Project Summary

Changes in the distribution of carbon within the ocean are caused by a combination of physicochemical and biological processes. The first of these two, the so-called “solubility pump”, injects carbon into the deep sea through the sinking of cold waters at high latitudes where CO_2 solubility is enhanced (Feely et al., 2001; Sabine et al., 2004). The so-called oceanic “biological pump” is highly dynamic and variable in space and time. This process operates through the production of organic carbon by organisms in the surface ocean and the subsequent sequestration of this material below the winter mixed layer (Volk and Hoffert, 1985). Significant effort has gone into understanding the controls of the biological pump and while the general function is understood, the details remain elusive. At present, we know much more about processes in the surface euphotic zone, than in the Twilight Zone (i.e. mesopelagic). It is within the poorly understood Twilight Zone where changes in C attenuation on sinking particles and the composition of sinking material have important consequences for the rates of C uptake and exchange at the surface ocean with the atmosphere, and for longer term C sequestration in the deep sea.

This proposal sets out to develop improved particle flux collectors and use these to answer key science questions associated with C fluxes and exchange via sinking particles at the Bermuda Atlantic Time-series Study (BATS) site (e.g. Michaels and Knap, 1996). Currently at BATS, we can’t balance surface ocean C budgets, annual new production estimates, or link production and community structure to predict particle export, and regularly fail to capture episodic flux events. At the same time, we are trying to answer these questions using an imperfect tool, the drifting sediment trap, a device that has served us well but has not changed significantly since the early 1980’s.

This program is both innovative and ambitious, with the development and engineering of new tools and its emphasis on the collection of multi-annual time-series data, while being realistic in starting from proven technology. We start by building upon our recent success with the neutrally buoyant sediment trap (NBST), but recognize that continuous flux collection and swimmer free samples are needed, as envisioned for our new design- the Twilight Zone EXplorer (TZEX).

In context of the C and Water in the Earth System Program, this proposal advances our understanding of the carbon cycle by combining the following multidisciplinary elements:

- basic research in ocean biology obtained from ship based observations and remote sensing
- geochemistry of particles and waters and how these change with depth and time
- modeling of biological processes and particle transport in moving fluids
- the engineering and application of novel observational equipment to capture sinking particles

These unique sediment trap devices will open up a new window to assess the ocean’s role as a C sink and how marine export production will change in response to climate change (Bopp et al., 2001, 2005). This study provides parallel science and engineering opportunities over longer time-series which are difficult to support in core programs, but are essential if we are to make a major improvement in our understanding of ocean C fluxes.

Broader Impacts

By improving understanding of the carbon cycle in the mesopelagic twilight zone, this project will implicitly contribute to society’s ability to anticipate the impacts of global climate change as well as formulate remediation strategies. Explicitly, we have initiated five activities that will maximize the educational and public outreach impact of our research. First, we will make available berth space during our three 7-day cruises to high school, undergraduate and graduate students that make use of BBSR’s educational programs. Secondly, we will seek to accommodate journalists interested in covering the “climate beat” to invite them on board, as done during VERTIGO (http://www.csmonitor.com/2004/0212/p14s01-sten.html). Thirdly, we are also fortunate to have WHOI internal funds ($5K) to support participation of an undergraduate summer student fellow on one of the summer cruises and take part in pre/post cruise analyses. There will also be graduate student involvement in this project (at least VIMS & WHOI). Finally, in accord with other broader impact interests of NSF, there is a significant instrumentation development and application component of our proposed research, that will bear significant fruit for many researchers for years to come.

TABLE OF CONTENTS

For font size and page formatting specifications, see GPG section II.C.

Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

TABLE OF CONTENTS

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1. INTRODUCTION

The ocean contains the largest variable pool of carbon and can impact the global C cycle on timescales ranging from months to millions of years. Changes in the distribution of carbon within the ocean are caused by a combination of physicochemical and biological processes. The first of these two, the so-called "solubility pump", injects carbon into the deep sea through the sinking of cold waters at high latitudes where CO_2 solubility is enhanced. This is a large oceanic carbon flux that is relatively stable and predictable (Feely et al., 2001; Sabine et al., 2004). In contrast, the so-called oceanic "biological pump" is highly dynamic and variable in space and time. This process operates through the production of organic carbon by organisms in the surface ocean and the subsequent sequestration of this material below the wind mixed layer of the ocean (Volk and Hoffert, 1985). Trapped in this way, the organic carbon temporarily avoids respiration/oxidation in either the larger dissolved organic carbon pool, and/or is removed from active exchange with the atmosphere via transport on sinking particles to the deep sea and underlying sediments. If the biological pump were somehow shut off, atmospheric CO_2 levels are predicted to increase by 200 ppmv (Sarmiento, 1984).

Much effort has gone into understanding the controls and sensitivities of the biological pump, and while the general function is understood, the details remain elusive. This is especially true of the endless "snowfall" of marine particles through the water column. It is well known, for example, that only a small fraction of the organic material fixed in the surface ocean is transported on sinking particles to the deep sea. However, the controls on flux of organic matter and its attenuation and variability in space and time are the subject of much debate and the central theme of this proposal. Predictive understanding of how the biological pump will respond to future climate change requires that we fill in these details.

Using satellite remote sensing, we can now monitor continuously for surface ocean properties, including light, temperature, Chlorophyll and C biomass, and thus derive global C fixation rates (e.g. McClain et al., 2004, Siegel et al., 2005, Behrenfeld et al., 2005). Moreover, remote sensing algorithms to identify phytoplankton functional groups are being developed (Subramanian and Carpenter, 1994; Merico et al., 2003; Alvain et al., 2005). We can also monitor deep ocean particle fluxes with moored time-series sediment traps (Deuser et al., 1986; Conte et al., 2001). While we know that flux attenuation is greatest at shallow depths and not uniform in space and time, linking the deep fluxes to upper ocean processes in a continuous fashion eludes us (Figure 1). This gap in knowledge is due to both the limitations of current particle flux collectors (see **2b**), and the lack of continuous observations of upper ocean particle fluxes, and inherent issues in the sampling of a spatially heterogeneous rain of particles (see **2d**).

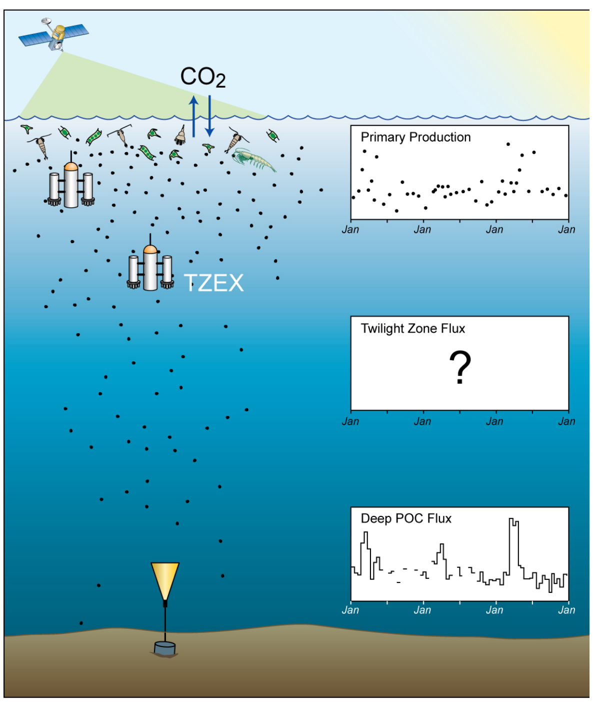

Figure 1. Schematic showing links between continuous remote sensing of surface ocean C uptake, twilight zone flux (this proposal) and deep ocean flux.

This proposal sets out to build the tools to fill in this gap by developing improved particle flux collectors and use these to answer key science questions associated with C fluxes and exchange via sinking particles at the Bermuda Atlantic Time-series Study (BATS) site (Michaels and Knap, 1996; Steinberg et al., 2001; Conte et al., 2001). Our expectation is that C flux out of the surface ocean and through mesopelagic depths is much more variable in space, depth and time than previous estimates. Because we miss much of these dynamics with current approaches, we continue to be confounded by the marine particle cycle and its links to C uptake and sequestration.

Currently at BATS, we can't balance surface ocean C budgets, annual new production estimates, or link production and community structure to predict particle export, and regularly fail to capture episodic flux events. At the same time, we are trying to answer these questions using an imperfect tool, the drifting sediment trap, a device that has served us well but has not changed significantly since the early 1980's. A key to unlocking the controls on C flux to depth lies in teasing out the sources of variability in the flux records.

