A Physical Framework for Evaluating the Biological Carbon Pump in the Sargasso Sea

Abstract

Virtually all studies of the biological carbon pump have utilized traditional approaches of binning time series data in depth and/or density layers, and seasons defined by calendar months. These can blur connections between the physical forcing and biogeochemical responses, and thus contribute to inadequate accounting of variability on seasonal to interannual timescales. To address these drawbacks, we have constructed a framework defined by seasons and vertical layers that reflect dynamical, physical and biogeochemical zones, and employed a nearly continuous 18-month record of glider observations to demonstrate its ability to transcend temporally varying vertical water mass structure associated with winter mixing, mesoscale eddies and varying light penetration. Its purpose is to establish a unified context for cross-disciplinary evaluation of biogeochemical processes across interannual and seasonal boundaries in the central Sargasso Sea.

The following tables and figures describe the vertical zones, seasons, and mixed-layer depth definitions that have been developed and applied to the BIOS-SCOPE data sets.

Table 1. Vertical Zone Definitions (refer to Figs 1 & 2 below)

0 : Surface Mixed Layer (ML) Depth = 0 to base of surface mixed layer (MLD, defined where density >= sigma_theta at surface + 0.125 kg m^{-3}
1 : Upper Stratified Euphotic Zone (USEZ) MLD to top of DCM layer
2 : Deep Chlorophyll Maximum layer (DCM) defined as part of profile where ChlF is >= 0.35 of maximum chlorophyll value
3 : **Winter Mode Water layer (WMW)** base of DCM to density of local deep winter mixed layer (= sigma 26.32)
4 : Base of WMW to sigma = 26.50
5 : sigma 26.50 to 26.70
6: sigma 26.70 to 26.90
7 : sigma 26.90 to 27.10
8 : sigma 27.10 to 27.30 **corresponds to the Deep O2 Min**
9 : sigma 27.30 to 27.50
10 : anything deeper than Zone 9

Table 2. Season Definitions

Season	Begins	Ends
1= Mixed	MLD > DCM layer	MLD abruptly shoals to ~100m
2 =Spring Transition	*MLD abruptly shoals to ~100m*	*MLD shoals above DCM for remainder of summer*
3 = Stratified	MLD shallower than top of DCM layer	MLD deeper than DCM
4 = Fall Transition	*First entrainment of DCM into ML*	*Last appearance of DCM layer*

Glider observations

Between February 2017 and September 2018, time series of physical and biogeochemical properties were acquired near the BATS site using three separate Slocum G2 gliders deployed in 10 consecutive missions. Each glider carried a science payload that included a pumped CTD, WetLabs ECOpuck (ChlF and Bp700) and Aanderaa O_2 optode, and was programmed to spiral around a 0.5 km box (essentially holding station) and profile between 0 and ~900 meters depth. For five missions the glider was additionally equipped with a Submersible Underwater Nitrate Analyzer (SUNA). Monthly, co-located ship-based CTD and water sample profiles were used to calibrate each of the sensors. These time series demonstrate the relationship between vertical zones, seasons and biogeochemical property distributions.

