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Preface

Introduction to "Understanding the Ocean's biological pump: Results from VERTIGO"

"There is a 5th dimension beyond that which is known to man
It is the middle ground between light and shadow
It is an area, which we call, the Twilight Zone"
Rod Serling

Unknown and unexplained aspects of the human condition were the focus of a television series in the USA created by Rod Serling in the early 1960s. The term "the twilight zone" used in his show is even more pertinent to the mysterious region between 100 and 1000 m in the great oceans of the world, the "middle ground between light and shadow". It is here where the sunlight at the ocean surface is finally extinguished and replaced by occasional flashes of biological light. This mesopelagic zone, as it is more formally called, is a region of immense change with depth and it is here that most of the biogenic material that settles out of the sunlit or euphotic zone is broken down and returned to the dissolved state. The gravitational downward flux of particles thus decreases with depth in general, and the animals that traverse this great depth, some each and every day, exert a powerful influence on the distribution of many types of materials. The extent of mixing also declines dramatically with depth, such that the water at 1000 m is isolated from the atmosphere for many decades to centuries, and this has great significance when considering the influence of the oceans on the overlying atmosphere.

Just imagine if particles in the oceans did not sink. Advection and diffusion would be the only form of material transport. Except in regions of downwelling, particles and particle-reactive compounds would remain within the winter mixed layer until they were eventually removed via slow diffusive processes. There would also be no sediment accumulation (no paleoceanography and only hard rock geology!). Inputs of contaminants to surface-ocean waters would lead directly to their build up in concentration, as removal via physical dilution and mixing would take many centuries.

Now imagine an ocean where we know there are sinking particles, but we just cannot accurately quantify their sinking rates, composition or downward flux. Deep-sea sediments are the ultimate sediment trap, so we would know from cores and bottom photographs that there were spatial and temporal changes in sedimentation. In the upper 1000 m, we would struggle to understand to what degree particles leaving the surface escape remineralization and how fast they travel to depth. This would leave us at a loss to understand with any confidence the processes that control material export from the upper ocean and the effect of this on surface biogeochemistry and air–sea exchange. Without compositional information, linking surface processes to deep sediments becomes a guessing game and the "twilight zone" remains a black box.

This dramatic scenario illustrates and exaggerates why it is so important to be able to quantify and characterize with confidence particle fluxes and processes in the twilight zone. Since particulate fluxes of carbon link atmospheric CO_2 to the ocean interior where C can be sequestered for longer time scales, it is also important to understand one of the key linkages that regulates Earth's C balance among its various reservoirs.

But this volume is about much more than simply quantifying downward particle fluxes in the twilight zone. It addresses a wide range of topics associated with this flux including the production of organic matter by organisms in surface water, the formation and shallow mixing of dissolved organic matter and finally the transport of material both as sinking particles and via active vertical migration of zooplankton. The strength and efficiency of this so called biological pump is important in determining the oceanographic distribution of organisms, for the supply of energy to subsurface heterotrophic ecosystems, in setting the vertical and basin-scale distributions of many elements and for the balance of carbon dioxide and other gases between the atmosphere and the ocean. As just one example, if the biological pump were somehow shut-off, atmospheric CO_2 levels would increase by around 200 ppmv (Parekh et al., 2006; Sarmiento and Toggweiler, 1984).

The papers in this volume all came out of the VERtical Transport In the Global Ocean (VERTIGO) program, a multidisciplinary and international study that set out to answer the question: what controls the efficiency of particle transport between the surface and deep ocean?

The null hypothesis is that remineralization rates do not change in response to either changes in particle source characteristics or mid-water processing. This would result in a single particle flux vs. depth pattern. One of the pioneering studies of particle transport through the twilight zone was the VERtical Transport and EXchange (VERTEX) program. This study used particle interceptor traps (PITS) suspended from a drifting surface float to measure downward particle flux giving rise to the "Martin" curve: $F = F_{100}(z/100)^{-b}$, where F is the particle flux at depth, F_{100}, the flux at 100 m, z is the depth in meters and b is the empirically determined exponent that best fits the flux data (Martin et al., 1987). For particulate organic carbon (POC), they found $F = 1.53(z/100)^{-0.858}$ in units of $\mathrm{mol\,m^{-2}\,yr^{-1}}$. This parameterization of flux vs. depth has been used extensively, such as when predicting deep ocean flux based on surface primary production (Berger et al., 1988; Lampitt and Antia, 1997;

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Pace et al., 1987) and for example in global 3-D models of the ocean carbon cycle (Doney et al., 2004).

