Glider Measurements of Phytoplankton Physiology in Penguin Foraging Zones Along the Western Antarctic Peninsula.

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I. Introduction

The Western Antarctic Peninsula (WAP) is experiencing rapid warming that has altered sea ice and ecosystem dynamics. Primary producers are one of the key species being affected by warming but these impacts are being observed throughout the food web (12). Over the past 30 years, summer surface chlorophyll *a* concentration has decreased by 12% along the WAP (9). Warming has caused populations of sea-ice dependent species, across trophic levels, to become demographically displaced and replaced by ice avoiding species (1, 8, 9). Changes in phytoplankton dynamics along this region coincide with observed changes of krill and penguin populations.

The Long Term Ecological Research (LTER) Network was created by the National Science Foundation in 1980 in order to conduct research that would monitor changes that can last decades and stretch over large geographical areas. In 1990 the Palmer Station (PAL) LTER was established along the WAP. The PAL LTER study is primarily focused on the pelagic marine ecosystem along the WAP to better understand the ecological processes which link the extent of annual sea ice to the biological dynamics of different trophic levels. The goal of this project is to collect and maintain a time series dataset to investigate the systemic shifts in polar environments due to climate change.

Zodiac based oceanographic measurements of in situ physical and optical parameters, as well as acquisition of water samples for subsequent analysis are conducted from Palmer Station. A restrictive three-mile boating safety zone prohibits access (and thus sampling) of a nearby submarine canyon. The presence of this canyon, known as the Palmer Deep, provides a chute for warm Upper Circumpolar Deep Water (UCDW). Locally, UCDW increases primary production supporting a productive regional food web (11, 15).

To better understand the effects of climate change on phytoplankton productivity, it is necessary to examine phytoplankton physiology in situ. Measurements of photophysiological responses are limited in spatial and temporal coverage and generally require destructive sample manipulations (4). Traditional bench top Fluorescence Induction and Relaxation (FIRe) measurements are limited to discrete samples taken via Go-Flo/Niskan bottles at specific depths. In continuous mode during ship-board operations only the surface water is analyzed. Thus, these traditional methods leave a gap in our understanding about the spatial complexity of phytoplankton physiology.

Figure 1: Fluorescence Induction and Relaxation (FIRe) sensor integrated into a Teledyne Webb Research Slocum Glider payload.

The use of fluorescence kinetics is increasingly becoming an integral part of many oceanographic field programs, but its broad community use is limited by the complexity and high cost of the available instrumentation (13,14). The creation of a Slocum glider equipped with a FIRe sensor was formed to overcome some of these challenges. Teledyne Webb Research (TWR) Slocum gliders have rapidly become indispensable for marine research. These buoyancy driven autonomous underwater vehicles allow researchers to have a high endurance, low-cost, energy-efficient way of ocean observing. The Slocum glider's modular science payloads allow for different optical sensors, in addition to an external conductivity, temperature, depth (CTD) sensor, making it a versatile platform for collecting continuous samples through the water column. We outfitted a TWR Slocum Glider with a FIRe system enabling us to get full water profiles not limited to horizontal spacing. This sensor can measure a comprehensive

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suite of photosynthetic characteristics in phytoplankton including concentration, physiological state and productivity (13,14).

Since large observed declines in the northern Adelie penguin populations have been reported around the PAL LTER site, we deployed a glider with a FIRe payload in the surrounding coastal canyon to measure fluorescence. Mapping top-predators can identify "biological hotspots" or prime foraging zones (7).

II. Methods

A. Background

We deployed a Slocum Glider at the edge of the Palmer Station boating limits and piloted it into the canyon. The glider used during this mission, RU06, was rated to 100m and configured with a CTD and FIRe sensor. Both sensors were tested at Rutgers University for quality control purposes. The glider was then ballasted to match water characteristics at the PAL LTER site (O°C and 1026.5kg m-3).

