Turbulent Mixing and Biophysical Interactions
Working Group Report

Science drivers and the need for a regional-scale cabled observatory

Small-scale turbulence in the ocean has significant consequences for both carbon fluxes and marine biodiversity through direct and indirect effects on the marine ecosystem, as detailed in the SCOTS Report (Glenn and Dickey, 2003) and summarized below. In addition, turbulence has profound effects on air-sea exchanges of greenhouse gases and on the magnitude of the thermohaline circulation. Ignorance of the processes and locations of turbulent mixing in the ocean has such serious implications for global climate modelling and climate change projections that the Millennium Report identifies turbulence as one of the remaining 'big questions' in ocean science. While the focus of this group was the combination of turbulent mixing and biophysical interactions, group members felt it important to emphasize that our basic knowledge of small-scale ocean turbulence will be significantly advanced by the ability to make long time series measurements in an observatory setting. As well, the group expanded the scope of its charge to include biological interactions associated with "large-scale" turbulence, the ubiquitous ocean mesoscale.

Cabled systems are essential for tackling problems in small-scale turbulence and its interactions with all levels of the marine ecosystem. Both the ample power and, especially, the broad bandwidth that will be provided by cabled systems are required by present methods for measuring turbulence quantities (dissipation scales with microscale sensors or large-eddy scales with acoustics), and for those biological techniques (such as multi-frequency acoustics, multi-wavelength and sheet light optics, holography, and video/still photography) that can provide detail sufficient to adequately delineate ecosystem responses. A ***regional-scale cabled*** system with an adequate footprint is necessary for the investigation and comparison of turbulent mixing regimes with very different characters - deep-sea mixing driven by tidal flow over steep topography, upper mixed layers subject to very different combinations of wind and buoyancy forcing, and shelf regimes strongly influenced by tidal bottom boundary mixing. The character of embedded ecosystems also varies dramatically: the challenge is to discover how much of the bio-geographical variability arises through the direct and indirect effects of small-scale turbulence.

The recent SCOTS Report highlighted four areas in which fundamental questions associated with the interactions between turbulent and biological fields can best be tackled through cabled time series measurements. The following is a very brief description of the questions associated with these major themes, with an indication of the advantages brought by regional scale.

Plankton community structure

While it has long been appreciated that planktonic species composition varies dramatically from one biogeographical region to another, the reasons underlying this variation are poorly understood. Because planktonic organisms live in a surface layer exposed to wide ranges of mechanical and buoyant forcing, it is possible that species mix is determined by turbulence intensity, through direct effects such as biomechanical stresses, modulation of particle encounter rates, and/or modification of the vertical migration behavior of motile species. On more local spatial scales, do turbulence levels directly affect which species achieve dominance in a phytoplankton bloom? It is also possible that turbulence effects on ecosystems occur indirectly, through the interaction of species with environmental factors that are determined or strongly modulated by turbulence processes. Other suggested means of structuring planktonic communities may appear to be independent of turbulence influence. For example, it has been suggested that the *kind* of available nutrients may play a dominant role. While this is a seemingly separate question, it is actually closely related, since interplay between turbulent motions and light fields can result in modification of the nutrient menu present. Resolution of these broad issues associated with community structure requires a CRO that spans at least 2 distinct biogeographical "provinces".

Formation, dissolution and export of marine snow

Marine snow aggregates are believed to play a variety of important roles in marine ecosystems and the ocean carbon cycle, fulfilling multiple functions as structured habitat, concentrated food/nutrient source, and vertical transport mechanism. In doing so, marine snow may play a significant, presently unappreciated, role in structuring marine ecosystems. While the existence of marine snow is rooted in the bio-particles that form the aggregates, it is also strongly influenced by turbulence in the environment that contains them. It is generally agreed that increasing turbulence levels first enhance the formation of marine snow aggregates, by increasing collision rates of biological particles, but eventually leads to their destruction, as turbulent shears become sufficiently large to tear them apart. What is the formation/dissolution threshold level? The net escape of marine snow particles from the bio-active surface layer is believed to be a significant contribution to the net carbon export to the deep sea. Is the rate of net escape determined by the "fast" time scale of intermittent turbulent mixing events at the base of the surface mixing layer, or by the "slower" diurnal or seasonal variation in mixed layer depth?

