ON THE DYNAMICS OF TURBULENCE NEAR A STRESS-FREE SURFACE

James J. Riley*, Oscar Flores**& Alexander R. Horner-Devine*
*University of Washington, Seattle, Washington, USA
**Universidad Carlos III, Madrid, Spain

Summary Horizontal energy spectra of horizontal velocity in turbulence data taken very near the free surface of a tidally-influenced river under very calm conditions indicate a fairly extensive -5/3 range at length scales above the locally-isotropic range, inconsistent with Kolmogorov's classical arguments. These data are, however, qualitatively consistent with numerical simulations of strongly stratified flows, and with some atmospheric and ocean measurements. To interpret the data we have performed high-resolution numerical simulations of turbulence near a free-slip surface, and find that the simulation results are not inconsistent with the field data and with simulations of strongly stratified flows. Very near the surface -5/3 energy spectra at horizontal scales above the locally-isotropic range develop, while spectra at smaller scales exhibit approximate local isotropy. Away from the surface at the larger scales, the spectra relax towards three-dimensional turbulence spectra.

Motivation for the study

Recently Chickadel et al. [1] have made both acoustic doppler velocimetry (ADV) and infrared-based particle image velocimetry (PIV) measurements of the turbulent velocity in the Snohomish River in Washington State, which flows into the Puget Sound. The measurements were made in a tidally-influenced region 15 km upstream of the mouth of the river, and at the surface for the PIV and about 2 cm below the surface for the ADV (see Figure 1). Although the data are given in terms of frequency spectra, the mean current speed was about 0.8 m/s. With Taylor's hypothesis, and defining the horizontal components of the velocity as u and v, respectively, and the vertical component as w, one observes an approximately isotropic range above a horizontal wave number of about $0.8\,\mathrm{m}^{-1}$. Below this wave number the vertical velocity spectrum becomes very small compared to the horizontal velocity spectra, as the free surface suppresses the larger-scale vertical motions. Interestingly, there is an about one-decade long range where the spectra of the horizontal velocities are proportional to $k_H^{-5/3}$, where k_H is the horizontal wave number. Since the flow in this region is highly non-isotropic, Kolmogorov's classical arguments do not hold here, and some other explanation is needed to explain this behavior.

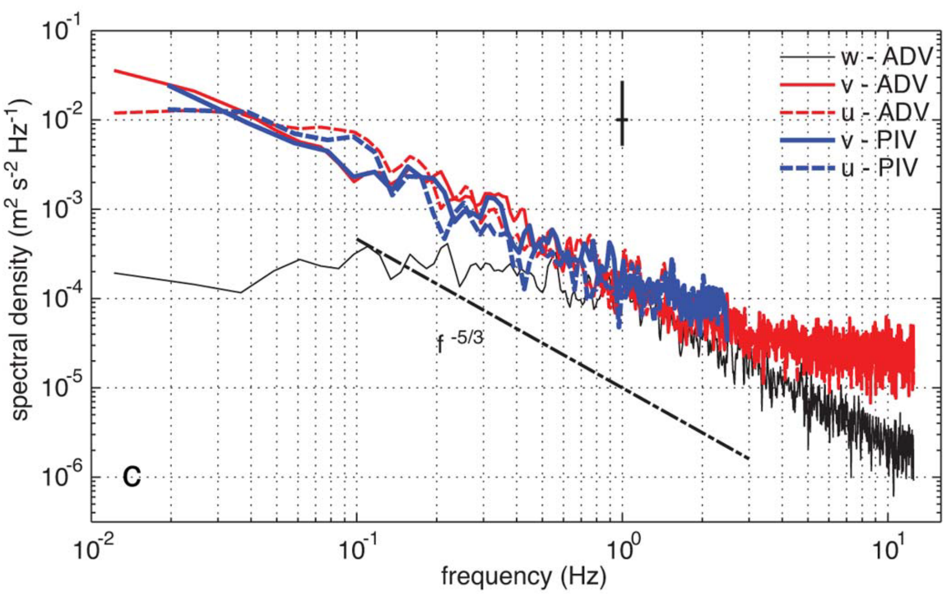

Figure 1. Energy spectra taken very near the surface of a tidally-influenced river (from Chickadel et al. [1])

Hypothesis

This spectral behavior is very similar to that observed in numerical simulations of strongly stably stratified flow, and also in some atmospheric and ocean measurements (Riley and Lindborg [2]). In these flows the larger-scale vertical velocity is inhibited by the stable stratification, but strong vertical shearing of the horizontal motion develops (Lilly [3], Billant and Chomaz [4]), resulting in instabilities and three-dimensional turbulence at smaller scale, but strong downscale cascade at intermediate scales. This downscale cascade dependens mainly on the energy dissipation rate, leading to the $k_H^{-5/3}$ dependence at intermediate scales. We hypothesize that an analogous mechanism occurs near the free surface of the river.

a) Corresponding author. E-mail: rileyj@u.washington.edu.

