

## **Abstracts of Invited talks**

### **Are we observationally ready to quantify the impact of the submesoscale?**

**Allen, John T., A. Martin, E. Popova, P. Statham, J. Kaiser, M. Piggott and T. Rippeth**  
**National Oceanography Centre, Southampton, United Kingdom**

Baroclinic instability is the open ocean mechanism through which available potential energy is released. High resolution modelling studies have indicated that dynamic small scale flows associated with oceanic fronts and eddies are a dominant component of this mechanism for the observed patchiness of marine algae (phytoplankton) blooms. High resolution observations have shown that sub-mesoscale flows (~5-20 km scale) may provide both the fertilisation mechanism for nutrient depleted surface waters and a subduction mechanism for the rapid export of phytoplankton biomass to the deep ocean. We present a multidisciplinary analysis of the data from an example of these studies in which we have the first direct observations of the sub-mesoscale transport of phytoplankton. These data confirm this transport is constrained by the requirement to conserve angular momentum, expressed in a stratified water column as the conservation of potential vorticity.

Understanding the basin scale impact of these small scale processes presents our biggest observational challenge. We present a consideration of the processes behind Munk's recipes and show that theory, models and observations suggest traditional mixed layer depth nutrient budget estimates for open ocean new production may be out by a factor of 2. We highlight how a historic perception of the thermohaline circulation has led to a systematic misunderstanding of the annual supply of new nutrients to the photic zone of the open ocean. Finally we consider an international programme to exploit new observational capabilities. We investigate how the analysis of the distribution of naturally occurring radionuclides, the deployments of fleets of autonomous gliders, swath altimetry, radical new data analyses and simulation techniques and the advancement of adaptive grid models will all play an important role in future observational programmes to quantify the dynamic component of the biological carbon pump.

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### **The Canary Islands CTZ region: Ecosystem response to the interplay between upwelling filaments, eddies and island wakes.**

**Arístegui, Javier<sup>1</sup>, Eric D. Barton<sup>2</sup>, Pablo Sangrà<sup>1</sup>, Evan Mason<sup>1</sup>**

<sup>1</sup>*Facultad de Ciencias del Mar, Universidad de Las Palmas de Gran Canaria, Spain*

<sup>2</sup>*Instituto de Investigaciones Marinas de Vigo, CSIC, Spain*

The Canaries-Coastal Transition Zone (CTZ) spans a region of high mesoscale and submesoscale activity between the NW African coast and the open ocean waters of the subtropical gyre. Wind and current shear at the flanks of the islands produce convergence and divergence fronts, which increase primary productivity and affect plankton distribution. Downstream of the islands, mesoscale eddies are generated by a combined mechanism of flow perturbation and Ekman pumping. Counter-paired eddies act as a two-way biological pump accelerating the production and transport of organic matter in the water column. Overall, the eddy field south of the islands contributes per surface unit as much as the nearby coastal upwelling to new production in the region, enhancing the sinking carbon flux with respect to far-field stations. Eddies may interact with coastal upwelling filaments exchanging water and biological properties. In situ and remote sensing observations have revealed a permanent zonal "eddy corridor" that may behave as a recurrent offshore pump of organic matter from the coastal upwelling to the subtropical gyre. High-spatial resolution observations at boundary regions between filaments and eddies indicate that convergence fronts favour the accumulation and sinking of small particles to higher density layers in the dark ocean, where organic matter accumulates. Suspended particles may be transported offshore in intermediate layers contributing more than the sinking flux to the remineralization rates in the dark ocean. Recent modelling studies suggest that submesoscale transient fronts with strong vertical velocities are widespread and could largely contribute to the productivity and carbon fluxes in the CTZ region

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**Upper ocean submesoscale frontal turbulence: manifestation, processes and effects.**  
**Capet, Xavier. LPO, Brest, France**

Horizontal resolution for regional-scale observation campaigns and model solutions now routinely reaches down to  $O(1\text{ km})$ . This has led to ample evidences that the near-surface flow is energized at scales around 5km (i.e. within the submesoscale range) in conjunction with increased thermohaline frontal activity. On the other hand, submesoscale frontal activity manifests itself in various ways and can be difficult to quantify (e.g. using spectral methods). In this talk, some aspects of submesoscale turbulence are reviewed: its manifestations in the ocean, underlying processes, role for the larger scale ocean functioning and remaining open issues. To connect with ocean biogeochemistry, particular emphasis is put on tracer fluxes driven by submesoscale turbulence.

