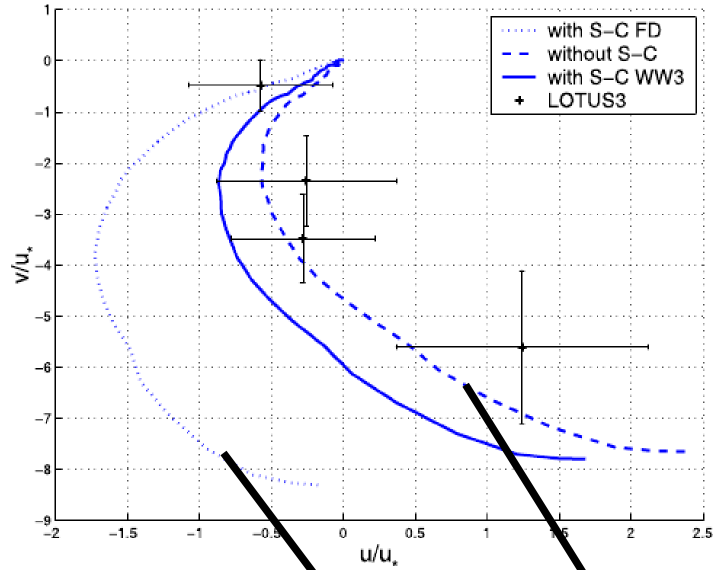
The depth-integral of u + Us is zero
and the depth-integral of v is the usual Ekman transport tau/f

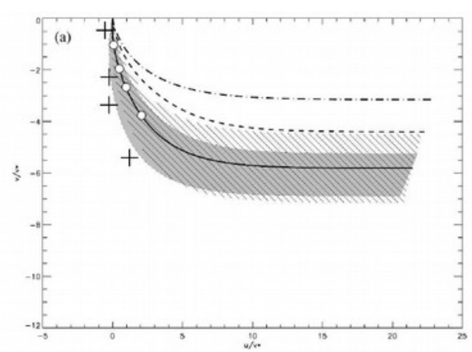
3. Wave-current interaction

The 1D model

How good are the vertical current profiles predicted ? (Rascle & Ardhuin JGR 2009)







