A seasonal cycle of surface instabilities and physically-driven export from gliders in the northeast Atlantic Ocean

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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 (submesoscale) instabilities can cause large vertical velocities of $\mathcal{O}(100\text{ m/day})$,[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 Seagliders during the OSMOSIS (Ocean Surface Mixing, Ocean Sub-mesoscale Interaction Study) project[3] 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.

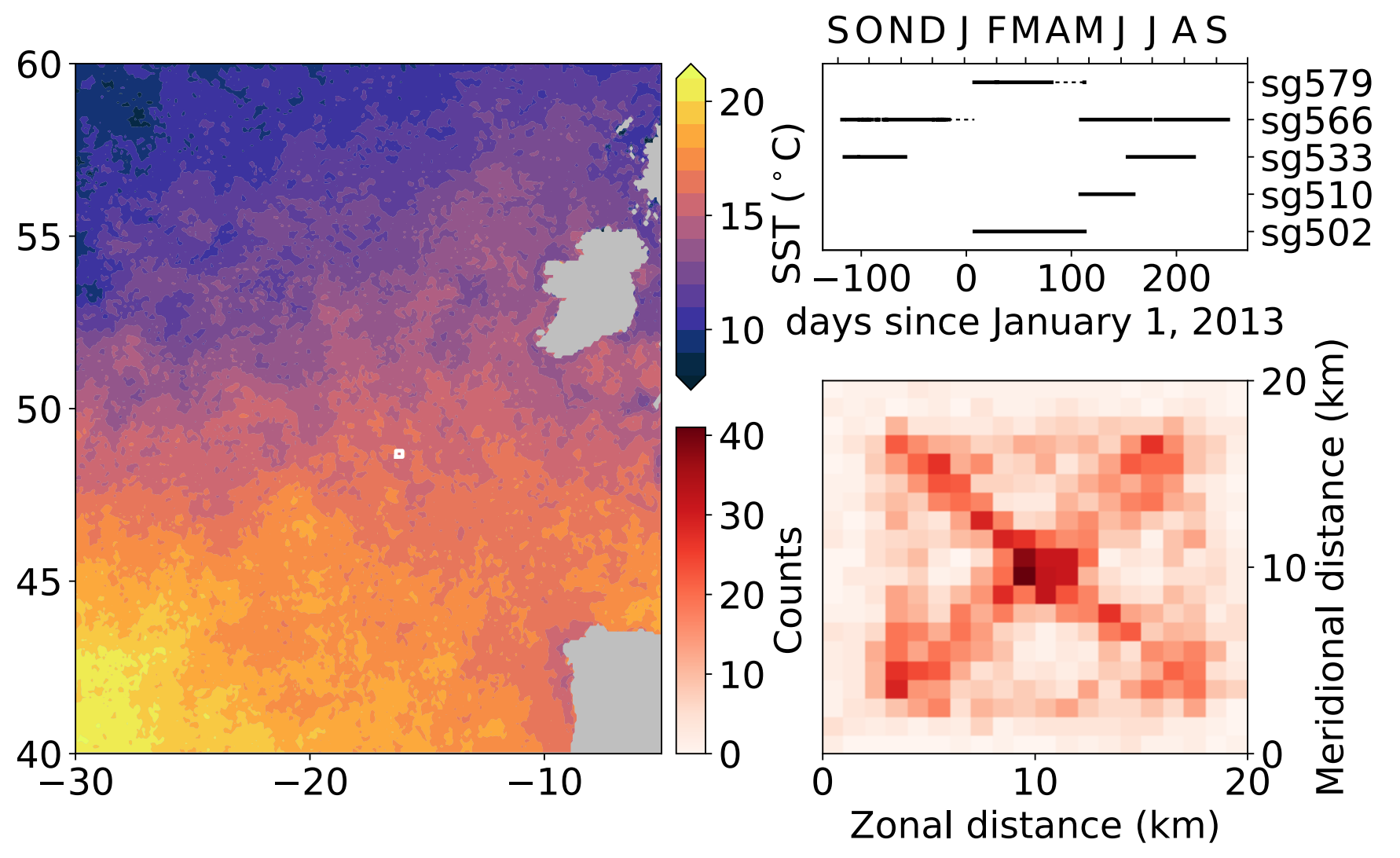

Figure 1: Average SST in the northeast Atlantic ocean from MODIS Aqua for 2013 **(left)**. White box gives OSMOSIS location. Time series of glider deployments; dashed line denotes time periods with sensor issues **(top right)**. Heat map of glider dive locations from the OSMOSIS deployments; each pixel is 1 km^2 **(bottom right)**.

