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Process study of baroclinic circulation in Lunenburg Bay using a three-dimensional ocean circulation model

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Observations in Lunenburg Bay made in 2003 demonstrate that circulation and temperature/salinity distributions in the region are affected by tides, wind and advection of shelf waters from outside of the bay. Vertical stratification is weak in spring and fall and stronger in summer. Vertical stratification in the top 10 m of the bay disappeared occasionally in summer 2003, due mainly to strong vertical mixing associated with surface wind. A three-dimensional ocean circulation model known as CANDIE was used to study the coastal ocean response of Lunenburg Bay to tides and idealized wind forcing. The model results demonstrate that the baroclinic tidal currents have more vertical structure than barotropic tidal currents. For the steady wind forcing cases, eastward wind favors upwelling at the head of the bay, northward wind causes upwelling along the south shore, and southward wind causes upwelling along the north shore in the bay. In the westward wind case, by comparison, the horizontal distributions of the near-surface temperature in the bay are relatively uniform due primarily to inshore advection of shelf waters from outside of the bay.

Biophysical modeling study in the canadian coastal waters : Lunenburg Bay, Nova Scotia

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In order to get a real-time observation and prediction system of a coastal inlet (Lunenburg Bay, Nova Scotia) some biological measurements (Nutrients, Chlorophyll, CDOM) as well as physical (temperature, salinity and currents) and optical measurements from instrumented moorings, weekly samplings and grid surveys of the bay have been carried out since 2002. A NPZD ecological model and a P-Growth model (Palhow, 2004) are being implemented on a full 3-D primitive equation model CANDIE (Sheng et al, 1998) to better understand the biodynamics within this area. Some biological-physical numerical simulations have been carried out to investigate the potential role of the physical processes on the biological ones both characterizing the bay and the adjacent shelf. We present here some results from sensitivity studies (wind, tides, vertical mixing) on the biological parameters space and time variations.

Biological variability in Lunenburg Bay: From data to ecosystem modelling

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Coastal planktonic ecosystems are modeled by a balance between biological (grazing, remineralization, competition) and physical processes (advection, mixing). The influence of physical forcing on their dynamics is important to understand, but also to predict their variability.

One of the objectives of the CMEP observing system in Lunenburg Bay is to develop and test ecosystem models that will provide an insight into the biological dynamics of the bay. The array of buoys provides a set of high frequency physical (temperature, salinity, current velocity) and optical (*Kd*, irradiance, reflectance) data that is completed by weekly sampling of the water column (CTD casts and water samples for the analysis of nutrients, chlorophyll and other pigments). The set of data available so far gives an indication on the scale of biological variability in the bay (low nutrient and chlorophyll concentration/variability in summer) as well as on the processes that might influence the phytoplankton variability during the summer (water temperature, stratification, upwellings).

This dataset will be discussed and compared with the Station 2 biweekly data (Halifax Line, Scotian Shelf). The first steps in the development of the ecosystem models, using box models, will be presented as well, along with future directions of research.

Forecasting sea fog at Lunenburg Bay: issues relating to mesoscale modelling

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Fog is a common occurrence in Nova Scotia, up to one-third of the year in certain locations like Halifax. A significant number of these observed at land stations are due to inland advection of fog banks forming over the ocean.

In general fog forms in three ways: mixing, where warm moist air is mixed with cold dry air; moistening, where moisture is increased by surface evaporation or precipitation; and cooling, where air moisture capacity is reduced by decreasing air temperature. To correctly model each process precise data is necessary, and especially so for fogs due to cooling.

Mesoscale models rely on objective analyses assimilated from various sources to provide initial and boundary conditions. These analyses are best guess fields that incorporate information available at given intervals, and are not optimized for specific applications. This leads to a condition where less than ideal analyses with their associated measurement errors are used to initialize simulations of highly sensitive phenomena, resulting in significant degradation of model forecast quality.

One way to improve the analyses is to assimilate fog-specific measurements such as fog boundaries from satellite images, and vertical moisture profiles from the RASS instrument at Lunenburg Bay. In addition, model results should benefit from increasing vertical resolution to capture fog vertical structure.