Polton et al. (2005)
no stratification, stationary,
small surface mixing

No SC

SC based on PM
spectrum

3. Wave-current interaction

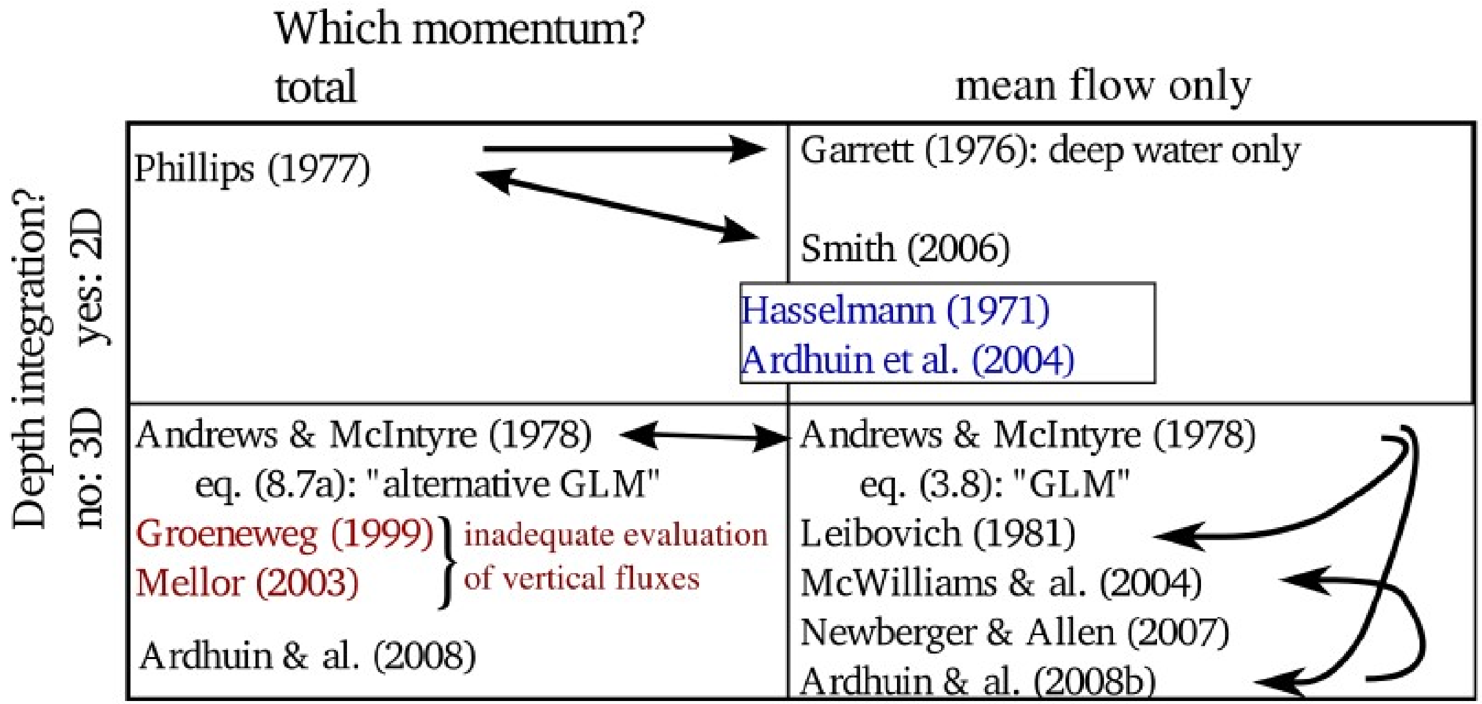
Going 3D …

Momentum equation formulated for:

- total momentum (includes Stokes drift): this is too complex

(vertical flux of wave momentum is a strange beast)

- mean flow momentum only



Going 3D …

Original GLM for constant density:

$$\overline{D}^L\left(\widehat{u}_i\right) + \epsilon_{i3j} f_3 \overline{u}_j^L + \frac{\partial}{\partial x_i}\left(\frac{\overline{p}^L}{\rho_w} - \frac{\overline{u_j^l u_j^l}}{2}\right) - \widehat{X}_i + g\delta_{i3} = P_j \frac{\partial \overline{u}_j^L}{\partial x_i}$$

$$\frac{\partial \widehat{u}_\alpha}{\partial t} + \widehat{u}_\beta \frac{\partial \widehat{u}_\alpha}{\partial x_\beta} + \widehat{w}\frac{\partial \widehat{u}_\alpha}{\partial z} + \epsilon_{\alpha 3 \beta}\left[f_3 \widehat{u}_\beta + \left(f_3 + \omega_3\right) P_\beta\right] + \frac{1}{\rho_w}\frac{\partial p^H}{\partial x_\alpha}$$

$$= -\frac{\partial}{\partial x_\alpha}\left(S^{\mathrm{J}} + S^{\mathrm{shear}}\right) + \widehat{X}_\alpha .$$

Vortex force

hydrostatic pressure

pressure modification by waves (adiabatic)

Adiabatic equations consistent with McWilliams et al (2004)

Diabatic effects : mixing plus + source of momentum from waves (parameterization necessary for vertical profiles)

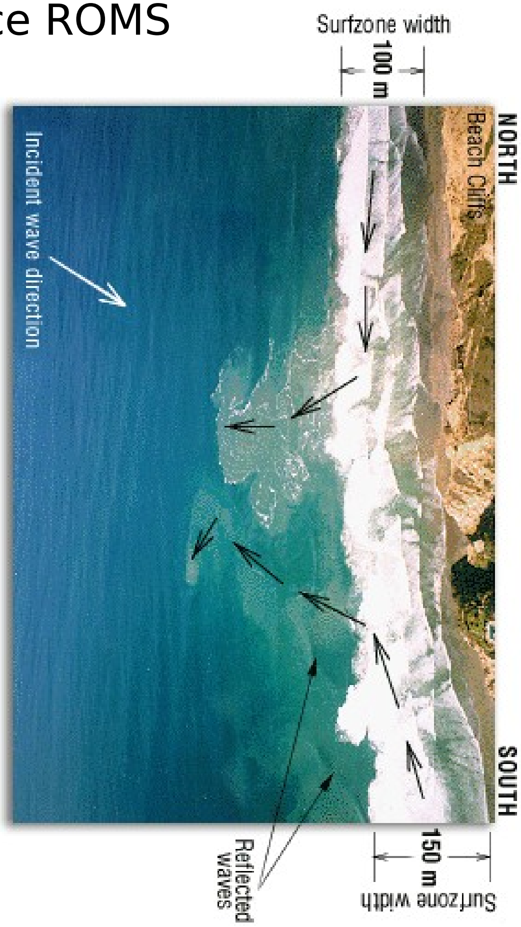
Traditional but partly inadequate parameterization:

