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Upper ocean dynamics with waves

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Background

- Several past and ongoing projects at MET focusing on the impact of surface waves on the upper ocean dynamics, e.g.
    - MyWave (FP7)
    - BIOWAVE (RCN)
    - Oilwave (RCN)
    - Waves in oil and ice (RCN)
    - WAMFLUX (FP7)
    - Deep-C (GoMRI)
- In general, the waves have an impact on air-sea fluxes of mass, momentum and energy, as well as a direct influence on the oceanic momentum balance and turbulent kinetic energy.

Some papers in recent years

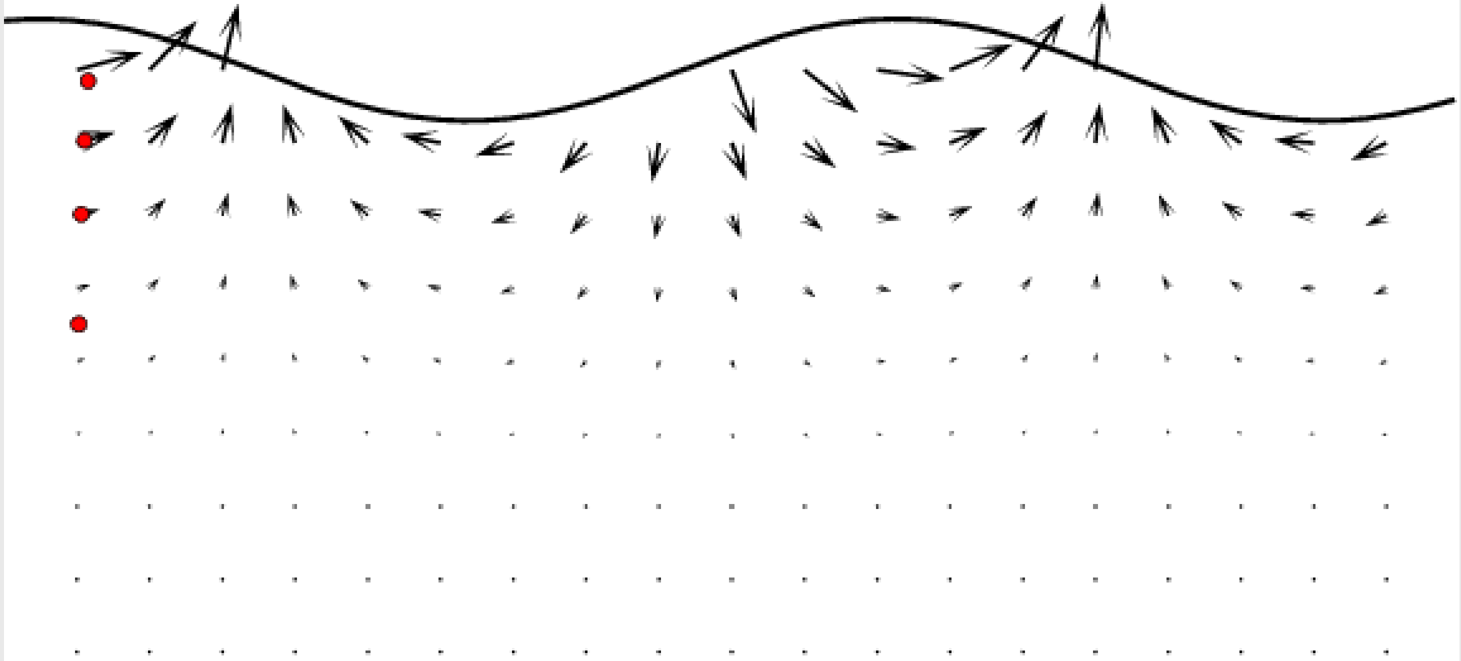
1) Röhrs, J., and Christensen, K.H., ”Drift in the uppermost part of the ocean”, *Geophys. Res. Lett.*, submitted.
2) Weber, J.E.H., Drivdal, M., Christensen, K.H., and Broström, G., "Some aspects of the Coriolis-Stokes forcing in the oceanic momentum and energy budgets", *J. Geophys. Res.*, in press.
3) Breivik, Ø., Mogensen, K., Bidlot, J.-R., Balmaseda M.A., and Janssen, P.A.E.M., "Surface wave effects in the NEMO ocean model: Forced and coupled experiments." *J. Geophys. Res.*, **120**, 2973-2992 (2015).
4) Röhrs, J., Sperrevik, A.K., Christensen, K.H., Broström, G., and Breivik, Ø., "Comparison of HF radar measurements with Eulerian and Lagrangian surface currents", *Ocean Dyn.*, **65**, 679-690 (2015).
5) Carrasco, A., Semedo, A., Isachsen, P.E., Christensen, K.H. and Saetra, Ø., "Global Surface Wave Drift Climate from ERA-40: The contributions from wind-sea and swell", *Ocean Dyn.*, **64**, 1815-1829 (2014).
6) Breivik, Ø., Janssen, P.A.E.M., and Bidlot, J.-R., ”Approximate Stokes Drift Profiles in Deep Water”, *J. Phys. Oceanogr.*, **44**, 2433-2445 (2014).
7) Drivdal, M., Broström, G., and Christensen, K.H., "Wave induced mixing and transport of buoyant particles: Application to the Statfjord A oil spill", *Ocean Sci.*, **10**, 1-15 (2014).
8) Taskjelle, T., Barthel, K., Christensen, K.H., Furaca, N., Gammelsrød, T., Hoguane, A.M., and Nharreluga, B., "Modelling alongshore flow in a semi-enclosed lagoon strongly forced by tides and waves", *Est. Coast. Shelf Sci.*, **149**, 294-301 (2014).
9) Broström, G., Christensen, K.H., Drivdal, M. and Weber, J.E.H., “Note on Coriolis-Stokes force and energy”, *Ocean Dyn.*, **64**, 1039-1045 (2014).
10) Röhrs, J., Christensen, K.H., Vikebø, F., Sundby S., Saetra, Ø., and Broström, G., “Wave induced transport and vertical mixing of pelagic eggs and larvae”, *Limnol. Oceanogr.*, **59**, 1213-1227 (2014).
11) Sutherland, G., Christensen, K.H., Ward, B., “Evaluating Langmuir turbulence parameterizations in the ocean surface boundary layer”, *J. Geophys. Res.*, **119**, 1899-1910 (2014).
12) Weber, J.E.H., Christensen, K.H., and Broström, G., “Stokes drift in internal equatorial Kelvin waves; continuous stratification versus two-layer models”, *J. Phys. Oceanogr.*, **44**, 591-599 (2014).
13) Christensen, K.H., Röhrs, J., Ward, B., Fer, I., Broström, G., Saetra, Ø., and Breivik, Ø., “Surface wave measurements using a ship-mounted ultrasonic altimeter”, *Methods Oceanogr.*, **6**, 1-15 (2013).
14) Bell, T.G, De Bruyn, W., Miller, S.D, Ward, B., Christensen, K.H., and Saltzmann, E.S., “Air/sea DMS gas transfer in the North Atlantic: evidence for limited interfacial gas exchange at high wind speed”, *Atmos. Chem. Phys.*, **13**, 11073–11087 (2013).
15) Sutherland, G., Ward, B., and Christensen, K.H., “Wave-turbulence scaling in the ocean mixed layer”, *Ocean Sci.*, **9**, 597-608 (2013).
16) Röhrs, J., Christensen, K.H., Hole, L.R., Broström, G., Drivdal, M., and Sundby, S., “Observation based evaluation of surface wave effects on trajectory forecasts”, *Ocean Dyn.*, **62**(10-12), 1519-1533 (2012).

