Mixing Efficiency in the Ocean

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Mixing efficiency is the ratio of the net change in potential energy to the energy expended in producing the mixing. Parameterizations of efficiency and of related mixing coefficients are needed to estimate diapycnal diffusivity from measurements of the turbulent dissipation rate. Comparing diffusivities from microstructure profiling with four simultaneous tracer releases has verified, within observational accuracy, 0.2 as the mixing coefficient over a 30-fold range of diapycnal diffusivities. Although some mixing coefficients can be estimated from pycnocline measurements, at present mixing efficiency must be obtained from channel flows, laboratory experiments and numerical simulations. Reviewing the different approaches demonstrates that estimates and parameterizations for mixing efficiency and coefficients are not converging beyond the at-sea comparisons with tracer releases, leading to recommendations for a community approach to address this important issue.

Estimating eddy diffusivities in the ocean

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Away from the surface and bottom boundaries, the interior of the oceans is stably stratified in general, and mixing occurs there due to turbulence generated by shear instability and under appropriate conditions, double-diffusive convection. The resulting eddy diffusivities of momentum and scalar properties are determined by the gradient Richardson number *Ri* in the case of shear instability and the density ratio R_{rho} in the case of double diffusive convection. However, in oceanic regions susceptible to double-diffusive convection, velocity shear may not be negligible, in which case, both *Ri* and R_{rho} play a role in determining the intensity of mixing and hence the prevailing diffusivities. Which mode of mixing dominates, depends on the precise values of these parameters. For low Richardson numbers, shear driven instability prevails and for high Richardson numbers, double diffusion can dominate. As such, when measuring eddy diffusivities in the ocean interior, it is essential to deploy a microstructure profiler along with an ADCP so that the precise location of the oceanic region in the *Ri* - R_{rho} parameter space can be determined. In this talk, we provide an overview of theoretical, observational and numerical model studies of eddy diffusivities in the ocean, with particular emphasis on double diffusive convection, and present some results from recent observational campaigns.

Keywords: Ocean mixing, Double diffusive convection, Salt fingers, Diffusive convection, eddy diffusivities

The Probability Distribution of Kinetic Energy Dissipation Rate in Ocean

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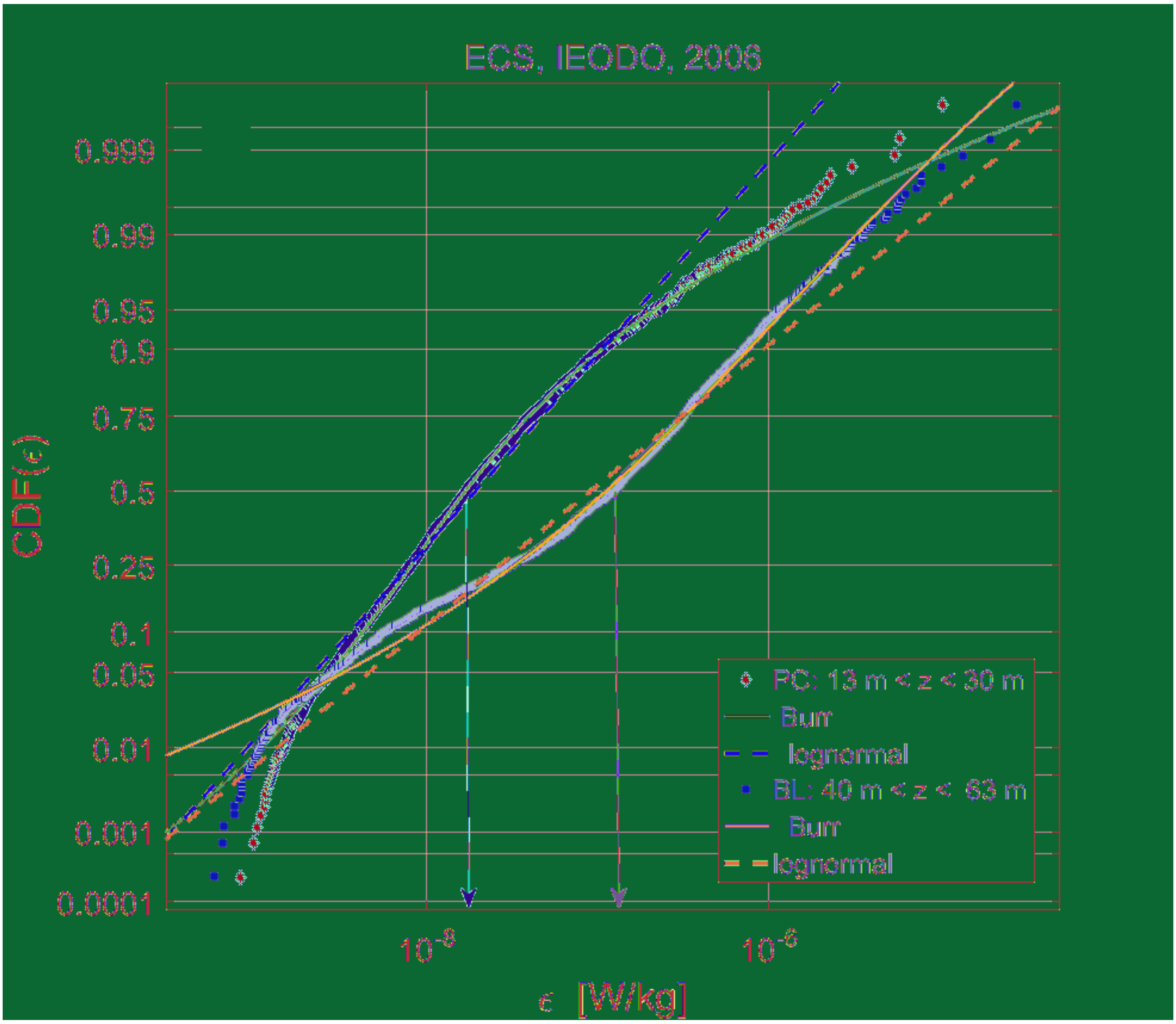
Ocean turbulence is highly intermittent in space and time with characteristic vertical scales of active turbulent zones (patches), varying from tens of centimeters up to several or sometimes tens of meters. The patches are separated by layers of relatively low turbulence activity, which is usually quantified in terms of the turbulent kinetic energy dissipation rate *eps* averaged over particular volumes or radius *r*. Such spatial inhomogeneity of dissipation has been specified as "mesoscale" or "external" intermittency in order to be distinguished from "internal" or genuine intermittency of *eps*, which is attributed to random distribution of vortex filaments within turbulent regions, where they stretch and dissipate energy in isolation. Internal intermittency of *eps* belongs to inertial-convective and diffusive subranges, between an outer turbulent scale L_o ~ 1 m or less in stratified ocean and the dissipative Kolmogorov scale L_K of the order of less than 1 cm. The refined similarity hypothesis of Kolmogorov [1962] assumes random fluctuations of dissipation rate in the inertial-convective subrange and the probability distribution of the dissipation intermittency is lognormal. Although the lognormal model and its modifications has been successfully applied to various turbulent flows under high Reynolds numbers, it appears to be mathematically ill-posed. Yet, many researchers regard lognormal distribution as reasonably good practical approximation for *eps* that characterizes internal/genuine intermittency of turbulence generated continuously or by individual events/overturns.