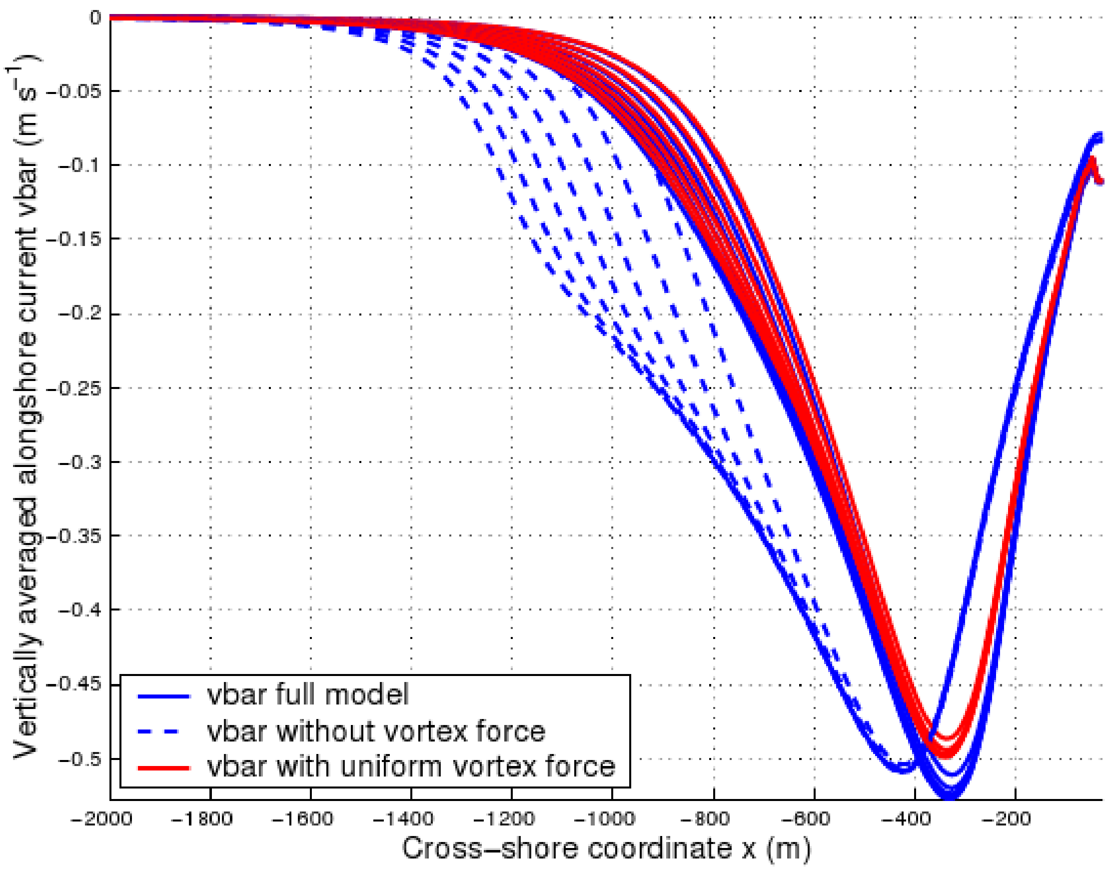
$$\widehat{X}_\alpha = \frac{\partial R_{\alpha\beta}}{\partial x_\beta} + \frac{\partial}{\partial z}\left(K_z \frac{\partial \widehat{u}_\alpha}{\partial z}\right) - T_\alpha^{\mathrm{wc}} - T_\alpha^{\mathrm{turb}} - T_\alpha^{\mathrm{bfric}}$$