Large Wave Events in a Shallow Coastal Bay

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Lunenburg Bay is a coastal inlet located on the southern shore of Nova Scotia, Canada, and is approximately 8 km long and 4 km wide. It has irregular and shallow bathymetry characterized by a typical depth of 10 m and is exposed to wave energy from the North Atlantic Ocean. Within the bay, an array of sensors has been deployed to collect physical, biological and atmospheric data as part of a real-time coastal observing system. The wave array consists of bottom-mounted instruments including acoustic doppler current profilers capable of resolving wave spectra, single-point velocimeters with co-located pressure sensors and standard acoustic doppler profilers, and a surface-moored directional wave-rider buoy. The set of instruments is capable of observing directional spectra at 0.5-hr intervals for wave events at several locations in Lunenburg Bay. This presentation summarizes the dataset collected in fall 2002, summer-fall 2003 and summer-fall 2004. Extreme wave events are highlighted and compared with respect to differences in atmospheric forcing (wind, pressure, duration, storm type and scale) and attenuation within the bay from observed wave spectral properties (peak direction and directional spread, significant wave height and peak period). Extreme events include the close passage of several hurricanes (Gustav, Fabian, Juan, Lisa), tropical storms (Nicole) stronger but more distant hurricanes (Isabelle) and larger-scale mid-latitude low pressure systems. The most notable wave event in the bay was driven by Hurricane Juan with a deep-water significant wave height of 9 m, more than double that of the second largest event in the observation period. Strong attenuation between instrument locations inside the bay is attributed to refraction and breaking. Observed significant wave heights and near-bed orbital velocities are compared to numerical model simulations from the SWAN model for peak conditions of extreme events with varying agreement. Future work on measurement and modelling of waves and wave-induced currents are discussed.

Monitoring feeding activity, forecasting growth and quantifying environmental impact in shellfish farms using low-cost bio-optical moorings

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Shellfish aquaculture stock grows by feeding on naturally-occurring food (i.e. phytoplankton and detritus). As a direct consequence, shellfish farming is perhaps the lowest-cost means to produce animal protein and with the least degree of environmental impact. The great challenge, however, is to determine how much "naturally-occurring food" is available for shellfish in a given site (i.e. determination of carrying capacity). Many models have been developed to address this question. They all specify (measure or model) food inputs by advection and turbulent diffusion, but they all model (not measure) food outputs by shellfish feeding. We used a literature review of feeding rates of one of the most studied invertebrates (blue mussel, *Mytilus edulis*) to argue that our ability to accurately predict shellfish feeding is rather limited. We proposed a method to measure food concentration and food depletion using low-cost optical moorings to assess the multispectral diffuse attenuation coefficient of sunlight, $K_d(\lambda)$, in and around shellfish farms. AquaNet funds have been granted to us to finalize the development of the prototype low-cost optical instruments; to validate the instruments ability to accurately measure $K_d(\lambda)$, food concentration and depletion; to forecast growth using these measurements in carrying capacity models; and to relate our finding to results from an ongoing program for environmental impact assessment that uses sediment samples. The project is likely to be conducted in 3 sites: Ship Harbour (Nova Scotia), Alfacs Bay (Spain) and a site in British Columbia. The method and low-cost instruments were designed following recommendations to the Coastal Module of the Global Ocean Observing System (C-GOOS) and can be adapted to assess gradients of other ecologically relevant substances (i.e. colored dissolved organic matter, phytoplankton and seston) for questions related to many phenomena in the coastal ocean.

Seasonal Estimates of Photochemical Production of Dissolved Inorganic Carbon From Terrestrial Organic Matter in an Atlandic Canada Coastal Zone (ACCZ) Estuary

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Photochemical degradation of riverine dissolved organic matter (DOM) was investigated in surface waters (top 1 m) collected in early fall (November), spring (April) and summer (July) along a salinity gradient extending from the mouth of the Medway Harbour estuary (Nova Scotia) to the mouth of the Medway River in the Atlantic Canada Coastal Zone (ACCZ). The photochemical degradation of dissolved organic matter (DOM) was determined by calculating the spectral photochemical efficiency, or apparent quantum yield (AQY), for the production of dissolved inorganic carbon (DIC) using a multispectral statitistical method and a solar simulator. Seasonal variability of AQY was examined in relation to CDOM spectra, river-runoff and mixing data collected on 2 consecutive days over the 3 seasons at the same 3 sample locations located at the bay mouth, mid-bay and freshwater end-member. DIC production rates were highest for the riverine samples in all 3 seasons with a single exception. Fall AQYs were significantly lower (2 orders of magnitude lower than summer and an order of magnitude lower than spring). The general slope and magnitude of AQYs determined in this study were of similar slope and magnitude with those previously determined for estuarine and coastal waters (Johannessen and Miller, 2000, Marine Chemistry, 76; 271-283).

