PROJECT DESCRIPTION

1 Motivations

The warm, northward-flowing waters of the Kuroshio western boundary current leave the Japanese coast to flow eastward into the North Pacific as a free jet – the Kuroshio Extension. The Kuroshio Extension forms a vigorously meandering boundary between the warm subtropical and cold northern waters of the Pacific. This region experiences air-sea heat exchanges that are among the world's most extreme and is also located along the track of winter storms and intense tropical cyclones (typhoons). The work proposed here focuses on how the regional strong atmospheric forcing impacts the properties of the upper and deep ocean.

Inertial oscillations are a fundamental part of the ocean's response to variable winds, and they often dominate the kinetic energy of the mixed layer and the vertical shear at its base. Mixed-layer inertial oscillations forced by the wind radiate energy to the deep ocean, and there has been sustained interest in understanding the forcing, evolution, and global impact of near-inertial waves. Inertial oscillations play an important role in dynamics of phenomena ranging from the local mixed layer heat budget to determining the global mixing rate (e.g. Pollard and Millard, 1970; Large et al., 1986; D'Asaro, 1985; Alford, 2003).

The Subtropical Mode Water (STMW) is found just south of the Kuroshio Extension and is often cited as a large upper-ocean heat reservoir closely linked to the climate system (Joyce et al., 2000). This mode water is formed at the surface during winter, and horizontal advection and local mixing are believed to play a major role in its evolution (Qiu et al., 2007; Rainville et al., 2007). Near-inertial motions, in particular, can create large velocity shear at the base of the mixed layer, enhancing vertical mixing and directly affecting the heat and momentum balance of the mixed layer (Large et al., 1986; Large and Crawford, 1995). While the STMW layer is in contact with the atmosphere during winter, a pycnocline and new mixed layer form on top of the mode water during summer heating, with impacts on the subsequent evolution of STMW. Episodic mixing events, such as those associated with typhoons and mixed-layer near-inertial oscillations, will cause exchange of fluid between the two layers. We propose that these phenomena should be considered together.

The Kuroshio Extension is a region of very high mesoscale kinetic energy. Understanding the role of the mesoscale eddies and of the Kuroshio jet on the ocean response to the atmospheric forcing will be a constant theme throughout the proposed work. It is expected that mesoscale eddies impact the generation of near-inertial oscillations in the mixed layer (Zhai and Greatbatch, 2007) and the transfer of inertial energy to the deep ocean (Lee and Niiler, 1998). As they steer, stretch, and squeeze the near-inertial internal waves, the background currents can directly contribute to mixing as well as influence where and how fast the waves propagate (Kunze, 1985; Zhai et al., 2004). Mesoscale eddies may also affect air-sea fluxes of heat and momentum (e.g., Xie, 2004; Small et al., 2005), as well as water mass formation and evolution.

2 Kuroshio Extension System Study (KESS)

With the goal of better understanding the processes that govern intense meandering, eddy variability, recirculation gyres, and STMW associated with the Kuroshio Extension, the KESS moored array was deployed in summer 2004 and recovered summer 2006 to measure the time-varying density and velocity fields with 4-D mesoscale resolution (Fig. 1). The array was centered on the first quasi-stationary meander crest and trough east of Japan, which is also the region of highest eddy kinetic energy. The KESS array comprised inverted echo sounders equipped with current meters and bottom pressure gauges (CPIES) and a series of subsurface moorings deployed across the jet. The subsurface moorings, equipped with upward-looking acoustic Doppler current profilers

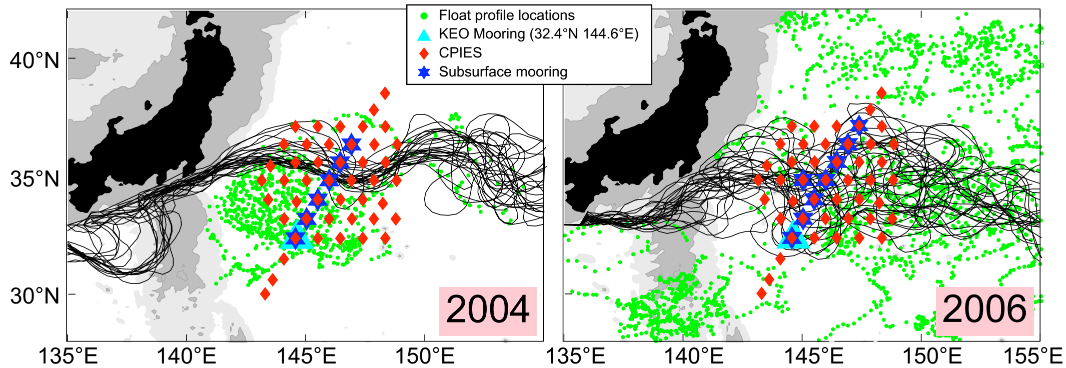

Figure 1: Maps of the biweekly Kuroshio Extension path defined by the 170 cm contours of sea surface height based on combined hydrographic and altimeter data (Qiu and Chen, 2005) for 2004 and 2006. The KESS array consists of CPIES (red diamonds) and MMPs (blue stars) and the KEO buoy (light blue triangle). Locations of profiling-float hydrocasts are denoted by green dots. The 2000 and 4000 m isobaths are shown. The increase in variability of the Kuroshio Extension between 2004 and 2006 reflects a dynamical regime change.