3. Wave-current interaction

Going 3D …

Rascle (2007) used a simple Thornton & Guza model to force ROMS

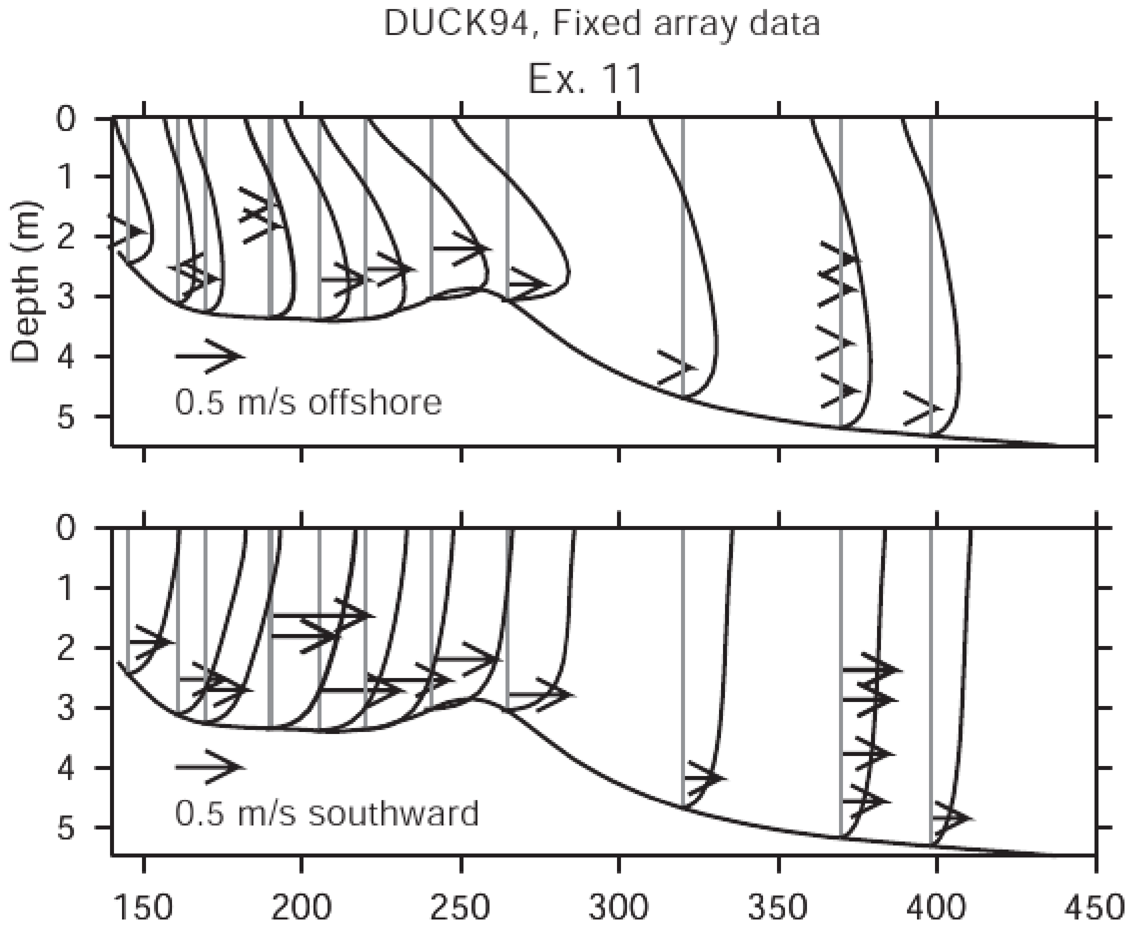




3. Wave-current interaction

Going 3D …

A related approach has been used by Newberger and Allen (JGR 2007) for surf zones



3. Wave-current interaction

Going 3D …

A proper averaging of the mixing (with a not-so-proper mixing parameterization) gives the observed current profiles

(Groeneweg and Klopman JFM 1998).

