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ABSTRACTS 2007

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Mixing and wave energy dissipation in the presence of surface gravity waves: a review

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Surface gravity waves are the largest source of turbulent kinetic energy (TKE) for the world ocean, shaping the surface boundary layer and forcing the mean circulation in shallow waters where the divergence in wave momentum flux generates energetic currents. Constraints on wind-wave growth and observed turbulence below breaking waves gives some information on the magnitude of the surface flux of TKE and its depth of penetration. In reverse, the observed wind stress in the presence of swell gives a constraint of the upward flux of momentum and energy to the atmosphere.

These constraints may be used to refine models of turbulence closure in the presence of waves. These are well developed for the atmospheric boundary layer with visco-elastic models that account for the rapid distortion of the turbulence outside of an inner layer. These models may provide swell attenuation rates, a major unknown in today's operational wave forecasting models. We give here some first applications and calibrations of this type of model on the global scale and a comparison with observed swell attenuation rates. On the water-side, it has been shown that the same rapid distortion approach for short waves provides a rate of production of TKE due to the mean straining of turbulence by the Stokes drift. Besides, other types of models, using classical eddy viscosities or k-l turbulence closures have also lead to successful results for explaining the modification of current profiles in the presence of waves. We argue that the k-l model of Groeneweg and Klopman (J. Fluid Mech. 1998) may be modified to apply to Generalized Lagrangian Mean equations for the quasi-Eulerian mean flow, with a proper representation of wave-current interactions.

Internal tides, bores, and associated dissipation rates near the sill of a fjord basin.

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Tidal mixing in the basin water of Gullmar Fjord was investigated with a microstructure profiler, and moored ADCPs and CT loggers. During three days in late September 2004, three stations at 60, 70 and 80 m depth just inside the 43 m deep sill of the 120 m deep Gullmar Fjord were visited repeatedly with two-hour intervals between bursts of 4 microstructure profiles at each station.

Dissipation rates in the bottom layer (below the sill level pycnocline) show a strong tidal variation with maximum levels occurring near flood tide, which is also the time of minimum baroclinic perturbation pressure in the bottom layer. Around this time, two fronts pass the 80 m station. First, a general downslope flow in the bottom layer is turned into an almost unmoving, 10 m thick, overturning region above an intensified bottom current. The overturning region has dissipation rates in the order of 10^{-7} W kg^{-1}. Then, after about one hour, the isopycnals within the bottom layer rise quickly with the entrance of a front of denser water moving up the slope. The dissipation levels are still elevated in the range 10^{-8} – 10^{-7} W/kg for some hours, before they decrease towards the background level of less than 10^{-8} W/kg.

Baroclinic tidal pressure and velocity perturbation fields show an energy flux towards the sill mainly below sill level. Normal mode decomposition reveals a domination of the first vertical mode with both inward- and outward-propagating horizontal components, but with a net flux towards the sill. This net flux is about 20% of the energy loss from the barotropic tide deduced from surface elevation time series inside and outside the sill. The lack of internal wave energy radiating away from the sill means that the main tidal dissipation must happen in the sill region in accordance with earlier observations [*Arneborg et al.*, 2004].

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Large eddy simulations for quasi-2D turbulence in shallow flows

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Shallow flows are confined turbulent shear flows and widely observed in nature. Estuaries as well as coastal regions have a very shallow bathymetry [*Jirka and Uijttewaal 2004*]. The confined turbulent shallow flows are characterized by two distinct separated scales of turbulence: the three-dimensional turbulence generated by the wall bounded shear flow, and the quasi-2D turbulence with vortex scales typically larger than the water depth [*Nadaoka and Yagi 1998*]. The quasi-2D turbulence might be created due to a topographic forcing, internal transverse shear instabilities, or secondary instabilities of the base flow [*Jirka and Uijttewaal 2004*]. The three-dimensional large eddy simulation (3D-LES) is not feasible for large-scale applications due to the limitation of the present computing capacity. Thus, the two-dimensional large eddy simulation (2D-LES) is a useful tool, in which the only resolved motion is the quasi-2D turbulence [*Awad 2005*].

In this study, the performance of our two-dimensional large eddy simulation module developed at the University of Leuven (2D-LES, KULeuven module) [*Awad 2005*] is assessed.

The results of the 2D-LES, KULeuven module based on a one-length and a two-length subgrid scale models are analyzed. A comparison has also been conducted between the outputs of the 2D-LES, KULeuven module and another LES code developed at the University of Brussels (LES-VUB). These two codes have been implemented for a backward facing step (BFS) flow test case.

It has been found that the two-length scale approach produces more elongated and less isotropic vortex comparing to the one-length scale model.

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On shear- and wave-generated turbulence in stratified fluids.

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Based on a series of challenging observations and previous studies [e.g. *Peters* 1999, 2003; *Baumert & Peters* 2004, Chapters 3 - 5 and 39 in *Baumert et al.* 2005], we present a novel, integrated closure of turbulence in stratified flows. Beyond turbulence production by mean-flow shear, wave-generated turbulence is integrated in the closure in a physically transparent form. The approach is designed to be consistent with the open ocean internal wave-generated dissipation model of *Gregg* [1989]. It predicts turbulence levels even at large gradient Richardson numbers *Ri* well beyond ¼, where traditional closure schemes predict re-laminarization. For neutrally stratified conditions at solid walls, our closure produces the logarithmic law of the wall as a unique solution with a von-Kármán constant of $1/\sqrt{2\pi} \approx 0.399$. For flows initially without internal waves, the closure reproduces the collapse of turbulence into waves at $\Omega(t) = N$ as found in the high-*Ri* laboratory experiments of *Dickey & Mellor* [1980]. Here, Ω is the turbulent vorticity and N the buoyancy frequency. The new, integrated picture rests critically on a generalized form of the turbulent Prandtl number σ, introduced earlier by *Baumert & Peters* [2004] : $\sigma = \sigma_0 / \left(1 - N^2/\Omega^2\right)$. For the mixing efficiency of 0.2 often assumed in oceanic studies and for vanishing mean-flow shear, we show that a wave background typical of oceanic conditions guarantees σ to remain fairly constant near 0.56 for all $Ri \gtrsim 0.1$. Although of lesser relevance in natural waters, finally we show that horizontal shear may principally change this picture by redistributing energy from turbulence and waves into the vertical mode, in agreement with idealized DNS studies by *Jacobitz* [2002].

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A comparison of four vertical mixing schemes with an application to the Pacific Ocean

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In this study, we compare four turbulence models which are used for the parametrization of the oceanic boundary layer. Two of these models, called R224 and R22, are new and the others are Pacanowski and Philander's model (PP model, 1981) and Gent's model, 1989. These four models depend on the bulk Richardson number. This modelization is coherent with the studied region, the Tropical Pacific Ocean, in particular the West Pacific Warm Pool, because of the large mean shear associated with the equatorial undercurrent. For the numerical implementation, we use a non-conservative numerical scheme. We consider as initial conditions the climatology of the TOGATAO experiment at 165° E, 0° N. In parallel, we study the mathematical stability of the equilibrium solution. The numerical simulations show that the new model called R224 has a larger resolution spectrum than PP model and Gent's model. The results of the mathematical study show that R224 has better mathematical properties than the others. In fact, this model is good for the case of static stability and static instability. In addition, it is numerically more robust than the others. The mathematical part is to appear in Applied Mathematical Letters and the results of numerical simulations will be shown in an article which is in preparation. In the future, we plan to compare R224 with the KPP [*Large et al.,* 1998]. This work was done in collaboration between the University of Rennes 1 and the University of Sevilla, the member of the team being: AC. Bennis, M. Gomez Marmol, T. Chacon and R. Lewandowski.

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Latest research on how to further integrate the E.C.M.W.F. operational forecast models for air, sea and waves.

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The European Centre for Medium Range Weather Forecasts (ECMWF) runs state of the art operational forecast models for the prediction of the evolution of the atmosphere, the oceans and the waves at the air-sea interface. The interactions between the atmosphere and the ocean and between the atmosphere and the ocean waves have already been accounted for by the two-way coupling between the respective systems. However, ocean waves are at the interface between the ocean and the atmosphere and are known to be intimately involved in the exchanges across this interface. Therefore, a wave model is needed to compute not only the wave spectrum evolution, but also the processes at the air-sea interface that govern the fluxes across the interface. It is in this context that the sea-state dependent surface stress was introduced in the wave model used at ECMWF and its impact on the atmospheric circulation was later added by feeding back the information to the atmospheric model.

Because ECMWF has the different model components, we have the opportunity to test different configurations to determine which ones might be relevant in the contest of an operational system. A possible next step is to study the impact of the sea state on the ocean circulation. From a physical point of view, the ocean surface layer is controlled by the physics of breaking waves. Therefore, a sea state dependent formulation for the energy and momentum fluxes that are applied to the ocean surface has been tested [*Janssen et al.*, 2004].

The study of the impact of the ocean waves on the ocean circulation is only beginning. We are currently addressing some of the issues of extending the interface between the different components of the operational system to include parameterisation and forcing terms for which the dependence on the sea state has in the past been ignored. Similarly, we are looking at adding ocean current effects where they might be relevant.

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A Finite Element Model Study of the Importance of the Advection of Turbulence Closure Variables.

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In marine flows, it is often assumed that the timescale characterizing the advection of turbulence closure variables is much larger than that associated with the source/sink terms relevant to these variables. This is why the advection of turbulent variables is neglected in many models. The well-foundedness of this approach has rarely been put into question. Doing so is precisely the objective of the present study.

A dimensionless parameter is introduced in order for the importance of advection of turbulent variables to be assessed with respect to the corresponding production/destruction terms. A series of numerical simulations of idealised and realistic, non-buoyant flows is carried out that confirms the relevance of this dimensionless parameter, showing that it is for relatively small horizontal scales that advection of turbulent variables must be taken into account. These results also point to the existence of a range of horizontal scales that are both sufficiently small for advection to be important and sufficiently large for the hydrostatic equilibrium to remain valid.

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Development of a fully coupled wave-current interaction model. The POLCOMS-WAM system.

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Momentum transfer due to wind on the ocean surface not only generates surface waves, it also generates ocean currents. Due to the spatial and time scales of ocean and shelf sea applications and due to the randomness of the turbulent and the wave induced motions involved, only integrated (in time and space) effects of turbulence and waves on the mean motion can be taken into account. [Mellor, 2003; 2005], [Rascle et al., 2006], a.o. have worked on a consistent physical framework to describe the dynamics of the system. A more consistent treatment of the interaction between waves and currents may improve our ability to deal with dispersion and transport of particles such as pollutants, larvae, etc. and would therefore also be of particular interest in ROFI (Regions Of Fresh water Influence) environments.

From a practical point of view, such a framework can be brought into practice if it can be filled largely with existing codes. Therefore after presenting briefly this physical framework, the approach for the practical implementation using a fully coupled spectral wave model (WAM) and a 3D circulation model (POLCOMS) will be outlined and some of the practical difficulties will be highlighted. Finally an illustration will be given for the microtidal environment of the Catalan Coast, where due to oceanographic properties currents are typically less than 20 cm/s and modification of waves due to the effect of currents is expected to be small. However, the wave induced currents, due to Stokes' drift processes and enhanced wind drag due to waves, may produce a current of about the same order of magnitude as the ambient one and thus become an important source of mass transport.

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Using Computational Fluid Dynamics to study the interaction between shape and turbulence in the life of phytoplankton

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Floating and sinking are crucial events in the life of phytoplankton. Cope with, or possibly managing them would result in better matching their basic needs of capturing light and nutrients, mitigating mortality and and favouring mating. Laboratory experiments have shown buoyancy control capability in large cells up to reach positive buoyancy in calm water while, showing accelerated sinking in turbulent flow field.

The shape of the organism can have a profound impact on its interaction with the surrounding fluid environment, maximizing or minimizing its sensitivity to small scale motions. With the aim to analyze in close detail that interaction we have developed a numerical solution of the incompressible Navier-Stokes equations on unstructured grid, including a moving grid formulation, capable of tracking the motion of bodies of arbitrary shape within calm or turbulent environments.

The code uses second order schemes both in space and time, is completely built using an Object-Oriented approach, and has practically no limitations on the complexity of shapes that can be examined. Among the phenomena that can be studied with such type of codes, there are:

1) The effect of the shape on the terminal falling velocity that can be reached both in calm and turbulent conditions;

2) How shape and/or the velocity field around the body can affect osmotic fluxes at the surface of the organism;

3) How the organism is affected by the surrounding velocity field at different values of the density ratio (density of the organism / density of water).

In this work we present the basic ideas on which our approach is rooted and the preliminary results we obtained. We will also discuss the implications of the methodology in the ecophysiological perspective and the possible additional applications for it.

Inertial convective subrange in the bottom boundary layer of Rockall Channel

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Deep-ocean high resolution moored temperature data were analyzed with a focus on super-buoyant frequencies. The existence of a buoyancy subrange (BSR) in between the inertia-gravity wave (IGW) frequency range and the inertial convective subrange was addressed. Potential energy spectra gave evidence of a direct transition from the IGW range to an inertial convective subrange (ICS) characterized by a -5/3 slope regardless the energy level in the IGW band. A fit for these potential energy spectra at super-buoyant frequencies, higher than twice the buoyancy frequency, is proposed that depends on the potential energy within the IGW band, PE_{IGW}, and the buoyancy frequency, N. The scaling for kinetic energy dissipation is $\varepsilon \sim 0.3\ PE_{IGW}\ N$ assuming a mixing efficiency of 0.2. This result is in contrast with classical fine-scale parameterization in which $\varepsilon \sim PE_{IGW}^2$ valid for situations close to the Garret and Munk spectral model. The presence of strongly stratified sheets that are well-known in the BSR are evidenced in the ICS in the present dataset and the spatial distribution of these structures is found to be set by the Ozmidov scale.

Breaking of inertia-gravity waves as inferred from direct numerical simulations

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In the ocean large-scale down to submesoscale variability is strongly influenced by rotation and stratification. Instead, at small scales the dynamics is isotropic and the inertial subrange of 3D turbulence is retreived. In the frequency domain, rotation and stratification come into play at frequencies smaller than the buoyancy frequency. Within this frequency range for supra-inertial frequencies, inertia-gravity waves "IGW" are an important source of turbulence when they break. Previous work suggests that the transition from a wave regime to small-scale turbulence depends on the energy level of the wave field. For the equilibrium energy level, defined by the Garrett-Munk model, there is an intermediate spectral range, the so-called buoyancy subrange "BSR", in between the IGW domain and that of small-scale turbulence. However, for high energy levels the question of the existence of the BSR is raised, because the transition scale between the BSR and the inertial subrange increases with the energy level.

Our work focuses on this wave to turbulence transition using direct numerical simulations. We show how this transition depends on the dynamical regime at sub-buoyant frequencies. We show with the numerical simulations that the shape of energy spectra depends on breaking mechanisms such as convective or shear instabilities. A fine-scale parameterization for energy dissipation resulting from IGW breaking is inferred from these results. Another related question is to characterize the intermittency of this turbulence. Numerical simulations and observations gave evidence of strongly stratified sheets that form as a consequence of wavebreaking events. While these structures were observed in the BSR, we show that these sheets still exist in more turbulent regimes.

Estimates of vertical mixing due to dense bottom currents in the Western Baltic Sea

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Only recently, medium intensity inflow events into the Baltic Sea have gained more awareness because of their potential to ventilate intermediate layers in the Southern Baltic Sea basins ([*Mohrholz et al.,* 2006]). With the present high-resolution model study of the Western Baltic Sea a first attempt is made to obtain model based realistic estimates of turbulent mixing in this area where dense bottom currents resulting from medium intensity inflow events are weakened by turbulent entrainment.

The numerical model simulation which is carried out using the General Estuarine Transport Model (GETM, see www.getm.eu and [*Burchard and Bolding,* 2002]) during nine months in 2003 and 2004 is first validated by means of three automatic stations at the Drogden and Darss Sills and in the Arkona Sea. In order to obtain good agreement between observations and model results, the 0.5 × 0.5 nautical mile bathymetry had to be adjusted in order to account for the fact that even at that scale many relevant topographic features are not resolved. Current velocity and salinity observations during a medium intensity inflow event through the Øresund (see [*Sellschopp et al.,* 2006], [*Arneborg et al.,* 2007]) are then compared to the model results. Given the general problems of point to point comparisons between observations and model simulations, the agreement is fairly good with the characteristic features of the inflow event well represented by the model simulations.

Two different bulk measures for mixing activity are then introduced, the vertically integrated decay of salinity variance, which is equal to the production of micro-scale salinity variance, and the vertically integrated turbulent salt flux, which is related to an increase of potential energy due to vertical mixing of stably stratified flow. Both measures give qualitatively similar results and identify the Drogden and Darss Sills as well as the Bornholm Channel as mixing hot spots. Further regions of strong mixing are the dense bottom current pathways from these sills into the Arkona Sea, areas around Kriegers Flak (a shoal in the western Arkona Sea) and north-west of the island of Rügen.

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Some new results in modeling mixing processes in the ocean.

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In my talk I will discuss some recent developments concerning Ocean Mixing Processes. The first is the formulation of a model for stably stratified flows with no Ri(cr) which for decades has been taken to be order unity or less. Several data show quite directly that many mixing variables are non-zero way past Ri(cr)=1, actaully all the way to Ri=100. A new SOC model will be discussed that allows such possibilty. A second topic will be the discussion of how tidal energy gets dissipated at the bottom of the ocean and how that increases local mixing. How does that affect the global ocean properties? I will discuss the results of a recent mixing model with tides and the results of a stand-alone OGCM. Thirdly, I will discuss a new mesoscale model for the ML that entails re-stratification and thus a shallower ML. The model predictions were assessed against an eddy resolvng code.

