SAN FRANCISCO ESTUARY & WATERSHED SCIENCE
Published by the California Bay-Delta Authority Science Program and the John Muir Institute of the Environment

A Note on the Effect of Wind Waves on Vertical Mixing in Franks Tract, Sacramento-San Joaquin Delta, California

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ABSTRACT

A one-dimensional numerical model that simulates the effects of whitecapping waves was used to investigate the importance of whitecapping waves to vertical mixing at a 3-meter-deep site in Franks Tract in the Sacramento-San Joaquin Delta over an 11-day period. Locally-generated waves of mean period approximately 2 s were generated under strong wind conditions; significant wave heights ranged from 0 to 0.3 m. A surface turbulent kinetic energy flux was used to model whitecapping waves during periods when wind speeds > 5 m s^{-1} (62% of observations). The surface was modeled as a wind stress log-layer for the remaining 38% of the observations. The model results demonstrated that under moderate wind conditions (5–8 m s^{-1} at 10 m above water level), and hence moderate wave heights, whitecapping waves provided the dominant source of turbulent kinetic energy to only the top 10% of the water column. Under stronger wind (> 8 m s^{-1}), and hence larger wave conditions, whitecapping waves provided the dominant source of turbulent kinetic energy over a larger portion of the water column; however, this region extended to the bottom half of the water column for only 7% of the observation period. The model results indicated that phytoplankton concentrations close to the bed were unlikely to be affected by the whitecapping of waves, and that the formation of concentration boundary layers due to benthic grazing was unlikely to be disrupted by whitecapping waves. Furthermore, vertical mixing of suspended sediment was unlikely to be affected by whitecapping waves under the conditions experienced during the 11-day experiment. Instead, the bed stress provided by tidal currents was the dominant source of turbulent kinetic energy over the bottom half of the water column for the majority of the 11-day period.

KEYWORDS

Franks Tract, whitecapping waves, vertical mixing, shallow water, benthic grazing

SUGGESTED CITATION

Jones, Nicole L.; Janet K. Thompson; and Stephen G. Monismith. 2008. A Note on the Effect of Wind Waves on Vertical Mixing in Franks Tract,

Sacramento-San Joaquin Delta, California. San Francisco Estuary and Watershed Science. Vol. 6, Issue 2 (June), Article 4.

INTRODUCTION

Shallow water habitat is recognized as central to the productivity of turbid estuarine systems such as the San Francisco Estuary. However, primary production in shallow waters can be limited by benthic grazing by siphonate bivalves (Alpine and Cloern 1992; Cloern 1982) or by reduced light availability due to the resuspension of the fine bottom sediments found in these regions (May et al. 2003). Both grazing and turbidity are two of the multiple factors that limit primary productivity to low levels in the San Francisco Estuary relative to other tidal estuaries (Jassby et al. 2002). Primary productivity in this system has declined in the last two decades despite high nutrient concentrations and declining turbidity. This reduction in biomass at the base of the food-web is believed to be partially responsible for the decreasing populations of some ecologically important primary consumers of the phytoplankton: the zooplankton and mysids (Kimmerer and Orsi 1996; Mecum and Orsi 2001; Orsi and Mecum 1996). Fish species in the Sacramento-San Joaquin Delta have also declined over the past several decades (Bennett and Moyle 1996), and some of the declines may be due to a limited food supply (Kimmerer 2002). The CALFED Ecosystem Restoration Program plans to create and restore large areas of shallow water habitat for the Sacramento-San Joaquin Delta, Suisun Marsh, and North San Francisco Bay (CALFED 2000). This plan is based on the belief that shallow water habitat is favorable both to endangered native fish species and for primary production. Creating suitable habitat requires detailed knowledge of the processes that determine how the habitat will function (Lucas et al. 2002). Despite the obvious importance of shallow water habitats to ecological processes in the Sacramento-San Joaquin Delta/San Francisco Estuary system, data on the structure of flows and mixing in shallow waters are extremely limited.

Benthic grazing can be limited if near-bed phytoplankton is not replenished at a rate commensurate or greater than the grazing rate, resulting in the formation of concentration boundary layers (Jones et al. 2008). Accordingly, benthic grazing rates are a function of the vertical mixing rate. The limited knowledge of the influence of different hydrodynamic conditions on grazing rates makes it difficult to assess the system-wide effect of the benthic ecosystem on phytoplankton concentrations. Furthermore, light availability in areas with fine substrate will be influenced by vertical mixing through the distribution of suspended sediment. Vertical mixing rates are a function of tide- and wind-driven currents and bottom roughness. In open, shallow water bodies, the development of wind waves may also affect the vertical mixing rates. Surface waves can modify hydrodynamics near the free surface in three ways (Craig and Banner 1994). First, the interaction of the wave Stokes drift (the time-averaged drift of a particle being moved by a wave) with the wind-driven surface shear current can result in Langmuir circulation formation (as reported by Craik and Leibovich 1976; Skyllingstad and Denbo 1995; Teixeira and Belcher 2002). Second, Reynolds stresses (the mean forces imposed on the mean flow by turbulent fluctuations) can be created when the waves are not perfectly irrotational (e.g., Magnaudet and Thais 1995). Third, breaking waves generate turbulent kinetic energy that is available to be mixed down into the surface layer (e.g., Agrawal et al. 1992; Terray et al. 1996); it is the importance of this contribution to vertical mixing that we explore here.