Ecosystem effects of atmospheric variability on ENSO/decadal time scales

Variation of marine ecosystems in synchrony with ENSO/PDO variability is well-established in a correlational sense. However we have as yet no understanding of the mechanistic connections involved in this co-variability. A CRO that spans a significant gyral boundary, operating over several years (ENSO) to a few decades (PDO) would allow quantitative assessment of the hypothesis that the modulation of upper ocean turbulence levels by changes in atmospheric driving forces is this missing mechanistic connection. Equally important, it would allow quantitative assessment the impacts on the composition, vertical structure and dynamics of major ecosystem components including phytoplankton, zooplankton and fish.

Benthic community structure

The structure and variability of the turbulent bottom boundary layer (BBL) is, apart from substrate, the major factor influencing the structure of benthic communities, yet the observational knowledge of this structure is limited. How for example is the underlying benthos affected by changes in the structure of the turbulent BBL in the transition from continental shelves to deep ocean? Temporal variability may be an even more important issue. It is possible that the structure of benthic communities is determined less by background norms than by episodic turbulent "mega-events", i.e., the occurrence of major eruptive events or debris flows on deep-sea benthos, or infrequent but intense interactions between surface (wind-driven) and bottom (current-and wave-driven) boundary layers on the benthos of shallow coastal regions. The net export of organic material from continental shelves is believed to be a major fraction of the organic carbon flux to long-term "storage" in the deep sea. Does the time-average cross-shelf structure of the turbulent bottom boundary layer influence this export rate, or is the rate set instead by irregular exchanges associated with mesoscale motions? Answers to these questions requires a CRO that spans the shelf/slope transition in a number of locations.

Our choices of observational sites is based on these broad scientific questions, as well as other fundamental questions that arose during the Working Group discussions. The chosen sites (Figure 1) are focused in the following three broad areas.