Measurements and modeling turbulent properties in the upper layers of the southern Adriatic Sea under various meteorological conditions during 2006

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Despite the great importance of upper ocean turbulent mixing in oceanography, turbulence measurements are not yet routinely performed during sea trials. As part of the DART06-A and -B observational campaign, carried out from the NATO RV *Alliance* in March and August 2006, CNR-ISMAR coordinated a series of turbulence measurements by using a microstructure profiler that was deployed in the upper layers of the southern Adriatic Sea. More than 500 casts were made, resulting in a very large upper layer turbulence dataset for this semi-enclosed sea. A very high number (163) of these were made in August, near the location where a long term mooring (B90) was deployed at 90 m to measure profiles of temperature, salinity and velocities, and meteorological and surface wave conditions. The accumulated dataset enhances considerably the knowledge on turbulence in the northern and central Adriatic Sea gained from previously collected microstructure profiles, and will hopefully contribute in improving existing Turbulence Closure Models (TCMs). We were able to measure turbulence properties in the upper layers under a variety of atmospheric forcing conditions that included strong wind forcing, nighttime convection, mixed convection and wind forcing, weak wind forcing and strong insolation. From these cases, we calculated a series of turbulence properties and turbulent mixing above, below and in the strong, summer pycnocline present at a depth of 15 to 25 m. The measured dissipation rates in the mixed layer are consistent with relevant similarity scaling by the observed friction velocity $u*$ and the surface buoyancy flux J_{b0}. Below the mixed layer, they agree well with those derived using the Thorpe scale. These measurements provide a diverse dataset for comparison to modeled properties using state-of-the-art turbulence/hydrodynamic models.

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Decaying 2D turbulence in rotating electromagnetically forced thin layer flows.

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Two dimensional turbulence has been widely studied during the last few decades for its relevance both in geophysics and in astrophysics. Flows in the atmosphere and in the ocean are turbulent; however the combined effect of rotation and stratification inhibits vertical motion and the large-scale motion can be considered quasi two-dimensional and can be described by the quasigeostrophic vorticity equation [*Rhines*, 1994]. Starting from this equation and considering a balance between the beta and the advective terms, it is possible to identify two different regimes: if the nonlinear advective terms prevail the flow is characterized by isotropic two-dimensional turbulence while in the case of an intense beta effect the dynamics of 2D turbulence are significantly modified, showing a strong anisotropy in the energy flux. In this case [*Rhines*, 1975] the energy cascade towards slowest modes typically associated to two-dimensional turbulence is arrested in correspondence of a characteristic scale (*i.e.* Rhines scale) and the formation of stationary zonal jets is observed. Moreover, the corresponding energy spectrum is characterized by a steeper slope than the classical Kraichanan prediction [*Kraichanan*, 1967]. Rhines theory has been successively confirmed by many numerical simulation [*Cho and Polvani*, 1996; *Yoden and Yamada*, 1993; *Vallis and Maltrud*, 1993] and some laboratory experiments [*Afanayasev and Wells*, 2005].

In this context, the evolution of a two-dimensional turbulent decaying flow is experimentally analysed in a rotating system considering the effect of the change of the Coriolis force with latitude. The flow is generated using an electro-magnetic cell, *i.e.* by electromagnetically forcing a thin layer of a saline solution, in a rotating reference frame. The effect of the variation of the Coriolis force with the latitude is modelled both by the parabolic profile assumed by the fluid under rotation and considering a bottom topography. A Feature Tracking technique is used to measure the flow field allowing the reconstruction of high resolution velocity and vorticity fields. In agreement with theoretical prediction and previous experiments, results corresponding to high values of the beta parameter show a preferential transfer of energy towards zonal modes and the consequent organization of a weak anticyclonic circulation in the polar zone. Moreover, the analysis of the one-dimensional energy spectra shows a scaling steeper than Kolmogorov law and a peak near the Rhines scale indicating a soft barrier of the energy transfer towards low wave-numbers. As expected, energy decays exponentially in time indicating the fundamental role played by the bottom drag in the dynamics of thin layers flows.

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Mixing induced in a dense plume flowing down a sloping bottom in a rotating fluid: a new entrainment parameterization?

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We will discuss laboratory experiments investigating mixing in a density driven current flowing down a sloping bottom in a rotating homogenous fluid. A systematic study spanning a wide range of Froude, Fr, and Reynolds, Re, numbers was conducted by varying four parameters: the rotation rate, the bottom slope, the flowrate, and the density of the dense fluid. Different flow regimes, i.e. laminar, wave, turbulent and eddy regimes, were observed either in different experiments, while changing the above parameters, or simultaneously in the same experiment, as the current descended the slope. Mixing in the density driven current was quantified within the observed different flow regimes and at different locations on the slope. The dependence of mixing on the relevant non-dimensional numbers, i.e. Fr and Re, will be discussed. Mixing increased with increasing Fr. For low Fr the magnitude of the mixing was comparable to mixing in the ocean. For large Fr and Re, mixing was comparable, or slightly lower, than in previous laboratory experiments that presented the classic turbulent entrainment behavior with larger Re. We will suggest a new empirical parameterization for entrainment in dense currents that presents two novelties when compared to the classical Ellison and Turner [1959] parameterization. First, it depends both on the Fr and Re of the flow and it accurately predicts both ocean and laboratory estimates of mixing. Second, it takes into account subcritical (Fr<1) mixing. The subcritical mixing observed in the present experiments could be of fundamental importance when determining the final water mass characteristics of a dense overflow current descending the continental slope. A weak but non zero entrainment can substantially change the final density and, consequently, the location of important water masses, such as the North Atlantic Deep Water, in the open ocean water column. Finally, a comparison of the laboratory results to those of a "stream tube" model will be presented. We will show that the model predictions are consistent with laboratory observations when the new entrainment parameterization is employed.

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Wave-Turbulence Interaction for Multifractal Thermal Structure in the Western Philippine Sea Upper Layer

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Upper layer (above 140 m depth) temperature in the western Philippine Sea near Taiwan was sampled using a coastal monitoring buoy (CMB) with attached 15 thermistors during July 28 – August 7, 2005. The data were collected every 10 minutes at 1, 3, 5, 10, 15, and 20 m using the CMB sensors, and every 15 seconds at 15 different depths between 25 m and 140 m in order to observe turbulent thermal structure.

Internal waves and solitons were also identified using the empirical orthogonal function analysis. Without the internal waves and solitons, the power spectra, structure functions, and singular measures (representing the intermittency) of temperature field satisfy the power law with multi-scale characteristics at all depths.

Without the internal waves and solitons (turbulence-dominated type), the temperature fluctuation has maximum values at the surface, decreases with depth to mid-depths (60-65 m deep), and then increases with depth to 140 m deep. Such depth dependent (decreasing then increasing) pattern preserves during the internal wave propagation during 1000-1500 GMT July 29, 2005. However, this was altered during the internal soliton propagation to a pattern that increases with depth from the surface to 60 m deep, decreases with depth from 60 m deep to 100 m deep, and increases again with depth from 100 m to 140 m deep. The temperature fluctuation enhances with the internal wave and soliton propagation. Between the two, the internal solitons bring larger fluctuations.

The observed temperature profile does not oscillate if there is no internal wave and soliton propagation. It oscillates evidently in the upper layer above 50 m with the internal wave propagation and above 80 m with the internal soliton propagation. The amplitude of the oscillation is much larger during the internal soliton propagation (maximum amplitude around 4^{o}C) than the internal wave propagation (maximum amplitude around 2^{o}C). The EOF analysis on the ispopycnal displacement shows that the first baroclinic mode dominates the variability for internal waves (86.0% of variance) and internal solitons (74.4% of variance). The maximum variability is located at different depths with 30 m for the internal waves and 60 m for the Internal solitons. The amplitude of this mode fluctuates on two time scales with 4 CPH as a high frequency and around cycle per 5 hr as a low frequency for the internal waves, and on one time scale with frequency around 4 CPH for the internal solitons. The maximum amplitude is more than three times larger in the internal solitons than in the internal waves.

Three types of thermal variability are identified: IW-turbulence, IS-turbulence, and turbulence-dominated. The power spectra of temperature at all the depths have multi-scale characteristics. For the IW-turbulence type and turbulence-dominated type, the spectral exponent β is in the range of (1, 2) and thus the temperature field is nonstationary with stationary increments. For the IS-turbulence type, the spectrum is quite different and the spectral exponent β is less than 1 for the low wavenumber domain. The structure function satisfies the power law with multifractal characteristics (Chu, 2004) for the IW-turbulence type and turbulence-dominated type, but not for the IS-turbulence type. The internal waves increase the power of the structure function especially for high moments. The internal solitons destroy the multifractal characteristics of the structure function. The power law is broken approximately at the lag of 8 min, which is nearly half period of the IS (with frequency of 4 CPH).

The internal waves do not change the basic characteristics of the multifractal structure. However, the internal solitons change the power exponent of the power spectra drastically especially in the low wave number domain; break down the power law of the structure function; and increase the intermittency parameter. The physical mechanisms causing these different effects are also presented.

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Numerical study of internal tide transformation and dissipation

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Internal wave shoaling is the main source of turbulent mixing in the ocean and is therefore believed to play a crucial role in oceanic circulation [*Munk and Wunsch*, 1998]. Recent estimations show that internal tide which is generated by the interaction of barotropic tide with topography represents almost half of the total internal wave energy. Several mechanisms that depend on latitude and stratification such as parametric subharmonic instability and solibore generation can initiate internal tide breaking. We aim to get further insight into internal tide shoaling mechanisms using direct numerical simulations. We focus on the processes leading to solibore generation as a result of the interaction of the internal tide energy beam and the pycnocline. Recently it was shown that a simple scaling law for kinetic energy dissipation in the form $\varepsilon \propto EN$, could be efficiently adopted in the the pycnocline to represent internal tide induced mixing in the Indonesian throughflow [*Koch Larrouy et al, 2006*]. Such a scaling law was found above the Wave-Turbulence transition, in a domain where energy transfer is controlled by instabilities and turbulence by *D'Asaro and Lien*, 2000. We will try to characterize under which conditions (stratification, latitude, energy) such a scaling law can be adopted to model internal tide breaking, we will notably try to determine whether such a law is well suited to represent solibore dissipation mechanisms.

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Degeneration of basin-scale seiches in a sub-alpine lake

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We characterize and model linear and nonlinear internal wave climate in a long narrow sub-alpine lake: Lake Bourget in France. Field measurements using thermistor chains at different points and comparison with linear models show that the most energetic internal wave motion is a standing internal seiche motion with one node on the vertical and one node on the horizontal dimension (V1H1 mode). In spring wind forcing is usually strong, and the stratification is relatively weak with a thin epilimnion. As a consequence, the Wedderburn number defined as the ratio of the epilimnion thickness to the metalimnion maximum tilting shows weak values. For such low values of the Wedderburn number, nonlinear effects can no more be neglected and the V1H1 internal seiche evolves as a progressive surge [Horn *et al* 2001]. Under the influence of non-hydrostatics effects, a train of high frequency nonlinear waves is then generated. We model the degeneration of the standing internal

seiche into an internal surge and high frequency nonlinear waves using the weakly non linear, weakly dispersive Korteweg de Vries equation. Comparisons of isotherm series as derived from measurements and from modelling show good agreements. These high frequency nonlinear waves are believed to generate high dissipation rate and high turbulent dispersion when shoaling at the lake boundaries and may therefore provide a path-way for nutrients between hypolimnion and epilimnion, forcing by the way some of the important ecological processes in the lake.

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Interleaving of a dye tracer in a shallow pycnocline: Evidence for the collapse of mixing patches?

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The Oregon shelf is a region where patchy mixing results from the interaction between internal waves, shoaling topography and frontal features. A fluorescent dye tracer was injected into the pycnocline in this environment and spread rapidly cross-shelf as two distinct layers separated by interleaving dye-free water. The vertical and horizontal scales of the layers were of order 1m and 1km respectively after an inertial period. Steps in the underlying density field showed similar scales and appeared to be closely related to dye structures. Both dye layers and density steps were slightly tilted in density space. The possibility that the structures observed were formed by the horizontal collapse of mixing patches is investigated. Such processes have implications for horizontal dispersion and cross-shelf transport.

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2D and quasi-geostrophic turbulence: theory vs. observations

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The classical theory of 2D and quasi-geostrophic turbulence deals with highly idealised systems and predicts inverse energy cascade toward large scales and also spectral laws for the eddy kinetic energy. It turns out that the real world systems like the atmosphere and ocean are following these predictions only very approximately.

The talk touches briefly the basic issues of the theory and explains them from a physical viewpoint. These will include the notion of the inverse cascade, formation of jets and the Rhines scale, and interaction between barotropic/baroclinic modes in quasigeostrophic flows. They will be compared to the observations available in the atmosphere and in the ocean.

The basic conclusion is that the idea of the inverse energy cascade in barotropic mode is supported, yet cascades in the original sense are never observed as energy generation and energy dissipation occur over approximately same intervals of wavenumbers.

On the mathematical stability of the stratified flow models that include a sophisticated turbulence closure scheme

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A large number of present-day models of geophysical and environmental fluid flows rely on Fourier-Fick parameterisations of the vertical turbulent fluxes of momentum, heat, and tracers: the flux of the relevant quantity is expressed as the product of its vertical derivative and a suitably-defined eddy coefficient. Nowadays, the latter is rarely assumed to be a constant. More often than not, it is obtained from sophisticated models. Some of them rely on additional differential equations, which govern the evolution of variables describing the state of turbulent fluctuations.

Occasionally, the numerical simulations based on such models exhibit small-scale oscillations, causing the eddy coefficients to vary over several orders of magnitude. Theoretical developments suggest that these spurious oscillations are due to a lack of stability of turbulence closure schemes.

Let λ_m represent the eddy diffusivity relevant to ψ_m, the m-th variable of the model under consideration. By studying the evolution of a small-amplitude and small-time/space scale perturbations a stability condition is obtained: the eigenvalues of the matrix $\lambda_m \delta_{m,n} + \psi_{m,z} \partial \lambda_m / \partial \psi_{n,z}$ must be positive — where $\delta_{m,n}$ is the Kronecker symbol and $\psi_{n,z}$ is the vertical derivative of ψ_n.

Though strong simplifications are needed to derive the stability criterion above, a series of numerical experiments points to its relevance for a number of water column models relying on turbulence closure schemes ranging from that of Munk-Anderson to the Mellor-Yamada level 2.5 model.

It is believed that the present theory may be relevant to all local turbulence closure schemes applied in atmospheric and oceanic modelling. Whether or not it could be of use for studying the stability of non-local approaches is still an open question.

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Upper ocean mixing processes in the equatorial Atlantic Ocean

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The shallow thermocline in the equatorial Atlantic Ocean is a major mixing hot spot and turbulent heat flux in this region is a dominant term in the mixed layer heat balance. Here, we investigate the seasonal variability of upper ocean mixing processes within the cold tongue of the equatorial Atlantic Ocean from microstructure measurements collected during several recent cruises. The data set reveals pronounced seasonal variability in turbulent mixing intensity and associated heat flux. During the development phase of the cold tongue in early boreal summer, intense mixing and elevated turbulent heat flux is observed in the region of the Equatorial Undercurrent (EUC). These intense mixing levels are associated with shallow mixed layer depths and deep-diurnal cycle turbulence. Elevated mixing levels due to deep cycle turbulence are also observed in September, suggesting that this process is important in maintaining the cold tongue. In this period, deep cycle turbulence was not only associated with vertical shear from the EUC, but was also present in a region away from the EUC where vertical shear was solely caused by Tropical Instability Waves. Low mixing levels were observed during cruises carried out in November and December.

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Turbulence models for mesoscale eddies

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Possibilities for a turbulence closure for the effects of mesoscale eddies in non-eddy-resolving ocean models are explored. A pragmatic viewpoint is taken and the closure is constructed using elements of simple models of boundary layer turbulence. An eddy kinetic energy (EKE) budget, which can be prognostically integrated in a numerical ocean model, is combined with a diagnostic relation for an eddy length scale, which is given by the minimum between Rossby radius and Rhines scale. Combining EKE and the length scale in a standard mixing length assumption gives the thickness diffusivity according to the Gent and McWilliams parameterisation. Using the same diffusivity, down-gradient diffusion of potential vorticity can also be implemented allowing for the possibility of up-gradient momentum fluxes.

The proposed closure is evaluated using synthetic data of two different eddyresolving models covering the North Atlantic Ocean and the Southern Ocean, respectively. The diagnosis shows that the mixing length assumption together with the definition of eddy length scales and energy dissipation appears to be valid for the thickness diffusivity. The evaluation also shows consistently in all cases that a simplified local closure yields reasonable results with respect to the thickness diffusivity.

Characterization of phytoplankton photophysiological responses in the ocean mixed layer

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Variability in nutrient supply and light availability, both in amplitude and spectral properties is a basic constraint phytoplankton has to cope with for their survival. In parallel with the in depth analysis of photophysiological responses of aquatic unicellular autotrophs conducted in the laboratory, pioneering studies on their impact in the mixed layer were developed since the late eighties using modelistic lagrangian approaches. Though, in most of the existing models cell displacement due to mixing is mimicked through a random walk, using estimated or measured eddy diffusivity in place of the diffusion coefficient. This approach does, very likely, overlooks other scales of motion present in the mixed layer, such as those due to Langmuir cells, convective plumes etc. To investigate to what extent those scales affect the responses of phytoplankton and the resultant competition among species as driven by light and nutrient variability, we implemented a model which embed also the scales neglected in the random walk approach and should allow a more realistic displacement of the cells thus improving the reconstruction of their photophysiological responses. The model is Individual Based and lagrangian. Results of set of simulation performed at different chlorophyll concentration (turbidity of the water) have been analyzed both in term of averaged values and probability distribution function between photophysiological properties and carbon fixation rates of the individuals. The two photophysiological acclimation considered (modification in the pigment content and photo-inhibition at high irradiances) compensate as mixing increase, producing growth rate comparable in different mixing and light conditions.

Additional analyzes performed with the transilient turbulent theory modified for the application to the photophysiological properties of the Individuals have permitted to distinguish the typical movements connected with “advantaged” organisms and “disadvantaged” ones.

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Boundary layer simulations with a third-order closure model

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In this work we present a closure model, based on the Reynolds stress approach ([*Canuto,* 1992]), with the aim of investigating turbulence processes in the boundary layer. The model employed includes up to the third order moments equations and is able to take into account the non-local properties of turbulent transport.

The results of two full simulations of the boundary layer performed are presented. The flows investigated are a shear-free buoyancy driven boundary layer and a buoyancy and shear driven boundary layer. The model assumes the fourth-order moments to be Gaussian distributed according to the Quasi-Normal approximation. To avoid the problems connected to the use of the Quasi-Normal parameterization, namely the unphysical growth of the third-order moments due to the insufficient damping of the turbulent vertical transport, a specific approach is suggested ([*Ferrero,* 2005] and [*Ferrero and Colonna,* 2006]). This takes into account an integral length scale based on the turbulent kinetic energy and its dissipation rate, which represent the eddy size variation across the boundary layer.