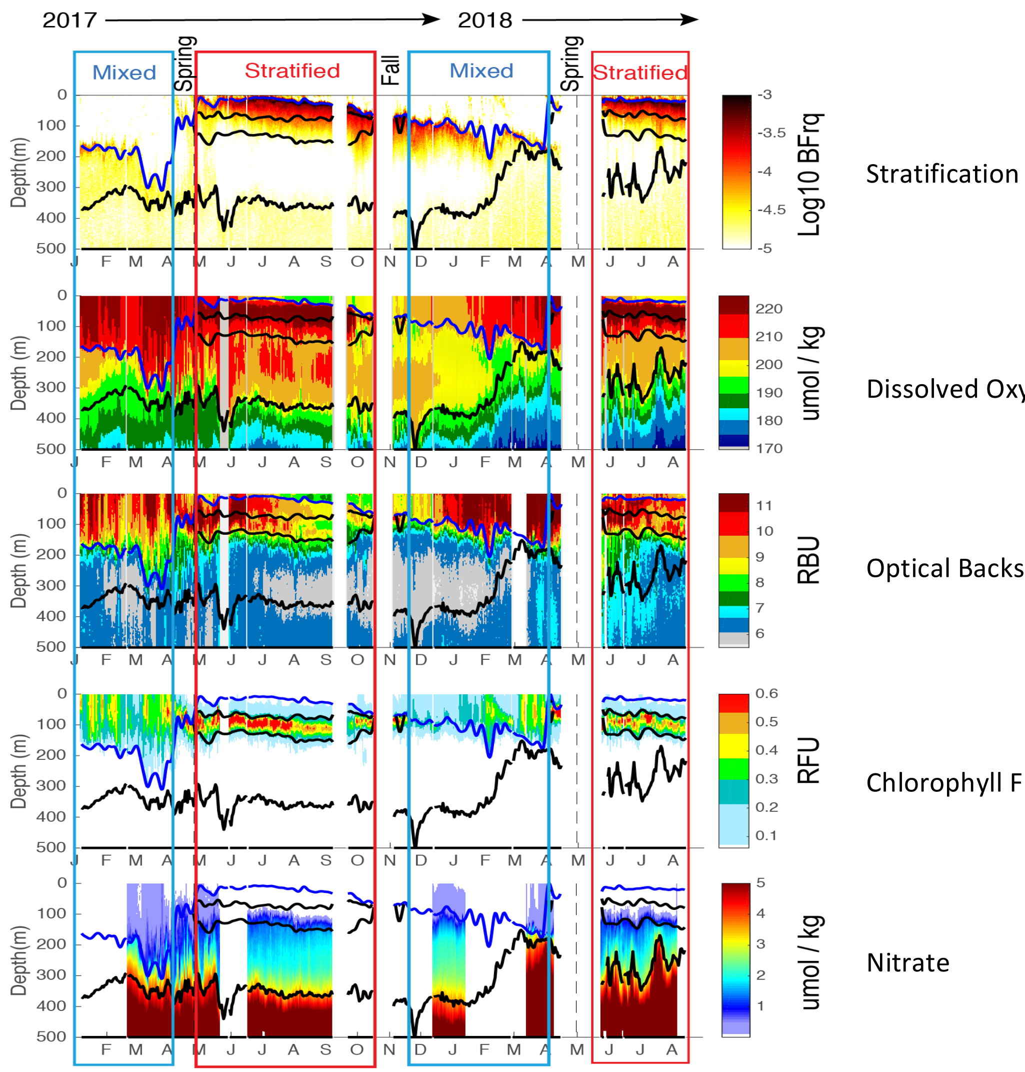


Figure 1. Time series of upper ocean properties spanning the euphotic zone and underlying Winter Mode Water layer: buoyancy frequency (stratification), O2, optical backscatter, chlorophyll fluorescence and nitrate. The heavy contours depict the boundaries of vertical zones 0-3. MLD (base of zone 0) is the blue contour. Note that zones 1 & 2 occur seasonally (they are subsumed into zone 0 during the Mixed season).

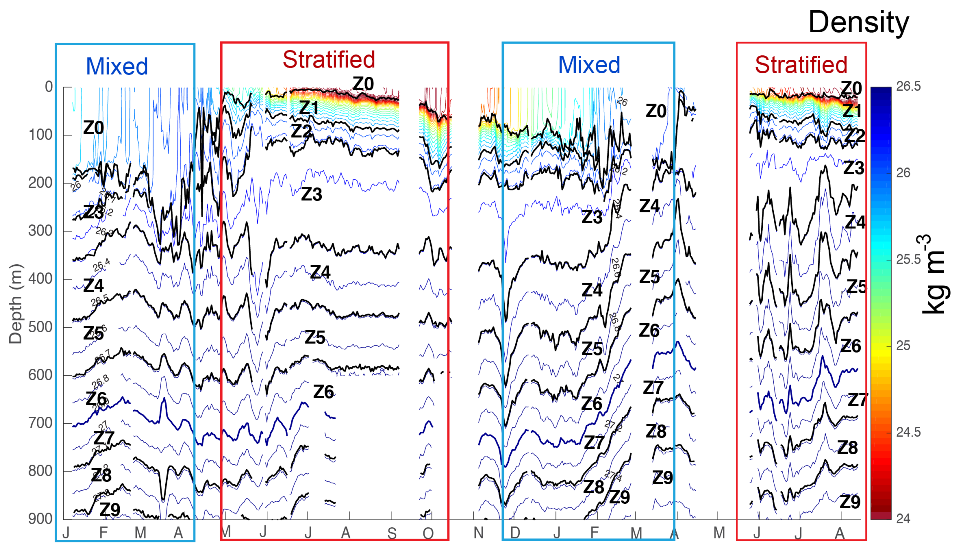


Figure 2. Time series of density contours labeled with the layer boundaries (Z0 – Z9, black contours) and seasons defined in Tables 1 and 2. These layers span the ventilated thermocline in the subtropical gyre.

