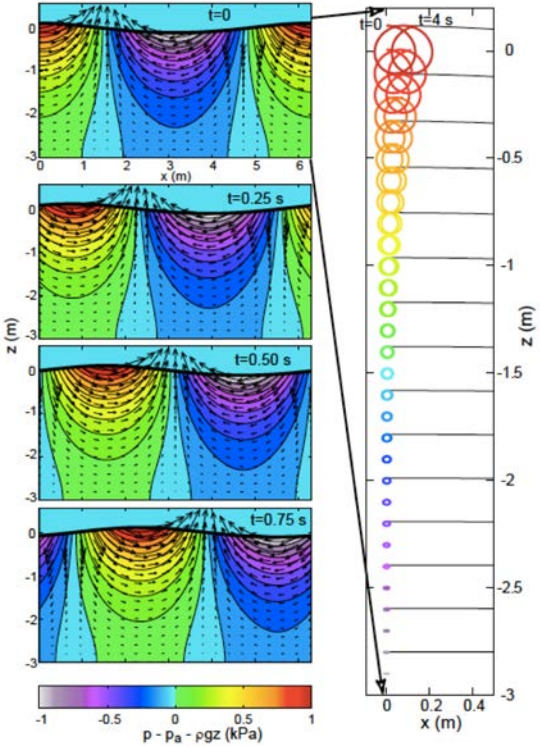
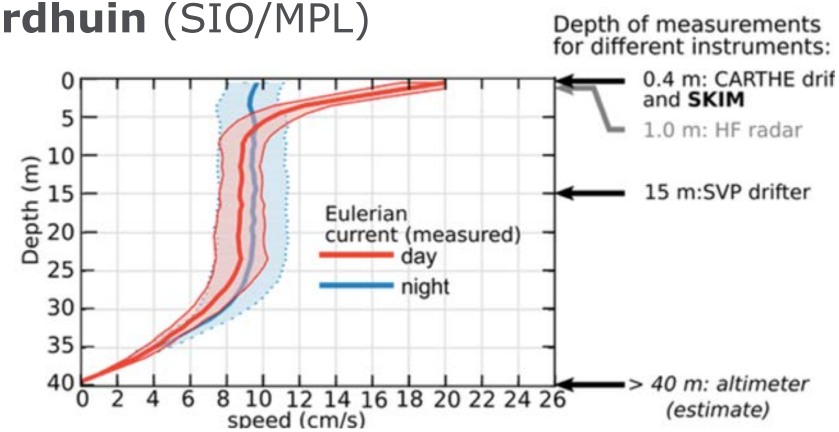
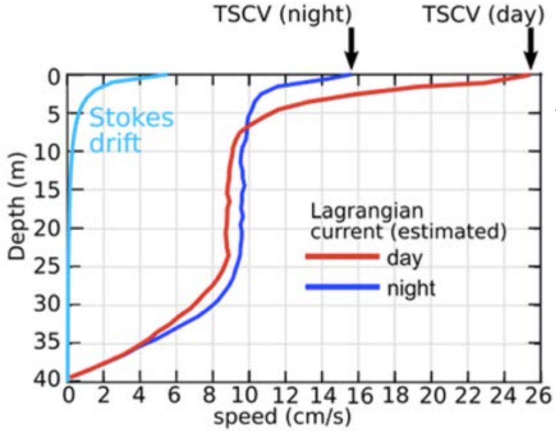
Stokes drift and vertical shear at the sea surface: upper ocean transport, mixing, remote sensing

Fabrice Ardhuin (SIO/MPL)







Adapted from Sutherland et al. (JPO 2016) (26 N, 36 W)

1. Oscillating motions can transport mass…

Linear Airy wave theory, monochromatic waves in deep water

- Phase speed: $C \sim 10$ m/s
- Orbital velocity: $u = (ak)\ C \sim 1$ m/s ,
- Stokes drift: $U_S = (ak)^2\, C \sim 0.1$ m/s ,

Quadratic quantities:

Wave energy: $E = \rho g\, a^2/2$ [J/m^2]

Mass transport: $M_w = E/C$ [kg/m/s]

(depth integrated. Mw =E/C is very general)

$$
\begin{aligned}
\mathbf{u}\left(\mathbf{x}(t'), z(t'), t'\right) = {} & \mathbf{u}\left(\mathbf{x}(0), z(0), t'\right) \\
& + \mathbf{u}_2\left(\mathbf{x}(0), z(0), t'\right) \\
& + \xi_h(t') \cdot \nabla \mathbf{u}\left(\xi_h(0), \xi_3(0), t'\right) + \xi_3(t') \frac{\partial}{\partial z} \mathbf{u}\left(\xi_h(0), \xi_3(0), t'\right) + O(\varepsilon^3)
\end{aligned}
$$