The lognormal model has been applied to *eps* measured in well-mixed relatively deep turbulent boundary layers near the sea surface and near the ocean floor and in large turbulent overturns (~10 m or more in diameter) that are observed in the ocean interior. However, conventional equidistant estimates of *eps*, which are usually calculated over relatively small vertical domains (typical averaging distance *l* = 1-2 m), represent a random field of the dissipation samples observed at various stages of turbulence evolution. The probability distributions of this dissipation field in a specific region can characterize external/mesoscale intermittency of turbulence influenced by larger scale dynamical processes, which depends on energy sources and ambient stratification. It has been recently shown that the probability distribution of the logarithm of the dissipation rate in a strongly stratified pycnocline can follow the generalized extreme value distribution due to rare random generation of energetic turbulence events, which form patches of high dissipation rate, while most of the background turbulence is confined to weakly dissipative regions at final stages of turbulence decay.

The notion that the probability distribution of the dissipation rate measured in stratified ocean by airfoil sensors substantially deviates from the classic lognormal approximation, often to follow the Burr probability distribution, is discussed here based on several field campaigns carried out by the authors during the last decade. The measurements have been taken in the East China Sea, Northern Bay of Bengal, to the south and to the east from Sri Lanka, and in the Gulf Stream region to the east from the North Carolina shelf. The background dynamics in the regions is characterized by distributions of the buoyancy frequency N^2 and buoyancy Reynolds number Re_b.

Keywords: turbulence, dissipation rate, intermittency, probability distribution



Submesoscale resolving ocean simulations with multiple ocean mixing parameterizations

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Motions with higher degree of ageostrophy appear in the oceanic simulations when sub-mesoscale eddies and associated boundary layer processes begin to be resolved in ocean models. These are quintessentially related to horizontal density gradients related to oceanic fronts. These motions have O(1) Rossby and O(1) Richardson numbers, much larger vertical exchange than their large scale counterparts and appear at O(1-10 km) scales in the ocean. There has been much recent interest in their interaction with both relatively smaller and larger scales. We focus on the former.

We have conducted simulations for forced submesoscale eddy resolving simulations using multiple ocean mixing closure schemes using a non-hydrostatic three dimensional process study ocean model (PSOM) including k-epsilon models and K-Profile parameterization, for both mid-latitude deep ocean mixed layers (e.g. North Atlantic) and spicy subtropical oceans with shallow mixed layers but higher density gradients (e.g. Indian ocean). We show that ocean mixing matters for the sub-mesoscale as the rate of re-stratification near oceanic fronts is sensitive to the ocean mixing parameterization. We discuss both its physical and ecosystem implications.

Keywords: submesoscale, ocean fronts, mixing parameterization

Revisiting fine-scale parameterizations for enhanced tidal mixing over a rough ocean bottom

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Although an accurate representation of ocean mixing processes into global circulation models is essential for accurate climate predictions,, existing parameterizations of mixing over rough bathymetry have plenty of room for improvement. For example, they do not take into account the fact that, as tide-topography interactions strengthen ($k_H U_0/\Omega > 1$), the generated internal waves transform from linear internal tides to quasi-steady internal lee waves where U_0 is the amplitude of the tidal flow dominating the background flow in the Garrett-Munk (GM) internal wave field, k_H is the horizontal wavenumber of the bottom topography, and $\Omega$is the semidiurnal tidal frequency.

In the present study, using a fixed value of the buoyancy frequency, we perform a series of eikonal calculations to examine the energy transfer from upward propagating quasi-steady internal lee waves to dissipation through nonlinear interactions with the background GM internal waves in a vertical two-dimensional plane. It is shown that the vertical structure of the mixing hotspot becomes dominated by U_0 rather than k_H; as U_0 increases, the fraction of energy dissipated at the ocean bottom decreases and the energy dissipation region extends vertically upward off the ocean bottom. These calculated results can be interpreted in terms of the vertical group velocity, C_{gz}, and the life time, τ, of the upward propagating quasi-steady lee wave packet. For a fixed density stratification, as k_H increases while keeping U_0 constant, C_{gz} becomes larger but becomes smaller so that the vertical decay scale of the energy dissipation rate remains nearly constant, whereas C_{gz} becomes larger but remains unchanged as U_0 increases while keeping k_H constant so that the vertical decay scale of the energy dissipation rate rapidly increases. This means that the resulting mixing hotspot extends further upward as U_0 increases, independent of k_H. This is in contrast to the result of the previous study by *Iwamae et al.* [2009] and *Iwamae and Hibiya* [2012] who showed that the concentration of the mixing hotspot becomes more focused nearer the ocean bottom as k_H increases, independent of U_0, although a trade-off relationship is found between the fraction of energy dissipated at the ocean bottom and the vertical extent of the energy dissipation region off the ocean bottom. A possible explanation for this difference is that C_{gz} and $\tau$are both inversely proportional to k_H for linear internal tides.