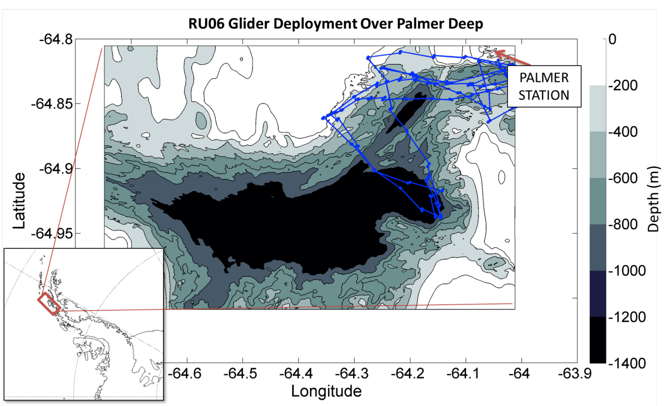

Figure 2: Regional map of Palmer Deep with RU06 deployment track and insert of the Western Antarctic Peninsula.

B. Mechanics of the FIRe Sensor

The FIRe sensor is able to measure the quantum yield of photochemistry, the functional absorption cross section of Photosystem II (PS II) and the kinetics of electron transport on the acceptor side of PS II in individual algal cells (3). In order to obtain these variables a series of very short, rapid, pulses of light are delivered and absorbed by the reaction center (2). Overtime this process cumulatively saturates the reaction center within a single electron turnover (2). To accommodate diverse functional groups within phytoplankton communities a multicolor excitation source was developed that uses high luminosity blue (450nm and 480nm) and green (500nm and 530nm) light emitting diodes (LEDs)(5). The LED driver is computer controlled and delivers pulses with the duration varied from 0.5µs to 50ms, which ensures fast saturation of PS II within the single photosynthetic turnover (5). A sensitive avalanche photodiode module detects the fluorescence signal, which is isolated by red (680nm or 730nm) or infra-red (880nm) interference filters (5).

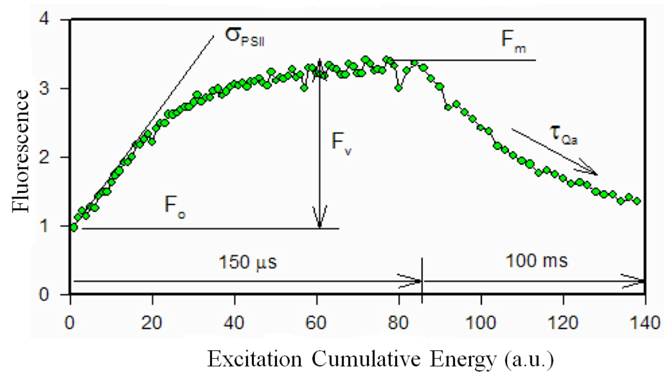

Figure 3: The parameters obtained from FIRe measurements during Single Turnover Flashes from Iluz & Dubinsky, 2013.

Variable fluorescence, Fv, is the difference between Fm and F_O fluorescence levels (2). Where F_O and F_m are the minimum and maximum yields of chlorophyll *a* fluorescence (4). F_v/F_m is defined as the maximum quantum yield of photochemistry in PS II (4). Nutrient-replete phytoplankton tend to have a measured F_v/F_m ranging from 0.62 to 0.66. These parameters are used to quantify the cell-specific photosynthetic performance in natural phytoplankton assemblages in aquatic ecosystems (3). Until now we have only been able to get an idea of phytoplankton biomass through optical sensors on the glider, which give us chlorophyll *a* concentration values. The integration of the FIRe system on the glider provides a detailed picture of which photosynthetic status can be deduced. We were able to see physiological responses from algal cells and be able to determine the health of the cell by looking at its efficiency rate.