We are now poised to move ahead. This program is both innovative and ambitious, with the development and engineering of new tools and its emphasis on the collection of multi-annual time-series data, while being realistic in starting from proven technology. We start by building upon our recent success with the neutrally buoyant sediment trap (NBST), but recognize that continuous flux collection and swimmer free samples are needed, as envisioned for our new design- the Twilight Zone EXplorer (TZEX). The BATS site is representative of oligotrophic conditions which are common to a large fraction of ocean surface area and account for half or more of marine export production (e.g. Najjar and Keeling, 2000). The results from this study will also be immediately relevant to the decades of work at BATS and the Ocean Flux Program (OFP) deep sediment trap time-series (see attached letter from Conte). With regular access on BATS cruises, sharing of BBSR technical help, and proximity to WHOI, we can think of no better site to develop this next wave of ocean flux explorers. With a multi-disciplinary set of skills in engineering, geochemistry, biology, remote sensing and physical oceanography, this group is ready to address not just how much and how deep, but the why's of ocean C flux.

We have divided this project into a series of overlapping engineering development and field stages, and have summarized below the expected improvements and how they help us resolve important C cycling questions, namely:

Stage 1. Deploy NBSTs for 18 months during BATS cruises- this will be the first long term NBST sampling program.

Improvement 1. The quality and quantity of flux caught in a NBST has been shown to differ at times with traditional tethered traps, likely due to reduced hydrodynamic biases.

Questions 1. With improved flux collectors, we can more accurately determine the relationship between carbon flux and community structure in the euphotic zone. The comparison between NBST and standard tethered traps at BATS will allow us to gain further understanding as to how these differences relate to changing particle types and physical conditions. In addition, we anticipate an improved seasonal and annual balance between C flux, C budgets and new production at BATS.

Stage 2. Design and test sediment traps that incorporate swimmer avoidance technology, such as the rotating sphere (Peterson et al., 1993), and closed sample cups.

Improvement 2. The number of swimmers in these traps will be greatly reduced. A NBST with a swimmer avoidance mechanism will improve our ability to make net C flux estimates.

Questions 2. With the swimmer bias removed and closed sample cups, we will be able to resolve whether or not particulate material is lost to the supernate in traps at shallow depths and whether this loss is variable between elements. This is critical to the interpretation of data from longer trap deployments from upper ocean and mesopelagic depths.

Stage 3. Design, test and deploy the Twilight Zone EXplorer (TZEX), an autonomous, swimmer avoidance NBST capable of collecting high frequency (weekly) sinking particle samples, for one year in the Sargasso Sea.

Improvement 3. This allows us to capture episodic events and obtain the first time-series flux record below the euphotic zone (150m) and the depth of maximal winter mixing (300m). On board sensors will also provide information on changing biogeochemical conditions above the trap, and remote sensing will allow for comparison of changes in particle source area and surface biological conditions.

Questions 3. With the TZEX we can resolve whether episodic events contribute disproportionately to fluxes. Inclusion of these rare events will improve C budgets, new production estimates, and allow for direct comparison of continuous remote measurements of surface C uptake, export through the twilight zone and deep flux. Variability in POC, PIC and bSi export and their controls on C transport efficiency can only be understood with continuous monitoring of upper ocean particle fluxes.

Stage 4. Conduct focused flux vs. depth studies during different seasons using NBSTs and TZEX devices.

Improvement 4. This provides key information on particle transport efficiency in the upper 1000m, essentially filling in the "Martin curve" for the major biogenic flux components at BATS under differing flux conditions.

Questions 4. At BATS, we expect to observe changes in remineralization length scales as a result of changes in surface and mesopelagic conditions. These data are essential to resolve a range of important questions, such as: how food webs control upper ocean fluxes; the role of ballast in enhancing export efficiency; the impact of heterotrophic processes in the mesopelagic on flux; and how variability in POC, PIC and bSi fluxes are related to ocean C uptake, C transfer and C preservation though the upper 1000m.

In context of the C and Water in the Earth System Program, this proposal advances our understanding of the carbon cycle by combining the following multidisciplinary elements:

- basic research in ocean biology obtained from ship based observations and remote sensing
- geochemistry of particles and waters and how these change with depth and time
- modeling of biological processes and particle transport in moving fluids
- the engineering and application of novel observational equipment to capture sinking particles

These unique sediment trap devices will open up a new window to assess the ocean's role as a C sink, and how marine export production will change in response to climate change (Bopp et al., 2001, 2005). This study builds upon recent success by the PI's using NBSTs and provides parallel science and engineering opportunities over longer time-series which are difficult to support in core programs, but are essential if we are to make a major improvement in our understanding of ocean C fluxes.

2. BACKGROUND

2a. Patterns and variability in current mesopelagic flux records

Among the most extensive measurements of upper ocean POC flux were those conducted during VERTEX (VERtical Transport and EXchange) programs in the 1980's. Drifting sediment traps (i.e. suspended by tethers from surface floats) were used to estimate flux vs. depth patterns in several locations in the Pacific, and from a large data set of 123 individual C flux measurements, the Open Ocean Composite (OOC) profile of POC flux vs. depth was obtained (Martin et al., 1987). A normalized power function was thought to best fit the OOC profile of the form: $F = F_{100}(z/100)^{-b}$ where z was the depth of the trap, and the best fit for F_{100}, the C flux at 100m, was 4.2 mM C m^{-2} d^{-1}, and b was 0.86 (larger b values represent more rapid flux attenuation). This empirical formulation (the "Martin Curve") is widely used in models to describe the biological pump. However, variability in F_{100} and b seen between sites and seasons were commented upon by the original authors, and a mechanistic understanding of the sources of this variability is still missing.

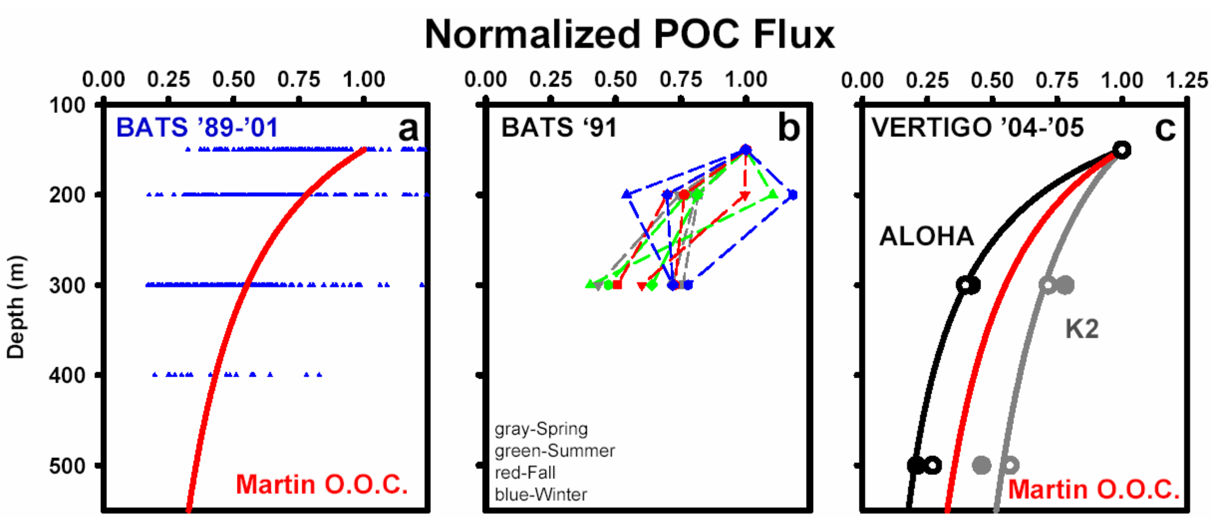

Figure 2. Vertical trends in particulate organic carbon flux illustrating a) variations in export flux at BATS normalized to the average flux at 150m relative to Martin OOC (red), b) variability in individual flux profiles from BATS in 1991, and c) NBST flux at Hawaii ALOHA (black) and NW Pacific K2 (gray).

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Similar flux vs. depth data have been collected at BATS using standard tethered traps (blue dots Fig. 2a). The range in flux at each depth for any given deployment varies significantly (F_{150} varies from 1.0 to 2.3 mM C m^{-2} d^{-1}; 1989-2001 n=150). Further, there appears to be no single flux vs. depth relationship to describe individual deployments (b ranges from –1.0 to 2.4). With the assumption that source particle quality and quantity changes seasonally, color-coding individual deployments by season suggests that the flux vs. depth relationships may have some coherence (Fig. 2b) and hints at ways we need to start looking at variability in flux attenuation.

