Open-ocean submesoscale motions:
Seasonal variations in mixed layer instabilities from gliders

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The importance of submesoscale instabilities, particularly mixed-layer baroclinic instability and symmetric instability, on upper ocean mixing and energetics has been well documented in regions of strong, persistent fronts such as the Kuroshio and the Gulf Stream (D'Asaro *et al.* 2011). Less attention has been devoted to studying submesoscale flows in the open ocean, far from long-term mean geostrophic fronts, which characterizes a large proportion of the global ocean. We present a year-long, submesoscale-resolving time series of near-surface buoyancy gradients, potential vorticity and instability characteristics, collected by ocean gliders, that provides insight into open-ocean submesoscale dynamics over a full annual cycle. The gliders continuously sampled a 225 sq. km region in the subtropical northeast Atlantic, measuring temperature, salinity and pressure along 292 short (~20 km) hydrographic sections.

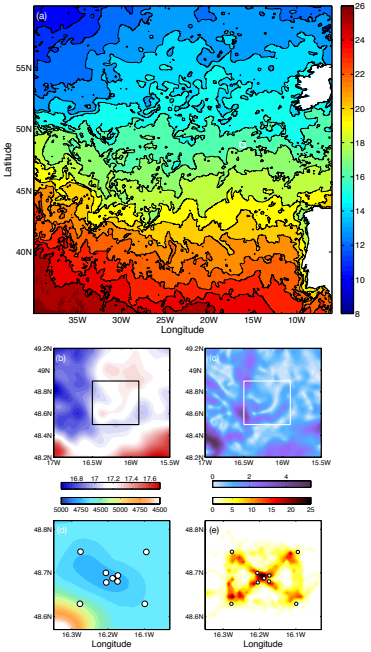

Figure 1. (a) Snapshot of sea surface temperature (SST, °C) on 1 September, 2012. The white box indicates the site of the OSMOSIS study region. (b,c) An expanded view of SST (°C) and SST gradient (10^{-5} °C m^{-1}) from the same day. The boxes represent the OSMOSIS study region. (d) Bathymetry (m) at the OSMOSIS site. The mooring locations are indicated by the white circles. (e) Heat map showing the number of dives in a 0.01° longitude and latitude grid, as visited by gliders SG566 (fall), SG502 (winter) and SG566 (spring/summer).

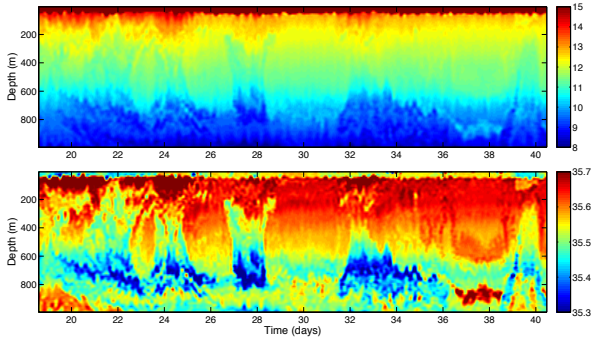

Figure 2. Typical time series of (top) temperature and (bottom) salinity from the OSMOSIS deployment. Variations in temperature and salinity are strongly compensated. Each glider completes one dive every four to five hours. A complete circuit around the butterfly pattern takes approximately three days.

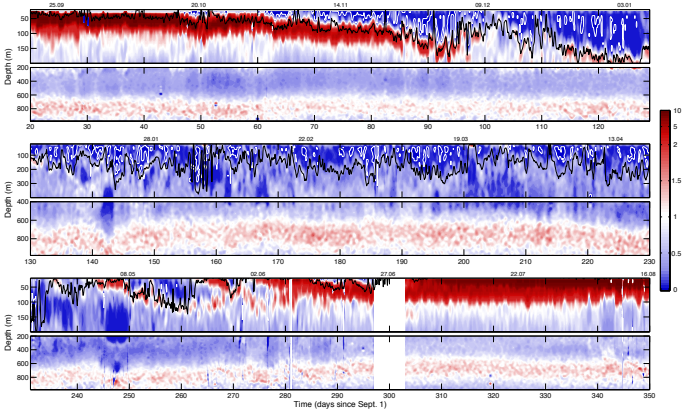

Figure 3. Year-long time series of potential vorticity (10^{-9} s^{-3}) calculated from the glider data as described in (6). The time series is divided into (top) fall, (middle) winter and (bottom) spring/summer periods; calendar dates (dd.mm) are provided along the top of the panels. The while contour indicates the zero potential vorticity contour, while the black contour is the mixed layer depth

$$PV = (\mathbf{f} + \nabla \times \mathbf{u}) \cdot \nabla b \approx fN^2 - M^4/f$$

$$b = -g(\rho - \rho_0)/\rho_0; \quad N^2 = b_z; \quad M^2 = b_x \qquad \phi_{Ri_B} \equiv \left(-\frac{|\nabla_h b|^2}{f^2 N^2}\right)$$