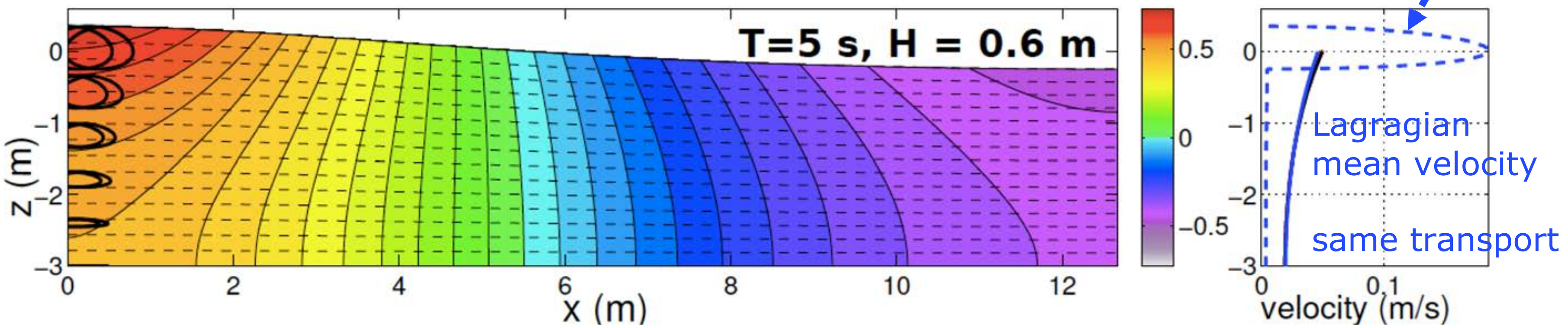
linear Eulerian velocity

non-linear Eulerian velocity

horizontal displacement

vertical displacement

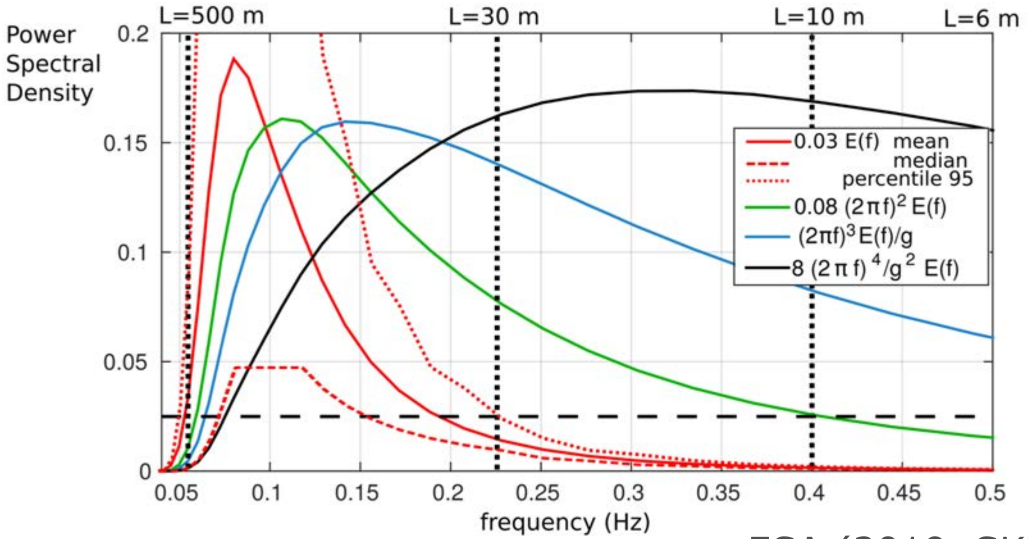
Eulerian mean velocity



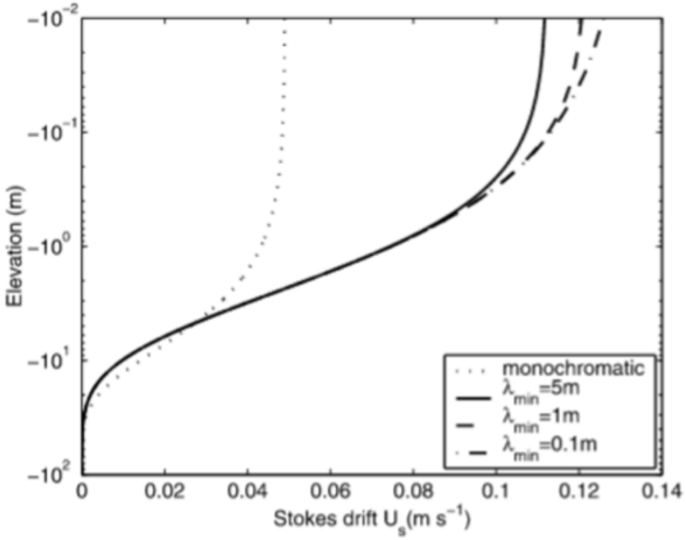
2. Beyond simple waves

- Non-linear effects: limited for monochromatic waves in deep water

- Random waves: Kenyon (1969)



ESA (2019, SKIM RfMS)

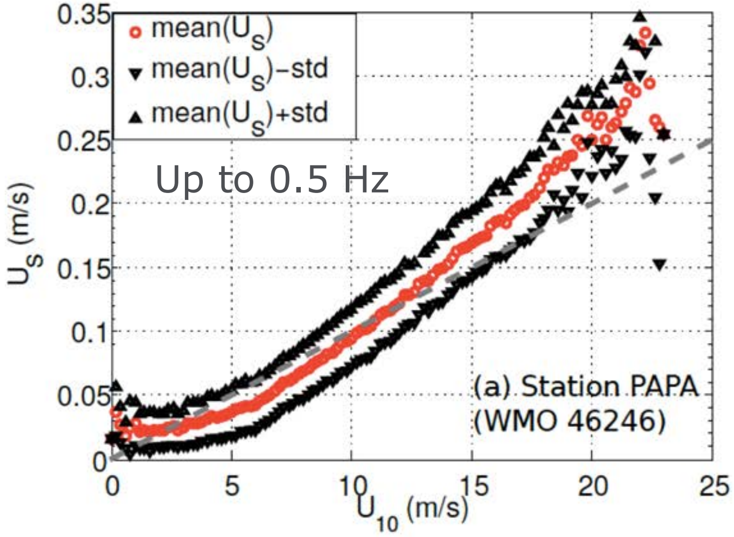


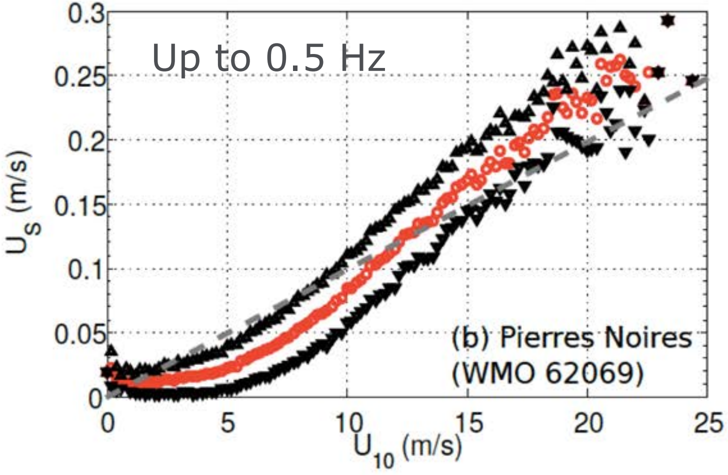
Rascle et al. (JGR 2006)

2. Beyond simple waves

- Random waves (continued): it is not just the wind :

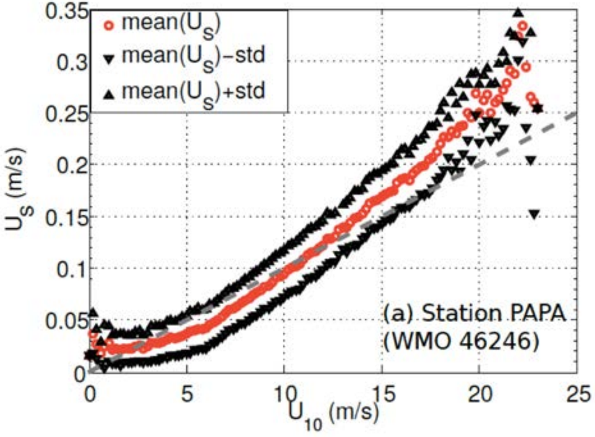
average Us for 5 to 10 m/s is 20% higher at PAPA (data courtesy J. Thomson / CDIP) compared to East Atlantic buoy 62069.

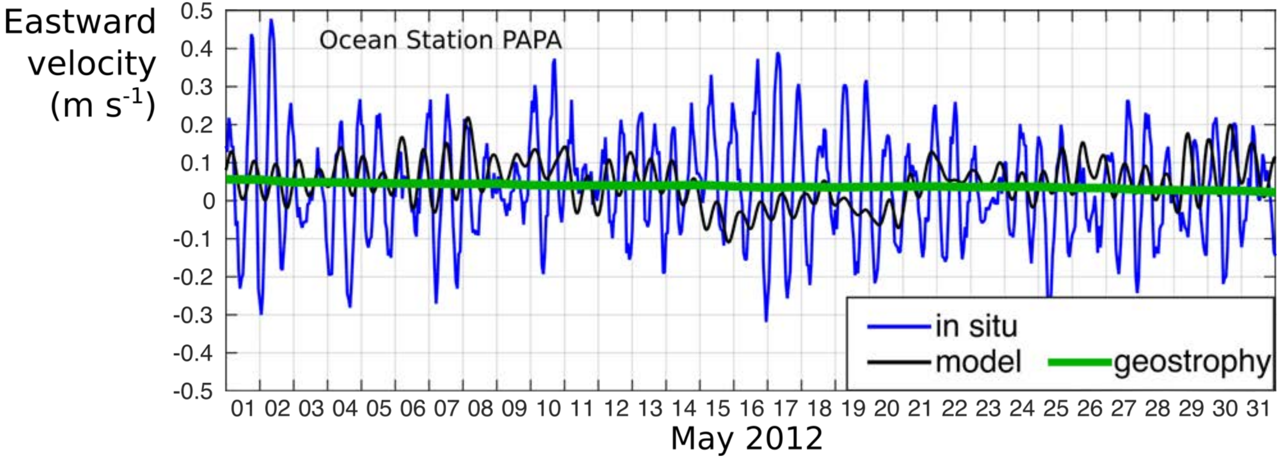




2. Beyond simple waves ... and context

Now compared to PAPA currents (courtesy of Cronin et al. PMEL)