The results of this study should be reflected in the parameterization of mixing over rough bathymetry to improve the accuracy of ocean general circulation models.

Keywords: Bottom-intensified turbulent mixing, Quasi-steady lee waves, Vertical group velocity, Nonlinear interaction time, Tidal flow amplitude, Ocean bottom roughness

The Dependence of Tidal Effects Including Internal Tides and Mixing on Latitude

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The effects of latitude on internal tides, internal waves and mixing were investigated using Regional Ocean Modeling System (ROMS) simulations by shifting a small domain with a seamount from 20.6° to 28.6° S. The critical latitude is the latitude where the inertial frequency equals the tidal frequency, which for the K_1 constituent is 30° and O_1 is 27.6°. Linear internal wave theory says that internal tides are trapped and will not propagate poleward of their respective critical latitudes. The same topography and hydrography from Barcoo Seamount off New South Wales collected during SS0906 were used in all simulations.
The largest diurnal tides occurred near the critical latitudes and for 3-6° equatorward of critical latitude. The diurnal internal tides equatorward of the diurnal critical latitudes propagated in beams in agreement with linear theory. At the diurnal critical latitudes, diurnal energy peaked. Poleward of critical latitude, the diurnal internal waves had a signature which encompassed more of the water column vertically and they did not propagate in a beam-like pattern. By 8° poleward of the K_1 critical latitude, critical latitude effects had ceased. Poleward of the diurnal critical latitudes, significant diurnal internal tidal energy shifted to the semidiurnal constituents, harmonics, and high frequencies. As a result, semidiurnal internal tidal energy peaked just poleward of the diurnal critical latitude, as did energy at the tidal harmonic frequencies, 3, 4, 6, 8, cpd. Bispectra confirmed these energy transfers. Tidal residuals, mean velocities generated by the tides, were latitude and depth dependent, with the largest residuals near the critical latitudes and within 6 ° poleward of them. The latitudes 4-6° poleward of the K_1 critical latitude had the highest vertical temperature diffusivities along the flanks of the seamount and they showed the largest temperature changes in the neighbourhood of the permanent pycnocline, 500-100 m depth. The average diffusivities of both temperature and momentum increased with increasing latitude until near the critical latitude, where they dipped at both critical latitudes. Poleward of the critical latitudes, the diffusivities peaked 4° poleward of the K_1 critical latitude and then decreased with increasing latitude. Due to vertical shifts in the location of the higher diffusivities, changes in potential temperature and salinity were significantly larger and of the opposite sign for the latitudes 4-6° poleward of the K_1 critical latitude than for the other latitudes.

Keywords: mixing, internal tides, critical latitude

How the Tokara strait cultivates the Kuroshio

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Previous studies have reported clear signs of vigorous turbulent mixing in the Kuroshio due to the presences of shallow and steep topographies in its path (e.g., Hasegawa et al., 2004 and 2008, Chang et al., 2016). Turbulent mixing is one of the most important processes supplying nutrients to the surface euphotic zone from the deep water; however, a quantitative understanding of the turbulent vertical nutrient flux is still limited. On November 2016, we have conducted intensive survey around the Tokara strait by drifting the T/V Kagoshima-maru with the Kuroshio's stream and passed across the shallow (~100 m) sill while deploying a submersible ultraviolet nitrate analyzer (Deep SUNA by Satlantic) attached on a turbulence ocean microstructure profiler (TurboMAP-L by JAC). Occurrence of a flow separation and a hydraulic jump on the sill have been identified from a high resolution velocity survey. The rate of dissipation of kinetic energy reaches $O(10^{-5}$ W kg$^{-1})$, and the turbulent vertical nitrate flux reaches $O(1$ mmol m^{-2} day$^{-1})$, which is the highest value ever reported for the open ocean.

Keywords: Turbulence, Mixing, Topography, Nutrient, Nitrate, Flux

Observations of bands of strong turbulence associated with high wavenumber near-inertial wave shear below the Kuroshio origin using a tow-yo microstructure profiler