The physical structure of the water column, as delineated by the magnitude and source of the turbulent kinetic energy, is determined by the relative strength of the bed stress, wind stress, and whitecapping waves (Figure 1). The formation of whitecapping waves leads to a surface layer that is dominated by turbulent kinetic energy generated by the breaking waves, termed the wave affected surface layer. Within this layer, turbulent kinetic energy dissipation (hereafter referred to as dissipation) scales with the rate of energy input to the waves from the wind and a wave-dependent length scale (i.e., wave height or inverse wave number) and decays as z'^{-2}, where z' is the depth below the water surface (e.g., Jones and Monismith 2008a; Terray et al. 1996). A wind stress log-layer (where velocity varies logarithmically with distance below the water surface) may be present

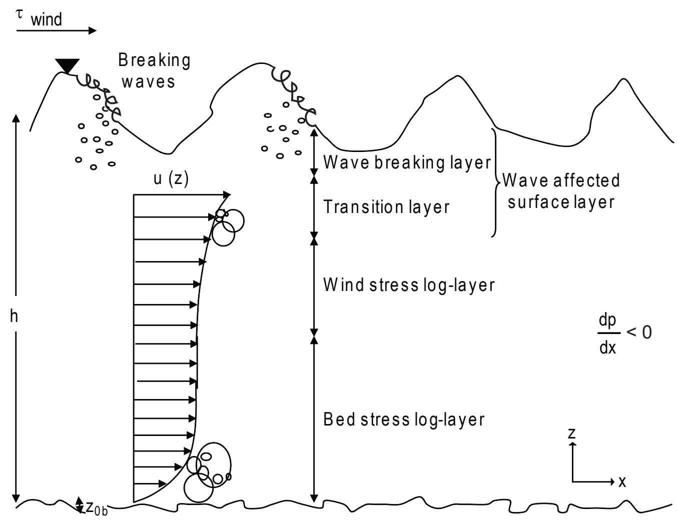

Figure 1. Schematic overview of the vertical structure of a shallow water column resulting from the combined forcing of a wind stress and tidal pressure gradient (from Jones and Monismith 2008b). Turbulent eddies are represented by the circles and ellipses in this diagram.

below the wave affected surface layer, where wind-generated turbulent kinetic energy shear production (hereafter referred to as shear production) and dissipation are in balance. Finally, in the layer closest to the bed—the bottom log-layer—shear production due to the tidal pressure gradient is the dominant source of turbulent kinetic energy, and shear production and dissipation are again in balance.

Estuaries are often exposed to strong onshore winds resulting from the temperature difference between the land and ocean, particularly in the summer. The prevailing winds in the Sacramento-San Joaquin Delta/San Francisco Estuary area are from the west and northwest from March through October (Conomos et al. 1985). The winds generally follow a diurnal pattern in strength, with maximum wind speeds occurring in the afternoon. These winds generate waves with maximum periods of 2–3 s, and wave heights of up to 1 meter (Conomos et al. 1985). During the winter months, the prevailing winds remain westerly; however, wind speeds are generally low. Winter storms generate strong winds from the east or southeast (Conomos et al. 1985).

Field experiments in Grizzly Bay, San Francisco Estuary, showed that whitecapping waves could provide the dominant source of turbulent kinetic energy throughout the shallow water column (mean depth 2.5 meters) during whitecapping conditions (Jones and Monismith 2008a). During whitecapping conditions (~90% of the month-long experiment), the dominant source of turbulent kinetic energy over 90% (or more) of the water column was provided by whitecapping waves for half of the observations. Whitecapping waves provided the dominant source of turbulent kinetic energy over 50% or less of the water column for only 10% of the conditions. The relative importance of whitecapping waves to vertical mixing in other shallow, open water bodies, such as those in the Sacramento-San Joaquin Delta, has not previously been addressed and we do so here in a morphologically different shallow water body.

Franks Tract is an open water body in the Sacramento-San Joaquin Delta that experiences strong winds and wave development (Figure 2). The water column is slightly deeper than at the Grizzly Bay site, averaging 3 meters, and the fetch to the measurement site is smaller at the Franks Tract site. Franks Tract supports a large population of the introduced clam *Corbicula fluminea* (biomass ranges from ~100–2,000 g tissue weight (Lucas et al. 2002)). Recent work by Lucas et al. (2002) shows that grazing by *C. fluminea* is a primary factor in determining whether the shallow systems of the Delta are net phytoplankton sources or net phytoplankton sinks, and thus this is a relevant environment in which to examine the potential effect of whitecapping waves on vertical mixing.

The aim of this study was to assess the impact of whitecapping waves as a source of turbulent kinetic energy and, therefore, of vertical mixing in Franks Tract under typical warm-weather diurnal wind conditions. This was achieved using a one-dimensional numerical model, previously verified with the extensive Grizzly Bay data-set (Jones and Monismith 2008b).

METHODS

Field Experiment

Franks Tract is a tidal lake of fairly uniform depth. An introduced aquatic weed, *Egeria densa*, is prevalent across the lake, except along a clear passage extending from the False River opening to the openings on the east shore (Figure 2). The instruments were located in the clear passage approximately 1 km from the False River opening.

Currents were measured using an upward-looking 1,200-kHz acoustic Doppler current profiler (ADCP, RD Instruments) operating in mode 12 with 7–cm bins, and the first bin approximately 50 cm above the bottom. The currents close to the bed were measured using an array of three Vector acoustic Doppler velocimeters (ADVs, Nortek) sampling synchronously at 25 Hz at heights of approximately 0.15, 0.25, and 0.4 m above the bed. Reynolds stresses were calculated via the Shaw and Trowbridge (2001) method. The pressure record from the ADVs was used to calculate wave height and period using linear wave theory (Jones and Monismith 2007).

Vertical temperature structure was measured by an array of thermistors (SBE39, Seabird Electronics), positioned every 0.5 m, sampling at 2-minute intervals. A wind station (Model 05103, RM Young) was mounted 4.7 meters above the water on a houseboat stationed at the measurement site, to provide 10-minute-averaged wind speed and direction data. The wind stress was estimated from the measured wind velocity using the Donelan (1990) algorithm, which was developed for fetch-limited lakes, and accounts for the effect of waves and whitecapping on the wind stress.