Photograph by Joseph Baylor Roberts

Reasonably simple, model coupling mainly through sea state dependent air-sea fluxes and body forces proportional to the Stokes drift. Mixing still an open question. Weakly nonlinear theory is OK.

Complicated, highly nonlinear problem. Wave-mean flow interactions through radiation stresses/ vortex forces. Models for vertically integrated quantities are common.

Surface waves possess mean momentum



(The Stokes drift by Johannes Röhrs)

Mass and momentum balances

Coriolis-Stokes force

Craik-Leibovich vortex force (type II)

$$\frac{\partial \bar{\mathbf{u}}}{\partial t} = \ldots - f\hat{\mathbf{k}} \times \mathbf{u}^{St} + \mathbf{u}^{St} \times \bar{\omega},$$

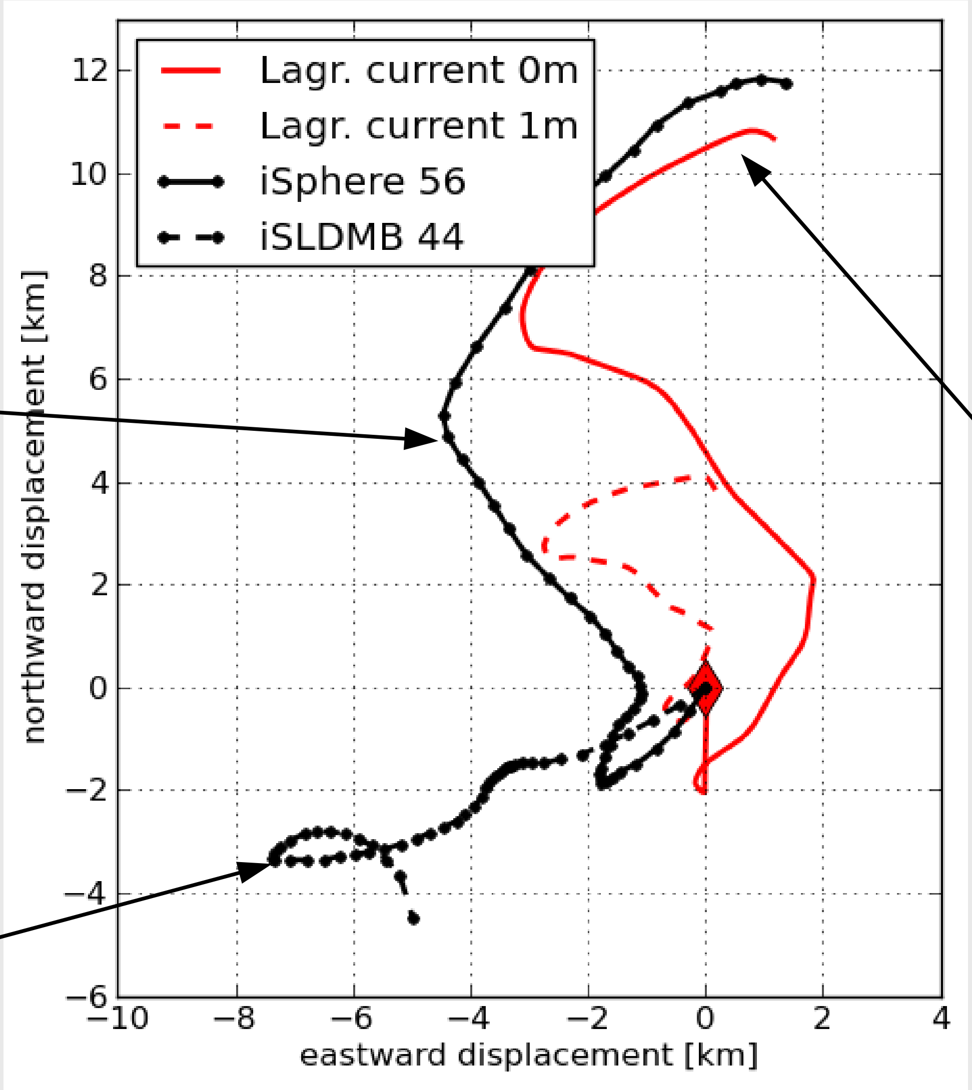
$$\frac{\partial \bar{\rho}}{\partial t} = \ldots - \mathbf{u}^{St} \cdot \nabla \bar{\rho},$$

Stokes drift

CS force – a bit extra veering
CL2 force – Langmuir turbulence
Stokes drift – advection of tracers etc.