(ADCP), McLane moored profilers (MMP), and current meters, resolve the fluctuations in the density and velocity fields throughout the water column for time scales from hourly to seasonal over the observational period. The deep temperature sensors and current meters (1500, 2000, 3500, and 5000 m) and ADCPs (20 to 250 m) yielded almost complete time series at all subsurface mooring sites (over 80% data return). For the sites that were occupied for the two consecutive years, the MMPs provided temperature, salinity and velocity measurements between 250 and 1500 m. The MMPs suffered some mechanical failures. Their overall data return was 55% (up to 72% at a given site), but fortunately their data return was good during the passage of tropical storms during the months after the June 2004 and June 2005 deployments. The MMPs give detailed additional information on the vertical structure of stratification and velocity that will be useful in studying the high-frequency response of the ocean to atmospheric forcing.

A CPIES measures round-trip travel time of sound from the sea floor to the sea surface, deep pressure and near-bottom current. Using empirical relationships established with historical hydrography, the CPIES acoustic-echo-time measurement permits an estimate of the temperature and density profiles (Watts et al., 2001). With the measurements of deep pressure and near-bottom currents, the array thus provides maps of density, and baroclinic and barotropic velocities. The KESS array yielded maps of density and current for the entire region from June 2004 through October 2005 (16 months). The region decreased subsequently as some instruments failed, so that in January 2006 (April 2006) about 75% (55%) of the area could still be mapped.

The KESS collaboration also deployed 48 profiling floats within the southern recirculation gyre, which provided a detailed description of the temporal evolution of the temperature and salinity structures in the upper water column. During the deployment, turn-around, and recovery cruises, shipboard surveys using conductivity-temperature-depth (CTD) casts and ADCPs provided measurements of the broad-scale density and velocity structure.

A moored surface buoy, the Kuroshio Extension Observatory (KEO), deployed in the southern recirculation gyre, carries a suite of sensors to monitor air-sea heat, moisture and momentum fluxes, and upper ocean temperature, salinity, and velocity. KEO, funded by NOAA, is part of the global network of OceanSITES time series reference sites and is ongoing.

The dynamic state of the Kuroshio Extension oscillates on decadal time-scales between a stable, weakly meandering path and an unstable, vigorously meandering state (Qiu and Chen, 2005). The KESS field program fortuitously captured this regime-transition in late 2004. The most recent stable pattern, which had begun in 2001, exhibited the characteristic pattern of two quasi-stationary meanders and a strong zonally-elongated recirculation gyre. In December 2004 the Kuroshio Extension switched into its unstable state. As a result its path became highly variable, eddy energy increased dramatically, and the recirculation gyre weakened (Fig. 1, black lines). The regime shift will allow us to contrast our results for periods of small and high mesoscale activity.

3 Objectives

This proposal expands the scope of the initial KESS proposal and experiment design by looking at the interplay of large scale and mesoscale circulation with the changes that are observed on the time scale of hours to days and spatial scales of a few tens of kilometers. We believe understanding the relationship between episodic atmospheric forcing, near-intertial motions, and mixing is fundamental towards identifying and quantifying the dynamic and thermodynamic processes governing STWM, and more broadly towards a overall synthesis of the KESS dataset. Here we propose to make use of the different components of KESS, KEO, satellite observations, and historical data to investigate the Kuroshio Extension's response to atmospheric forcing. Specifically, we seek to:

Understand the generation and propagation, vertically and horizontally, of near-inertial motions in the large scale and mesoscale flow fields:

(1) Generation: Compare the measured mixed-layer currents with the wind forcing to improve our understanding of the generation (via wind work) and damping (horizontal and vertical radiation) of inertial motions in the mixed layer.

(2) Propagation: Both statistically and for individual wind events, quantify how the inertial energy escapes the mixed layer and propagates to the deep ocean. Relate this radiation to the 'damping' used by slab mixed-layer models, and to the mesoscale field, different for each storm and season. We will test hypotheses about how the meso- and large-scale advection and relative vorticity structure refract and focus near-inertial waves in the vertical and horizontal.

(3) Dissipation: Synthesizing the above analyses, we seek to understand the dissipation of the near-inertial oscillations at the base of the mixed layer and in the interior of the ocean. In what part is the mesoscale trapping and dissipating the near-inertial waves?

Understand the thermal response to episodic atmospheric forcing:

(1) What are the role of episodic forcing in the formation and erosion of STMW? The mixed layer heat budget at KEO shows that enhanced mixing is partially responsible for the erosion of the seasonal thermocline. What is the source of enhanced mixing?

(2) What is the response to the passage of typhoons? What is the role of late season typhoons in eroding the seasonal thermocline? What is the response to typhoons?

Following this structure, the next two sections start with a background discussion, and then identify specific hypothesis and objectives for each topic (listed as bullet points) before providing details of the proposed methodology to address these goals.

4 Near-inertial motions

4.1 Background

Generation: Because of their important role in the global energy budget of the ocean, there has been a long-standing interest in estimating the total energy input from the wind to mixed-layer inertial oscillations (Alford, 2001; Watanabe and Hibiya, 2002; Alford, 2003). These studies used the damped-slab model, as formulated by D'Asaro (1985), which parameterizes energy loss from the mixed layer using a linear drag term meant to mimic the radiation of energy from the mixed layer to deeper levels. The damped-slab model is appealing for estimation of the global wind energy input to mixed-layer near-inertial oscillations because it requires only wind stress. Plueddemann and Farrar (2006) developed a technique to use observations of mixed-layer velocity, mixed-layer depth, and wind stress to make a more direct estimate of the wind energy input to mixed-layer near-inertial motions and examined terms in the energy budget of mixed-layer near-inertial motions at several sites. This technique assumes that the mixed-layer behaves as a slab, but, unlike estimates of energy input made using the damped-slab model, no assumption about or parameterization of the energy loss terms related to wave radiation and turbulence is required.