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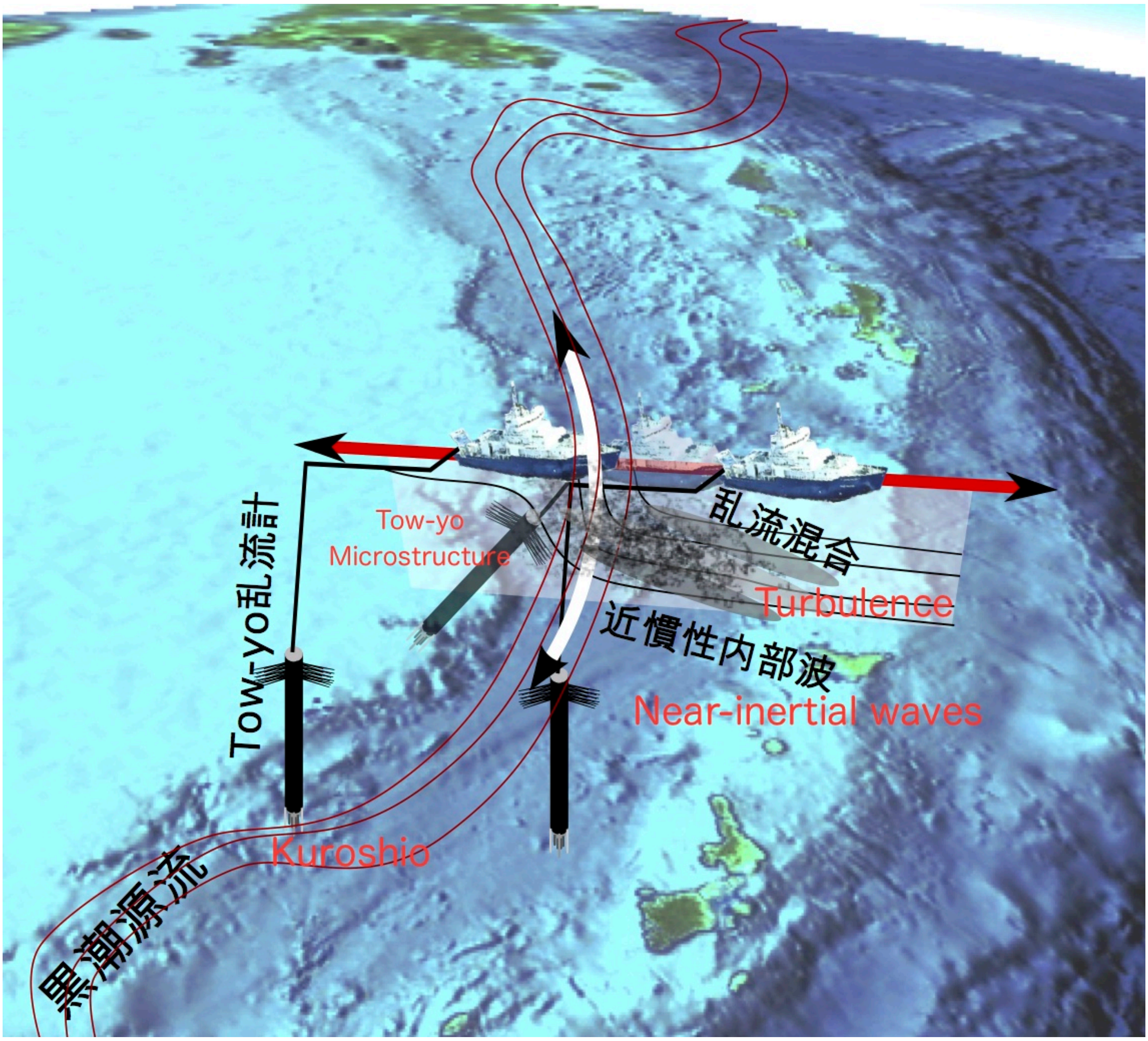
The upstream Kuroshio flows through Okinawa trough and Tokara island chains. In these regions, latitude is near 28.9 degree N, as known as the critical latitude, where M_2 internal tides can be converted to near-initial internal waves of high vertical wavenumber through parametric subharmonic instability and associated strong turbulent mixing is expected (MacKinnon and Winters 2005, Hibiya and Nagasawa 2004). Furthermore, the Kuroshio has to go through the region near the continental shelf of East China Sea and shallow seamounts near the Tokara strait, where the lee wave generation by the geostrophic current over the topography and associated near-inertial waves (Nikurashin and Ferrari 2011) are likely to occur. Also, the Kuroshio is forced to meander to flow southward after it approaches off Kyushu, where the spontaneous generation of near-inertial internal waves is possible (Nagai et al. 2015). The in-situ observations by Rainville and Pinkel (2004) using the ADCP and LADCP show that large amplitude near-inertial wave shear of high vertical wavenumber is found in and below the Kuroshio thermocline. These near-inertial internal waves can be trapped on the south side and/or underneath the Kuroshio due to its strong negative relative vorticity and vertical shear of the horizontal geostrophic flow (Kunze 1985, Whitt and Thomas 2013), and possibly break into microscale turbulence. However, the in-situ observations of microscale turbulence is very limited in these regions. In this study, in-situ observations of microscale turbulence near the Tokara strait were conducted during Nov. 12-20 2016 using R/T/V Kagoshima-maru. The new underway tow-yo microstructure profiler (Underway-VMP) was used, and we successfully measured turbulence along and across the Kuroshio Front with 1-2 km lateral resolution. The shipboard ADCP measurements show bands of high vertical wavenumber shear nearly along isopycnal, which are reminiscent of the results by Rainville and Pinkel (2004). The ray path calculated assuming quiescent condition suggests that the observed shear bands are caused by the internal waves of near-inertial frequencies. The hodograph of shear and rotary spectra suggest that these internal waves propagate energy both up and downward directions. The measured turbulent kinetic energy dissipation rates along and across the Kuroshio show bands of strong turbulence >O(10^{-7} W/kg) clearly associated with the high vertical wavenumber near-inertial shear, suggesting that propagating near-inertial waves underneath the Kuroshio induces the strong turbulent mixing. The comparison of observed turbulent dissipation rates with the strain based internal-wave parameterization by Kunzel et al. (2006) shows certain proportionality between the observations and the parameterization, which supports the conclusion that the measured strong turbulence is caused by the observed high vertical wavenumber near-inertial waves. The estimated vertical eddy diffusivity using the method of Osborn (1980) with observed dissipation rates and stratification, shows O(10^{-4} m^2/s) of eddy diffusivities on average within these bands of turbulent layers. These results suggest that the high vertical wavenumber near-inertial waves propagating in and below the Kuroshio near the Tokara strait could cause large impacts on the local watermass formations, tracer and momentum mixing, and associated biogeochemical responses in its downstream.

