

Air-Sea Turbulent Fluxes and Upper-Ocean Currents during the TURBORADAR-TURBIDENT Experiments

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EGU2019-14294

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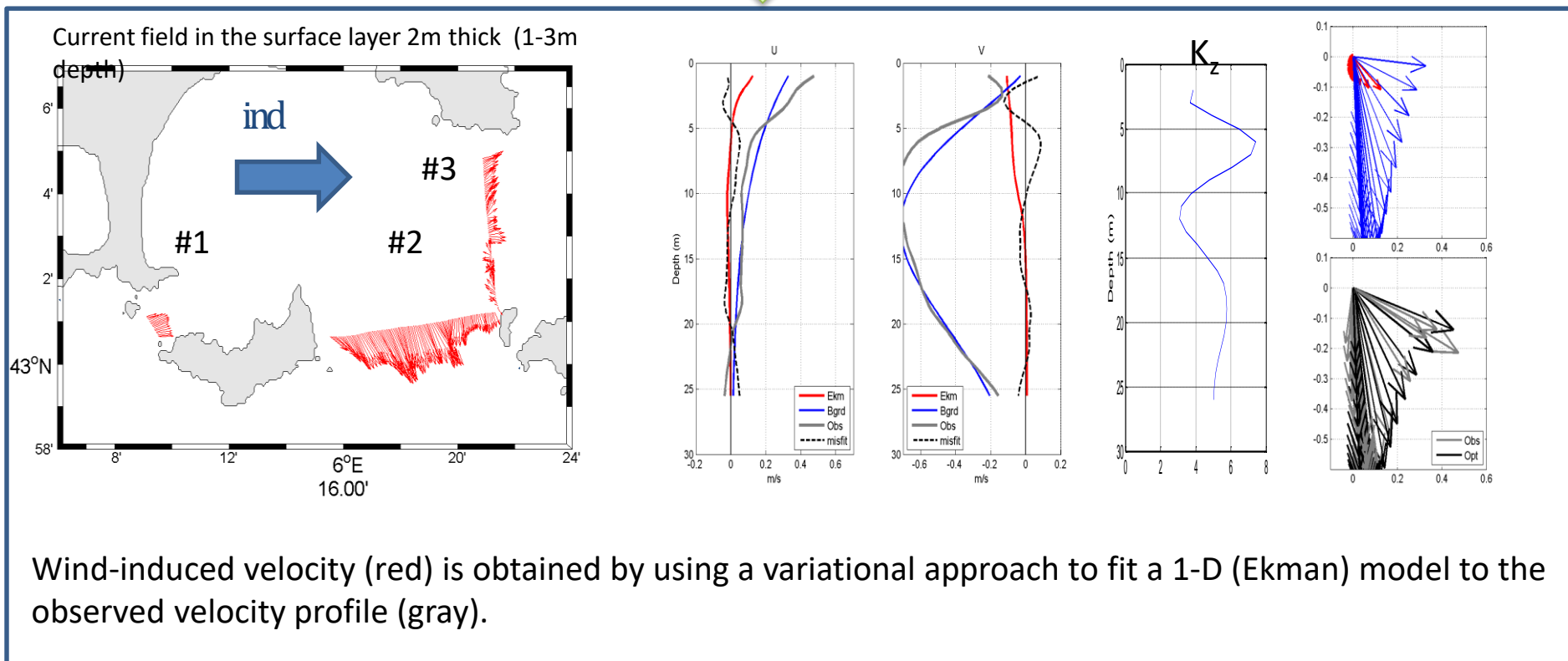
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The TURBORADAR and TURBIDENT experiments are devoted to the study of

- The circulation and the properties of a region of the **NW Mediterranean** in response to **strong wind events (mistral)**
- Eddy diffusivity coefficients in the mixed layer
- Surface current shear, from an array of ground-based HF RADARs

Surface currents, subsurface circulation, and thermal configuration **were already documented in the poster EGU 2019-13256** : Identification of eddy viscosity profile in the marine surface layer in transient wind conditions, by P. Fraunié et al. (fraunie@univ-tln.fr)