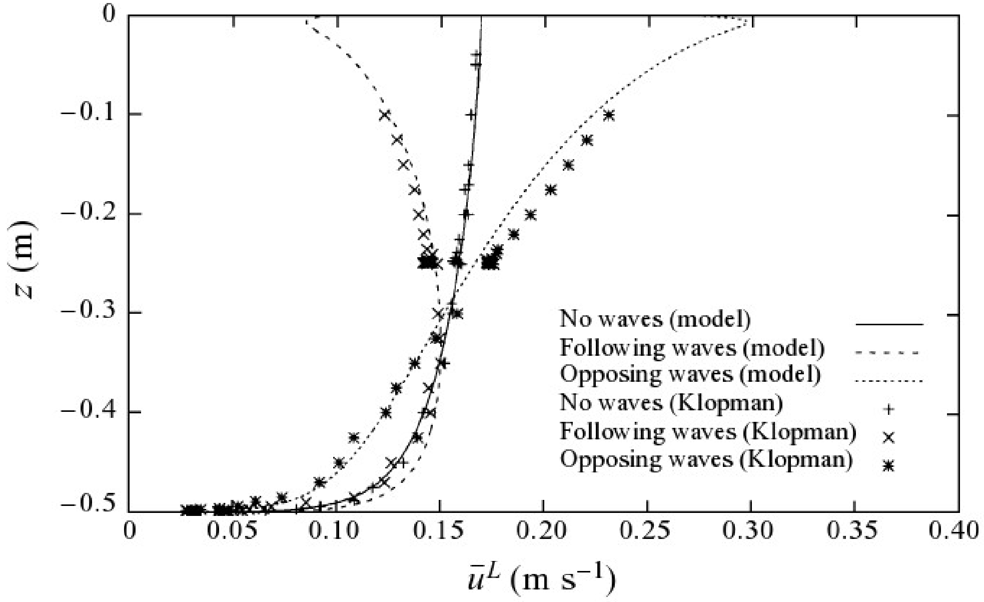
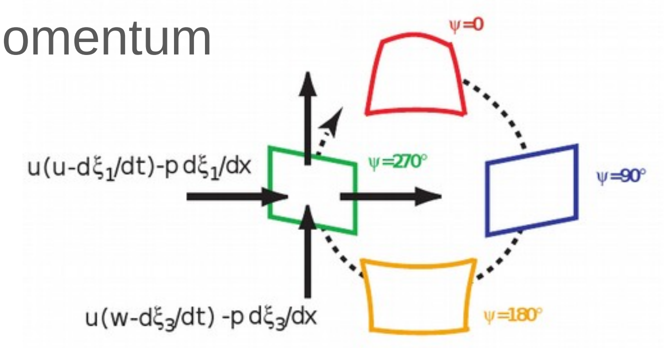


FIGURE 3. GLM results (present model) and experimental results (Klopman 1994) for the Eulerian-mean horizontal velocity profile.

3. Wave-current interaction
Going 3D …

Mellor (2003) and and Mellor (2008) use total momentum

but …



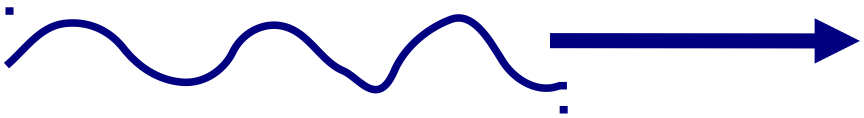
- improper approximation for the vertical flux
 <p ds/dx> in Mellor (2003)

