Turbulence generation by large-scale extreme vertical drafts in stratified geophysical flows

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Extreme Vertical Drafts in Stratified Flows

Feraco et. al. (*EPL*, 2018 & 2021) have shown that the vertical component of the velocity field (*w*) exhibits in the Boussinesq framework a large scale intermittent behavior - in both space and time - in a range of Froude number (*Fr*) of geophysical interest, as recently observed in the mesosphere lower termosphere - MLT (Chau et al., *GRL*, 2021). Direct numerical simulations (DNS) of stratified turbulent flows with $0.01 < Fr < 0.3$ were found to develop systematically powerful vertical drafts that make the statistics of *w* strongly non-Gaussian at the large scale, with such extreme events being associated to unstable regions of the domain and enhanced small-scale mixing. This phenomenon can be interpreted as the result of the interplay of gravity waves and turbulent motions in a resonant regime of the governing parameters, where solutions of the vertical dynamics diverge much faster than in the analogous homogeneous isotropic case without stratification.

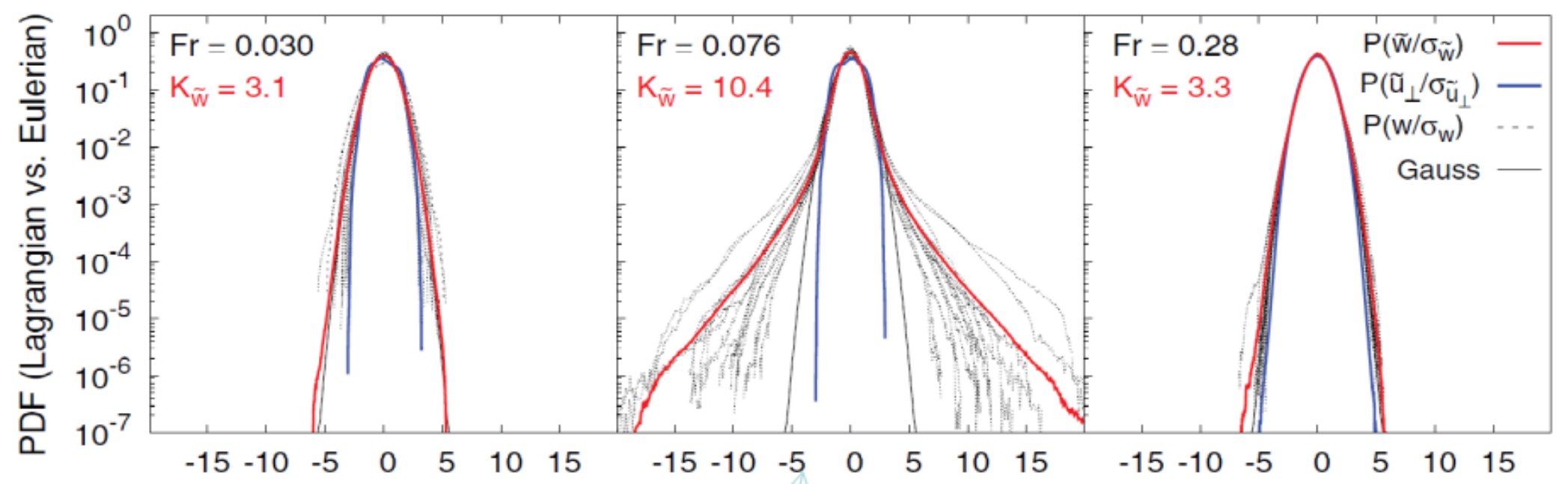
$$\partial_t \mathbf{u} + (\mathbf{u}\cdot\nabla)\mathbf{u} = -\nabla p + N\theta\hat{z} + \mathbf{F}_u + \nu\nabla^2\mathbf{u}$$

$$\partial_t\theta + \mathbf{u}\cdot\nabla\theta = Nw + \kappa\nabla^2\theta$$

τ_ν : **viscous time**

τ_{NL}: **non-linear time**

τ_{W_g}: **time associated to the Brunt-Vaisala freq. *N* (gravity waves)**



Run	P1	P2	P3	P4	P5	P6	P7	P8	P9
Re $[\times 10^3]$	2.4	2.6	3.6	3.8	3.8	3.8	3.8	1.2	0.8
Fr $[\times 10^{-1}]$	∞	2.8	1.1	0.81	0.76	0.3	0.26	0.76	0.71
R_B	∞	206	43.8	24.8	22.1	3.4	2.6	6.8	4.2
$\nu[\times 10^{-3} L_0 U_0]$	1.5	1	1	1	1	1	1	3	4
$N\ [U_0/L_0]$	0	1.5	5	7.37	8	20	23.5	7.37	7.37
t_{tot}/τ_{NL}	30	55	103	452	406	91	62	526	422