The occurrence, behaviour and fate of natural and synthetic estrogenic compounds in Halifax Harbour

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Endocrine disrupting compounds (EDCs) may affect the health of organisms in environments receiving sewage effluents. Several recent studies have made a link between the level of natural or synthetic estrogenic compounds in the water phase and specific reproductive and developmental effects in fish and invertebrates. An important question raised about estrogenic compounds regards their behaviour and fate in aquatic systems. To date there is a limited amount of research dealing with these issues in marine environments. The goal of this study is to develop an analytical method that can be used to detect three phenolic estrogenic compounds in Halifax Harbour. The target

compounds include the natural hormone estradiol (E2), the pharmaceutical ethynylestradiol (EE2) and the industrial compound bisphenol-A (BPA). To detect for the presence of estrogenic compounds, seawater samples were collected from several locations in Halifax Harbour. These samples underwent a series of extraction and fractionation procedures to concentrate and separate the target compounds prior to analysis using a GC-MS method developed specifically for these compounds. Preliminary analysis yielded concentrations of 2-12 ng/L for E2 and EE2 and 47-55 ng/L for BPA. To study the partitioning and biodegradation of the target compounds, a series of laboratory experiments were conducted using mixtures of seawater and sediment from the Harbour. These mixtures were spiked with the target compounds and the concentrations in both the aqueous and sediment phases were monitored over time. In general, the partitioning of the compounds from water to sediment phases was higher for organic rich sediments. The synthetic compounds EE2 and BPA were also found at higher concentrations in the sediments than E2, as predicted by their higher Kow values. In the biodegradation experiments, E2 was more rapidly biodegraded than EE2 and BPA. No significant difference was observed in the biodegradation rates of samples containing high levels of sewage bacteria verses samples from an uncontaminated reference site.

Temporal and spatial variability in larval and colony abundance of an invasive bryozoan

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Invasive species are recognised as one of the greatest threats to biodiversity worldwide. The epiphytic bryozoan *Membranipora membranacea* is a recent (early 1990s) invader to Nova Scotia's rocky subtidal ecosystem. *M. membranacea* settles preferentially upon macroalgal blades, increasing their vulnerability to fragmentation and breakage during periods of intense wave action. Since the presence of *M. membranacea* can result in the removal of kelp from the benthos, it facilitates the recruitment of other invasive benthic species, such as the green alga *Codium fragile*. By contributing to the removal and displacement of kelp, *M. membranacea* has a negative impact upon commercially valuable species that utilise kelp for habitat and food, such as lobster and sea urchins. Adult colonies demonstrate considerable variability in abundance over spatial (10-1000s of m) and temporal (weeks-years) scales. This research will attempt to identify causes of the observed variability in adult abundance, with a focus on larval supply. Laboratory and field studies will examine the relationships between variability in larval and adult colony abundance, and abiotic factors such as temperature, substrate availability, and currents. This study will contribute to our understanding of the mechanisms of marine species invasion, and will have implications for our understanding of population connectivity, a key issue in marine conservation.

Estimating the decadal predictability of a coupled atmosphere-ocean general circulation model

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On seasonal time scales, ENSO prediction has become feasible in an operational framework in recent years. On decadal to multidecadal time scales, the variability of the oceanic circulation is assumed to provide a potential for climate prediction. To investigate the decadal predictability of the coupled atmosphere-ocean general circulation model (AOGCM) ECHAM5/MPI-OM, a 500-year-long control integration and "perfect model" predictability experiments are analyzed. The results show that the sea surface temperatures (SSTs) of the North Atlantic, Nordic Seas, and Southern Ocean exhibit predictability on multidecadal time scales. Over the ocean the predictability of surface air temperature (SAT) is very similar to that of SST. Over land there is little evidence of decadal predictability of SAT except for some small maritime-influenced regions of Europe.