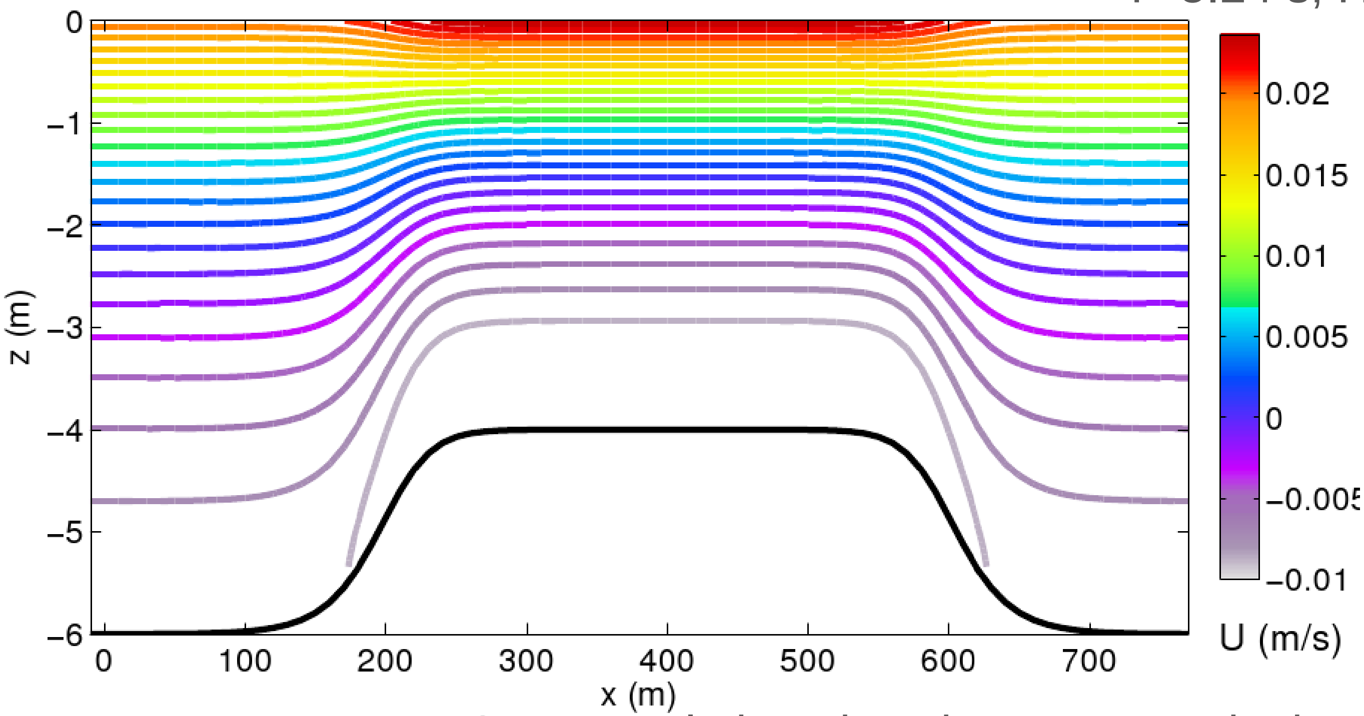
- vertical flux <p ds/dx> completely absent in Mellor (2008)

Is that important ?

Going 3D …

Let's take a simple case without dissipative effects: shoaling





Waves go from left to right.

T=5.24 s, Hs= 1.02 m

Cg change: 5.4%

Hs change: 2.7%

C change: 16 %

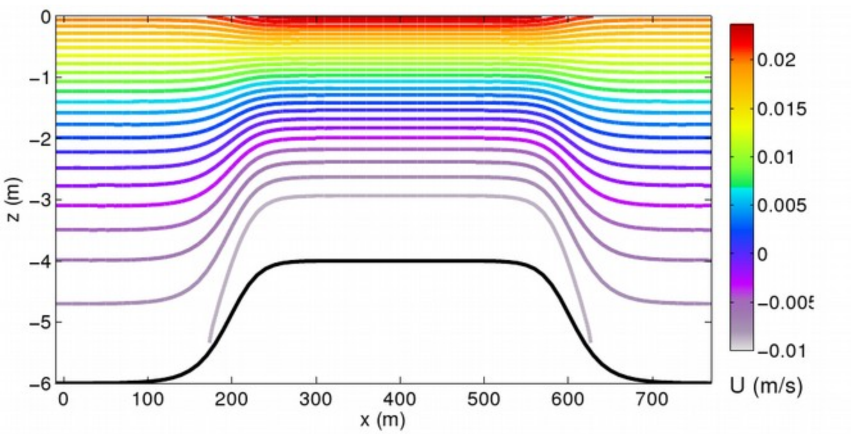
Us change > 20%

Correct solution given by Longuet-Higgins, Rivero & Sanchez Arcilla … (Eulerian analysis), confirmed by good numerical solution for Lagrangian flow (Ardhuin et al. OM 2008)