Propagation: The mesoscale flow field can have a significant effect on the forced response and subsequent evolution of near-inertial waves (Weller, 1982; Kunze and Sanford, 1984; Kunze, 1985; Lee and Eriksen, 1997; Park and Watts, 2005). Most theoretical and model studies have considered how small wave packets interact with a large-scale and slowly varying background currents. However, there is often no scale separation between the near-inertial waves and the medium they propagate through. Observations are often too limited in space or time to resolve both the mesoscale and inertial motions. Recent work with high-resolution numerical models suggests that properties of wind-forced near-inertial waves may be significantly different in western boundary currents than in the relatively quiescent basin interior, and that these differences have a systematic effect on the magnitude and global distribution of wind energy input to near-inertial motions (Zhai et al., 2007). The effect of the mesoscale velocity field on the forced response of near-inertial waves has been neglected in previous efforts to quantify the global input of energy from the wind to near-inertial motions (e.g., Alford, 2003), in part because of the previous lack of observational opportunity to understand the systematic effects of mesoscale variability on wind-forced inertial variability.

Dissipation: What is the relative amount of mixed-layer near-inertial energy that actually reaches the deep ocean and how does it contribute to determine the abyssal stratification? Despite probable systematic errors in global estimates of the energy flux from the wind to near-inertial motions, the wind is believed to supply energy to the ocean at a rate on the order of 0.5–0.7 TW (1 TW=10^{12}W) (Watanabe and Hibiya, 2002; Alford, 2003; Wunsch and Ferrari, 2004). A significant fraction of the near-inertial kinetic energy put in at the surface may be dissipated in the upper ocean before it can propagate to the deep ocean. Certainly, there is near-inertial energy in the deep ocean, but the relative contributions to this energy from surface forcing and other mechanisms for generation of inertial waves (e.g., topographic generation, nonlinear wave-wave interaction) is poorly constrained. Numerical studies of wind-forced inertial oscillations suggest that about half of the wind energy input may be dissipated in the mixed layer and at its base during forcing events (Crawford and Large, 1996; Skyllingstad et al., 2000). Isolated, short-term field observations of turbulent dissipation (Hebert and Moum, 1994; Alford and Gregg, 2001) suggest that 20–40% of near-inertial energy may be dissipated as the waves propagate through the pycnocline.

4.2 Proposed analyses and approaches (near-inertial motions)

4.2.1 Generation of inertial oscillations in the mixed layer:

- Wind work is the result of a wind field acting on the mixed layer flow field, both of which vary on many different scales. The KESS data provide us with an opportunity to relate directly measured mixed-layer currents over several hundred kilometers to the atmospheric wind field.
- We will be able to calculate the coherence and the spin-up and decay time scales of the inertial oscillations in the mixed layer.

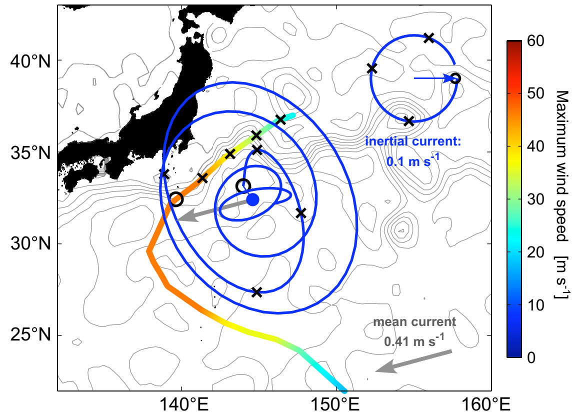

Figure 2: Path of typhoon Saola passing through the KESS array and mixed layer response. Colors along the track are the storm maximum wind speed. The blue line shows the mixed layer velocity measured at the KEO site: a straight line from the mooring (blue dot) to the line would represent the velocity vector (scale in top right corner). We start plotting velocities when the storm reaches the latitude of the mooring (24 Sept. 2005 19:30, "o"), and every 6 hours thereafter is marked with a "x". A build-up and decay of near-inertial motion as the storm passes is evident. The low-frequency velocity at the mooring site is plotted in gray.

We will follow the procedure of Plueddemann and Farrar (2006) to quantify the energy flux from the wind to near-inertial motions in the mixed layer using observations of the surface forcing and evolution of mixed-layer depth and velocity. Air-sea fluxes, wind, and radiation conditions are measured every 10 minutes at KEO. Along the mooring line, 12 sensors measure water temperature in the upper 500 m (7 in the upper 100 m) during the first year, and 29 the second year (12 for the top 100 m). Currents are directly measured at 15 and 35 m during the second year. The procedure involves using the observations to evaluate the expression for the energy input derived from the slab model, but unlike approaches that use only the wind stress, no assumption about dissipative and radiative energy loss is required. This procedure will be modified to account for the effect of the strong mesoscale flow by incorporating results from previous studies of the interaction of near-inertial variability with mesoscale motions (e.g., Weller, 1982; Kunze, 1985; Lee and Eriksen, 1997; Park and Watts, 2005). Specifically, the momentum equation used to derive the expression for the energy flux would be linearized about the mesoscale flow estimated from the KESS array.

At each subsurface mooring site, mixed-layer currents were resolved by upward-looking ADCPs which accurately measured velocity below 20 m. Fig. 2 shows the mixed layer currents at KEO during the passage of typhoon Saola (Sept. 2005). As soon as the typhoon reaches the latitude of the mooring, strong inertial currents start to develop, grow significantly over the next day, and finally start to decay. This storm passed through the center of the KESS array and enhanced near-inertial motion can be seen in the upper ocean at each of the moorings. During each summer of the KESS field program, about half-a-dozen tropical cyclones reached the array.

