Can we link theory to observations in natural flows?

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PSI, 14 February 2017

ÉCOLE POLYTECHNIQUE
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CV in one slide

What	When
Batchelor in Chemistry (Uni Trieste, IT)	2001-2005
Internship at INOGS (IT)	2005
Master in Physics (Uni Trieste, IT)	2005-2008
Internship at Elettra Synchrothron (IT)	2008
PhD at KNMI/Uni Utrecht (NL)	2009-2013
Post-doc at NIOZ (NL)	2013-2016
Post-doc at EPFL (CH)	2016-2018

- 17 peer-reviewed papers and proceedings
- Lots of (open-source) software
- Several datasets collected
- Conferences, workshops (EGU, Euromech,...)
- Summer schools: DAMTP Cambridge, Alpine Summer School

Turbulence and internal waves in geophysical flows

- Can we link theory to observations?

An overview of my work at NIOZ and EPFL

A statistical perspective on fluid motions

Context: Increasing *amount* and *quality* of observational data.

Opportunity to obtain a *"statistical"* description.

- Focus on full dataset instead of single events.
- In practice: spectra, structure functions, PDFs, PCA,…

A statistical perspective on fluid motions

Statistics of temperature, velocity,...

- scale-dependence of variability;
- intermittency (e.g., time/space dispersion of turbulence events);
- hints on underlying physical mechanisms;
- identification of different regimes at different scales.

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Well-established field (IWs, turbulence):

- relatively well understood theory (single-process level);
- laboratory studies.

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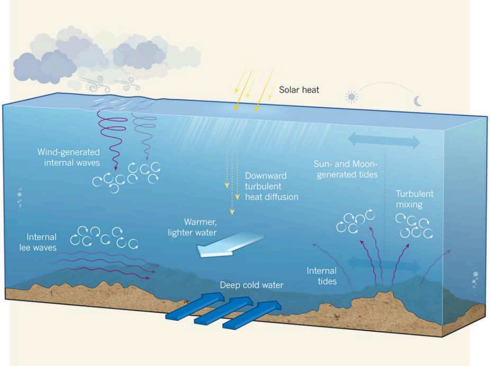
In the field:

- We cannot control what we observe in the field,
  - e.g. control parameters are variable / undefined.
- Statistics can help extracting information from “noisy” data.

Turbulent transport in the deep ocean (NIOZ)

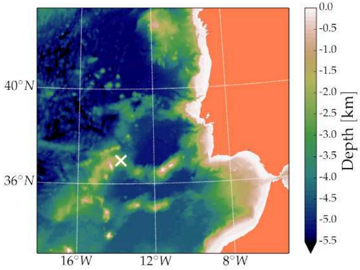
- Vertical transport in the ocean interior is poorly understood
- Hypothesis of mixing "hot-spots" with sloping bottom
- Sparse observations, poorly understood dynamics



MacKinnon, 2013

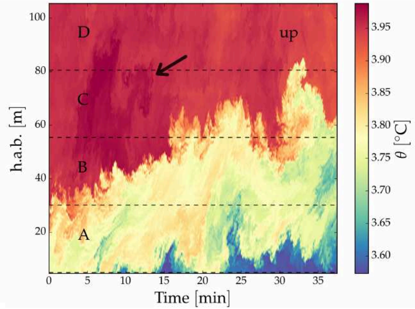
Data

Latitude	36° 58.885′ N
Longitude	13° 45.523′ W
Max. depth	2205 m
Min. height above seafloor	5 m
Seafloor slope	9.4°
Number of sensors	144
Vertical spacing	0.7 m
Depth range	100.1 m
Deployment	13 Apr 2013
Recovery	12 Ago 2013
Sampling rate	1 Hz

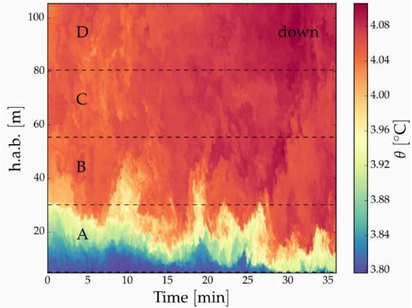


Data

Cooling phase (upslope)



Warming phase (downslope)



Generalised structure functions (GSF)