2. Beyond simple waves

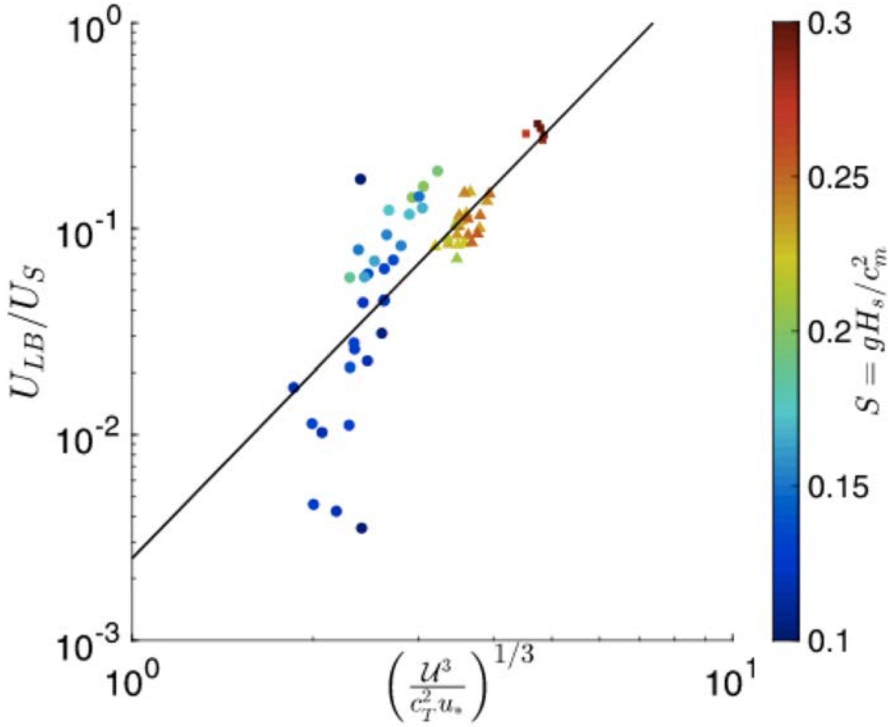
-Nonlinear random waves …? harmonics, modulation …

-Breaking:
Pizzo et al. JPO (2019):

breaking-induced drift may be 30%

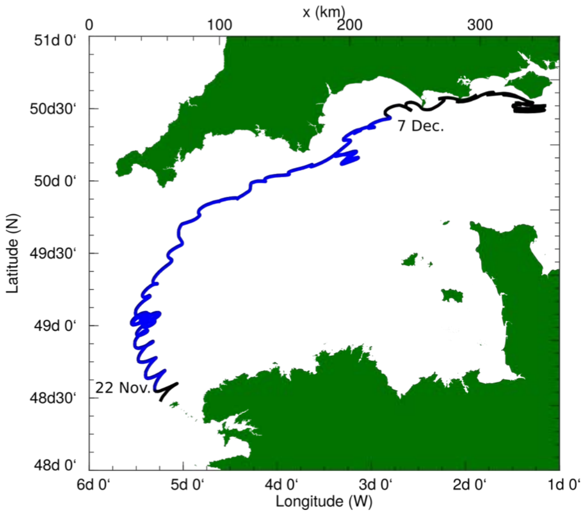
E. Terray (pers. Comm.):
breaking-induced may be up to 50%

Is that part of the current or
Stokes drift?

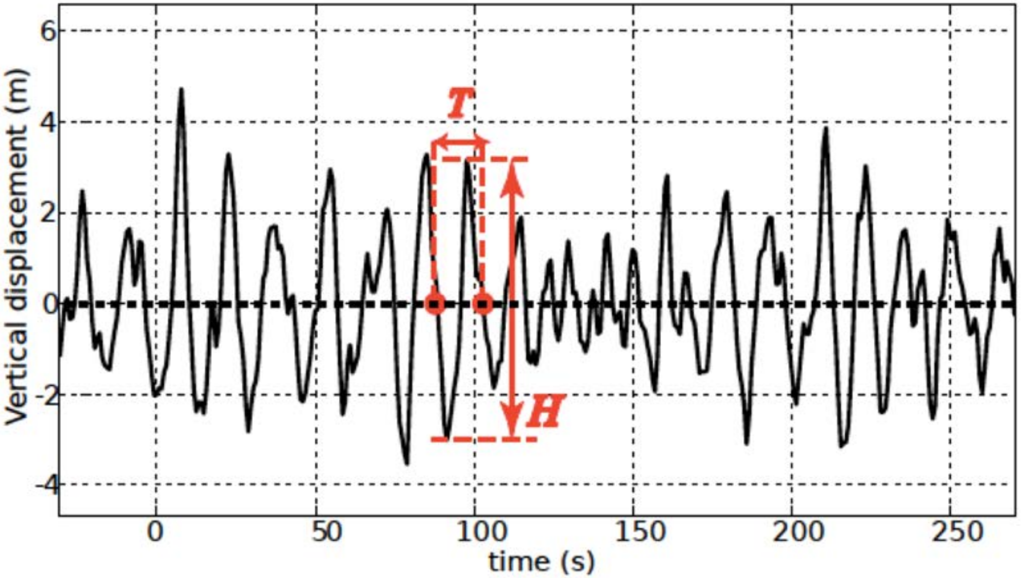


3. Can we measure Stokes drift separately?

Surface buoy drift

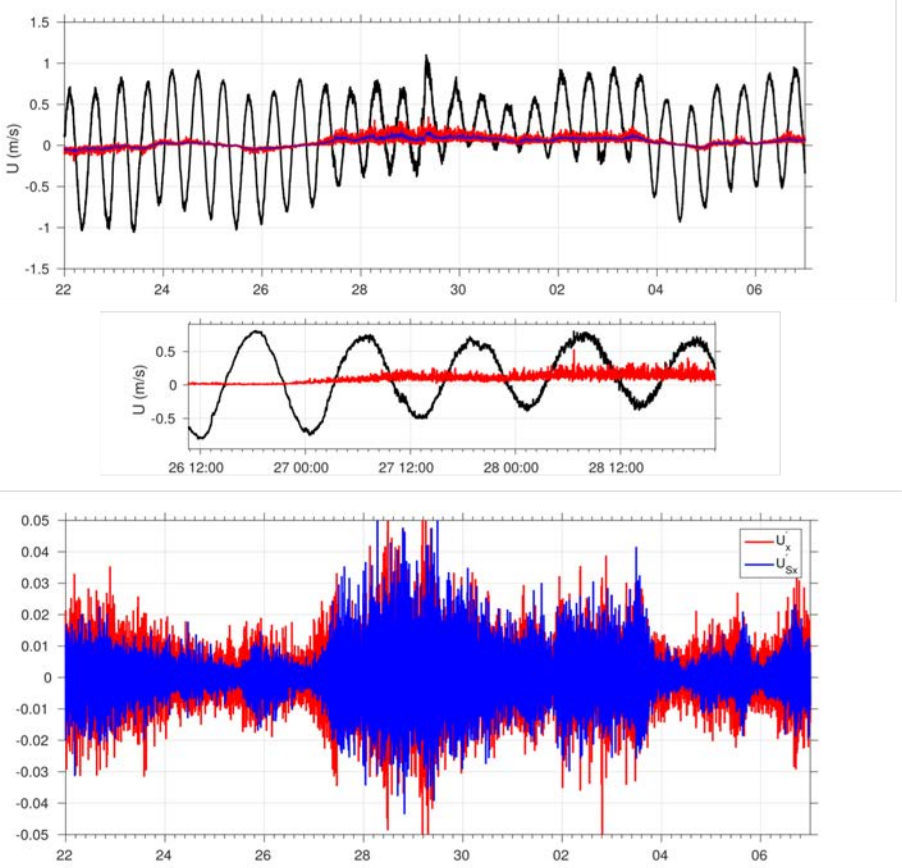


Typical wave time series:

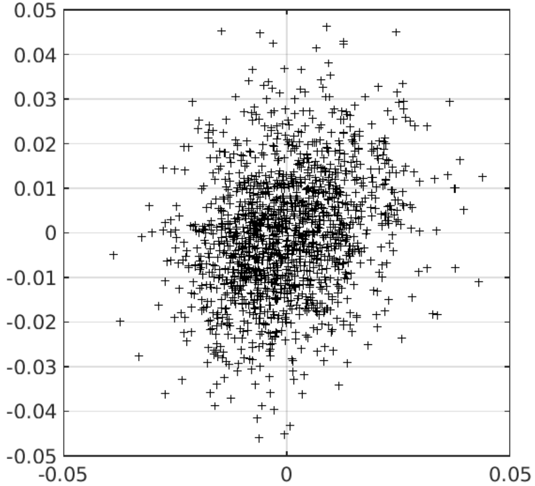


3. Can we measure Stokes drift separately?

Fluctuation of U_S (wave groups) and U



Variance of U'_S and U′ are related, but correlation of U'_S and U′ is weak:



More analysis to be done …

4. Coriolis effect and Stokes drift

Lagrangian mean velocity: U^L
quasi-Eulerian velocity : $\hat{u} = U^L - U_s$ (Jenkins Deut. Hydr. Zeit. 1989)

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

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

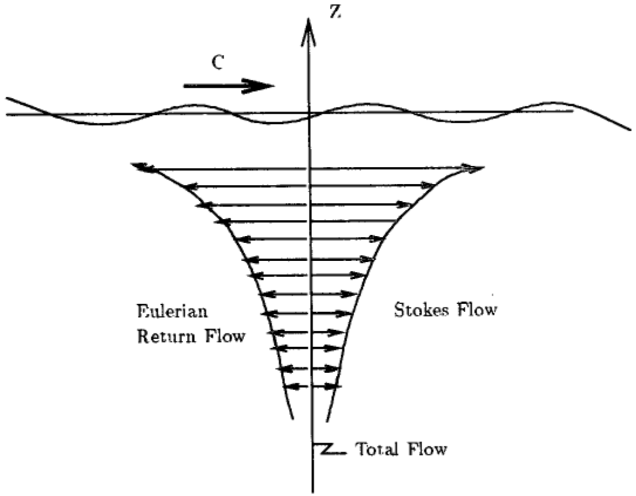
This gives a an almost uniform û near the surface (except for very short fetch)

4. Coriolis effect and Stokes drift

With the Earth rotation, a transversal component (v) appears, it is in phase with w, so that d<vw>/dz is f^*U_S

this « Hasselmann stress » sets up a current that opposes the Stokes drift

(Hasselmann 1970, see also Xu and Bowen JPO 1994).



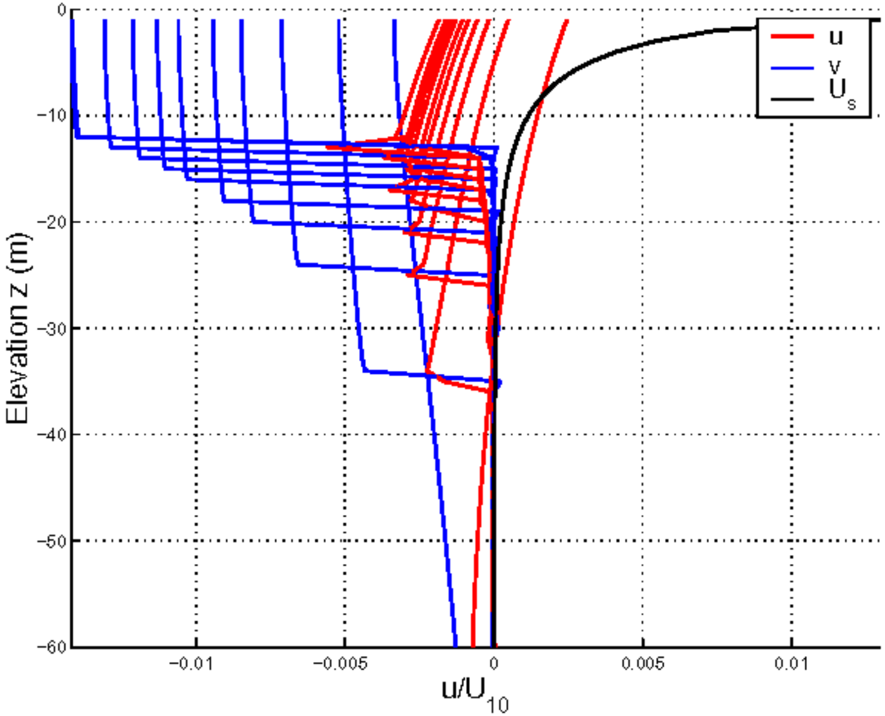
In steady state without mixing we have:

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

Can we measure this Hasselmann / Sokes-Coriolis effect ?

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

4. Coriolis effect and Stokes drift



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

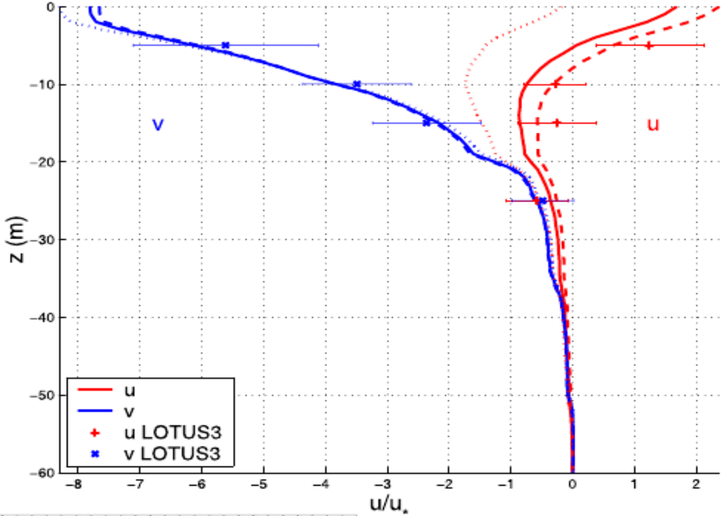
The “counter-drift” is contained
in the red quasi-Eulerian profile

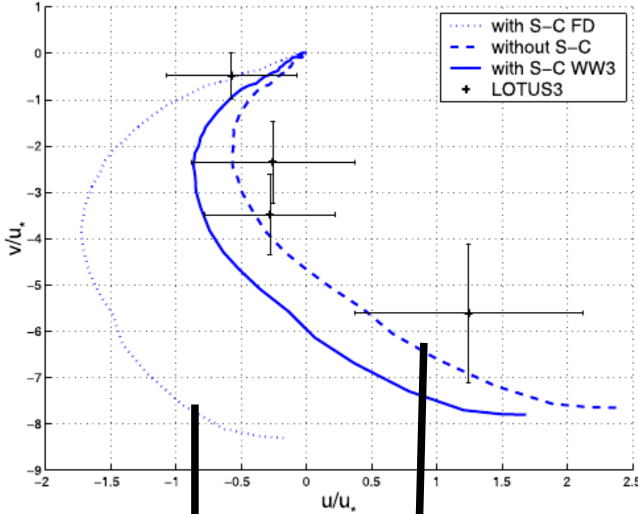
The depth-integral of û + Us is zero

The depth-integral of v
is the usual Ekman transport tau/f

4. Coriolis effect and Stokes drift

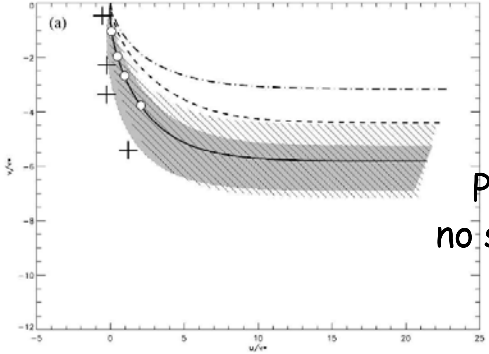
How good are the vertical current profiles predicted ? (Rascle & Ardhuin JGR 2009)