C. FIRe Sensor Integration in a Slocum Glider

The prototype FIRe system for the glider was built and verified against a standard FIRe system. The preliminary tests confirmed that the performance of the glider optical unit is as good as that of a bench top FIRe system and ensures measurements at extremely low chlorophyll concentrations down to $0.05mg/m^3$ (14). The FIRe profile in the Glider-Fire system is characterized by a slower fluorescence rise (~50us versus 30us in the bench-top FIRe) due to lower photon flux density of the excitation light. However, the photon flux density is high enough to saturate fluorescence yield within less than 100us (14). The Glider-Fire utilizes many of the same basic design elements of the bench top system, however some modifications were made in order to comply with the Slocum Gliders low energy budget as well as to fit the size constraints of a science payload (length 30cm, diameter 21.3cm, max weight 4kg). Most noteworthy is the complete redesign of the bench top PC104 computer system into a compact, low power microprocessor system, which then necessitated a complete rewrite of FIRe software. In order to accommodate chlorophyll *a* concentrations ranging from natural phytoplankton assemblages to laboratory cultures, the gain is automatically adjusted in the detector unit over the range of three orders of magnitude (5). The excitation protocols and data acquisition are controlled by a low power embedded board that also performs real time data analysis using a custom analysis toolbox (5). This redesign allowed for a significant reduction in size, complexity, and power consumption of the computer system (14).

The integration of the FIRe sensor carries a higher power demand than most other available glider payloads. A typical glider operates at 2.5 W, which leaves enough energy for mission durations of 3-4 weeks. The FIRe sensor itself uses almost 5 W of power, a 200% increase in power vs. a standard glider. This allows for mission durations of just over a week when running the FIRe full time. In order to make the tradeoff for more duration and distance covered it was decided to operate the FIRe sensor only at night. This effectively increases mission durations from a week to almost two weeks. Operating the FIRe sensor during the night also helps alleviate non-photochemical quenching (NPQ). In almost all photosynthetic eukaryotes the process of NPQ occurs to help regulate and protect photosynthesis in environments where light energy absorption exceeds the capacity for light utilization (10).

III. Results

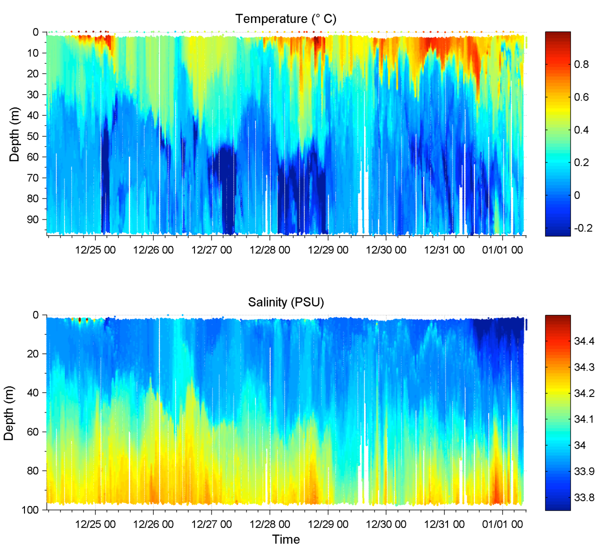

Figure 4: Standard temperature and salinity plots from a Slocum Glider. This dataset is from RU06 deployed in the Palmer Deep during the 2009-2010 summer field season.

RU06 was deployed for roughly nine days from Dec. 24th 2009 to Jan. 1st 2010 and flew approximately 158km. During this experiment we were able to verify the integrity of the FIRe sensor onboard the glider. We had a known sampling gap due to the lack of sampling instrumentation in the Palmer Deep. This flight allowed us to not only fill the sampling gap with instrumentation that has been proven to work (Slocum Gliders) but also with a new sensor (Glider-FIRe) providing us with a high resolution dataset over the Palmer Deep.

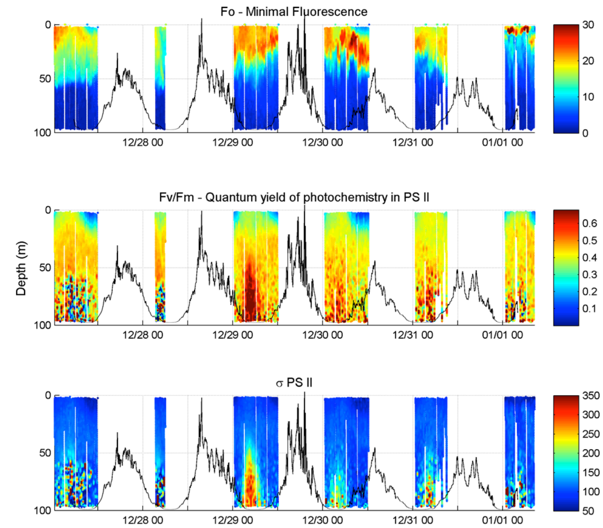

Figure 5: Variables collected from the FIRe sensor integrated on a Slocum Glider. Note the PAR overlay signifying that the FIRe sensor was turned off during the day.