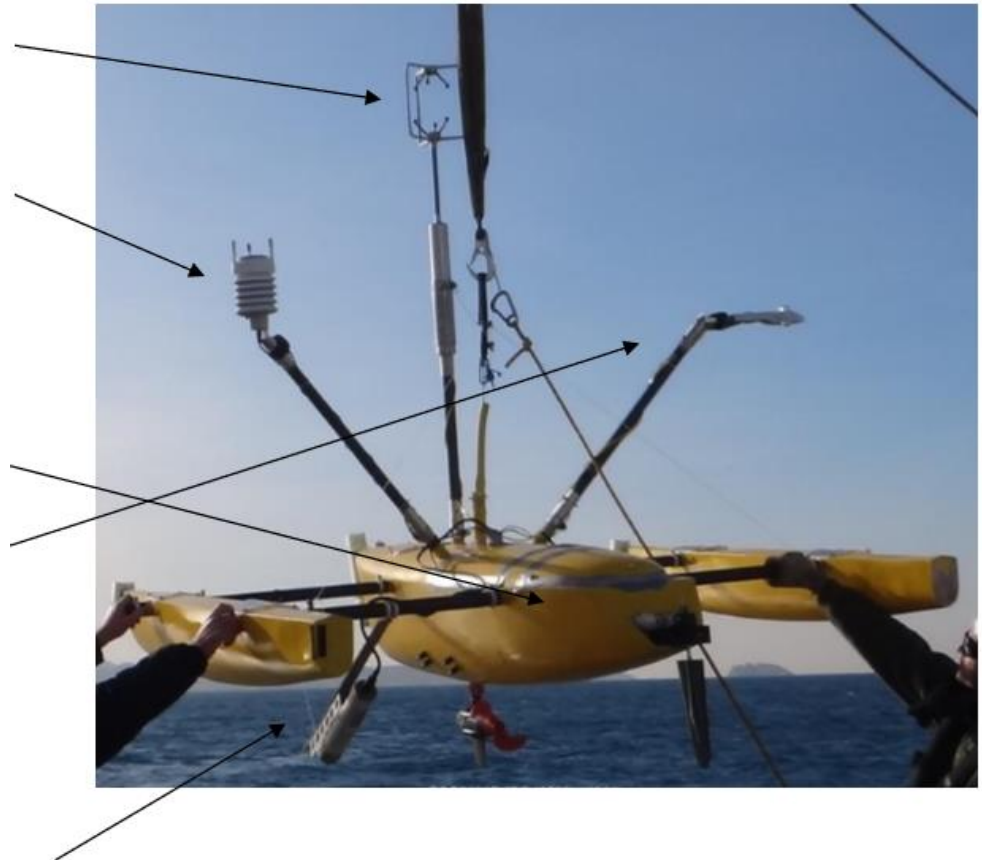


This talk focuses on OCARINA data, a surface drifting and **wave-following platform** dedicated to turbulent **air-sea flux** measurements in the wave-boundary layer.



- Wave-follower, 2m x 2m foot print, weight is 35 kg
- In operation since 2011 (Bourras et al. 2014)
<https://journals.ametsoc.org/doi/full/10.1175/JTECH-D-13-00055.1>
- Height of turbulence instruments is $h=1.6\text{ m}$, $k\zeta = 0.1$

- Gill R3-50 sonic anemometer (u,v,w+ sonic temperature) at 50 Hz
- Vaisala WXT-520 weather station (T,p,RH) at 1 Hz
- Xsens MTI-G IMU (accelerations, gyroscopes, GPS, magnetometers and barometer), at 50 Hz
- Campbell CNR4 pyranometer and pyrgeometer for upward and downward radiation fluxes
- Seabird SBE37-SI : Sea surface temperature and salinity



Issues addressed:

- Does it make sense to measure wind turbulence with a low-profile wave-following platform?
- How are the friction velocity (u_*) estimates modified in unsteady conditions?

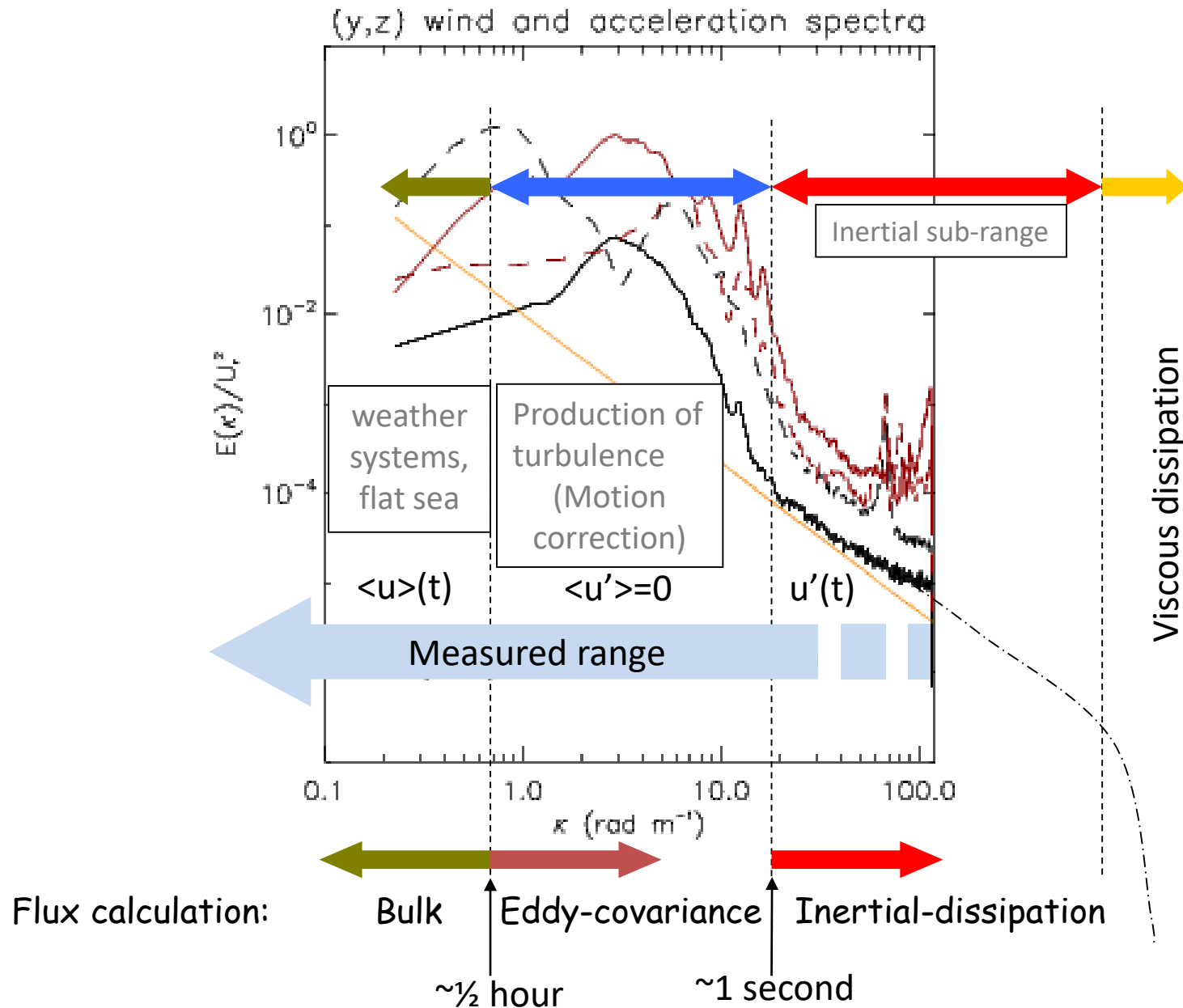
PART I: Required notions

- I.1 Wind spectrum: three separate frequency ranges
- I.2 Context of the Wave-Boundary Layer (WBL)