The wind stress driving the near-inertial currents during KESS will be specified most directly by the hourly surface meteorological measurements from the KEO mooring. For other locations where the atmospheric variables were not directly measured, the wind stress is available from the ECMWF and NCEP reanalyses. These products provide reasonably reliable estimates of the winds for the region (Qiu et al., 2004; Bond and Cronin, 2008), but their coarse resolution means that the wind fields lack mesoscale variability. Other products, like the recently extended WHOI OAFlux products (Yu and Weller, 2004), address some of these limitations. Superior spatial resolution is provided by scatterometers such as QuikSCAT, but these products are available only every few days, compared with 6-hour intervals from the reanalyses. We plan to use scatterometer-based winds to validate reanalysis-based wind fields, and to quantify the typical magnitude of mesoscale variations. (We expect that mesoscale vorticity variations in the ocean will be more important to the near-inertial response than small scale variations in the wind field, but we will carefully reconsider the validity of this expectation.) Finally, the output from high-resolution numerical weather prediction model simulations will be available for selected cases. These simulations are being carried out as part of a separate project on air-sea interaction in the vicinity of KEO (PIs: Cronin and Bond). This model output will represent a synthetic data set with high temporal and spatial resolution of the atmospheric forcing for several (6–10) events during KESS, including typhoons and wintertime storms. In summary, the combination of these sources is sufficient to specify the broad-scale patterns in wind stress during the entire KESS project, and the detailed distributions of the wind stresses during the stronger events.

To complement and guide the analysis of the forcing of near-inertial motions in the presence of a strong mesoscale velocity field, we will use a three-dimensional, primitive-equation, hydrostatic numerical model (Price et al., 1994). This model was designed for simulation of the upper-ocean response to hurricanes, and the vertical mixing scheme used in the model and its one-dimensional predecessor (Price et al., 1986) has been shown to do a reasonably good job of simulating the vertical mixing and energy dissipation observed during both moderately and extremely strong near-inertial forcing events (Price et al., 1994; Plueddemann and Farrar, 2006; Sanford et al., 2007). We will examine the upper-ocean response to particular wind events in the KESS region by forcing the model with the aforementioned high-resolution wind stress fields and initializing the model with a geostrophically-balanced mesoscale velocity field estimated from the KESS observations. We will also conduct idealized experiments to better understand the effect of the mesoscale flow field on the generation and propagation of near-inertial waves. A limitation of this model is that it considers the ocean to be infinitely deep (i.e., it employs the reduced-gravity approximation), but previous work suggests that this approximation does not seriously distort the response in the upper few hundred meters (Price et al., 1994; Sanford et al., 2007). We will consider using a more sophisticated model if other aspects of the proposed analysis indicate that understanding of the response of the upper- and mid-ocean requires explicit consideration of the response near the seafloor or if it becomes clear that understanding of the deep-ocean inertial response would be significantly improved using such a model.

The imbalance of wind-energy input and the rate of change of mixed-layer near-inertial kinetic energy gives an estimate of the combined contributions to the mixed-layer near inertial kinetic energy balance from wave radiation, interaction with the mesoscale flow, turbulent dissipation, and conversion of kinetic to potential energy during vertical mixing and entrainment. Understanding the amount of wind-forced near-inertial energy that actually reaches the deep ocean is essential to understanding the role of near-inertial waves in the global ocean energy balance. A shortcoming of the observations analyzed by Plueddemann and Farrar (2006) was the lack of vertical coverage and horizontal resolution required to study the (local) loss of energy from the mixed layer by wave radiation. The KESS moorings will allow quantitative assessment of the vertical flux of near-inertial kinetic energy after forcing events. The array is located in a region neighboring strong near-inertial energy flux from surface wind disturbances, and is especially well suited to address the shortcomings of our current understanding of the role of near-inertial oscillations in mixed layer dynamics.

4.2.2 Vertical and horizontal propagation of inertial oscillations:

- The KESS data provide us with a unique opportunity to describe the spatial extent and coherence of the near-inertial waves as they propagate to the deep ocean.
- The near-inertial energy flux can be calculated from sub-surface moorings to infer propagation direction and how much energy escapes the generation region.
- The CPIES array and moorings capture the low-mode and bottom inertial energy across the entire Kuroshio Extension region, allowing us to describe the near-inertial potential and kinetic energies and their relation to atmospheric forcing for individual events as well as in terms of seasonal variability (winter storms vs. tropical cyclones) and changes in mesoscale variability (regime changes).

- We can quantify the effect of mesoscale currents on the generation of near-inertial oscillation in the mixed later and in the deep ocean. Do eddies play a first order role in funneling the near-inertial motion to depth? Is the energy of the near-inertial waves dissipated primarily in mesoscale features?

The high density of observations at each of the mooring site will allow us to compute the vertical distribution of near-inertial energy. All moorings have a near-complete record of velocity from 20 to 250 m from the ADCPs. Current meters at 1500, 2000, 3500, and 5000 m will allow to effectively resolve the deep ocean. The MMPs profiled with a period of 15 hours, aliasing the near-inertial frequency to periods of about 2 days (45.4 hours at KEO), fortunately a minimum in variance between mesoscale and internal wave variability. By band-passing around the aliased frequency, the near-inertial velocity and isopycnal displacements in the main thermocline can be inferred with a time scale of about 2.5 days. In early January 2005, a software glitch made the MMP of the subsurface mooring nearest to KEO (KESS 7) profile every 2 hours (also from 250 to 1500 m), thus resolving the near-inertial frequencies for almost a month during strong winter forcing, before running out of power later that month. The good vertical and temporal resolution of stratification and velocity from this MMP will allow an indirect estimate of the dissipation of turbulent kinetic energy (e.g. Gregg et al., 2003), and we will use this information to examine the energy budget for near-inertial waves and to determine whether the coarser vertical resolution of the subsurface moorings will allow similar estimates over a longer time period.