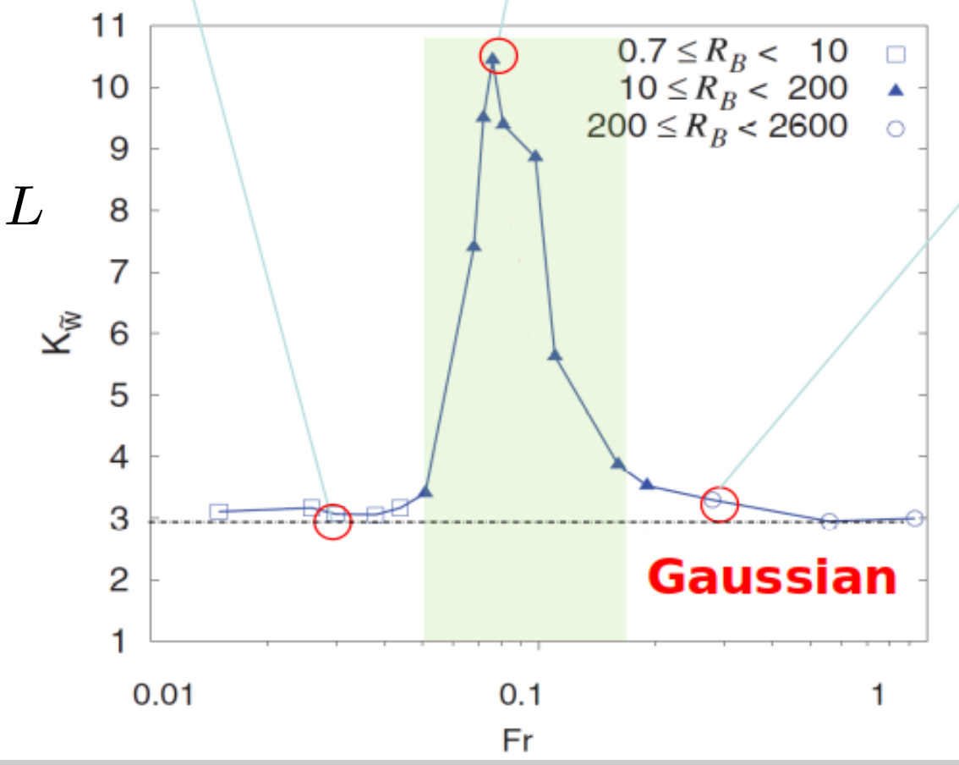
Tab. 1. DNS parameters. *N* is the Brunt-Vaisala frequancy and ν the kinematic viscosity.

Reynolds
$\mathrm{Re} = \tau_\nu/\tau_{NL}$

Froude
$Fr = \tau_{W_g}/\tau_{NL}$

Buoyancy Reynolds
$\mathrm{R}_B = ReFr^2$

Kurtosis of w: $\mathrm{K}_w = \frac{\langle w-\overline{w}\rangle^4}{\langle (w-\overline{w})^2\rangle^2}$