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]

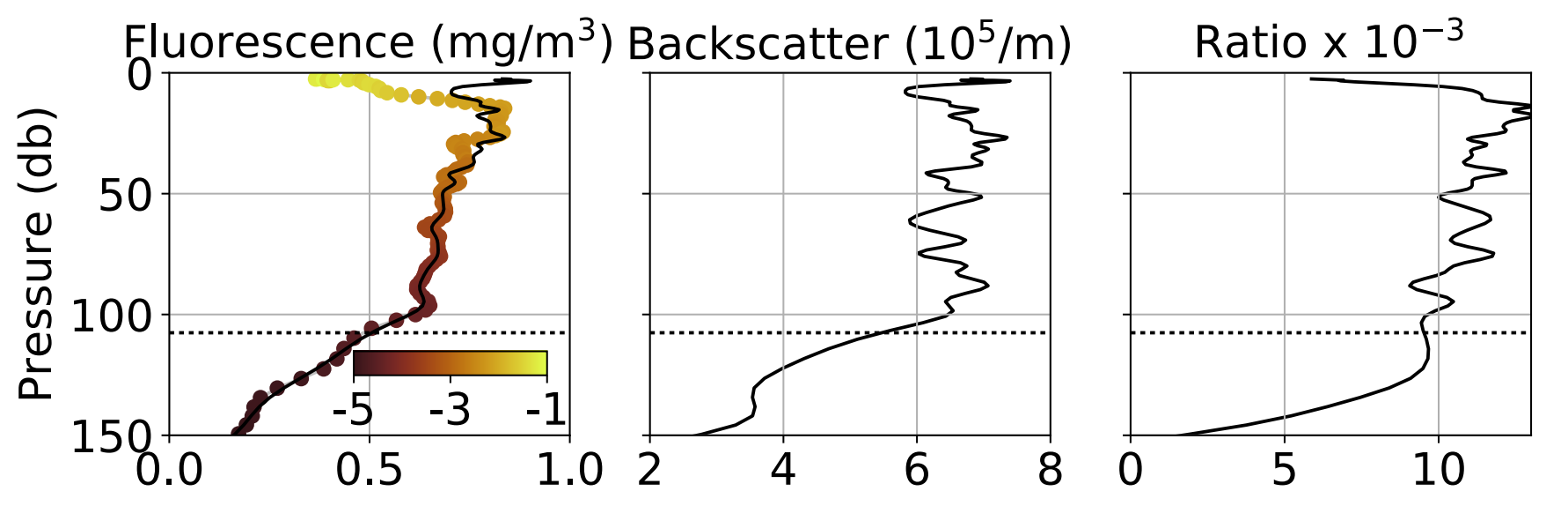

Figure 2: **Left:** Fluorescence (gray line), co-located PAR (μmole/s/cm^2; circles), and NPQ-corrected fluorescence (black line). **Middle:** Backscatter. **Right:** Fluorescence:backscatter ratio. Dashed black line denotes the ML depth.

Distribution of chlorophyll

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

$$D(\mathbf{s}) = \overline{(C(\mathbf{x}) - C(\mathbf{x}+\mathbf{s}))^2},$$

provides information on the relevant dynamics of the region.[7] 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.