Air-sea turbulent flux calculation methods (classical view):

- I.3 Bulk (similarity, flux-gradient) $\tau/\rho = C_D \bar{U}^2 = u_*^2$
- I.4 Eddy-Covariance (EC) $\tau/\rho = \left(\overline{u'w'}^2 + \overline{v'w'}^2 \right)^{1/2}$
- I.5 Inertial-Dissipation (ID) K41: $\epsilon = \frac{2\pi}{U_r} \left(\frac{|E_U(f)|^2}{c} \right)^{\frac{3}{2}} f^{\frac{5}{2}}$
TKE: $u_* = (\kappa z \epsilon)^{\frac{1}{3}} (\phi_m(\zeta) - \zeta - \phi_{imb})^{-\frac{1}{3}}$

I.1 Wind spectrum vs scale



I.2 Measurements in the WBL

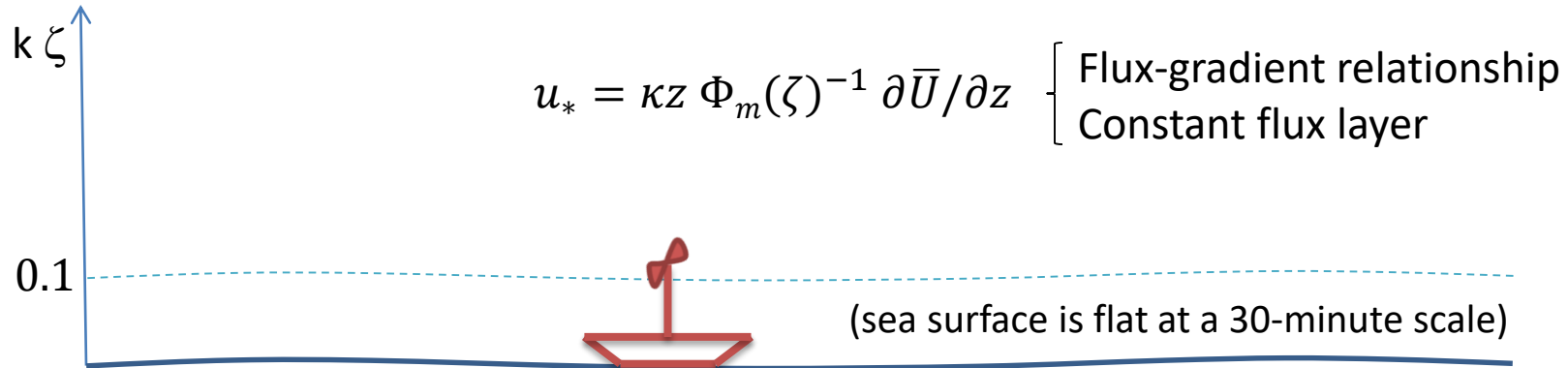
- Close to the surface,
 - the viscous dissipation ε decreases
 - the turbulent flux decreases
 - the wave-pressure term in the TKE equation increases
- Notion of total momentum flux = turbulent + wave-induced flux

Helpful references: a lot of material is borrowed from Hara & Sullivan (2015) hereafter:

- **Cifuentes-Lorenzen**, A., Edson, J.B. & Zappa, C.J. (2018). Air–Sea Interaction in the Southern Ocean: Exploring the Height of the Wave Boundary Layer at the Air–Sea Interface. *Boundary-Layer Meteorology*, 169: 461. <https://doi.org/10.1007/s10546-018-0376-0>
- **Edson**, J. B., Jampana, V., Weller, R. A., Bigorre, S. P., Plueddemann, A. J., Fairall, C. W., Miller, S. D., Mahrt, L., et al. (2013). On the Exchange of Momentum over the Open Ocean. *Journal of Physical Oceanography*, 43(8), 1589-610. <https://doi.org/10.1175/JPO-D-12-0173.1>
- **Hara**, T., & Sullivan, P. P. (2015). Wave Boundary Layer Turbulence over Surface Waves in a Strongly Forced Condition. *Journal of Physical Oceanography*, 45, 868-883. <https://doi.org/10.1175/JPO-D-14-0116.1>