The high horizontal density of KESS CPIES array will allow us to compute the horizontal distribution of near-inertial energy. Park and Watts (2005) demonstrated the instrumental capability of the inverted echo sounder for detecting near-inertial waves. The CPIES array will be used to estimate to estimate the low-mode near-inertial kinetic and potential energy, resolving its spatial and temporal variability over the course of the 2-year observational period. The bottom current meters will provide a direct measurement of the magnitude of inertial oscillation near the bottom.

In particular, we will be able to describe the oceanic response to **individual events**. The KESS field program featured a number of strong forcing events, namely strong cold-air outbreaks, wintertime extratropical storms, and tropical cyclones (typhoons). The latter passed through, to the west, and to the east of the KESS array, providing the opportunity to document the response to winds rotating both clockwise and counterclockwise with time at a particular location. At the tall subsurface mooring sites, the velocity and temperature time series data will be used to compute potential energy, kinetic energy, and baroclinic wave energy flux in near-inertial frequency bands. Methods described by Nash et al. (2004) and Alford and Zhao (2007) will be followed. The consistency of the near-inertial energy distribution over the array with the energy flux vectors from the moorings and the storm tracks will be quantified.

By contrasting the response to winter storms to that of the summer tropical cyclones, we anticipate that our results will give insights in the **seasonal variability** of the inertial oscillations and their contribution to the mixed-layer heat budget and thermocline mixing (Alford and Whitmont, 2008).

Since the 2-year KESS program captured a regime change (from low to high mesoscale activity), and the ongoing KEO measurements, we can discuss statistics calculated over several months in terms of the mean mesoscale kinetic energy and hence **long-term variability** (decadal). As an example of the potential impact of the mesoscale flow field on levels of near-inertial energy in the deep ocean, we carried out a preliminary calculation of power spectra using KESS near-bottom current meter data. The left panel of Fig. 3 shows variance-preserving power spectra for zonal and meridional currents in the 14 to 33 hour band including local inertial periods. At almost all locations, we observe a blue shift, consistent with the idea that the variability was generated at the surface at a higher latitude (Garrett, 2001). At A2 and B5 (located north of the Kuroshio), the spectra show

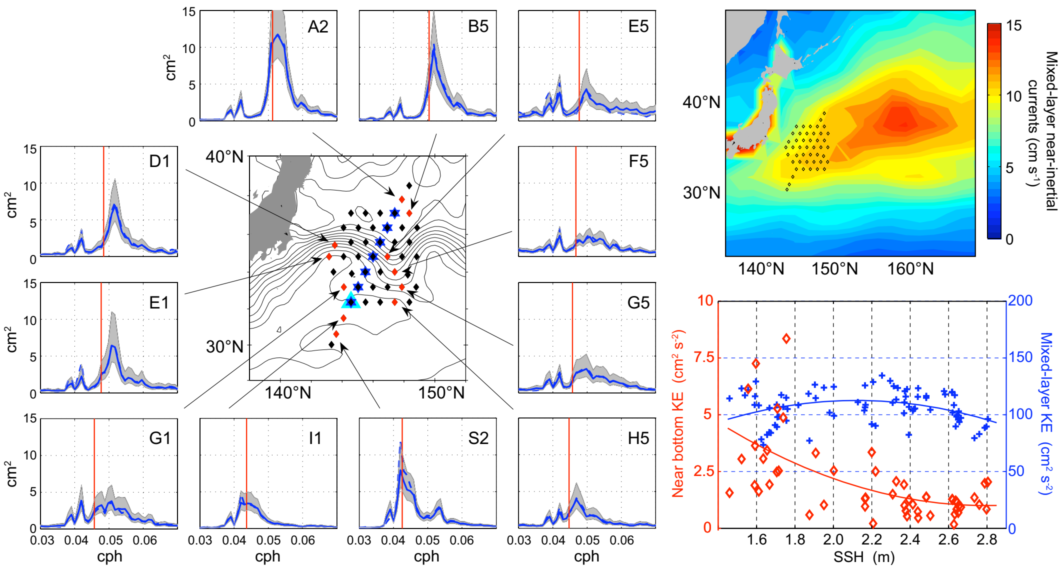

Figure 3: Left panels: Variance-preserving power spectra for zonal (solid blue line) and meridional (dashed blue line) components of near-bottom currents at 12 CPIES sites as shown. Vertical red line and gray-shading in each power spectrum frame indicate the local inertial frequency and 95% confidence interval, respectively. Upper right panel: Mean amplitude of near-inertial current in the surface mixed layer during winters 2004 and 2005 (Nov.-Mar.), predicted from NCEP/NCAR wind data using a simple slab mixed-layer model. Lower right panel: Scatter plot near-inertial kinetic energy near bottom (red diamonds) and in the mixed layer (from slab-model, blue crosses) estimated during the two winters at the CPIES sites. Red and blue lines are fitted by second-order least-squares.

strong near-inertial energy peaks. Western sites D1 and E1 show relatively strong near-inertial energy peaks having the most significant blue shifts. Instruments spanning the current (E5, F5, G5, and H5) reveal a progressively decreasing and increasing near-inertial energy trend across the Kuroshio meandering trough.