(from Sullivan and McWilliams, 2010)

(Röhrs *et al.*, 2012)



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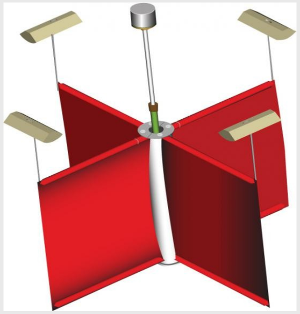
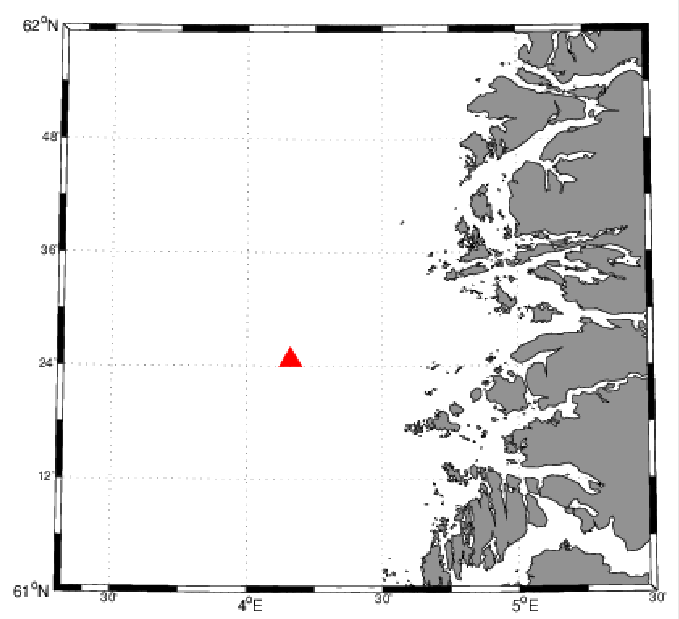
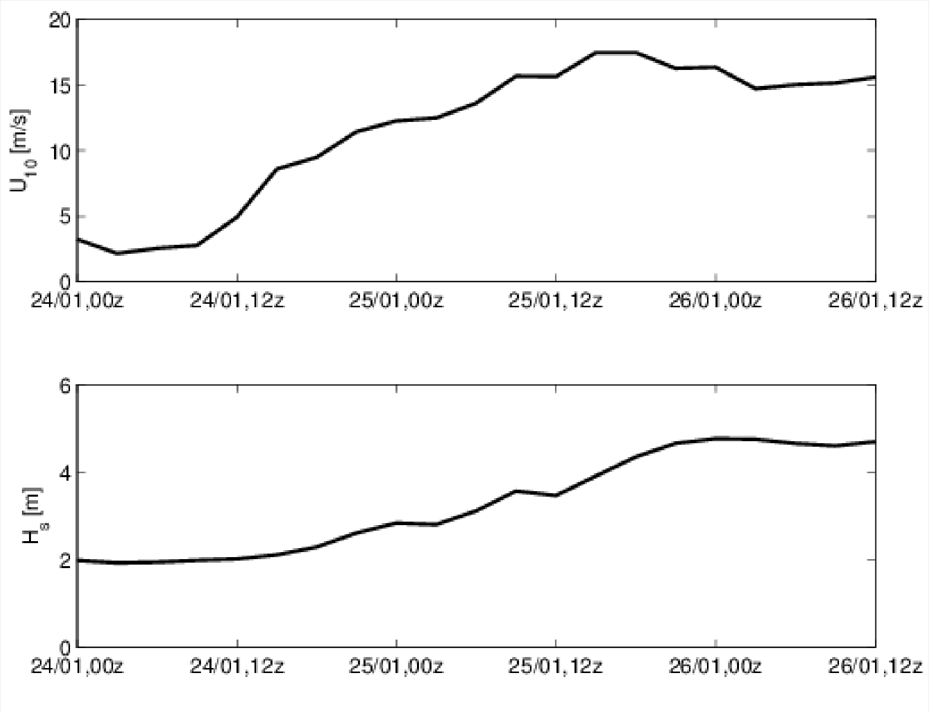