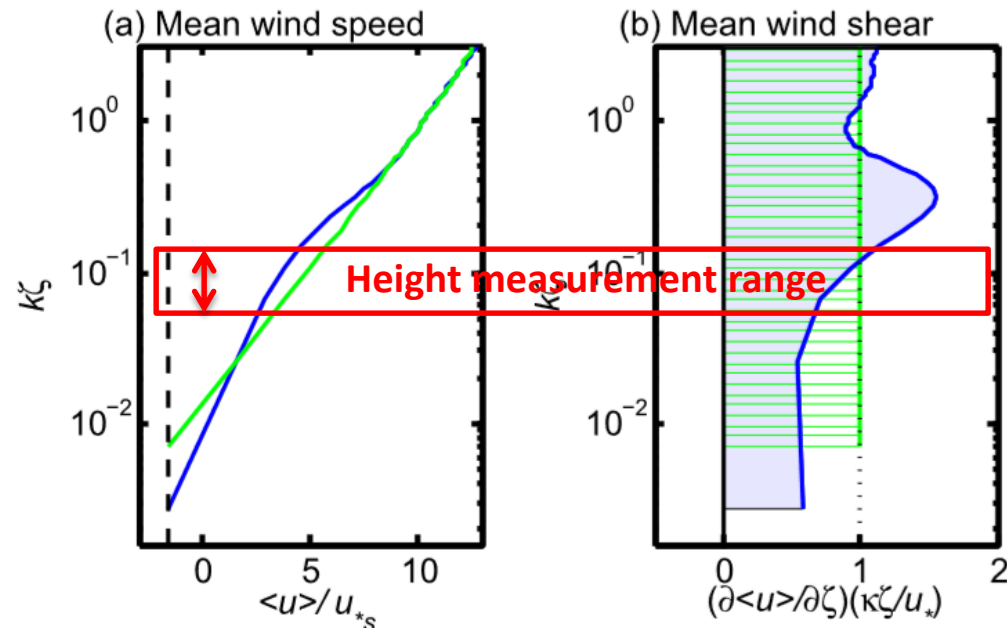
I.3 BULK estimation method

The mean values of \bar{U} and $\partial\bar{U}/\partial z$ may be impacted in a worst case scenario



In moderate wind & sea conditions, the bulk estimates of u_* should compare to measurements above the WBL, *i.e.* to 3-10 m height data (see slide 13)

Figure on the right by Hara and Sullivan (2015)
LES simulations with **strong wind** forcing and **steep sine waves**.

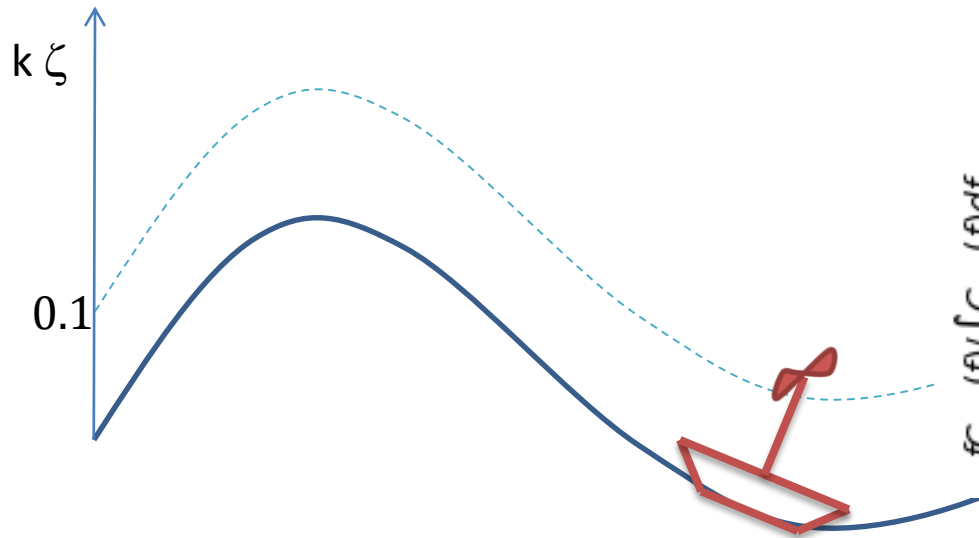


Green is similarity (constant shear)
Blue is LES results

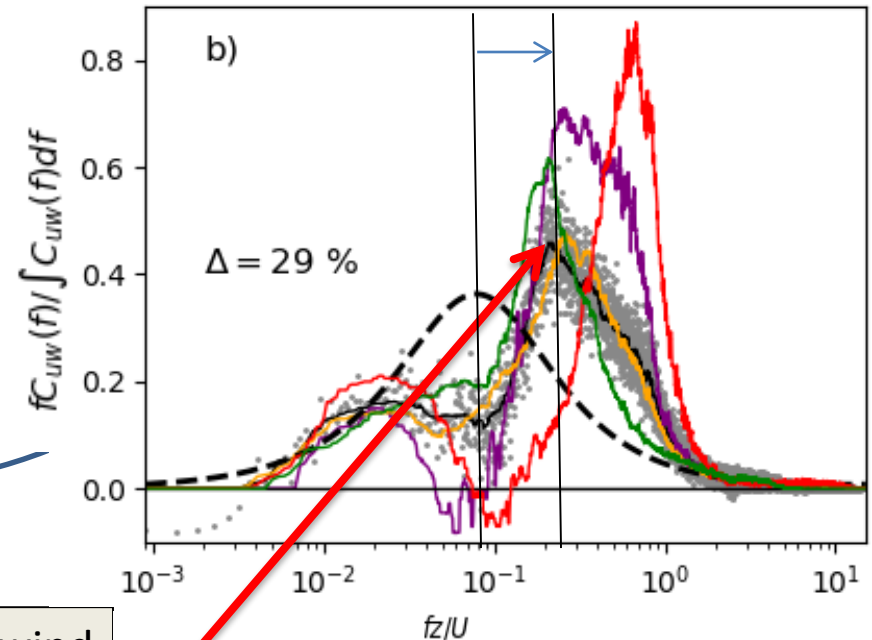
FIG. 2. Blue lines show (a) normalized mean velocity $\langle u \rangle / u_{*s}$ and (b) normalized mean velocity shear $(\partial\langle u \rangle / \partial \zeta)(\kappa\zeta / u_*)$, plotted against normalized height $k\zeta$. Green lines show an extrapolation of the profiles with the normalized mean velocity shear set to be 1. Note that the area shaded in blue and the area with green hatches are approximately equal.

I.4 EC estimation method

With a wave follower, a **total stress** (turbulent + wave-induced) is measured
(Hara & Sullivan, 2015, p880)



Co-spectra from STRASSE 2012 data^(*)



Additional remarks :

- Motion correction for the vertical wind component w is **required or not**, depending on wave steepness^(*)
- The co-spectrum maximum peak may occasionally be **shifted toward large values of fz/U** , suggesting that Kaimal (1972) normalization may have to account for wave characteristics^(*)

- Averaged co-spectrum
- Filtered averaged SC co-spectrum
- Filtered averaged DS co-spectrum
- Filtered averaged non-corrected co-spectrum
- - - Kaimal (1972)

Unstable ($Rb < -0.015$) in red
Neutral ($|Rb| < 0.008$) in green
Stable ($Rb > 0.01$) in blue

^(*) Bourras et al. (2019, in revision at JGR Oceans)

1.5 ID estimation method

Dissipation of turbulence ε is **reduced** close to the surface.