GSFs provide a way to characterise variability in a flow:

$$\gamma_q \equiv \gamma_q(r) = \left\langle |\Delta_r \theta|^q \right\rangle$$

So-called "scaling ranges" have been predicted by theory and observed in the laboratory:

$$\gamma_q \sim r^{\zeta(q)}.$$

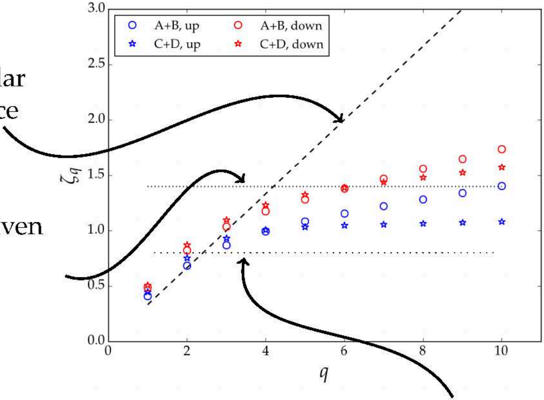
- $\zeta(q) = q/3$ if turbulence were fully self-similar (non-intermittent), for r within the "turbulence inertial range".
- In reality, $\zeta(q) = \zeta_\infty$ for $q > 10$ (*saturation*):
  - Grid turbulence, shear driven $\rightarrow \zeta_\infty \approx 1.4$
  - Convective turbulence, buoyancy driven $\rightarrow \zeta_\infty \approx 0.8$

Generalised structure functions (GSF)

...many steps afterwards...

Scaling exponent within the turbulence inertial range.

Self-similar turbulence



Shear-driven ζ_∞

Convective ζ_∞

Generalised structure functions (GSF)

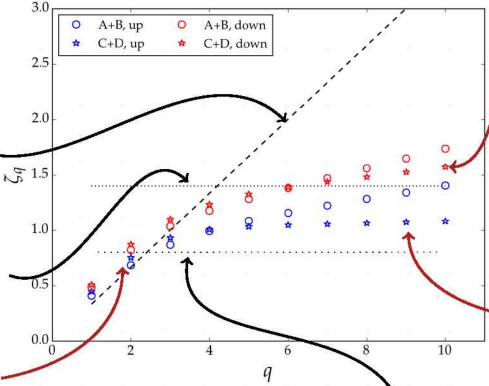
...many steps afterwards...

Scaling exponent within the turbulence inertial range.

Self-similar turbulence

Shear-driven ζ_∞

Low-order deviations

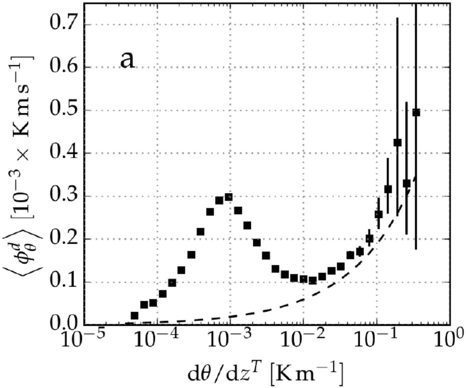


No saturation, above shear-driven ζ_∞

Saturation

Convective ζ_∞

Flux–gradient relation



Long-term averaging enables to identify simple *mean* behaviour in an otherwise highly variable environment.

Conclusions I

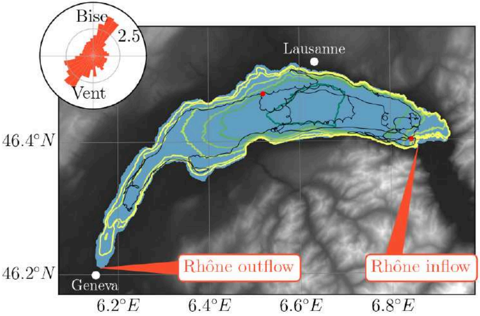
Evidence of convection in field observations

- Previously hypothesised, but hard to measure.
- Implications for efficiency of turbulent transport:
  - Implications for transport of heat, CO_2, nutrients,…
- Generalised structure functions enable to identify points of contact between laboratory and field results…
- …and discrepancies!
- *Much more not shown here.*

- A. A. Cimatoribus and H. van Haren. Temperature statistics above a deep-ocean sloping boundary. *J. Fluid Mech.*, 775:415–435, 2015.
- A. A. Cimatoribus and H. van Haren. Estimates of the temperature flux–temperature gradient relation above a sea floor. *J. Fluid Mech.*, 793:504–523, 2016.