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**Competitive dynamics of phytoplankton: from calm to turbulent waters.**  
**Cermeño, Pedro. Universidad de Vigo, Spain**

Ocean physics strongly influences the distribution of marine planktonic microbes, yet the specific mechanisms involved are not fully understood. In this presentation I will first review concepts and empirical evidence linking phytoplankton functional groups to upper ocean physical structures. Then, I will present results of competition experiments between two species of marine phytoplankton, a diatom and a coccolithophore, growing in continuous culture systems with nitrate as a single limiting nutrient. These experiments, simulating the response of primary producers to variable nutrient inputs, demonstrate how the dynamics of nutrient injection select for specific phytoplankton taxa. Assessing the importance of mesoscale and submesoscale physical processes in delaying, diverting or resetting phytoplankton succession in the ocean requires a better understanding of how phytoplankton communities respond to variable resource supply and implies the need for experimental approaches and modelling analyses at high spatial resolution.

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**High resolution remote sensing synergy in studies of mesoscale and submesoscale dynamics**  
**Chapron, Bertrand. LOS, Brest, France**

Ubiquitous surface signatures are revealed by high resolution remote sensing measurements such as data from high resolution optical, infrared and radar images. Today, satellite altimetry data cannot resolve small scales, and such a wealth of information is very difficult to fully interpret and use. Despite the importance of upper ocean dynamics, many aspects at scales smaller than 20km are thus still unknown.

To address this issue, recent efforts are directed on the synergy using the different available surface measurements. Especially, it will be discussed analysis to efficiently combine the lower resolution altimeter data with sequences and snapshots of higher resolution images. In such a context, we will present recent developments to help identification of the upper ocean small scales by an approach combining remote sensing low and high resolution products, realistic high-resolution modelling and theory/idealized models.

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**Modelling Diverse Marine Ecosystems: How does resolution matter?**

**Clayton, Sophie. Department of Earth, Atmospheric and Planetary Sciences, MIT, and, Physical Oceanography Dept, WHOI**

Small scale physical processes in the ocean are known to be important for primary production but are not typically resolved in global ocean models. Recent studies comparing highly idealized models run at differing resolutions, from large- to meso- to submeso-scales, show that increasing resolution can have a dramatic effect on rates of production and biomass for simple NPZ type models. However very few of these studies have sought to explore the effect on community structure. In this study we compare the output from a global ocean model with a diverse plankton ecosystem, run at both 10 and 1/60 (eddy-permitting) resolution. Where previous studies have concentrated on the effect of resolution on bulk ecosystem properties such as biomass and primary production and export rates, we explore how the structure of the ecosystem is affected by changes in model resolution. We find that although the regional bulk biogeochemical properties of the models are quite different,

when globally integrated they are very similar. The modelled plankton ecosystem is robust between runs with only small changes in diversity and rank abundance of modeled plankton types.

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### **Observations of submesoscale flows and their effects on productivity**

**D'Asaro, Eric. Applied Physics Laboratory, University of Washington, Seattle, Washington USA**

We have explored submesoscale flows by surveying the 3D time-evolving structure around a Lagrangian trajectory marked by a neutrally buoyant float using either a profiling body towed by a ship or an array of autonomous gliders. Detailed studies of the kilometer-sized volumes along density fronts have revealed thin stripes of negative potential vorticity caused by down-front wind stress, evidence for symmetric instability within these stripes and suggestions of interaction with larger scale, near-inertial motions. Longer term studies of the 5-50 km scale evolution of the springtime North Atlantic bloom show significant modulation of the bloom intensity and timing, and of associated carbon export, by submesoscale features.