Mixed Layer Definitions

The CTD, bottle and glider profiles are labeled with 3 definitions of MLD reflecting processes that affect stratification on different time scales:

ML_dens125 is defined as the depth where sigma-theta is greater than the surface density by 0.125 kg m^{-3} . It reflects the deepest reach of seasonal convective mixing, exhibits the LOWEST frequency variability, and is DEEPEST of three MLD variables.

ML_densT2 is defined as the depth where sigma-theta exceeds the surface density + 0.2 * alpha (the thermal expansion coefficient) and marks intermediate episodes of convective mixing. It exhibits MEDIUM variability and depths between the other two definitions. This is equivalent to **MLD_BATS**

Reference:

Sprintall, J., and M. Tomczak (1992), Evidence of the barrier layer in the surface layer of the tropics, *J. Geophys. Res.*, 97, 7305– 7316.

ML_bvfrq is defined as the depth where the buoyancy frequency (N^2) first exceeds the standard deviation of N^2 . It responds to diurnal scales of restratification/mixing and has been adopted by the NAAMES program. It exhibits HIGHEST frequencies and SHALLOWEST depths of the three ML variables.

Reference:

Mojica and Gaube, in review. "Estimates of mixing and mixed layer depth in Western North Atlantic". See website https://github.com/nbaetge/naames_export_ms/blob/master/Rmd/ARGO.m.

Comparisons of these ML properties are illustrated in Figures 3, 4 & 5.