The Model

The hydrodynamic model used was the Global Ocean Turbulence Model (GOTM) (Burchard 2001; Burchard and Petersen 1999; Umlauf and Burchard 2003; Umlauf and Burchard 2005) with the κ-ω turbulence closure model (Umlauf et al. 2003). The model parameters we used are summarized in Table 1. The downward flux of turbulent kinetic energy at the surface—used to simulate the effect of wave breaking—was parameterized as αu_{*w}^3 (e.g., Craig and Banner 1994). Here u_{*w} is the surface stress provided by the wind and α is the wave energy parameter; we used $\alpha = 60$ because it was found to best describe the shal-

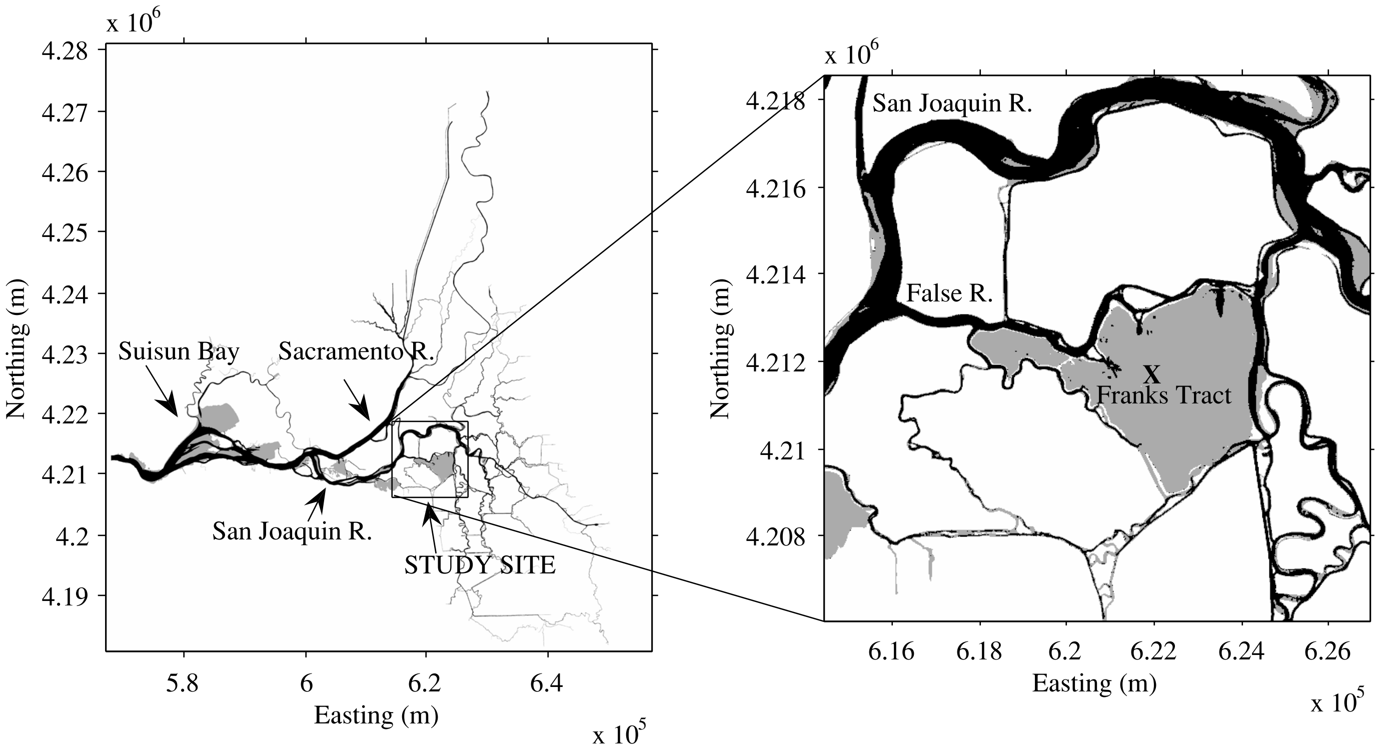

Figure 2. Bathymetric contours and site map of Franks Tract, within the Sacramento-San Joaquin Delta, showing the location of the instruments (cross). The black areas indicate depth greater than 3 m.

Table 1. Model constants and variables

Name	Units	Value/ Range	Description
α		60	Wave energy parameter
u_{*w}	m s^{-1}	0–0.54	Wind shear velocity–from field measurements
z_{0s}	m	$1.3H_{sig}$	Surface roughness
τ_b	N m^{-2}	0–0.2	Bed shear stress–from field measurements
H_{sig}	m	0–0.3	Significant wave height–from field measurements
P_s	m^2 s^{-3}	Model output	Shear production of turbulent kinetic energy
ε	m^2 s^{-3}	Model output	Dissipation of turbulent kinetic energy

Note: Constants are derived from the Grizzly Bay field data (Jones and Monismith 2008b).

low estuary measurements of Jones and Monismith (2008a). The water column surface roughness z_{0s} was parameterized as $z_{0s} = 1.3H_{sig}$. Here H_{sig} is the significant wave height. Comparison of the model output with the Grizzly Bay data-set showed that this was the most appropriate choice (Jones and Monismith 2008b). Because the range of waves' ages (defined as the peak wave phase speed normalized by the wind shear stress) was similar in the Franks Tract and Grizzly Bay experiments, it was reasonable to assume that parameterization of the turbulent kinetic energy flux and surface roughness would be similar. The parameterizations used for α and z_{0s} are within the range of previous studies. Wang and Huang (2004) found $\alpha = 80$ for the Surface Wave Dynamics Experiment (SWADE) (Drennan et al. 1996) and Water Air Vertical Exchange Studies (WAVES) (Terray et al. 1996) data-sets, showing that α was relatively insensitive to wave age. Umlauf (2003) found $z_{0s} = H_{sig}$ to best reproduce the SWADE (Drennan et al. 1996) and WAVES (Terray et al. 1996) data-sets.