Numerical simulations

In order to test this hypothesis we performed high-resolution direct numerical simulations of decaying turbulence with a free-slip top surface to mimic the river surface under calm conditions. The initial spectra were somewhat narrow-banded homogeneous, isotropic turbulence. The flow was taken to be periodic in both horizontal directions, with a no-slip bottom boundary. Fourier-spectral methods were used in the horizontal directions, with high-order compact differencing in the vertical direction. Figure 2 gives the horizontal energy spectra of the horizontal components of the velocity at three

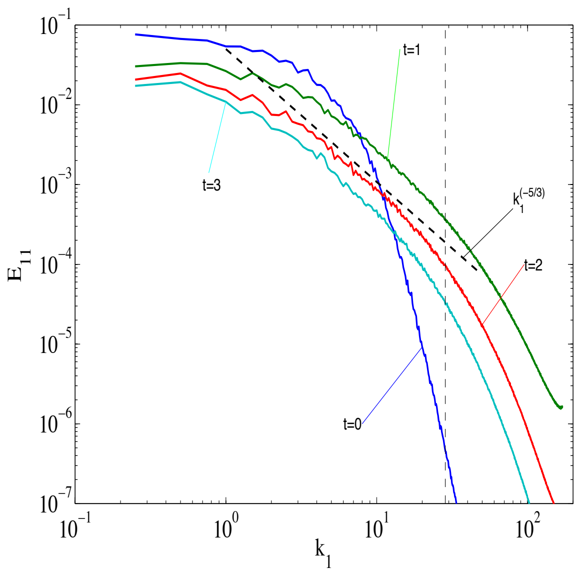

Figure 2. Horizontal energy spectra of the horizontal velocity for three consecutive times after the initial condition ($t = 0$.) The vertical dashed line is at $1/z$, where z is the distance from the free surface.

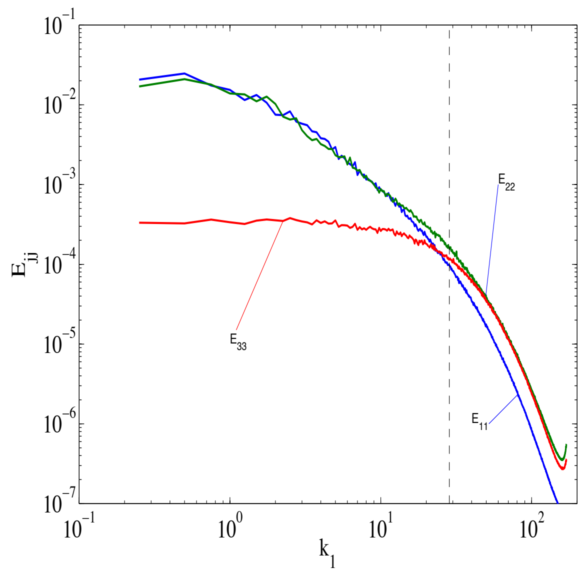

Figure 3. Horizontal energy spectra of all three components of the velocity at the time $t = 2$ (see Figure 2).

different times after the start of the simulation. It is seen that the horizontal spectra broaden considerably with time, and a roughly -5/3 region does develop for later times. Figure 3 gives the spectra of all three components of the velocity at $t = 2$. Above a wave number of about $1/z$, where z is the distance from the free surface, the three spectral components obey the proper isotropic relationships. Between waves numbers of about 2 and 20, however, there is a region with behavior close to -5/3, similar to the field data.

Conclusions

We find that the results of our numerical simulations are not inconsistent with the field data and the analogy with strongly stratified flows. In particular, near the free surface at intermediate horizontal scales, horizontal spectra of horizontal velocity with $k_H^{-5/3}$ behavior are obtained. At smaller scales the flow become approximately isotropic. Also, away from the free surface the spectra relax towards spectra for three-dimensional turbulence.

The interpretation of strongly stratified flow suggests that, due to the suppression of the larger-scale vertical velocity, strong vertical shearing of the horizontal velocity develops, leading to a strong downscale cascade of energy and the observed -5/3 spectra at intermediate scales. The results also suggest that similar dynamics might result in other flows where one component of the velocity is suppressed, for example in flows in rivers and estuaries at horizontal scales much larger than the depth.

It must be emphasized, however, that the numerical results are preliminary. Much higher horizontal resolutions is needed, for simulations at much higher Reynolds numbers. In addition, more accurate statistics can be obtained if the flow is forced to a statistically steady state. And finally there is a need to analyze the simulation results in more detail, for example the equation for the evolution of the spectral energy, including the pressure/strain-rate and vertical energy flux terms.

References

[1] Chickadel C.C., Talke S.A., Horner-Devine A.R., Jessup A.T.: Infrared-based measurements of velocity, turbulent kinetic energy, and dissipation at the water surface in a tidal river. *IEEE Geosc. Remote Sens.* **8**(5):849-853, 2011.

[2] Riley J.J, Lindborg E.: Stratified turbulence: a possible explanation of some geophysical turbulence measurements. *J. Atmos. Sci.* **65**(7):2416-2424.

[3] Lilly D.K.: Stratified turbulence and the mesoscale variability of the atmosphere. *J. Atmos. Sci.* **40**(3):749-761.

[4] Billant P, Chomaz J.-M.: Self-similarity of strongly stratified inviscid flows. *Phys. Fluids* **13**(6):1645-1651.