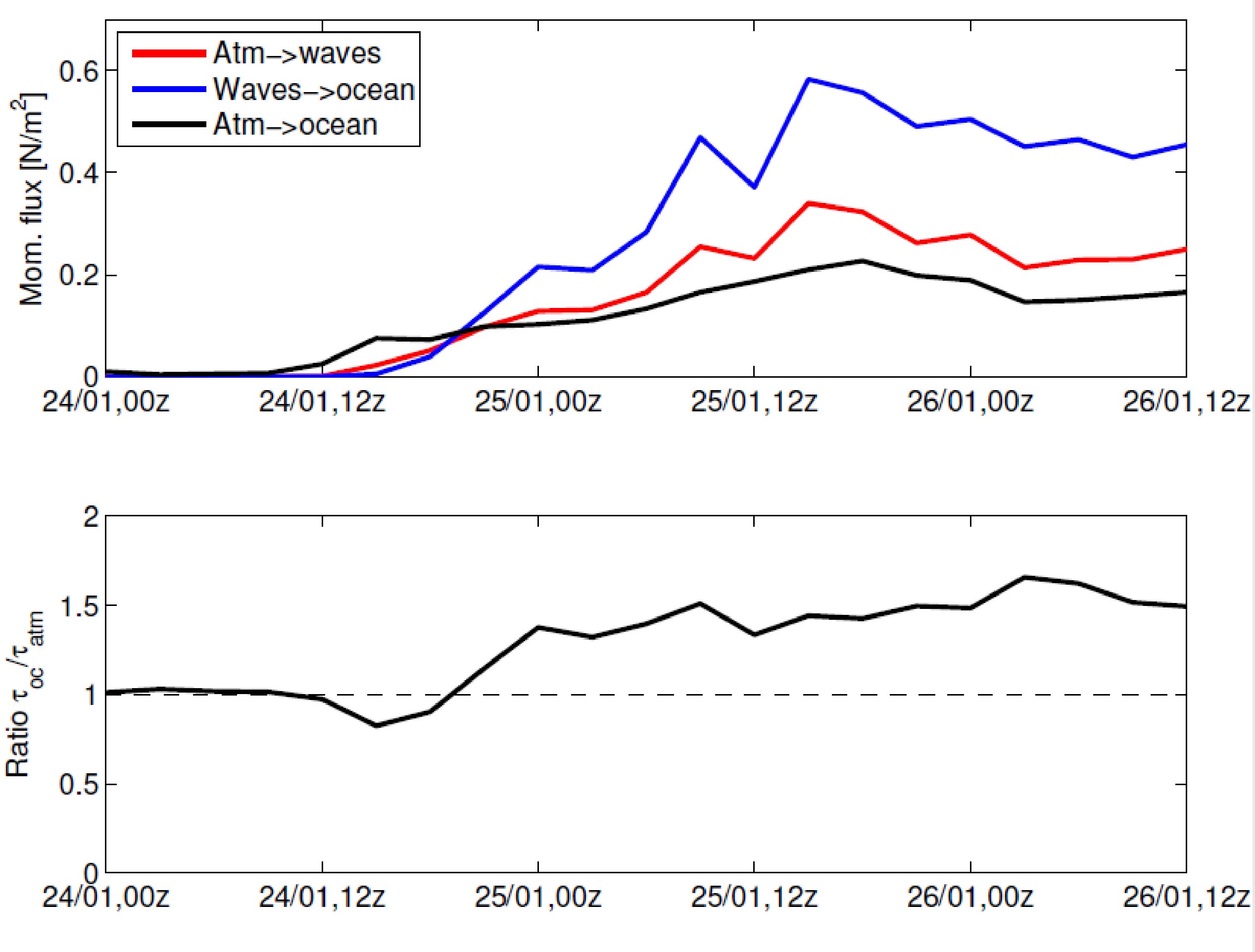
Air-sea fluxes

- Easy to calculate from wave model 2D spectra
- Local balances not required as waves can radiate away
- Momentum:
  - total atmospheric flux = wave growth + Ekman current
  - loss of mean wave momentum = increase in Ekman current
- Energy:
  - dissipating waves = flux of TKE into ocean

Example: momentum flux



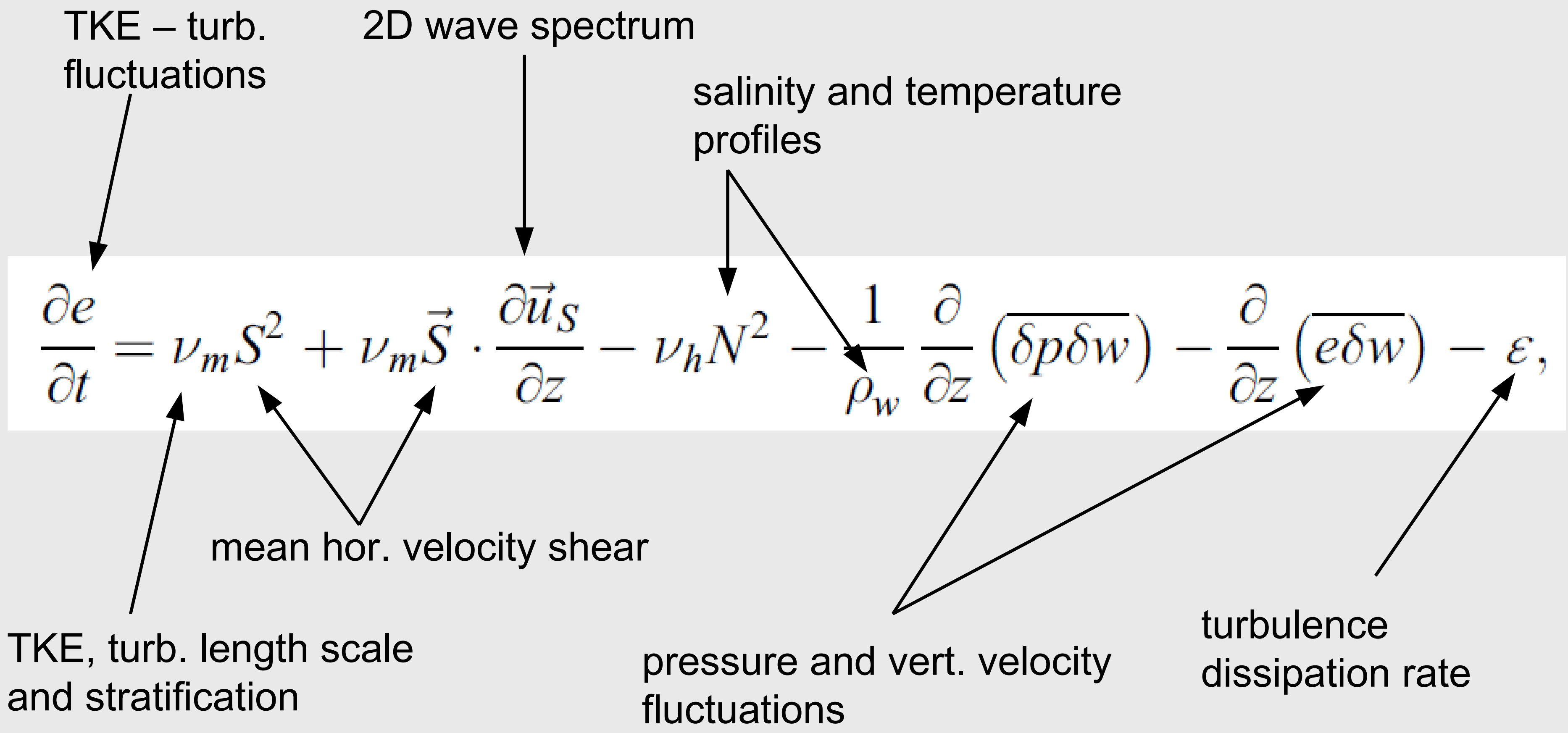



Atm−>waves
Waves−>ocean
Atm−>ocean
Mom. flux [N/m^2]
0
0.2
0.4
0.6
24/01,00z
24/01,12z
25/01,00z
25/01,12z
26/01,00z
26/01,12z
Ratio τ_{oc}/τ_{atm}
0
0.5
1
1.5
2
24/01,00z
24/01,12z
25/01,00z
25/01,12z
26/01,00z
26/01,12z

Wave-induced turbulent mixing

- Combination of several potentially important processes, e.g.
    - TKE fluxes by dissipating waves
    - Langmuir turbulence
    - Stokes drift shear
    - (direct) wave-induced turbulence
- No lack of theories, severe lack of observations
- Different theories can be hard to compare depending on analysis methods (Lagrangian, semi-Lagrangian, Eulerian)
- Use of LES as «truth» for validating parameterizations is problematic