The surface turbulent kinetic energy flux was implemented for wind speeds equal to or greater than 5 m s^{-1}; the Grizzly Bay measurements established that the probability of the occurrence of whitecapping reached 50% for wind speeds greater than 5 m s^{-1} (Jones and Monismith 2008a). For wind speeds less than 5 m s^{-1}, the turbulent kinetic energy flux was assumed to be zero, and the water surface was modeled as a wind stress log-layer.

The model was forced with the measured wind, wave, and tide conditions at Franks Tract for the 11-day period. The model was run to steady state at 0.5-hour intervals (e.g., Craig 1996).

RESULTS

Wind, Wave, and Tide Conditions

The mean velocities displayed strong asymmetry between the magnitude of flooding and ebbing tides due to the jet that formed as the water passed from the narrow False River inlet into Franks Tract on flood tide (Figure 3). The larger fluctuating components seen in the cross-stream current during flooding were most likely due to the largest eddies of the turbulent jet. The bed roughness z_{0b} (the height at which the mean velocity becomes zero when extrapolating the logarithmic velocity profile downward towards the bed) was estimated to be 0.02 mm based on the near-bed Reynolds stress estimates and the mean velocity at 1 meter above the bed. The near-bed Reynolds stress estimates showed that the surface waves did not lead to enhanced bottom drag (Figure 5B) (e.g., Bricker et al. 2005).

The winds were dominantly westerly and followed a diurnal pattern in strength (Figure 5C). Locally-generated waves of mean period approximately 2 s formed under strong wind conditions. Significant wave height ranged from 0 to 0.3 m (Figure 3D).

Whitecapping wind waves and wind-rows of bubbles—the surface signature of Langmuir circulations—were observed throughout part of the experiment (Figure 4).

Measurements of temperature revealed periodic occurrences of vertical temperature stratification; the water remained fresh throughout the study. Periods of stable stratification were identified by estimating the logarithm of the Richardson number (Ri: the ratio of buoyant production or consumption of turbulence to the shear production of turbulence that characterizes the vertical stability of the water column) normalized by the critical Richardson number (Ri_c) (Figure 3). Here we define $Ri_c = 0.25$ such that $\log_{10}(Ri/Ri_c) > 0$ indicates stable stratification (Lewis 1997). Vertical stratification typically formed through strain during ebb tides when warmer water from the shallow, vegetated zones of Franks Tract moved over the cooler water of the main channel (i.e., strain-induced periodic stratification as described by Simpson et al. 1990).

Model Results

The wind speed was below 5 m s^{-1} for 38% of the observations during the 11-day period. During these periods, the surface dynamics were modeled as a wind stress log-layer. For the remaining 62% of observations, the surface layer was modeled with the surface turbulent kinetic energy flux representing the influence of the whitecapping waves.

The simulations provided detailed vertical resolution of the mean and turbulent flow variables, allowing the layers where turbulent kinetic energy was predominantly produced by one of the three different sources (i.e., whitecapping, wind stress, or bed stress) to be readily identified. The layers were identified by investigating the ratio of turbulent kinetic energy shear production P_s to turbulent kinetic energy dis-