Variations in *b* are not uncommon, even in the original VERTEX data set (*b* ranges from −0.32 to −0.97 Martin et al., 1987) and as seen in analyses of larger deep sediment trap data sets (Berelson, 2001; Francois et al., 2002; Lutz et al., 2002); thus, alternatives to the null hypothesis should be explored in more detail. Two alternative hypotheses that were explored in VERTIGO and are highlighted in this volume are that: (1) particle source characteristics are the dominant export control, and/or that (2) mid-water processing, either by zooplankton and/or bacteria, controls the amount of sinking material that reaches the deep sea.

VERTIGO was designed around two process studies at contrasting sites in the North Pacific. Each study occupied a single site for 3 weeks in order to capture any processes going on in the surface euphotic zone that might take several days to see as an export response at depth. To place these single cruises in context of the annual cycle, time-series sites were chosen where more information was known about the seasonal progression of upper-ocean food-webs and changing biogeochemistry before and after these occupations. Data collected during VERTIGO on the physical setting was used to determine 3-D trajectories of particles as they sink at different rates into different sediment trap types (Siegel et al., 2007).

The sites chosen were station ALOHA, off Hawaii, an oligotrophic time-series site for the US Hawaii Ocean Time series (HOT) program (Karl et al., 1996) and the K2 site in the NW Pacific, where a Japanese mooring and seasonal occupations have documented large shifts in the magnitude and character of surface water production and deep ocean export fluxes (Honda et al., 2006). The regional, seasonal and flux characteristics of these sites are described in an overview paper by Buesseler et al. (2008) in this volume. A primary finding of VERTIGO is that the efficiencies of particle transport to depth, or the "*b*" value for the particle flux curves, vary quite dramatically between the two sites (Buesseler et al., 2007). K2 is characterized by a surface ecosystem dominated by large diatoms that bloom seasonally in this colder and more nutrient-rich setting, and by larger and considerably more abundant zooplankton.

The details of the elemental fluxes are provided in two papers by Lamborg et al. (2008a, b) in this issue. These address the major biogenic fluxes of POC, PON, opal and carbonate, and also trace constituents, such as Fe, Al and Mn. VERTIGO included the deployment of new flux collectors, the neutrally buoyant sediment trap (NBST) with multiple instruments operating independently at the same and different depths. The manuscripts by Lamborg et al. (2008a, b) document the variability in flux between these devices, studies of differences in sample preservation protocols and variations in attenuation between elements that are characteristic of each site. While all elemental fluxes attenuate more quickly at ALOHA than K2, at K2 there is a dramatic difference in the behavior of POC and the major bioelements, which are attenuated by 50% between 150 and 500 m, and some trace metals such as Fe and Mn, whose fluxes actually increase with depth. This contrasting behavior is explored in the context of another VERTIGO publication on the lateral source of suspended particulate Fe and Mn from coastal margins at K2 (Lam and Bishop, 2008), and how these suspended layers of fine particulates may "feed" the mid water zooplankton particle packagers at K2.

Surface ocean algal studies defined the particle sources at both K2 and ALOHA, and rates of primary and new production were carefully evaluated and coupled to the subsurface export responses in manuscripts by both Boyd et al. (2008) and Elskens et al. (2008). The high fraction of C uptake by the larger diatoms at K2 was evident from these studies, and a shift from higher to lower rates of production was seen during the two trap deployment periods at K2, in contrast to more steady rates at ALOHA. Using a size fractionated algal foodweb model, Boyd et al. demonstrated a strong surface–subsurface coupling and the work suggests that phytoplankton productivity and floristics play a key role in setting export flux at K2. Elskens et al. focused on N cycling at K2, and they documented a considerable remineralization above the shallowest trap at 150 m. Zhang et al. (2008) focused their attention on the smaller picoplankton community, and extended their work beyond K2, to the structure and depth distributions of picoplankton across different Pacific provinces. From this comparison they concluded that picoplankton were both an important source of new organic carbon for higher trophic level organisms and a source for detritus production, especially in the oligotrophic subtropical gyre.