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### **The submesoscale structuring role of horizontal stirring on marine ecological and biogeochemical dynamics.**

**D'Ovidio, Francesco. ISC-PIF/LOCEAN, Paris, France**

On the ecological timescale of planktonic blooms (days/weeks), the horizontal stirring structures the ocean upper layer in submesoscale filamentary domains of contrasted physical and biogeochemical properties. The role of submesoscale filament dynamics on fuelling and organizing in space primary production is now recognized, but its effect on the community structure of phytoplankton - and possibly higher level of the trophic chains - is mostly unknown. Nevertheless, this information is of critical relevance for many issues like fishery management, ecosystem conservation, understanding marine biodiversity, and for better integrating the ecological processes into the biogeochemical cycles. Focusing on Lagrangian diagnostics like the Lyapunov exponent calculation, here I will show how synoptic maps of submesoscale filaments can be reconstructed from available global datasets like altimetry-derived surface velocities. In this way, some of the submesoscale ocean variability can be retrieved at the global scale. By combining this information with phytoplankton and tagged marine predator data, I will argue that submesoscale filaments can be considered as the building blocks of the planktonic ecological landscape, playing the role of fluid dynamical niches. The possibility of identifying these niches in real time opens new perspective for in situ surveys, allowing to design a novel type of experiments, aimed at better quantifying the role of plankton ecology on the biogeochemical cycles.

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### **On mesoscale and submesoscale influences on a self-organizing ecosystem model with application to the California Current System**

**Edwards, Christopher. University of California, Santa Cruz, USA**

Traditional ocean ecosystem models are usually constructed with a small number of autotrophic organisms. While the limited biological representation minimizes computational cost and simplifies model analysis, it also eliminates the potential for unique community response to environmental niches created by the physical circulation. We report on a new ecosystem modelling approach with substantially greater biological resolution. The model consists of 78 phytoplankton types that fall within 4 functional groups and whose physiological traits are randomly selected within reasonable bounds. The model is applied to a circulation model for the California Current System (CCS), the collection of poleward and equatorward surface and subsurface currents found off the west coast of North America. Realistic models of the CCS exhibit rich mesoscale and, depending on resolution, submesoscale features. The ecosystem model produces a robust seasonal cycle and biogeography that resembles that of the CCS. In particular, nearshore upwelling zones are characterized by diatom blooms, offshore regions are rich in Prochlorococcus-type organisms, and small picoeukaryote-like phytoplankton are relatively ubiquitous. In this talk, we describe the structure of seasonally varying fields obtained with this model for the CCS and examine how mesoscale and submesoscale features influence the trophic structure and phytoplankton succession.

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**From stirring to mixing at the ocean submesoscale: physics and biology**  
**Ferrari, Raffaele, Massachusetts Institute of Technology, USA**

Eddy fluxes of momentum, buoyancy, and material tracers exert a profound influence on the oceanic general circulation and on the overall biogeochemical cycles. The traditional view is that these fluxes are dominated by geostrophic eddies at the mesoscale and three dimensional eddies at the microscale. In this study we analyze the interactions between these two classes of motions and show how they modify the development of turbulence and biological processes in the ocean. Interactions between mesoscale and microscale turbulence happen at the submesoscale, i.e. scales between tens of kilometers and tens of meters. In the ocean interior, microscale turbulence homogenizes the submesoscale tracer filaments generated by geostrophic eddies; there is no evidence for a strong modulation of microscale turbulence by geostrophic eddies. In the upper ocean, instead, microscale turbulence is enhanced at submesoscale fronts generated by geostrophic eddy stirring. These observational results are interpreted in view of recent developments in the theory of geostrophic turbulence. In the upper ocean, the presence of a free surface allows for the development of sharp density fronts. These lateral fronts modulate the air-sea fluxes and profoundly affect microscale turbulence in the surface boundary layers. The modulation of microscale turbulence further affects productivity in the upper ocean. We will conclude by discussing the implications of these results for the representation of turbulence and biological processes in ocean models.