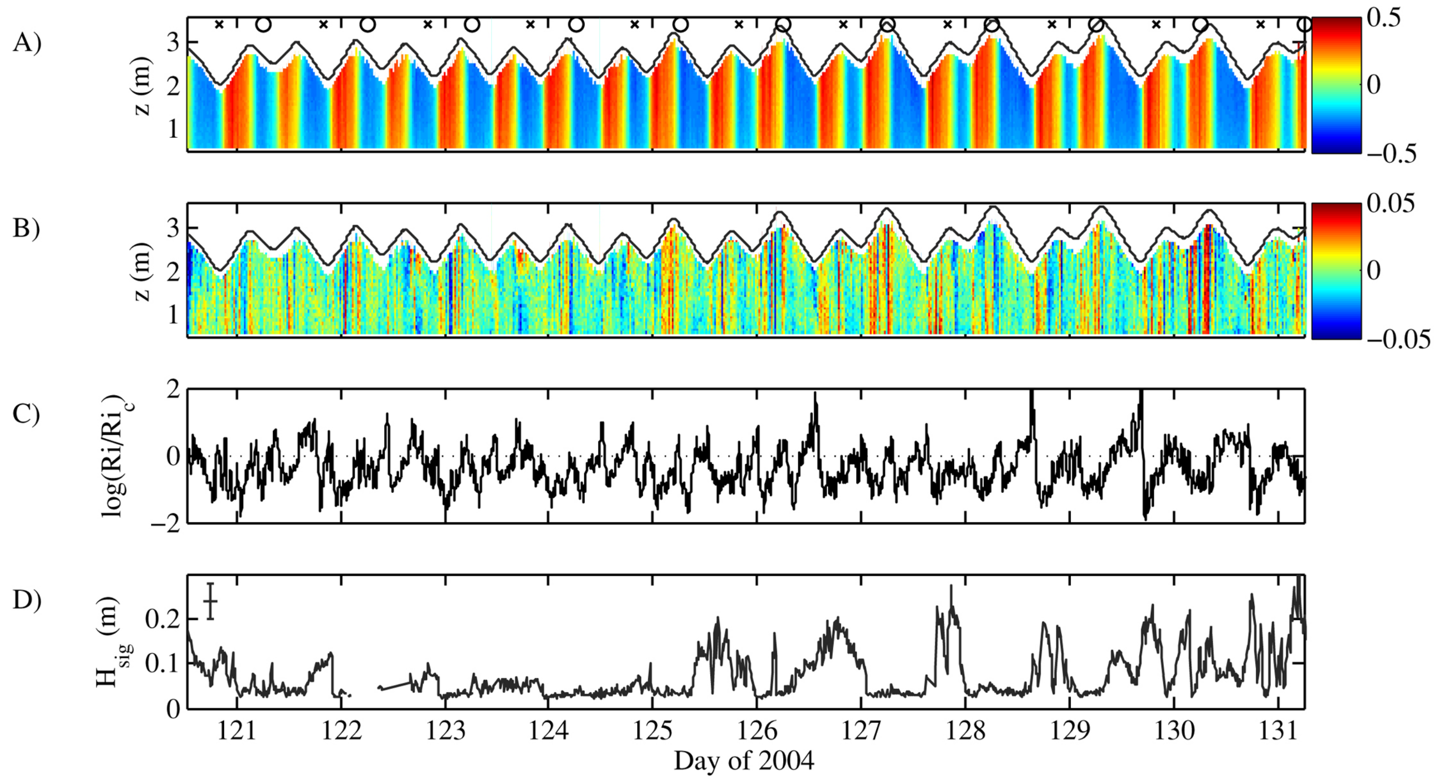

Figure 3. Time series of (A) streamwise currents (m s^{-1}); (B) cross-stream currents (m s^{-1}); (C) normalized Richardson number ($\log(Ri/Ri_c)$) and (D) significant wave height H_{sig} (m), for the duration of the experiment in Franks Tract. The x and o at the top of panel (A) indicate the times of sunset and sunrise, respectively.

Figure 4. Whitecapping wind waves and wind-rows of bubbles aligned with the wind direction were observed at Franks Tract. The wind-rows are the surface manifestation of Langmuir circulations.

sipation ε (Figure 5A). A ratio of $P_s/\varepsilon \sim 1$ indicates a bed stress log-layer or a wind stress log-layer. A ratio $P_s/\varepsilon \sim 0$ extending from the surface downward indicates the presence of a wave affected surface layer. The bed stress and surface stress are presented in Figure 5 to show the physical forcing that produced the calculated vertical structure of turbulent kinetic energy shear production and turbulent kinetic energy dissipation. Smaller bed shear stresses during ebb tides led to smaller bed stress log-layers than during flood tide, for a similar magnitude wind stress. During strong winds, the wave affected surface layer extended over a larger part of the water column, sometimes eliminating the wind stress log-layer. During periods of weak surface stresses, the ratio P_s/ε was close to 1 over most of the water column.

Comparison between the relative magnitudes of shear production to dissipation and consideration of the

