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Shallow Turbulence in Rivers and Estuaries

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LONG-TERM GOALS

The long-term goal of the "Shallow Turbulence in Rivers and Estuaries" project is to improve our understanding of turbulent mixing processes and energy dissipation in estuaries and rivers. Specifically, the project goals are to improve understanding of the eddying motion occurring at horizontal length scales greater than the water depth, and their interaction with bottom boundary turbulence. Our study is leading to an improved understanding of shallow turbulence and its role in lateral transport and dispersion in estuaries and rivers, and better interpretation and use of remotely-sensed signatures. The parameterization of lateral transport and its interpretation within hydrodynamic models may also be improved.

OBJECTIVES

The "Shallow Turbulence in Rivers and Estuaries" project is analyzing and comparing existing field data, remotely sensed data, and Delft3D numerical data for evidence of large scale, quasi-2D eddies that are much larger than the depth. Specific objectives are to:

1. *Determine spatial patterns of shallow turbulence from in-situ and remote sensing data and investigate the effects and interactions of these structures with bottom boundary layer processes and turbulence statistics;*
2. *Elucidate shallow turbulence properties and processes through numerical modeling studies, and statistically reproduce the large-scale turbulence observed from in-situ records; and*
3. *Synthesize and understand the implications of shallow turbulence by means of the turbulent kinetic energy balance, statistical methods, and collapsing data onto a phase diagram.*

APPROACH

Our approach combines 1) analysis of existing data, and 2) numerical modeling to study the dynamics and significance of shallow turbulence in rivers and estuaries. The Delft3D modeling system is being used to simulate the Columbia River Estuary (CRE), with a focus on analyzing large-scale, horizontal eddying motions. Previously measured infra-red images and surface currents are being analyzed from the Snohomish River, WA (see Chickadel et al., 2011) and the New-River Inlet. In-situ flow data from the Snohomish River (Talke et al., 2012) and "Mega-Transect data" from the Columbia River mouth (Moritz et al., 2005) are being compared to remote sensing data and modeling results, respectively. CODAR velocity data from http://cencalcurrents.org/DataRealTime/Totals/SF_Bay/ of central San Francisco Bay is also being analyzed. The data spans an approximately 11x11 km grid is available at half-hourly increments with a 400m resolution from 2009-2013. The length and spatial extent of the data set allows for the comparison of different bathymetric, tidal, river flow, and salinity conditions

Our analysis strategy consists of (a) identifying and characterizing large scale 2D eddies, and (b) analyzing 2D and 3D (bottom boundary layer, BBL) flow dynamics and turbulence statistics. The turbulent flow field is foundby first removing the mean, then removing tidal flow components through harmonic analysis. Vector plots, vorticity maps, and swirl analysis are then used to detect coherent eddying motion (Zhou et al., 1996, 1999, and Adrian et al, 2000). The integral length scale L_I and TKE are also calculated and a 'dissipation' value is estimated the K-epsilon turbulence model: $\epsilon = \frac{(TKE)^{3/2}}{L_I}$. In the BBL, components of the turbulent kinetic energy (TKE) budget such as TKE flux divergence, production, and dissipation are calculated using standard methods (e.g., Stacey, 2003; Stacey et al., 1999; Wiles et al., 2006; Chickadel et al., 2011). From surface data

WORK COMPLETED

Over the past year we have (a) further analyzed and clarified the interpretation of in-situ and surface turbulence from the Snohomish River (Talke); (b) trained a student to run and analyze sensitivity studies of the Columbia River estuary using different roughness and grid conditions (Talke & Zaron); (c) processed and analyzed CODAR data from Central San Francisco Bay, to gain insights on large-scale turbulence for different river flow conditions (Talke); (d) processed New River Inlet surface IR data to look for shallow turbulence signatures (Chickadel) ; and (e) processed both in-situ and remote sensing data of the Columbia River Estuary (Zaron & Chickadel). Two manuscripts were revised and are currently under editorial review (Talke), while another manuscript is in preparation (Zaron). A book chapter containing results from the COHSTREX experiment was published.