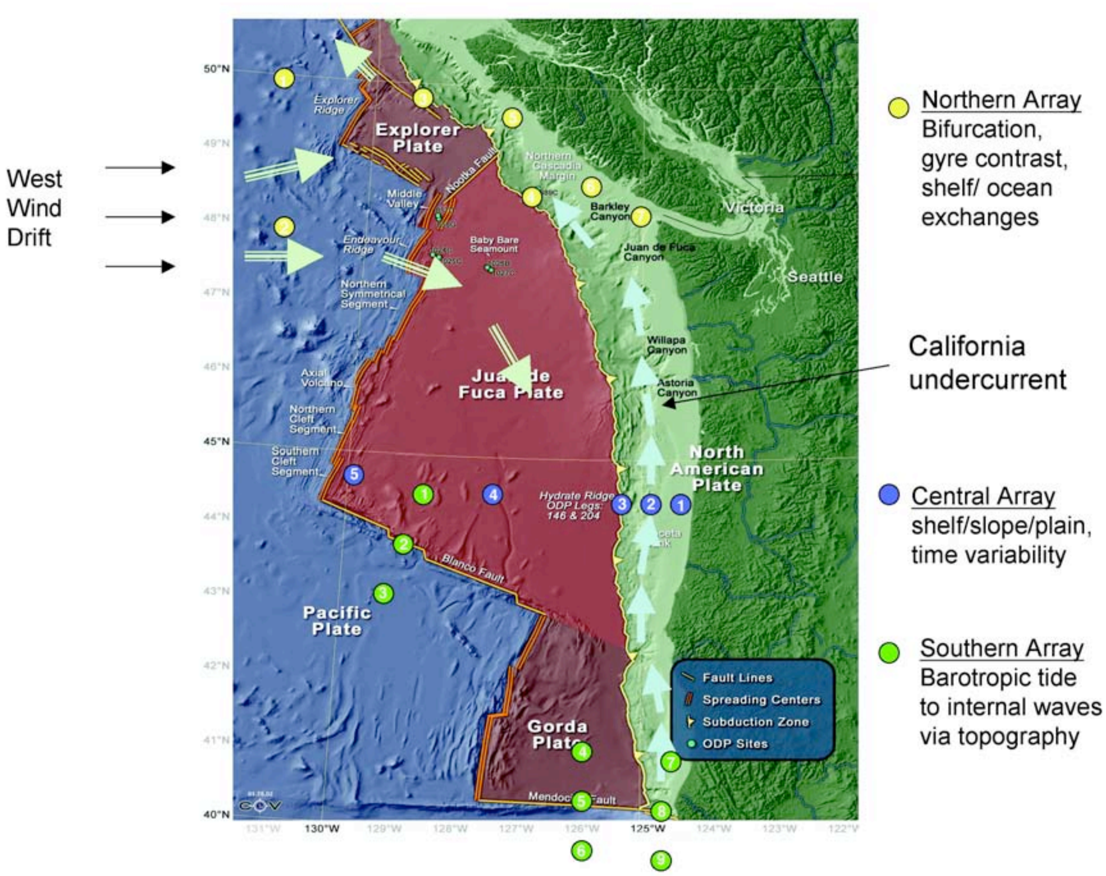

Figure 1. Map of the northeast pacific cabled regional observatory showing geological provinces, major current systems and potential locations for the proposed northern, central and southern arrays. Each of the locations would have an EOM riser from the bottom to a subsurface instrument node within100-200 m of the surface (see Figure 2), enabling the near-surface access that is critical to addressing turbulence/biophysical scientific questions. This figure shows a design for fully implemented array that is optimized for addressing turbulence/biophysical interaction issues.

1. Northern Array: Processes at gyre boundaries

The northern part of the NEPTUNE region is dominated by the boundary between the subtropical and subarctic gyres. The two gyres are fundamentally different physically, biologically and biogeochemically: the subtropical gyre is characterized by wind-forced downwelling, the subarctic by upwelling. The current separating the gyres, commonly known as the West Wind Drift, flows eastward, meets the eastern boundary, and bifurcates into northward and southward flowing branches. The southward branch provides the source water of the California Current, while the northward branch feeds the

Alaska Current. These currents interact with flows of the shelf/slope region through upwelling and mesoscale processes.

The confluence of gyral and coastal biogeochemical provinces provides a number of ideal settings for the study of exchanges of physical and biogeochemical properties between the various provinces. For example, what are the horizontal exchanges between subtropical and subarctic gyres, and between the deep ocean and shelf? What are the vertical exchanges between thermocline and mixed layer, and how do they vary across provinces? The Northern Array consists of 7 water column "tree" sites (we define a "tree" as an EOM riser from the bottom to a subsurface instrument node within100-200 m of the surface, enabling the near-surface access that is critical to addressing turbulence/biophysical scientific questions: for prototype (see Figure 2). Locations of these sites were chosen to address the widest possible range of physical and biogeochemical science questions in this region.

Sites 1 & 2 address science issues involves processes spanning the gyre boundary in the open ocean:

- Contrasting vertical turbulent fluxes and biogeochemistry
- Decadal changes in vertical structure
- Mesoscale fluxes between gyres

Sites 3 & 4 were chosen to address science questions involving the bifurcation region and the source waters of the California and Alaska Currents:

- Interannual variability of location of bifurcation, flux magnitudes
- Interaction of bifurcation with shelf/slope processes
- Variability and export of the source physical and biogeochemical properties

Sites 3-6 will allow investigation of the communication between the open ocean and shelf/slope in an area that exhibits seasonal upwelling plumes and mesoscale eddies:

- Flux of material across and along shelf/slope

Site 7 was included to investigate biological retention processes and estuarine bottom water renewal processes at the entrance to Juan de Fuca Strait.

- Ocean influence on estuarine processes
- Interannual variability of retention and California Current System