- If $\phi_{imb} = 0$ then the turbulent stress is estimated
- if $\phi_{imb} = 0.4$ then the total flux is retrieved (wave-pressure term in the TKE equation)

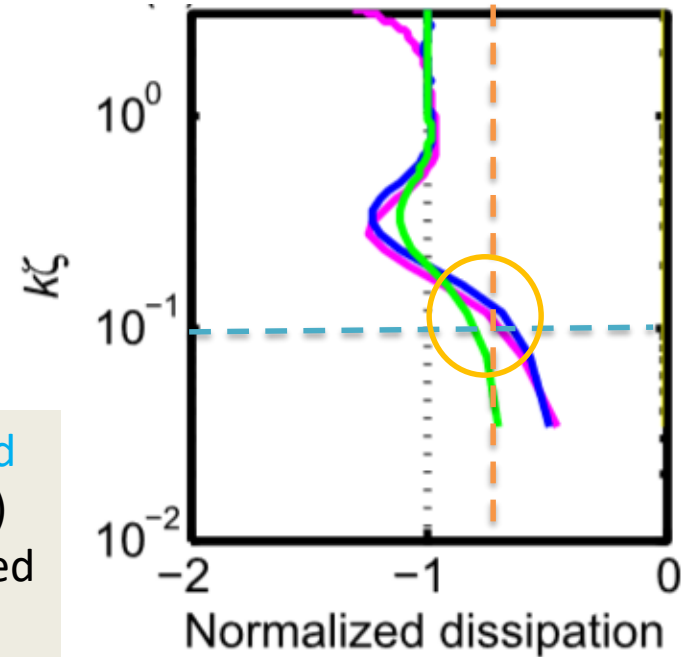
$$\text{K41: } \varepsilon = \frac{2\pi}{U_r} \left(\frac{|E_U(f)|^2}{c} \right)^{\frac{3}{2}} f^{\frac{5}{2}}$$

$$\text{TKE: } u_* = (\kappa z \varepsilon)^{\frac{1}{3}} (\phi_m(\zeta) - \zeta - \phi_{imb})^{-\frac{1}{3}}$$

If $\phi_{imb} = 0$, the ID u_* estimates (derived from the **wind variance frequency spectrum** in the inertial sub-range) correspond to **pure turbulence**: they are underestimated compared to EC estimates (*)



Wave-pressure term $\phi_{imb} = 0.4$ was evaluated on seven data sets (*)



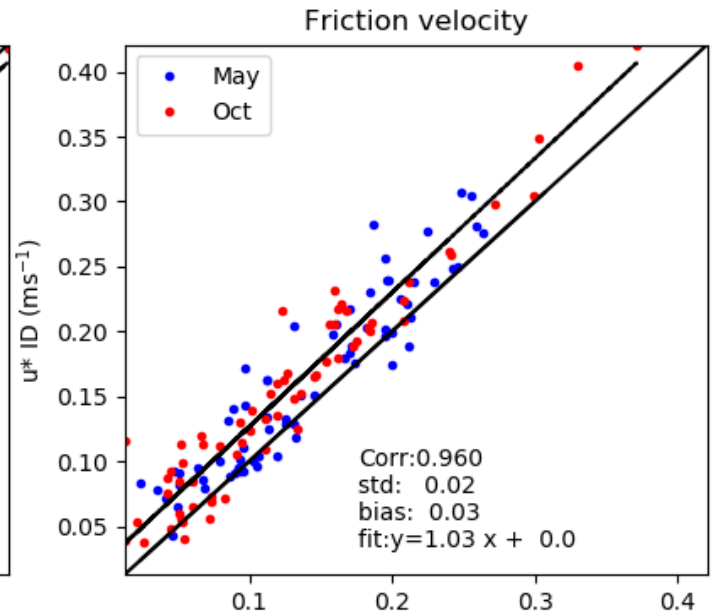
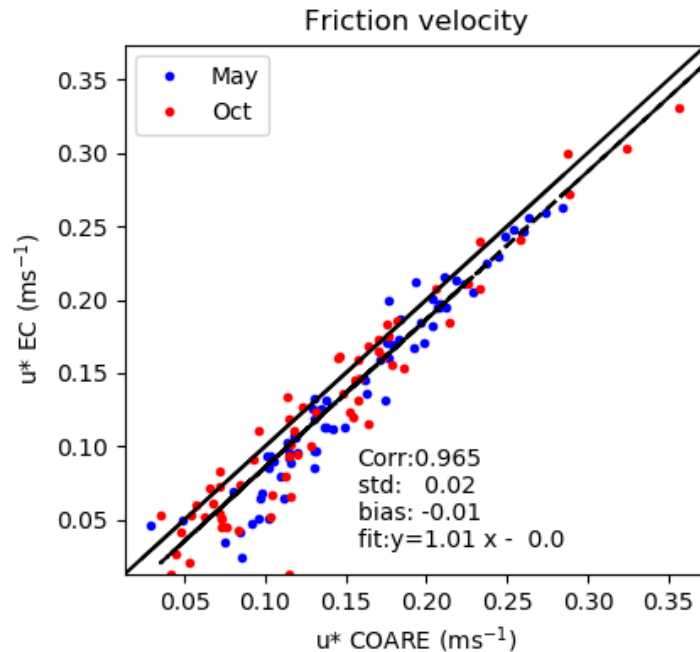
Above figure from Hara and Sullivan (2015)
Colored lines denote different parameterizations