Example: ocean TKE budget



TKE – turb. fluctuations

2D wave spectrum

salinity and temperature profiles

$$\frac{\partial e}{\partial t} = \nu_m S^2 + \nu_m \vec{S}\cdot\frac{\partial \vec{u}_S}{\partial z} - \nu_h N^2 - \frac{1}{\rho_w}\frac{\partial}{\partial z}\left(\overline{\delta p \delta w}\right) - \frac{\partial}{\partial z}\left(\overline{e\delta w}\right) - \varepsilon,$$

mean hor. velocity shear

TKE, turb. length scale and stratification

pressure and vert. velocity fluctuations

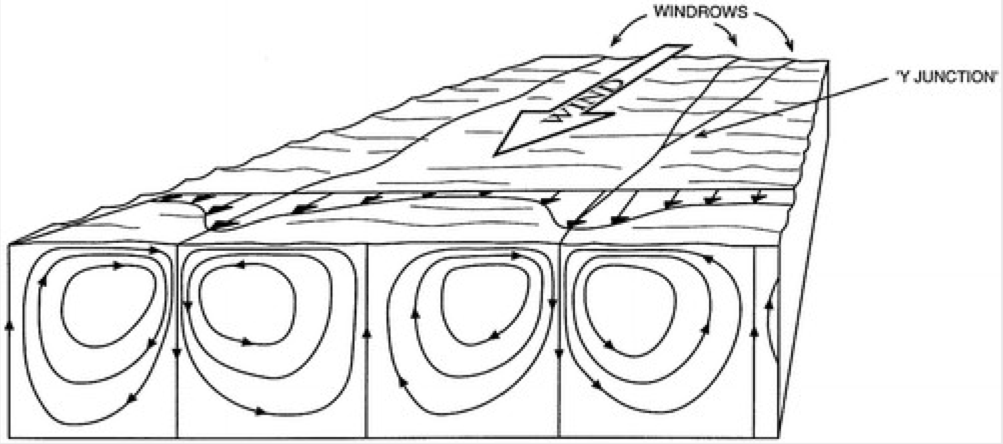
turbulence dissipation rate

(Janssen, 2012)

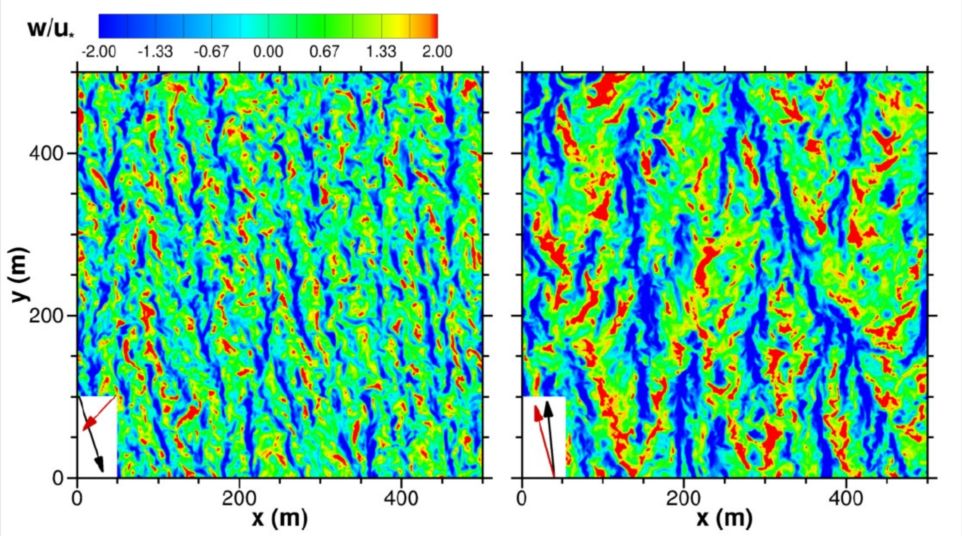
Scale separation

- Assuming $u = u' + \tilde{u} + \hat{u}$, what is the proper averaging procedure? It depends on the theoretical formulation!
- Example 1: Waves induce Langmuir turbulence, which has a slower time scale than the waves but influences the mean oceanic flow (Gargett and Grosch, 2014)
  - $T(\tilde{u}) << T(u') << T(\hat{u})$
- Example 2: Small scale turbulence and wave decay (Milgram, 1999)
  - $T(u') << T(\tilde{u}) << T(\hat{u})$

Langmuir turbulence



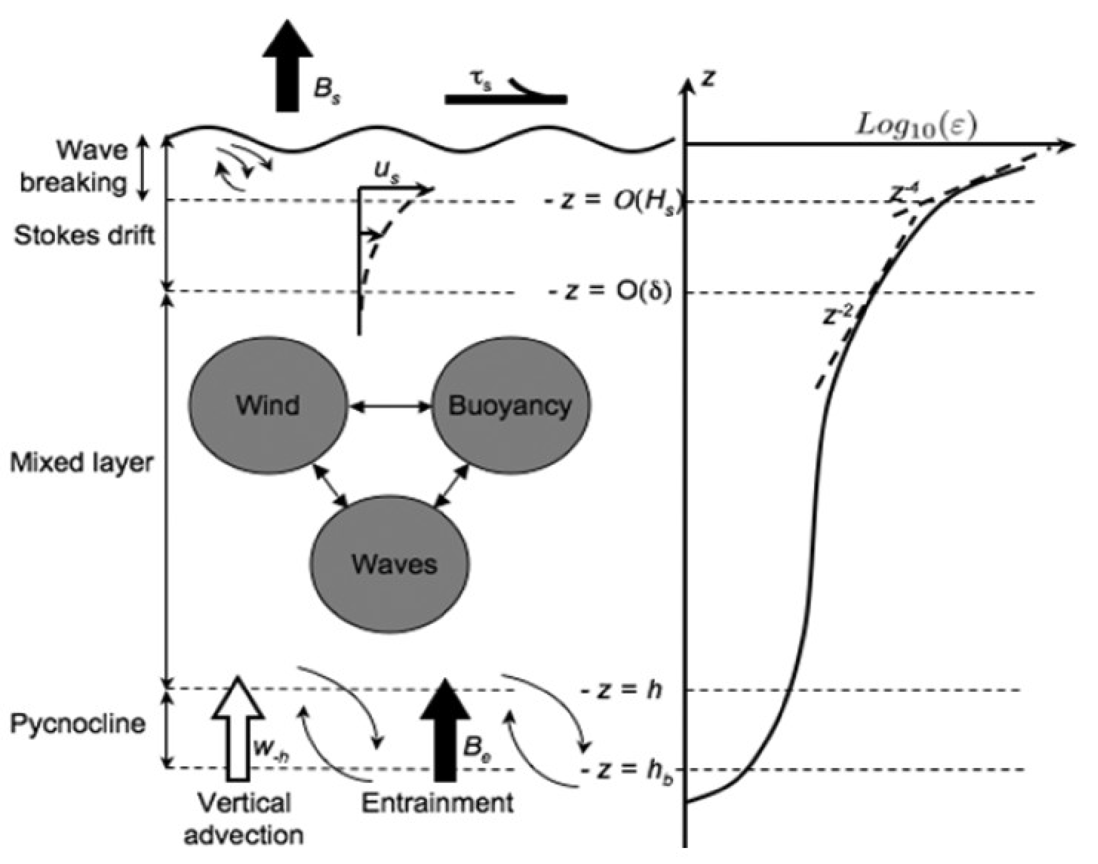
(Thorpe, 2004)