Keywords: Kuroshio, near-inertial shear bands, bands of strong turbulent layer



Assessment of the existing fine-scale parameterizations of deep ocean mixing in the Antarctic Circumpolar Current regeon

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The intensity of the observed deep ocean mixing is obviously falling short of the required value to sustain the global overturning circulation. The most likely candidates for this missing mixing are breaking of near-inertial waves induced by strong westerly wind and internal lee waves generated by Antarctic Circumpolar Current (ACC) impinging on rough topography in the Southern Ocean. Quantification of the turbulent mixing in the Southern Ocean is, therefore, an important issue to elucidate the structure of the global overturning circulation.

Because of the difficulty of direct microstructure measurements, it is common to employ finescale parameterizations (especially, Gregg-Henyey-Polzin (GHP) parameterization) to estimate turbulent energy dissipation rates. In these parameterizations, however, turbulent dissipation rates are assumed to be predicted as the rate of energy transfer to small dissipation scales by wave-wave interactions within the background internal wave spectrum and the effects of geostrophic current shear and mesoscale eddies, both of which are ubiquitous in the Southern Ocean, are not taken into account.

In this study, we carried out simultaneous measurements of microscale turbulence and finescale shear/strain in the Southern Ocean, south of Australia to assess the validity of the existing finescale parameterizations in the ACC region where geostrophic flows and mesoscale eddies coexist with the background internal wavefield.

Although the turbulent dissipation rate and derived diapycnal diffusivity were overall small, the internal wave energy was larger than the Garrett-Munk (GM) value. The finescale shear/strain ratio (R_ω) well exceeded the GM value at the stations south of Southern ACC Front, suggesting that the local internal wave spectra were significantly biased to lower frequencies.

Through the comparison of the turbulent dissipation rates inferred from parameterizations with the directly measured values, we find that GHP and Ijichi-Hibiya (IH) parameterizations, both of which take into account the spectral distortion in terms of R_ω, can well predict the observed turbulent dissipation rates in many places, while the shear-based parameterization (the strain-based parameterization) tends to overestimate (underestimate) the observed values, consistent with the large value of R_ω.

However, at the stations where the vertical shear of mean flow, presumably associated with geostrophic flows and/or mesoscale eddies, is enhanced, even GHP and IH parameterizations tend to overestimate turbulent dissipation rates by up to a factor of 3. At one of these stations, in particular, we find dominant downward-propagating near-inertial waves with their vertical wavenumbers possibly doppler-shifted up to the breaking limit at the critical layer. The overestimated turbulent dissipation rates mentioned above might be explained by the fact that the near-inertial wave energy lost at the critical layer is not completely dissipated but partially transferred to the background mean flow.

Keywords: Antarctic Circumpolar Current, Southern Ocean, deep ocean mixing, finescale parameterizations

Submesoscale cascade processes in the S. China Sea

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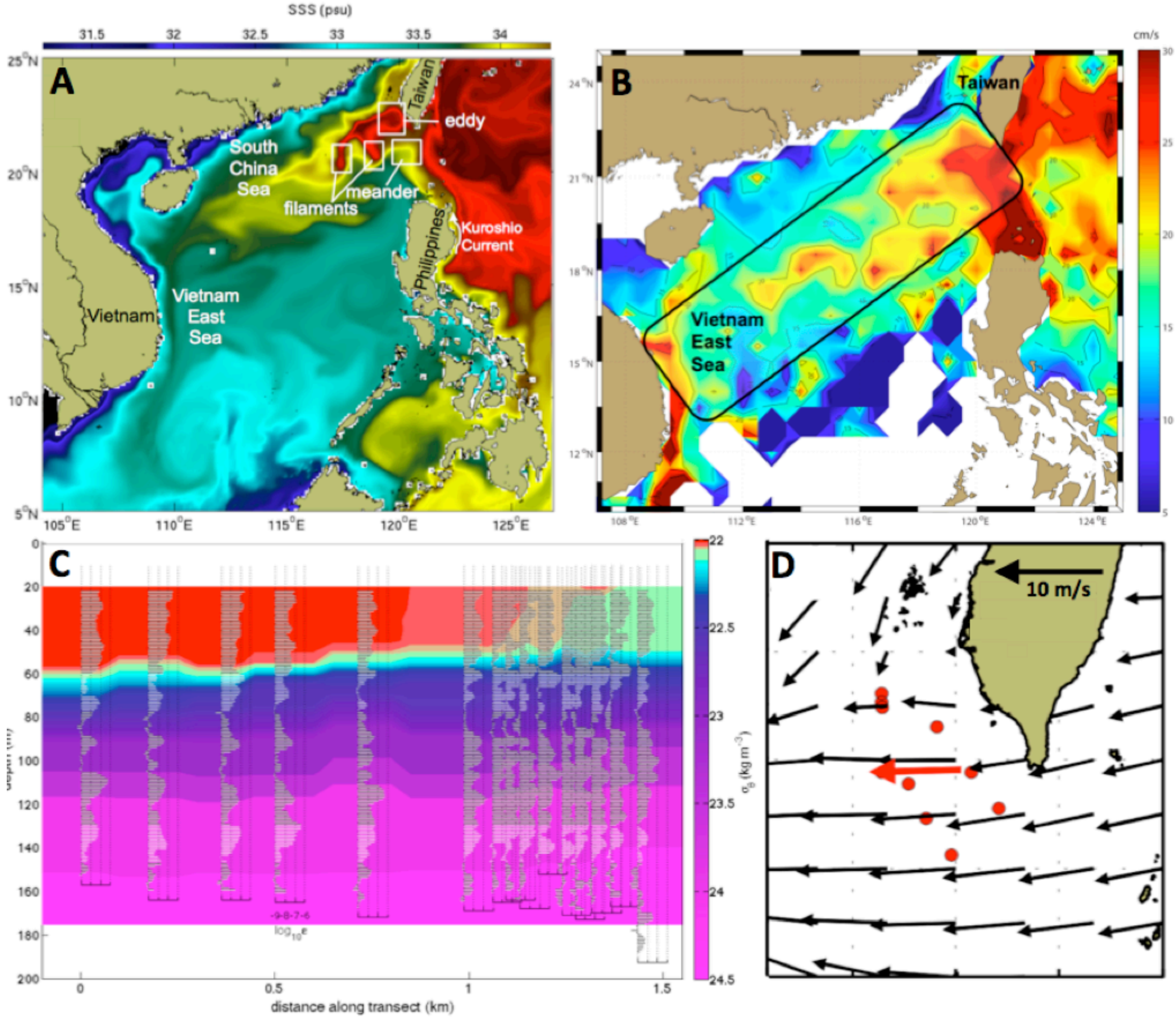
The S. China Sea is understood to be one of the most energetic regional seas in the global ocean. The combination of the Kuroshio Current, the monsoon, strong tides, and the dramatic topography of the Luzon Strait lead to a rich physical forcing environment. In addition to the enhanced internal wave environment that has been the focus of much work (ASIAEX, NLIWI and IWISE), the region southwest of Taiwan has been documented as a maximum in eddy kinetic energy. However, outside of the realm of internal wave processes, the physics of the submesoscale cascade of energy has been poorly studied.