(*) Bourras et al. (2019, in revision at JGR Oceans)

Proposed approach for qualifying turbulence data and justify what is measured : reconcile u_* estimates derived from EC, ID and bulk

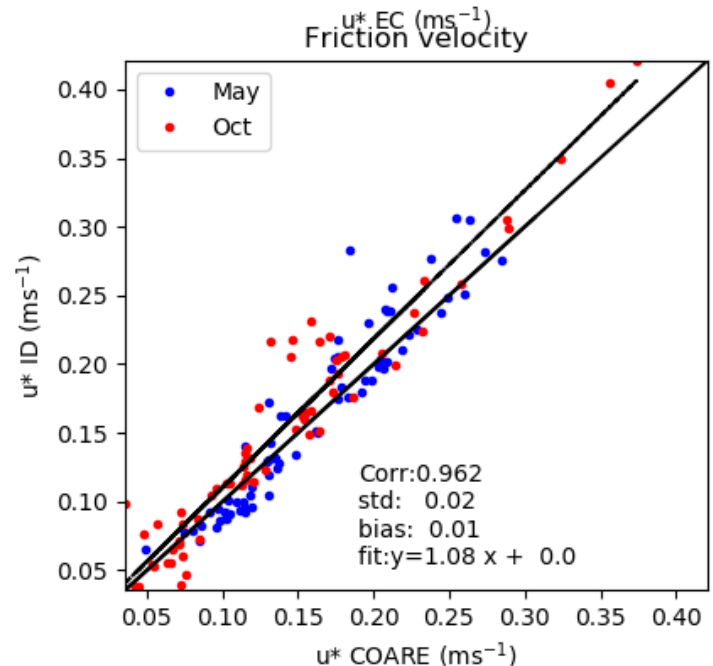
- **Application of the EC method:**
 - Our reference
 - Gives an estimation of the total stress
 - It is next used to
 - estimate the **imbalance term** in the TKE equation
 - find a parameterization of the **bulk drag coefficient**
- **Adjustment of the ID method:**
 - Gives the total stress (or just the turbulent part of the stress if no imbalance term is accounted for), or equivalently of the turbulent stress above the WBL.
- **Adjustment of the Bulk method:**
 - Drag coefficient can be compared to existing parameterizations

PART II.1: Results for TURBORADAR 2018 (u_* comparisons)



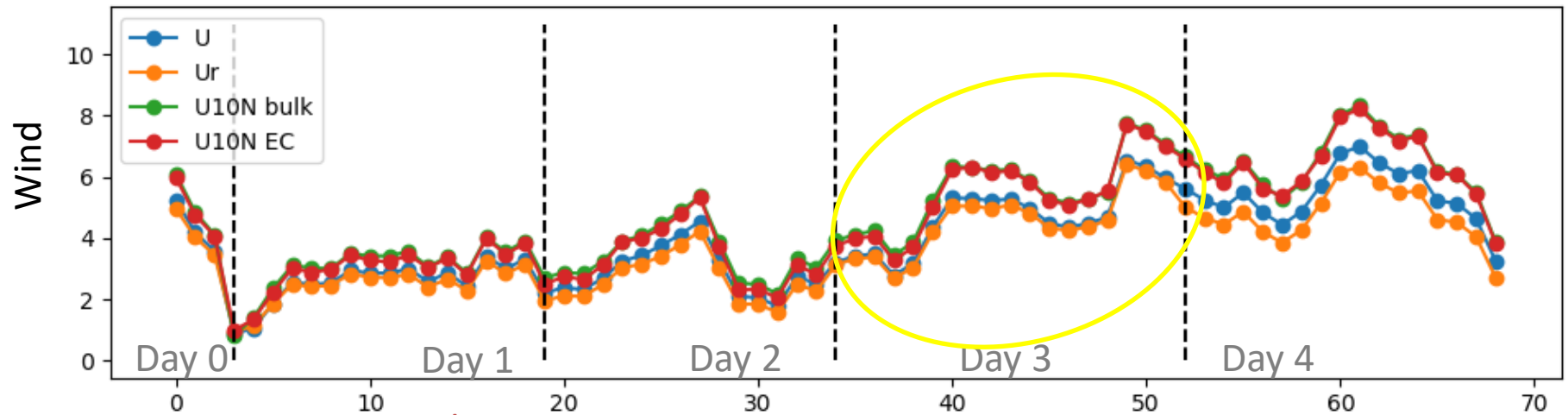
- ID : Adapted sub-range (1-3 Hz w/unsteady) and $\phi_{imb} = 0.4$
- EC : mean motion correction
- Bulk: z_0/CDN parameterization fitted to 7 years of data

Standard deviation of the difference is 2 cm/s (10 %)