Relationships between MLD, DCM and Seasons

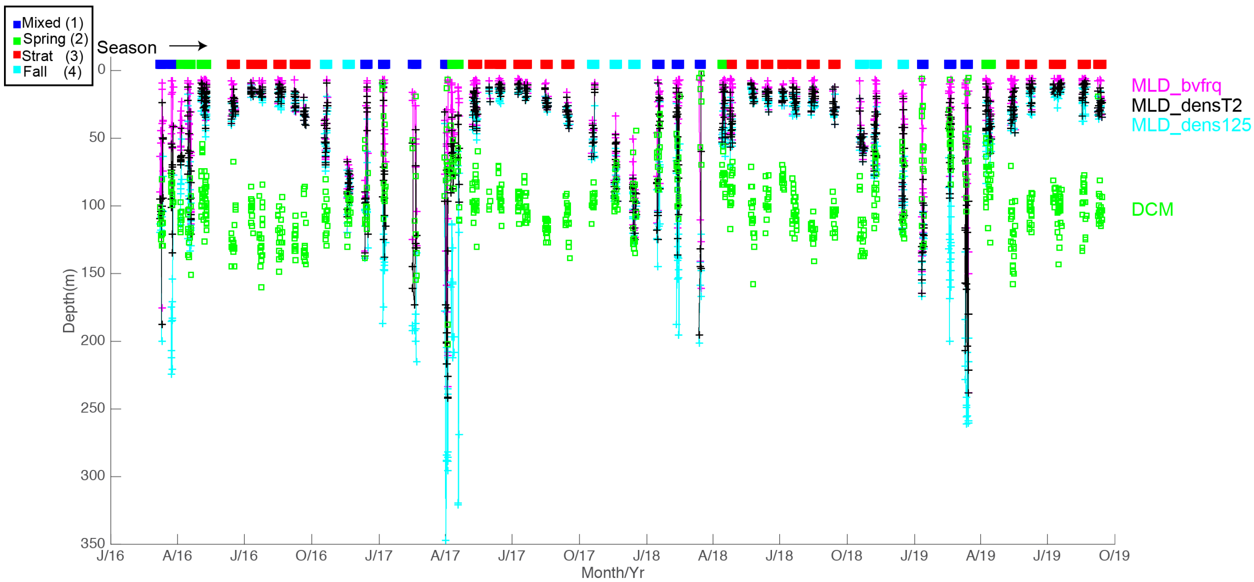


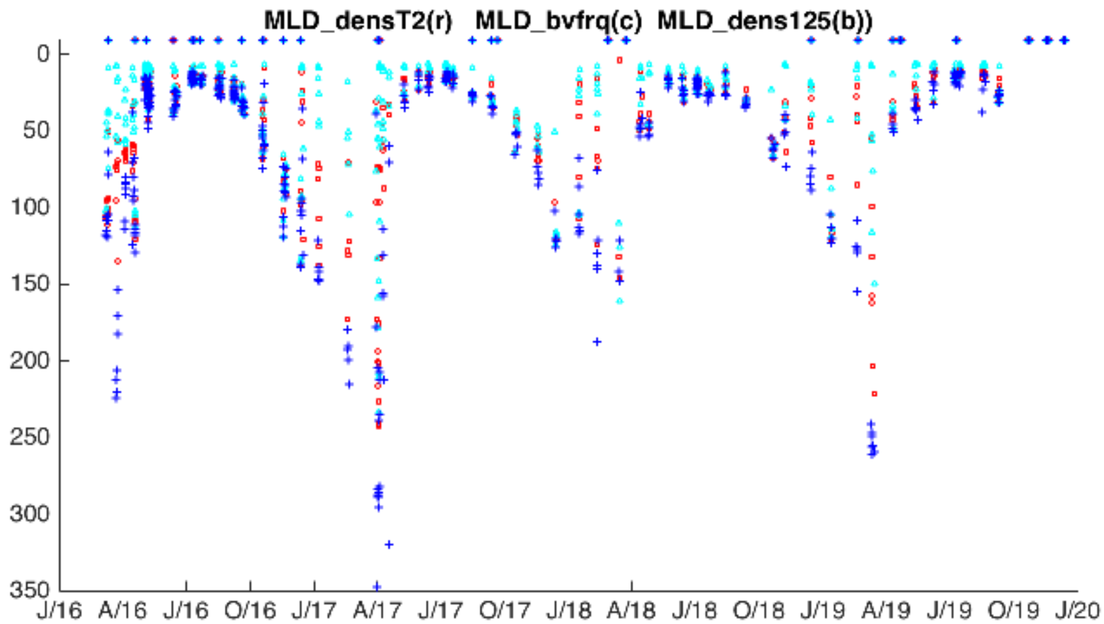
Figure 3. From BATS / BIOS-SCOPE CTD profiles: Relationships between DCM (green squares), MLD_bvfrq (magenta '+'), MLD_densT2 (black '+'), MLD_dens125 (cyan '+') and the Season Designation (1-4, filled squares along top of plot, color legend on left).

Take home messages:

- On any given day, the DCM and MLDs can vary considerably.
- MLD can be defined in multiple ways to highlight different mixing dynamics. For computing Vertical Zones I have used MLD_dens125 (the definition that best reflects the low frequency variability). The other 2 definitions respond to higher frequency diurnal changes in near-surface stratification which are useful for discerning active mixing.
- Seasonally there are 2 extreme periods -- Mixed and Stratified – with transition periods (Spring and Fall) between them. These are defined for each year, based on a review of all available profiles, and determination of the dates corresponding to criteria in Table 2. Beginning and end dates for each season are here:

```
.mixed =      ['01-Jan-2016',  '01-Apr-2016')
               '01-Dec-2016',  '10-Apr-2017');
               '01-Jan-2018'), '05-Apr-2018');
               '01-Jan-2019'), '26-Mar-2019')];
.spring =     ['01-Apr-2016'), '31-May-2016');
               '10-Apr-2017'), '26-Apr-2017');
               '05-Apr-2018'), '26-Apr-2018');
               '26-Mar-2019'), '18-Apr-2019')];
.stratified = ['31-May-2016'), '01-Oct-2016');
               '26-Apr-2017'), '16-Oct-2017');
               '26-Apr-2018'), '01-Oct-2018');
               '18-Apr-2019'), '05-Nov-2019')];
.fall =       ['01-Oct-2016'), '01-Dec-2016');
               '16-Oct-2017'), '01-Jan-2018');
               '01-Oct-2018'), '01-Jan-2019');
               '05-Nov-2019'), '06-Dec-2019')];
```