(Sullivan *et al.*, 2004)

Vertical length/velocity scales of LC turbulence

- In shallow water (Gargett *et al.*, 2004)
  - *L* = total water depth.
- In deep water without stratification (e.g. Polton and Belcher, 2007):
  - *L* ~ Ekman depth (assuming eddy viscosity scales as u_*^2/f).
- In deep water with stratification (e.g. Grant and Belcher, 2009):
  - *L* ~ mixed layer depth.
- Vertical velocity scale (see e.g. Gargett and Grosch, 2014):
  - w_* = (Stokes drift^2 x u_*)^1/3
  - w_* = (Stokes drift x u_*)^1/2



Some parameterizations are based on the mixed layer depth, e.g. Belcher *et al.* (2012) made a scaling of the turbulence dissipation rate based on LES results.

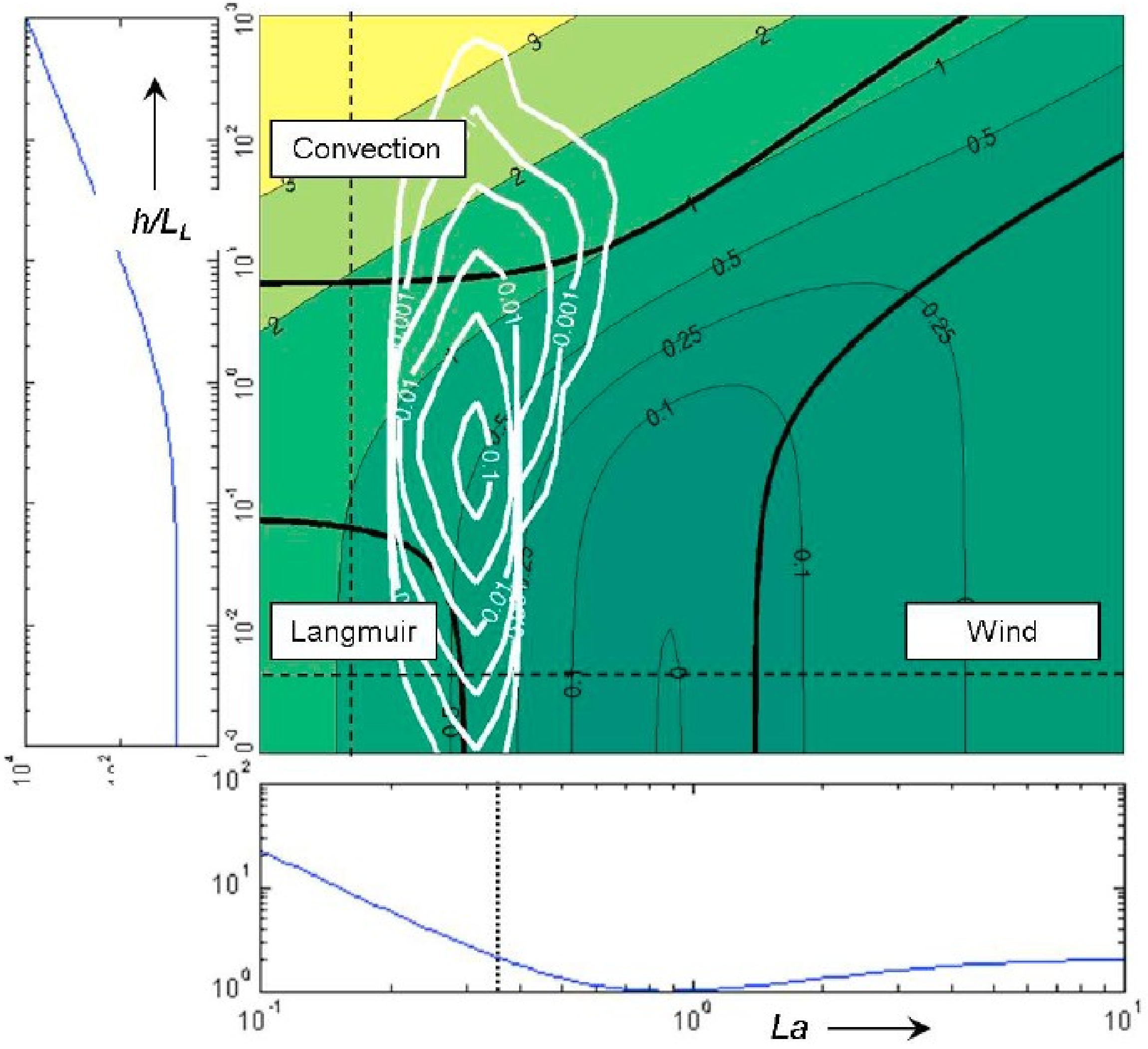
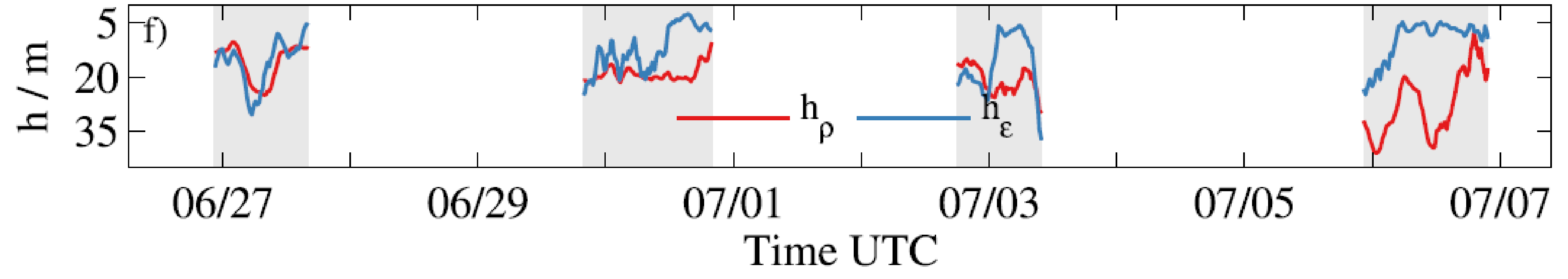
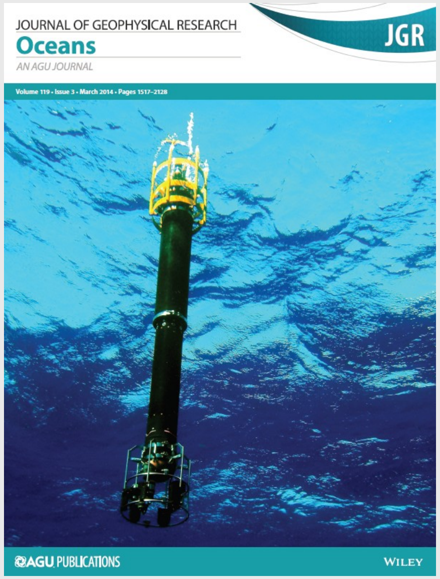