The results of the simulations are presented and compared with Large Eddy Simulations data and aircraft measurements.

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Mixing processes in coastal river plumes. A high resolution approach.

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The turbulent dispersion in the Rhône river plume has been investigated from in situ and numerical experiments. Small scale mixing processes are shown to be mainly driven by the wind forcing and to control the plume extension and residence time. A Lagrangian measurement approach for vertical profiles of temperature, salinity and momentum were used to parametrize the turbulent mixing as related to the local Richardslon number, using optimal control techniques. High order numerical modeling, including Large Eddy Simulations, allowed to explain secondary flows and filaments as observed from radar and satellite imagery.

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A quasi-normal scale elimination (QNSE) theory of stably stratified turbulence

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We present a quasi-normal scale elimination theory of stably stratified turbulence. The basic algorithm of this spectral theory is the successive elimination of small shells of fast Fourier modes of velocity and temperature which generates small corrections to the viscosity and diffusivity. The scale elimination process starts near the viscous dissipation cutoff, k_d, and continues to an arbitrary wave number $k<k_d$. This procedure yields scale-dependent eddy viscosity and eddy diffusivity which, due to the effect of stable vertical stratification, develop considerable anisotropy. In the limit of weak stratification, one can derive analytical expressions for eddy viscosities and eddy diffusivities. For strong stratification, the expressions for the turbulent exchange coefficients are obtained numerically. Among other important results of the QNSE model are the dispersion relation for internal waves and the threshold criterion for internal wave generation in the presence of turbulence. An interesting detail, turbulence anisotropization and internal wave radiation start at about the same scales. Partial scale elimination yields the subgrid-scale (SGS) parameterization that can be used in large-eddy simulations (LES). If all fluctuating scales are eliminated, one obtains a Reynolds-averaged (RANS) model in which eddy viscosities and eddy diffusivities can be expressed as functions of either the Richardson or the Froude numbers. Both the vertical eddy viscosity and eddy diffusivity decrease with the increasing stratification; however, while the eddy diffusivity can be reduced almost to its molecular value, $\square_0$, the eddy viscosity remains higher than $\square_0$ even for very strong stratifications. This behaviour reflects the contribution of internal waves that mix momentum but not scalar. This behaviour of the vertical eddy viscosity and eddy diffusivity combined with the enhanced horizontal mixing of both momentum and scalar indicate that stable stratification cannot laminarize turbulence for any value of the Richardson number thus making the concept of the critical Richardson number devoid of its meaning. The QNSE model can be used to derive expressions for various one-dimensional spectra which recover the $N^2k_z^{-3}$ scaling for the vertical spectrum of the horizontal velocity and $\square^{2/3}k_h^{-5/3}$ for the horizontal spectrum of the horizontal velocity, in good agreement with observational data up to the numerical coefficients. The QNSE-based RANS models have been tested in simulations of stably stratified atmospheric boundary layers and generally provided good agreement with experimental and observational data. We suggest that the QNSE-based RANS models offer a viable alternative to Reynolds stress models for simulations of small-scale atmospheric, oceanic and planetary turbulence.

On wave scales and wave-breaking induced turbulence

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The turbulence field beneath surface waves is rather complex and provides great challenges for detailed observations. Only in recent years the direct link between wave breaking and enhanced near-surface turbulence levels has been shown. The Duncan-Phillips concept, which is based on towed hydrofoil laboratory experiments combined with simple conceptual models, suggested more than 2 decades ago that breaking-wave induced dissipation rates scale as the fifth power of the breaking wave phase speed. Thus, one would expect a very strong dependence of turbulence enhancement and breaking wave scale.

In a recent field experiment in Lake Washington we deployed three pulse-coherent Doppler sonars, monitoring the near–surface velocity field, the surface elevation and the breaking activity. Here I will present first results from this experiment, which covered a range of strongly forced wave developments at 7 km fetch and wind speeds up to 18 m/s. Energy dissipation rates are estimated from the velocity profiles at a high temporal and spatial resolution. Detailed scale-resolved dissipation rates beneath breaking and non-breaking waves will be presented and the relation between breaker scales and turbulence levels will be evaluated.

The Role of Turbulence in Thin Plankton Layers

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As a part of the research program Layered Organization of the Coastal Ocean (LOCO) a series of experiments were undertaken off Monterey, California USA in the summer of 2005 and 2006 to examine the biological and physical mechanisms in the formation, evolution, and breakdown of thin layers of phytoplankton and zooplankton. These features are typically centimeters to a meter in vertical scale, can extend several kilometers horizontally and last of order hours to a day. This talk will present results from the 2005 and 2006 study on examining the nature of the turbulence and fine structure field within and surrounding these thin layers and their relationship to thin phytoplankton layer formation and breakdown.

The approach has been to use the SMAST Autonomous Underwater Vehicle, T-REMUS which is a custom designed extended REMUS vehicle containing the Rockland Microstructure Measurements System (RMMS). The RMMS turbulence package consists of two orthogonal thrust probes, two FP07 fast response thermistors, three orthogonal accelerometers and a fast response pressure sensor. Also contained on the T-REMUS vehicle are an upward and downward looking 1.2 mHz ADCP, a FASTCAT CTD, a Wet Labs BB2F Combination Spectral Backscattering Meter/ Chlorophyll Fluorometer, and a variety of "hotel" sensors measuring pitch, roll, yaw, and many other internal dynamical characteristics of the T-REMUS vehicle. The physical measurements are made concomitantly with very high spatial resolution (vertical scale of centimeters, horizontal scales of 100s of meters) measurements of chlorophyll fluorescence and optical scattering at 470 nm and 700 nm wavelength. The turbulent and fine scale parameters which can be estimated from the data collected by the T-REMUS include: the turbulent dissipation rate, the inferred turbulent eddy diffusivity, fine scale velocity shear, and fine scale stratification.

Analyses of the data from fixed LOCO stations indicate that there was a strong diel vertical migration of organisms. During the day organisms appeared to be, in general, relatively dispersed with subsurface aggregation at shallow depths (1~7m) with a small number of thin layers occurring very near the surface. At night there was high aggregate abundance, often occurring in thin layers typically located near the pycnocline at 7-13m depth. Analysis of the T-REMUS BB2F and turbulence data to date suggest that the very thin phytoplankton layers of vertical scale less than 50 cm have low turbulence values (epsilon of order or less than 10^-8 Watts/kg and rms turbulent velocity less than 1 mm/sec) while the thicker layers (> 1m) showed much larger turbulence values with dissipation rates (epsilon) as high as 10^-6 Watts/kg, and rms turbulent velocity as high as 1 cm/sec. There appeared to be a significant correlation between phytoplankton layer thickness and the turbulent diffusive time scale. It should be noted that the dominant phytoplankton species in these thin layers was the dinoflagellate Akashiwo Sanguinea, which has considerable motility and can move with speeds up to (of order) several meters /hr. In general within the very thin layers (< 50 cm thickness) the estimated turbulent velocity was observed to be of order or less than this speed.

In the 2006 experiment based on the samples collected, the dominant phytoplankton appears to be the diatom *Pseudo-nitzschia* with motile phytoplankton playing much less of role than in the LOCO 05 experiment. Consistently larger values of dissipation rate were observed in LOCO 06 than in LOCO 05, with dissipation rate (epsilon) values in LOCO 2006 reaching 10^-5 Watts/kg and estimated turbulent velocities of order several cm/sec. Strong short wavelength (solitary like) internal waves were observed to occur simultaneous with these large values.

We will assess and compare physical and optical data from these two experiments for the role that turbulence plays in: (1) direct dispersal of organisms as a function of thin layer thickness; and (2) the role that turbulence plays with motile phytoplankton in proscribing an escape velocity necessary to maintain position on an isopycnal surface. We will also examine the role that fine scale shear and buoyancy play in thin layer deformation.

Internal waves at the Celtic Sea shelf break

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The energy flux in internal waves generated at the Celtic Sea shelf break was estimated by (i) applying perturbation theory to a week-long data set from a mooring at 200 m depth, and (ii) using a 2D non-hydrostatic circulation model over the shelf break. The data set consisted of high resolution time-series of currents and vertical stratification together with two 25-hour sets of vertical profiles of the dissipation of turbulent kinetic energy. There has been suggestions that shelf break generated internal waves provide an important energy supply for the mixing on the central and inner part of the shelf. However, the observations indicated a net energy flux of 132 W m^{-1} along the shelf break towards the northwest. The net flux across the shelf break at the mooring was only 3 W m^{-1}, although waves propagating onshelf transported up to 200 W m^{-1}, but they were only present 11% of the time. A 2D model along a transect perpendicular to the shelf break showed a net onshelf energy flux of 153-425 W m^{-1} depending on the magnitude of the forcing. A divergence zone of the energy flux was found a few km offshore of the location of the observations in the model results, and fluxes on the order of several kW m^{-1} were present in the deep waters further offshelf from the divergence zone. The modelled fluxes exhibited qualitative agreements with the phase and instantaneous onshelf magnitudes of the observed energy fluxes. Both the observations and the model results show an intermittent onshelf energy flux of 100-200 W m^{-1}, but these waves could only propagate ~20-30 km onshore before dissipating. A comparison between the divergence of the baroclinic energy flux and observed dissipation within the seasonal thermocline at the mooring showed that the observed dissipation was at least one order of magnitude larger. We therefore conclude that shelf break generated internal waves are not the main source of energy for mixing on the inner part of the shelf.

Effects of coherent structures in convective turbulence: Why they are crucially important for higher-order closure models?

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Convective turbulence is common in nature. It is highly anisotropic and inhomogeneous due to forcing conditions. And it is very intermittent due to the presence of populations of coherent structures, i.e. semi-organised circulation cells (plumes or thermals), which are distributed in sizes up to the domain size. Coherent structures make the convective turbulence extremely nonlocal due to stirring of the fluid by populations of plumes. In the global challenge of turbulence modelling, one-point closure models prove useful in many ways. However, in their recent version they fail to describe convective turbulence accurately. The reason is that they are based on the Millionshchikov hypothesis [*Millionshchikov,* 1941] and do not take the large scale intermittency of convection into account. The Millionshchikov hypothesis states that in higher-order turbulence closure models the one-point four-order (FOM) moments can be approximated as quasi-normal, i.e. Gaussian even if the third-ordermoments are non-zero. For a long time this hypothesis was adopted without discussion in all turbulence closure models, explicitly in HOC models, e.g. such as EDQNM-like, and implicitly in lower order, since ideally all of them are derived from HOC models. Recently, see [*Gryanik and Hartmann,* 2002], FOM becomes available from aircraft data of low-to-moderate wind (ARTISTcampaign) as well as from LES. Were shown that: (i) only the FOM in along wind and cross wind horizontal velocities are close to Gaussian, (ii) FOM in vertical velocity and temperature are essentially non-Gaussian, (iii) theMillionshchikov hypothesis violates the realizability conditions, (iv) the Millionshchikov hypothesis leads to underestimation of the actual FOM. Only few theoretical studies are focussed on the refinement of the Millionshchikov hypothesis. In [*Ilyushin and Kurbatskii,* 1997] the $5-$ th order moments were considered. In [*Gryanik and Hartmann,* 2002], [*Gryanik et al.,* 2005] new FOM parameterisations which explicitly account for the effects of anisotropy and intermittency were developed. They depend on skewnesses. In [*Cheng et al.,* 2005] new closures are suggested based on parameterisation of divergence of the FOM rather then moments themselves using a best fit procedure to measurements and LES data. At present time only the parameterisation of [*Gryanik and Hartmann,* 2002], [*Gryanik et al.,* 2005] were tested. The testing shows a good agreement with measurements and LES of atmospheric boundary layer, and LES of deep convection in ocean [*Losch,* 2004] and solar and stellar granulation convection [*Kupka and Robinson,* 2007].

However some problems remain. They are: What is the region of applicability of the refined closures? How do the refined closures can be generalised? In particular: How does the Millionshchikov hypothesis need to be refined for convection with phase transitions, e.g. with clouds, and for the case of compressible convection? Which modifications are necessary for FOMof passive scalar and chemically active scalars in convective conditions? What is the most natural way for their implementation in current HOC models?

Finally, some of the abovementioned problems of convective turbulence will be discussed and new closures for HOM generalizing [*Gryanik and Hartmann,* 2002], [*Gryanik et al.,* 2005] closures will be suggested and tested against new LES data.

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Diapycnal mixing in the Faroe-Shetland Channel from density overturns and current shear

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The Faroe-Shetland Channel is an important passageway for watermass exchange between the North Atlantic and the Arctic Oceans, being the primary route of overflow waters from the Nordic Seas entering the Iceland Basin. The hydrography of the Channel is dominated by a permanent pycnocline that separates high salinity North Atlantic Water, flowing northward against the West Shetland slope in a barotropic slope current, and typically southward flowing intermediate and deep waters that originate in the Arctic basin. Mixing in the pycnocline may be enhanced by turbulent instabilities resulting from the shear flow or by internal waves generated along the West Shetland slope and over the Wyville-Thompson Ridge. During *F. S. Poseidon* cruise 328 in September 2005, three CTD/LADCP sections across the Faroe-Shetland Channel were completed and a station over the West Shetland slope occupied for 24 hours with a cast every hour. Two methods of calculating diapycnal eddy diffusivity (κ_ρ) from the cast data are used, scaling of density overturns [e.g., *Thorpe,* 1977], and comparison of the vertical shear spectrum with the Garrett and Munk model of the background internal wave field [*Garrett and Munk,* 1975] following the method of *Naveira Garabato et al.* [2004]. In the permanent pycnocline κ_ρ is found to be $\geq 10^{-3}$ m^2 s^{-1}, an order of magnitude larger than in the regions of weak stratification. Over the Faroe slope, mixing is enhanced through out the watercolumn with κ_ρ approaching 10^{-2} m^2 s^{-1}. Mixing is also enhanced where the pycnocline meets the West Shetland slope with a semi-diurnal cycle apparent in both the depth of the pycnocline and the strength of the mixing. In the slope current at the shelf edge κ_ρ is less, of the order $10^{-3.5}$ m^2 s^{-1}. There is good agreement between the methods in the regions of stratification, although where $N^2 < 10^{-5}$ s^{-2} Thorpe scaling estimates κ_ρ an order of magnitude larger than the vertical shear spectrum method.

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Representing Gravity Current Entrainment in Global Ocean Climate Models

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Watermass formation by gravity currents is a critical element in the long-term global ocean circulation. Adequately representing the key processes that collectively lead to this watermass formation remains a severe challenge for the large-scale ocean models used for climate studies. This presentation describes insights into the required processes and how they should be represented, based on a series of idealized regional simulations at a hierarchy of resolutions in hydrostatic and nonhydrostatic simulations. Physically consistent parameterizations are suggested for the distinct turbulent regimes driven by mechanically driven bottom turbulence and by interior stratified shear instability, which capture the distinct vigorously turbulent regimes observed in the well-mixed bottom boundary layer and the sheared, stratified transition layer of oceanic overflows. The results of using these new parameterizations are demonstrated in global climate simulations using an isopycnal coordinate ocean model, which avoids many of the traditional difficulties with excessive numerical mixing in the gravity current plumes. The remaining challenges for representing gravity currents in global climate models, stemming primarily from the coarse resolutions required for multi-century climate simulations, and strategies for overcoming these challenges, will also be discussed.

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On the use of the finite element method to simulate vertical mixing

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The goal of this work is to demonstrate the promises of the finite element method to simulate geophysical flows. While an extensive work has already been done with this numerical method to simulate horizontal processes, we are going to focus on the vertical ones. We aim to show that even in a 1D water column model, finite elements have significant advantages over the more traditional finite differences. The strength of the finite element method are mainly due to its geometrical and functional flexibility.

Geometrical flexibility

Within the finite element formalism, the model variables are discretized in terms of piecewise polynomial basis functions defined on a partition of the computational domain. That partition is generally called a mesh and can be totally arbitrary. Such a feature is particularly useful for 2D and 3D applications with complex geometries. In 1D, the finite element mesh obviously looks like a finite difference grid but its resolution can be easily changed during the course of the simulation in order to track features of interest. Mesh adaptation is based on the definition of an error estimator that indicates where resolution should be increased. Hence, by defining an error estimator that depends on the distance to the surface, distance to the bottom and density gradient, truly hybrid vertical coordinates can be obtained. Fig. 1 shows an example of vertical mesh movement where coordinate levels follow density gradients while still being clustered near the bottom and top of the water column. In that simulation, vertical turbulent fluxes are parameterized with Mellor and Yamada level 2.5 turbulence closure.

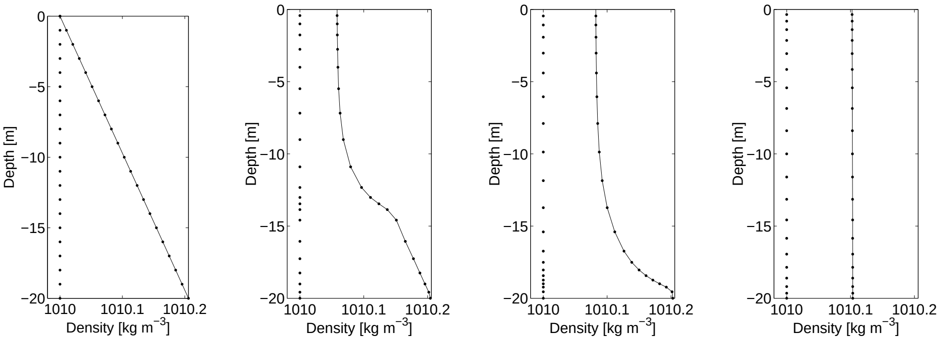

Figure 1: Stress driven penetration of a turbulent layer into a stratified fluid. The mesh resolution is increased near the surface and bottom while, in the middle of the domain, the mesh is able to follow isopycnals. Mesh nodes are represented by "•"

Functional flexibility

The second advantage of the finite element method is the possibility to locally change the order of the discrete solutions. This might achieved by either enriching or modifying the set of basis functions used to discretize the model variables. We illustrate the promises of this feature by simulating the behaviour of the velocity field in the bottom boundary layer. As the velocity field is asymptotically logarithmic near the bottom, the numerical discretization can be improved by taking this information into account. Two approaches are compared: The first one amounts to add some additional degrees of freedom in the bottommost element while the second keeps the same number of degrees of freedom but uses logarithmic basis functions instead the linear ones in the bottom element. Both approaches are compared with analytical and classical finite element solutions in the case of rotating and non-rotating flows. The basis functions used in the classical and improved finite element schemes are represented in Fig. 2.