Here, we describe a new examination of submesoscale processes in the S. China Sea. The focus is on the class of oceanographic variability that is poorly constrained in models including eddies, vortices and filaments, and their interactions with smaller-scale phenomena (Fig. 1A). While the whole S. China Sea system is of interest, including the Vietnam East Sea, the initial survey work has focused on the region just southwest of Taiwan. In this region, the Kuroshio Current feeds warm-salty water through the Luzon Strait. As the Current meanders into the Luzon Strait, it sheds eddies and filaments, which in turn interact with the local wind forcing. Along the southern tip of Taiwan, the wind field is complicated by the blocking effects of high mountains on the eastern side of Taiwan, with easterly winds south of Taiwan, and northerly winds in the Taiwan Strait. This combination of eddies, filaments, and wind lead to an active submesoscale cascade.

Keywords: Mixing, Monsoon, Cascade


SSS (psu)
31.5
32
32.5
33
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34
A
South China Sea
Taiwan
eddy
filaments
meander
Kuroshio Current
Philippines
Vietnam
Vietnam East Sea
25°N
20°N
15°N
10°N
5°N
105°E
110°E
115°E
120°E
125°E
B
Taiwan
Vietnam East Sea
cm/s
C
distance along transect (km)
σ_θ (kg m^{-3})
D
10 m/s

Non-hydrostatic simulations of tidally-induced mixing in the Halmahera Sea: A possible role in the transformation of the Indonesian Throughflow waters

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The Indonesian Throughflow (ITF) carries the relatively warm and saline Pacific waters into the Indian Ocean. These waters are significantly transformed while passing through the Indonesian Archipelago and eventually influence the large-scale ocean circulation such as Agulhas and Leeuwin Currents. Most OGCMs are, however, incapable of reproducing the transformation of the ITF waters, since tidal forcing is neglected in such models.
In the present study, we focus on the Halmahera Sea where the saline bias of the existing OGCMs is most significant. In order to clarify the physical mechanisms that control the water-mass transformation in the Halmahera Sea, we first drive a high-resolution (dx, dy ~ 180 m) non-hydrostatic three-dimensional numerical model incorporating realistic tidal forcing and bathymetric features. On the basis of the calculated results, we next evaluate each of the effects of tidally-enhanced vertical and horizontal mixing on the transformation of the ITF waters. It is shown that, although the water-mass transformation is dominated by the vertical mixing induced by breaking of internal tides, non-negligible contribution is found from the horizontal mixing enhanced by the sub-mesoscale eddies resulting from tidal flow interaction with complicated land configurations.

Keywords: Tidal mixing, Indonesian Throughflow, Water-mass transformation, Sub-mesoscale eddies

Mapping of vortex and internal waves interaction-induced mixing in the North Pacific from OFES30 output

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Breaking of internal waves are a major source of mixing that contributes to upwelling of nutrients, driving force of thermohaline circulation, water mass formation. The breaking of internal waves have been studied in the context of quiet ocean without a background flow. Recently, some studies have pointed that the interaction between a vortex and internal gravity waves affects the mixing. Those previous researches handle the interaction problem with WKB like methods which assume a scale separation between a large vortex and small waves. However, in the ocean, there are many small, strong vortices like submeso-scale ones are ubiquitous. These vortices violate the scale separation assumption, so that a WKB like approach is invalid. The interaction in this range is never covered in the past studies. We numerically investigated the interaction in a wide parameter range including submeso-scale vortices and long internal waves. Then, the result is applied to the output of a high resolution ocean general circulation model, and the energetic interaction-induced mixing region is mapped. Model settings, datasets and results are described below. MODEL SETTINGS: A three dimensional non-hydrostatic model named “kinaco” is used to simulate the interaction of a vortex and waves. As initial conditions, Barotropic cyclone is put on the center of the model region and internal gravity waves that propagate toward the vortex are put on near an end of the model region. The experiments are controlled by a parameter which scales advection by a vortex, arises from our non-dimensional analysis of the shallow-water system. DATA SETS: The output of OFES30 (Masumoto et al., 2004; Sasaki et al., 2012) is used to estimate the distribution and structure of vortices in the North Pacific Ocean. Interaction-induced mixing is estimated for each vortex for internal waves of M2 tidal frequency. Results: From numerical experiments, dynamics of the interaction is classified to three regimes; First, Incident waves are scattered in two particular directions and vortex only works as catalyst. Second, a part of the incident waves are trapped into the vortex core, residual are scattered to various directions. Third, in strong non-linear vortex case, almost all incident waves are trapped, forming spiral shape, then shrinking rapidly in the radial direction, resulting in increase of vertical wavenumber. The vortex is also affected by shrinked waves through divergence of wave activity flux. As the overall tendency, both increasing rate of vertical wave number and trapped rate of the incident waves energy show monotonic increase with increasing value of the non-dimensional parameter. This suggests that the parameter should be an indicator of interaction-induced mixing. This indicator is estimated using OFES30 output. Remarkably, an extent of regions with large interaction-induced mixing is considerable in the North Pacific Ocean.