SC based on PM spectrum

No SC



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

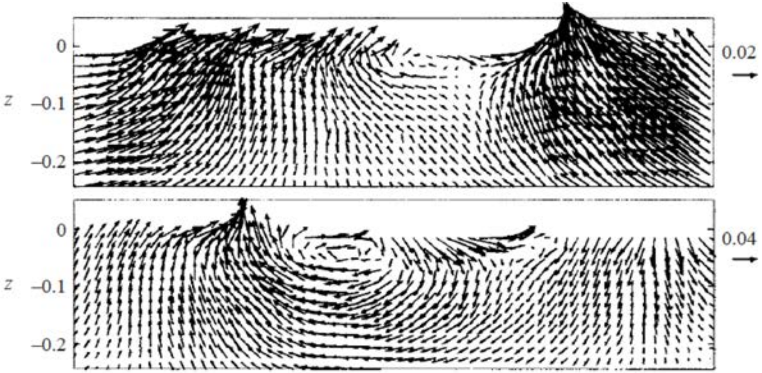
5. Stokes drift and 3D flow equations

Andrews & McIntyre (JFM 1978): two sets of eqs. for U and û

Leibovich (1980) derived the CL equations from AM78 under some simplifying assumptions -> basis for most « LES » simulations

Should we consider extensions to the CL equations?
- Effect of vertical shear on the wave forcing (McWilliams et al. JFM 2004)
- Feedback of Langmuir cells on the waves (Suzuki JFM 2019)
- Breaking (e.g. Sullivan et al. JFM 2004)

$$\frac{\partial \boldsymbol{u}}{\partial t} = -(\boldsymbol{u}\cdot\nabla)\boldsymbol{u} - \frac{1}{\rho}\nabla p + \nu\nabla^2\boldsymbol{u} + \boxed{\boldsymbol{A}}$$



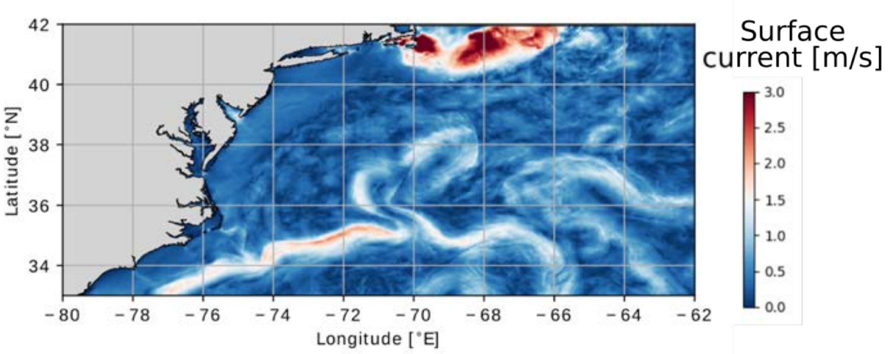
(Melville et al. JFM 2004)

5. Stokes drift and 3D flow equations

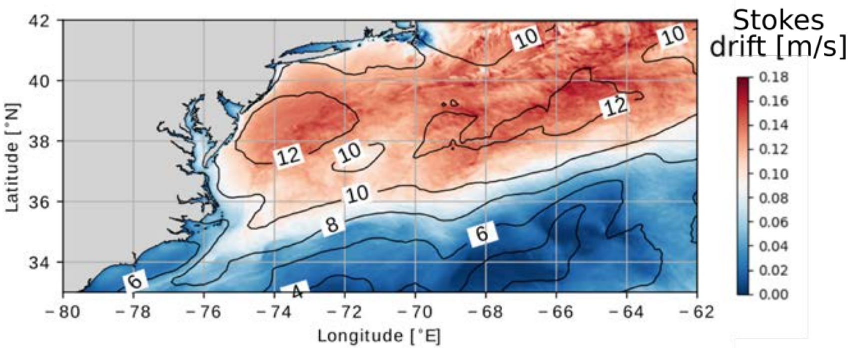
Larger scales: currents are the dominant source of wave variation

- Hs varies O(1) at mesoscales due to refraction (Quilfen & Chapron GRL 2019)
- mss varies O(10%) at sub-mesoscales due to convergence / strain
  (Kudryavtsev et al. JGR 2005, 2012, Rascle et al. JPO 2014…)

- What about Stokes drift? Probably Somewhere in between …
  to be verified



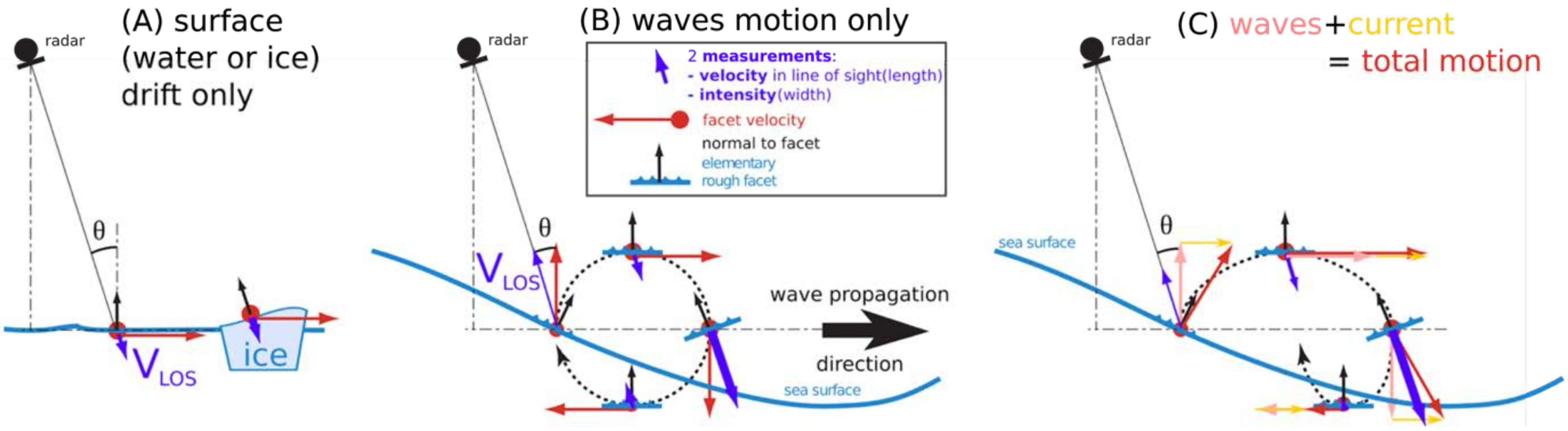
Surface current velocity snapshot in the Gulf Stream region (2011.11.15)



Stokes drift map and 10 m wind speed contours [m/s]

6. Stokes drift and remote sensing

Near-nadir Doppler measurements give a wave Doppler $U_{WD} \cong U_S$ / mss (specular reflection)