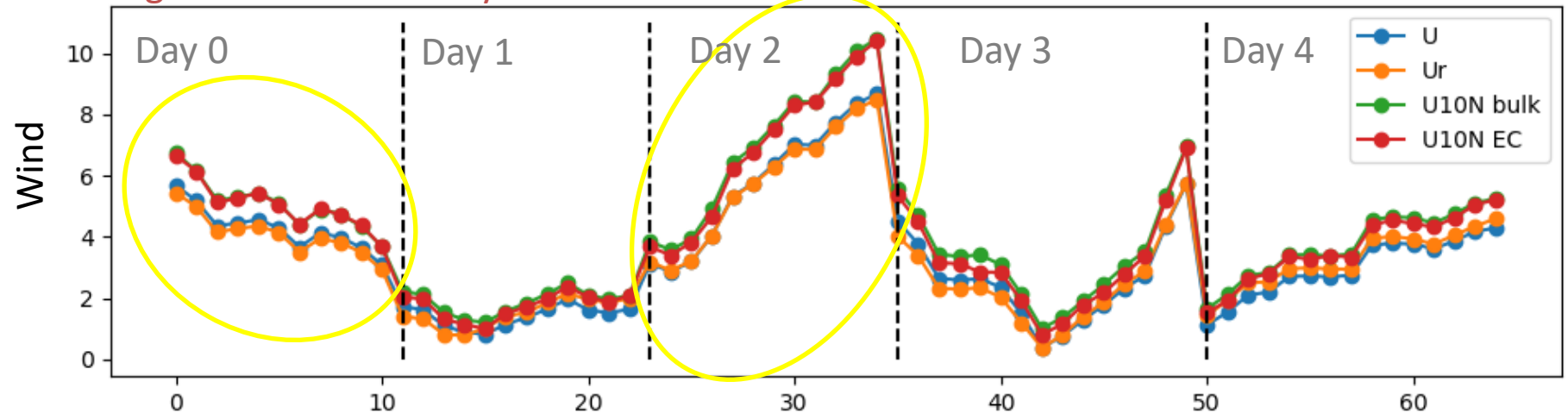


PART II.2: Unsteady conditions (Times series of wind)

Leg 1 : may 2018 : 5 days



Leg 2 : Oct 2018 : 5 days

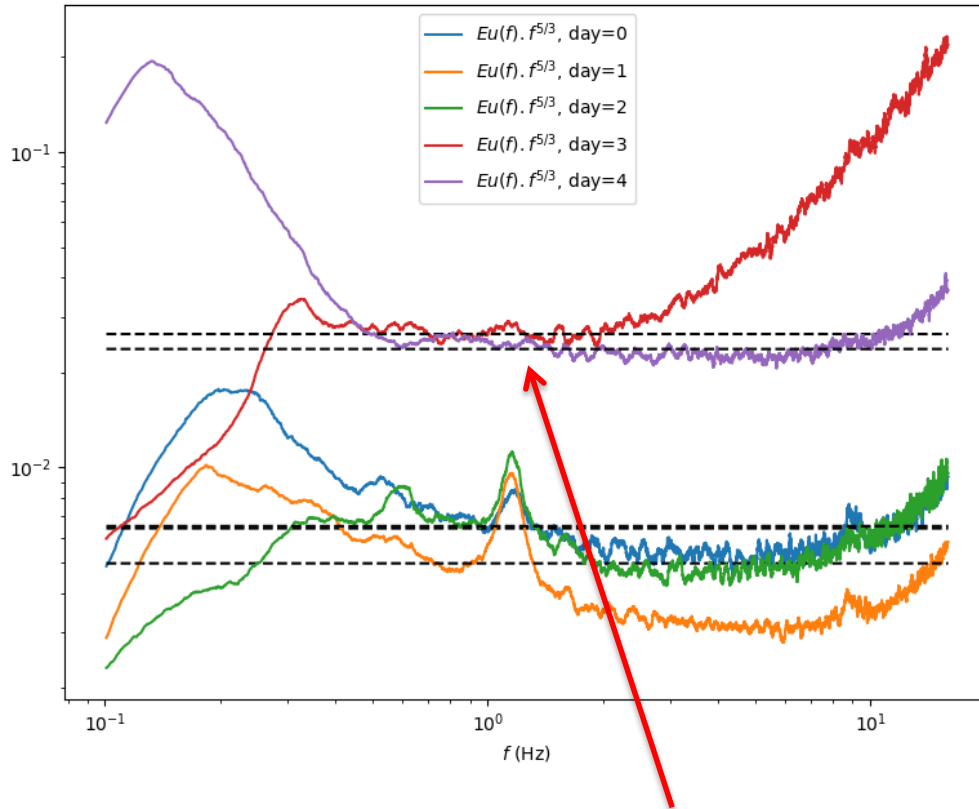


Time series (1 point is a 1 100 sec time average)

PART II.3: Unsteady conditions (Inertial sub-range)