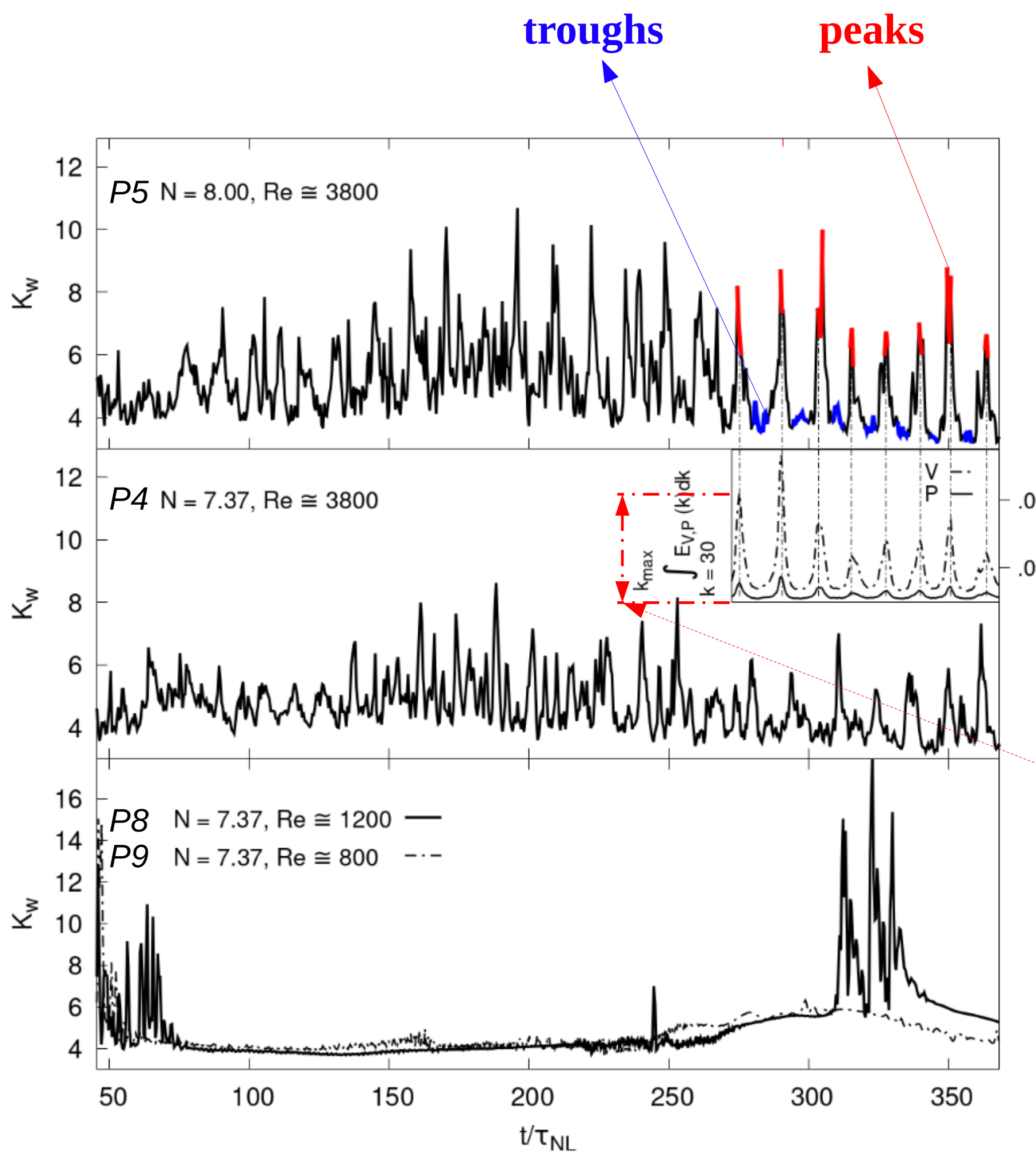


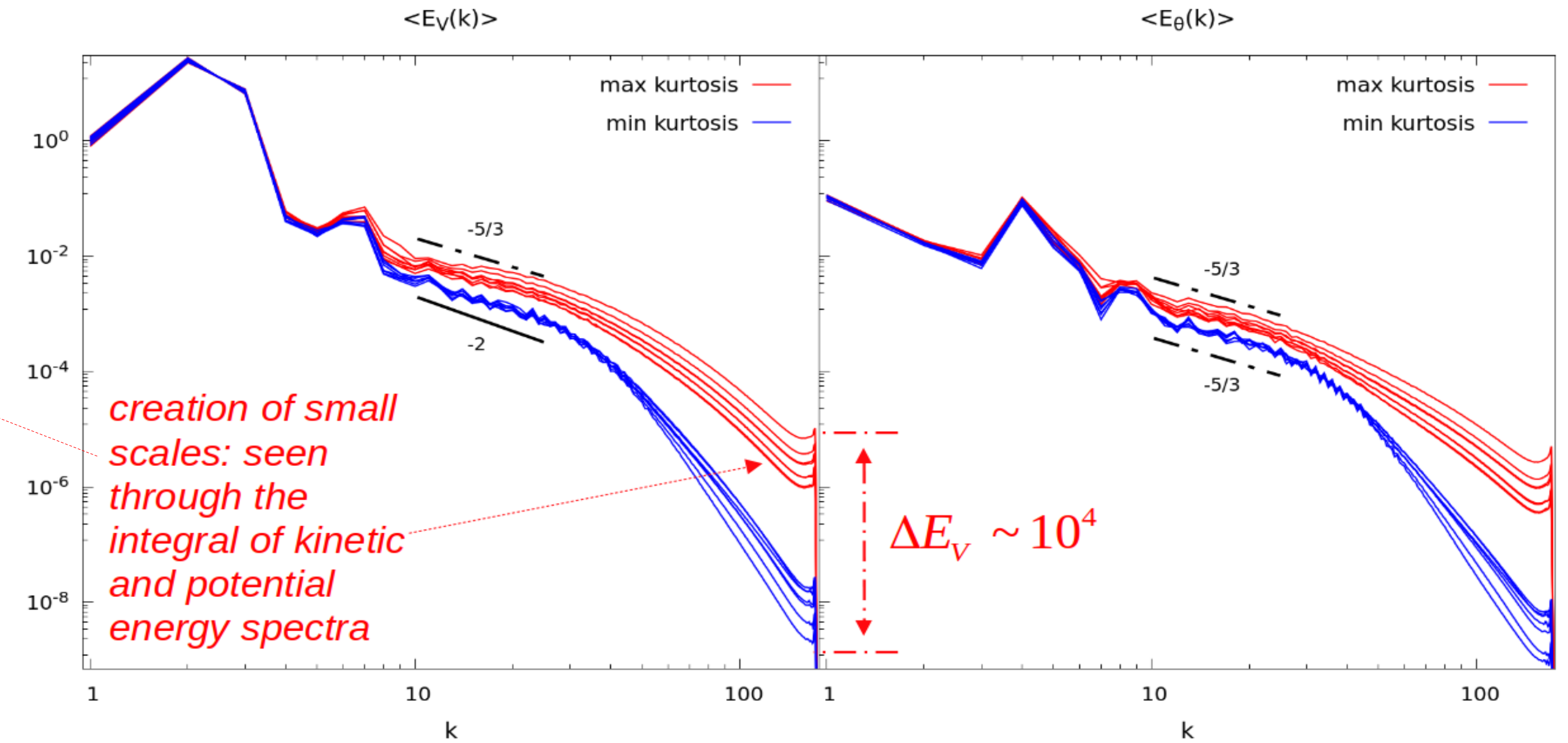
Feraco et al., *Europhys. Lett.*, 2018

Turbulence Generation by Large-Scale Intermittent Structures

In the present study a series of DNS of the Boussinesq equations (on grids of 512^3 pts, see **Tab. 1**), in the resonant regime of *Fr* identified by Feraco et al. (*EPL*, 2018). Here we provide first evidences of the generation of turbulence by the large-scale intermittent structures emerging in the vertical velocity (*w*). The system evolves