Figure 3. Regime diagram for mixing in the OSBL. Main panel: Colored contours show turbulent dissipation rate, $\log_{10}(\varepsilon h/u_*^3)$. Thick solid lines divide the regime diagram into regions where single forcings produce greater that 90% of total dissipation. Overlaid as white contours is the joint pdf of La and h/L_l computed for the Southern Ocean winter (JJA). Lower panel: Variation of $\varepsilon h/u_*^3$ with La along horizontal dashed line in main panel. The dotted line on the lower panel indicates $La = 0.35$, the value used in Figure 4. Left panel: Variation of $\varepsilon h/u_*^3$ with h/L_L along vertical dashed line in main panel.

(from Belcher *et al.*, 2012)

(from Sutherland *et al.*, 2014)





Distinction between *mixed layer* (already well mixed) and *mixing layer* (actively being mixed)

Mixed layer (MLD)

Mixing layer (XLD)

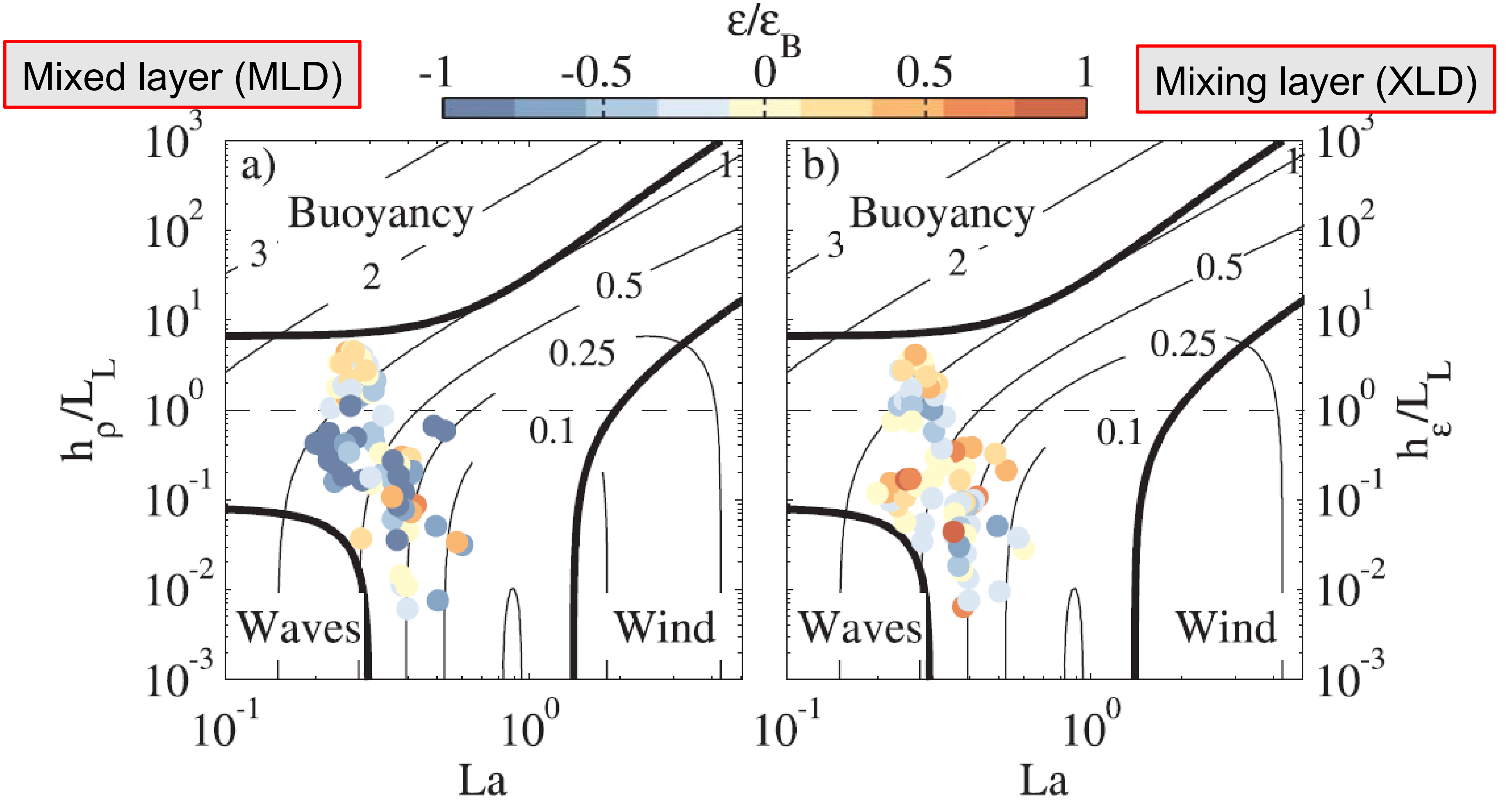


Figure 3. Measured values of ϵ at $z=h/2$ normalized by the dissipation of B12 (ϵ_B) using the (a) mixed layer depth h_ρ and (b) mixing layer depth h_ϵ for the turbulent length scale, respectively. The black lines show the contours for $\log_{10}\epsilon_B$ from equation (4) with the heavy black lines denoting where a single forcing accounts for 90% of the total dissipation. The dashed black line shows the $h/L_L=1$ threshold chosen to separate the buoyancy regime from the wind-wave regime.

(from Sutherland *et al.*, 2014)

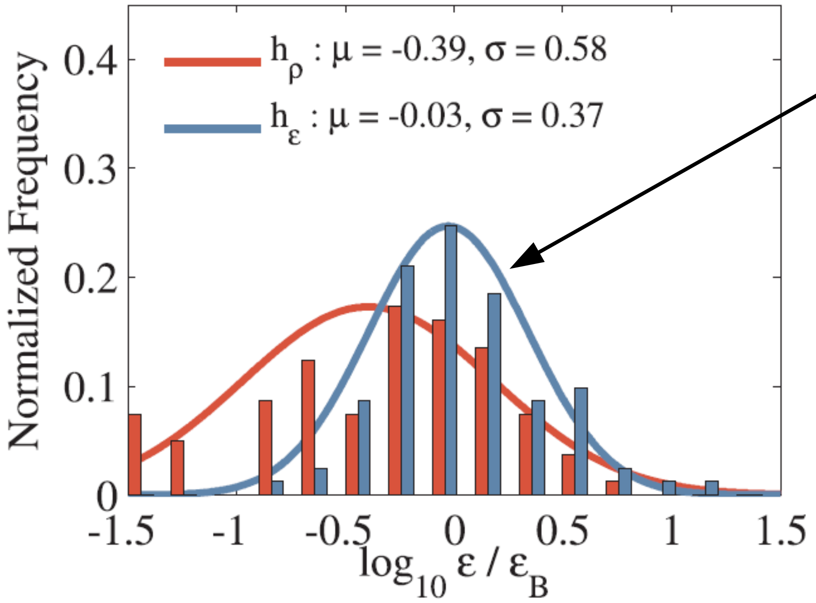


Figure 4. Histogram of $\log_{10}\epsilon/\epsilon_B$ from Figure 3. The blue and red lines denote the Gaussian curve calculated from the mean μ and standard deviation σ for the h_ρ and h_ϵ cases, respectively.