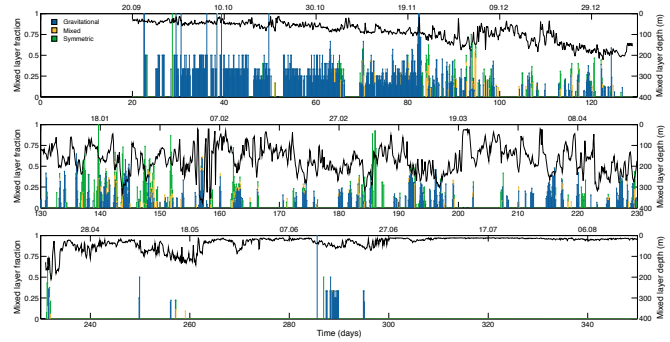

Figure 4. Summary of mixed layer instabilities throughout the entire year. The time series is divided into (top) fall (middle) winter and (bottom) summer time periods. Each bar represents a period of a tenth of a day. The bars show the percentage of the mixed layer that shows conditions favorable to (blue) gravitational instability, (orange) mixed gravitational/symmetric instability and (green) symmetric instability. Conditions for each of these cases is based on calculation of the Richardson angle (boxed equation, Thomas et al. 2013). Values are only provided where the mixed layer depth is greater than 20 m. Regions that are not covered by the bars indicate stable conditions, e.g. PV > 0. The solid curve in each panel shows the mixed layer depth (m) according to the inverted ordinate on the right hand side.

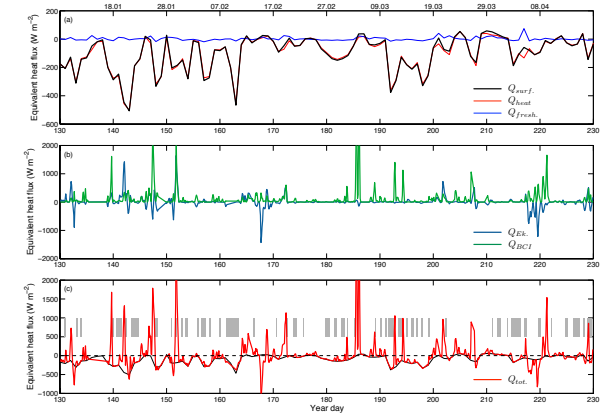

Figure 5. (a) Winter-time surface heat flux (red), freshwater flux (blue), expressed as an equivalent heat flux, and the sum of these two (black). (b) Winter-time submesoscale overturning due to wind-driven processes (blue) and due to mixed layer baroclinic instability (green), expressed as an equivalent heat flux (Mahadevan *et al.*2012). (c) Sum of the total surface buoyancy forcing, wind-driven processes and mixed layer instability, (red), expressed as an equivalent heat flux. The gray blocks indicate time periods where more than 15% of the mixed layer depth has an unstable vertical buoyancy stratification. The black curve shows the surface heat flux as in panel (a) for reference.

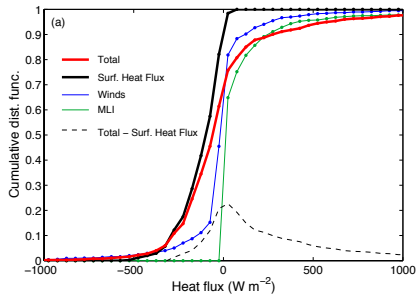

Figure 6. Cumulative distribution function of the winter-time surface heat flux (black), equivalent heat flux from the Ekman buoyancy flux (blue), equivalent heat flux from mixed layer instabilities (green) and the sum of these three (red). These values are the same shown in Figure 5.

Glider observations show a seasonal cycle in near-surface stratification. Throughout the fall (September through November), the mixed layer deepens, predominantly. During winter (December through March), mixed layer depths are variable, and estimates of the balanced Richardson angle, the ratio of lateral and vertical buoyancy gradients, depict conditions favorable to symmetric instability. The relative importance of mixed layer instabilities on the restratification of the mixed layer, as compared with surface heating and cooling, shows that submesoscale processes can reverse the sign of an equivalent heat flux up to 25\% of the time during winter. These results demonstrate that the open-ocean mixed layer hosts various forced and unforced instabilities, which become more prevalent during winter, and emphasize that accurate parameterizations of submesoscale processes are needed throughout the ocean.

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Mahadevan, A., E. D'Asaro, C. Lee, and M. J. Perry, 2012: Eddy-driven stratification initiates North Atlantic spring phytoplankton blooms. *Science*, **337**, 54–58.

Thomas, L.N., J.R. Taylor, R. Ferrari & T.M. Joyce, 2013. Symmetric instability in the Gulf Stream. *Deep-Sea Res. II*, **91**, 96-110.

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