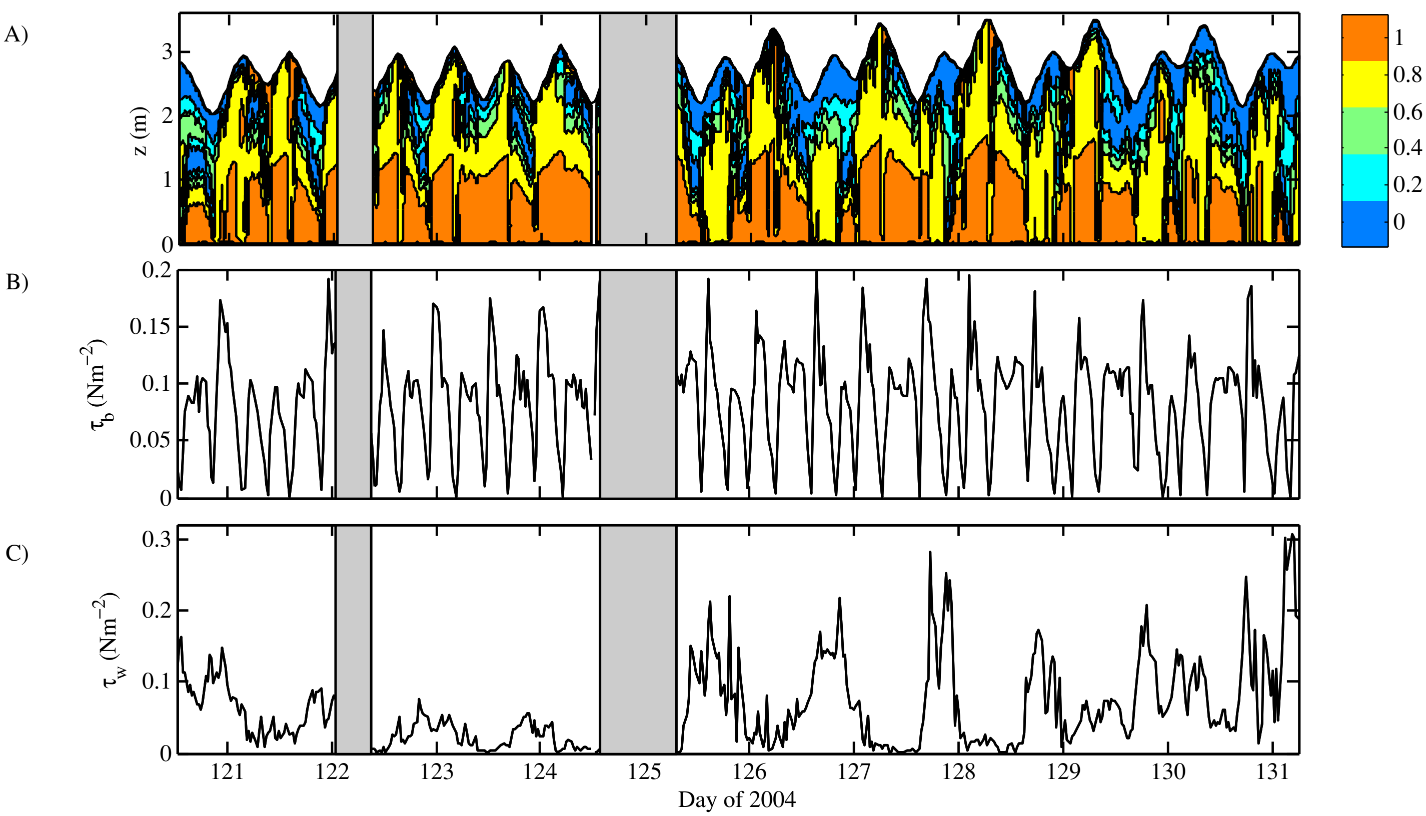

Figure 5. The relative distribution of turbulent kinetic energy shear production and turbulent kinetic energy dissipation as modeled for the Franks Tract field conditions. (A) Ratio of shear production P_s to dissipation ε (contours at intervals of 0.25); (B) Bed shear stress τ_b; (C) Surface shear stress due to wind τ_w. The gray boxes indicate periods where no data were collected.

vertical gradient of the streamwise velocity (used to identify the transition from bed stress log-layer to wind stress log-layer) allowed the transition depth between each of the layers to be identified for the duration of the simulations. Figure 6 shows the depth of penetration of the wave affected surface layer relative to the total water depth under whitecapping conditions. The shading distinguishes between cases where a wind stress log-layer existed (33%) and cases where the wave affected surface layer directly transitioned to the bed stress log-layer (29%). Under a moderate wind stress (U_{10} = 5–8 m s^{-1}), and hence moderate wave heights, the wave affected surface layer was dominantly restricted to the top 10% of the water column. Under stronger wind (U_{10} > 8 m s^{-1}), and hence stronger wave conditions, the whitecapping waves provided the dominant source of turbulent kinetic energy over a larger portion of the water column, eliminating the wind stress log-layer. However, the wave affected surface layer extended to the bottom half of the water column for only 7% of the observation period.

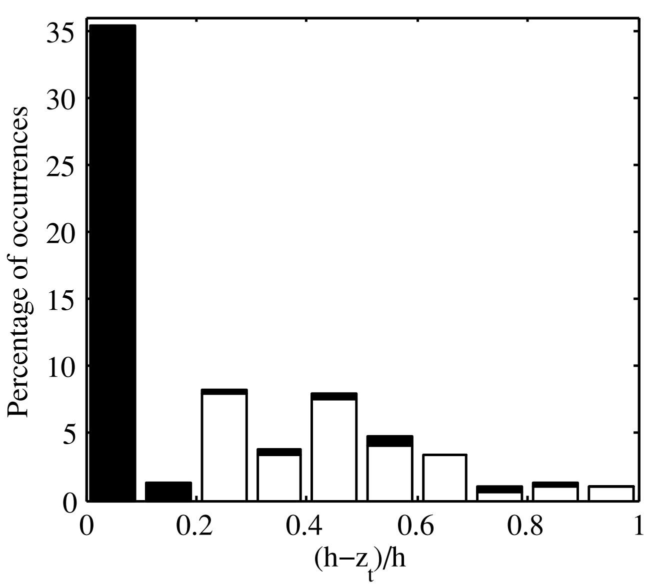

Figure 6. Depth of penetration of the wave affected surface layer $h - z_t$ as a fraction of the total water column height h for cases where the wave affected surface layer transitioned to the bed stress log-layer (white) and cases where the wave affected surface layer transitioned to the wind stress log-layer (black). Here $(h - z_t)/h$ = 1 means that the wave affected surface layer extends to the bed.

DISCUSSION

The model results indicated that whitecapping waves were not a large source of turbulent kinetic energy in the bottom half of the water column throughout the 11-day observation period. This means that phytoplankton concentrations close to the bed were largely unaffected by whitecapping waves, and that the formation of concentration boundary layers due to benthic grazing was not often disrupted by the whitecapping waves. It also means that vertical mixing of suspended sediment was largely unaffected by the whitecapping of waves under the conditions experienced during the 11-day experiment. The bed stress (resulting from the tidal current) provided the dominant source of turbulent kinetic energy over the bottom half of the water column for the majority of the 11-day period. These results are very different from those of the Grizzly Bay study (Jones and Monismith 2008a). The Grizzly Bay results imply that the mixing and transport of constituents such as sediment and phytoplankton would not be predicted accurately in numerical models without the whitecapping source of turbulent kinetic energy. This does not appear to be true at the Franks Tract site for the wind velocities observed.

The contribution of Langmuir circulations to turbulent kinetic energy production at the surface is small compared with that of whitecapping waves; however, Langmuir cells may contribute to enhanced dissipation at depth by vertically transporting wave-breaking–generated turbulence (Jones and Monismith 2008a). Langmuir cells were also observed during the Grizzly Bay site measurement period; therefore, we assume that any influence of the Langmuir circulation is captured in the parameterization of the model.

The magnitude and direction of the wind measured during the 11-day period was representative of conditions experienced throughout the diurnal westerly wind pattern season (March through October) (Conomos et al. 1985). Wave heights in Franks Tract have not been measured under winter storm conditions; however, whitecapping may be a more important source of turbulent kinetic energy under these conditions at the measurement site due to the increased fetch when the winds are from the east or southeast directions. Furthermore, conditions are likely to vary spatially within Franks Tract, particularly between open water and *E. densa* patches, where the wind energy needed to create whitecapping waves would need to be greater.