In addition to the study of algal communities, VERTIGO spent a considerable effort to characterize the zooplankton community from the surface down to 1000 m, as documented in this volume by Steinberg et al. (2008a), Wilson et al. (2008), Kobari et al. (2008). Steinberg et al. (2008b) already have shown how the active transport of C by seasonal and diel zooplankton migrators was needed to meet the metabolic demands of bacteria and zooplankton consumers in the twilight zone at both ALOHA and K2. In this volume, Steinberg et al. compare differences in the vertical structure and size distribution of zooplankton communities. These zooplankton are both larger in size and 10 times higher in biomass at K2 relative to ALOHA. This fits with the studies of zooplankton fecal pellets as presented by Wilson et al. who found both larger and more abundant pellets at K2 than at ALOHA. Furthermore, changes in the types of fecal pellets with depth provides evidence of mid-water repackaging of sinking particles and carnivory. Kobari et al. focused on the seasonal vertically migrating copepods at K2, which play a key role in C consumption and transport from surface to depth. Taken together these studies suggest that zooplankton play several important roles in the twilight zone not only as surface particle producers but also as consumers, repackagers and active transporters of material from the surface to mesopelagic depths.

Sources of nitrogen fueling particle export were examined at station ALOHA by Casciotti et al. (2008) through a nitrogen isotope mass balance approach. They found that the flux of nitrate into the euphotic zone is much closer in $\delta^{15}N$ to the sinking particle flux than previously assumed. These results led to the conclusion that while N_2 fixation is required to explain the isotopic data on multi-year timescales, it is less important than previously thought in fueling the instantaneous transport of N to depth in this setting. Dehairs et al. (2008) used excess particulate barium, as a proxy for flux and remineralization. More excess particulate Ba and higher bacterial production at depth demonstrated that more material was exported from the upper layers at K2 for remineralization at depths between 50 and 500 m.

In addition to new sediment traps to measure flux, Trull et al. (2008) describe results using a settling velocity trap, developed by Peterson et al. (2005), which acts as an in situ settling column to collect material in different collecting vessels on the basis of the sinking rates of the particles. Sinking rate is a key parameter in any study of particle flux, as the time spent traversing the mesopelagic affects the time available for degradation of the material and hence the degree of remineralization. That work suggests that at both sites greater than 50% of the material sinks faster than 100 m per day, leaving open questions about why particles at K2 that are larger and probably more dense appear to have similar sinking velocities as the material at ALOHA.

Taken together, these papers present a new look at the mysteries of the twilight zone. Other publications outside of this volume on the suspended particle distribution and water column optical properties (Bishop and Wood, 2008) also shed light on suspended and sinking particle interactions as observed by VERTIGO scientists. Work will continue on existing samples and interpretation of these results. It is clear that no single geochemical characteristic or biological process determines the magnitude of export and transfer efficiency to the deep sea, but that regional differences are larger than parameterized by a single attenuation factor for C and this differs between elements. Biological process are key in the production of particles and in the processes that attenuate and alter fluxes. So future studies of the twilight zone will require both biological and geochemical perspectives, as well as a knowledge of the physical setting and particle source regions.

Finally as a lasting legacy beyond VERTIGO, all data in these manuscripts and VERTIGO cruises are provided in an open database hosted by the US OCB program (http://www.us-ocb.org/data/index.html), so that future scientists will have immediate access to these unique results and may build upon this more readily. As acknowledged in each manuscript, support for these studies came from many different national programs, led by the US National Science Foundation programs in Chemical and Biological Oceanography with contributions from the US Department of Energy. We are grateful for NSF's support in providing the seagoing platform for operations and the ability to coordinate the many efforts within this program. We consider the broader international support and participation in VERTIGO to also be an important factor in the success of this program.

There is still much to learn about the twilight zone, and we believe this collection of papers makes significant progress towards unraveling some of its mysteries.

References

Berelson, W.M., 2001. The flux of particulate organic carbon into the ocean interior: a comparison of four US JGOFS regional studies. Oceanography 14 (4), 59–67.

Berger, W.H., Fischer, K., Lai, C., Wu, G., 1988. Ocean carbon flux: global maps of primary production and export production. In: Agegian, C.R. (Ed.), Biogeochemical Cycling and Fluxes Between the Deep Euphotic Zone and Other Oceanic Realms, pp. 131–176.