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**From subgrid physics to subgrid biophysics: Un défi submeso**  
**Fox-Kemper, Baylor, CIRES, University of Colorado, Boulder, USA.**

Developing subgrid parameterizations for physical processes is clarified by adapting the Reynolds-Averaging approach from turbulence modelling to mesoscale and submesoscale physics, and extrapolating across unknown scales using known scaling laws. Following the same approach for biophysical parameterizations is nontrivial. The known scaling laws do not apply to bioactive tracers, even though they may apply to nutrients in the absence of biology, for example. An analysis of the effects of incorporating a physical submesoscale eddy parameterization in a number of global climate models and challenges to extending this to a biophysical parameterization will be presented.

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**New tools to observe and model submesoscale dynamics**  
**Franks, Peter, Scripps Institution of Oceanography, La Jolla, USA**

This talk will have two parts. I will first describe a new sampling tool that Jules Jaffe (SIO) and I have developed: the miniAUE (Autonomous Underwater Explorer). These vehicles are about 1 liter in volume, and have active buoyancy control. They can receive communications from GPS-tracked surface drifters, allowing them to obtain 3D underwater location fixes. We envision deploying swarms of these drifters in the ocean, assimilating their data into physical models to obtain highly resolved estimates of the flows and fluxes in the ocean on the submesoscale. The second part of the talk will introduce a near-continuum size-structured plankton model that I have developed with Francis Poulin (U Waterloo). This model has analytical steady states, allowing a thorough exploration of the factors determining planktonic size structure. I will also analyze a time-dependent version of the model to understand how submesoscale-driven nutrient pulses might alter the size distributions of the plankton, and the time scales over which we would expect to see a response.

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**Development of High-resolution Wide-Swath Altimetry for Observing the Oceanic Submesoscales**  
**Fu, Lee-Lueng, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109**  
**Rosemary Morrow, Observatoire Midi Pyrenees, Toulouse, France**

Satellite altimetry has revolutionized the study of the global oceans for the past two decades. Precision altimetry missions like TOPEX/Poseidon, Jason-1, and OSTM/Jason-2, complemented by other missions like ERS 1 and 2, ENVISAT, and GFO, have provided unprecedented observations of the ocean surface topography

leading to significant advances in our understanding of global ocean circulation and sea level change. Data merged from two altimeter missions have provided two-dimensional maps of ocean variability at wavelengths larger than about 200 km and led to a rich discovery of the characteristics of ocean mesoscale eddies. Although along-track one-dimensional profiles of sea surface height have higher resolution, the limited measurement precision has prevented resolving wavelengths shorter than 50-100 km, including the submesoscales that are important for understanding the dynamics of the ocean kinetic energy and the vertical transfer processes in the ocean that account for 50% of the exchange of water properties (nutrients, dissolved CO<sub>2</sub>, etc.) between the upper and the deep ocean. These processes are critical to understanding the role of the ocean in the global carbon cycle and climate change. A new space mission called Surface Water and Ocean Topography (SWOT) is being developed jointly by international oceanographic and hydrological communities for making high-resolution measurement of the elevation of ocean surface topography and land surface water to study the oceanic submesoscale processes and the storage and discharge of land surface water. SWOT was recommended by the Decadal Survey of the US National Research Council involving wide representation of the Earth science community. The key instrument payload is a Ka-band radar interferometer capable of making high-resolution wide-swath altimetry measurement. The development of the mission has been proceeding as a joint effort of NASA and CNES, following the long-lasting tradition in collaboration in radar altimetry over the past 25 years. The science objectives and requirements as well as the measurement approach of SWOT will be presented.

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### **On the role of meso-scale eddies for productivity and carbon export in eastern boundary upwelling systems**

**Gruber, Nicolas<sup>1</sup>, Zouhair Lachkar<sup>1</sup>, Hartmut Frenzel<sup>2</sup>, Patrick Marchesiello<sup>3</sup>, Matthias Münnich<sup>1</sup>, James C. McWilliams<sup>2</sup>, and Takeyoshi Nagai<sup>4</sup>**

<sup>1</sup>Environmental Physics, Institute of Biogeochemistry and Pollutant Dynamics, ETH Zurich, Zurich, Switzerland.

<sup>2</sup>Department of Atmospheric and Oceanic Sciences and Institute of Geophysics and Planetary Physics, UCLA, Los Angeles, CA, USA.