We compared the mean inertial kinetic energy at the bottom with the kinetic energy of inertial motions in the mixed layer that are predicted from winter time NCEP/NCAR wind data using a damped-slab mixed-layer model (Pollard and Millard, 1970) with finite temporal wind sampling correction (Niwa and Hibiya, 1999). In this preliminary comparison, the mixed-layer depth and temporal damping scale are uniform and are set to 75 m and 4 days, respectively. This is not appropriate for the entire region and the work proposed in the previous section will improve on those issues and several more, but this serves as an illustration of our planed analysis. Overall, larger near-inertial energy is observed in a region north of the Kuroshio than south of the Kuroshio (lower right panel of Fig. 3), though the predicted wintertime-mean near-inertial energy input from the wind to the mixed layer shows relatively homogeneous distribution (upper right panel of Fig. 3). The impact of the Kuroshio and mesoscale field on the near-inertial waves cannot be ignored.

The mesoscale velocity field can dramatically affect the vertical propagation of near-inertial energy. In particular, near-inertial waves can become trapped in anticyclonic mesoscale eddies, leading to the so-called 'inertial chimney' effect (Kunze, 1985) in which the vorticity of an anticyclonic eddy acts as a waveguide to funnel near-inertial energy to the deep ocean. While there is some observational (Kunze et al., 1995; Park and Watts, 2005) and numerical (Lee and Niiler, 1998; Zhai et al., 2007) evidence for this effect, the importance and effectiveness of this mechanism compared to others (such as β-dispersion, D'Asaro (1989), or inertial pumping, Price (1983)) as a means for radiation of near-inertial energy to the deep ocean is still unclear. Numerical studies have suggested that near-inertial energy in the ocean resulting from the wind has a much smaller

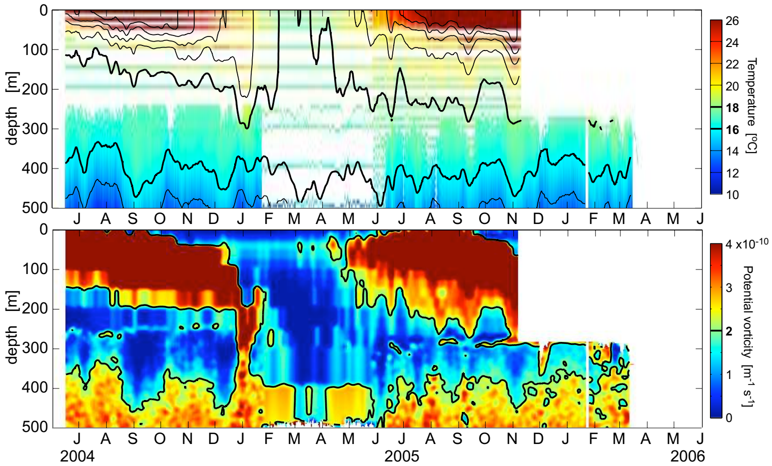

Figure 4: Upper ocean depth-time maps of temperature (top) and potential vorticity (bottom) at the KEO site. Temperatures in the upper 200 m are from individual sensors on the KEO mooring, and deeper measurements are from the nearby subsurface mooring. Isotherms (spaced by 2°C, 16 and 18°C in bold) and Q = 2×10^{-10} m^{-1} s^{-1} are plotted. The STMW (subsurface potential vorticity minimum) is renewed in winter when the mixed layer penetrates to 400m.

spatial scale than the expected spatial distribution set by the scale of the wind field (Zhai et al., 2005, 2007). In these studies, the mesoscale eddies also appear to be a dominant factor for the generation of near-inertial waves as well as their propagation. The CPIES array and the subsurface mooring line will allow us to examine these processes and experimentally track the ocean response to wind fields of varying scales (from large-scale winter storms to well-defined typhoons).

5 Thermal response to episodic atmospheric forcing

5.1 Background

Particularly in the Kuroshio Extension region, the oceanic response to atmospheric heat fluxes plays a important role for several dynamical processes. Here we emphasize that the thermal and mechanical/dynamical responses of the ocean to atmospheric forcing must be considered together.

Wintertime forcing: Although typically only tens of meters thick, the layer with nearly uniform density directly in contact with the atmosphere can reach 300 to 400 m in winter when cold-dry continental air is blowing across the warm Kuroshio Extension water, resulting in some of the largest net surface heat fluxes found in the entire North Pacific basin. In the spring, as the net-surface heat flux changes sign (becoming a heat gain rather than heat loss by the ocean), a seasonal thermocline begins to form, effectively trapping the mixed water, which then forms a 300 to 400-m thick layer with little stratification and nearly uniform temperature (T≈18°C, Fig. 4). This thick water mass, referred to as North Pacific Subtropical Mode Water (STMW), is found over most of the eastern part of the subtropical gyre (Masuzawa, 1969). To first order, the formation rates and properties of STMW are thought to be dependent on the winter-time atmospheric air-sea fluxes (Bingham, 1992; Suga and Hanawa, 1995), which are associated with synoptic weather patterns (cold-air outbreaks). The timing of these events relative the mesoscale eddies appears to be crucial (Qiu et al., 2007; Rainville et al., 2007). On interannual timescales, other processes including oceanic appear to influence the wintertime net heat flux (Bond and Cronin, 2008).