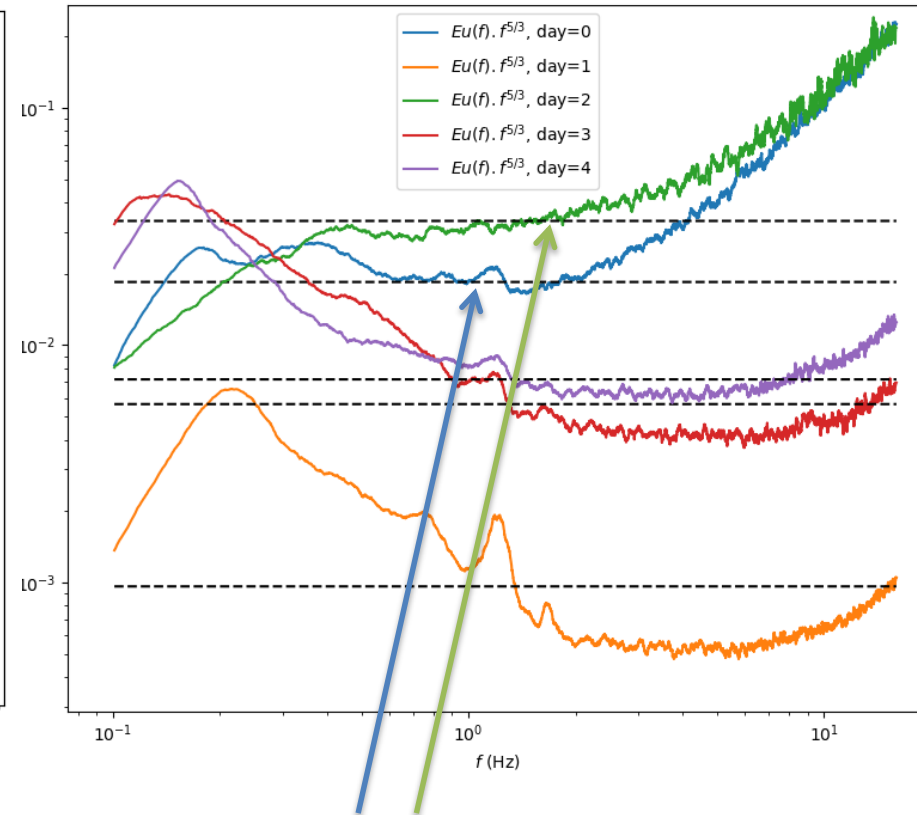
May 2018

Kolmogorov -5/3 slope check for longitudinal velocity



Oct 2018

Kolmogorov -5/3 slope check for longitudinal velocity

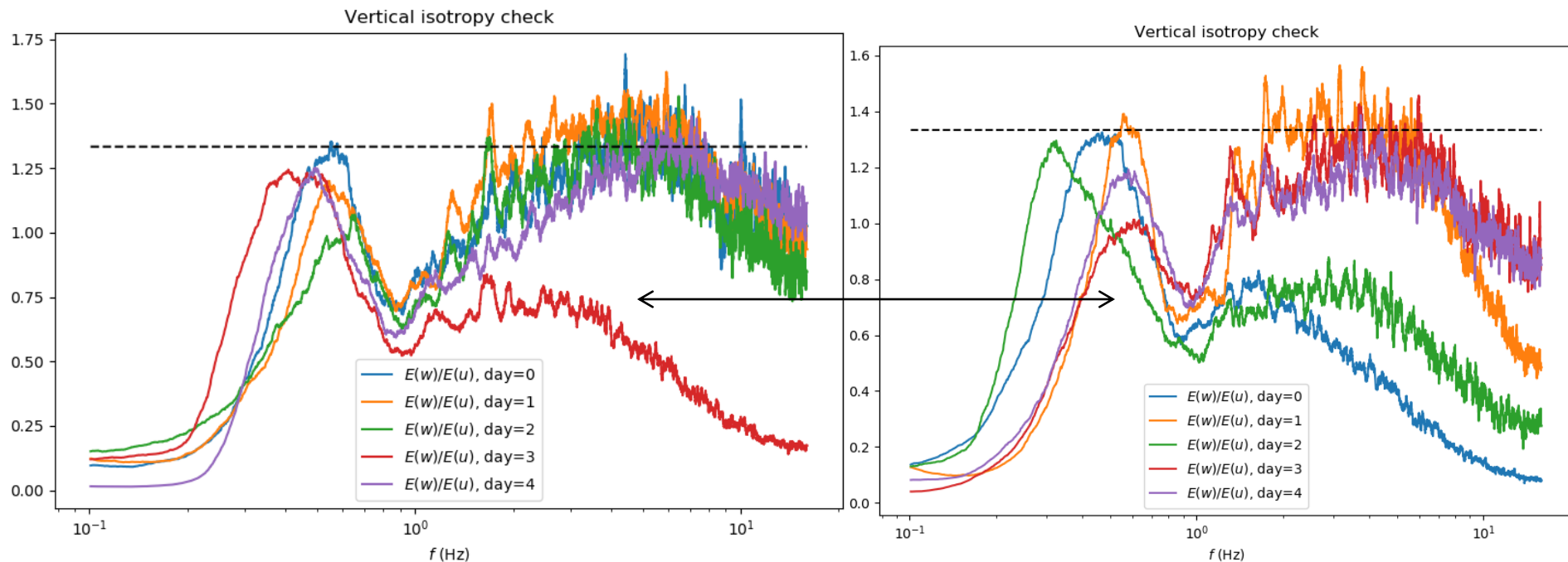


- The helpful part of the wind sub-range is in the range [3;6] Hz
- It is rejected toward smaller frequencies for day 3 (May) and days 0,2 (Oct)

PART II.4: Unsteady conditions (deviation to vertical isotropy)

May 2018

Oct 2018



- Isotropy in unsteady cases is ~ 0.7 in the inertial sub-range
- For the other days, it is close to the $4/3$ reference value

Conclusion

- A specific processing is required for our wave-following platform: wave-pressure term in the TKE equation ($\phi_{imb} = 0.4$), because dissipation rate is decreased close to the surface
- The agreement found between EC and adjusted bulk and ID u_* estimates is encouraging ($\sigma = 2 \text{ cm s}^{-1}$)
- The wind inertial sub-range and the mean value of vertical isotropy are modified in unsteady wind conditions
- More details in Bourras et al., Air-sea Turbulent Fluxes from Six Experiments with data from a Wave-Following Platform. JGR Oceans, in revision):
 - Evaluation of the dimensionless dissipation rate ($\epsilon \kappa z u_*^{-3}$)
 - New spectral and mean motion correction for the vertical wind component
 - Comparisons between drag coefficient, Charnock parameter, wave age, wave steepness, and wind module, in swell conditions

OCARINA Data from experiments before TURBORADAR are available at :
<https://www.seanoe.org/data/00486/59768/>

- Processed and raw data are already available for seven experiments
- TURBORADAR 2018 data available soon

<https://www.seanoe.org/data/00486/59768/>



SEANOE Sea scientific open data edition

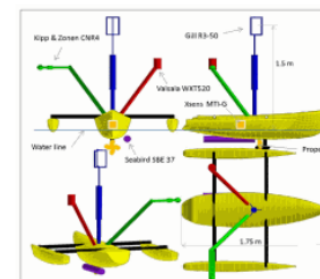
SEANOE

OCARINA (Ocean coupled to the atmosphere: instrumented research on an auxiliary ship)

Click
to download
the data

DATA

Date	2019-03-20
Temporal extent	2012-08-21 -2017-09-14
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DOI	10.17882/59768
Publisher	SEANOE



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