We have recently deployed NBSTs during single occupations at two contrasting sites in the Pacific, the oligotrophic station ALOHA off Hawaii, and the K2 site in the subarctic NW Pacific. Using NBSTs, we found much more rapid attenuation of POC flux at station ALOHA off Hawaii (b = 1.2) than at the end of a diatom bloom in the NW Pacific (b = 0.6; Fig. 2c- Buesseler et al., 2006a). Further, there was good coherence in the flux vs. depth records at each of these sites, despite widely varying values for shallow flux (F_{150} ranging from 1.5 mM C m^2 d^{-1} ALOHA and 1.9 to 5.2 in the NW Pacific during two 5 day deployments).

The shape of the Martin curve has been re-evaluated by many investigators under different conditions and with different assumptions (e.g. Armstrong et al., 2002; Lutz et al., 2002). It is not the intent to review these here, and we will not necessarily adopt this formulation, however the Martin curve does provide for an easy starting point to discuss the minimum set of measurements needed to study ocean particle fluxes, namely the shallow flux below the surface mixed layer, and the attenuation of flux vs. depth.

While it would be tempting to suggest that we immediately move to a large-scale study of flux vs. depth and an assessment of seasonal and interannual flux variability, this is both expensive and would require continuous occupation of multiple sites. We feel it is better to start by making a more accurate assessment of the variability in the shallow flux, F_{150}, at one site (BATS). We then move in stages to engineer improvements still needed to avoid swimmers, quantify sample preservation concerns and work to develop capabilities for long term deployment and remote collection of reliable time-series mesopelagic flux data. The last stages of this proposal fill in the Martin curve by examining flux vs. depth in more detail during differing seasonal flux conditions.

We believe that a careful study with new tools of the variability in shallow flux (F_{150}) and flux attenuation (b) at one site (BATS) will help elucidate the mechanisms controlling the biological pump.

We contend that the wide variability in both F_{150} and b values in the BATS flux record likely results from a combination of real and artifactual sources. Here we concentrate on three broad sources of variability:

1. trap accuracy [section **2b**]
2. source particle quality & composition [section **2c**]
3. spatial and temporal/episodic variability in source particles [section **2d**]

2b. Trap Accuracy Issues

Sediment traps have provided a first order view of upper ocean particle flux that has advanced our understanding of the ocean C cycle. However it is well known that traditional trap fluxes are influenced by hydrodynamic, swimmer and solubilization effects (details and references for this section can be found in: US JGOFS, 1989; Gardner, 2000; Buesseler et al., 2006b). The magnitude of these impacts vary depending upon the physical environment (current velocity, trap tilt, vertical mooring motions) as well as the particle type (sinking speed, density, chemical properties, size). High fluxes can be missed simply due to the episodic nature of high flux events and the typically short trap deployments during calm weather windows and/or loss of material due to tilt or mooring line motions and/or continued solubilization of particles after collection. Over collection during low flux periods can result from inclusion of swimmers in the net C flux, and/or entrainment of suspended particles in the trap via hydrodynamic induced flow within the trap. The end result has been an inadequate constraint of particle export in the upper ocean.

The idea of measuring sinking particle flux in an open tube or cone is simple enough, but the nature of capturing vertical flux in a moving fluid is surprisingly complex. Hydrodynamic biases refer to the combination of processes related to horizontal and vertical motions of the trap relative to the fluid that can at times, provide for inaccurate fluxes and/or particle sorting, i.e. collection biases based upon sinking speed or some other physical property- horizontal flow, tilt, etc. In general, hydrodynamic effects decrease with depth as horizontal velocities decrease, even on "free" drifting tethered traps where horizontal approach velocities are many cm/sec, some 10-100 times greater than sinking speeds of 100m/day. The most obvious solution to this artifact is the use of trapping systems that have no tethers at all, and are free to move with the fluids they are sampling, hence the NBST.

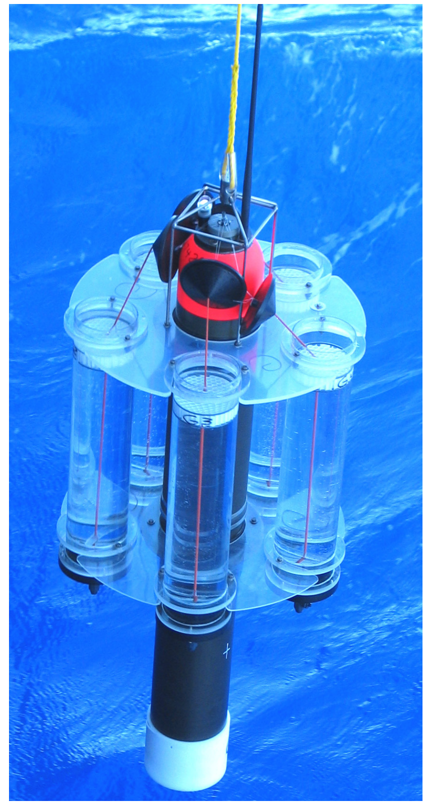

Figure 3: WHOI NBST system being deployed.

Although a tether-free trap may sound like a simple concept, the attachment of particle collection tubes to a neutrally buoyant float used by physical oceanographers to measure currents, has taken considerable engineering effort, and only two such systems have been successfully deployed, the WHOI NBST system (Fig. 3-right; Valdes and Price, 2000) and the PELAGRA system of R. Lampitt (2006). Our own studies have shown at times similar collection properties between drifting traps and NBST's, but important exceptions, including periods of higher collection by NBST's during high flux conditions and slightly lower collection by NBST's under low flux conditions (Figs. 4a and 4b).

We also see periods of undercollection and overcollection in traditional tethered traps at BATS when we compare the measured ^{234}Th flux in traps with calculated fluxes from water column activity balance (Fig. 4 in Buesseler et al. 2000). In addition, we have documented variability between the flux of different elements between NBSTs and standard tethered traps (Stanley et al., 2004). If collection efficiency varies as a function of both ambient conditions (for tethered traps this would include vertical motion on the mooring line, horizontal currents, etc) and the particle types (marine snow, fast sinking fecal pellets, diatom aggregates, etc.), then this variability in collection efficiency and between elements should not be surprising. The NBST has thus resolved, or at least greatly reduced hydrodynamic effects on particle sampling, and with our recent success with 17 NBST deployments during two process cruises in the Pacific, we are ready to start using these devices in a regular time-series mode at BATS to better sample (in parallel to standard BATS tethered traps) particle flux on standard 4-5 day deployments. This important first step in our proposal will yield an immediate refinement on the flux estimates made at BATS with tethered traps, and represent a crucial part of "side-by-side" comparison studies that would be required if neutral trapping is to become commonplace in the future.

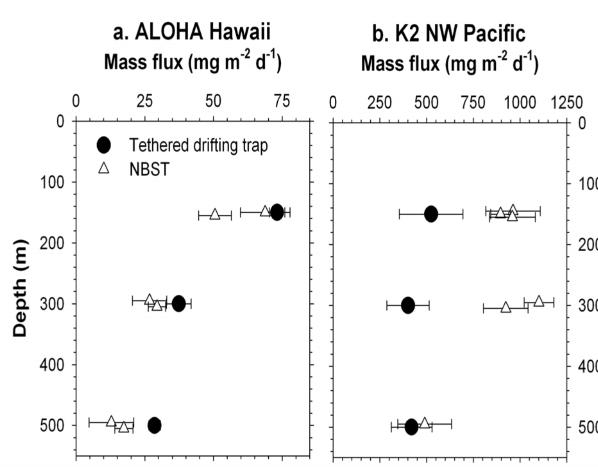

Fig. 4 Side by side mass flux comparison NBST and tethered drifting traps ALOHA (left) and K2 (right).

What has not been resolved with the current BATS traps or NBSTs is the issue of swimmer contamination, and currently active removal post collection of zooplankton that enter a trap is a time consuming "art" that is effective but requires careful attention and skill. Prior studies and our most recent data suggest that for the 150m traps at both a low flux site off Hawaii and a higher flux NW Pacific site, more swimmer C is removed from each trap tube than is left behind as net flux at 150m (Figure 5). This is common to all open tube trap designs, with swimmer flux decreasing with depth, presumably due to a decrease in zooplankton abundances. Thus small errors to swimmer removal methods, such as not removing all swimmer parts or cryptic gelatinous swimmers (Michaels et al., 1990), or taking out too much material by removing detrital particles attached to swimmers, are possible positive and negative flux biases, respectively, that can be significant and are difficult to quantify.