Some studies have suggested that the formation is a localized process and that the STMW is rapidly spread out over the entire gyre by horizontal advection (Suga and Hanawa, 1995). On the other hand, it has been suggested that STMW in the recirculation gyre is isolated and all the decay in the thickness observed over the course of the year is due to local vertical mixing (Qiu et al., 2006). By studying STMW erosion in a high-resolution model (POP model), Rainville et al. (2007) found that advection (particularly eddy transport) is critical, but enhanced vertical mixing is necessary to locally erode the STMW during the winter. They suggested that processes that can enhance dissipation, such as near-inertial internal wave breaking and trapping by eddies or mean currents, might play an important role in eroding STMW.

Preliminary analysis of a one-dimensional PWP upper-ocean model (Price et al., 1986), forced by the local surface heat fluxes observed at KEO, show that realistic erosion of the seasonal thermocline required vertical diffusivity values around 3×10^{-4} m^2 s^{-1} at least 3000 times the molecular diffusivity and elevated relative to values typically used in numerical models ($\sim 10^{-5}$ m^2 s^{-1}). This suggests that during the fall heat from the seasonal thermocline is mixed with the STMW below. The immediate question to be addressed in this study is what causes this enhanced mixing? Modification of the STMW temperature through mixing has implications on "reemergence" theories, whereby mode water whose temperature was set during the previous winter, reemerges in the following winter (Alexander et al., 1999; Sugimoto and Hanawa, 2005).

Summertime forcing: During the summertime, the ocean gains heat in the KESS region through solar radiation and the reduction in surface latent and sensible heat loss. The STMW is isolated from the atmosphere by a seasonal thermocline. Summertime variations in net surface heat flux tend to be associated with cyclones of tropical and extratropical origins, which cause a reduction in solar radiation due to clouds, and, in the case of tropical cyclones, are also associated with strong wind forcing. Recent studies (Emanuel, 2001; Sriver and Huber, 2007) have suggested that tropical cyclones play a major role in the upper-ocean heat budget and global ocean energy budget. Tropical cyclones induce strong near-inertial oscillations (see previous section), which can have strong vertical shear and erode the base of the mixed layer, effectively cooling the upper ocean (Large et al., 1986; Price et al., 1994).

Typically, many assumptions are involved in calculating the net effect of these storms: for example Sriver and Huber (2007) use satellite SST observation to measure the cold wake of tropical cyclones and assume that the depth of the anomalies are uniform (50 m), and assume the characteristic timescale of 24 hours for mixed-layer deepening and entrainment. The KESS upper ocean ADCP current profile measurements and the KEO surface flux and subsurface temperature and salinity measurements provide unprecedented direct observations of the surface forcing and subsurface response to typhoons, which will allow great refinement in estimating the relative impact of mechanical mixing and heat-flux forcing.

5.2 Proposed analyses and approaches

5.2.1 Subtropical Mode Water: impact of episodic heat fluxes and wind.

- The formation of STMW is a highly variable process in both space and time (Rainville et al., 2007). We can test if mode water formation is dominated by episodic events with time scales of days that can be directly related to wind storms.
- With this data set, we will be able to quantify the importance of lateral advection versus local mixing. Is the mode water eroded primarily by enhanced mixing? Is the local vertical mixing primarily due to enhanced near-inertial waves, or to the more continuous and predictable internal tides, or to the mesoscale eddy field?
- We will document how the formation of STMW is modulated by mesocale dynamics (Cerovečki and Marshall, 2007). In particular the orientation of the fronts relative to the wind direction is likely to play a major role in the local potential vorticity budget (Thomas and Lee, 2005).

A 3-dimensional heat-balance analysis of the upper mixed layer at KEO is currently underway. The analysis, led by M. Cronin (PMEL), uses the KEO surface-forcing and mixed-layer temperature observations from KEO, in combination with advection estimates based on KESS ADCP and subsurface-float data, and satellite fields. The residual of the temperature tendency balance provides a measure of the role of vertical exchange of fluid at the mixed-layer base (e.g., Cronin and

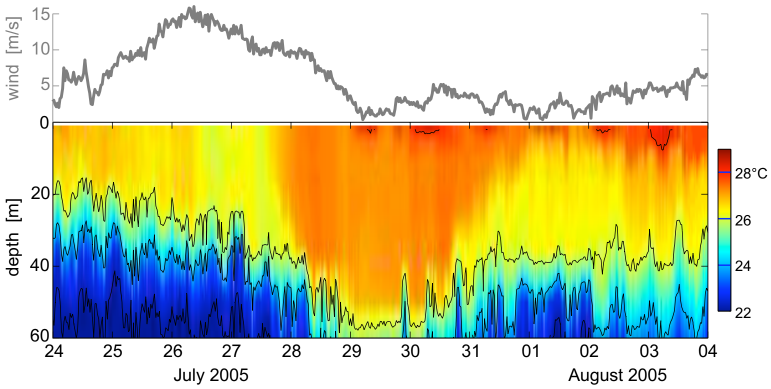

Figure 5: Depth-time map of the temperature in the upper 60 m after the passage of tropical storm Banyan northwest of KEO (local wind speed plotted in gray). Strong inertial oscillations are present, a cooling of the mixed layer is evident after the maximum winds (July 26), and soon after the signature of a a warm eddy is also seen. All scales need to be taken into account in order to understand the oceanic response.

McPhaden, 1997), and will be used for understanding the building and decay of the seasonal thermocline. This will allow us to determine the importance of pre-conditioning and of individual wind events in both the formation and erosion of STMW.