Figure 4. Comparison of mixed-layer depth variables computed in CTD / bottle profiles: MLD_densT2 (red), MLD_bvfrq (cyan), and MLD_dens125 (blue). NOTE that missing values are plotted as -9



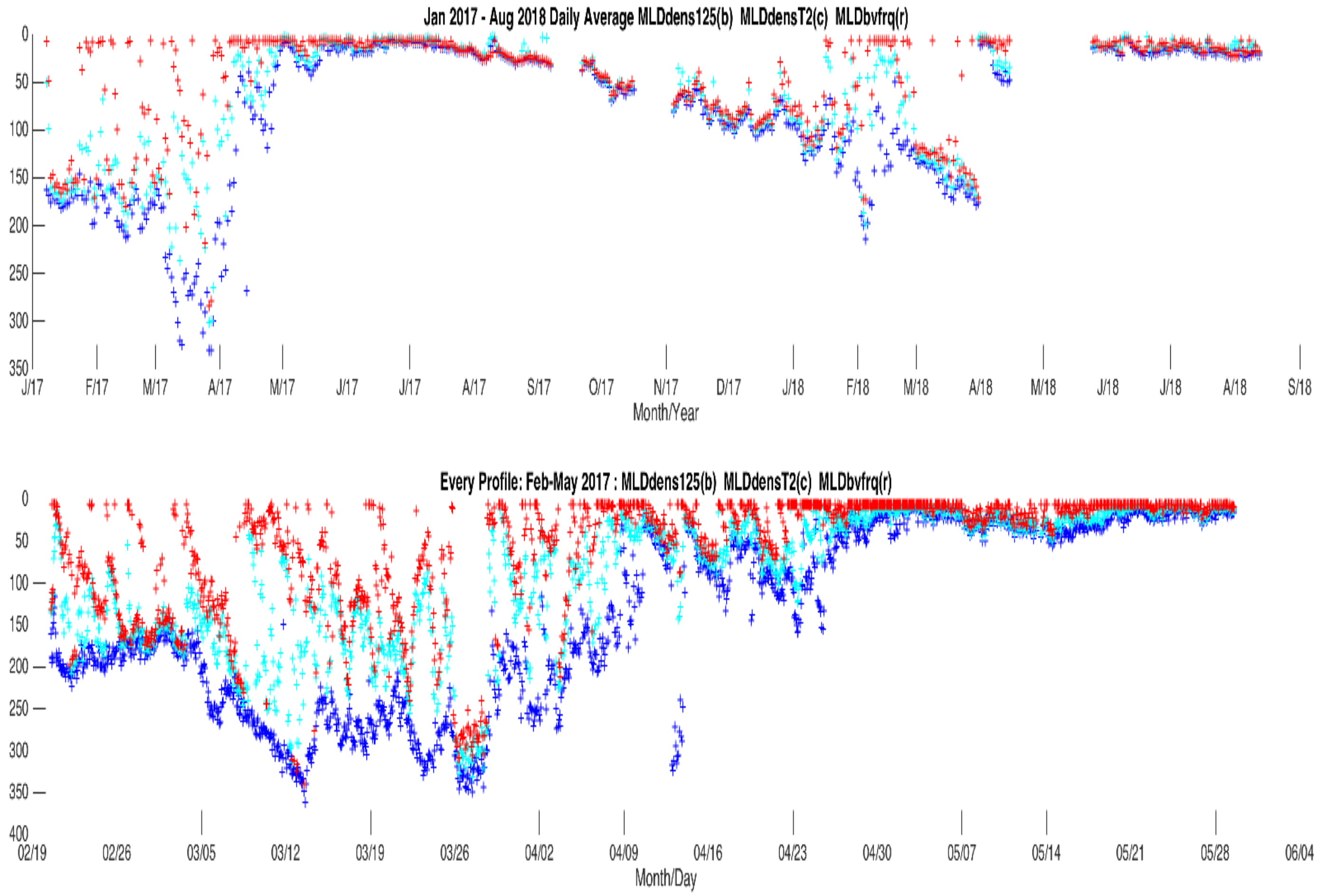


Figure 5. Comparisons of MLD variables in glider profiles.
Top panel shows daily averaged values for the period Jan 2017 to Aug 2018 (multiple glider missions). Bottom panel is every profile from a single glider mission Feb – May 2017.