6. Stokes drift and remote sensing

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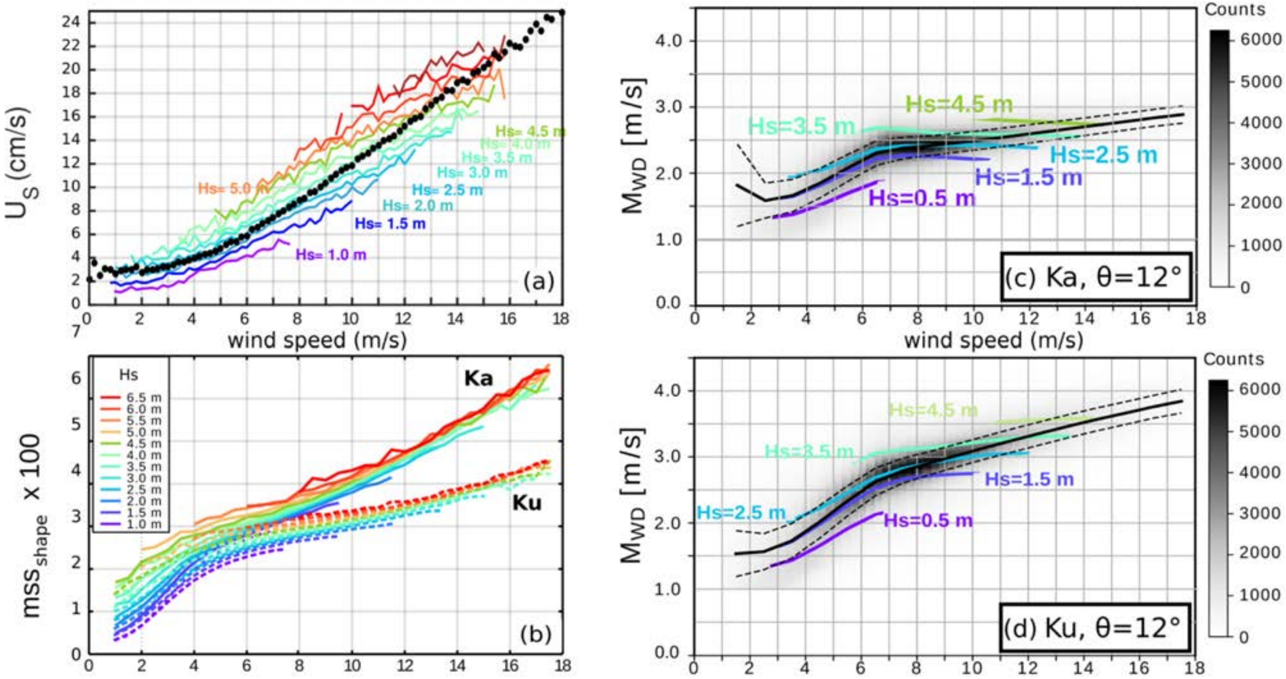
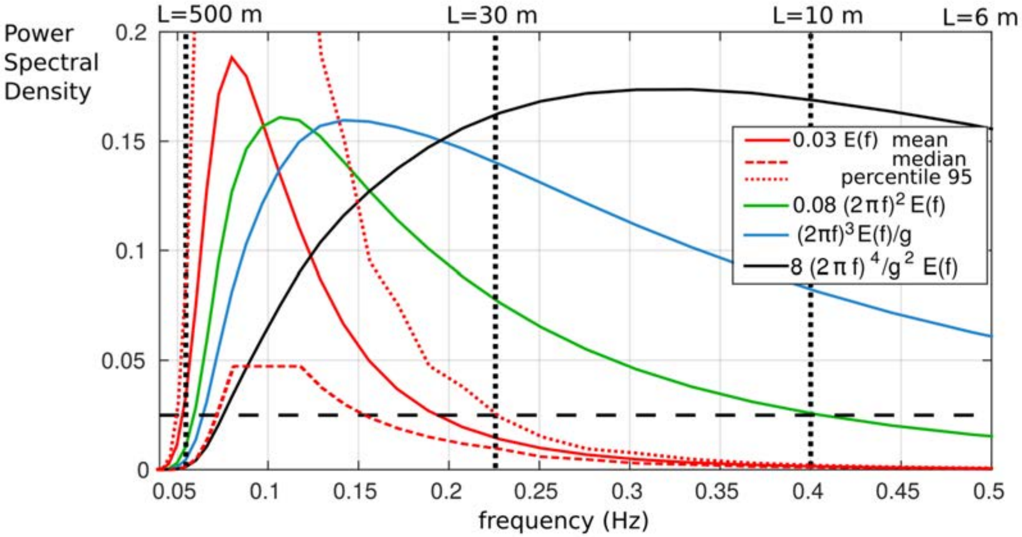


This theoretical prediction is consistent with platform & airborne data (Marié et al. OSD 2019)

6. Stokes drift and remote sensing

Measuring Stokes drift from wave spectra : we need to resolve L ~ 30 m.



Some challenges & suggestions

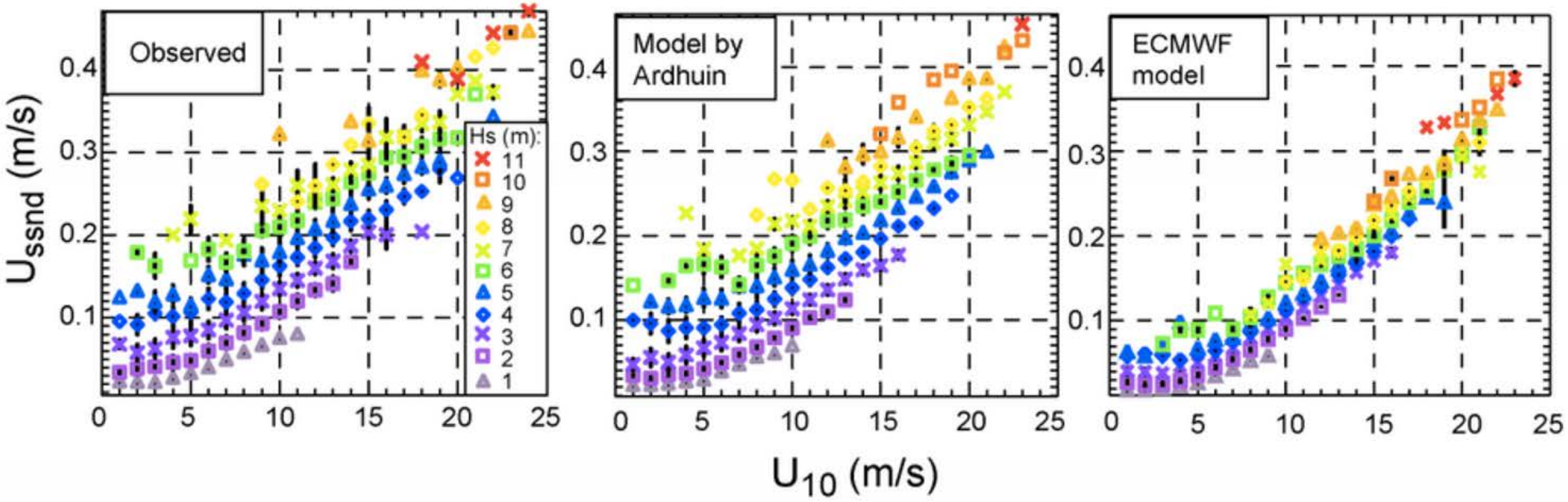
1. Which are the dataset with combined Eulerian, semi-Eulerian & Lagrangian data that can help us verify the properties of Stokes drift?