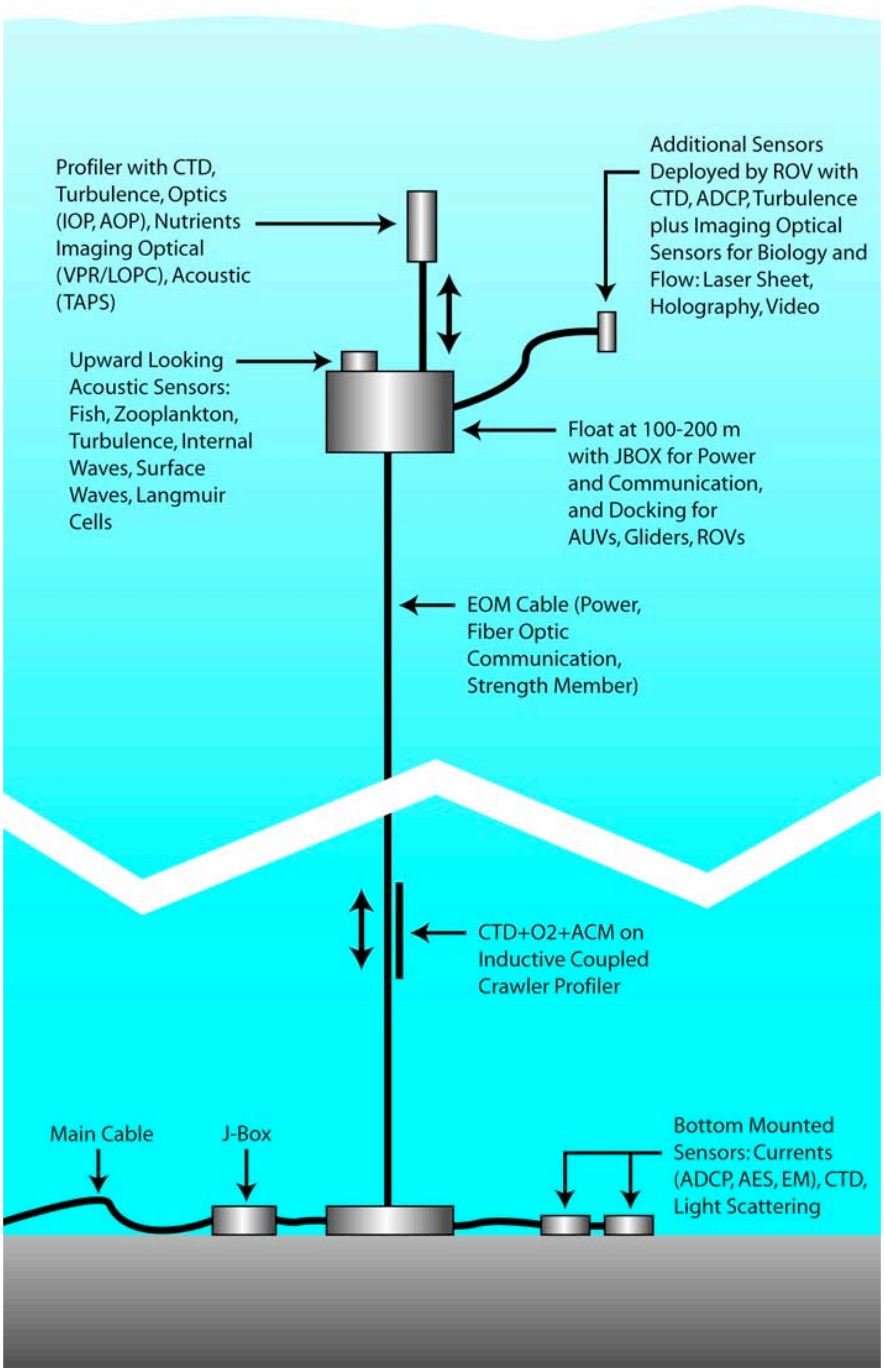

Figure 2. Potential design for EOM trees.

2. The Central Array: Shelf to Basin

This set of sites was chosen to provide comparative time series in a variety of biophysical regimes, as required by many of the science drivers discussed earlier in this section. Addressing the breadth of these science issues requires a series of 5 nodes: 2 on the shelf, 1 on the slope, 1 at mid-plate, and 1 near a hydrothermally active location on the Juan de Fuca Ridge. We have chosen the latitude (44° 39' N) of the cross-shelf "Newport Line" of hydrographic stations that has been maintained by Oregon State University since 1961, since this provides extensive historical information in which to view the new time series information. This location, in a region of year-round upwelling, provides contrast with the Northern Array coastal sites, and along with the Southern Array, provides an along-shelf antenna for N/S propagation of physical and biological changes driven by large-scale atmospheric variability. While the spatial resolution of this array is coarse, it will have unprecedented temporal resolution. Finally, extensive process and modeling work that has been and is being carried out in this area will help with interpretation of the time series data.

The sites of the Central Array are designed to address seven major issues, all involving advection, turbulent mixing, organism distributions, and bio-physical interactions.