<sup>3</sup>IRD Noumea Center, Noumea, New Caledonia.

<sup>4</sup>Tokyo University of Marine Science and Technology, Tokyo, Japan.

Several open ocean studies have suggested that eddies and other meso-scale processes tend to enhance biological production in the ocean, particularly in low nutrient environments. We propose that meso-scale processes have the opposite effect in eastern boundary upwelling systems, i.e. they tend to reduce biological production and the downward export of organic matter. We base these findings on a set of eddy-resolving simulations of the California and the Canary Current Systems with the Regional Oceanic Modelling System. We interpret this reduction effect to be primarily the result of eddies causing a net lateral loss of nutrients from the near-shore environment of these eastern boundary upwelling systems. This initial effect is enhanced through a positive feedback, whereby lower production and export leads to less remineralization and nutrient addition to the waters that later upwell, causing a further decrease in production and export. Eddies cause a loss of nutrients from eastern boundary upwelling systems because they induce a lateral transport that brings warm, nutrient-depleted waters toward the shore, thereby enhancing the stratification, and increasing the subduction of the upwelled waters at the sharpened upwelling front. The subducted water tends to take unutilized nutrients along, which are then transported further offshore by westward propagating eddies, resulting in a net loss of nutrients from the upwelling system. Our model-based conclusions are supported by observations from all eastern boundary upwelling systems that indicate that systems with higher eddy activity, such as the California Current System, tend to have lower productivity than expected on the basis of the strength of the upwelling favourable winds.

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### **Coupling of ocean interior with surface through submesoscales**

**Lapeyre, Guillaume. LMD/IPSL, Paris, France & Klein, Patrice LPO Brest, France**

Until the last 10 years, it was thought that the ocean dynamics at mesoscales (100-1000 km) was driven by interior potential vorticity anomalies. This led to the development of the geostrophic turbulence theory as initiated by Charney (1971), that helped to explain the partition of energy between potential and kinetic and the

typical length scale of mesoscale eddies. This could explain also the vertical and horizontal transport and mixing of tracers such as density compensated salinity-temperature anomalies. The last years have revisited the mesoscale dynamics taking into account the importance of surface density fronts at submesoscales (10-100km in width). The presence of surface submesoscale fronts has been shown to strongly modify the 3D partition of mesoscale energy. Also it strongly enhances the vertical exchanges of tracers in the upper ocean and the ageostrophic processes (cyclone-anticyclone asymmetry, restratification). In this talk, I will review our current understanding on this topic. I will also discuss the impact on biogeochemical processes: both in terms of a new vertical pump forced by surface mesoscales, and in terms of spatial organization of nutrients and phytoplankton.

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**Submesoscale control of the mixed layer depth and its implications for carbon uptake in the Ross Sea**  
**Leif, Thomas, Matthew Long, Department of Environmental Earth System Science, Stanford University, USA**

The presence of submesoscale flows in the upper ocean confounds the traditional one-dimensional paradigm for the evolution of the mixed layer (ML). In frontal regions submesoscale processes such as frontogenesis, Ekman advection of buoyancy, and ML instabilities can modify the stratification at rates that can easily exceed those associated with air-sea fluxes. In this presentation I will give an overview of the submesoscale potential vorticity dynamics that govern the re- and destratification of the ML and describe the implications for carbon uptake in high-latitude, nutrient-rich waters such as the Ross Sea. In these regions phytoplankton growth can be light-limited, and thus submesoscale processes that affect the shoaling and deepening of the ML can modulate the strength and variability of primary productivity. Observations from the Ross Sea suggest that this effect was particularly active at the start of the spring bloom. Underway and CTD data reveal high chlorophyll, low pCO<sub>2</sub> and enhanced stratification in the proximity of fronts. At the time of the observations, the predominant up-front winds were of the sense to drive Ekman restratification. Numerical simulations configured with fronts representative of the region and forced by observed air-sea fluxes confirm that Ekman advection of buoyancy contributes significantly to enhancing the stratification, productivity, and CO<sub>2</sub> fluxes in the Ross Sea.