We demonstrated the ability to turn the FIRe sensor on and off in conjunction with the diurnal cycle. Not only is this a way of saving energy and improving our power budget but turning the FIRe sensor off during the day was done to minimize the effects of photoquenching that we would see in the data. The PAR data overlay on the glider data demonstrates this correlation.

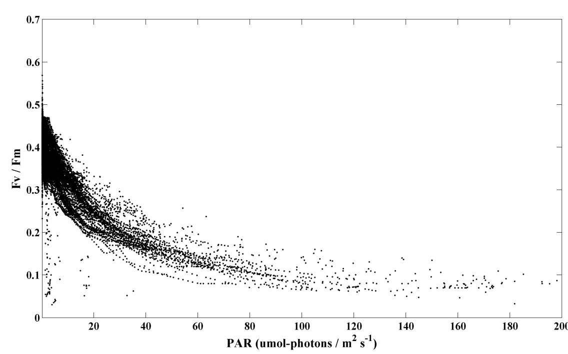

Figure 6: Correlation between light intensity (PAR) and Fv/Fm the efficiency of Photosystem II.

In addition to the PAR data from a surface mounted radiometer at Palmer Station, the FIRe sensor is also equipped with its own PAR sensor. There is a correlation between light intensity (PAR) and F_v/F_m. During periods of low light (lower PAR values), higher F_v/F_m values are observed; in contrast, higher PAR values (more light) correlate with much lower Fv/Fm values. This is due to the effects of photoquenching. While phytoplankton need light to photosynthesize, too much light acts as a stressor and will cause phytoplankton to exhibit a sunburn affect. The system can only handle so many photons and once you reach P_{max} (the maximum rate of electron transport), the system will switch to photoinhibition mode and become less efficient, revealing lower F_v/F_m values in association with high PAR values.

Combining glider data and FIRe data allowed for the construction of a unique series of temperature verse salinity plots. These plots show distinct changes in association with differing water masses. Furthur analysis is needed in order to determine which water masses may be preffered by various phytoplankton assemblages.

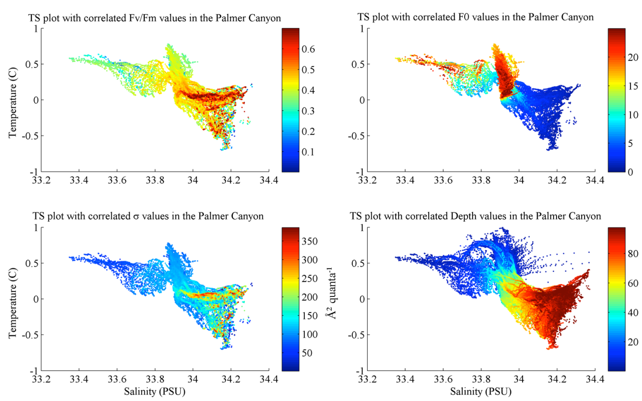

Figure 7: Combing glider temperature and salinity into TS plots with overlays of various FIRe sensor variables.

IV. Conclusions

Slocum Gliders have proven their usefulness in providing large volumes of high definition data but for the first time we were able to couple that with a FIRe system and look at the efficiency rates of phytoplankton in a hard to sample region of the world. The FIRe equipped glider allowed for high spatial and temporal resolution of physiological data vs. discrete samples taken with the traditional Go-Flo/Niskan bottle method and/or continuous flow through surface sampling via ships. We have identified numerous quality control measures that will need to be furthur explored for continued success of the sensor.

While the FIRe sensor is an energy intensive system, operating intelligently will maximize data quality and mission endurance. Possible sensor revisons such as the addition of a shroud are being considered to help with NPQ.

Acknowledgment

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