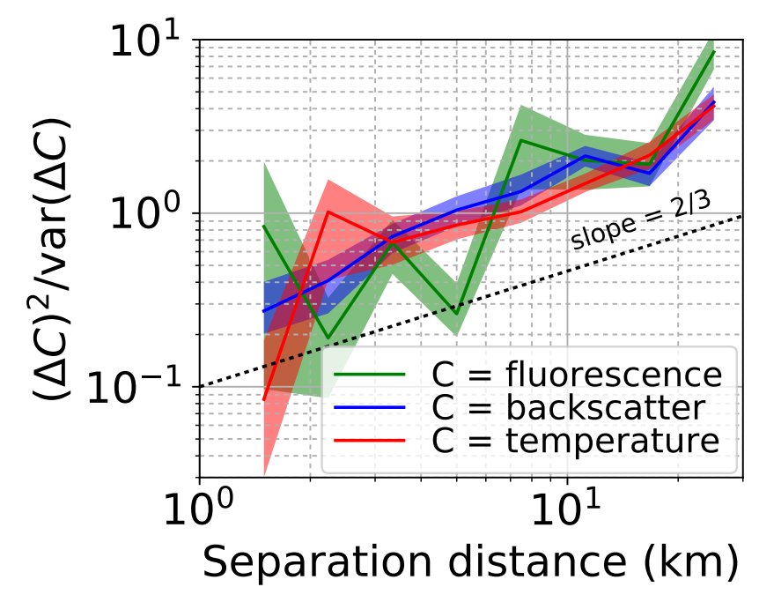

Figure 3: Average squared difference in NPQ-corrected fluorescence, backscatter (normalized by wavelength assuming a k^{-1} slope), and temperature within the upper 15 m binned by separation distance for all measurement pairings taken within 1 hour of each other in green, blue, and red, respectively.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