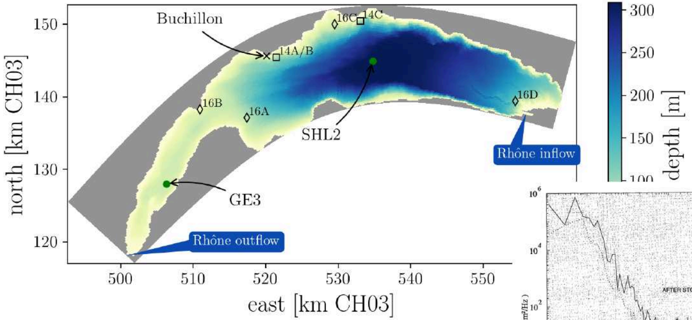
Transport in coastal areas (EPFL)

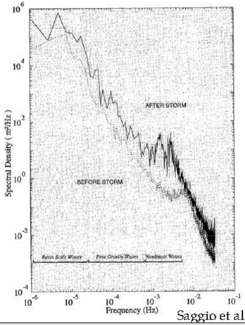
- In a linear, rotating flow, cross-isobath velocity is zero.
- How does cross-shore transport take place?



Velocity spectra

Lake Geneva





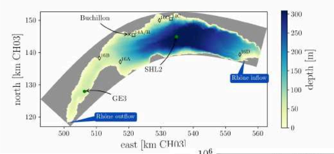
Saggio et al., 1998

"Standard" interpretation of observations:

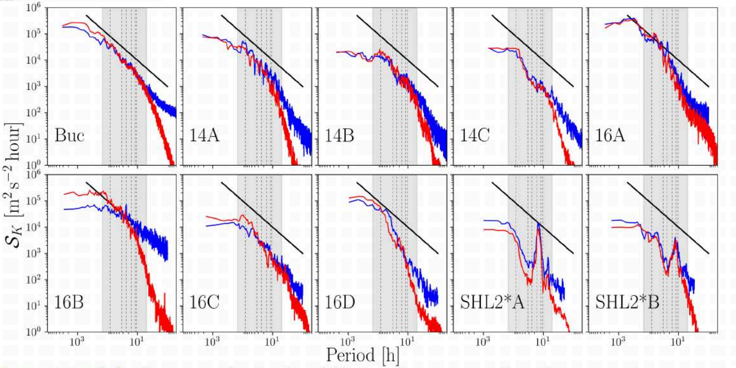
- combination of long internal waves (seiches)
- linear or weakly nonlinear

Velocity spectra

Lake Geneva



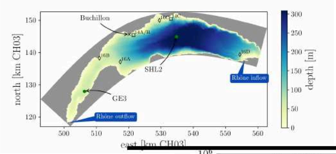
Kinetic energy spectra



Observations, model, slope = -1, dashed lines: linear modes frequencies

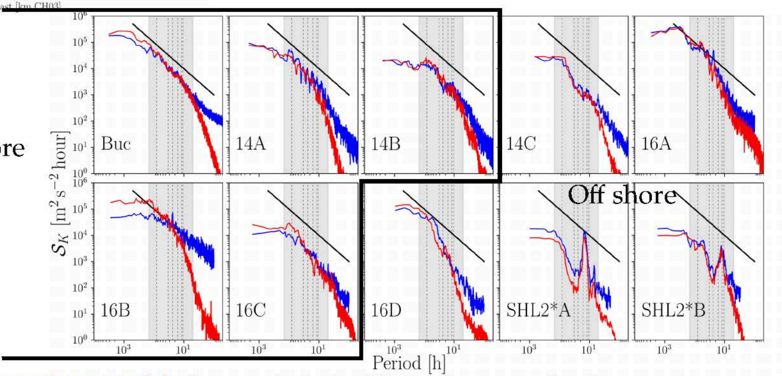
Velocity spectra

Lake Geneva



Kinetic energy spectra

Near shore



Observations, model, slope = -1, dashed lines: linear modes frequencies

Conclusions II

Nonlinearity cannot be neglected.

- Linear models predict sharp spectra, which are only observed off-shore,
  - or by considering short time intervals
- Broad spectra from longer time series suggest strongly nonlinear dynamics (more “turbulence”-like)
  - Confirmed by numerical modelling results.
- Classical tools like PCA, struggle to capture relevant dynamics in the highly variable, strongly forced, Lake Geneva.

- Andrea A. Cimatoribus, U. Lemmin, D. Bouffard, and D. A. Barry. Nonlinear Dynamics of the Nearshore Boundary Layer of a Large Lake (Lake Geneva). *J. Geophys. Res. Oceans*, in press, 2018.

Conclusions

- Field observations are growing in size and quality.
- A statistical description allows testing theories in a natural (uncontrolled) environment,
  - whose overall, mean behaviour is usually the most interesting one.
- Sometimes, statistical quantities can surprise:
  - Simple behaviour out of highly turbulent environments
  - Nonlinear behaviour (instabilities? vortices?) in a low energy environment
    - from very common power spectra!

Thanks for listening.

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[La Palma, Islas Canarias]