On the impact of a warm SST anomaly on a strong western North Pacific cyclone

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The classical interpretation of how warm SST anomalies impact the cold-season environment of a midlatitude cyclone is that they warm and moisten the environment and make it easier for a cyclone to develop. This implies that cold SST anomalies should have a negative impact on cyclones, but is this true all year round? Preliminary indications from SST anomalies found beneath strong cyclones are that cold SST anomalies may in fact be cyclogenetic if the atmosphere is already relatively warm and moist. To test this, an extended predictability experiment is performed using the environment of a cyclone that appears to benefit from the presence of a cold SST anomaly. A series of control simulations are initiated about 10-14 days before this cyclone forms. These are compared to simulations that are perturbed by removing the cold SST anomaly. The impact of the cold SST anomaly is interpreted by the net difference in intensity of the simulated cyclones.

Enhanced vertical propagation of storm-induced near-inertial energy in the presence of an eddy field

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The interaction between inertial oscillations generated by a storm and a mesoscale eddy field is studied using a Southern Ocean channel model. It is shown that the leakage of near-inertial energy out of the surface layer is strongly enhanced by the presence of the eddies, with the anticyclonic eddies acting as a conduit to the deep ocean. Given the ubiquity of the atmospheric storm tracks (a source of near-inertial energy for the ocean) and regions of strong ocean mesoscale variability, we argue that this effect could be important for understanding pathways by which near-inertial energy enters the ocean and is ultimately implicated in mixing.

Estimating food consumption in fish: What really matters?

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A simple model of the diel cycle of stomach contents in a fish (Atlantic cod, *Gadus morhua*) is developed from first principles using factors (predator weight (g), temperature (degC), prey concentration (kg m^{-2}), stomach fullness (dimensionless), feeding periodicity (dimensionless) and prey energy content (kJ g^{-1})) thought to be responsible for the majority of variation in food consumption estimates. Through comparing daily ration (DR) estimates (g day^{-1}) using Penningtons (1985) method, it is shown that, beyond a simple designation of linear ($a = 0$) vs. non-linear ($a = 0.5$, $a = 0.67$ and $a = 1$), the choice of the shaping parameter (a) of the stomach evacuation function is irrelevant.

Determined through sensitivity analysis, the majority of variation in the DR estimates is due to predator weight (g) and prey energy content (kJ g^{-1}). The Pennington method of estimating mean DR was found to be accurate when compared to both the mean actual model DR and actual consumption measured for trout (*Salmo trutta*) in the lab (Elliott and Persson 1978). This accuracy was tested and maintained using two published simplifications of the Pennington (1985) method.

Blinded by the light: nonphotochemical quenching in a marine diatom

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Nonphotochemical quenching (NPQ) of chlorophyll fluorescence occurs when excess absorbed irradiance is dissipated as heat, thereby preventing cell damage. NPQ is a dominant process governing fluorescence yield near the sea surface where irradiance is high. An understanding of the physiological control of NPQ is essential to interpreting variability in near surface sun-induced chlorophyll fluorescence, which is strongly linked to hydrographic forcing. However, the influence of phytoplankton physiology on NPQ is not well understood. Can measurements of NPQ be used as diagnostics of nutrition and light history? Using a PAM fluorometer, we measured NPQ ($qCN=(Fm-Fm)/Fm$) as a function of irradiance (E) up to 2000umol m-2 s-1 for the diatom Thalassiosira pseudonana under nutrient replete, acclimated N-limited, and N-starved conditions at growth irradiances of 50 and 500umol m-2 s-1. Curves of qCN vs. E fit to a non-linear model yield three parameters, threshold irradiance for induction of qCN, initial slope, and maximum qCN, that show relationships with both nutritional status and light history. These metrics can be used to improve the interpretation of time series from moorings and sun-induced fluorescence from satellites.

Numerical simulations of small-scale convection and extension velocity impact on melt production at rifted continental margins

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We use a fluid dynamic numerical code and a visco-plastic rheology to model convective mantle interaction with the continental lithosphere in an extensional setting, in order to study passive margins development.