RESULTS

Bottom Boundary Layer analysis: Two significant, related results have come out of this work, which is the continuation of analysis begun during the COHSTREX MURI project (2005-2010). Analysis of field data suggest that (a) a depth-dependent drag coefficient is a better parameterization of bottom stress than the often-used quadratic bed coefficient, and (b) turbulent statistics are only partially self-similar in the bottom boundary layer (with the consequence that production and dissipation need not balance). We reported (a) last year, and demonstrate (b) with new results below. For context, we note first that bed friction is often parameterized by a time invariant quadratic drag coefficient, with bottom stress proportional to the mean velocity squared (in fact, this is the default for ROMS, Delft3D, and other models). The quadratic drag coefficient is valid for an idealized, steady, and self similar boundary layer with the following characteristics: (a) the TKE production P equals the TKE dissipation rate, ε; (b) other TKE budget terms are negligible; (c) the TKE and Reynolds stress are constant, and (d) the velocity profile is logarithmic (Tennekes & Lumley, 1972). Further, the quadratic drag law conflicts with the emprically derived and often used Manning Equation, which is depth dependent (Dooge, 1992; Gioaa & Bombardelli, 2002). Which parameterization should be used? Hence, determining 'similarity' (or lack thereof) of turbulent statistics can help determine which parameterization to use.

Our processing of Snohomish River field data shows that turbulent statistics are not self-similar at this location. Figure 1 shows that the production P and dissipation ε are imbalanced in the water column, in violation of full similarity. Moreover, the vertical shape of the P and ε curve shifts as depth decreases, as observed by comparing the black crosses (P for depth of 4-5m) and yellow only (P when depth decreased to 2.5-3.5m). Hence, the curves are only partially self-similar, since full similarity would imply invariance with water depth changes. Other results confirm this inference: as depth is halved over an ebb tide, the maxima of various turbulence statistics occurs proportionaly higher in the (depth-normalized) water column (Fig. 1c). Interestingly, the absolute position of the turbulence maxima changes only slightly (Fig. 1b). Physically, turbulence production (e.g., due to flow separation) is not affected much by depth changes; as a result, turbulence production and other statistics occur proportionally higher in the water column.

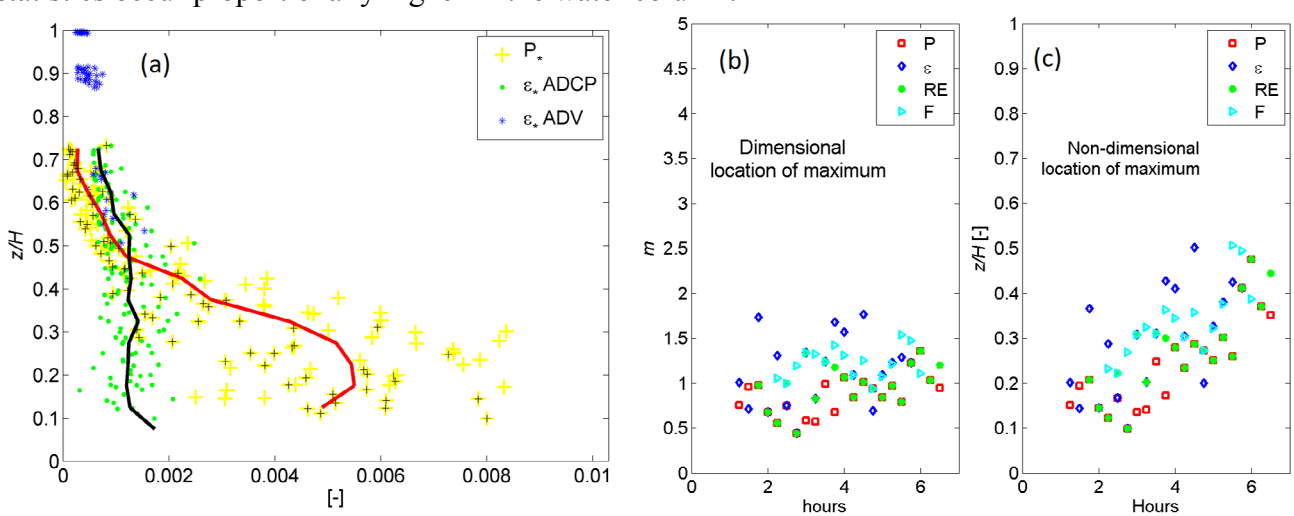

Fig. 1a: Normalized Production and Dissipation in the water column ; Fig. 1b,1c: Location of the maximum Production (P), dissipation (ε), Reynolds Stress (RE) and TKE Flux(F) vs. depth from bed (b) and vs. z/H, where H is the water depth (c).