under the action of a random forcing, isotropic in the Fourier space. The temporal evolution of K_w is characterized by the alternation "quite" regions, with values close to the Gaussian reference, and very "active" regions where K_w spikes up to ~ 11.

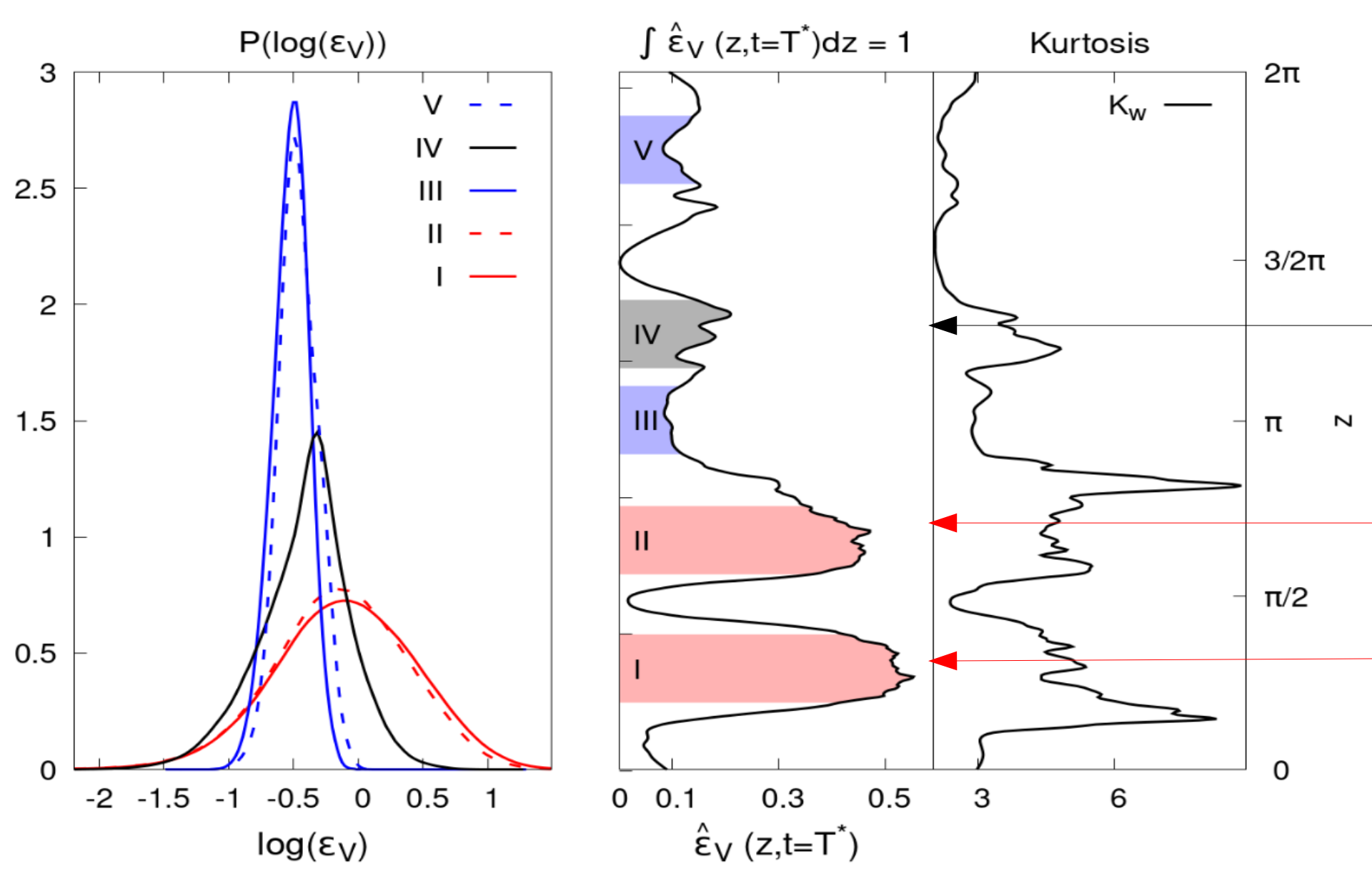
- Kinetic and potential energy spectra averaged over the indicated peaks and troughs show that in correspondence of the peaks of K_w, small (turbulent) scales are massively generated with a spectral redistribution of the kinetic energy compatible with a $k^{-5/3}$ slope in the inertial range (at intermediate scales).
- Conversely the spectra corresponding to the troughs are steeper and lower in magnitude for k>10, following a k^{-2} trend at the intermediate scale, with a much reduced spectral density at the smaller scales (up to four order of magnitude compare to the neighbor regions). The same happens for potential energy spectrum which, on the other hand, is always characterized by a $k^{-5/3}$ power law behavior inertial range (in both peaks and troughs).