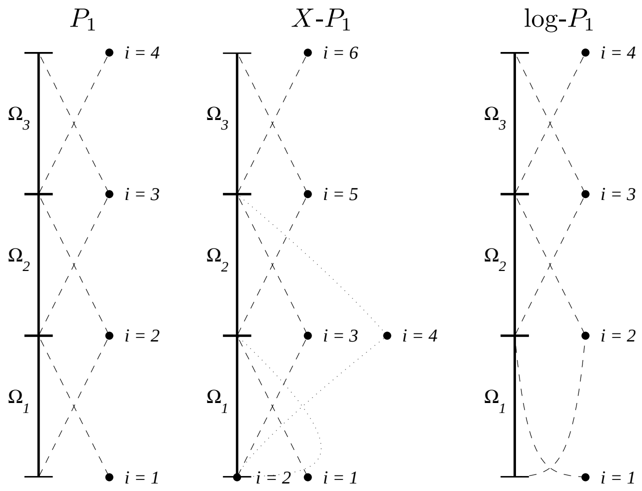

Figure 2: Sketch of the basis functions used on the first three elements of the 1D finite element mesh for a classical linear scheme with no improvement (denoted P_1, left), a linear scheme with two additional degrees of freedom in the bottom element (denoted $X - P_1$, center) and a scheme where the basis functions have been modified in the bottom element (denoted $\log - P_1$, right). The two additional basis functions used in the $X - P_1$ scheme are represented with a dotted line.

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Two Novel Autonomous Shear Micro-structure Profilers

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Two novel autonomous shear micro-structure profilers have been developed over the past 3 years under the MIDAS project (Micro-structure Instrument Development at SAMS): the prototype instruments and initial data-sets are reported here. The first profiler makes rising measurements from a sea-bed resident platform, whilst the second free-falls and resurfaces without a tether: both are capable of making ~200 profiles with complete autonomy. In both profilers the shear micro-structure package is a miniaturized version of the MSS60 instrument of Prandke and Stipps (1998); the sensor package comprises two PNS shear sensors, an accelerometer, a thermometrics FP07 negative coefficient fast response temperature sensor, and a pressure sensor. Additional conductivity, temperature and pressure measurements are made separately to the fast response MSS60 sensors. Both profilers also use a Persistor Inc. CF2 micro-processor (http://www.persistor.com) to control and log data from the MSS60 sensors with a sample rate of ~412 Hz.

Free-falling Profiler (MIDAS-A): A is for APEX; this instrument is based on the Webb Research Corp. APEX float (http://www.webbresearch.com). The modified MSS60 is attached to the base of the APEX profiler, and a CF2 micro-processor housed inside the modified APEX float collects both the SBE41 CTD and MSS data streams to allow all measurements to be made simultaneously during the downcast. In addition, by intercepting the SBE41 pressure record before feeding it to the float controller, it is possible to gain more control over the float buoyancy controller by providing false pressure records when appropriate, e.g. to terminate a profile early, or to vary the maximum depth profile by profile. To facilitate float location for recovery a GPS chip and Iridium modem have been incorporated; upon surfacing the float position is sent via SMS to a ship-based Iridium receiver. MIDAS-A has a maximum working depth of 2000m.

Rising Profiler (MIDAS-H): H is for HOMER; this profiler is based around the seabed resident winch system 'HOMER' (Homing Environmental Recorder) (Inall et al., 2005). Two versions of the system have been developed. The first system uses the modified MSS60 attached to the bespoke HOMER CTD unit (a 25cm diameter glass sphere), the second uses a standard MSS90 profiler, modified to have positive buoyancy and with an internal battery and CF2 controller unit. An ADCP has been incorporated into the seabed frame, giving simultaneous and co-located velocity fine structure observations. MIDAS-H can operate in water depths of up to 4000m, with a maximum profile length of 300m.

Initial result from trials in Loch Etive on the west coast of Scotland (maximum water depth 140m) are shown to demonstrate the ability of the profilers to obtain repeated, autonomous profiles of turbulent kinetic energy dissipation rates.

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A Parameterisation of Shear-Driven Turbulence for Ocean Climate Models.

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We present a new parameterisation for stratified, shear-driven mixing which is relevant to climate models, in particular the shear-driven mixing in overflows and the Equatorial Undercurrent (EUC). Critically for climate applications this parameterisation is simple enough to be implemented implicitly which allows the parameterisation to be used with timesteps that are long compared to the time on which the turbulence evolves. It also allows the parameterisation to be used with isopycnal coordinate, where the layer thickness can be small, as well as with z-coordinates.

The mixing is expressed in terms of a turbulent diffusivity which is dependent on the shear Richardson number, the shear forcing and the buoyancy length scale (the length scale over which the turbulence is affected by the stratification). The balance is non-local which allows a decay of turbulence vertically away from the low Richardson number region: a process our results show is important for mixing across a jet.

We conduct high resolution, nonhydrostatic simulations of 3D shear-driven, stratified mixing in both a shear layer and jet. These are compared to existing parameterisations and used to constrain parameters for our new parameterisation. We also demonstrate the results of our parameterisation on mixing in the overflows and EUC in a global climate model.

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Plume Frontal Mixing, Internal Wave Generation and Vorticity: Upwelling vs. Downwelling Conditions

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The Columbia River tidal plume or plume near-field is formed twice daily by the strong ebb outflow of the Columbia River. It is a part of a larger, anticyclonic plume bulge containing several days of outflow, which in turn is embedded in far-field plume and coastal waters. Because of the mixing caused directly and indirectly by plume fronts, the interaction of the tidal plume and bulge with the California Current upwelling regime plays a vital role in coastal productivity on the Oregon and Washington shelves. The tidal plume is initially supercritical with respect to the internal Froude number on all stronger ebbs. It is separated from the plume bulge by a front, whose properties are very different under upwelling vs. downwelling conditions. Under summer upwelling conditions, this front is sharp and narrow (only 50-100 m wide on its upwind or northern side) and marks a transition from supercritical to subcritical flow for 6-12 hours after high water. This sharp front is a source of strong turbulent mixing (fine structure estimates suggest dissipation values up to 10^{-3} Wkg^{-1}). Because the tidal plume may overlie newly upwelled waters, these fronts can mix nutrients into the plume, enhancing primary productivity. Because the plunge at the front disturbs the seabed when the plume is in waters <50-60 m deep, frontal mixing may also bring particles from the seabed up into the surface layer. Symmetry would suggest that there should be a sharp front south of the estuary mouth under summer downwelling conditions. Instead, the downwelling tidal plume front is usually broad (up to several km) and diffuse on the upstream side. Dissipation values appear to be one to two orders of magnitude smaller, and the water immediately below the plume consists of old plume and surface ocean waters, both low in nutrients. There is also a second upwelling-downwelling asymmetry. Supercritical upwelling plume fronts often generate solitons trains as they slow and transition to a subcritical state. These soliton trains contribute to vertical mixing in the plume bulge and have a non-zero Stokes drift so that they transport low-salinity water across the tidal plume. Trains of 5 to 20 solitons can move plume water as much as 1-2 km beyond the plume front. Under downwelling conditions, soliton formation is uncommon. Moreover, solition formation almost always begins on the south side of the plume so that the front “unzips” from south to north. This implies that a frontal transition from supercritical to subcritical conditions first occurs on the south side tidal plume, regardless of whether this is the upwind or downwind side of the plume.

This contribution describes and analyzes asymmetries in mixing and wave propagation using vessel data, SAR images and a vorticity analysis. Internal Froude number and plume depth are key parameters in distinguishing the upwelling and downwelling situations, and the observed asymmetries can be explained in terms of potential vorticity conservation. The tidal outflow embeds relative vorticity in the emerging tidal plume water mass. This vorticity controls the transition of the tidal plume front to a subcritical state and the timing and location of internal wave generation by plume fronts.

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Incorporation of the effects of surface waves within the turbulence closure model GOTM

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Scientific understanding of the effect of surface waves on the mean current was advanced considerably by the dynamically consistent formulation of this problem by [*Longuet-Higgins,* 1953], and the mechanism whereby momentum is conserved for wave motions and the mean flow in different coordinate systems was clarified by [*Andrews & McIntyre,* 1978] and subsequent workers.

Substantial progress was made in the modelling of turbulence and the hydrodynamics of the upper ocean with the parameterization by [*Craig & Banner,* 1994] of the generation of turbulent kinetic energy (TKE) via surface wave breaking. The unification of turbulence closure schemes and their implementation by [*Burchard et al.,*, 1999] in the GOTM computer code, with its wide availability and free distribution, has made a valuable tool available to the scientific community.

In this presentation we combine the above scientific and technical advances, by incorporating the effect of surface waves on the mean flow and the balance of mechanical energy explicitly into the GOTM model. We thus extend the Craig and Banner TKE parameterization so that it becomes a direct formulation, and enable a dynamically-consistent treatment of the mean flow and wave (pseudo)momentum in a coordinate system which effectively follows the water surface. In our formulation, the wave-induced Stokes drift allows for the presence of strong vertical shear in the near-surface drift current, as observed from the measured drift of oil slicks and floating objects, without unnecessarily reducing the turbulence intensity at the surface. We also discuss how the incorporation of wave effects may be performed with minimal disturbance to the GOTM model architecture.

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Tidal energy balance and turbulent energy dissipation in narrow strait

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Energy balance of tidal current and process of energy dissipation have been investigated by control volume analysis and turbulence measurements in a partially enclosed shelf sea (the Seto Inland Sea). It consists of a series of basins connected by narrow straits. The water column in straits is completely mixed all year around, resulting in a series of tidal fronts between the straits and basins during periods of stratification. Turbulent kinetic energy dissipation is estimated using free-falling/free-rising turbulence micro-structure profiler (TurboMap1 / TurboMap4) at several points over tidal cycle.

When tidal flow passes narrow strait, tidal jet and vortex are often formed in its vicinities. The result of control volume analysis between two cross sections using observed data of sea level and tidal current shows large energy loss was observed in a narrow strait, and it changed depending on the current direction. It is attributed to the energy loss associated with the tidal vortex formed over tidal time scale and internal turbulent dissipation, in addition to the loss by bottom friction. The internal turbulent dissipation was evident in the results of direct measurements.

The distributions and variations of biogeochemical properties suggested that the large turbulent energy generated by those internal processes have important effects on transport of sediment and particulate organic matter.

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Imaging turbulent oceanic microstructure using high-frequency broadband acoustic scattering

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High-frequency broadband (150-600 kHz) acoustic scattering techniques have been developed and used to obtain high-resolution images of non-linear internal solitary waves (ISWs) propagating shoreward over the New Jersey continental shelf. Multiple ISWs were tracked and imaged acoustically, while simultaneous direct microstructure measurements were performed. Multiple scattering layers were often associated to the ISWs, with the backscattering from the different layers exhibiting a different frequency response: A strong scattering layer was typically observed at low frequencies at depths associated with large temperature gradients, while at higher frequencies a deeper scattering layer, not associated to large temperature or salinity gradients, often dominated the scattering. Though high turbulence levels are associated with ISWs, the strongest scattering returns are not always associated to the highest turbulence levels. Instead, the strongest scattering, at some frequencies, is often associated to large temperature gradients. As a result of the strong temperature stratification, the scattering was found to be generally consistent with temperature and not salinity microstructure. In general, the interpretation of the acoustic returns in terms of turbulence parameters, such as the dissipation rate of turbulent kinetic energy, is confounded by the presence of biological scatterers. In contrast to traditional single-frequency echosounders, measurements of high-frequency broadband acoustic backscattering allow the frequency spectrum of the scattering to be determined, which, in combination with acoustic scattering models, allows regions in which the scattering is dominated from biology versus oceanic microstructure to be distinguished. Once these regions have been identified, the acoustic returns can be inverted, relying heavily on scattering models, for relevant parameters such as the dissipation rate of turbulent kinetic energy. Sources of error and confidence bounds are discussed.

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Hindcasting turbulent properties in the upper layers of the southern Adriatic Sea by means of GOTM and the GHER 1-D model

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Part of the DART06-A and -B observational campaigns, carried out by the NRV Alliance in March and August 2006 in the southern Adriatic Sea, consisted in turbulence measurements by means of a microstructure profiler. A very high number of casts were made in a location where a long-term mooring deployed at 90 m deep provided us with temperature, salinity and velocity profiles. In addition, meteorological and surface wave conditions were also collected at this point. Turbulent properties in the upper layer were measured under a variety of atmospheric forcings, including strong wind, nighttime convection, regular wind and mixed convection, as well as weak wind and strong isolation conditions.

This large dataset constitutes a great opportunity to validate, test and possibly improve existing hydrodynamic models. We thus have performed numerous simulations with GOTM [*Burhcard and Bolding*, 2000] – the well-known General Ocean Turbulence Model – and the GHER [*Beckers*, 1991] – GeoHydrodynamics and Environmental Research – 1-D model. On one hand, we have compared the outputs with the turbulent properties derived from the measurements, and on the other hand, with the outputs of each other. We have performed a lot of error analyses to characterize and explain the differences.

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In-situ Measurements to Understand The Mechanism of submerged turbulence detections from optical satellites

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Results from the Remote Anthropogenic Sensing Program (RASP 2002, 2003, and 2004) are presented. Ikonos and Quickbird optical satellite imagery of sea surface brightness reveals narrow wave number spectral anomalies at distances up to 20 km from the Honolulu Sand Island Municipal Outfall diffuser. To understand the mechanisms of this phenomenon, three international expeditions monitored the receiving waters with an array of hydrographic and turbulence microstructure sensors in the anomaly and ambient regions. Drifters set near the 40 m trapping depth of the effluent, as well as ADCP measurements, show complex currents (tides, lee eddies, freshwater run-off). Mean turbulence parameters for ~ 10^4 microstructure patches in the anomaly and ambient regions have been analyzed to understand the complex stratified turbulence processes. The collected data shows no significant difference between the hydrographic properties in the anomaly and ambient regions. Nevertheless, the results point to different possible mechanisms that connect the outfall diffuser with the sea surface anomalies observed in the satellite images: 1) internal waves produced by the outfall turbulence and/or buoyancy effects, 2) fossils and zombies of the outfall turbulence, 3) secondary and ambient internal waves. Future field measurements are being designed to provide solid evidence that can support the proposed models.

A profiler for bio-physical microstructure research - TurboMAP

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ALEC Electronics Co., Ltd is a manufacture of ocean instruments. Not only being excellent in conventional ocean instruments, we have started our development on measuring microstructure in water since 15 years ago. TurboMAP is a tethered profiler to measure microstructures when falling or uprising through water. The profiler is equipped with shear probes, fast response thermister and CTD sensors etc. Beyond these, we also developed bio-sensors to simultaneously measure biological microstructures from few mm scales (laser probe) to 2 cm (LED sensor). The correlations in between biological and physical properties are able to be studied.

Observations of the turbulent dissipation rate in the Yellow Sea

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The Yellow Sea (YS) is a typical shallow sea with a mean depth of 44 m, and it is one of the broadest marginal seas in the world [Tang and Su, 2000]. The YS is thought to be one of the principal regions of global ocean with strong tidal dissipation [e.g., Liu and Wei, 2007]. During stratified season, which is usually from late spring to early autumn, hydrological features of the YS are characterized by strong thermocline, tidal front and the Yellow Sea Cold Water Mass (YSCWM). The well-mixed inshore shallow regions are separated from the highly-stratified offshore deeper regions, where resides the YSCWM under the thermocline in shape of a platform, by the tidal front. Unique stratification in the stratified regions of the YS, i.e. the surface mixed layer and the bottom mixed layer were separated by a narrow (~2-10 m) very sharp (with a maximum temperature gradient of 4.5ºC/m) thermocline, mimic classic theoretical structures assumed in a number of laboratory and numerical experiments on nonlinear internal waves and associated turbulent mixing studies at the density interface. This makes observations in the YS particularly valuable in both revealing new oceanic processes and validation of the results of laboratory and numerical studies [e.g., Strang and Fernando, 2000a, b; Fringer and Street, 2003].

Although profiling measurements of the turbulent kinetic energy dissipation rate ε in the cean is not yet new, which is already for at least three decades, there are very few direct measurements of ε in the YS [*Liu and Wei,* 2007; *Lozovatsky et al.,* 2007a, b]. Strong tidal dissipation and mixing in the YS has been validated by numerical modeling and altimeter data [*Lee and Jung*, 1999; *Qiao et al.*, 2006; *Egbert and Ray*, 2000], but there are no yet in situ measurements to support. To this end, we conducted dissipation rate profiling measurements by using the microstructure profiler MSS-60, developed by Sea & Sun Technology GmbH (Germany), at two mooring sites S1 (35.01°N, 123.00°E, with a mean water depth of 73 m) and S2 (35.00°N, 121.50°E, with a mean water depth of 38 m) in the YS in September 2006. At each site, 3 casts, separated by 4-5 minutes (S1) or 2-3 minutes (S2), of MSS-60 were taken every 1 hour for two tidal cycles (25 hours). At site S2, an upward-looking 600 kHz RDI ADCP was moored on the seabed for the observations of the current velocity through the water column.

Large values for the turbulent dissipation rate were found near the surface, near the bottom, and around the thermocline at the deeper site S1. Strong dissipations (hence productions) near the surface are produced by surface wind forcing, and the near bottom dissipations are a result of bottom shear stress due to tidal currents. A distinct tidal bottom boundary layer (TBBL) with strong dissipation and mixing, which extended to ~13 meters above the bottom, was revealed in the time series of vertical structures of the turbulent dissipation rate and the vertical eddy diffusivity. Both the dissipation rate and the eddy diffusivity in the TBBL exhibited a strong quarter-diurnal variation (the flow is predominantly semi-diurnal M2 in the YS), with an evident phase lag with the height from the bottom. The strong dissipations around the thermocline were situated below the maximum temperature (density) gradient, where the water was less stratified, with a vertical thickness of ~8 meters. Shear instability and internal wave breaking are speculated to be responsible for the enhanced dissipations around the thermocline. The weakest mixing ($K_\rho \sim 10^{-7}\,\mathrm{m^2s^{-1}}$) was within the sharp thermocline due to high stratification ($N^2 \sim (1-3)\times10^{-2}\,\mathrm{s^{-2}}$). At the shallow site S2, the ~15-m-thick TBBL extended to the base of the thermocline, which made the water below the thermocline be fully occupied by the tidal-induced strong dissipation and mixing. The lowest values of dissipation and the weakest mixing were found in the water between the near-surface and the thermocline, where the water was weakly-stratified and the shear was very small. A transition, across the thermocline, from strong to weak for the dissipation and mixing was very distinct.