Observational results

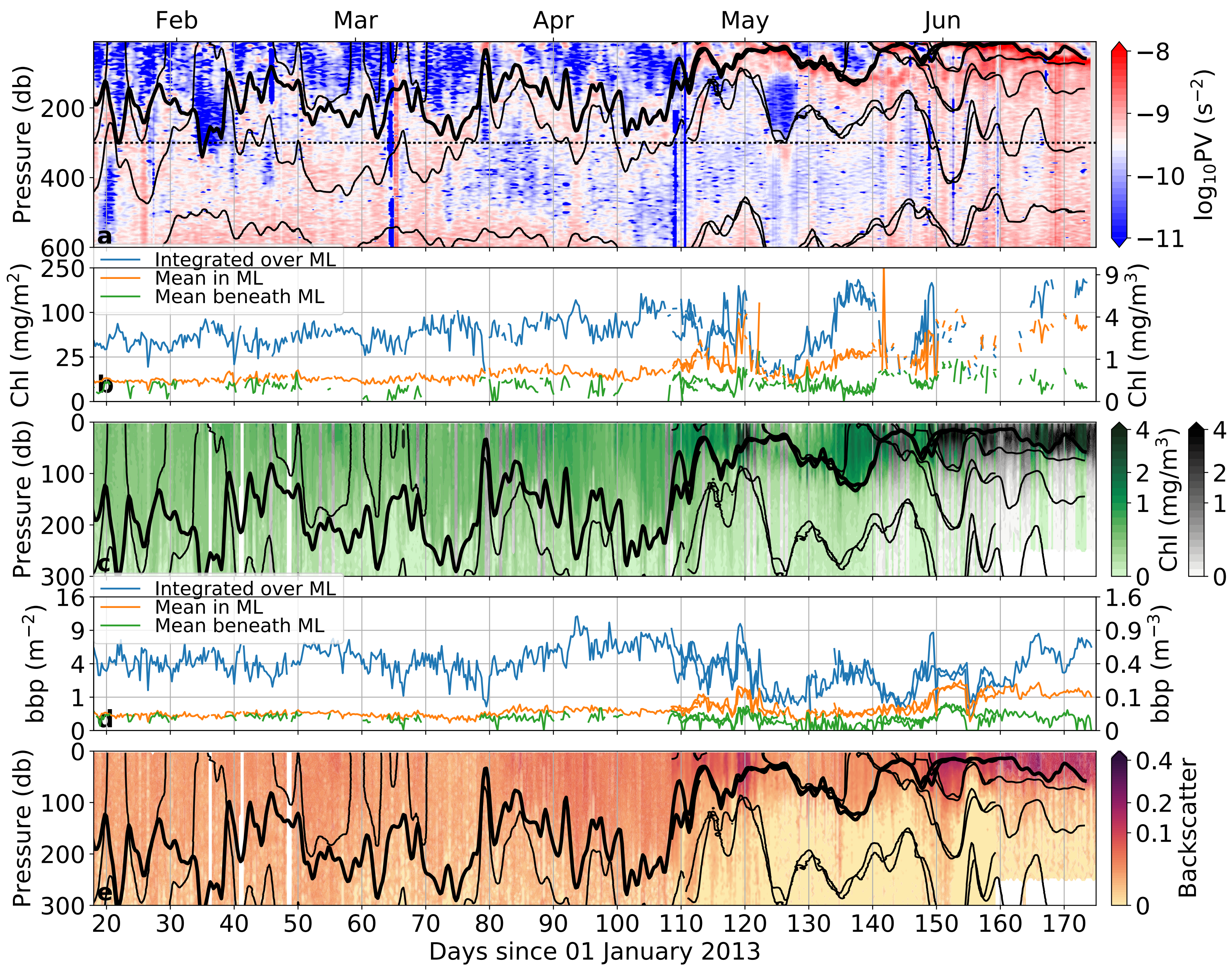

Figure 4: **(a)** Time series of potential vorticity (PV) within the upper 600 m. PV is calculated from the along-path glider data as $(f+\zeta)N^2 - M^4/f$, where $\zeta = \delta_x v$ is the along-path derivative of the cross-path depth-averaged current.[3] **(b)** Time series of integrated chlorophyll within the mixed layer (blue), mean chlorophyll within the mixed layer (yellow), and mean chlorophyll beneath 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^{-1} slope). Grey colors in **(c)** denote fluorescence measurements that were not able to be corrected for NPQ effects (see Figure 2). ML is shown in **(a,c,e)** in thick black, and isopycnals corresponding to 26.9, 27.0, 27.1, and 27.2 kg/m^3 are in thin black. Measurements from SG502, SG566, and SG510 (multiple ML and isopycnal lines are periods with multiple gliders).

- Recently subducted low PV waters are found below the ML throughout the winter.
- Often, these low PV waters directly follow ML restratification events (day 113-117, 140-146, 152-155). Another low PV event (day 123-127) may be left over from a previous stratification.
- ML restratifications through an isopycnal (e.g. day 142, 149) suggest diabatic processes.
- Previous research during the North Atlantic bloom shows increased particulate matter in recently subducted water.[2] We see evidence of this following diabatic restratification events (Figure 5e-g).
- Apparent oxygen utilization (AOU), the difference between saturated and in situ oxygen concentrations, reveals net respiration (grazing) or net photosynthesis in waters not in contact with the atmosphere. We see some evidence of low AOU values associated with recently subducted low-PV waters following diabatic restratification events (Figure 5h).