- What is the long-term variability in upwelling? How far offshore do the effects of variations in upwelling extend?
- What is the spatial variation (onshore to deep waters) in turbulence in the photic zone, the nutricline and the benthic boundary layer? How does that variation affect the distribution of plankton and fish through behavioral responses? How does it affect plankton population dynamics through effects on recruitment, mortality, lateral transport?
- What is the spatial variation (onshore to deep waters and south to north) in turbulence and ecosystem response to the Pacific Decadal Oscillation and ENSO?
- How do changes in the location and intensity of the West Wind Divergence affect oceanic ecosystems off the western United States (e.g.,the effects of subarctic waters that periodically head south)?
- What is the long-term variability in the intensity and offshore extent of cross shelf transport of plankton, biogenic material, and sediments?
- Is variability in the intensity, depth and offshore extent of the seasonal chlorophyll-A maximum related to variability of upwelling or changes in the intensity of tranport by the California Current?
- How does long-term variability in near bottom flows and turbulence affect the dispersion, lateral transport, and subsequent of benthic organisms that inhabit the shelf, slope, central plate and Juan de Fuca Ridge?

3. Southern Array: Tidally driven mixing

One of the most important issues in determining the large-scale ocean circulation is how the great bulk of the ocean is mixed. The utility of present circulation models is limited by their ability to parameterize both the turbulence that mixes the ocean and the instabilities that lead to turbulence. Results from isolated field experiments covering specialized geographical areas and cruise time scales (< 1 month) suggest that modification of the barotropic tide by its interaction with topography is a significant generator of high wavenumber internal gravity waves and turbulence. The power and bandwidth of a CRO offers a unique capability to assess the modulation of these tidal and flow interactions with topography over long time scales.

Within the region of the proposed NE Pacific cabled observatory, there are 2 areas that are of prime comparative value for such studies. Each represents a fundamentally distinct bottom topography and wave generator. The Mendocino Escarpment (sites 4-6) is a single sharp and long edge with a deep dropoff to the south. The sharp edge is oriented perpendicular to the BT tide, optimal for tidal flow/topography interactions. Further offshore, sites 1-3 across the Blanco Fault span topography that in contrast consists of multiple smaller amplitude ridges, still roughly normal to the barotopic tide. At both sites, deep turbulence observations would involve 3 sites - one north of, one south of, and one atop the ridge - equipped with water column "trees" to support a variety of flow and turbulence sensors.

Although not required for the fundamental comparative studies of deep sea turbulence generation by tide/topography interactions, addition of a set of sites (7-9) across the Mendecino Fault along the continental shelf would allow exploration of the effects of abrupt N/S depth variation coupled with abrupt transition of shelf width on a variety of physical and biological processes. For example, how does the California Undercurrent negotiate this transition zone? What is the fate of biological material moved offshore by the persistent mesoscale eddy that sits off Cape Mendocino? How do the answers to such questions change over annual/ ENSO/decadal time scales?

<u>Initial sites for water column observations</u>

Three of the Working Groups (Oceans, Climate and Biogeochemical Cycles; Turbulence and Biophysical Interactions; and Marine Ecosystems) suceeded in identifying 12 priority sites for initial implementation of water column observations. These locations were selected to provide immediate returns to a broad cross-section of the interested scientific community, and to initiate the sustained measurements necessary for investigating issues of climate variability and anthropogenic climate change. As described below, instrumented "trees" at many of the 12 sites shown in Figure 3 would fulfill multiple functions within the priority science identified by the three working groups. In addition, many of these sites are in locations of common interest to the other two groups.

1. The subset of sites [1,11,12,9] enables comparison of substantially different oceanicbiogeochemical provinces, ranging from the southern fringe of the highly productive micro-nutrient-limited HNLC subArctic gyre to a region with the lower

productivity associated with macro-nutrient limitation in the subtropical gyre. In addition, this coarse spatial array will allow monitoring of major variability in the N/S position of the West Wind Drift.