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Abyssal Mixing in the North Atlantic

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The interest on understanding and quantifying topographically induced turbulent mixing in oceans has increased profoundly during the last decade. Basin-scale dynamics of deep waters is known to depend on vertical mixing near the bottom and hence it must be correctly represented in the models of ocean circulation. Rough topography has been pointed out by many researchers as possible hotspots for deep-ocean mixing. This paper was motivated by the said gaps of knowledge about abyssal mixing, with the hope that study of fine structure in abyssal, topography-influenced waters will shed light on their contribution to global ocean mixing.

The basin-scale cross-Atlantic CTD sections are the data resource for our analysis. The WOCE-type CTD measurements along two trans-Atlantic sections were carried out in 1999 and 2000 by oceanographers of SIO RAS approximately along 48^{o}N (ASV-99) and 5^{o}N (AI-2000). The analysis of these data in conjunction with four zonal transects of the WOCE database (AR7E and AR12 along ~ 57^{o}N, AR01 ~ 24.5^{o}N, and A06 ~ 7.5^{o}N) is the first step of acquiring information on the thickness of isothermal (mixed) bottom layer IBL and topography-influenced characteristic lengthscales in the North Atlantic at several latitudes between Arctic and Equatorial waters.

Statistics of the IBL as well as the relationships between various fine structure and microstructure scales and the bottom roughness were studied. The cumulative probability functions of IBL thickness H_B can be approximated by log-normal distribution with the median value in the range 30-60 m. A characteristic ratio of H_B/D, where D is the ocean depth, is of the order of 1%. The mean height of IBL is generally larger along deeper transects. The median of $H_B/D = (1.1-1.4)\times 10^{-2}$ tends to increase from the equatorial to polar sections.

An objective characterization of bottom roughness is an important aspect of study on mixing in the abyss with the hope of linking topography irregularities with hydrodynamic variables of the deep waters. In our analysis of 2D sections, we calculated topographic irregularities along the ship track by applying a low-pass filtering to the cruise or 2-arc-minute bathymetry to separate "small-scale" $h'(x)$ and "large-scale" $\hat{h}(x)$ topographic features. The *rms* of $h'(x)$ was calculated for consecutive segments of length of our choice, representing a statistical measure of the bottom roughness z_r. This allows investigations of the dependence of turbulence scales in the abyss on roughness elements of various spatial scales assigned to $h'(x)$.

The Ellison L_E and Thorpe L_{Th} scales were calculated for the lower 1000-1500 m of the water column along the transects and the correlations between the two scales was analyzed. The Ellison scales were computed for different wavenumber cutoffs k_{fs} in order to separate fine-structure fluctuations from mean profiles (k_{fs} ranged from 1/10 to 1/80 cpm). It was found that the highest L_E occupied a larger portion of the water column for smaller k_{fs}. This implies that fluctuations of larger vertical scales are influenced by the bottom roughness over larger distances above the ocean floor. The highest coefficients of determination r^2 in linear regressions between z_r and L_E (r^2 = 0.67-0.77) were found at the height of 200-300 meters above the bottom. An approach of parameterizing a characteristic turbulence scale in the abyss as a function of the roughness parameter z_r and the thickness H_B of the bottom mixed layer is suggested.

Demonstration of the Coastal Microstructure Profiler VMP500

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The VMP500 is a vertical microstructure turbulence profiler for the measurement of dissipation-scale turbulence in oceans and inland waters up to 500 m depth. It is equipped with state-of-art microstructure velocity probes (shear probes), high-resolution temperature sensors (thermistors) and micro-conductivity sensors, as well as a high-accuracy CTD. A set of orthogonally mounted accelerometers monitors instrument attitude and high-frequency vibrations. The VMP500 was deployed on numerous occasions in coastal ocean environments as well as in shallow river environments. The data from these deployments demonstrate the VMP's excellent wavenumber response of measured velocity shear (du/dz, dv/dz) Dissipation rates of turbulent kinetic energy at levels of 1x10^(-10) W/kg can be resolved. This poster presentation shows data sets and dissipation spectra collected with the VMP in a quiescent coastal inlet in British Columbia (Saanich Inlet) and in a highly turbulent river environment in Florida (Wakulla Springs). Technical details and data processing techniques will be discussed.

The effect of turbulence in structuring microbial food webs under different scenarios of algal-bacterial competiton for nutrients.

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In marine systems, both phytoplankton and bacteria compete for inorganic nitrogen and phosphorus. It has been shown that the outcome of such competition will be in favour of diatoms when silicate (Si) is in excess and in favour of bacteria when Si is depleted [*Havskum et al*, 2003; *Thingstad et al* 2007]. We postulate that turbulence could change this competition interaction. Shear fields derived from turbulence increase nutrient fluxes mainly to large cells. Thus, turbulence should increase the phytoplankton competition capability for nutrients and reduce the organic matter utilisation by bacteria. When Si is in excess diatom growth should be further enhanced by turbulence.

We evaluated the effect of turbulence on the competition between bacteria and diatoms in experiments with natural plankton communities enclosed in microcosms. The response of plankton to turbulence versus still conditions was evaluated in four different nutrient conditions: C (glucose addition), Si (silicate addition), CSi (glucose and silicate addition), and B (no addition). In general, turbulence increased both heterotrophic and autotrophic biomass under all nutrient addition conditions, and enhanced the diatom competition for nutrients when Si was available. In addition, and contrary to our hypothesis and to previous experiments, turbulence did not change the ratio between autotrophic and heterotrophic biomass. We discuss the discrepancy between these results and previous data in terms of the level and frequency of nutrient additions, trophic interactions and initial conditions.

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Vertical Mixing Rates and Hypoxia in Western Long Island Sound

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The factors controlling summertime eutrophication and bottom hypoxia in the Western Long Island Sound (WLIS) are a primary concern for both ecological modeling and environmental management. While nutrification remains a probable root cause, evidence suggests that in 2004 the occurrence and duration of hypoxic events were controlled primarily by variations in the vertical O_2 fluxes caused by physical mixing.

We demonstrate a novel means of determining vertical mixing rates through measuring the attenuation of a surface signal as it propagates downwards and show that vertical eddy diffusivities can be calculated as:

$\kappa_V = \frac{1}{2\omega}\left(\frac{\Delta z}{\Delta t}\right)^2$ where Δt is the phase lag of a signal of frequency ω across a depth of Δz,

$\kappa_V = \frac{\omega \Delta z^2}{2\ln\left(\frac{A_1}{A_2}\right)}$ where $A_{1,2}$ are the signal amplitudes at the two depths, or

$\kappa_V = \frac{i\omega \Delta z^2}{\ln\left(\frac{A_1 - iB_1}{A_2 - iB_2}\right)}$ where $A_{1,2}$ and $B_{1,2}$ are the cosine and sine coefficients at the two depths.

Application of this methodology to time-series of 2004 WLIS buoy measurements using the diel O_2 signal generated by surface photosynthesis indicates a correlation between vertical mixing rates and measured rates of change in bottom dissolved oxygen levels. 2004 WLIS temperature and salinity signatures are also consistent with the conclusion that variations in vertical mixing rates were a primary control on bottom hypoxia occurrence and duration in the WLIS in 2004.

Modelling the Pressure Terms in the Second-Moment Equations

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One of the key issues in the second-order turbulence closure approach is the modelling of the pressure terms in the transport equations for the second-order moments. Various formulations for the pressure terms are discussed, emphasising their physical realism, their advantages and shortcomings, and their utility for modelling turbulence in geophysical flows.

A common approach nowadays to modelling the pressure redistribution terms in the Reynolds-stress and the scalar-flux equations is to decompose them into the contributions due to the non-linear interactions, referred to as the slow part of the pressure term, and due to the mean-gradient, buoyancy and the Coriolis effects, referred to as the rapid parts of the pressure term. These contributions are then modelled separately. The relaxation "return-to-isotropy" approximation [*Rotta,* 1951] is applied to the slow part of the pressure term. For the rapid parts, the linear models are most often used. The respective rapid parts are simply set proportional to the mean-gradient, buoyancy and Coriolis terms in the equations for the Reynolds stress and for the scalar fluxes. The proportionality coefficients are adjusted (tuned) so that to provide a good fit of the model results to observational and numerical data.

Although linear models of the pressure terms are in common use in geophysics and engineering, they entirely fail in many situations of interest. An illustrative example is turbulent convection driven by the surface buoyancy flux and affected by rotation. It is encountered, for instance, during the vertical mixing phase of open-ocean deep convection. In the seemingly simple case where the rotation axis is aligned with the vector of gravity, linear models are unable to properly account for the effect of rotation, leading to erroneous prediction of the Reynolds stress and of the scalar fluxes. Then, a more sophisticated non-linear formulation is required.

Of particular value are the so-called realisable models [*Schumann,* 1977], [*Lumley* 1978]. Prominent among them is a two-component limit (TCL) model [*Craft et al.,* 1996]. Examples of its application to convective flows are presented. A TCL formulation for the pressure gradient-potential temperature covariance that properly accounts for the effect of rotation [*Mironov,* 2001] is discussed in some detail. Results of its successful testing against large-eddy simulation data are presented. It is emphasised that the use of numerical (LES and DNS) data is the only viable alternative in situations where observational data are difficult or impossible to take. This is the case for the fluctuating pressure in turbulent flows.

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Estimation of TKE dissipation rate in an inflowing saline bottom plume using a PC-ADP

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Inflowing high saline waters from the North Sea are the sole source for oxygen in the deep Baltic basins below the halocline. The depth layer which is finally ventilated by an inflow is determined by the density of the inflowing saline water and the actual stratification in the central basins. Along the pathway through the western Baltic turbulent mixing and differential advection causes an entrainment of ambient water and change the properties of the inflowing saline water. However, observations of mixing parameters in spreading dense bottom water plumes are scarce, since their occurence is intermittent and not well predictable.

During a hydrographic survey in January 2006 the spreading of a newly formed saline bottom plume could be observed in the Arkona Sea. Two bottom mounted PC-ADPs were used to measure the near bottom current field of the dense plume with a high temporal (1s) and spatial resolution (5cm). In order to estimate the dissipation rate (ε) of turbulent kinetic energy (TKE) a structure function approch was applied to the beam velocity data of both devices. Contemporary measurements with an MSS-profiler and an ADV supplied independed data for the verification of the structure function method and additional measurements with standard CTD, near bottom towed ADCP and vessel mounted ADCP completed the data set. The estimated dissipation rates from the structure function approach fits surprisingly well with the values derived from the MSS profiler and the ADV. The dissipation rates ranged between 5e-6 and 5e-8 Wkg^{-1} depending on the current regime and stratification. Inside the plume the dissipation rates exceeds that of the overlaying brackish water by two orders of magnitude.

Additionally, a long term deployment of an PC-ADP north of Kriegers Flak is presented, which supplied time series of current profile and TKE dissipation rate in the near bottom layer for a series of subsequent inflowing saline plumes.

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Statistical properties of the calanoid copepod (*Centropages hamatus*) swimming behaviour under turbulent conditions

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Copepods are small (typically mm size) crustaceans common in any aquatic ecosystem. They have developed specific behaviour to cope with the intrinsic turbulent properties of their fluid environment, in order to maximize critical processes such as feeding and mating. The statistical study of behaviour types is then an efficient way to characterize their adaptation and more generally their ecology.

Here we consider the behavioural properties of the marine calanoid copepod *Centropages hamatus*. Individuals *C. hamatus* were tethered and filmed in the lab using an infrared sensitive camera under non-turbulent and turbulent conditions. Four types of behaviours are identified: break, slow swimming, fast swimming and grooming. The analysis is performed using symbolic dynamics: we estimate the probability density of residence times, and the transition probability matrix, providing the probability to switch from a state i to a state j ((i,j)=[1..4]). This modelling framework allows to describe fully the behaviour dynamics of *C. hamatus*. Numerical results are estimated separately for data corresponding to turbulent and non-turbulent conditions, and the results are compared. Our results thus highlight the impact of turbulence on copepod symbolic dynamic behaviour. The main difference between non-turbulent and turbulent conditions lies in the transition probability from slow swimming state to other states and the residence time of slow swimming and break moment. Some ecological implications of our results are provided.

Such a Big Ocean … So Many Scales …
Does it Really Make Sense to Measure Oceanic Turbulence?

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Reputable textbooks tell us that the distinguishing features of *geophysical* fluid dynamics are Earth's rotation and the internal density stratification of atmosphere and ocean. While tremendous advances have been made in defining aspects of global circulation by inclusion of these two factors, there is another distinguishing factor that is rarely mentioned. This is the great range of time and space scales that are excited in geophysical fluids. These contribute to the richness and beauty of fluid motions in ocean and atmosphere and complicate the efforts of modelers to adequately represent even mean flow fields. While it is the smallest of these scales that are of most interest at this meeting, it is the interactions between scales that we must understand.

In such a vast domain as Earth's oceans, our ability to observe turbulence over the full range of scales is limited. The tremendous variability in naturally-occurring turbulence requires data sets that include systematic and comprehensive sampling, and subsequent averaging. Such data sets now exist. From these, four key examples indicate the consistency of turbulence observations with coincident dynamics:

- measurements of turbulence dissipation rate in the upper part of convectively-driven surface mixed layers are consistently equal (within 50%) to the surface buoyancy flux and decrease linearly with depth to the mixed layer base. The resultant energy balance and linear flux profile are consistent with the Monin-Obukhof scalings that represent convectively-driven atmospheric mixed layers;
- observed turbulence momentum flux profiles from measurements at the equator extrapolate to the surface wind stress;
- nonlinear internal waves propagating across the continental shelf lose energy at observed turbulence dissipation rates;
- and perhaps the most significant demonstration comes from comparison to tracer release experiments. Diapycnal tracer spreading represents an integrative consequence of turbulent mixing not subject to the extremes of natural intermittency (at least not when the distribution of the tracer is sampled on annual time scales) and provides a meaningful yardstick for comparison with local turbulence flux estimates. It has been consistently found that there exists agreement of microstructure flux estimates with those determined from tracer release experiments in the main thermocline away from topographically-enhanced mixing sites.

These results arise from independent efforts by multiple groups of researchers. Taken together, they offer strong evidence that microstructure estimates provide a representative means of quantifying turbulence fluxes.

These results give us confidence to forge ahead with new ways to examine oceanic turbulence, such as moored mixing measurements.

Interfacial and benthic stresses in an outflow of dense Antarctic shelf water.

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We use hydrographic, velocity and scalar microstructure measurements to identify those processes determining the evolution of an energetic, bottom-trapped outflow of dense Antarctic shelf water exiting from the Drygalski Trough in the northwestern Ross Sea. The outflow exceeded 200 m in thickness and had a mean speed of ~0.6 m s^{-1}. Benthic and interfacial stresses acting on the outflow were both of order 1 Pa. The bulk Froude number was >1 over the upper slope. For two realizations of the outflow for which the upper boundary was well defined, the entrainment rate was ~10^{-3} m s^{-1}. Spring tidal currents (of order 1 m s^{-1} in magnitude) increased the mean benthic stress opposing the outflow by a factor of ~2.5 relative to an outflow with no tides, significantly enhancing downslope transport in the frictionally-controlled benthic layer. Cross-slope advection and energetic mixing associated with spring tidal currents over the sill were found to generate a pronounced spring/neap cycle in Antarctic Bottom Water generation and export from the region.

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Turbulence and Mixing in the Columbia River Plume

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The Columbia River represents three-quarters of the freshwater input on the US West Coast. It issues as highly-stratified tidal pulses, influencing coastal oceanography over 100s of kilometers. Turbulence occurs at plume fronts, within the highly-sheared interior, and at the bottom boundary layer, all of which are driven at tidal frequencies.

More than 20,000 profiles of turbulence were acquired during six weeks of observations over 3 field seasons in 2004-6. Transects were executed rapidly to resolve tidal variability, and capture a variety of river discharge rates, tidal forcings, and coastal conditions (upwelling/ downwelling). Here we explore different mixing regimes and methods of turbulence generation over a wide dynamic range of forcings.

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Mesoscale ocean dynamics using CVS in altimetric measurements of the Mediterranean Sea

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The Coherent Vortex Separation (CVS) method, which was originally designed for dealing with turbulent flows in numerical simulations [4; 5; 2], has been applied for the first time in the context of oceanic flows [8]. This technique provides assessment on fluid dynamics as a scaleinvariant scheme and it has a potential to be implemented in operational systems of marine modelling, providing stable ways to incorporate space-borne observations and in-situ data.

This methodology is based on wavelets and allows to separate and filter the contributions attributed to the presence of vortices (coherent part) from a random, noise-like contribution (incoherent part). As the coherent part is described by a small fraction of the total degrees of freedom (about 1 % in DNS of 2d turbulent flows), CVS provides a compact explanation on the dynamics and statistical features of turbulent flows. Mesoscale coherent vortices are known to play a key role in ocean dynamics due to their effectiveness in moving energy and matter through the ocean and their impact on mixing [1; 7]. In fact, recent studies have shown that velocity Probability Density Functions in the Mediterranean Sea exhibit non-Gaussian shapes attributed to the presence of coherent vortices [6]. Thus, considering coherent vortices as fundamental building blocks of the flow dynamics and combining CVS with satellite data, a new understanding of the ocean can be obtained.

We have applied CVS to velocity fields derived from Sea Level Anomaly (SLA) maps provided by SSALTO/DUACS for the Mediterranean area and during a whole year. We have performed a survey on different, standard wavelet bases in order to know which one is the best adapted to describe coherent vortices in SLA maps. Our results show that although the total enstrophy of the flow is well described by a small percentage of the total number of modes, CVS cannot explain a significant fraction of the total energy (of at least 20% of the total). Besides, the obtained incoherent parts are never Gaussianly distributed. A closer inspection on the coherent maps reveals that CVS is not properly representing vortices of intermediate energy, what can attributed to the fact that the separation criterion is globally defined (based on Donoho & Johnstone criterion [3]). We show preliminary results obtained when thresholds depending on the local geometry of the flow are used.