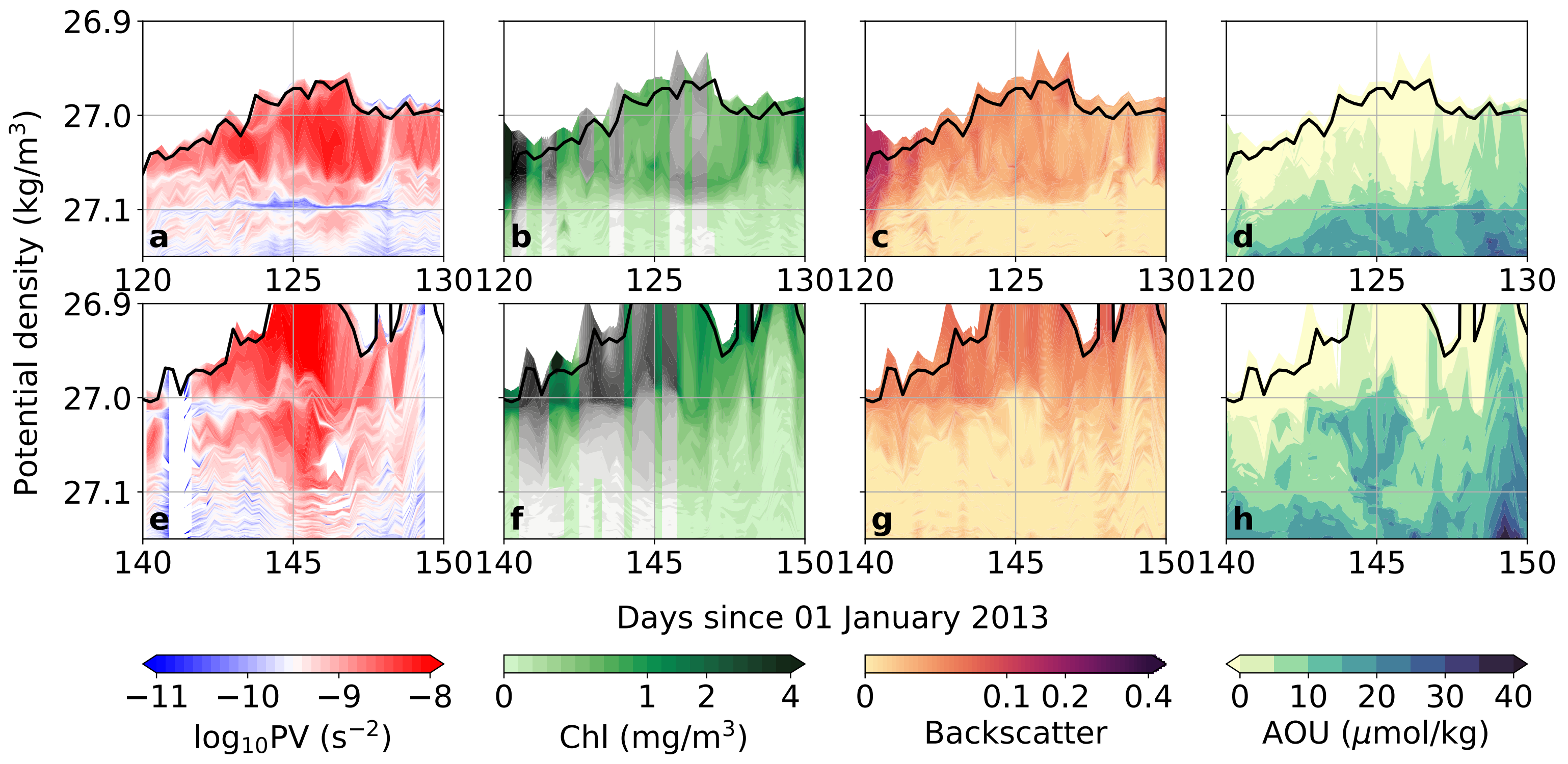

Figure 5: PV **(a,d)**, chlorophyll **(b,e)**, backscatter at 650 nm **(c,f)**, and AOU **(d,g)** for the time period directly following an adiabatic restratification event (days 108-118; **a-d**) and a diabatic restratification event (days 120-130; **e-g**) from SG510.

Types of instability[3,4]

- **Baroclinic (mixed layer) instability (BCI)**
  - Adiabatic processes which rearranges water parcels within the ML only.
  - Caused by large lateral buoyancy gradients.
  - Fueled by stores of available potential energy.
  - Equivalent heat flux: $Q_{BC} = 0.06\frac{M^2 MLD^2}{f}\frac{C_p\rho_0}{\alpha g}$
- **Gravitational instability**
  - Diabatic process generally due to surface forcing
  - Caused by a vertical buoyancy inversion ($N^2 < 0$).
  - Driven by direct surface heating (sensible and latent).
  - Also driven by advection of dense water over light from Ekman forcing.
  - Equivalent heat flux: $Q_{Ek} = -\frac{M^2\tau^y}{f}\frac{C_p}{\alpha g}$.
- **Symmetric instability**
  - Diabatic process caused by shear forces.
  - Fueled by stores of kinetic energy.
  - Diagnosed by oppositely signed planetary vorticity and PV.

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 re-arrange 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.