Bishop, J.K.B., Wood, T.J., 2008. Particulate matter chemistry and dynamics in the twilight zone at VERTIGO ALOHA and K2 sites. Deep-Sea Research I (submitted).

Boyd, P.W., Gall, M.P., Silver, M.W., JLKB, B., 2008. Quantifying the surface-subsurface biogeochemical coupling during the VERTIGO ALOHA and K2 studies. Deep-Sea Research II, this issue [doi:10.1016/j.dsr2.2008.04.010].

Buesseler, K.O., Lamborg, C.H., Boyd, P.W., Lam, P.J., Trull, T.W., Bidigare, R.R., Bishop, J.K.B., Casciotti, K.L., Dehairs, F., Elskens, M., Honda, M., Karl, D.M., Siegel, D.A., Silver, M.W., Steinberg, D.K., Valdes, J., Van Mooy, B., Wilson, S., 2007. Revisiting carbon flux through the ocean's twilight zone. Science 316, 567–570.

Buesseler, K.O., Trull, T.W., Steinberg, D.K., Silver, M.W., Siegel, D.A., Saitoh, S.-I., Lamborg, C.H., Lam, P.J., Karl, D.M., Jiao, N.Z., Honda, M.C., Elskens, M., Dehairs, F., Brown, S.L., Boyd, P.W., Bishop, J.K.B., Bidigare, R.R., 2008. VERTIGO (VERtical transport in the global ocean): a study of particle sources and flux attenuation in the North Pacific. Deep-Sea Research II, this issue [doi:10.1016/j.dsr2.2008.04.024].

Casciotti, K.L., Glover, D., Trull, T., Davies, D., 2008. Constraints on nitrogen cycling at the subtropical North Pacific station ALOHA from isotopic measurements of nitrate and particulate nitrogen. Deep-Sea Research II, this issue [doi:10.1016/j.dsr2.2008.04.017].

Dehairs, F., Jacquet, S., Savoye, N., Van Mooy, B.A.S., Buesseler, K., Bishop, J.K., Lamborg, C., Elskens, M., Baeyens, W., Boyd, P., Casciotti, K.L., Monnin, C., 2008. Barium in twilight zone suspended matter as a proxy for particulate organic carbon remineralization: results for the North Pacific. Deep-Sea Research II, this issue [doi:10.1016/j.dsr2.2008.04.020].

Doney, S.C., Lindsay, K., Caldeira, K., Campin, J.M., Drange, H., Dutay, J.C., Follows, M., Gao, Y., Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., Madec, G., Maier-Reimer, E., Marshall, J.C., Matear, R.J., Monfray, P., Mouchet, A., Najjar, R., Orr, J.C., Plattner, G.K., Sarmiento, J., Schlitzer, R., Slater, R., Totterdell, I.J., Weirig, M.F., Yamanaka, Y., Yool, A., 2004. Evaluating global ocean carbon models: the importance of realistic physics. Global Biogeochemical Cycles 18 (3).

Elskens, M., Baeyens, W., Boyd, P., Buesseler, K., Dehairs, F., Savoye, N., Van Mooy, B., 2008. Primary, new and export production in the NW Pacific Subarctic Gyre during the VERTIGO K2 experiments. Deep-Sea Research II, this issue [doi:10.1016/j.dsr2.2008.04.013].

Francois, R., Honjo, S., Krishfield, R., Manganini, S., 2002. Factors controlling the flux of organic carbon to the bathypelagic zone of the ocean. Global Biogechemical Cycles 16 (4), 1087.

Honda, M.C., Kawakama, H., Sasaoka, K., Watanabe, S., Dickey, T., 2006. Quick transport of primary produced organic carbon in the ocean interior. Geophysical Research Letters 33, L16603.

Karl, D.M., Christian, J.R., Dore, J.E., Hebel, D.V., Letelier, R.M., Tupas, L.M., Winn, C.D., 1996. Seasonal and interannual variability in primary production and particle flux at station ALOHA. Deep-Sea Research II 43 (2–3), 539–568.

Kobari, T., Steinberg, D.K., Ueda, A., Tsuda, A., Silver, M.W., Kitamura, M., 2008. Impacts of ontogenetically migrating copepods on downward carbon flux in the western subarctic Pacific Ocean. Deep-Sea Research II, this issue [doi:10.1016/j.dsr2.2008.04.016].