Keywords: internal wave, submeso-scale vortex, mixing

Wind-induced mixing in the North Pacific

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Temporal variability of the winter input of wind energy flux (wind power) and its relationship to internal wave fields were examined in the North Pacific. The dominant long-term variability of the wind power input, estimated from the mixed layer slab model, was inferred from an empirical orthogonal function analysis and corresponded to the strength and movement of the Aleutian Low. Responses of the internal wave field to the input of wind power were examined for two winters with a meridional float array along 170°W at a sampling interval of 2 dbar. Time series of the vertical diffusivities inferred from density profiles were enhanced during autumn and winter. After comparing diffusivities inferred from densities sampling at 2-dbar and 20-dbar intervals, we used Argo floats with a vertical resolution of 20 dbar to detect spatial and temporal variability of storm-related mixing between 700 and 1000 dbar in the North Pacific for 10 years. Horizontal maps of seasonal inferred diffusivities also suggested that the diffusivities were enhanced in autumn and winter. However, it is unlikely that there is a simple linear relationship between the input of wind power and the inferred mixing.

Intra-seasonal Variations of Upper-Ocean Mixing in Western North Pacific

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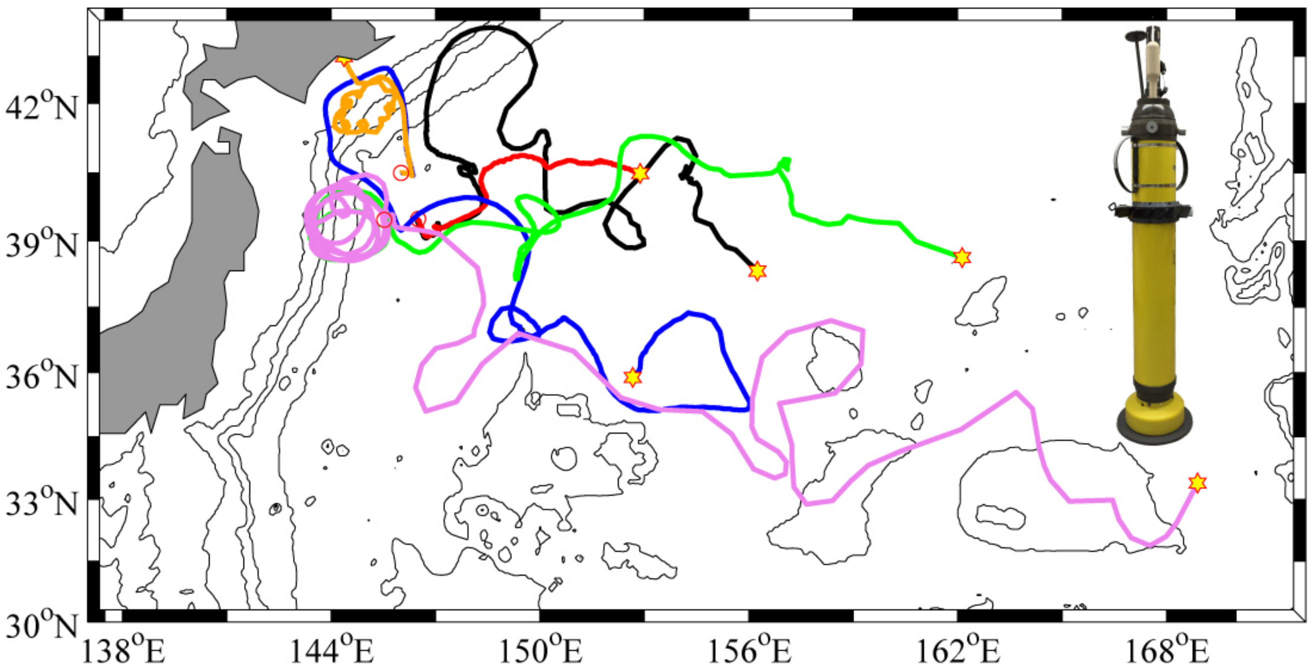
Previous studies suggest that the strongest inertial wind power injected into the ocean occurs in the western North Pacific during fall storm inertial wave generation. The energy pathway of these storm-driven inertial waves is not well known. Studies based on mooring observations suggest that only 15-25% of inertial wave energy propagate away from the forcing field as low modes, implying that 75-85% of the inertial wave power dissipated in the nearfield. Deployed in late August 2016, six microstructure EM-APEX floats collected nearly 5-months of measurements of water mass, horizontal current, and turbulence in the Kuroshio-Oyashio confluence. Intra-seasonal variations of turbulent mixing in the surface mixed layer and thermocline are revealed. Preliminary results will be presented. Turbulence kinetic energy dissipation rates, averaged over the upper 120 m, increase from ~5 x 10^{-9} W kg^{-1} at the late summer to 10^{-7} W kg^{-1} by mid-fall, a factor of 20 enhancement in two months. This enhanced turbulent mixing is correlated with increased inertial wind power from the passage of multiple fall tropical cyclones and lows, elevated upper-ocean inertial wave energy and mixed-layer deepening. Strong near-inertial waves propagate vertically to nearly1000-m depth and last as much as one week after storm passage.