3. Wave-current interaction

Going 3D …

Let's take a simple case without dissipative effects: shoaling

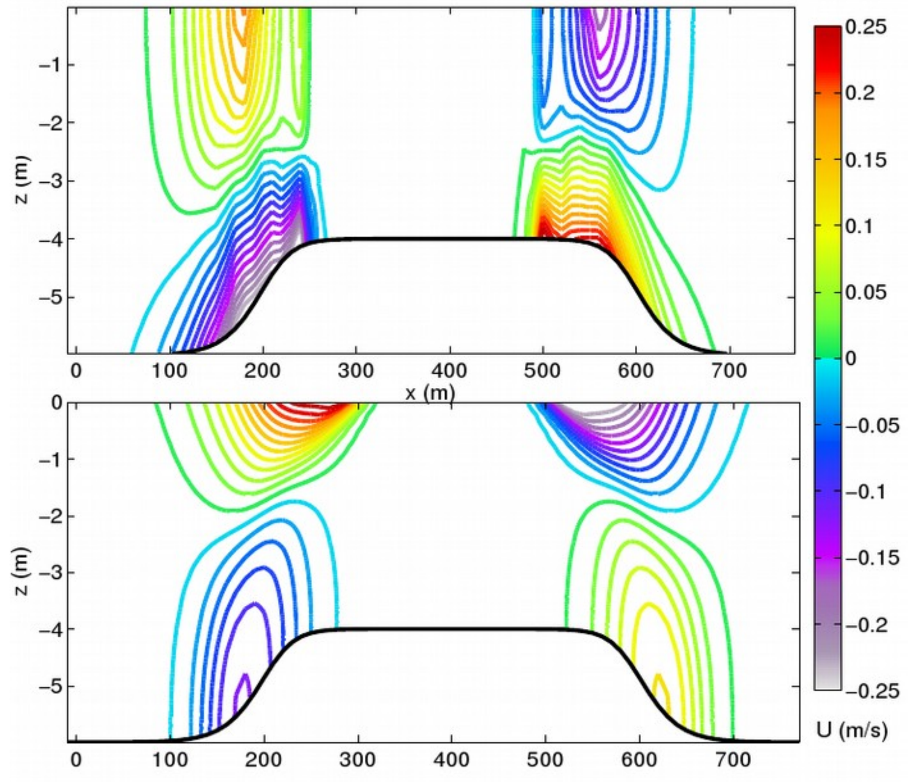


Correct solution by U=u+Us

(steady state)

Numerical result (MARS3D-WWATCH)