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**Coupling between physics, biology and chemistry in the ocean at the sub-mesoscale : how does it affect oceanic pCO<sub>2</sub> and carbon export ?**

**Lévy, Marina. LOCEAN-IPSL, CNRS/UPMC/IRD/MNH, Paris, France**

The ocean is a turbulent flow, populated by numerous, strongly interacting, mesoscale eddies. These eddies have diameter of the order of 100 km and a life time of a few months. Their interaction leads to intense sub-mesoscale features, mostly in the form of filaments of only a few km width and duration of a few days.

Oceanic filaments are highly energetic, and their signature is evident on satellite images of sea-surface temperature and chlorophyll. However, observing and modelling filaments is a challenge, due to the required space and time resolution. Currently, the variability of oceanic pCO<sub>2</sub> associated to these filaments is often omitted in our analyses of the carbon cycle. What are the processes responsible for the sub-mesoscale variability of oceanic pCO<sub>2</sub>? Do sub-mesoscale filaments participate to the export of carbon below the euphotic layer? What kind of errors should we expect from their omission, in models, in data analysis?

In this presentation, I will review the physical mechanisms occurring at sub-mesoscale and show how they can affect sources, sinks and distribution of pCO<sub>2</sub>. I will distinguish between lateral stirring processes, which create large pCO<sub>2</sub> gradients over very small spatial scale, and vertical processes, which modify the supplies of all the tracers involved in the pCO<sub>2</sub> and modify the biogeochemical properties of water masses that are subducted. I will provide some first global maps, showing the importance of these two types of processes.

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**Regulation of photosynthetic light, nutrients and carbon by submesoscale dynamics**

**Mahadevan, Amala. Boston University, USA**

We explore some of the roles that submesoscale processes play in influencing the growth of phytoplankton. These include (i) the generation of stratification in the mixed layer, which alters exposure to light, (ii) the vertical supply of nutrients by advective fluxes across the base of the mixed layer, and (iii) the lateral transport

and subduction of phytoplankton from regions of active production. Using numerical simulations of mixed layer eddies, eddy-driven vertical fluxes at fronts, and cross-frontal transport in filaments, we describe the dynamics underlying each of the phenomena and their effect on the production and export of phytoplankton.

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### **Mechanisms of interplay between ocean turbulence and the marine ecosystem**

**Pasquero, Claudia. Earth System Science Dept - University of California, USA.**

Several mechanisms that depend on the fluid dynamics and are potentially important for the marine ecosystem will be summarized. The importance of spatial and temporal variability of the nutrient fluxes, the role of mesoscale lateral advection, the effect of vertical motion at the submesoscales are some issues that will be discussed, together with their impact on large scale ecosystem and climate models. The results presented are based on studies performed with ocean models of different complexity, ranging from simple idealized box models to regional primitive equation ocean models coupled with simple ecosystem models.

Finally, we will move to the microscales, giving a brief description of the interaction between individual plankton motion and three dimensional eddies in a turbulent environment. New numerical results will be presented, and a novel mechanism that affects the encounter rate between individuals and the settling rate will be introduced.

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### **Observing horizontal structure in the upper ocean: From ships to underwater gliders**

**Rudnick, Daniel. Scripps Institution of Oceanography, La Jolla, USA**

The observation of horizontal structure in the upper ocean has progressed tremendously over the past few decades. Ship surveys progressed from discrete stations to the widespread use of towed vehicles in the late 1980's and early 1990's. These undulating towed vehicles led to an explosion of observational research into what is now called the submesoscale. Parallel to this advance in platforms was the development of primarily optical sensors to measure biological variables. The measurement of physical and biological variables with the same fine spatial resolution has led to fundamental research of physical/biological interactions. Central to the upper ocean biogeochemical cycle is the vertical flux of tracers. The estimation of these fluxes is an active area of research, with the use of omega equations to infer vertical velocity as an ongoing thread. Underwater gliders hold promise for a major advance in knowledge of the submesoscale because of their sustained presence and fine horizontal resolution. The first results from gliders are beginning to demonstrate such findings as the seasonal modulation of the submesoscale. Challenges involved in using gliders include their relative slowness and limited payload.

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