2. What are the key variables? Surface Stokes drift, Stokes transport… what about whitecap parameters?

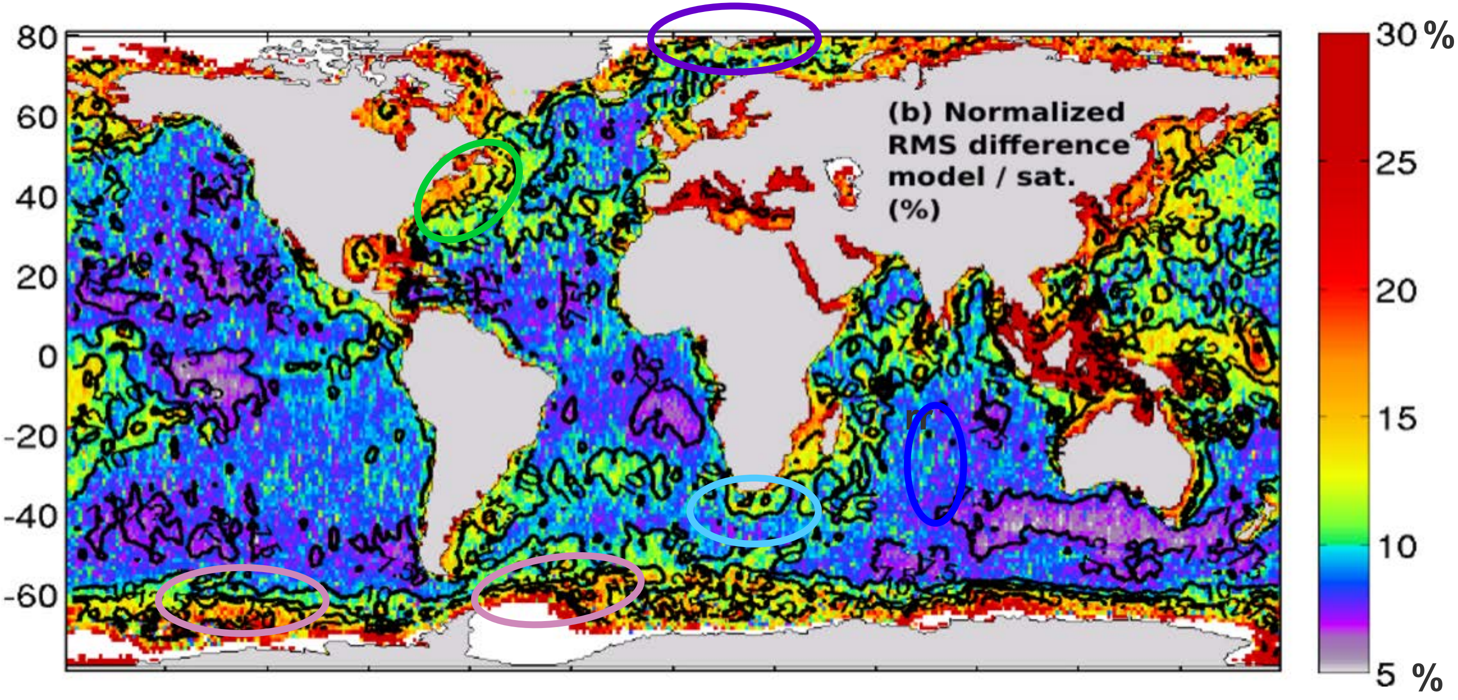
3. Wave-current interactions at all scales:
   - How should we treat breaking-induced drift?
   - Is there an intermittent wind drift? How big is it?

   - What is the impact of short-long wave modulation?
   - How important are wave-current correlations from the LC scale to the mesoscale?

Extra slides


Observed
Model by Ardhuin
ECMWF model
Hs (m):
11
10
9
8
7
6
5
4
3
2
1
U_{ssnd} (m/s)
U_{10} (m/s)
0.1
0.2
0.3
0.4
0
5
10
15
20
25

How good are models? For Hs we can tell…



Model – satellite RMS difference

Model:
LOPS / Ifremer hincast for 2008 (no currents, no assimilation)

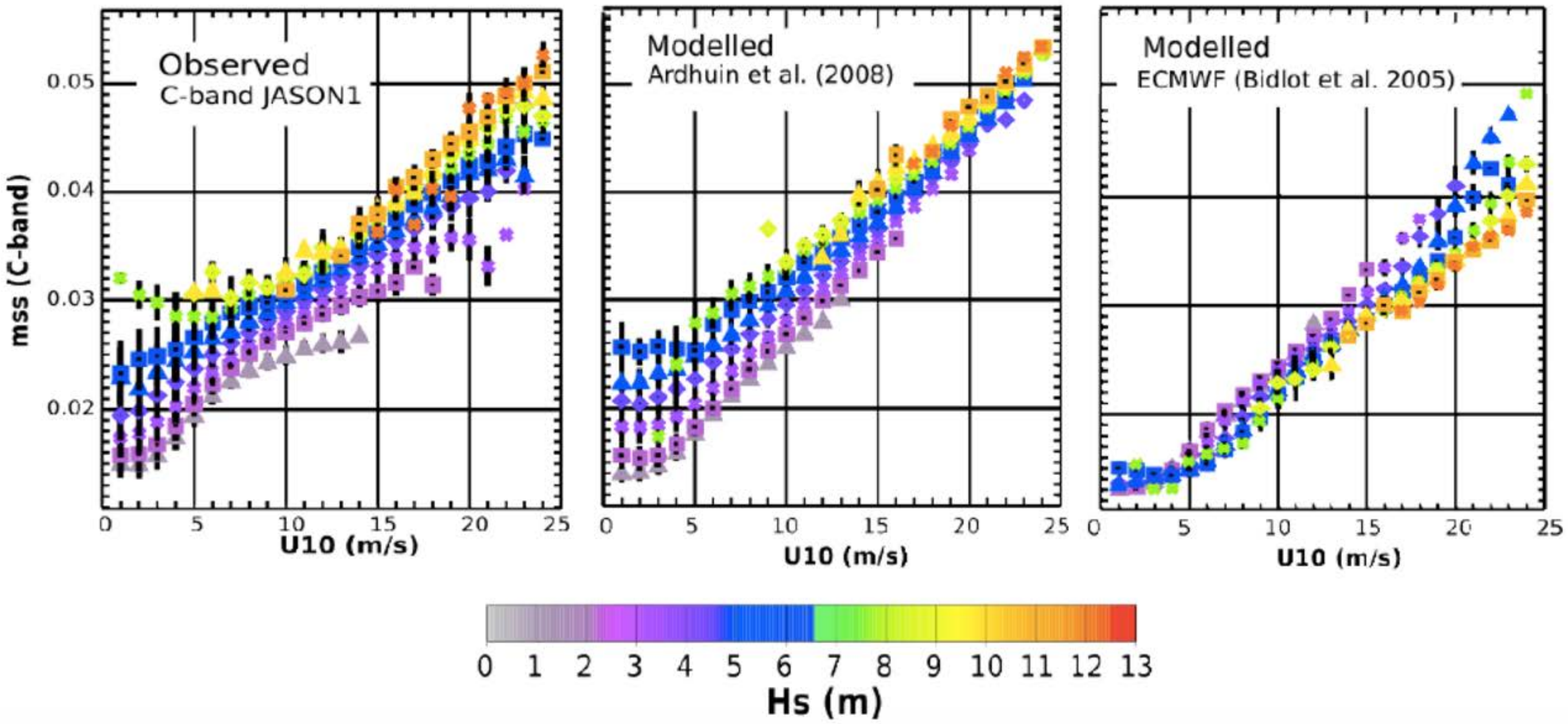
Satellite:
LOPS / Ifremer calibrated GDRs (Queffeulou & al. 2014) 100 km avg along-track