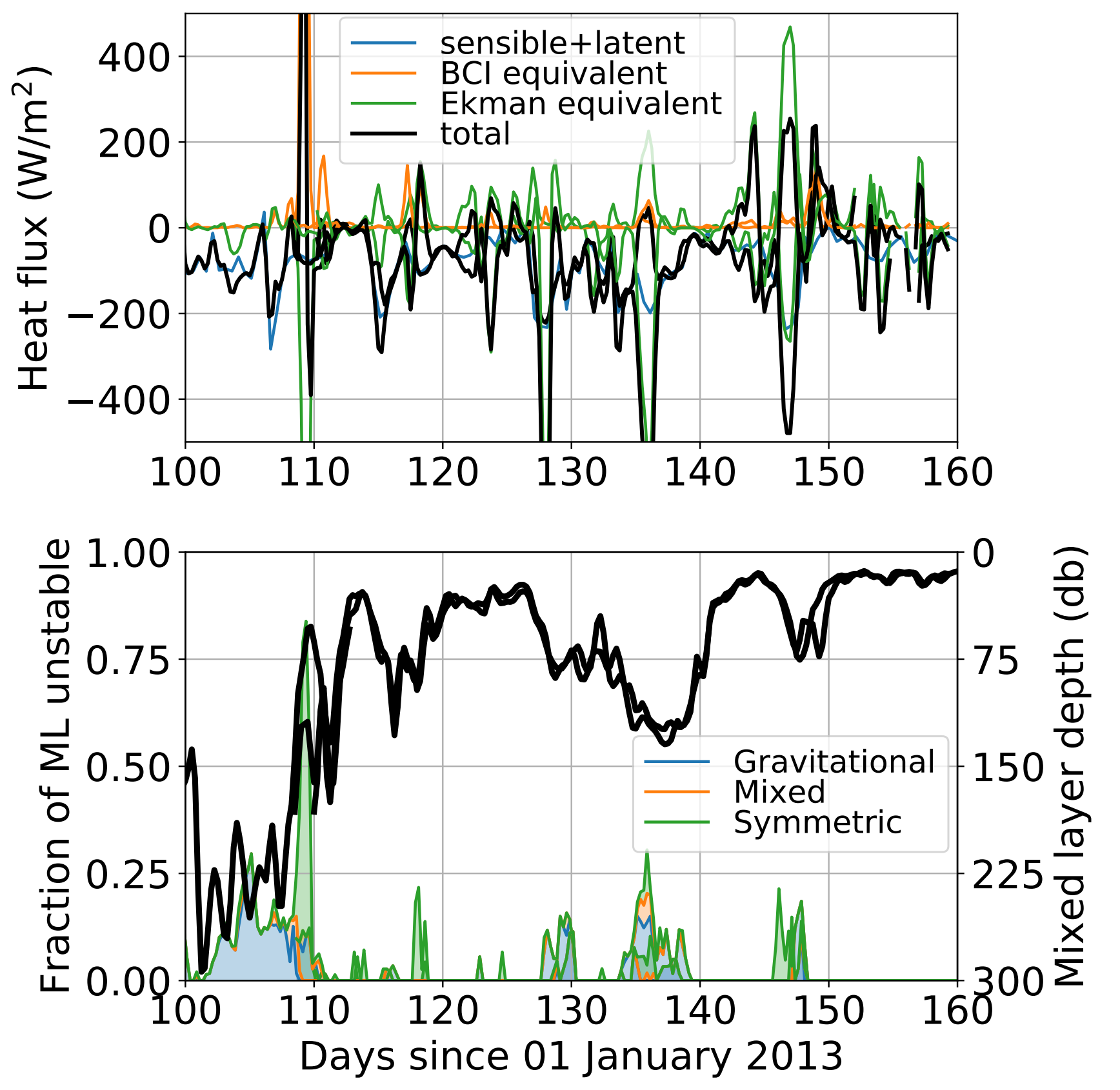

Figure 6: Heat fluxes from surface, baroclinic (mixed layer) instability (BCI), and Ekman (gravitational instability) forcing **(top)**. Total heat flux is the sum of these three components. Percentage of the mixed layer unstable to gravitational and symmetric instabilities **(bottom)**. Mixed layer depth shown in black on the bottom panel. Measurements from SG502, SG566, and SG510.

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 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[8]):

- 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 (fPV < 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 spatial-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 instabilities are present, leading to potential export, requires further study.

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1. Lévy, M. et al. (2012), *Geophys. Res. Lett.*, **39**, L14602.
2. Omand, M. et al. (2015), *Science*, **348**, 222-225.
3. Thompson, A. F. et al. (2016), *J. Phys. Oc.*, **46**, 1285-1307.
4. Thomas, L. N. et al. (2013), *Deep-Sea Res.*, **91**, 96-110.
5. Cullen, J. J. (1982), *Can. J. Fish. Aquat. Sci.*, **39**, 791-803.
6. Boss, E. et al. (2008), *Limnol. Oceanogr.*, **53**, 2112-2122.
7. McCaffrey, K. et al. (2015), *J. Phys. Oc.*, **45**, 1773-1793.
8. Siegel, D. A. et al. (2016), *Front. Mar. Sci.*, **3**, 1-10.