An implication of partial self-similarity is that turbulent mixing will be larger in the mid-water column in shallow water vs. deep water, even given the same average flow velocity. This is shown in Fig. 4, using the along-beam velocity from a downward looking, surface ADCP. The water column turbulent fluctuations are much more vigorous for the smaller depth situation, even though the depth-averaged velocity is the same. We qualitatively observe more intense boiling in surface IR video as depth decreases. Hence, surface turbulence intensity is a function of both water depth and the drag coefficient. A depth-dependent drag-coefficient likely impacts shallow turbulence through the so-called 'shear stability number', $S = \frac{\varepsilon_{BBL}}{\varepsilon_{2D}} = \frac{WC_d}{H}$, which is defined as the ratio between bottom boundary generated dissipation and dissipation generated from quasi-2D, large aspect ratio eddies with width *W*. At the Snohomish River field site, the drag-dependent shear stability parameter varies from 0.1 (early ebb) to 0.4 (late ebb), which suggests that BBL processes are becoming more important.

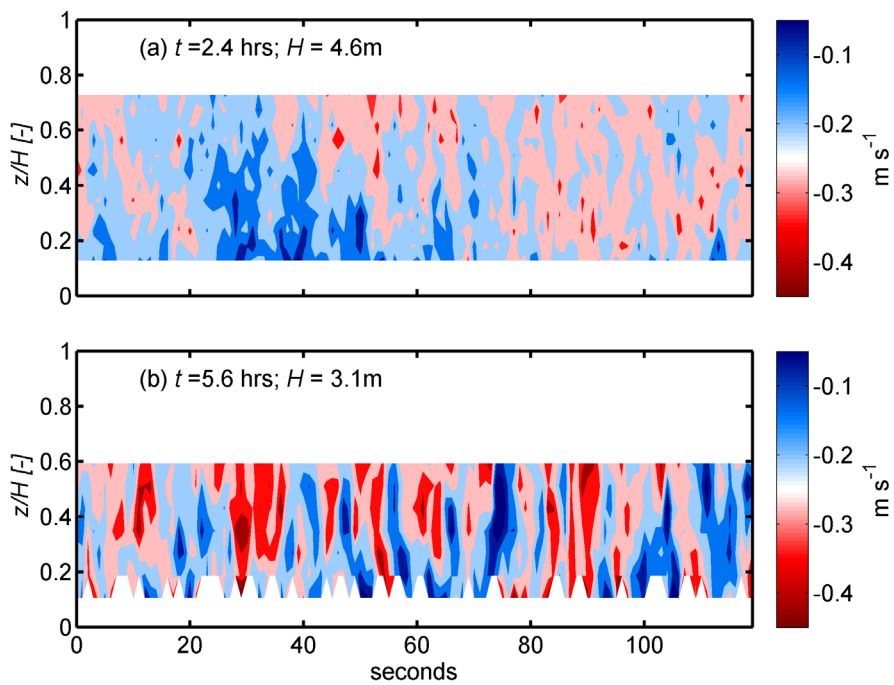

Fig. 2: Along beam ADCP velocity fluctuations for U_{avg} = 0.5m/s. Turbulence is much more vigorous at the smaller depth.

Remote Sensing Analysis– CODAR in San Francisco: As river flow increases during winter storm events, both the tidal flow field and the large-scale turbulence field in CODAR velocity data are affected. The M2 tidal velocity magnitude is noticeably damped by up to 0.2 m/s during elevated flow conditions, primarily near the Golden Gate and Angel Island (Fig. 3a &b). This damping is also observed at the SF tide gauge, and is attributed to frictional damping of the tide by river flow (Moftakhari et al, 2013). During both low and high flow, large coherent eddies are observed in the residual (non-tidal) flow at scales from 2km to 5km, most often around slack tide . The physical mechansims that form these eddies may include separated frow off topography, wind-forcing, and enhanced baroclinic forcing during low energy periods. The observed motions are 'forced' vortices, in which the tangential velocity v_θ scales with *r*, the distance from the center of rotation. Such forced vortices occurr in 'rotational' turbulent flow and do not conserve energy (i.e., dissipation occurs).