Painting the ocean blue, pixel after pixel = fixing issues

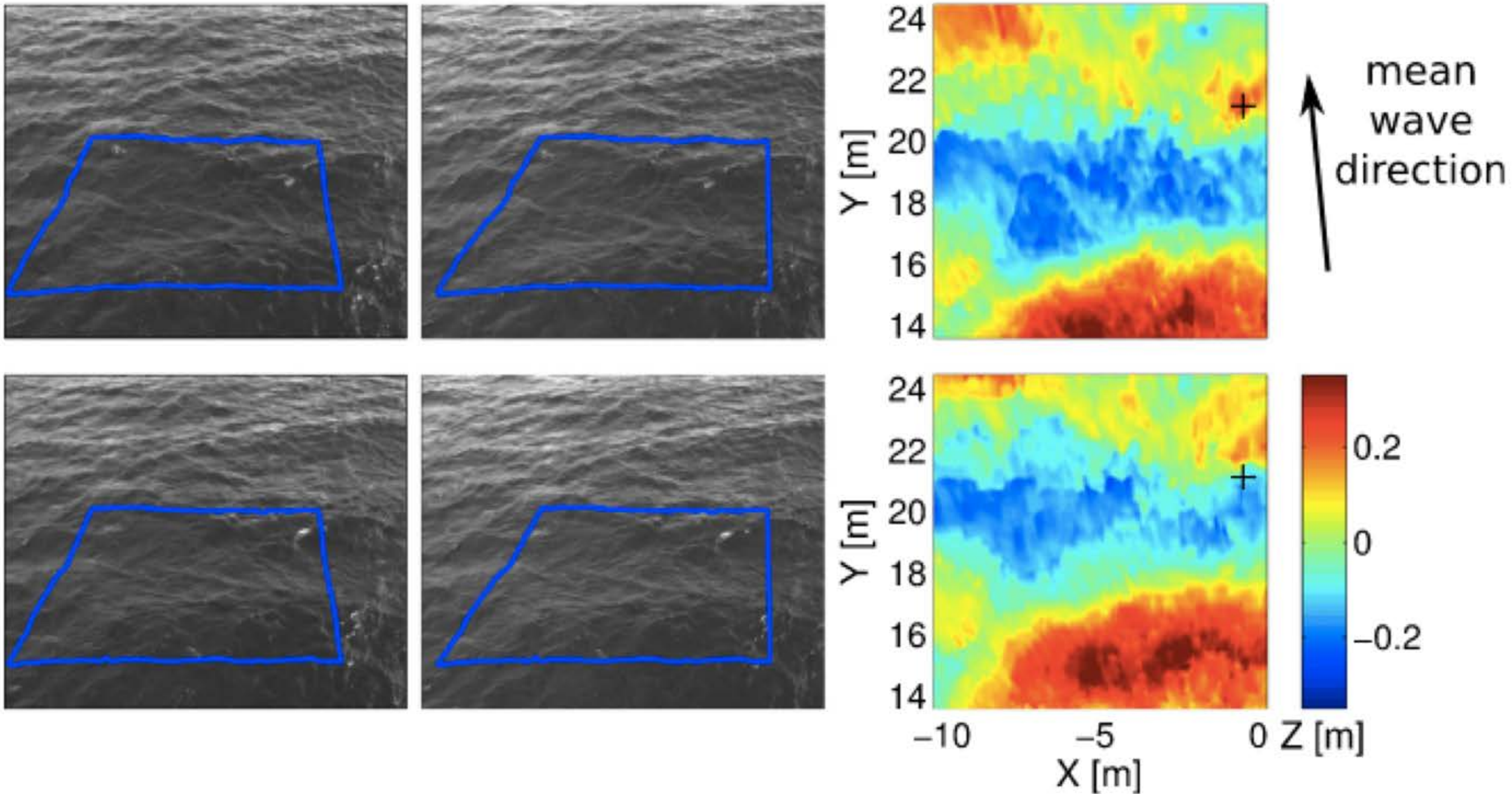
- forcing : **winds**, **currents**, **sea ice**, **icebergs**
- satellite data quality: progress with CCI-v1 dataset (Quilfen & Chapron GRL 2019)
- parameterizations : swell dissipation, growth of young waves, wave breaking…

1.1 Non-local and local steepness

strong influence on the high frequencies, illustrated here with the mss



Trying to get the high-frequency tail right



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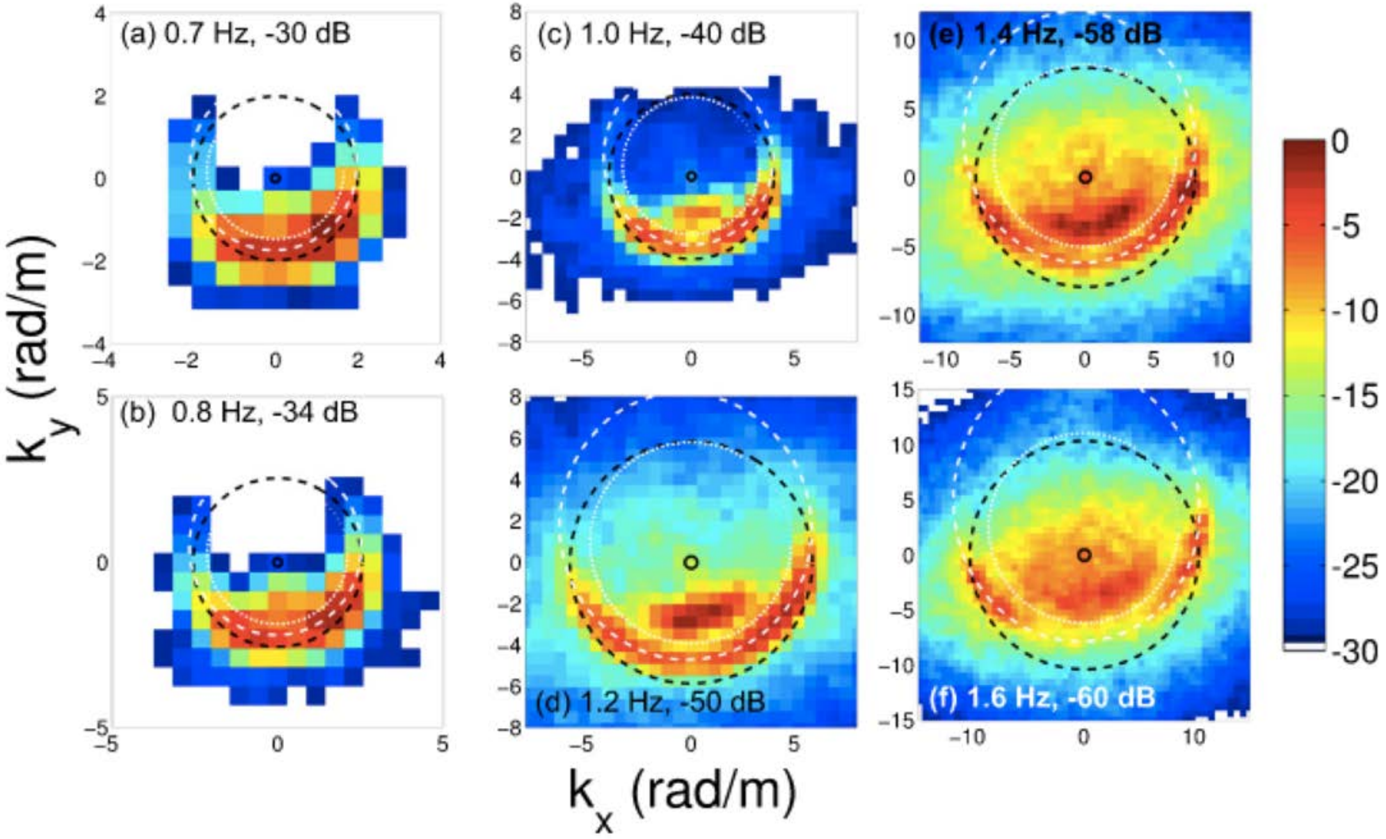
Trying to get the high-frequency tail right



Leckler et al. (JPO 2015)

Trying to get the high-frequency tail right

Still struggling to get the
Cross-wind vs down-wind slopes

And beware that harmonics
are there for f > 3 fp

Collected data coming
(Guimaraes et al. 2020, submitted)
- Adriatic Sea
- Korean platform
- Black Sea

Walter's inconvenients sea truths,
and anomalies from these
(remote sensing provides « bulk » mss,
not spectrally resolved, but everywhere)