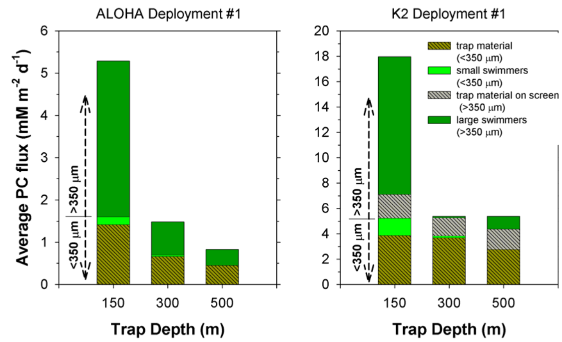

Figure 5. Comparison of swimmer C caught in trap (green bars, here separated by 350µm screen) relative to net C in trap. Aloha (left) and K2 (right). Also quantified are small swimmers that pass through screen and particles caught on screen.

It would be far better to keep swimmers from entering the trap in the first place. The most effective swimmer avoidance method to date is to use an indented rotating sphere, or IRS design whereby particles falling in the trap tube land on an indented ball that slowly rotates on a frequent basis (every 10-15min). This motion drops sinking debris into the collection cup below without the zooplankton being able to follow into the lower trap sections (Peterson et al., 1993, 2005). While changes to the material after deposition on the rotating ball are possible (changes in density of fragile aggregates; heterotrophic feeding and C loss), this device would still be an improvement relative to the difficulty of removal methods and magnitude of swimmer C (and this will be tested- Stage 2). The IRS device has never been used on an NBST, though in one test by this group on a tethered trap, the IRS ball reduced swimmer numbers by a factor of 10. We propose adapting and testing an IRS type ball device on the NBSTs.

Finally, the 3rd major issue in trap accuracy is our inability to keep, even with poisons, all particles once collected from breaking up and releasing included fluids (Knauer, 1979; Karl and Knauer, 1989; Lee at al., 1988). The magnitude of this solubilization/fragmentation loss is most often determined by the difference in solution phase concentrations before and after collection of particles on filters (Fig. 6). Such solution measurements are difficult to interpret if the collection tube is open to exchange with different ambient waters (i.e. different DOC conditions) during deployment, retrieval and while at depth, and/or if there are many swimmers that enter the trap and herniate and die (Peterson and Dam, 1990) in the typical high salinity brines and poisons used to kill swimmers so they can be removed (without poisons, a larger bias might be expected if they entered and left w/o notice after eating or defecating). For short time deployments, such as during VERTIGO and in the initial phases of the work proposed here, we have found this effect to be modest (<10% change) for most elements other than P (ca. 20%). For longer term deployments, however, this effect could be very serious. In our floating NBST-IRS, the sample will be caught below the IRS ball in a small sampling cup, and the ball and rotating cup mechanism will serve as a double seal to both limit mixing and prohibit zooplankton from entering the poisoned collection cup, thus allowing for

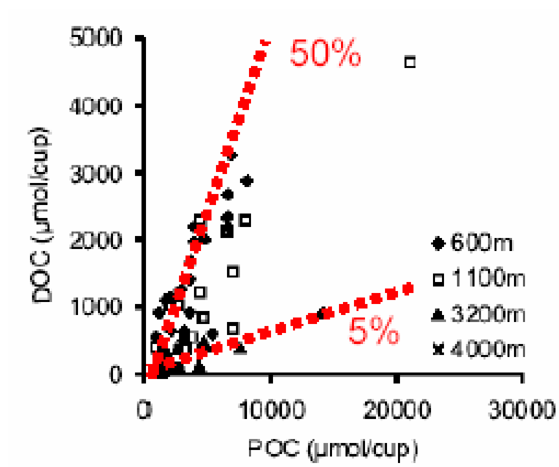

Fig. 6. POC in trap vs excess DOC in trap supernate attributed to particle solubilization or fragmentation in long term deployments (adapted from Antia, 2005).

quantification of any solution phase concentration increases, something not possible with current shallow trap designs.

2c. Variability in flux and source particle composition

Early studies hypothesized that there would be a direct link between total C uptake (primary productivity) and C export via sinking particles (Suess et al.,1980; Berger et al., 1987; Pace et al., 1987). However, the time-series data on primary production and trap flux at BATS (and many other sites) show no direct correlation (Michaels and Knap, 1996). Obviously, it is not just total C uptake, but the community structure of the phytoplankton assemblage (Smetacek et al., 1984; Michaels and Silver, 1988; Peinert et al., 1989; Legrandre and Michaud, 1998; Boyd and Newton, 1995, 1999) and their physiological status (Kiørboe and Hansen, 1993; Alldredge et al., 1993; Waite and Nodder, 2001) that are key determinants in the magnitude of downward particle flux. The former will also influence the structure of the grazer community in the upper ocean, which will in turn establish further (secondary) particle transformations via grazing (e.g. Michaels and Silver, 1988).

The relative importance of the main agents of vertical particle flux – aggregates of marine snow (comprised of sedimenting phytoplankton, or larvacean 'houses', for example) and zooplankton fecal pellets – vary significantly with a number of factors including season, environment, and depth. A review of more than 500 sediment trap studies (Turner 2002, and references within) reveals the zooplankton fecal pellet contribution to total POC flux varies from < 1 - 100% as a result of the changes in planktonic community structure associated with many factors. We thus should expect considerable variability in the flux out of the euphotic zone and its composition.

When examined in closer detail at BATS, a direct relationship between community structure and POC flux has proven difficult to elucidate. Lomas and Bates (2004) found only a weak positive correlation between diatom pigments and POC flux in time-series data. This is despite the fact that other studies suggest a greater importance for diatoms in export at BATS (Goldman, 1993; Nelson and Brzezinski, 1997; Goldman and McGillicuddy, 2003; Sweeney et al., 2003), even though they are generally only a minor component of the total phytoplankton biomass (Steinberg et al., 2001). In fact, the best predictor of POC flux at BATS is the relative abundance of haptophytes and prochlorophytes, but the relationships are not strong (Lomas and Bates, 2004). However, we may be missing episodic diatom blooms and export events in this analysis (Lomas et al., 2006; see **2d**).

In addition to community controls on shallow fluxes, or F_{150}, the export efficiency, b, is thought by some to be controlled by the biomineral content. In particular, higher particulate inorganic carbon (PIC, or carobante) content is thought to lead to higher POC export at depth due to its effect as a mineral ballast which increases sinking speeds, and/or from the protective nature of carbonate for a fraction of the POC produced in the surface ocean (Francois et al., 2002; Armstrong et al., 2002; Berelson, 2002; Klaas and Archer, 2002). While this might hold on a regional scale or when compared to modeled export at shallow depths, seasonal POC flux data from depth after diatom blooms and recent data from traps in the twilight zone by this PI suggest efficient POC transport to depth in association with diatom driven flux events (Buesseler et al., 2006a), so there can be high C export efficiency in both biogenic Si and carbonate dominated systems. Others contend that it is not ballast that controls POC flux per se, but that POC fluxes control the ballast content in deep sea fluxes (Passow, 2004; Passow and De La Roche, 2006). Changes in POC:PIC are also significant since the formation of carbonate in the surface water has an opposite effect on surface pCO_2 as the formation of POC, and thus the rain ratio of POC:PIC may have climatological significance (Archer and Maier-Reimer, 1994; Ridgwell, 2003; Feely et al., 2004).

In this proposal, we will examine phytoplankton community structure at BATS to look for linkages between the primary producers and C export. We will also examine changes in the morphology of sinking particles vs. time and depth, which tell us something about the source of sinking material and processing via the mesopelagic community (see **3b**). We will measure POC, PIC, bSi and lithogenic content to examine changes with time and depth in ballast minerals using our improved traps.

2d. Capturing spatial and temporal variability in sinking particles

Our assessment of the vertical rain of particulate C is limited by our inability to continuously and adequately sample a spatially heterogeneous rain of particles. The particle rain is both spatially complex and temporally episodic – reflecting the episodic nature of both food web and physical processes. Shown in Figure 7 are 5-day composite, multi-satellite merged chlorophyll images for a 4^o box in the BATS region spanning the year 2004 (BATS is 31.67^oN, 64.17^oW).