Lam, P.J., Bishop, J.K.B., 2008. The continental margin is a key source of iron to the HNLC North Pacific Ocean. Geophysical Research Letters 35, L07608 [doi:10.1029/2008GL033294].

Lamborg, C.H., Buesseler, K.O., Lam, P.J., 2008a. Sinking fluxes of minor and trace elements in the North Pacific Ocean measured during the VERTIGO program. Deep-Sea Research II, this issue [doi:10.1016/j.dsr2.2008.04.012].

Lamborg, C.H., Buesseler, K.O., Valdes, J., Bertrand, C.H., Bidigare, R., Manganini, S., Pike, S., Steinberg, D., Trull, T., Wilson, S., 2008b. The flux of bio- and lithogenic material associated with sinking particles in the mesopelagic "twilight zone" of the Northwest and North Central Pacific Ocean. Deep-Sea Research II, this issue [doi:10.1016/j.dsr2.2008.04.011].

Lampitt, R.S., Antia, A.N., 1997. Particle flux in deep seas: regional characteristics and temporal variability. Deep Sea Research Part 1 44 (8), 1377–1403.

Lutz, M., Dunbar, R., Caldeira, K., 2002. Regional variability in the vertical flux of particulate organic carbon in the ocean interior. Global Biogeochemical Cycles 16 (3), 10.1029/2000GB001383.

Martin, J.H., Knauer, G.A., Karl, D.M., Broenkow, W.W., 1987. VERTEX: Carbon cycling in the northeast Pacific. Deep-Sea Research A 34 (2), 267–285.

Pace, M.L., Knauer, G.A., Karl, D.M., Martin, J.H., 1987. Primary production, new production and vertical flux in the eastern Pacific Ocean. Nature 325, 803–804.

Parekh, P., Dutkiewicz, S., Follows, M., Ito, T., 2006. Atmospheric carbon dioxide in a less dusty world. Geophysical Research Letters 33, L03610.

Peterson, M.L., Wakeham, S.G., Lee, C., Askea, M.A., Miquel, J.-C., 2005. Novel techniques for collection of sinking particles in the ocean and determining their settling rates. Limnology and Oceanography: Methods 3, 520–532.

Sarmiento, J.L., Toggweiler, J.R., 1984. A new model for the role of the oceans in determining atmospheric pCO_2. Nature 308, 620–624.

Siegel, D.A., Fields, E., Buesseler, K.O., 2007. A bottom-up view of the biological pump: modeling statistical funnels above ocean sediment traps. Deep-Sea Research Part 1 55 (1), 108–127.

Steinberg, D.K., Cope, J.S., Wilson, S.E., Kobari, T., 2008a. A comparison of mesopelagic mesozooplankton community structure in the subtropical and subarctic North Pacific Ocean. Deep-Sea Research II, this issue [doi:10.1016/j.dsr2.2008.04.025].

Steinberg, D.K., Van Mooy, B.A.S., Buesseler, K.O., Boyd, P.W., Kobari, T., Karl, D.M., 2008b. Bacterial vs. zooplankton control of sinking particle flux in the ocean's twilight zone. Limnology and Oceanography 53 (4), 1327–1338.

Trull, T., Buesseler, K., Bray, S., Moy, C., Ebersbach, F., Lamborg, C., Pike, S., Manganini, S., 2008. In-situ measurement of mesopelagic particle sinking rates and the control of carbon transfer to the ocean interior during the vertical flux in the global ocean (VERTIGO) voyages in the north pacific. Deep-Sea Research II, this issue [doi:10.1016/j.dsr2.2008.04.021].

Wilson, S.E., Steinberg, D.K., Buesseler, K.O., 2008. Changes in fecal pellet characteristics with depth as indicators of zooplankton repackaging of particles in the mesopelagic zone of the subtropical and subarctic North Pacific Ocean. Deep-Sea Research II, this issue [doi:10.1016/j.dsr2.2008.04.019].

Zhang, Y., Jiao, N.Z., Hong, N., 2008. Comparative study of picoplankton biomass and community structure in different provinces from subarctic to subtropical oceans. Deep-Sea Research II, this issue [doi:10.1016/j.dsr2.2008.04.014].

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