Keywords: Storm Forced Inertial Waves, Upper Ocean Turbulence Mixing, Kuroshio-Oyashio Confluence



The role of wind gusts in upper ocean diurnal variability.

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Upper ocean processes play a key role in air-sea coupling, with variability on both short and long timescales. The diurnal cycle associated with diurnal solar insolation and night-time cooling, may act, along with stochastic wind variability, on upper ocean temperatures and stratification resulting in a diurnal warm layer and a nonlinear rectified effect on longer timescales.

This study describes diurnal changes in temperature in the upper 10 m of the water column for a location in the equatorial Indian Ocean, using observations from the Dynamics of the Madden-Julian Oscillation field campaign, a high vertical resolution 1-D process model, and a diurnal cycling scheme *[Large and Caron, 2015]*. Solar forcing is the main driver of diurnal variability in ocean temperature and stratification. Yet wind gusts regulate how fast the solar radiation warmed water is mixed to greater depths in time. Wind gusts are much stronger than diurnal winds. Even using no diurnal winds and stochastic wind gusts as input in a 1-D process model yields an estimate of diurnal temperature that compares well with observations.

A new version of the *Large and Caron [2015]* parameterization scheme (LC2015) provides an estimate of upper ocean diurnal temperature that is consistent with observations. LC2015 has the advantage of being suitable for implementation in a climate model, with the goal to improve SST estimates, hence the simulated heat flux at the air-sea interface. Yet LC2015 is not very sensitive to the inclusion or omission of the high-frequency component of the wind.

Keywords: Diurnal variability, Wind gusts, Upper ocean temperature

Turbulence induced by near-surface inertial oscillations and its impact on sea surface temperature variability

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It is well known that inertial oscillations in the surface mixed layer impact the evolution of sea surface temperature (SST) through turbulent mixing. SST is a key parameter controlling the climate and its variability. On the diurnal timescale, diurnal warm layers are observed to form in diverse oceanic regions under calm conditions. Properly modeling their formation and erosion in tropical areas is key to improving simulations of intraseasonal variability. Inertial oscillations may be present even under fairly calm conditions and are an important factor impacting both the formation and erosion of diurnal warm layers. We will present and discuss results from observations and modeling studies. We focus on the role that inertial oscillations play in the dynamics of diurnal warm layers and SST, through the analysis of several case studies, covering different background regimes and a variety of strengths of the inertial oscillation. Our results, suggest the important role that background stratification plays, both directly and indirectly (via internal wave radiation) in moderating the exchange of heat between surface and thermocline, more so than the intensity of the turbulence at the mixed layer base.

Keywords: turbulence, inertial oscillations, sea surface temperature , mixing, stratification

Turbulent Control of the Thermal Structure in Continental Shelf Seas

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Microstructure measurements made using a buoyancy driven ocean glider are used to investigate the mechanisms controlling the seasonal thermal structure of a temperate continental shelf sea. The autonomous nature of the Ocean Microstructure Glider (OMG) permits resolution of turbulence and mixing within the near surface region. We use these data to investigate the varying controls from wind, wave and buoyancy forcing on the formation and maintenance of seasonal stratification and the contribution from tidal boundary mixing and internal mixing from internal gravity waves and wind-triggered inertial motions. We will characterize the relative effects of wind and wave forcing on turbulence in the upper ocean later using the turbulent Langmuir number (La_t) and examine the observed variability in surface forcing relative to subsequent changes in heat and momentum transfer to the upper ocean and thermocline. We find that wind and wave effects appear well balanced (typified by a La_t~0.3) and that turbulence can be well described by a classic law of the wall profile, scaled with the surface friction velocity alone. During a brief period when waves do dominate we find that turbulence scales directly with Stokes drift. Rather than following an z^{-1} decay, turbulence under these conditions is driven deep into the upper mixed layer. The relative importance of surface driven turbulence on the overall thermal structure is investigated and balanced against contributions from internal and bottom boundary mixing mechanisms.

Keywords: Ocean Turbulence, boundary layer, ocean gliders

Kinetic Energy Flux Budget Across Air-sea Interface

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The kinetic energy (KE) fluxes into subsurface currents (EF_c) is important boundary condition for vertical mixing in ocean circulation models. Traditionally, numerical models assume the KE flux from wind is identical to the KE flux into subsurface currents, that is, no net KE is gained (or lost) by surface waves. This assumption, however, is invalid when the surface wave field is not fully developed. When the surface wave field grows in space or time, it acquires kinetic energy, hence, reduces the KE fluxes into subsurface currents compared to the fluxes from wind. In this study, numerical experiments are performed to investigate the KE flux budget across the air-sea interface under both uniform and idealized tropical cyclone winds. The wave fields are simulated using the WAVEWATCH III model under various wind forcing. The difference between the KE flux from wind and that into ocean currents is estimated using an air-sea KE budget model. To address the uncertainty of these estimates resides in the variation of source functions, two source function packages are used for this study: the coupled wind wave model by Moon et al (2004) and the ST4 source package by Ardhuin et al (2010). Simulated KE flux into the ocean currents are found to be consistent with field observations by Terray et al. (1996) and Drennan et al (1996). It is significantly reduced relative to the KE flux input from wind under growing seas. The reduction can be as large as 20%, and the variation of this ratio is highly dependent on the choice of source function for the wave model. Our results also suggest that the normalized KE flux by the friction velocity cube (u_*^3) may depend on both wave age and friction velocity (u_*), and a new parameterization for EF_c is proposed.

Keywords: turbulent kinetic energy, surface gravity waves, high winds