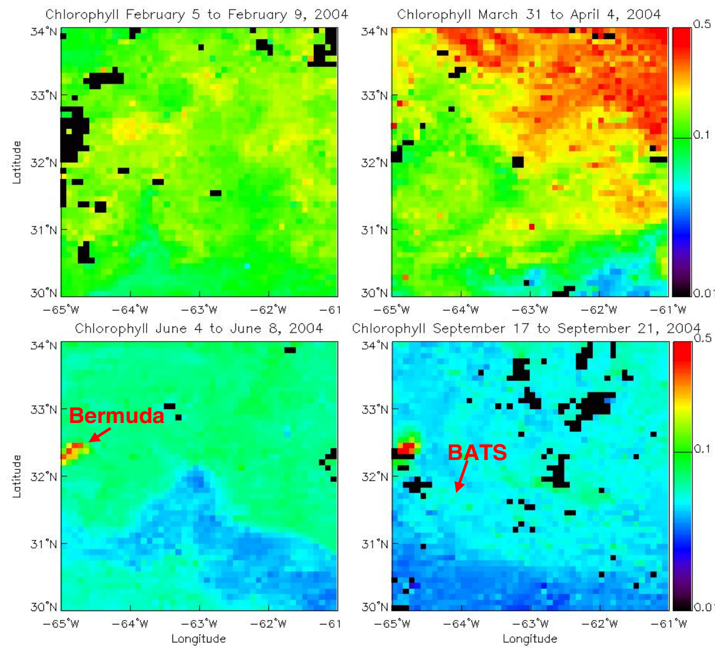

Figure 7 *– Five day composite chlorophyll images. Dates are centered on (upper left panel) Feb. 7, 2004, (upper right) Apr. 2, 2004, (lower left) June 6, 2004 and (lower right) Sep. 21, 2004. These are created by merging both SeaWiFS & MODIS-Aqua ocean color imagery following the procedures of Maritorena & Siegel [2005]. The merging procedure maximizes the coverage with a spatial resolution of 9 km^2. Black pixels are missing data (clouds) and a logarithmic color bar scale is used . Data available via on-going NASA supported projects at UCSB.*

Clearly, there are large (>2x) spatial gradients in the upper layer chlorophyll distribution (Chl) over scales of 20 to 100 km. Further, the relative scale of these spatial variations in Chl does not change dramatically throughout the year (the coefficient of variation of Chl within 50 km of BATS actually increases in the summer; figure not shown). Presumably, these spatial changes in Chl are manifest in export as modified by community structure (see **2b**). These data along with the modeling of net primary production (e.g., Siegel et al. 2001; Behrenfeld et al. 2005) provide useful remote proxies for assessing the importance of spatial inhomogeneities of C fixation.

The key element here is the relationship between the scales of phytoplankton patchiness and the particle source regions for the trap deployments. Recent analyses of the sampling characteristics of NBST during VERTIGO showed particle source regions (the locations from which trap collected particles have originated in the surface mixed layer) typically within 20 km of the mean location of the trap (Fields et al., 2006; Siegel et al. 2006). This modeling requires the determination of the 3-D current field through which the particles sink and an assessment of the mean sinking rate of collected particles. This sampling scale is smaller than typical spatial scales in the Chl distribution (Figure 7) suggesting that knowing the location of the trap may be sufficient for initial purposes. Improvements in the estimation of source funnel characteristics will be made using horizontal current data from the ship's ADCP system and available satellite altimeters.

Another attribute that might be expected in a complete and accurate record of mesopelagic particle flux is a more pulsed or episodic character to C flux. Deep traps for example use rotating cups to collect continuous 1-4 week records of particle flux, and in many sites most of the annual flux arrives in a single or few cups. This deep flux is often tied to short-lived surface ocean biological events that can be missed if sampling is only for short periods (3-5 day trapping periods) and during calm weather windows. In the upper ocean at BATS, there is evidence of pulsed export following rare salp blooms that consume particles and produce abundant and fast sinking pellets (Steinberg et al., 2000). Likewise, short-lived winter diatom blooms are thought to be an important cause of particulate export flux at this site (Brzezinski and Nelson, 1995). A recent study has documented that short-lived winter blooms of diatoms and other nano-eukaryotic phytoplankton result in significantly higher (2-3x) export production than observed at BATS during the same time of year (Lomas et al., 2006; Krause et al., 2006). It has also been postulated that it is not the POC, PIC or bSi flux ratios per se that determine export efficiency, but rather the pulsed nature of export, with more episodic events having greater shallow flux, but lower transport efficiency (higher F_{150} and higher b; Antia et al., 2001). It is therefore essential to capture these rare and episodic events, and we propose continuous sampling of upper ocean particle fluxes by stage 3 of this proposal, a feature that is unique to our effort.

Winter mixing of measurable macronutrients in to the surface layer has been thought to fuel the spring bloom at BATS. Balancing the drawdown in DIC (dissolved inorganic C), DOC, biological uptake and export of C has proven to be difficult, however, and this imbalance has been blamed on either problems associated with trapping, and/or on unquantified horizontal processes (Michaels et al., 1994). Also, large-scale indicators of annual new production are higher than measured fluxes by other methods (e.g. Jenkins and Doney, 2003), including standard traps, leading to the continued search for "missing" C flux. This has led in part to consideration of the impact of passing eddies on local biogeochemistry (McGillicuddy et al., 1998), and on the significance of nitrogen fixation to fuel new production at BATS (Hansell et al., 2004; Capone et al., 2005). We suggest that at least some of the mismatch between the new production estimates at BATS and difficulties in balancing the C budget might be explained by the mismatch in space and time in particle sampling, and large scale C and nutrient balances. With the application of remote sensing and collection via the TZEX of near continuous mesopelagic flux data, this proposal sets out to sample rare export events and place the particle rain rates in context of a spatially and temporally changing biological, physical and chemical environment.

3. PROPOSED WORK

We have divided this project into a series of overlapping engineering development and field stages, and have summarized below the four stages and details thereof. This is followed by experimental methods, project management and duties, a time line and data management plan.

Stage 1- Start regular monthly deployment for 18 months of existing NBSTs as part of BATS time-series. This will be the first long term NBST sampling program.

Details- NBSTs have now been shown to be a reliable and improved flux collector for sinking particles in the open ocean (Stanley et al., 2004; Buesseler et al., 2006a). In order to improve our estimates of the export flux at 150m at BATS, two of these devices will be deployed at 150m (for replication and in case of failure) along with the standard tethered PITS trap array as part of the BATS program starting in year 1 (BATS traps are at 150, 200 and 300m; see **Timeline**). This parallel deployment allows for direct comparison of flux over different physical and particle compositions and provides a tighter constraint on the flux below the euphotic zone throughout an annual cycle. It employs new but proven trapping technology to examine seasonal changes in flux for comparison to changes to BATS monthly estimates of primary and bacterial production, biological community structure, zooplankton biomass and water column properties such as DIC, DOC, POC and nutrients.

Stage 2- Design and test better swimmer avoidance mechanisms for deployment on an NBST.

Details- All shallow traps are plagued by considerable C and other associated elements being carried in to the traps by active zooplankton swimmers (Fig. 5). The rotating IRS ball is the most promising device to date used to exclude swimmers (Peterson et al., 1993), but it still needs to be further tested and optimized. Starting in year 1, using trap tubes attached to a separate frame on the BATS floating array, we will test new IRS designs and use simple in situ digital cameras to study the behavior of zooplankton within the trap (see **Timeline**). These first steps are important as while we have seen a 10-fold reduction in swimmer numbers in one test, there are still zooplankton getting below the IRS device and into the poisoned sample chamber/cup. Samples will be picked (at BBSR) and swimmers identified (at VIMS) to learn if specific species are excluded more efficiently by changing rotation time, speed (fast rotation might exclude swimmers better but resuspend low density aggregates), forward/reverse motion of the ball, etc. In situ cameras are needed to verify that we do not attract a local zooplankton community to the particles/food source on the ball and to look for particle resuspension. We have noted 25% lower POC fluxes in one test of IRS traps (Andrews et al. 2006). To see if this is related to zooplankton grazing or bacterial decomposition, we propose to compare multiple IRS devices with rotation cycles varying from continuous, to every 10, 30, or 60 minutes (lower rotation cycles will conserve valuable power in later applications) on one floating array. Variations in ball design have also proven to be critical (ball groves vs. dimples & seal/flange within tube) and testing of various designs is needed.