This suggests that this method could be improved by choosing a threshold derived from physical considerations and not only from statistical properties. We will also give prospects on introducing a totally new decomposition scheme based on the connections of the marginal PDFs of wavelet coefficients with the turbulent cascade. The final outcome is that CVS potentially allows a description of the role of coherent structures which dominate the organization and the dynamics of the ocean at mesoscale.

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LES of an ocean mixed layer under the stabilizing surface heat flux

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A larg eddy simulation (LES) model of the ocean mixed layer was developed, in which both wave breaking (WB) and Langmuir circulation (LC) were realized by a random forcing consistent with the observed near-surface turbulence and the Craig-Leibovich vortex force, respectively [*Noh et al*, 2004]. Using the LES model, we investigated the effects of the stabilizing surface heat flux on the structure of the ocean mixed layer, and examined the parameterization of vertical mixing used in the ocean mixed layer model [*Noh & Kim*, 1999; *Noh et al*., 2002]. LC is weakened under the surface heating, and ultimately broken down if the intensity of the surface heating becomes sufficiently strong. The critical condition for the breakdown of LC is mainly determined by the Hoenicker number Ho, and the trasition occurs at Ho ~ 1-2. The breakdown of LC leads to a drastic change in the characteristics of the ocean mixed layer, including the variation of rms horizontal velocities with time and the pitch. A diurnal thermocline is formed naturally at a certain depth within the ocean mixed layer under the surface heating, and it suppresses the downward transports of heat, momentum, and TKE. Under the influence of WB and LC, turbulence production in the upper ocean mixed layer is dominated by the TKE flux, contrary to the case in the atmospheric boundary layer, and the balance between the TKE flux and buoyancy flux leads to the formation of a diurnal thermocline. The depth of a diurnal thermocline is determined by both the Monin-Obukhov length scale and the Ekman length scale. Analysis of the LES data reveals that the effect of stratification must be parameterized in terms of the Richardson number based on TKE, rather than that based on mean velocity shear, and the Prandtl number must increase with increasing stratification.

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On the Role of Form Drag on Overflows

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In light of the pressing need for development of parameterizations of overflow entrainment in ocean general circulation models, the behaviour of turbulent gravity currents in the presence of ambient stratification is studied via numerical simulation, for cases in which equilibrated product water masses are formed. Numerical experiments are based on the high-order three-dimensional nonhydrostatic spectral element model Nek5000, which combines the geometrical flexibility of finite element models with the numerical accuracy of spectral models.

In a recent investigation, it was shown that for the case of constant sloping smooth topography and linear ambient stratification, the gravity current separates from the bottom such that the entrained mass flux is independent of the slope angle. The entrainment mass transport, product mass transport, and product salinity then depend only on the ambient stratification, and these quantities were approximated as simple algebraic functions of the ambient stratification parameter that modify the source properties. However, the separation level of the plume did not differ significantly from the neutral equilibrium level in the absence of mixing.

In this study, we put forth that complex bottom topography can affect significantly the equilibrium level of the plume by acting as a conduit to dilute the near-bottom water masses, which otherwise escape the shear-induced mixing taking place at the interface of the gravity current and the ambient flow. The effect of topographic roughness on the propagation speed, separation level from the bottom, the salinity of the product water masses, and the transport and entrainment of the gravity current is quantified.

It is shown that topographic roughness can significantly influence the separation depth of the plume. One of the surprising findings of this study is that the form drag coefficient can be much larger than the bottom viscous stress coefficient. The form drag is a quantity which is challenging to measure in oceanic overflows.

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Internal mixing processes in a seasonally stratified shelf sea

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A key process in the maintenance of enhanced levels of primary production in the summer stratified regions of continental shelf seas is thermocline mixing. Current vertical exchange models however fail to accurately simulate turbulent processes in stratified regions and are heavily dependent on the inclusion of unjustified levels of background diffusion. We therefore seek to better understand internal mixing processes and to improve current turbulence models.

Using measurements of current velocity, vertical structure and turbulent dissipation rate made at a site in the Celtic Sea interior the three likely candidate processes responsible for internal mixing are investigated, they are,

Internal tide/internal waves generated at the shelf break and propagating on to the shelf.

Internal waves or lee waves generated locally by hydraulic control over shelf sea banks and bumps.

Inertial oscillations, most likely generated by changes in wind forcing.

Internal waves generated at the shelf break were found to make no significant contribution to the energy available for mixing at our site. The thermocline is shown to be held in a marginally stable state by a strong and persistent thermocline shear layer, dominated for much of the time by low frequency, inertial shear. It is suggested that sporadically enhanced levels of shear from either inertial waves or a weak internal wave field add to an already tenuous background state, potentially fuelling turbulence via instability.

Using our high quality dataset, the dependence of the turbulent dissipation rate, ε, on local shear and buoyancy frequency is examined and compared to current turbulence parametisations. Traditional models based on local stability fail to replicate any of our observations, however, a simple turbulence model suggested by MacKinnon and Gregg (2003) which scales dissipation rates to low frequency N^2 and S^2 successfully simulates much of the characteristics of thermocline ε.

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Effects of open boundary conditions on coastal circulation

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The performance of a 2-D barotropic, hydrodynamic model and that of a 3-D hydrodynamic model, with respect to several types of open boundary conditions (o.b.c.), was examined in the framework of an oil spill transport and fate study in the area of Saronikos Gulf, just outside of Athens-Greece. The o.b.c.'s were imposed on two particular geometries having two and tree open boundaries, respectively.

Four common types of o.b.c.'s, namely: clamped, sponge layer, free radiation and Orlanski, were implemented in the model. A fifth type, more recent and uncommon, the absorbing-generating o.b.c., was also tried.

The performance of both codes was assessed, and various conclusions are drawn.

Interaction of nutrient load and turbulence in coastal systems.

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Nutrient enrichment and turbulence are important driving forces in the dynamics of coastal ecosystems. In recent years, turbulence has been shown to affect several processes in the water column including the encounter of food particles with predators, the nutrient flux towards algal cells and the settling of particles.

Experiments were conducted subjecting coastal waters from a Norwegian fjord and from the NW Mediterranean to gradients of nutrient load (0 to 24 µM nitrate) or turbulence intensity ($2 \cdot 10^{-9}$ to 10^{-4} $cm^2 s^{-3}$) in controlled land-based containers. Phosphate and silicate were added in Redfield proportions with respect to nitrate. Turbulence was generated with vertically oscillating grids and estimated from spectral analyses of acoustic Doppler velocimeter data. Chlorophyll showed peaks within 2 to 5 days. These peaks increased with nutrient load and turbulence intensity and showed a positive synergistic effect of both variables. The amount of material settling out to the bottom of the containers was estimated from the decrease in total phophorous over time in the water column. Settling of particulate material was apparent in all containers. A regression model showed that nutrient load increased and turbulence decreased the amount of settled material, although some interactions were also apparent. The results show the importance to consider both nutrient load and turbulence in determining coastal ecosystem dynamics, especially since both variables are expected to increase their means and/or variances in global change scenarios of coastal zones.

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The Structure of (Some) Gravity Currents

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The outflows from the Red Sea and from the Mediterranean show a characteristic streamwise–vertical structure with a mixed bottom layer (BL) and a relatively thicker, stratified and sheared interfacial layer (IL). As a function of downstream distance, the dilution of the BL in the Red Sea outflow is less than the dilution of the whole plume. The BL contains highly saline water to the equilibration point of the gravity current, as far as 120 km from the source of the outflow at Bab el Mandeb. In contrast to the limited mixing of the BL with the overlying waters, the IL is mixing vigorously. Hence it is the IL that is the site of “entrainment.” Again a a function of downstream distance, the IL thickens and carries an increasing fraction of the total gravity current transport, dominating the BL transport near the lower end of the Red Sea outflow.

Do we understand the dynamics that give rise to the described structure? What are the implications for parameterizing mixing in these gravity currents? Which other outflows in the ocean and in the laboratory do or do not show a similar structure?

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Microstructure-turbulence profiler series MSS

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The MSS Profiler is a multi-parameter probe for the measurement of microstructure and turbulence in marine and limnic waters. It is equipped with high resolution microstructure and turbulence sensors (temperature, current shear) and standard CTD sensors (temperature, electrical conductivity, pressure). Further sensors, e.g. oxygen, light scattering, and fluorescence can be added. Maximal 9 sensors can be plugged to the profiler. House-keeping sensors control vibrations and tilt of the profiler itself.

The MSS is available in different versions:

MSS 60	Light weight profiler, can be easily deployed manually
MSS 90	Standard profiler for depth range to 500m
MSS 90L	Standard profiler with longer housing
MSS 90D	Heavy profiler for depth range up to 2000m

A turbulence profiler for the full ocean depth is under construction

The MSS Profiler can be used to carry out free sinking or rising measurements. Its sinking or rising velocity can be adjusted by a combination of weights and buoyancy elements.

All profiler have online data transmission. The resolution for all channels is 16 bit, the sampling rate is 1024 per sec.

Components of the MSS system:

- MSS Profiler
- Special ship winch (different types)
- Probe interface for data transmission to PC (USB)
- PC or Laptop for data acquisition
- High speed data acquisition program
- Data evaluation software DatPro

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Vertical Mixing and biogeochemical fluxes in the Shelf Sea Seasonal Thermocline

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At the last Ocean Turbulence Leige Colloquium in 1997 we presented microstructure measurements from the seasonal thermocline in the western Irish Sea which showed that TKE dissipation rates are many orders of magnitude higher than those predicted by vertical exchange schemes used in standard 3-D shelf numerical models [Simpson et al., 1996]. Although this discrepancy has been “corrected” by imposing artificial background diffusivities and dissipations [eg. Burchard et al., 1998] these modification do not reflect the true nature of the processes responsible for this additional turbulence.

In this presentation, we will examine a range of observations from this area, including more recent microstructure measurements made in 2002 and 2006, with the aim of identifying the external forcing and mechanisms responsible for the enhanced levels of turbulent dissipation found within the thermocline region. We will then combine the new observations with simultaneous biogeochemical observations to demonstrate the key role this mixing plays in critical biogeochemical cycles.

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On the theory of turbulent effects on biological physical interactions in the upper ocean

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A nonlinear model for the biodynamical interaction of plankton and nutrients in a laminar upwelling flow field [Robinson, 1999] is extended to the case of a turbulent mixed layer. A random walk velocity field is used to model the effects of turbulence for both diffusion and turbulence induced fluctuation correlations of biological state variables. Lagrangian and Eulerian probability density functions for fluid displacement fields are derived and applied to the Robinson formalism to obtain the statistics of the biological state variables. The approach leads to closed form solutions for the ensemble averaged mean fields. No additional assumption is required to close the mean field equations. To illustrate the theory, the simple nonlinear uptake of Nutrient by Phytoplankton in a uniform light field with a linear strain mean upwelling field is explored in detail. Solutions for the mean *P* and *N* fields are obtained in terms of the mean advective parameter, the ratio of advection to uptake of nutrients, and the Peclet number, the ratio of mean advection to turbulent diffusion. It is shown that the mean net primary production is equal in the extreme limits of $Pe = 0$ and $Pe = \infty$ and exhibits a maximum at some intermediate value of *Pe*. The quantity termed the “turbulent flux gradient function” is shown to play a key role in determining the role of turbulence in net primary production.

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Intermittent turbulence in a littoral zone: Microstructure patches and lengthscales

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Microstructure measurements analyzed in this study were conducted in June 2004 in the littoral zone of Mediterranean Sea at two stations located 20 and 28 km from the coast (Punta de la Banya, Catalonia, Spain) at the depths of 50 and 80 m, respectively. Mesoscale dynamics in the region was influenced by the outflow of River Ebre and the south-western Catalan Current originated in the Gulf of Genova. The near bottom current velocity was about 5-8 cm/s being affected by inertial oscillations. A steady north-eastern wind of 6 m/s was disturbed by short wind gusts up to 35 m/s.

The mean depth of the upper mixed layer was ~ 15 m, the thermocline occupied the depth range between 15 and 30 m, and the thickness of the bottom boundary layer varied from 8 to 12 m. The mean squared buoyancy frequency in the water interior between the pycnocline and BBL was $6\text{x}10^{-5}$ -10^{-4} s^{-2}. The upper layer was slightly freshened (S ~ 37.1 psu) due to the influence of the river inflow. Below the mixed layer, salinity ranged from 37.9 to 38.1 psu. The concentration of particles in the near bottom nepheloid layer was 4.5 mg/l; the mean diameter of particles ~ 4 mμ.

Data obtained with the MSS microstructure profiler [*Prandke and Stips*, 1998] were used to identify microstructure patches following *Ferron et al.,* [1998] and to calculate the Thorpe L_T and Ozmidov L_O scales and the buoyancy Reynolds number $Re_b = \varepsilon/20\,\nu N^2$ [*Yamayaki and Osborn*, 1990]. Based on the criterion $Re_b > 1$, about 30% of the patches were found to be in active state.

The probability distribution of the ratio $R_{OT} = L_O/L_T$ for all microstructure patches showed a median value slightly larger than 1. For active patches, however, we obtained a strong linear fit $L_O = 3.8\ L_T$ with the coefficient of determination $r^2 = 0.92$. For non active patches, the mean value of R_{OT} was less than 3.8 and a lineal regression between L_O and L_T showed a low confidence level ($r^2 < 0.3$).

The ratio L_{Tmax}/L_T was also dependent on the state of turbulence. In active patches, $L_{Tmax} = 2.6L_T$ with $r^2 = 0.96$ and therefore $L_O = 1.4L_{Tmax}$, which is in agreement with findings of *Lozovatsky and Fernando* [2002)] for sheared turbulence. If the same analysis is applied to equal-distance segments of vertical profiles rather than to microstructure patches, the relationship between L_{Tmax} and L_T is not linear but better approximated by a power function $L_{Tmax} = cL_T^{0.85}$, which is consistent with findings of *Lorke and Wüest* [1998] who also employed the equal-distance segmentation analysis. Turbulent scales in specific layers of the water column have also been examined.

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A comparison of strength and mechanisms of diapycnal mixing during three cruises in the upwelling region off Mauritania

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A key mechanism for the strength of biomass production in coastal areas is the diapycnal transport of scalars like nutrients into the euphotic zone. These fluxes are driven by vertical mixing within the thermocline. To advance understanding of the processes driving diapycnal fluxes in upwelling regions, a measurement program consisting of three recent cruises was carried out off Mauritania. The data set combines microstructure measurements, shipboard velocity observations and CTD data with chemical and biological parameters like nutrients, POC, pCO2 and N2O.

The upwelling and the related strong primary production in the coastal area of Mauritania shows a prominent seasonal cycle with its maximum in boreal winter and minimum during July to September. We carried out two cruises during high upwelling season when trade winds were strongest and one cruise in summer when low wind prevailed.

We look into the variability of turbulence in this area and explore the processes that force diapycnal diffusivity like bottom friction and interactions of internal waves at topography.

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Analysis of turbulent fluctuations and its intermittency properties in the surf zone using Empirical Mode Decomposition

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One of the main properties of homogeneous and isotropic turbulence is its inertial range intermittent properties (see e.g. [*Schmitt*, 2006; *Schmitt and Seuront*, 2007]), between a large-scale injection of energy and a small-scale dissipation. In the surf zone, when waves break the wave energy is transferred into turbulent motions through a violent, highly energetic process associated to breaking wave times scales (typically a few seconds) [*Trowbridge and Elgar*, 2001]. The turbulent intermittent fluctuations are then dissipated at smaller scales. The characterization of this small-scale intermittency is important for many applications such as sediment transport, interfacial fluxes, and turbulence-plankton and turbulence-benthic organisms interactions. It is then important in this context to be able to separate highly energetic breaking waves scales from smaller turbulent scales. This separation of turbulence from waves is not an easy task because of the unsteadiness of breaking waves: phase-average methods are not straightworward since the wave forcing is not monochromatic; ocean breaking waves are nonlinear and present random components. We use here for this decomposition the Empirical Mode Decomposition method which has been introduced by Huang et al. as a new time series analysis technique able to separate a given time series into a sum of modes, each one associated to well defined scales [*Huang et al.*, 1998]. This method is most efficient and interesting for nonstationary and nonlinear time series, and is efficient to separate trends from small-scale fluctuations. Since its introduction, it has been successfully applied to many topics in the natural and applied sciences, including one study on nonstationary wind-induced ocean wave data [*Hwang et al.*, 2003].

We recorded velocity fluctuations in the surf zone of the Eastern English Channel (Wimereux, France) using a 25 Hz resolution 3 components velocity Accoustic Doppler Velocimeter (Sontek, ADV) with measurements at microscale (volume of about 250 mm^3). Two measurement campaigns have been done, each one for a tidal cycle. The time series have been analyzed using the EMD method, separating the energetic breaking waves scales (the trend), and the small-scale turbulent fluctuations. As a second step, we analyzed the intermittency properties of the small-scale turbulence: we characterize the high-frequency properties of the kinetic energy and consider the pdf, the second characteristic function and the memory properties of the small-scale velocity fluctuations. We finally show how to synthetically generate such time series.

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Turbulence Re-Revisited: Intermittency and Marine Ecosystems Structure and Function

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Turbulence is a ubiquitous feature of aquatic ecosystems, and much has been written about its potential effects on plankton biology and ecology. Despite the acknowledged intermittent nature of turbulent flows [*Seuront et al.*, 2004; *Seuront & Schmitt*, 2005a, b], little is still known on the potential impact of turbulence intermittency on plankton distributions and related processes such as encounter rates (predator-prey, sexual partner, host-pathogen), nutrient fluxes toward phytoplankton cells and matter fluxes towards the deep ocean. After briefly reviewing the stochastic properties of turbulent flows, we propose a general modelling framework that might be use to re-revisit the effects of turbulence on biological processes such as encounter and diffusion rates and on 'characteristic' space-time scales such as the Batchelor and the Kolmogorov length scales. Combining large data sets of small and microscale distributions of nutrients, phytoplankton and zooplankton, we further illustrate (i) how the intermittent nature of plankton populations is commonplace in aquatic ecosystems, (ii) how these distributions are related to each other and (iii) how they are controlled by/independent of the intensity of turbulent flows. More specifically, under the field data supported assumption that turbulence intensity controls small-scale nutrient patchiness, we introduce the hypothesis that under nutrient limitation, 'turbulent history' (i.e. the turbulence conditions experienced by phytoplankton cells) conditions the efficiency of phytoplankton cells to uptake ephemeral inorganic nitrogen patches of different concentrations. In this intermittent framework, the implicit steady-state assumption ruling the use of Michaelis-Menten equation ceases to be the rule, and phytoplankton cells are likely to have developed specific adaptations to enhance nutrient uptake in response to ephemeral point source. Using nitrogen pulse experiments, we thus show that under nutrient limitation that phytoplankton cells exposed to high turbulence intensities prior to the pulse were more efficient to uptake high concentration nitrogen pulses. In contrast, under low turbulence conditions uptake rates were higher for low concentration nitrogen pulses. These results suggest that under nutrient limitation, natural phytoplankton populations respond to high turbulence intensities through a decrease in affinity for nutrients and an increase in their transport rate, and vice versa. The consequences of other intermittent, unsteady distributions including bacteria enzymatic activity and the microscale distributions of viral and bacterial populations in a variety of marine environments are discussed.