However, elevated vorticity is not consistently measured within these eddies (Fig. 3c,d), and hence their interpretation is still somewhat unclear and must be addressed by modelling.

Since large coherent eddies are only observed intermittently, we apply a statistical approach to evaluate the net dynamical effect of shallow turbulence on estuarine dynamics. We therefore estimate TKE and the integral lengthscale L_I, which is the largest scale of turbulent motions. Results suggest that L_I, is larger during winter than summer, but only weakly correlates with flow. The largest variations are observed over the shallow sub-tidal flats on the eastern fringe of the Bay, perhaps due to the senstivity of this region to changes in winter/summer wind conditions (Talke & Stacey, 2003). By contrast, surface TKE is largest during stormy conditions and elevated river flow (not shown). Dissipation estimates using $\varepsilon = \frac{Ak^{3/2}}{L_I}$ are (perhaps surprisingly, given the course resoluton and analysis assumptions) reasonable and in-line with scaling estimates. Large seasonal and spatial variation are observed: Subtidal flats exhibit the smallest dissipation, while energetic tidal straits exhibit eleveated dissipation. More tidal energy is dissipated during stormy conditions with elevated river flow than during low-flow conditions; this observation helps explain the decrease in tidal velocity amplitudes observed during the same period. The interpretation of this ‘ dissipation’ estimate need to be evaluated (e.g., can the condition of isotropy be relaxed, and is the estimate valid?), and the results need to be ground-truthed against in-situ or modeling data.

Remote Sensing Analysis– IR surface velocity data: During this year we have focused on analyzing the RIVET measurements at the New River Inlet from May 2012. As port of this effort APL-UW recorded thermal imagery of the inlet from a nearby tower, capturing ebb and flood patterns of surface temperature. We have produced reliable and unbiased 1D estimates of the surface velocity using Chickadel et a., 2003, since a standard 2D PIV method was unreliable during low contrast daylight hours. Analysis of an 18 day time series of along-inlet currents is underway, and focuses on removing the tidal signal via harmonic analysis to reveal persistent eddies. Figure 4 demonstrates what appear to be surface flow features in the de-tided velocity during early ebb on 5 May 2012. The large features (100m-200m) move at approximately the mean velocity in the region (0.3 m/s). Future analysis will focus on quantitative estimation of the scale, velocity and distribution of the observed eddies, with a goal of estimating the total TKE and TKE dissipation they represent at this site.