Part of Stage 2 will be adaptation of the best IRS design to a standard NBST tube to collect single samples on deployment for short periods (1-5 days) on standard BATS cruises (n=2 modified NBSTs to be used in Stage 4). The end result will be an optimized IRS device that excludes most swimmers, has low power consumption and has buoyancy attributes suitable for application on our time-series floats. The development of the IRS device also means that the sample cup with its included poison/brine goes in closed and comes back closed and free of zooplankton swimmers. As such by measuring total dissolved organic C in the supernatant before and after deployment, we will be able to test whether or not significant organic C losses from particles to overlying solution take place prior to separation of the particles via filtration (and similarly check Si for opal dissolution, pH and alkalinity for $CaCO_3$, etc.). This type of data is sorely lacking for upper ocean traps and is not possible to obtain using open tube designs.

Stage 3- Develop and deploy the Twilight Zone Explorer (TZEX- Figure 8) , a free vehicle with swimmer avoidance capabilities and a carousel for collecting multiple samples. Also included are on board sensors for profiling optical and particle properties, a strobe light, a GPS and communications abilities to relay data and commands to/from TZEX while at the surface.

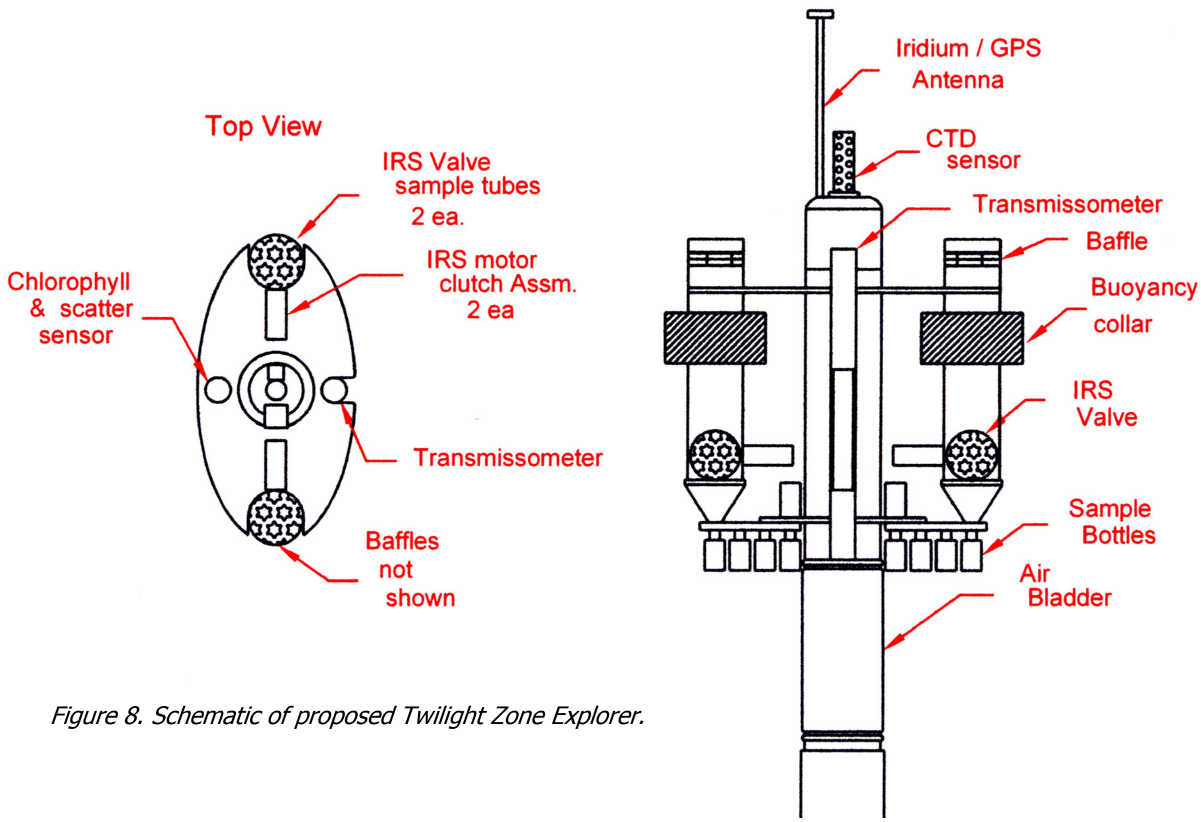

Figure 8. Schematic of proposed Twilight Zone Explorer.

Details- Continuous records of shallow particle flux are not available at this time, requiring at best, multiple short deployments with drifting traps. Since episodic events can dominate the particle export of C, we need to be able to collect time-series samples of flux throughout the twilight zone. Our objective is to deploy two free vehicles, or TZEX devices, each with the ability to collect sinking particles on a one week collection cycle (collection times are programmable for different missions), for 4 cycles per month. The TZEX is retrieved and returned to the BATS site (expect distances traveled are <50 - >150 miles based upon local current velocities and prior experience of trap and NBST drift), and samples are taken on shore for detailed geochemical and microscopic analyses. We intend to start in fall 2008 with the standard NBSTs and launch a 12 month continuous particle flux record at 150m (below the euphotic zone) and 300m (below the maximum extent of winter mixing). The TZEXs would have an on board CTD (salinity/temperature/depth) and be programmed to act as an isopycnal float, following the internal waves at the local density surface (to avoid rapid vertical motion that would bias capturing local settling particles).

There is no communication with the TZEX while submerged, so after each 1 week collection cycle, the float will be programmed to return to the surface, relaying its position and collecting on board sensor data during the up and down profiles. We are proposing to use commercially available sensors found on ocean moorings, floats and gliders to measure light transmission (small particle abundances), scattering (large particle fields) and fluorescence (Chl indicator; last 2 on WETlabs ECO Puck). When at the surface, data are transmitted to shore, including position information for spatial comparisons to remote sensing data and for planning retrieval of the float (2 ship days on average are budgeted as BATS add-on activity to collect and redeploy two TZEXs). Small changes to the mission (for example, abort for early retrieval or stay at depth longer to avoid storms) could be sent to the float at that time as well. The system would be flexible for other missions, but we have chosen a 4 samples/month cycle to reduce the offset in space between the TZEX trajectory and data being collected at BATS and to reduce steaming time necessary for float retrieval as well as to have sufficient on board battery power. The NBST and IRS mechanisms would have been tested in Stages I and II, and sample changing carousels will be built and tested (at a minimum, 4 sample cups and one open space are needed). To monitor and predict both particle source regions and changes in surface production, i.e. to answer the question of whether fluxes are changing due to regional productivity shifts, or for example passage of TZEX across fronts or eddies, we will rely on the satellite remote sensing observations led by UCSB to put our flux data into context of the regional data and longer term time-series program at BATS (see **2d** and attached letter from Dickey).

Stage 4- Three targeted one week cruises at BATS would be conducted to more fully quantify changing flux vs. depth patterns under differing seasonal conditions.

Details- We have shown during our current project VERTIGO (VERtical Transport in the Global Ocean) that the attenuation length scales vary dramatically between sites (Fig. 2c; Hawaii < NW Pacific), and for different elements (for example remineralization rates POC>bSi>PIC), but these were only snap shots in a changing particle source field and under differing mesopelagic conditions. While it would be informative to track more than one or two depths continuously, a first step would be to take one site, in this case BATS, and plan short cruises to measure flux vs. depth during different seasons (winter, spring, summer- years 3 & 4- see **Timeline**). Existing TZEX and NBST devices would be deployed during these cruises. This proposal would support the same basic flux vs. depth measurements as conducted on all of the other stage I, II and III cruises (see **3b**). Other PI's would be invited on board for studies of euphotic zone and mesopelagic processes. Putting traps at an expanded number of depths- 150, 300, 500, 800m, allows us to better define these attenuation length scales and make a more direct link to the deeper time-series records at moored traps at Bermuda as part of the Ocean Flux Program. Shorter cruises and provide sufficient sample material, and as we learned in VERTIGO, minimize chances for TZEXs and NBSTs at different depths to drift into differing particle source regions.