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The formation of some features in spatial distribution of zoobenthos by hydrological condition in the coastal ecosystems.

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The attempt is undertaken for estimation of influence of coastal currents on distribution of certain species and benthic communities in the marine ecosystems of the Crimea Coast (Black Sea). The linear theory of wind was used for calculation of flows (in the homogeneous sea) without a horizontal exchange of momentum. The meanings of speed and direction of wind were used from natural observations.

The negative correlation is revealed between benthic biomass and value of vertical components in speed of flows. The congestions of benthic animals were registered on separate parts of sea bottom with low value of speed in vertical component of coastal currents. The numerical modeling was executed for estimation of transportation of mollusc larvas by system of coastal currents in the investigated water areas. Spatial distribution of the benthic communities was predetermined by variability of the hydrological conditions formed under influence vertical components of speed of coastal flows. High variability and non-steady-state coastal currents can be the determining factors for bottom animals in formation of congestions and communities. This follows from results of numerical and statistical modeling.

Intense mixing at the base of a constrained deep ocean cascade

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The overflow that occurs across the Wyville Thomson Ridge at the southern end of the Färoe-Shetland Channel carries cold Norwegian Sea Deep Water (NSDW) down a narrow gully and into the Rockall Trough. It is highly intermittent with maximum transports of order 2 Sv and minima close to 0 Sv. During high flows the gully sides prevent the current from spreading out, and the bulk Richardson number can be of order 5 so that entrainment at the interface is relatively small. Two major events are examined in detail - one from a bottom mounted ADCP and the other from ship borne CTD sections across the gully. During high flow the velocity profile is highly sheared in the bottom 50 - 60 m, and maximum speeds (> 1.5 m s^{-1}) are observed 150 m above the seabed. Internal tidal currents become significantly amplified during such events (compared with other times) but appear to have a marginal impact on bottom stress. CTD data show that as the plume descends from the ridge to the Rockall Trough, its temperature near the sea-bed can warm by over 3 °C in about a day. Very large overturns (up to 50 m) are evident in some CTD profiles, and it is demonstrated from Thorpe scale calculations that vertical diffusion coefficients near the sea-bed can be as high as 10^{-1} m^2 s^{-1}. Thus the warming of the bottom waters is due to shear induced bottom mixing within the plume rather than entrainment at the interface. It is likely that some of the NSDW had mixed with warm northward flowing North Atlantic Water before the overflow crossed the ridge. The water that flowed into the northern part of the Rockall Trough had a temperature profile that ranged from about 3 ºC at the bottom to 8 ºC at the interface. Mixing in the plume determines the subsequent fate of the overflow. Water with a temperature of > 6 ºC probably escapes into the Iceland Basin between the banks that line the north-western part of the Trough. Cooler water must have travel down the eastern side of the Rockall Bank.

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Turbulent dissipation across a tidal mixing front

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We report on an intensive campaign in the summer of 2006 to observe turbulent mixing processes in the vicinity of a tidal mixing front (TMF) in the western Irish Sea. TMFs are characterised by strong gradients of turbulent stirring by the tide and resultant changes in stratification. Turbulence was observed on a section across the front by a combination of vertical profiles with the FLY dissipation profiler and horizontal profiles by shear sensors mounted on an AUV (AUTOSUB). Mean flow conditions and stratification were obtained from a bed mounted ADCP and a vertical chain of thermistors on a mooring. During an AUTOSUB mission of 60 hours, the vehicle moving at a speed of ~1.2 m/s completed 10 frontal crossings between end points which were allowed to move with the mean flow. Two sensors measured the fine scale of velocity shear as $\partial v/\partial x$ and $\partial w/\partial x$ to provide estimates of ε the rate of TKE dissipation. Similar measurements of ε were made for periods of up to 25 hours at positions along the AUTOSUB track using the FLY profiler deployed from the R.V.Prince Madog. There is a high degree of consistency between the FLY and AUTOSUB measurements when the AUOTSUB passed close to the research vessel and the two data sets are being integrated to test model concepts of the space-time evolution of turbulence in the frontal zone. The results will also be related to the ADCP measurement of the mean flow structure which, in addition to the expected barotropic tidal flow, indicates the presence of a marked baroclinic component of flow in the less strongly stratified water close to the front.

Turbulence and suspended sediment in estuaries and shelf seas.

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Measurements of Reynolds stresses, turbulence production, water column temperature structure and suspended sediment concentrations have been carried out over at several location including estuaries, coastal lagoons and shelf seas. The measurements were carried out using a moored fast sampling ADCP. The observations were supplemented by intense periods of observations, in which vertical profiles were carried out, for at least a tidal cycle, using a CTD, equipped with optical sensors (e.g. transmissometers, LISST-100, or OBS) , as well as obtaining water samples to estimate SPM concentrations .

In general the observations indicate a strong correlation between suspended sediment concentrations and levels of turbulent kinetic energy (TKE), mainly related to the tidal flow. The principal variations of SPM concentration are due to resuspension and settling of bed material. There are clear spring-neap and M_4 variability in both suspended sediment and TKE, with a time lag increasing with height. This particularly true for the case of the Gulf of California; which shows strong agreement with theory. Nevertheless it is apparent in most of the other observations that flocculation processes are important, so that the SPM distribution is a fine balance between resuspension, advection and flocculation. It is also apparent that the acoustic backscatter is good to estimate gravimetric concentrations and not so good for the volumetric concentrations, so that some discrepancies between LISST-100 data and ADCP data will arise, specially when low density large flocs are present.

Comparisons of these data with numerical model results will be carried out to test hypotheses of different processes controlling the SPM and turbulence distribution in different shelf seas scenarios.

Turbulent mixing in the seasonally-stratified Western Irish Sea: a Thorpe Scale perspective.

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In stratified shelf seas, mixing is primarily driven by bottom-boundary tidal stresses, surface-boundary wind stresses and convective processes; although shear driven by near-inertial oscillations, internal tide and topographic lee waves may also be an important source of instability within the interior of the water column. These interior processes are particularly important if they drive a flux of nutrients across the base of the thermocline into the sub-surface chlorophyll maximum.

Microstructure measurements of the rate of dissipation of turbulent kinetic energy (using shear probes) are now commonly used to study turbulent mixing in the ocean and shelf seas, however a technique that has seen a resurgence in recent years is the use of the Thorpe scale (the overturning length scale obtained by taking the root-mean square of the vertical displacements required to reorder a profile of potential density so that it is gravitationally stable) and the relationship between the Thorpe and Ozmidov scale to infer turbulent mixing.

In July 2006 a 29-hour, single-point, time-series of water column structure, turbulent dissipation rate and current velocity profiles was made at a site in the summer-stratified Western Irish Sea. Series of FLY dropsonde profiles were interspersed with CTD profiles yielding a data set of 172 microstructure profiles (shear probe data) and 58 finestructure profiles (CTD data). Initial estimates of the rate of turbulent kinetic energy dissipation from microstructure and Thorpe scale methods show strong signals in response to tidal stresses near the bed (order 10^{-2} W m^{-3}) with qualitatively similar temporal and spatial patterns. In the interior of the water column, however, the relationship is less clear.

We compare the temporal and spatial agreement of the dissipation rates derived from the two approaches. We also consider possible causes of discrepancy.

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Limits of the k-ε model to simulate shear enhanced eddy diffusivity below the surface mixed layer: the Gulf of Finland case study

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Profiles of current velocity, density and shear microstructure were obtained at the entrance to the Gulf of Finland, in July 1998. Three time series of shear microstructure measurements (duration 13, 24 and 14 h respectively) were performed in 3 different wind forcing regimes as well as in 3 different background stratification and shear situations. Vertical shear of current velocity was enhanced by near-inertial waves during the first (A1) and third (A3) time series. We compared a Richardson number based parameterization and an estimation using the two equation k-ε turbulence closure (General Ocean Turbulence Model, GOTM) with "measured" eddy diffusivities. For two out of the three time series eddy diffusivities calculated via a Richardson number parameterization and via simulation using the k-ε model agreed well to the experimental data. In the case of relatively high shear and weak background stratification (time series A3) both applied methods resulted in a remarkable discrepancy against the measured eddy diffusivity.

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Are cascading flows stable?

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We consider the stability of flows cascading as dense inclined underwater plumes, using data obtained by Ozen and Lemmin (EPFL, Switzerland) in Lake Geneva during winter periods of severe cooling. A conjecture by Turner, based on the classic experiments of Ellison and Turner, that the flow may be in a state of marginal stability is confirmed: the observed mean velocity and density profiles are unstable to Kelvin-Helmholtz instability, but only marginally so; the growth rates of the most unstable small disturbances to the cascading flow are small, with e-folding periods of about 2 hrs. A reduction in the maximum velocity by about 20% is required to stabilise the flow.

The possibility that stationary hydraulic jumps may occur in the flow is also considered. Several plausible flow states downstream of transitions are examined, allowing for mixing and entrainment of the overlying fluid to occur in a hydraulic jump. No downstream state is found that conserves the fluxes of volume, mass and momentum, in which the energy flux does not increase, and that is ‘stable’ in the sense that no further transition is possible to a similar flow state without more entrainment. Only small increases in the observed flow speeds are however required before transitions to flows with profiles of velocity and density differing from those observed become possible; the flow state may be regarded as stable to finite changes involving hydraulic jumps but, again, only marginally so.

Other stratified shear flows, such as that forced by wind in the upper ocean boundary layer, may also be in a marginal state.

Overflows on the Mid-Atlantic Ridge

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In order to close the global overturning circulation, buoyancy lost from the ocean to the atmosphere at high latitudes must be gained elsewhere along the path of the flow. In case of the deep and bottom waters this buoyancy gain is primarily accomplished by mechanical mixing with overlying water. Microstructure observations suggest that mixing in ridge-flank canyons (esp. fracture zones) and rift valleys on slow-spreading mid-ocean ridges account for a significant fraction of the required buoyancy fluxes. One of these ridges, the Mid-Atlantic Ridge (MAR), covers more than 50% of the entire seafloor of the Atlantic Ocean.

Here, we present data covering ~350 km of rift valley in the North Atlantic near the Azores islands. This stretch of rift valley hosts several major hydrothermal vent fields and has, therefore, been the focus of several research projects during which physical oceanographic measurements were taken. Similar to the situation in many of the ridge-flank canyons in the South Atlantic, the hydrography in the rift valley is characterized by a monotonic density gradient, which is maintained by a balance between along-valley advection and diapycnal diffusion. Due to the segmentation of the MAR, the axial topography of the rift valley in this region is characterized by a sequence of deep basins separated every 30 km or so by shallower sills. On crossing these sills, the persistent northward along-valley flow transporting order 0.1 Sv of water forms overflows with velocities exceeding 20 cm/s, strong vertical shear and mixing. Diapycnal diffusivities reach 0.01 m^2/s in these overflows and strong dissipation has been observed to extend into the lower thermocline.

Geophysical considerations suggest that there are order 10,000 sills in ridge-flank canyons and rift valleys on the global mid-ocean ridge. Available hydrographic data indicate that along-valley density gradients (and, therefore, persistent along-valley flows) characterize the hydrography/dynamics in many of these canyons. These considerations suggest that overflow mixing on mid-ocean ridges may contribute significantly to the oceanic buoyancy budget.

Upscaling near-bottom sediment-turbulence interaction effects for large-scale 3D sediment transport modelling

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Currently used 3D sediment transport models still fail to make good quantitative predictions. Several causes can be attributed to the inadequate description of physical processes which occur at the subgrid scale level. Specific attention is given to the modelling of turbulent mixing, particle-turbulence interactions and near-bottom boundary layer processes. Due to these processes the effective bottom roughness is modified, resulting in different flux balances. These important effects are not yet incorporated into current hydrodynamic calculations and can explain discrepancies in predicted flow fields. A procedure for the development of new subgrid scale closures for the simulation of sediment-laden turbulent flow with engineering models applied to problems at geophysical scales of coastal waters and estuaries is described It is based on two-phase flow theory and data generated by Large Eddy Simulation and low-Reynolds RANS models. This leads to a three-layer approach, comprising a supersaturated near-bed layer, a transition layer (under certain conditions) and the fully developed turbulent water column.

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Turbulence and hydrographic observations in an estuary during the onset of a Harmful Algal Bloom

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A large pool of evidence suggests that Harmful Algal Blooms have increased in frequency and impact on human and ecosystem health and economic losses over the past decades [Glibert and Pitcher , 2001; Zhang , 1994]. Dinoflagellates constitute one of the larger groups responsible for HABs [Zingone and Enevoldsen, 2000]. Dinoflagellates typical of frontal areas, upwelling relaxation and coastal current entrainment (mixing-drift adapted life-form as classified by Smayda [2002]) are adapted to increased vertical velocities and can swim. The Rias Baixas (four bays on the NW Iberian peninsula including the Ria de Vigo) has the highest mussel production in Europe and suffer from frequent HAB episodes. *Gymnodinium Catenatum* has been responsible for HAB events in the Ria de Vigo for decades [Estrada et al, 1984, Figueiras et al 1994] and has been linked to the onset of downwelling conditions at the end of the upwelling season April-September, [Fraga et al., 1988; Figueiras et al., 1994; Sordo et al., 2001]. During recent field work (25-30 September 2006), physical and biochemical conditions were measured in the Ria de Vigo at unprecedented temporal and spatial resolution. The field work coincided with the development of a *Gymnodinium Catenatum* HAB event in the inner part of the ria. Measurements of horizontal currents from nine Acoustic current profilers (7 fixed platforms and 2 vessel mounted), hydrography from an undulating CTD and turbulence probe accurately described the physical conditions in the Ria de Vigo. Initial analyses support the idea of accumulation of a seed population of *Gymnodinium Catenatum* in the inner ria promoting the development of the HAB event. Turbulence data will be analysed and related to the extent and growth of the HAB event. The spatial variability of mixing in the Ria de Vigo will be shown and its implications for ecosystem functioning discussed.

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Laboratory modeling of excitation of internal waves by turbulent buoyant plumes discharged from a submerged wastewater outfall

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Disposal of wastewaters of coastal cities to the ocean is a usual world practice. A typical outfall construction consists of a submarine pipeline with a diffuser section at the far offshore end – a manifold with many small holes [*Koh, Brooks*, 1975]. Fresh water is discharged to ambient salty ocean water at rates 1-5 m/s to form buoyant plumes producing sensible stress on coastal water areas including effects on hydrodynamics of coastal zone and coastal ecosystems. Modern methods of investigation of the outfall area include modeling [*Koh, Brooks*, 1975, *Bondur etal*, 2006], contact field measurements [*Bondur etal*, 2004] and remote sensing by airborne and spaceborne instruments [*Bondur etal*, 2005]. The latter method is based on surface manifestation of the submerged outfalls hypothetically due to effect of internal waves generated by buoyant plums [*Bondur etal*, 2005]. The main aim of the present work is investigation of possibility of internal wave excitation by buoyant turbulent plumes and estimate of efficiency of such mechanism basing on laboratory scale modeling.

The experiments were carried out in the large thermostratified tank (overall sizes 20m×4m×2m) with artificial thermocline-like temperature stratification. The alcohol solution with density 0.93 g/cm was discharged at the rates $U_0 = 0.3 \div 1.9$ m/s from b_0=0.3cm holes forming turbulent plumes trapped by the tank thermocline. These parameters provided scale modeling of Sand Island Honolulu wastewater outfall in Mamala bay (Hawaii) with the geometrical scale 1/27. U_0=1 m/s provide similarity in dimensionless parameters of the problem: the Richardson number $Ri = g\Delta\rho_0 b_0 \big/ \rho_0 U_0^2$ and the dimensionless parameter of the ambient stratification $Str = N_0^2 b_0 \rho_0 \big/ g\Delta\rho_0$ (here $\Delta\rho_0$ is the initial difference between the plum and ambient densities, N_0^2 is the maximum buoyancy frequency, g is the gravity acceleration). Excitation of intensive temperature oscillations was observed at significant distance (1.3÷4 m) from the diffuser. For the discharge rates 95-105 m/s, corresponding to the scale-modeling conditions the amplitude of the isotherm oscillations was 3÷5cm, which gives to 0.8-1.3 m for the field conditions according to the scale coefficient 1/27. The measured dependency of the amplitudes of oscillations on the control parameter of the problem *Ri* was typical for the presence of the Hopf bifurcation to the self-sustained oscillations of the buoyant plume [*Huerre, Monkewitz*, 1990]. The observed internal waves were interpreted as a result of impact of the oscillations on the thermocline.

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Geometrical multifractal signature in remote sensing data of the ocean and its connection with universal cascade processes

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Since Kolmogorov's 1941 theory on energy dissipation in a turbulent flow [3], turbulent energy dissipation at a given scale r has been regarded as a random process completely defined by the scaling exponents ζ_p associated to the structure functions $S_p(r) = \langle \epsilon_r^p \rangle \sim r^{\zeta_p}$. Kolmogorov's picture regarded dissipation as a constant injection rate depending only on the scale ratio; this necessarily leads to a "normal scaling" of the scaling exponents $\zeta_p = Hp + \beta$. It was however soon evident that anomalous scaling was much more frequent than normal scaling, and so energy dissipation among scales should be take the shape of a infinitely divisible random process [6], the so-called random cascade. Random cascades show up not only on turbulent energy dissipation but in the small-scale structure of scalar fields submitted to the flow [4]. With the introduction of multifractal theory, Parisi and Frisch [7] showed that the cascade can be interpreted as the result of an underlying hierarchy of fractal manifolds, each one affected by different, scale-invariant dissipation rates: the multifractal hierarchy. The fractal dimensions of the fractal components are connected with the scaling exponents of the structure functions as $\zeta_p = \inf_h \{ph + d - D(h)\}$ where $D(h)$ is named the *singularity spectrum*.