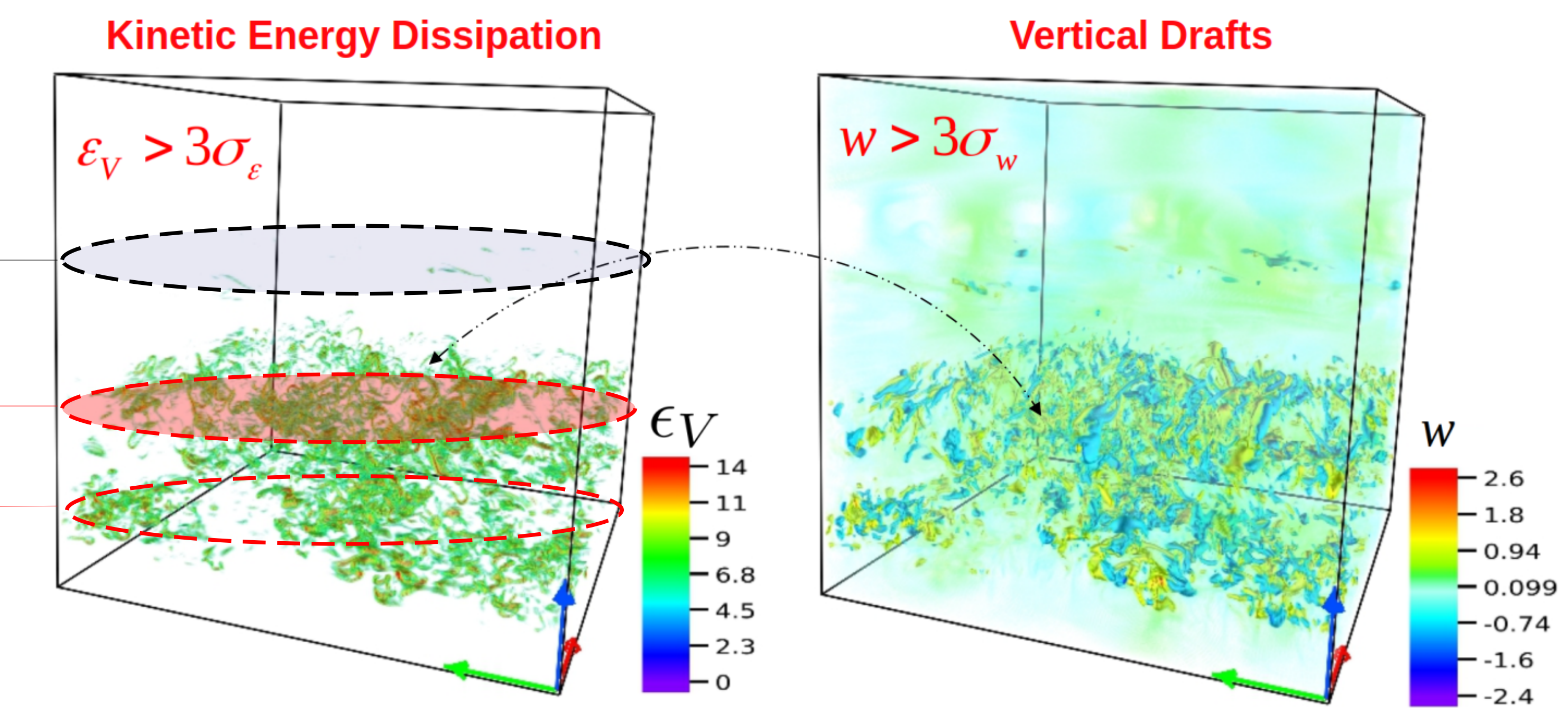




Dissipation Efficiency in Stratified Flows

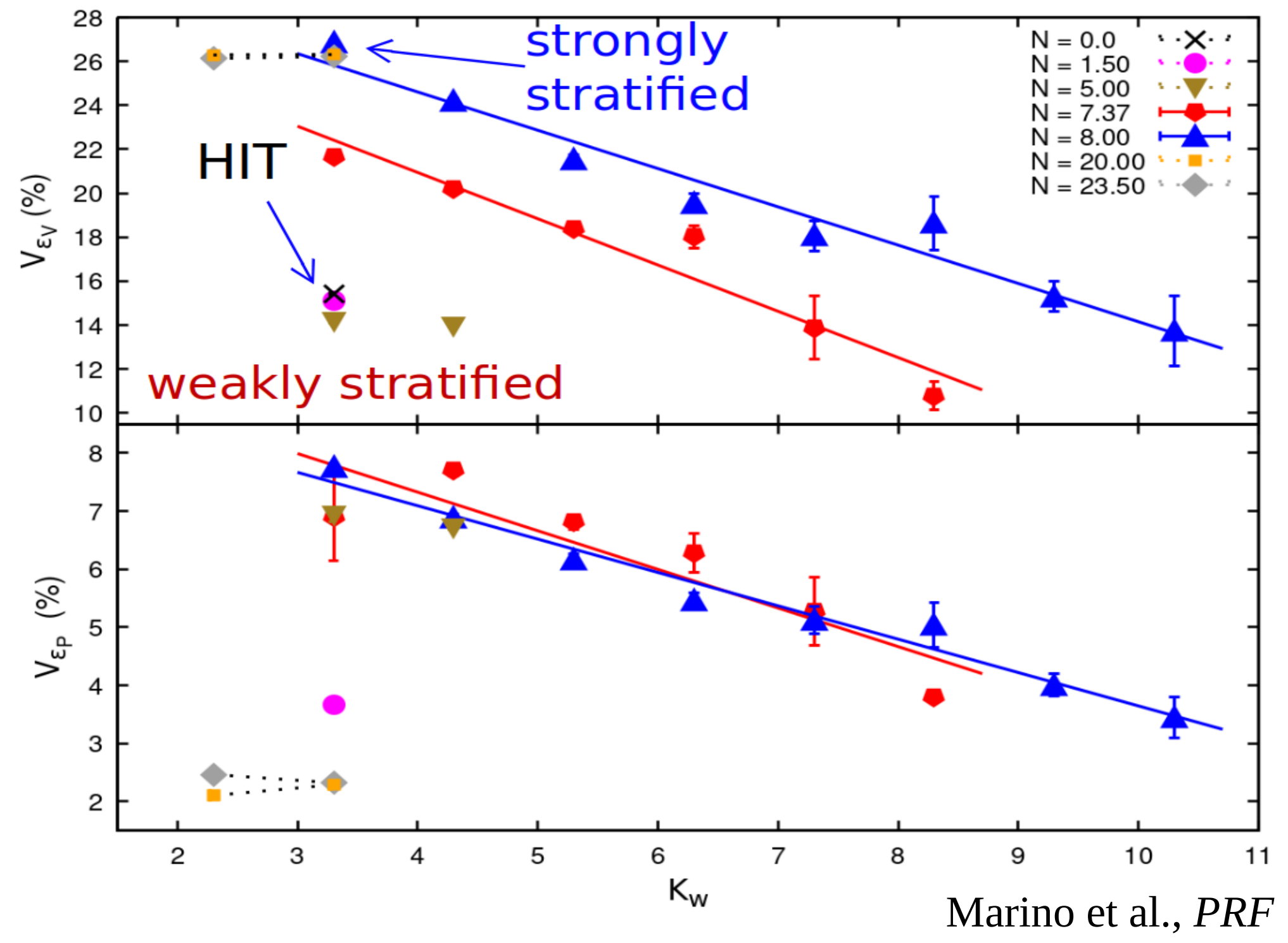
A study of the statistics of kinetic and potential energy dissipation rates respectively $\epsilon_V = \nu(\partial u_i/\partial x_j)(\partial u_i/\partial x_j)$ and $\epsilon_P = \kappa|\boldsymbol{\nabla}\theta|^2$ reveals that the extreme vertical drafts strongly feedback on ϵ_V and ϵ_P, and play a major role in the way energy is dissipated in stratified turbulence. Large-scale intermittent structures in the vertical velocity do generate small turbulent scales and dissipation, thus modulating the distribution of the kinetic energy dissipation rate.