3b. Trap sample processing & analyses- all Stages

All trap samples will be processed according to procedures developed and tested during the current VERTIGO project. Briefly, trap samples (brine and particles) are gravity fed through a 350μm pore sized screen to remove large swimmers and then rinsed with prefiltered seawater, and subsequently wet split 8 ways (custom unit) for immediate processing for different analytical procedures (filtration on to quartz filters and drying for CHN; on to Ag filters for bSi; onto pre-weighed nucleopore filters for mass; onto quartz for HPLC pigments and storage in LN_2, preserved with additional formalin for microscopic analyses for small swimmers; etc.). All processing steps are conducted as soon as possible after collection, in this case at BBSR on shore labs and steps are either sealed from the atmosphere or conducted in a HEPA filtered clean air bench to avoid contamination. Both screens used to remove swimmers and a sample after splitting are viewed under a microscope at BBSR to pick out and quantify either detrital material caught inadvertently on the screen, or smaller mesozooplankton swimmers that pass through the screen (this step should be much easier/unnecessary after development of swimmer avoidance IRS). Processing of samples will focus on POC, PIC and bSi (WHOI lead). PON is obtained along with PC during CHN analyses as well. Inorganic carbon is determined by acidification of the sample with phosphoric acid and titration of CO_2 by the coulometric method with the UIC coulometric analyzer and acidification module. Biogenic Silica is determined by a modified alkali extraction method of (Eggimann et al., 1980). Measurements of HPLC derived phytoplankton pigments will be examined to link source changes in community structure with exported particles (BBSR lead), and one sample will be treated as an ID tube w/o screening or splitting for microscopic analyses and identification of major particle types (VIMS lead). Sample supernates will be analyzed to look at solubilization effects in the trap cup (WHOI lead). A closed tube is used as an analytical blank which we have found to be very useful in low flux settings such as expected here.

In addition to geochemical analyses, we will microscopically examine sediment trap material from the different deployments to compare the different trap designs and to investigate seasonal and episodic changes in flux of different particle classes at BATS. The number, size, shape, and color of fecal pellets will be counted and measured to determine the relative contribution of different zooplankton groups to flux. Different major taxa of zooplankton produce distinctive size and shape fecal pellets which Steinberg's group can distinguish (see Fig. 9). Color can also be indicative of food source (green for herbivorous feeding, red for carnivorous). The relative contribution of sinking phytoplankton aggregates (or other major recognizable particle classes such as larvacean houses) vs. zooplankton fecal pellets will be determined using the fecal pellet counts and volume to carbon conversions (e.g., Silver and Gowing 1991, Carroll et al. 1998, Urban-Rich et al. 1998). The fecal pellet C flux will then be compared to the total sinking flux to determine the relative importance of fecal pellets to flux (e.g. Bishop et al. 1977, Pilskaln and Honjo 1987, Silver and Gowing 1991; Carroll et al. 1998) and compared between the different trap designs and over time.

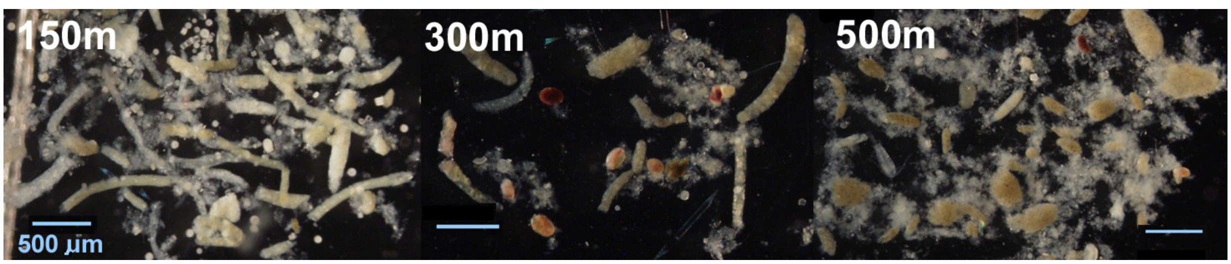

Figure 9. Example of changes in fecal pellets from sediment traps at three depths in the subarctic North Pacific (K2). Note the primarily cylindrical copepod pellets at 150 m, the red, carnivore-produced pellets at 300m, and the large, ellipsoid larvacean pellets at 500m. (Wilson, Steinberg, and Buesseler, in prep.)

3c. Remote sensing- satellites & particle source funnels

As outlined above (**2d**), we propose to combine remote sensing and numerical modeling to assess the role of time/space variability of export on the monthly inferences of C export. Merged ocean color imagery will be used to assess the time/space variability of Chl and net primary production (NPP) surrounding each deployment enabling us to assess the importance of episodic blooms. Estimates of source funnel distributions will be made for each deployment and compared with the measured trap fluxes. Our hypothesis is that fluctuations in trap fluxes above or below the mean seasonal cycle will be created by sampling in or out of regions of high export. At the start of the project, we will first reanalyze the BATS trap fluxes since late 1997 (when SeaWiFS ocean color imagery first became available) to investigate if a relationship exists between source region Chl or NPP and the measured fluxes. During the field campaigns, the UCSB group will reassess the sampling scales of the NBST and tethered traps deployed here (e.g., Siegel et al 2006). The UCSB group will also help in at-field sampling by forecasting where the deployed TZEX and NBST traps will go (Fields et al., 2006; Siegel et al., 2006).

4. TIMELINE AND MANAGEMENT PLAN

This is a complex proposal, with parallel efforts in engineering, sampling and analyses. A timeline has been provided to separate the four stages of this proposal as described above, including a breakdown by the various tasks for the groups assembled, with notes on the ship time needs and gross sample numbers that were used for budgeting analytical costs (see Timeline). The details of the 4 stages (above) provides a discussion of specific duties and the management plan below elaborates upon responsibilities and interactions between PI's. It should also be noted that the 5 PI's from WHOI, VIMS and UCSB have just completed a successful field project VERTIGO, and that all 3 of these groups have worked in the past out of BBSR and with Lomas to varying degrees individually. Thus we are confident that the team assembled has both scientific skills needed to complete this project, and has built over time the interpersonal relationships that should serve well in completing an involved engineering and labor intensive time-series effort such as proposed here.

Timeline of Field Activities and Workshops

	Y1 Sept-Feb	Y1 Mar-Aug	Y2 Sept-Feb	Y2 Mar-Aug	Y3 Sept-Feb	Y3 Mar-Aug	Y4 Sept-Feb	Y4 Mar-Aug	Y5 Sept-Feb	Y5 Mar-Aug
Stage 1 (NBSTs)		time-series								
Stage 2 (NBST-IRS)		development								
Stage 3 (TZEX)			development		time-series					
Stage 4 (Traps and Profiles)										
Trap Sample Nos.*	4	24	32	32	96	112	16	16		
WHOI-Valdes	IRS-PITs	IRS-PITs	IRS-TZEX	IRS-TZEX	support TZEX	support TZEX	support TZEX	support TZEX		
WHOI-Buesseler	IRS-PITs	IRS-PITs and NBST	TZEX & NBST	TZEX & NBST	TZEX & NBST	TZEX & cruise 1	TZEX & cruise 2	TZEX & cruise 3		
BBSR	timeshare tech.	timeshare tech.	timeshare tech.	timeshare tech.	timeshare tech.	timeshare tech.	timeshare tech.	timeshare tech.		
VIMS	lim. swim. analysis	trap ID work	trap ID work	trap ID work	trap ID work	trap ID work	trap ID work	trap ID work	trap ID work	
UCSB	sat. hist.	sat. hist.	sat. supp.	sat. supp.	sat. supp.	sat. supp.	sat. supp.	sat. supp.	sat. supp.	
Shipdays +BATS	no additional	no additional	no additional	2	12	12	2	none	none	none
Dedicated Cruise Days	none	none	none	none	none	7	7	7	none	none
Workshops					BBSR					WHOI

Table does not specify PI time for data interpretation, synthesis and manuscript preparation other than the 2 PI workshops.
*Trap Sample Nos. includes multiple devices at several depths and replicates. e.g., NBST time series include 2 devices deployed each month, 2 samples per device, hence 24 samples per half year. The TZEX time series includes 2 devices, 8 samples per month, giving 96 samples per half year.