2. The site pairs [1-2], [3-4], and [5-7] will allow comparison of onshore/offshore processes and fluxes at locations characterized by different upwelling and mean current regimes.
3. The site pair [1,11] monitors variability in biophysical fields being advected towards the coast in the West Wind Drift, while the pair [2,10] should delineate associated variability in the N/S divergence of fluxes of mass and biogenic material feeding into either the Alaskan Stream or the California Current. Knowledge of fluxes into the eastern subtropical gyre at its northern boundary provides an essential upstream condition for biophysical conditions within the entire California Current system.
4. Sites [4,7] provide an estimate of along-shelf variability in biophysical fields. Despite the coarse spatial scale, co-variability (or lack thereof) between extended time series observations in these two locations would provide improved tests of various hypotheses relating ocean productivity to the success of commercially important fisheries.
5. Sites [3,12] are located at major venting locations along the Juan de Fuca Ridge, locations that will be intensively occupied by the geophysical part of the observatory community. The water column observation sites would be located along the flanks of the ridge at these locations, concentrating on variability in the along-ridge flows and their ability to transport larvae of vent animals between venting sites, as well as fortuitous measurements of the biophysical signatures of mega-plumes.
6. Sites [5,8,9], located on either side of the crest of the Blanco Fault, will begin to provide long-term measurements of the deep mixing associated with barotropic tidal flow normal to major sub-sea topography: as well, Site 5 is a part of the comparative suite of locations (see 2. above) which will characterize shelf to basin variation in turbulence and biophysical processes.
7. Site 4 is of major interest as a site of larval retention, harmful algal bloom development and a source of deepwater renewal for large areas of the inner coastal waters of southern British Columbia and northern Washington.
8. Site 11 will be located near major seamounts that are characteristic of the region, allowing access to this unique deep-sea environment.

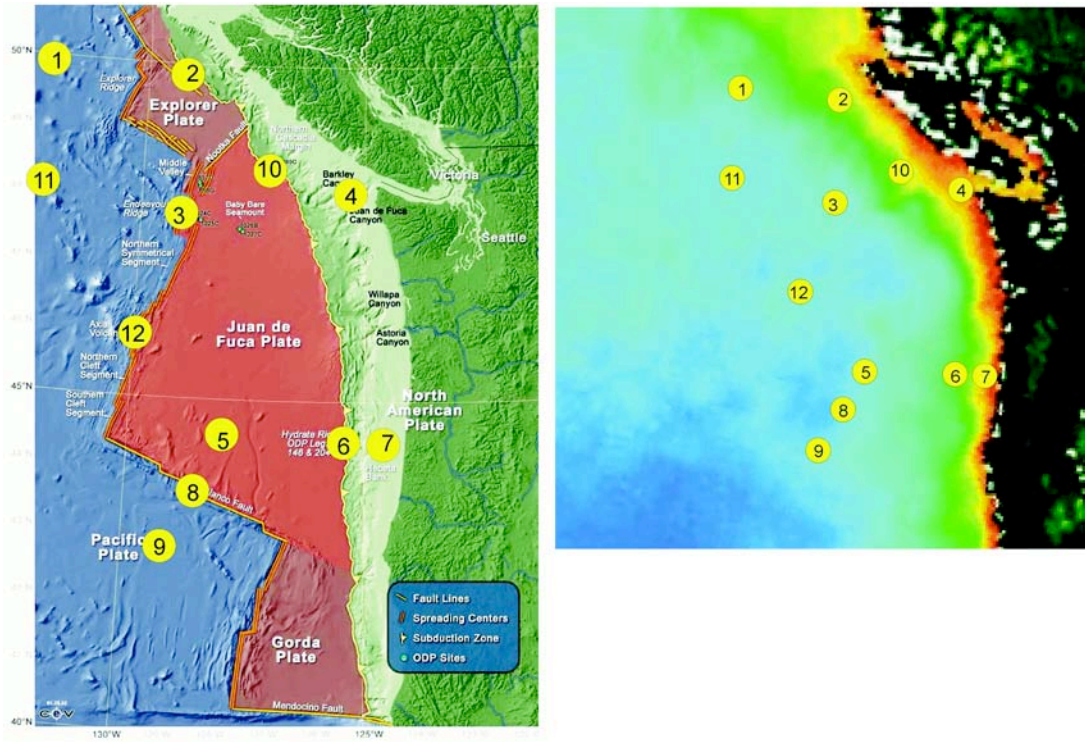

Figure 3: Left panel shows sites over bottom topography and plate structure; right panel shows site locations overlaid on an image of summertime ocean color.