Parameterization works if the MLD is substituted with the XLD.

We have a problem if wave mixing parameterizations based on model state variables fail. More research is needed.

Transport of buoyant particles

(from Drivdal *et al.*, 2014)

- Balance between rise velocity and turbulent downward mixing (Sundby, 1983).
- In addition we have advection by Stokes drift and modifications to the Ekman current due to waves.
- Correctly modeling the vertical distribution is crucial (more on that later on).

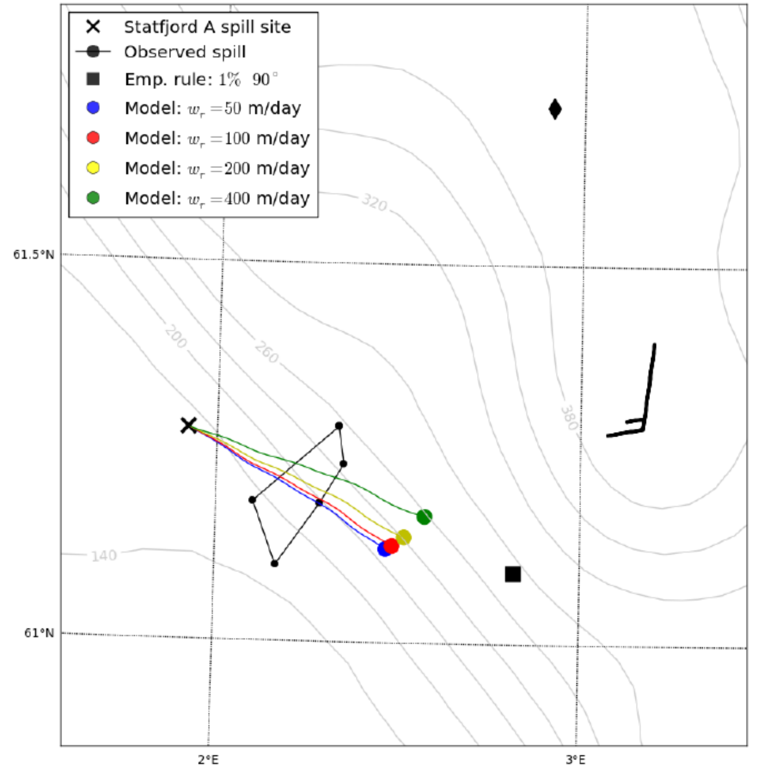


Figure 11. Mean location of oil predicted by the model for different rise velocities of the particles. The model is initialized with particle concentrations evenly spread in the water column. Also shown is the mean locations predicted by empirically based relations between the drift and the mean wind vector. The observed oil slick is shown with coordinates from observation (14 December 2007 13:48 UTC) connected with lines.

Outstanding issues

- Understanding the vertical structure of oceanic turbulence is crucial, and progress cannot be made unless more detailed measurements become available. This includes (at least)
  - air-sea turbulent momentum and heat fluxes
  - 2D wave spectra
  - hires upper ocean Eulerian mean currents
  - hires upper ocean stratification
  - upper ocean turbulence dissipation rates
- Measuring the impact on buoyant tracers is useful since they rise to the surface unless actively being mixed down (cf. MLD vs. XLD).
- Vertical profiles of buoyant tracers are difficult to obtain, but there is maybe some hope in new acoustic techniques (more on that later on).

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