- Patches of intense kinetic (and potential) energy dissipation are intermittent (in space/time), determining the shape of the probability distribution $P(log(\epsilon_V))$
- Extreme drafts necessary in order to have dissipation as efficient as in the Homogeneous and Isotropic case
- The 50% of the total kinetic energy dissipation occurs in only the 10% of the domain volume
- Stratified flows are more efficient in dissipating potential energy than kinetic energy

Ocean: 90% of the kinetic energy dissipation is accomplished within the 10% of the global oceanic volume (Pearson & Fox-Kemper, *PRL* 2018)

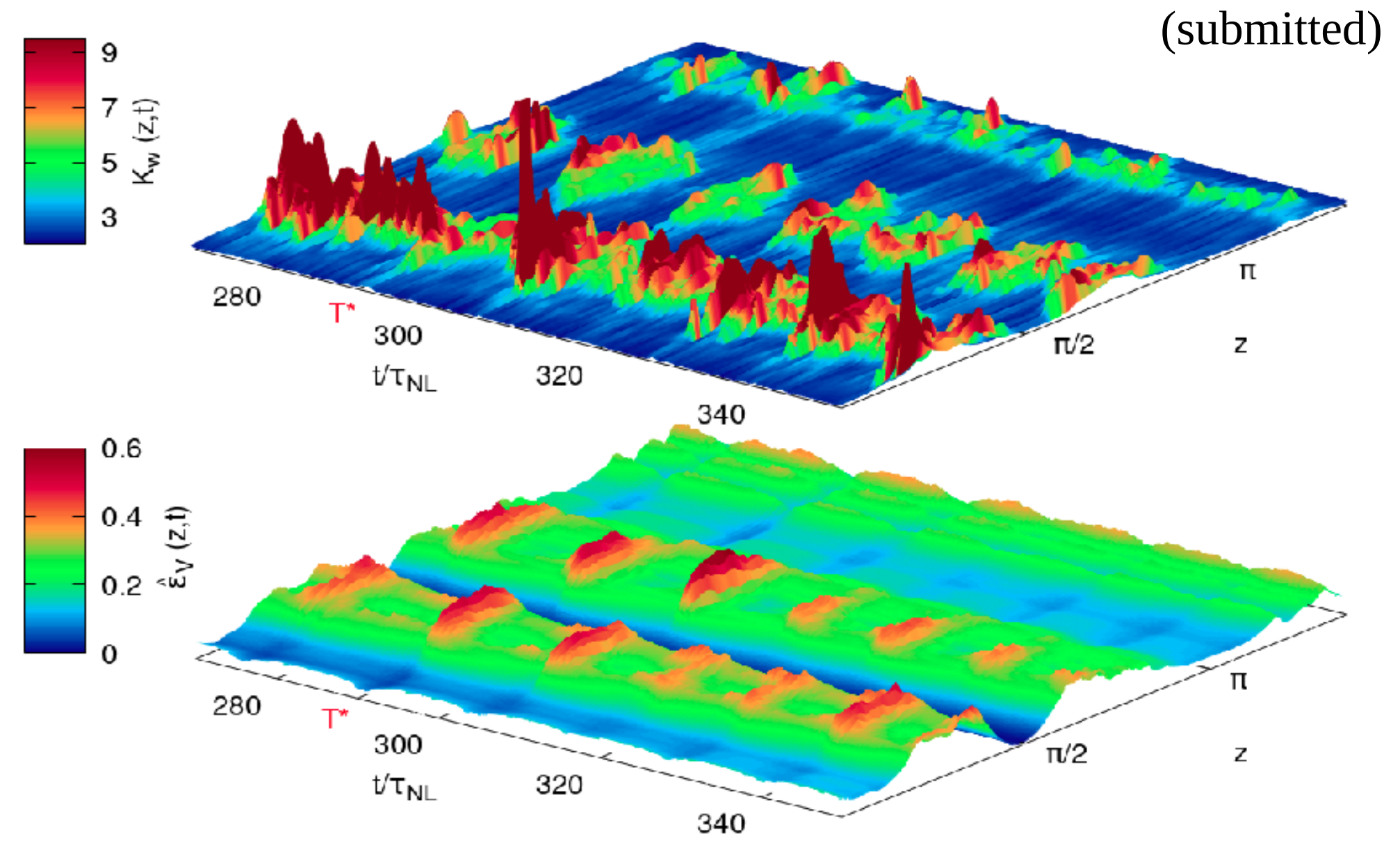


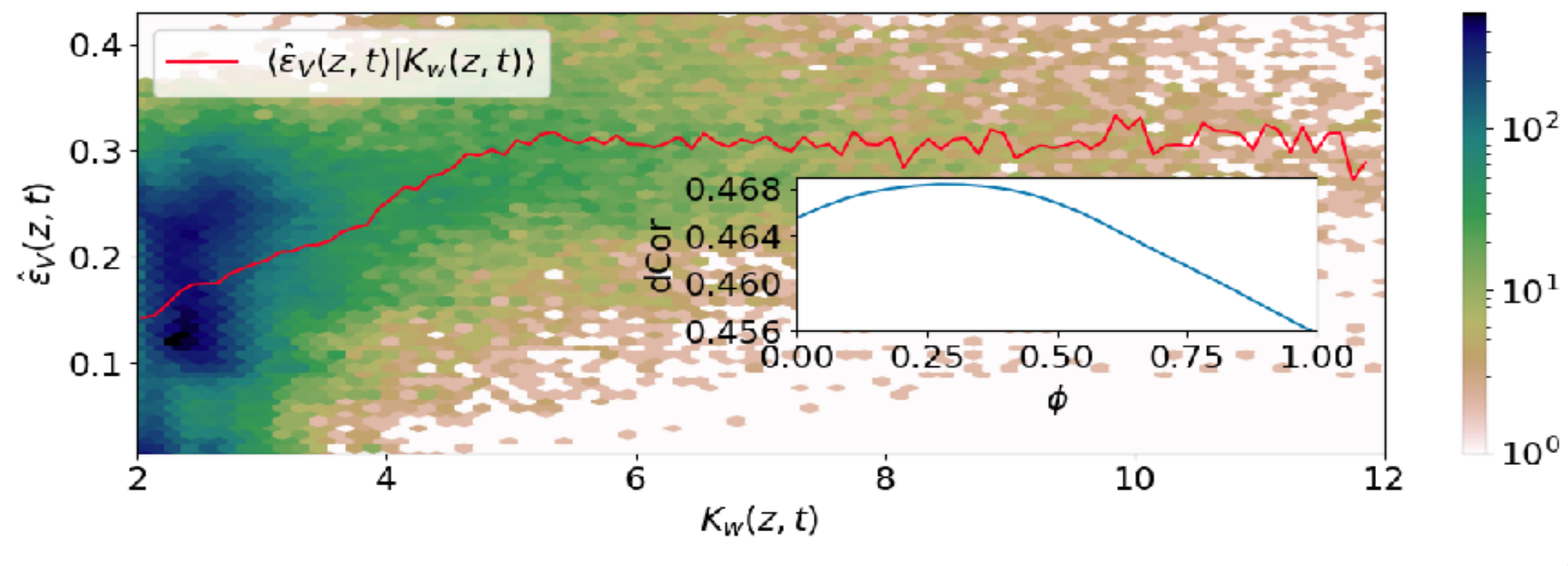
Marino et al., *PRF* (submitted)

Causation

Visualizations of the vertical profiles of the by-plane kurtosis $K_w(z,t)$ and of the normalized kinetic energy dissipation $\widehat{\epsilon}_V(z,t)$ (as a function of time, for run *P5*) emphasize the spatial correlation between the emergence of vertical drafts (detected through the amplitude of the kurtosis) and the enhancements of the kinetic energy dissipation along the z-axis. <u>The large peaks of dissipation occur immediately after strong vertical drafts develop in the same layer of the flow</u>. Although the small temporal shift cannot be appreciated from the visualized signals, its existence results from the bottom panel showing how the (point-wise) values of the quantities rendered in top-mid panels are maximally correlated for a time delay $\phi \approx \tau_{NL}/3$. This stems from the analysis of the distance correlation coefficient $dCor_{XY}$, proving causation. Indeed $dCor_{XY}$ measures both linear and nonlinear correlations between $X = K_w(z,t)$ and $Y = \widehat{\epsilon}_V(z,t+\phi)$ for different temporal shifts ϕ (as shown in the inset):

$$\mathrm{dCor}_{XY} = \frac{\mu_{XY}}{(\mu^2_{XX}\mu^2_{YY})^{1/4}}$$





References

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[3] Feraco et al., Europhys. Lett., 2021, Vol. 135, p.14001
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