A ~100 km thick lithosphere, initially at a statistically equilibrium state, is stretched by a constant extensional velocity of 0.5, 2, or 5 cm/yr. Two end members have thus been observed for an asthenospheric temperature of 1380 ± 20^0C. For low extension velocity partial melting occurs delayed compared to the necking onset and small amount of melt is observed over a preiod of ca. 8 Ma, contrary to intermediate and fast imposed extension velocities, which show a quasi-syn necking partial melting and a large amount of melt production over a preiod as short as ca. 2-4.7 Ma prior to breakup. It appears that both extension velocity and small-scale convection developing at the base of the lithosphere play active roles on competitive effect of conductive cooling and stretching, and thus on lithospheric necking and melt production.

The dynamical role of the geothermal heat flux through the ocean floor: Some insights from a simple model

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The convection driven by differential heating at a horizontal boundary is a useful conceptual model of the thermally-driven component of the meridional overturning circulation. Previous studies have shown that 'horizontal convection' can lead to a vigorous and asymmetric overturning cell throughout the full depth of the basin (Mullarney *et al.* 2004). This analogue model can be viewed as a simplified representation of a single basin (equator to pole) circulation with a subtropical thermocline, a highly localised downwelling in the polar regions and slow return flow.

We report numerical experiments examining the effects of imposing on the above circulation, an additional (yet small) heat flux at the sea floor. Both stabilising and destabilising fluxes are examined. In both cases, the additional heat flux results in a dramatic change in the flow pattern. When the flux is stabilising, a steady two-cell flow regime emerges, whereas a destabilising flux tends to promote full-depth overturning. Consequences for the meridional overturning circulation are discussed. In particular, the destabilising case may be of relevance to understanding the effects of the geothermal heat flux through the seafloor.

Adventures in Histology: defining the size-based recruitment stage of an hydrothermal vent gastropod

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Ecological research at hydrothermal vents is still in its infancy. Fundamental questions regarding the manner in which invertebrate species maintain their populations in these patchy and ephemeral habitats remain unanswered. Survival of these fragmented populations is dependent not only on larval dispersal, but also on successful recruitment, as variation in recruitment can affect the number and condition of adults available at time of reproduction. However, for most benthic invertebrate species, recruitment is not a distinct stage in the life cycle, and thus there is difficulty in comparing recruitment rates across sites, times and studies. Defining recruitment as the number of new juveniles undergoing the transition into adulthood yields a biologically meaningful, easily quantified, and standardized measure of this demographic process.

The purpose of this study is to define the recruitment stage of the vent gastropod *Lepetodrilus fucensis* in a size-based manner, in order to estimate the number of new juveniles entering the adult population based on their size. Histological techniques are used to examine the gonads of male and

female *L. fucensis* for percentage spermatozoa cover, and oocyte stages and size frequencies, respectively, to assess maturity of gonad and continuity of reproduction. This data may also have further applications in determining fecundity of female *L. fucensis*, and providing evidence of protandry in this species.

Tracer dynamics in a lattice-automaton model of bioturbation

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The vast expanses of the world's oceans overlie sediments: complex biogeochemical systems of which we have only a modest understanding. The majority of surficial sediments are mixed by benthic fauna, altering the physical structure and chemical nature of the sediment. To account for the influence of animal-sediment interactions upon sedimentary properties and processes, an accurate measure of biogenic sediment reworking (i.e. bioturbation) is required.

Bioturbation typically is described as a diffusive process, quantified by modelling the vertical distribution of particle-bound radioisotopes. The resulting diffusion coefficient (D_b) that characterises the intensity of the mixing regime often exhibits a dependence on tracer half-life; short-lived radioisotopes (e.g.^{234}Th) tend to yield larger D_b values than longer-lived radioisotopes (e.g.^{210}Pb). While it has previously been hypothesized that this dependence is due to differential mixing of tracers by particle-selective benthos, modelling work presented here demonstrates that this trend can result from a more fundamental mechanism: violation of the assumptions required for bioturbation to be considered diffusive.