(after 15') with Mellor (2003) equations

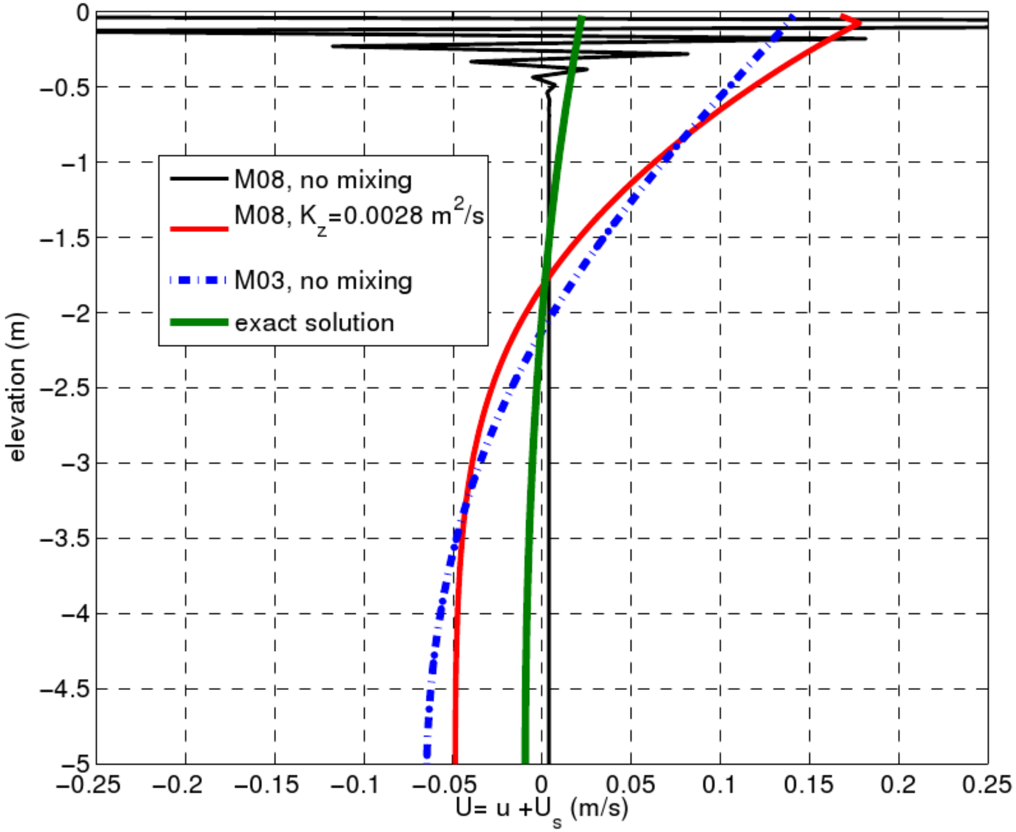


3. Wave-current interaction

Going 3D …

Mellor (2008) is even worse: - depth-integrated equations are not correct (different from Phillips 1977)

$$\int_{-h}^{\widehat{\eta}} \frac{\partial S_{xx}^{M08}}{\partial x} dz = \frac{\partial S_{xx}^{P77}}{\partial x} - S_{xx}^{M08}(z=-h)\frac{\partial h}{\partial x} - S_{xx}^{M08}(z=\widehat{\eta})\frac{\partial \eta}{\partial x}.$$



And velocity profiles are … crazy!

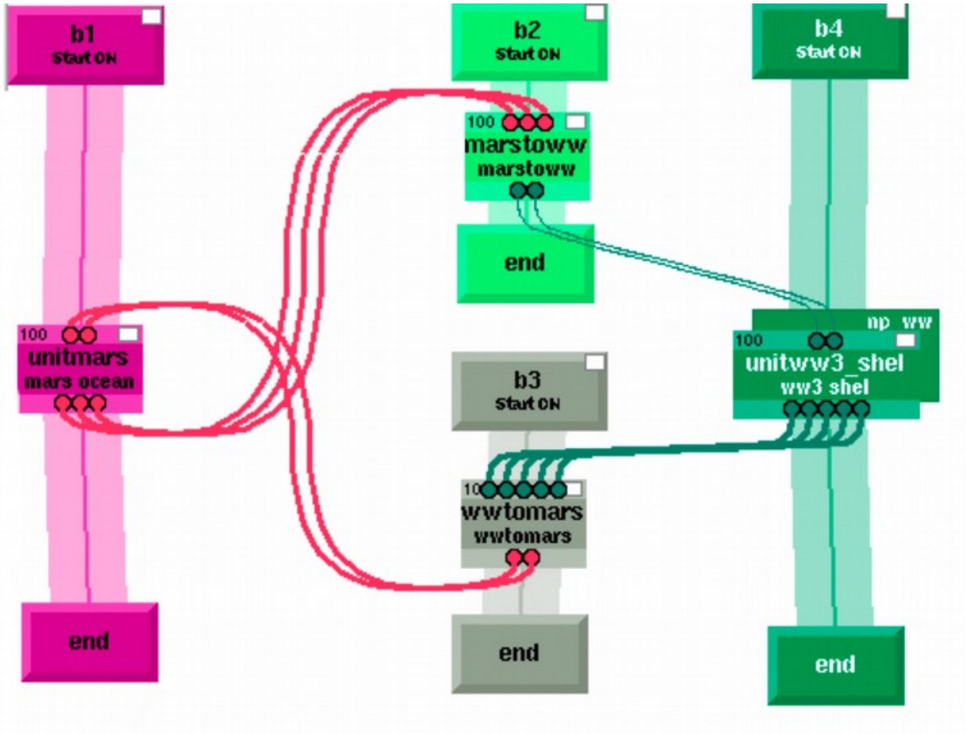
No surprise:

delta function on the vertical …

« Old approach »

2-way coupling of WAVEWATCH III and MARS3D with PALM

- based on WWATCH version 3.14_Ifremer&SHOM and MARS3D version 8.0
- wrong equations (Mellor 2003 and 2008) well implemented
- correct equations



4. Coupling implementation

« New approaches »

- use of OASIS-MCT : coupling through the MPI communicator
- ESMF