Although geometric in its conception, the multifractal structure of flows has been often regarded as a statistical signature only: this is the Canonical Approach. The alternative would be try to obtain the different fractal manifolds from a given velocity field, what could serve to characterize spatial inhomogeneities in energy dissipation; such a geometry-oriented approach is known as the Microcanonical Approach [1]. Some attempts to apply the Microcanonical Approach to different fields have been essayed since long ago [1; 5], but the difficulties to obtain quality data under real situations prevented to explore further the advantages of this formalism.

Quite recently, the Microcanonical Multifractal Formalism (MMF) has been applied to scalar fields of Sea Surface Temperature (SST) data derived from satellite sensors [8; 2]. The major processing issues have been solved by the introduction of appropriate wavelet techniques [9; 10], devised as singularity analysis methods. With these new techniques, each point $\vec{x}$ in the flow can be assigned a local scaling exponent $h(\vec{x})$, which are the microcanonical counterparts to the canonical scaling exponents ζ_p. The multifractal decomposition of the flow is readily obtained, as each fractal manifold is associated to a particular value of singularity exponent h.

In this talk, we will show that the singularity exponents h of a scalar for which advective transport is important enough in the short time scales (compared to the resolution scales of data) are passively advected by the flow. As results show this seems to be the case of SST. Even more, the obtained fractal dimensions of the fractal components ($D(h)$) are in agreement with Parisi & Frisch's derivation. So that, $D(h)$ can be used to characterize the cascade process in the ocean with improved precision and less data than the canonical approach [11]. Besides, the associated cascade process is the same for many different regions in the global ocean. We also shown that singularities derived from other satellite-acquired scalars (chlorophyll concentration maps) are quite resembling to the ones derived from SST; also, they lead to the same cascade process as SST singularities. These experimental facts evidence that the multifractal structure of the scalars in the ocean are induced by a common mechanism acting on them, the underlying turbulent flow. As a consequence, singularity analysis obtained when SST images are processed can be used to delineate the streamlines of the flow [2]. As a practical application, we will show that singularity-derived streamlines evaluated from micro-wave SST maps almost perfectly align with the geostrophic velocities derived from new products of satellite altimetry data. To end, we will discuss the astonishing picture of the global ocean circulation depicted by singularity analysis.

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Transverse structure of turbulence and dynamics of rotating gravity currents in a channel

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Simultaneously measured transects of turbulence, velocity, and stratification in strong gravity currents observed in two channels in the Western Baltic Sea are presented. The horizontal scale and thickness of theses gravity currents are of the order of 10 km and 10 m, respectively. At low to intermediate Froude numbers the currents reach velocities of up to 0.7 m s^{-1}. Due to their high horizontal and vertical resolution, our transects provide, for the first time, a detailed and synoptic two-dimensional picture of the turbulence structure inside rotating gravity currents. Strong boundary-layer and interfacial turbulence can be distinguished from a quiet core, and a strong asymmetry of mixing near the outer edges of the gravity current is apparent. This asymmetry is mirrored by the computed entrainment velocities, varying approximately by a factor of 5 across the gravity currents. It is argued that the asymmetry is due to rotational effects that can be clearly identified also in the velocity and density fields. High-resolution cross-channel variations of the relevant non-dimensional parameters (Froude number, Ekman number, entrainment parameter) are computed from our data, and compared to available entrainment models. The results are compared to a two-dimensional (cross-sectional) second-moment turbulence model for a gravity current evolving in an idealized channel. The agreement with observations is excellent, and the model is used to draw further conclusions about the rotationally influenced dynamics inside the gravity current.

The energy balance of the North Sea.

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The input of kinetic energy to a basin like the North Sea by tide and winds is averagely balanced by the dissipation into heat. The net energy input by the tide can be estimated from the Kelvin waves entering the area from the Northwest and the South, and leaving the North Sea basin at the upper North side. The energy input by winds can be estimated from the wind stress at the water surface for various wind conditions.

All incoming energy is transferred to horizontal and three-dimensional turbulence. In the 2D regime there is some transfer from smaller to larger scales but finally the two-dimensional eddies yield their energy to the 3D regime by shearing processes, so that finally all energy passes the 3D domain on its way to the heat drain. One can expect that the corresponding part of the kinetic energy spectrum has the characteristics of an inertial range with $k^{-5/3}$ structure. This is confirmed by the spectrum derived from dispersion experiments [*Van Dam* et al., 1999]. The level of the $k^{-5/3}$ energy curve determines the total amount of dissipated energy.

In this paper the energy quantities of the various inputs (under various conditions) are mutually compared as well as to the dissipation determined from the energy spectrum. The results from tracer experiments indicate that the amount of 3D turbulent energy per unit volume close to the surface can be considerably higher than in deeper layers, supposedly due to a direct effect of wind. More observations are required for a better quantitative analysis.

A summary is given of the method of deriving the energy spectrum from the tracer dispersion rate at various scales, including the method for separating the contribution of horizontal eddies to the dispersion and the contribution of vertical shear and the accompanying vertical mixing.

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Flow interactions over plant- and animal assemblages: is the overall effect equal to the sum of the constituents?

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Biotic structures are well known to modify near bed flow. This modification of the physical conditions in the environment modifies the habitat is called ecosystem engineering. Benthic organisms vary widely in flexibility, protrusion height, shape and size. Rough, hard structures such as epibenthic bivalves, tube worms and corals create turbulence in the boundary layer. Filter feeding bivalves can add to this by the effect of the interaction of their exhalent jets with the boundary layer flow. Aquatic plants severely reduce flow speeds inside the plant canopy. Although turbulence intensity inside the canopy is increased, the flow reduction is often large enough to create a relatively calm environment, where sedimentation is increased and bed shear stress is severely reduced.

In recent years a numer of studies have been devoted to the interaction of individual species and boundary layer flow, e.g. the effect of seagrass on flow. Most natural systems actually consist of communities of species. E.g. in the Mediterranean large bivalves (*Pinna nobilis*) grow inside seagrass meadows, creating a substrate of large, rough elements submerged inside a flexible canopy. In the Oosterschelde lawns of tube worms (*Lanice conchilega*) can be invaded by clumps of Pacific Oysters, creating a bed surface with roughness elements of different orders of magnitude.

Within the framework of the EU marine biodiversity network MarBEF, a workshop has taken place where the individual species effects of different biological roughness structures as well as the cumulative effect of mixes of these structures were analysed. An attempt will be made to relate energy dissipation per unit biomass in the boundary layer to exposed surface area, surface to volume ratio, flexibility of organisms, protrusion height of the canopy / community and “porosity” of the community.

Using fast-sampling ADCP for observing vigorous processes above sloping ocean bottoms.

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Above sloping bottoms in the ocean, mixing processes are not predominantly generated by shear induced turbulence. Instead, the interaction of buoyancy and internal wave variations create a highly non-linearly varying environment. Most vigorous [mixing] processes that dominate sediment resuspension occur during the passage of frontal bores or solitary boluses. Such fronts pass a site within a few minutes, extending some 50 m above the bottom and occurring once per tidal or sub-inertial period. In order to observe the details of such bore one needs specific, fast-sampling equipment. A suitable piece of equipment is a bottom-mounted 4-beam 300 kHz acoustic Doppler current profiler (ADCP), provided it samples at a rate of once per second over a period of typically several weeks. Not just the three components of current velocity [u,v,w], but also the relative 'echo intensity' dI, a measure for suspended matter and stratified turbulence, are monitored over a range of some 80 m at 1 m intervals. Here, several observationals are discussed from various deep sloping bottom sites.

For example, the 3-60 m horizontal beam spread and the 1-2 Hz sampling allow the distinction of different arrival times t_i, $i = 1,\ldots,4$, at different distances in the acoustic beams from sharp changes in dI-content associated with frontal non-linear and turbulent bores or 'waves'. The changes in dI are partially due to variations in amounts of resuspended material carried by the near-bottom turbulence, and partially due to the fast variations in density stratification ('stratified turbulence'), as inferred from 1-Hz sampled thermistor string data above the ADCP. Such bores are observed to pass the mooring up to 80 m above the bottom having typical propagation speeds $c = 0.15\text{-}0.5$ m s^{-1}, as determined from $dI(t_i)$. Particle speeds in the immediate environment of a bore amount to $|u|_{env} = c \pm 0.05$ m s^{-1}, the equality being a necessary condition for kinematic instability, whilst the maximum particle speeds amount $|u|_{max} = 1.2\text{-}2c$. The dI-determined directions of up-, down- and alongslope processes are all to within ±10° of the ADCP's beam-spread averaged current (particle velocity) data.

Wave Modulated Turbulent Fields at the Ocean Surface and Related Air-Sea Fluxes

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Ocean surface processes and air-interaction in general, have recently received increased attention and it is now accepted that small-scale surface phenomena such as surface waves, turbulence, bubbles and droplets, can play a crucial role in the air-sea fluxes of heat, mass and momentum, with important implications for weather and climate studies. Yet, despite good progress in recent years, the air-sea interface and the adjacent atmospheric and marine boundary layers have proven to be difficult to measure in all but the most benign conditions. This is in part because, as opposed to the flow over a solid flat boundary, from which models of air-sea fluxes are derived, the ocean surface is subject to drift currents and populated with surface waves and turbulent eddies over a large spectrum of scales. The difficulty of making measurements is further complicated by the fact that there may be significant interactions between the currents, the surface waves, and the turbulence.

We present data from three field experiments from *R/P FLIP* and Scripps pier where we have used novel optical and infrared techniques aimed at simultaneously studying multiple aspects of the air-sea interface. The data show that the skin layer temperature is modulated by the surface wave field. This is not a novel result, but we show here in addition, that the surface kinematic fields such as the divergence and vorticity are also coherent with the temperature field. This is the result of the presence of Langmuir circulations (or Langmuir turbulence) at the ocean surface which is in fact, one of the better understood interactions between vortical fields and the Stokes drift generated by the surface waves. Consequently, we show that the surface turbulence and kinematic fields are in turn modulated by the surface waves, just as the skin temperature is. For example, the vortex lines are stretched and compressed by travelling surface waves leading to enhanced vertical vorticity at the crest of the waves. The turbulence is modulated by the waves in a fashion that is qualitatively consistent with rapid distortion theory whereby the shearing effect of the wave orbital motion is more important to that of turbulence self interaction. In summary, our results show that the surface waves modulate the thermal molecular layer as well as the turbulence at the surface of the ocean.

These results will be discussed on the context of their influence on the modulation of air-sea fluxes.

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Laboratory observations of increased plume entrainment in the presence of submarine canyons and ridges.

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The continental slopes in the ocean are often intersected by small-scale topographic features such as submarine canyons and/or ridges. Cold, dense ocean currents that move geostrophically along the slope may encounter such features and portions or all of the dense water can then be steered by the topography down towards the deep sea. When the water is redirected in this manner it follows a shorter path to the deep sea, and it seems plausible that less total mixing will take place in the plume since the distance over which it entrains water can be much shorter.

In order to investigate this question, a laboratory experiment has been conducted at the Coriolis rotating platform. A dense source was placed on top of a slope, and experiments were repeated with a straight slope, with a ridge, and with a canyon. The time development of the stratification in the receiving basin was monitored, and from this the total plume mixing could be calculated. Contrary to what was expected, the presence of a submarine canyon as well as a ridge increased the total mixing that took place in the plume. The product water that ended up in the laboratory basin was less dense when a canyon or a ridge was placed on the slope, compared to when they were removed. The reason for this extra mixing appears to be that the plume speeds up when it is steered by the topography, which has also been observed in the dense plume that moves along the Weddell Sea continental slope.

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Turbulence in low energy bottom boundary layers

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Turbulence in the aquatic bottom boundary layer is essential to coupling the water column to the underlying sediment. Turbulence controls the vertical flux of momentum and scalars (e.g. carbon, nutrients, oxygen) between the sediment and the water column above.

Much effort has been made in understanding turbulence in the aquatic bottom boundary layer. Over the past 2 decades, the advent of 'off the shelf' acoustic Doppler current profilers has revolutionised the measurement of velocity and turbulence profiles. This paper presents data from experiments using acoustic Doppler current profilers to estimate turbulence in two low energy benthic environments. Two different approaches are taken to estimate turbulence dissipation rate profiles in the bottom boundary layer. The first examines the spectra of along beam velocities from a pulse coherent acoustic Doppler profiler and fits this to Kolmogorov's 5/3 law and the second looks at the spatial decorrelation in turbulent fluctuations using a structure function method. These approaches are described then compared against each other and against parallel measurements from temperature microstructure profiler.

The first dataset is from a deployment in Lake Alpnach, Switzerland, which is accompanied by measurements from a temperature microstructure profiler. The second dataset is from Llyn Tegid in Wales. Both lakes exhibit an internal seiche (period 18 hours in Alpnach and 20 hours in Tegid) which drives turbulence in the bottom boundary layer. The measurements show the capacity of acoustic Doppler profilers to estimate turbulence dissipation rates at low energy levels ($\varepsilon \sim 10^{-6}$ W m^{-3}).

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Mean Circulation and Structures of Tilted Ocean Deep Convection

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Convection in a homogeneous ocean is investigated by numerically integrating the three dimensional Boussinesq equations in a tilted-rotating frame (f-F-plane) subject to a negative buoyancy flux (cooling) at the surface. The study focuses on determining the influence of the angle (tilt) between the axis of rotation and gravity on the convection process. To this end we vary two essential parameters: (i) the magnitude of the surface heat flux, and (ii) the angle (tilt) between the axis of rotation and gravity. The range of the parameters investigated is a subset of typical open ocean deep convection events.

We demonstrate that when gravity and rotation vector are tilted with respect to each other: (i) the Taylor-Proudman-Poincaré theorem leaves an imprint in the convective structures, (ii) a horizontal mean circulation is established, (iii) the second order moments involving horizontal velocity components are considerably increased.

Tilted rotation thus leaves a substantial imprint in the dynamics of ocean convection.

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Microscale fluorescence structures in the ocean

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We have developed a freefall microscale structure profiler (TurboMAP) that measures high resolution fluorescence field in the upper ocean. TurboMAP carries conventional shear probes, temperature, fast temperature and conductivity probe, and a new LED microscale fluorescence probe (ca.2 cm resolution). We present the performance of TurboMAP and the calibration method of the LED probe. In addition, we have also developed a new laser fluorescence probe that can resolve scales at least ten times smaller (a few mm) than the original LED probe. We mount both the LED and the laser probe on a newly designed profiler. When the microscale sclae fluorecence signals for the LED and the laser probe are averaged over one meter, the averages agreed with signals from a conventional CTD mounted fluorescence field. We present microscale features of fluorescence field from both sensors.

A New Look at Richardson Number Mixing Schemes for Equatorial Ocean Modeling

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It is thought that the realism and fidelity of ocean general circulation models has been improved by the use of empirical parameterizations of shear-driven mixing. These parameterizations express the turbulence mixing coefficients in terms of the local gradient Richardson number (Ri), the ratio of the squared buoyancy frequency (N^2) to the squared shear (S^2). These schemes have been widely used because of their computational simplicity, and because of the failure of practicable 2-equation closure schemes to model free shear layers. However, there is an intrinsic limitation to this approach: while the stability of stratified shear flows depends on Ri, the intensity of the turbulence must depend on other parameters. Mathematically this can be understood via dimensional analysis or the Buckingham Pi Theorem; namely, the shear and buoyancy frequencies alone do not provide enough dimensional groups to define a mixing coefficient.

In this poster, we compare the widely used K-Profile Parameterization (KPP) interior Ri-scheme with microstructure turbulence, CTD, and ADCP data collected on the Equator during the Tropical Instability Wave Experiment in 1991. Averaging over fixed intervals of Ri, we find that the KPP interior scheme leads to mixing coefficients that are 5 to 10 times those computed with the dissipation method from turbulence microstructure data. There is a factor of four difference in the vertical fluxes computed by these methods in the depth range from 60 to $100m$, where the shear-generated mixing is active.

A family of new parameterizations that respect the Buckingham Pi Theorem are analyzed. These express the vertical turbulence viscosity and diffusivity in terms of non-dimensional parameters computed from the non-turbulent fields and their local derivatives. The simplest extension of KPP interior proves to be the most effective at reproducing the observed relationship between mean Ri and the mixing coefficients, K_θ, namely,

$$K_\theta = \phi_\theta(Ri)|U|^2/S,$$

where $|U|$ is the horizontal speed of the non-turbulent flow and ϕ_θ is a non-dimensional function of the Richardson number. This relation collapses onto a single curve the observations in the sheared regions above and below the Equatorial Undercurrent.

In spite of its apparent success at collapsing the mean observations, the proposed scheme is ineffective at modeling the vertical turbulence fluxes. Essentially, this is because variability in Ri, coupled with the large curvature of ϕ_θ near the critical Richardson number, causes the mean value, $\overline{\phi_\theta(Ri)}$, to be a biased estimator for $\phi_\theta(\overline{Ri})$. The time-averaged fluxes are biased high where temporal variability of Ri is significant. This poster documents these findings and outlines some ideas for further research.

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Air-sea fluxes and turbulence profiles in the presence of waves and films

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Sir Benjamin Franklin stilled the water with a drop of oil. This classical experiment demonstrates the impact of surface films on the dynamics of capillary-gravity waves. These waves play a key role for the air-sea exchange of momentum and passive tracers at moderate wind speeds. While much information is available for the fluxes of momentum, heat and moisture, the correct form of the transfer velocity for weakly soluble gases with small diffusion coefficients such as carbon dioxide is still not finally agreed upon. However, proper parameterizations are required in biogeochemical models. The observation of key parameters for gas exchange is debated, too.

A theoretical framework is presented which unifies several theoretical and experimental findings. Central quantity is the dissipation rate. For the turbulent bulk layer Monin-Obukhov similarity theory is used while Levich's approach is applied to the molecular skin layer. As a result, a consistent description for momentum, heat, moisture and gases is developed extending Brutsaert's recommendations. The proposed theory includes dependencies of the transfer velocity, surface roughness, dissipation and renewal rates on wind speed, buoyancy flux, diffusion coefficient and film elasticity. It accounts for the effects of wind-stirring, stable and unstable stratification, capillary-gravity waves and film coverage. Further, it allows for a discussion of different transfer velocity parameterizations in terms of observed wind speed, surface slope, renewal rate and dissipation rate.