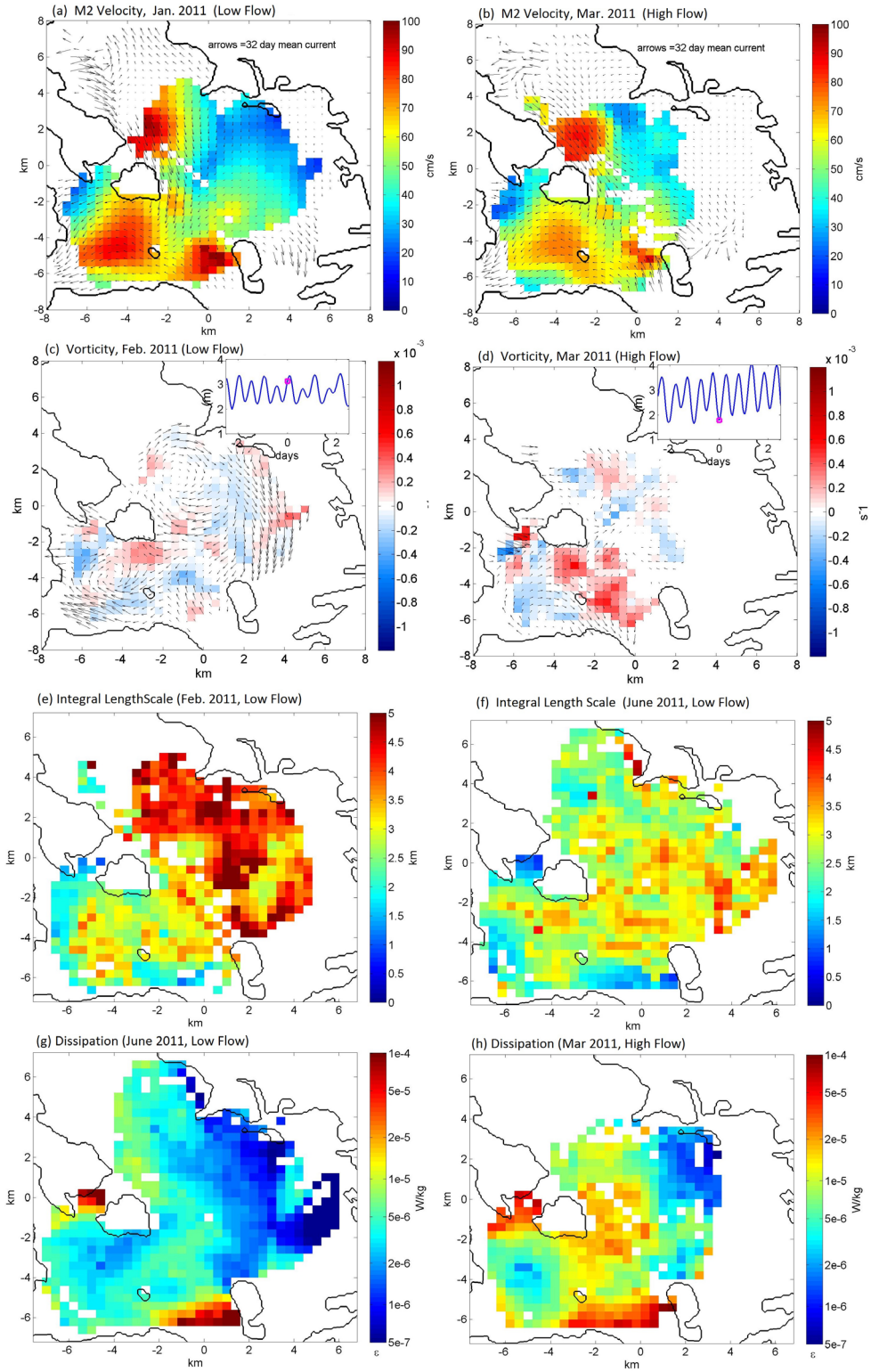

Fig. 3: Comparison of M2 velocity magnitude (a,b), large scale eddies and vorticity (c,d), the integral length-scale (e,f) and TKE dissipation (g,h) in Central San Francisco Bay for both low river flow conditions (~600 m^3/s) and elevated river flow conditions (~3300 m^3/s).