1,11,12,9: North-South subarctic/subtropical comparison, resolution of N/S fluctuations in the West Wind Drift
1-2, 3-4, 5-7: offshore-onshore transports, contrasts
3,12: vent and ridge dynamics
5,8,9: tidal flow/ topography interactions, deep mixing experiments
4,7: N-S along-shelf comparisons
2,10: bifurcation of the West Wind Drift

It is realized that time series measurements alone can lead to spatial aliasing in regions of strong lateral variability. Ideally, each time series site should be supplemented by spatial measurements with a degree of resolution determined by the local decorrelation scales (which ~1 to 5 km for worst-case locations on the shelves). During the mature stage of observatory operation, it is expected that AUVs/Gliders will be available to resolve the fine-scale structure of both physical and ecosystem structures around the time series "trees". However in the initial stages, it will be necessary to estimate the degree of spatial aliasing, using remotely sensed fields and/or numerical models. The possibility of spatial aliasing should not keep us from establishing water column time series at the earliest stage of observatory deployment, any more than the possibility of temporal aliasing has kept us from making shipborne measurements.

Sensor Recommendations for Turbulence and Biophysical Interactions

This working group unanimously agreed that at least 12 of the regional observatory nodes (defined in Figure 3) should have EOM"trees," providing essential access to the water column and the near-surface zone. These EOM trees need to be equipped with sensors that can simultaneously measure the vertical distribution of the biota (phytoplankton, zooplankton, fish), current velocity, turbulence, and physical structure (temperature, salinity, density). These EOM tree-based measurements will be particularly important near the surface (upper 200 m) where the effects of turbulence and biophysical interactions are very large, but undetectable by bottom mounted sensors. Trees will support three types of sensor packages: (1) sensors mounted at the top of the vertical riser at about 200m depth, (2) a profiler that can collect data from 200m to the surface, and (3) a mobile "traveler" that can make repeated profiles between bottom and upper nodes. The upper node should have a base instrument suite that includes a CTD (pressure, conductivity, temperature) and oxygen sensor for collecting time series data at the depth of the node and upward-looking ADCP for measuring vertical profiles of horizontal currents. This upper node should also include acoustic sensors for measuring the vertical structure of internal waves, zooplankton and fish. The upper water column profiler should include a base suite of instruments including a CTD, an oxygen sensor, and standard optical package for measuring inherent optical properties, as well as more experimental instrumentation designed to measure turbulence levels and biophysical interactions. The mobile traveler that makes repeated profiles between bottom and upper nodes should have a base instrument suite that includes a CTD, oxygen sensor, and a compact optical package for measuring suspended particulate load. It should also be complemented by bottom-mounted package that includes a CTD, an optical backscatter sensor (suspended particle load), an ADCP, an inverted echo sounder (heat content/baroclinic currents), a horizontal electrometer (barotropic currents), and dual ADVOs (turbulence). The working group felt that a fully implemented cabled observatory should have this bottom-mounted package duplicated at all the bottom nodes.

ADDITIONAL LOCATIONS FOR REGIONAL OBSERVATORIES:

1. Convergent *boundary of distinct BGC provinces*, where very different BGC communities exist in close proximity because of convergent gyre flows. In particular, an appropriately sited observatory on the east coast of the USA would also incorporate features that are not present in the NE Pacific, specifically
- western boundary current /shelf interactions
- the contrast of reducing (wide) shelves *vs* the oxidized (narrow) shelves

2. Arctic/GIN Seas

This is an area of deep water formation, driven by surface buoyancy losses. Although the GIN Seas are more accessible than other deep and bottom water formation areas (in ice-covered Antarctic regions), it is a hostile observational environment during the wintertime formation period. Since this is perhaps *the* most important region for determining global climate, on all time scales from interannual through decadal to millennial (ice age), the ability to make extended measurements of turbulence is of great interest.

3. Antarctic, Drake Passage/Scotian Arc

The Southern Ocean is the most extreme turbulent environment in the world ocean. The enormous air-sea fluxes of buoyancy and momentum that occur in this region are assumed to drive high levels of small-scale turbulence and water mass modification: however no direct turbulence measurements have yet been made in this region. Mesoscale fluctuations driven by instabilities of the Antarctic Circumpolar Current produce large horizontal transfers of water properties and biological material. A CRO would provide improved observing capabilities in this extreme environment.