Overall management of the proposal lies with the lead PI, Buesseler at WHOI. This includes project oversight, involvement in engineering and experimental design, participation in field campaigns, sample processing, analytical QC appropriate for time-series measurements, data interpretation, synthesis, presentation & publications. The engineer Valdes leads an independent group in a different Department at WHOI. He has primary responsibility for all in water gear as proposed, including the design, engineering and testing of new equipment that is central to the success of this proposal. It is clear that the engineering work is "front loaded", i.e. most of the supplies, design, assembly and testing comes early, though the engineer and his assistants will remain involved as needed throughout the proposal. Lamborg is a new geochemist at WHOI, and he currently manages the sample processing and analytical operations for the VERTIGO trapping program that ends in 2006. Collectively, the WHOI group will work on field deployment/retrieval steps, improvements to sample processing/methods at sea and in the lab, revise engineering designs, conduct new tests, and ultimately end up with a streamlined and reliable ocean going piece of sampling gear. The goal of this proposal is to enlist BBSR support (time share technicians, supervised by Lomas), to be trained in these procedures, so that the monthly deployment of NBSTs and TZEXs can be conducted without WHOI personnel participating on every cruise.

BBSR involvement is critical to this experiment for a number of reasons. First and foremost, the wealth of data provided by the BATS programs makes this an ideal location within which to launch new particle flux measurements (and these can be compared directly to traditional trap methods being conducted at BATS). Lomas is a PI on the BATS project, and his role in managing that effort and working our interests in to these cruises is invaluable to the success of this project. In addition, his biological background and expertise on the role of phytoplankton community structure in determining the fate of C, either as buildup in dissolved or loss via particulate pools, is a particularly important dimension to this effort.

We have enlisted the help of D. Steinberg (VIMS PI) in part because we need a zooplankton expert to assist in design questions and for examination of the zooplankton that are still caught in the IRS traps to see if there is a common species, size or behavioral trait that can be used to reduce these artifacts and improve IRS design. She also will play a lead role in understanding flux vs. depth variability by microscopic examination of the trap materials, including major plankton species that are caught and identifying the source of fecal pellets at depth (see Fig. 9).

The UCSB team (D. Siegel lead) is in charge of predicting particle source funnels, as described above. This begins with reanalyses of BATS trap fluxes, the spatial scales of particle collections, and the remotely sensed surface chlorophyll fields, and continues (and becomes more complicated) as we move to the longer time-series deployments. Of particular importance as the TZEX time-series begins, will be mapping changes in surface ocean chlorophyll, currents and fronts/eddies on weekly time scales, which are needed to related the two separate 150 and 300m TZEX flux records and on board sensor data to the regular monthly BATS work at a single site. In addition to the 150 and 300m particle source funnels, the collection ranges for the deeper moored OFP traps will also be evaluated to make the surface to deep connection between upper ocean, twilight zone and deep C fluxes.

The Timeline of activities also includes scheduled workshops after 2 1/2 years (coincident with the end of NBST time-series) and 4 1/2 years (end of field programs). While there will be more frequent meetings of PI's at BBSR and WHOI, we think it is wise to schedule and budget for specific small group gatherings of PI's, students, post docs and technical staff who have been actively working on this new time-series record.

5. DATA MANAGEMENT

One important task in any project, and in particular for time-series studies, is to commit early on to an organized data management plan and timely release of these unique flux data. The lead PI is committed to placing all results from this project in a common format, with supporting meta data on his own site (http://cafethorium.whoi.edu) and working with a public access site- either in coordination with BATS data management efforts or the Ocean Carbon Biogeochemistry data management office at WHOI (http://ocb.whoi.edu/). Each PI will be responsible for submittal of their own results, and we will use the workshops at the end of the NBST and TZEX deployments as mile stones for making data public in stages prior rather than waiting to the end of the project.

6. BROADER IMPACTS

By improving understanding of the carbon cycle in the mesopelagic twilight zone, this project will implicitly contribute to society's ability to anticipate the impacts of global climate change as well as formulate remediation strategies. Explicitly, we have initiated five activities that will maximize the educational and public outreach impact of our research. First, we have been in contact with Dr. Gerry Plumley (see attached letter) of the Bermuda Biological Station for Research, Inc., and will seek to make available berth space during our three 7-day cruises to high school, undergraduate and graduate students that make use of BBSR's educational programs. The PI's of this proposal will eagerly participate in these activities as time permits during the cruises. Secondly, have also been in contact with the WHOI Media Relations Office regarding our projected berth availability and will seek to accommodate journalists interested in covering the "climate beat" to invite them on board, as done during VERTIGO (http://www.csmonitor.com/2004/0212/p14s01-sten.html). Thirdly, we are also fortunate to have WHOI internal funds ($5K) to support participation of an undergraduate summer student fellow on one of the summer research cruises and take part in pre/post cruise analyses. There will also be graduate student involvement in this project (at least VIMS & WHOI). Finally, in accord with other broader impact interests of NSF, we re-emphasize here the significant instrumentation development and application component of our proposed research, and contend that this TZEX development will bear significant fruit for many researchers for years to come.

7. RESULTS OF PRIOR WORK

Ken Buesseler has received NSF support since 1987. This research has included the use of artificial and natural radionuclides as well as traps, to study the marine particle cycle. Of particular relevance is the current project entitled "VERtical Transport In the Global Ocean" (VERTIGO; OCE-9912044) with KOB as lead PI. VERTIGO brought NBSTs and a multi-disciplinary group of scientists on two three week process study cruises at two contrasting flux sites (Hawaii-2004 & NW Pacific-2005) to examine controls on the efficiency of particle export. 18 VERTIGO talks and posters were presented at 2006 Ocean Sciences (copies can be found at http://cafethorium.whoi.edu). A final PI meeting and joint publication of a DSRII special issue are planned for Sept. 2006. The results of VERTIGO are used to argue for engineering improvements proposed here and the application of NBSTs in a continuous time-series mode.

Carl Lamborg is currently completing his first NSF funded project as a PI (OCE-0454148). This research focused on the analysis of minor and trace element components in sinking and suspended oceanic particles collected during VERTIGO, which included the ultraclean collection and handling of sediment trap samples and the analysis of lithogenic fractions of particles. This project has resulted in 5 papers in various stages of completion (including 2 in press) and findings have been shared at 3 major conferences in the form of 6 posters and 2 oral presentations. He has also been a participant in the recent VERTIGO workshop.

James Valdes has provided engineering services to a number of NSF funded PI's for more than 20 years. Most recently (2002) he was a Co-PI on the NSF funded project; A Submersible Autonomous Launch Platform (SALP: OCE-0136255), responsible for the design, fabrication, and deployment of the PopUP drifters. He is also a Co-PI on VERTIGO (OCE-9912044) responsible for most of the over the side instrumentation developed at WHOI (see Buesseler).

Michael Lomas has received NSF support since 1999. This research has included the use of stable isotopes to study the physiological ecology of marine phytoplankton. Particularly relevant to this proposal is the BATS program (currently funded through July 2008) on which MWL is a co-PI. Relevant objectives of this project are: 1) to document seasonal to decadal scale variability in carbon (C) and nutrient cycles, and biological community structure; 2) to document the role of physical, atmospheric, and climate forcing on biological community structure and function; and 3) to validate and test new oceanographic tools, technologies, hypotheses and paradigms. During this current award cycle, Lomas has been first author on three publications acknowledging this award and two additional manuscripts with Lomas as an author are in review and four are in preparation.

Deborah Steinberg has received NSF support since 1997. Her research has focused on the role of zooplankton in biogeochemical cycling and marine snow/particle dynamics. Highly relevant to this proposal are the JGOFS Bermuda Atlantic Time-series Study (BATS) (OCE-9801950), and VERTIGO. Steinberg's research at BATS focused on the role of zooplankton in vertical transport of C and nutrients to the deep sea, and on particle flux. This grant resulted in 11 peer-reviewed papers plus 31 published abstracts with Steinberg as author, one PhD dissertation, and supported four NSF REU students. In VERTIGO (OCE-0324402), Steinberg is determining how zooplankton affect the efficiency of particle export by comparing the metabolic carbon demand of mesopelagic zooplankton with the loss of sinking POC with depth. Her group is also analyzing sediment trap material and finds changes in sinking particle classes (fecal pellets) with depth that indicate zooplankton repackaging of sinking POC in the mesopelagic zone.

David Siegel has received NSF support since 1991. His research investigates the interactions among physical, biological, biogeochemical and optical oceanographic processes. Along with Buesseler, Valdes and Steinberg he is a co-PI on the VERTIGO project (OCE-0327318). He is also PI of the Bermuda BioOptics Program (BBOP) which has been collecting optical profile and inherent optical property data in collaboration with the BATS program since 1992. Initial support for BBOP came from NSF (OCE 9116372) and it is now supported by NASA (Norman Nelson is now lead-PI). BBOP has resulted in nearly 40 refereed journal publications, 3 PhD dissertations and 4 MS theses.

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