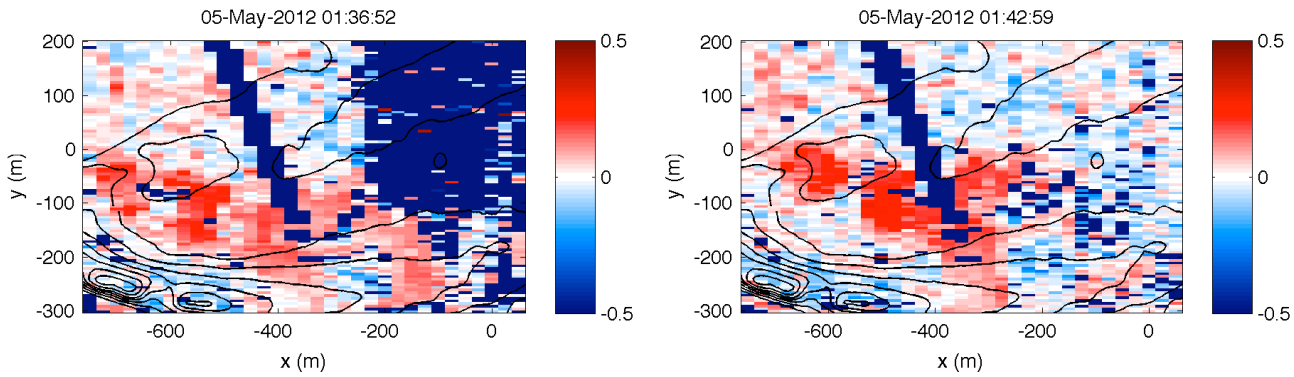

Figure 4. An example of advected surface velocity features seen in the residual (de-tided)along-inlet velocity field in New River Inlet, NC, measured via IR-dervied 1D PIV. Flow was to the right (+x) at approximately 0.3 m/s; missing data is shown as dark blue. Time is in UTC.

Delft3D Modeling results and comparison with in-situ data: Delft3D modeling and analysis of field data from the Columbia River show similar results to the San Francisco CODAR results. The residual (de-meaned, non-tidal) velocity shows evidence of large coherent eddies that scale with the width of the river mouth (Fig. 5). Interestingly, the eddies are often associated with, but offset from, ribbons of elevated vorticity that are likely due to fronts and/or tidal jets. A similar process is observed in SF CODAR data. The association of eddies with fronts makes sense: at a convergence, flow is likely diverted both sideways and downwards, leading to circulatory flow structures. Moreover, a moving front/shear zone can cause or sustain rotary motion (i.e., a forced vortex).

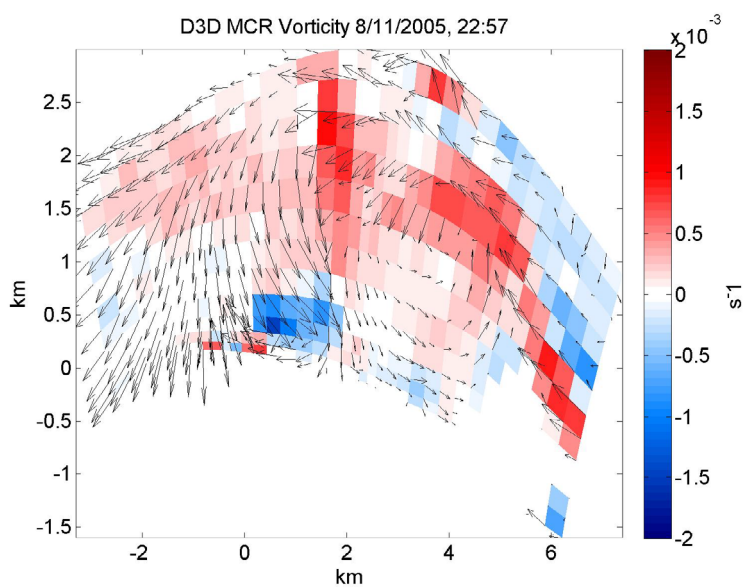

Fig. 5 Coherent eddies at the mouth of the Columbia River, from Delft3D model results. The tidal and tidally-averaged flow has been removed.

Power spectra in both model results, remote sensing spectra, and in-situ data (not shown) exhibit a -5/3 spectra from the semi-diurnal tide frequency down to approximately 20-30 cycles per day (Fig. 6), suggesting that energy is being transferred to/from tidal scales to shallow turbulence scales, which have a time-scale of approximately 1hr. At frequencies above 30cpd, the modelled spectrum has a 'kink' and exhibits a larger slope that might indicate an 'enstrophy' cascade to smaller scales (slope = -3); however, a more likely cause is numerical damping or lack of horizontal resolution, which acts as a low-pass filter. Moreover, a forward cascade of energy to smaller scales is physically plausible, since tidal energy is known to transfer from the semidiurnal M2 tide to higher harmonics. In analogy with the atmosphere, energy transfer may occur in both directions. However, a direct spectral connection to depth-scale turbulence has not yet been modelled (our current computational power limits us to 25-50m grid spacing). Hence, while the balance of results suggests a turbulence cascade, the presence of alternate explanations (e.g., red noise) illustrates the difficulty in correctly interpreting large-scale data.