This study showed that the contribution of whitecapping waves to vertical mixing can differ greatly between different shallow water bodies. For an identical wind stress, the vertical extent of the wave affected surface layer was greater in Grizzly Bay than in Franks Tract. This difference was due to four differences in the systems. First, the fetch is greater in Grizzly Bay, and thus the waves can become larger. Second, wave damping by *E. densa* may contribute to the reduced wave heights at Franks Tract. Third, increased bed stress due to stronger tidal currents at the Franks Tract site diminished the relative importance of the whitecapping turbulent kinetic energy source. Finally, the deeper water at Franks Tract confined the influence of the wave affected surface layer to the upper half of the water column.

These findings will help us improve our understanding of the San Francisco Estuary ecosystem in two ways. First, the results of this study allow us to more aptly estimate losses of phytoplankton to the benthic grazers in this Estuary. This study has furthered our understanding of the temporal and spatial dynamics of vertical mixing in this Estuary and in shallow water systems in general, therefore improving our ability to predict the formation and strength of concentration boundary layers. Benthic grazing rates have been assumed to be limited by a concentration boundary layer in some shallow systems (e.g., Lopez et al. 2006; Lucas et al. 2002); however, it is apparent from this work that there are likely to be periods in the windy spring and summer seasons in Grizzly Bay when concentration boundary layers are not present. Under similar wind conditions at the Franks Tract measurement site, there are likely to be fewer periods where concentration boundary layer formation would be disrupted by whitecapping waves. Grazing rates in Grizzly Bay can therefore be estimated from pumping rates (a physiological measure that depends on species, temperature, and animal size) and abundance for much of the time. Grazing rates in Franks Tract will need to be based on pumping rates that are suitably reduced (to account for concentration boundary layer formation) during periods of limited vertical mixing (Thompson 1999). It should be noted that grazing rates that are calculated either way are likely to be over-estimates due to our poor understanding of the periods of bivalve inactivity that have been observed in the laboratory (Cole et al. 1992) and in the field (Thompson 1999). However, another study has shown that removal rates at the bed can greatly exceed estimated biological pumping rates, suggesting that physical removal mechanisms may dominate in some areas of the San Francisco Estuary (Jones et al. 2008). This removal mechanism was hypothesized to result from the aggregation of phytoplankton in a near-bed fluff layer (Jones et al. 2008).

Second, nuisance algae blooms are a cause of concern in all urban estuaries. San Francisco Estuary, like many others, has been invaded by the toxic blue-green alga, *Microcystis aeruginosa*, and resource and restoration managers are struggling with methods to control and understand algal bloom distribution. Several studies have reported that *M. aeruginosa* colonies are disaggregated under high rates of turbulent mixing, thereby reducing the colonies' viability (e.g., O'Brien et al. 2004). The relatively low turbulence estimated for the surface water over the 11-day period at the Franks Tract site may help explain why many of the shallow open water areas in the tidal freshwater Estuary (Lehman et al. 2005) are good habitat for blue-green algae.

ACKNOWLEDGEMENTS

Thanks are due to F. Parchaso, B. Richards, and M. Shouse from the U.S. Geological Survey for assistance with the field experiment. We would also like to thank A. Anderson, M. Brennan, K. Davies, D. Fong, J. Hench, G. Ketefian, M. Lionberger, G. Misra, R. Lowe, D. Ormerod, M. Plumlee, N. Nidzieko, N. Riegels, J. Rosman and L. Shih for their help in collecting the field data-set. This work was generously supported by the CALFED Bay Delta Authority Restoration Program (ERP02P22) and The Foundation for Young Australians Centenary Scholarship Award.

REFERENCES

Agrawal YC, Terray EA, Donelan MA, Hwang PA, Williams AJ, Drennan WM, Kahma KK, Kitaigorodskii SA. 1992. Enhanced dissipation of kinetic-energy beneath surface-waves. Nature 359(6392):219-220.

Alpine AE, Cloern JE. 1992. Trophic interactions and direct physical effects control phytoplankton biomass and production in an estuary. Limnology and Oceanography 37(5):946-955.

Bennett WA, Moyle PB. 1996. Where have all the fishes gone? Interactive factors producing fish declines in the Sacramento–San Joaquin Estuary. In: Hollibaugh JT, editor. San Francisco Bay: the ecosystem. San Francisco: Pacific Division of the American Association for the Advancement of Science. p 519-542.

Bricker JD, Inagaki S, Monismith SG. 2005. Bed drag coefficient variability under wind waves in a tidal estuary. ASCE Journal of Hydraulic Engineering 131(6):497-508.

Burchard H. 2001. Simulating the wave-enhanced layer under breaking surface waves with two-equation turbulence models. Journal of Physical Oceanography 31(11):3133-45.

Burchard H, Petersen O. 1999. Models of turbulence in the marine environment - a comparative study of two-equation turbulence models. Journal of Marine Systems 21(1-4):29-53.

CALFED. 2000. Ecosystem restoration plan, Volume II: Ecological management zone visions. CALFED Bay-Delta Program. http://www.delta.dfg.ca.gov/erp/docs/reports_docs/ERPP_Vol_2.pdf

Cloern JE. 1982. Does the benthos control phytoplankton biomass in South San Francisco Bay? Marine Ecology Progress Series 9(2):191-202.

Cole BE, Thompson JK, Cloern JE. 1992. Measurement of filtration-rates by infaunal bivalves in a recirculating flume. Marine Biology 113(2):219-225.

Conomos TJ, Smith RE, Gartner JW. 1985. Environmental Setting of San Francisco Bay. Hydrobiologia 129(OCT):1-12.

Craig PD. 1996. Velocity profiles and surface roughness under breaking waves. Journal of Geophysical Research 101(C1):1265-77.

Craig PD, Banner ML. 1994. Modeling wave-enhanced turbulence in the ocean surface-layer. Journal of Physical Oceanography 24(12):2546-2559.

