Motivation

Export of biologically-fixed carbon out of the euphotic zone is mediated by biological (aggregation and sinking) and physical (vertical transport) processes. Small-scale (sub-mesoscale) instabilities can cause large vertical velocities of O(100 m/day),\(^1\) leading to a potentially large, but ill-defined, physical transport of physiologically active phytoplankton out of the surface ocean.\(^2\) We use a full seasonal cycle of temperature, salinity, oxygen, chlorophyll fluorescence, and backscatter data from Songliders during the OSMOBS (Ocean State, Modelling, Ocean Sensing) project\(^3,\)\(^4\) to investigate the seasonal cycle of gravitational, mixed layer, and symmetric instabilities,\(^4\) and the extent to which these contribute to the physical export of fixed carbon out of the surface ocean.

Chlorophyll measurements

Under high light conditions, fluorescence decreases due to non-photochemical quenching (NPQ) effects.\(^5\) During the daytime, we correct for this by multiplying backscatter measurements by a constant fluorescence-backscatter ratio within the mixed layer (ML).\(^6\)

Distribution of chlorophyll

The difference between spatially-separated measurements taken at the same time,

\[
D(x) = C(x) - C'(x) - \langle s \rangle^2,
\]

provides information on the relevant dynamics of the region.\(^1\) If there is no length dependence on properties, the (log-log) slope of the average squared difference between measurements as a function of separation distance will be 0. A slope of 2/3 corresponds to a spectral slope of \(k^{-5/3}\) suggestive of a fully turbulent regime dominating the dynamics of all three properties.

Distribution of backscatter

The slope of the log-log plot of \(<\sigma^2\rangle\) vs. \(x/S\) can be used to determine the degree of backscatter variability, which is a function of the number of particles in the water column.

Figure 1: Average SST in the northeast Atlantic Ocean from MODIS Aqua for 2013 (left). White box gives OSMOSIS location. Time series of glider deployments; dashed line denotes time periods with sensor issues (top right). Heat map of glider dive locations from the OSMOSIS interaction study project to investigate the seasonal cycle of gravitational, mixed layer, and symmetric instabilities, and the extent to which these contribute to the physical export of fixed carbon out of the surface ocean.

Figure 2: Left: Fluorescence (gray line), co-located PAR (\(\mu\)mol/m\(^2\), circles), and NPQ-corrected fluorescence (black line). Middle: Backscatter. Right: Fluorescence-backscatter ratio. Dashed black line denotes the ML depth.

Figure 3: Average squared difference in NPQ-corrected fluorescence, backscatter (normalized by wavelength assuming a \(k^{-5}\) slope), and temperature within the upper 15 m by separation distance for all measurement pairs taken within a window of 1 hour of each other. Purple, blue, and red, respectively. Values are normalized by the overall variance for each property. Shading gives 90% confidence via a bootstrap analysis.

Figure 4: (a) Time series of potential vorticity (PV) within the upper 600 m. PV is calculated from the along-path glider data as \(f = V \times \nabla \times \mathbf{U}\), where \(f = 2\pi \times 10^{-5}\) is the angle between the cross-path layers. (b) Time series of integrated chlorophyll within the mixed layer (blue), and chlorophyll within the mixed layer (red). (c) Time series of chlorophyll within the upper 300 m. (d,e) As with (b,c) but for optical backscatter (normalized by wavelength assuming a \(k^{-5}\) slope). Grey colors in (e) denote fluorescence measurements that were not able to be corrected for NPQ effects (see Figure 2). ML is shown in (a,b,c) in thick black, and isopycnal corresponding to 26.9, 27.0, 27.1, and 27.2 kg/m\(^3\) in each of the ML.

Figure 5: PV (a,c), chlorophyll (b), backscatter at 650 nm (e,f), and AOU (d,g) for the time period directly following an adiabatic restratification event (days 108-116, a,d) and a diabatic restratification event (days 120-123, e,g) from SG502.

Types of instability\(^3,\)\(^4\)

- Baroclinic (mixed layer) instability (BCI): Adiabatic processes which rearranges water parcels within the ML only.
- Gravitational instability: Diabatic process caused by shear forces.
- Symmetric instability: Diabatic process caused by shear forces.

Restratification and export

Vertical motion from surface instabilities can export fixed carbon out of the ML. Effective export requires vertical motion across the base of the ML. Mixed layer instabilities (MLI) which act only to rearrange water masses within the mixed layer, therefore do not contribute to export. Many restratification events are associated with symmetric instabilities within the ML, which can also reach below the ML and contribute to subduction of fixed carbon. Gravitational restratification, present mostly during the winter months, can also trigger export through forming a new mixed layer if the remnant mixed layer is beneath the euphotic zone.

Conclusions

The OSMOSIS project provides a submesoscale Eulerian view of a region representative of the open ocean. Glider measurements of oxygen, fluorescence, and backscatter provide a primarily a qualitative biological understanding. Future Lagrangian studies in open-ocean regions will provide a more complete picture of bloom-evolution and possible export through the surface instabilities described here. The following conclusions will aid in planning and interpreting these future projects (e.g., EXPORTS\(^7\)).

- Adiabatic processes, such as mixed layer instability, do not lead to export out of the mixed layer.
- Diabatic processes, such as gravitational (\(N^2 < 0\)) or symmetric (\(\nu > 0\)) instabilities, can lead to export out of the mixed layer.
- Submesoscale processes are important and require sampling strategies that can resolve small time- and space-scales.
- Shallow MLs lead to weaker submesoscale instabilities.
- The strongest seasonal overlap in submesoscale processes and photosynthesis is in early spring before the ML permanently restratifies.
- The window during which chlorophyll locations are significant and surface instability are present, leading to potential export, requires further study.

References