Measuring Particle Dynamics in Arctic and Aquaculture Environments

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A portable device, BEAST (Benthic Environmental Assessment Sediment Tool) designed for measuring sediment resuspension has been developed and calibrated to yield sediment bed shear velocity (U*). The BEAST consists of a clear plexiglass core within which a horizontal perforated grid oscillates vertically. Sediment cores with water overlying them, whose properties are to be determined are placed beneath the oscillating grid. The grid oscillates in the water and creates turbulence which penetrates down to the sediment-water interface and causes resuspension. The amount of material resuspended is proportional to the frequency of the grid oscillation. The equivalent shear stresses created by the BEASTs oscillating grid were determined by comparison of results from known results of shear stress values on a shear stress probe calibrated with fluid flow experiments performed in a calibrated laboratory flume. The BEAST is a portable device which can be used to estimate erosion rates, critical shear stress and particle size distributions on resuspended sediment particles in cores from fresh, undisturbed sediment from either sediment grabs or cores collected by divers. Using the BEAST, settling columns, DV cameras, CTD's and sediment traps, particle dynamics have been investigated around mussel aquaculture sites in the Magdalen Islands and PEI, in addition to studies carried out on the carbon fluxes in the Mackenzie Shelf and Beaufort Sea.

Observations of Shoaling Internal Waves and Sediment Transport on the Scotian Slope

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In order to quantify the resuspension and transport of sediment under the effect of shoaling internal waves, a bottom-mounted quadrapod named RALPH was deployed in 280m of water on the Halifax line (42^o59 N Lat., 61° 45 W Lon.) during Aug. 16-Oct. 20, 2002 and July 14-Nov. 3 2003. Different sensors were installed on RALPH to measures waves, currents and nearbed sediment concentration. In addition, a video camera was used to monitor the configuration of sediments on the seafloor, and the surficial sediment was collected for grain-size analysis and OBS/ABS calibration experiments.

Power spectral density estimates on the velocity data of ADCP 2002/2003 indicate that internal tides of semidiurnal and diurnal frequencies (M2, S2, K1, O1) are dominant components. Grains-size analysis indicates that surficial sediment is very fine and moderately sorted sand. The seabed was

mobile as indicated by the images of sediment bedforms. OBS calibration experiments indicate that there is good correlation between the suspended sediment concentration and the OBS reading; and the combined results of the OBS calibration experiments by respectively using the fine- and coarse-size sediment are almost the same as the results of the OBS calibration experiment by using all the grain-sizes of the surficial sediment. The vertical distribution of suspended sediment concentration is reasonable. Two sediment resuspension events and one abnormally high suspended sediment concentration period were identified.

Upslope propagation of an internal solitary wave train

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Internal solitary waves (ISWs) are common features that travel along the thermocline in lakes, estuaries, and oceans. They have a recognized role in shear-induced turbulent transport of nutrients and other tracers across the thermocline. When the water below the thermocline is deeper than the mixed layer, an ISW causes a single depression of the thermocline. If the water below the thermocline is shallower than the mixed layer depth, the wave produces an elevation rather than a depression (i.e. it will have a different *polarity*). This study examines ISWs changing polarity as they transgress upslope in the Saint Lawrence Estuary. As an ISW travels into water shallower than the thermocline depth itself, we observe the watermass associated with the wave detaching from the thermocline and continuing to travel upslope. This provides a new potential mechanism for mixing tracers across the thermocline and for advecting suspended sediment upslope.

Intrusions: breaking the symmetry

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The density of the ocean is not uniform. When vertical mixing occurs between two layers, the resulting water with an intermediate density will propagate between the layers. This intrusion may facilitate the transport of nutrients and can generate internal waves. Symmetric intrusions, where the upper and lower layers are the same depth and the density of the intrusion is the average of the two layers, have been well studied. However, layers in the ocean are rarely the same depth and any mixing that occurs will generally not result in water with an average density. A series of lock-release experiments were performed to investigate the effects of moving away from symmetry. When the density of an intrusion is the depth-weighted average between layers, its speed reaches a maximum when the depths are identical. An internal wave is generated that travels faster than the intrusion if the density is not the depth-weighted average. Further experiments including effects of rotation are discussed as well as possible ways to detect the presence of intrusions in the ocean.