Craik ADD, Leibovich S. 1976. A rational model for Langmuir circulations. Journal of Fluid Mechanics 73(3):401-426, [doi:10.1017/S0022112076001420].

Donelan MA. 1990. Air-Sea Interaction. In: LeMehaute B, Hanes DM, editors. Ocean engineering science. New York: Wiley. p 239-292.

Drennan WM, Donelan M.A., Terray E.A., Katsaros K.B. 1996. Oceanic turbulence dissipation measurements in SWADE. Journal of Physical Oceanography 26(5):808-815.

Jassby AD, Cloern JE, Cole BE. 2002. Annual primary production: Patterns and mechanisms of change in a nutrient-rich tidal ecosystem. Limnology and Oceanography 47(3):698-712.

Jones NL, Monismith SG. 2007. Measuring short-period wind waves in a tidally forced environment with a subsurface pressure gauge. Limnology and Oceanography: Methods 5:317-327.

Jones NL, Monismith SG. 2008a. The influence of whitecapping waves on the vertical structure of turbulence in a shallow estuarine embayment. Journal of Physical Oceanography doi:10.1175/2007JPO3766.1.

Jones NL, Monismith SG. 2008b. Modeling the influence of wave enhanced turbulence in a shallow tide- and wind-driven water column. Journal of Geophysical Research 113, C03009, doi:10.1029/2007JC004246.

Jones NL, Thompson JK, Arrigo KR, Monismith SG. 2008. Hydrodynamic control of phytoplankton loss to the benthos in an estuarine environment. Limnology and Oceanography (in review).

Kimmerer WJ. 2002. Effects of freshwater flow on abundance of estuarine organisms: physical effects or trophic linkages? Marine Ecology Progress Series 243:39-55.

Kimmerer WJ, Orsi JJ. 1996. Changes in the zooplankton of the San Francisco Bay Estuary since the introduction of the clam Potamocorbula amurensis. In: Hollibaugh JT, editor. San Francisco Bay: The ecosystem. Pacific Division of the American Association for the Advancement of Science. p 403-424.

Lehman PW, Boyer G, Hall C, Waller S, Gehrts K. 2005. Distribution and toxicity of a new colonial *Microcystis aeruginosa* bloom in the San Francisco Bay Estuary, California. Hydrobiologia 541(1):87-99.

Lewis R. 1997. Dispersion in estuaries and coastal waters. New York: John Wiley and Sons.

Lopez CB, Cloern JE, Schraga TS, Little AJ, Lucas LV, Thompson JK, Burau JR. 2006. Ecological values of shallow water habitats: Implications for the restoration of disturbed ecosystems. Ecosystems 9(3):422-440.

Lucas LV, Cloern JE, Thompson JK, Monsen NE. 2002. Functional variability of habitats within the Sacramento-San Joaquin Delta: Restoration implications. Ecological Applications 12(5):1528-1547.

Magnaudet J, Thais L. 1995. Orbital rotational motion and turbulence below laboratory wind water-waves. Journal of Geophysical Research 100(C1):757-771.

May CL, Koseff JR, Lucas LV, Cloern JE, Schoellhamer DH. 2003. Effects of spatial and temporal variability of turbidity on phytoplankton blooms. Marine Ecology Progress Series 254:111-128.

Mecum WL, Orsi JJ. 2001. Zooplankton and mysid shrimp. IEP Newsletter (California Department of Water Resources, Sacramento) 14(2):12-15.

O'Brien KR, Meyer DL, Waite AM, Ivey GN, Hamilton DP. 2004. Disaggregation of *Microcystis aeruginosa* colonies under turbulent mixing: laboratory experiments in a grid-stirred tank. Hydrobiologia 519(1–3):143-152.

Orsi JJ, Mecum WL. 1996. Food limitation as the probable cause of long-term decline in the abundance of *Neomysis mercedis* the opossum shrimp in the Sacramento-San Joaquin Estuary. In: Hollibaugh JT, editor. San Francisco Bay: the ecosystem. San Francisco: Pacific Division of the American Association for the Advancement of Science. p 375-401.

Shaw WJ, Trowbridge JH. 2001. The direct estimation of near-bottom turbulent fluxes in the presence of energetic wave motions. Journal of Atmospheric and Oceanic Technology 18(9):1540-1557.

Simpson JH, Brown J, Matthews J, Allen G. 1990. Tidal straining, density currents, and stirring in the control of estuarine stratification. Estuaries 13(2):125-132.

Skyllingstad ED, Denbo DW. 1995. An ocean large-eddy simulation of Langmuir circulations and convection in the surface mixed-layer. Journal of Geophysical Research 100(C5):8501-8522.

Teixeira MAC, Belcher SE. 2002. On the distortion of turbulence by a progressive surface wave. Journal of Fluid Mechanics 458:229-267.

Terray EA, Donelan MA, Agrawal YC, Drennan WM, Kahma KK, Williams AJ, Hwang PA, Kitaigorodskii SA. 1996. Estimates of kinetic energy dissipation under breaking waves. Journal of Physical Oceanography 26(5):792-807.

Thompson JK. 1999. The effect of infaunal bivalve grazing on phytoplankton bloom development in South San Francisco Bay [dissertation]. Palo Alto: Stanford University.

Umlauf L, Burchard H. 2003. A generic length-scale equation for geophysical turbulence models. Journal of Marine Research 61(2):235-265.

Umlauf L, Burchard H. 2005. Second-order turbulence closure models for geophysical boundary layers. A review of recent work. Continental Shelf Research 25(7-8):795-827.

Umlauf L, Burchard H, Hutter K. 2003. Extending the k-omega turbulence model towards oceanic applications. Ocean Modelling 5(3):195-218.

Wang W, Huang RX. 2004. Wind energy input to the surface waves. Journal of Physical Oceanography 34(5):1276-1280.