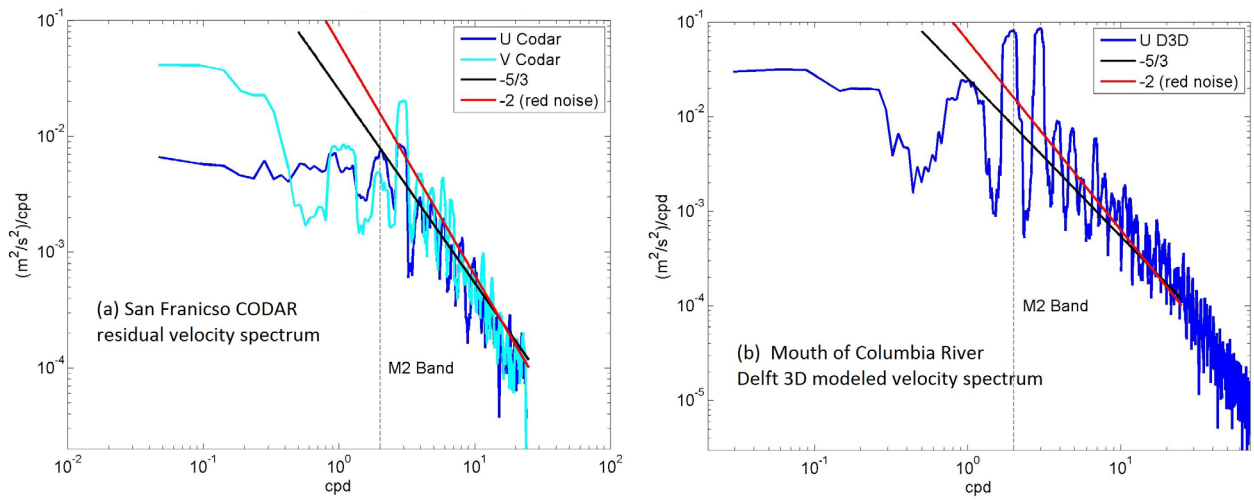

Fig. 6 Turbulent Spectra from San Francisco CODAR data (left) and from Delft3D modeling results of the mouth of the Columbia River (right).

Our interpretation of the significance of the spectrum of large-scale motions is evolving. Lateral Reynolds stresses computed from the MegaTransect data in the CRE lead to an estimated horizontal turbulence viscosity as large as $20m^2/s$, similar to reports by Colbo (2006) in the Strait of Juan de Fuca. But we note that Reynolds stress of the non-tidal residual (the large-scale eddies) is correlated with the Reynolds stress of the tidal flow. Thus, it may be that the large-scale eddies are simply a manifestation of non-stationarity of the tide, i.e., oscillations of the tidal ellipses. We are currently working to develop a synthesis and interpretation of observations from model simulations.

IMPACT/APPLICATIONS

The observed imbalance in production and dissipation in the water column and the incomplete similarity in the water column challenge widespread assumptions made in parameterizing the drag coefficient. Using a more correct, depth dependent friction parameterization such as the Manning Equation may help improve numerical models, particularly in areas subject to large depth variations.

The observed flow dependence of the tide and energy dissipation suggests that river discharge into estuaries could be measured remotely through these quantities. Moreover, the remotely observed flow variability and seasonality are metrics against which a model can and should be calibrated. The connection of large scale motions to turbulence properties such as dissipation and the integral scale potentially allows for the entire system—and a model-- to be evaluated in an integrated sense. Characterizing large-scale, quasi 2D turbulence helps elucidate the mechanisms by which energy is extracted from the mean tidal flow and is transferred between different scales. Therefore, if the large scale is measured or modelled correctly, the smaller scale can be inferred.

RELATED PROJECTS

The ONR-sponsered "Young-Investigator" award for Talke aims to improve numerical models of transport by analyzing satellite data, primarily through scalars such as sediment, salinity, and temperature. There is therefore some synergy and cross-over, particularly in the analysis of CODAR data.

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Talke, S.A., A.R. Horner-Devine, C.C. Chickadel, and A. T. Jessup,(2012), *in review.* Turbulent kinetic energy and coherent structures in a tidal river Part I: water column turbulence. *submitted to Journal of Geophysical Research.*

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HONORS/AWARDS/PRIZES

Outstanding Reviewer Award, Estuaries and Coasts, 2013 (Talke)