Towards this goal, we propose to calculate a mass and heat budget of the STMW layer. The entrainment and mixing terms of the mixed-layer budget from Cronin can be viewed as the upper-boundary condition when the STMW is isolated from the atmosphere. In this case, the impact of the near-inertial oscillations obtained from the analyses described earlier will be essential to understand the local mixing at the top and base of the STMW layer. This will be part of the calculation of a regional heat balance (Kelly and Dong, 2004) that includes all components of the KESS data set and the best available satellite products: The total surface currents from OSCAR (http://www.oscar.noaa.gov) will be blended with the full-water column geostrophic currents by combining the C-PIES, moorings, and floats measurements with satellite sea-surface height. The moorings and high number of floats can provide the temperature and salinity fields with the best spatial and temporal resolution available anywhere. As mentioned earlier, atmospheric fluxes are available from NCEP and other sources, and will be corrected for biases based upon KEO.

5.2.2 Analysis of mixed layer dynamics during and after typhoons:

- Estimate the relative roles of surface fluxes, horizontal advection, and vertical mixing, and entrainment in the mixed layer response to typhoon forcing.
- Quantify the contribution of late-season typhoons in eroding the seasonal thermocline and thus contributing to STMW formation.

During the KESS study period, several typhoons passed through the KESS study region, providing an unprecedented opportunity to analyze the ocean subsurface response to typhoon forcing. In several cases (e.g., Ting-Ting), the typhoon passed to the east of KEO, while in other cases (e.g., Saola shown in Fig. 2), the typhoon passed to the west. Because the potential resonance between the turning of the winds and the currents is much higher on the righthand side of the typhoon track, the near-inertial response is expected to be quite different for these different passages. Presumably the mixed layer also responds differently in the two cases, in terms of the importance of wind mixing relative to the surface heat fluxes. To the degree that typhoons feel and respond to the ocean SST, understanding how the SST and heat content are affected by the passage of the typhoons could lead to better typhoon forecasts.

The forcing of mixed-layer near-inertial oscillations and the mixed-layer heat budget during periods of strong typhoons/storms are intimately linked. During the brief period when the winds are strong and energy is being put into mixed-layer near-inertial motions, wind-driven vertical mixing and cooling causes the mixed layer to deepen, entraining fluid from the transition layer below. This deepening can be seen on 26 July 2005 in Fig. 5, during the passage of tropical storm Banyan near KEO. This mixed-layer deepening and concomitant change in stratification is associated with turbulent dissipation of kinetic energy and conversion of kinetic energy to potential energy, affecting the kinetic energy budget of the mixed layer and the subsequent input of kinetic energy from the wind (Plueddemann and Farrar, 2006). For a given wind event, the extent of this deepening of the mixed layer depends on the pre-existing stratification, which is set in part by the history of the surface heat and momentum fluxes. The deepening of the mixed-layer during strong wind forcing has important consequences for the inertial response, but it is also of obvious importance for the heat budget of the mixed layer. Thus, we view these two aspects of the proposed analysis as being intertwined. Mesoscale dynamics cannot be ignored either. For example, warm water was advected past KEO just after the storm Banyan (Fig. 5). The analysis of oceanic response to short-lived storms involves multiple processes and the KESS data set offers an unprecedented opportunity to resolve many of the time and spacial scales involved.

6 Relevance to CLIVAR programs

6.1 KESS collaboration

The KESS proposed goals were to identify and quantify the dynamic and thermodynamic processes governing the variability of and the interaction between the Kuroshio Extension and the recirculation gyre. The field program comprised quasi-real-time data quasi-real-time data sets (satellite, KEO met-buoy, and a dedicated suite of profiling Argo floats) and 2-year moored observations (subsurface moorings and CPIES array). The KESS observational program was highly successful; initial data processing and cleanup have recently been completed; and a KESS website has been developed (http://uskess.org) to disseminate results. Several publications have used the real-time data sets (Qiu et al., 2006, 2007; Bond and Cronin, 2008). Ongoing analyses are addressing a suite of originally proposed objectives under the above broad goals.

The ideas put forth in this new proposal are a natural outgrowth of a large experiment, developing partly from the originally envisioned goals of KESS and building upon new opportunities realized by investigators that continue to be entrained into KESS since its inception. In fact, only one of the PIs (Jayne) was a PI on the NSF-funded KESS field proposal. Current work by other KESS PIs (R. Watts, K. Donohue, and N. Hogg) and a future proposal focusing on horizontal exchanges and larger spatial and temporal scales (mesoscale dynamics) will overlap with our effort.

6.2 Related programs

KESS has been included in CLIVAR from its planning phase. We are collaborating closely with the investigators involved in CLIMODE, a project to study the subtropical mode water of the North Atlantic. This project has taken different approach than KESS – primarily conducting direct (shipboard) observations of air-sea fluxes, and small- and fine-scale oceanic surveys of the Gulf Stream frontal region during winter mode water formation regions. Our approaches are complementary, and together we will investigate processes common to all subtropical mode waters in the world ocean. In that context, we have also been in contact with the SAMFLOC group, investigating Antarctic Intermediate Water formation in the southeast Pacific. The high density of our observations can help understanding the same dynamical processes at play in the Southern Ocean, and their observations will also broaden the scope of the proposed research. The processes discussed here are will also be a fundamental part of DIMES (studies of mixing in the Southern Ocean, an international project in which Rainville is involved), due to start field work next year. We are committed to sharing ideas and results with US and international colleagues, and panel and working group activities, such as U.S. CLIVAR Process Study and Model Improvement Panel (PSMIP) and

U.S. CLIVAR Working Group on Western Boundary Current Ocean-Atmosphere Interaction. Bond is a member of the latter, which considers a role of air-sea interaction in the Kuroshio Extension region on climate models in various scales. We also plan to travel to Asia to share results with international colleagues.

We are already part of a collaboration to assimilate the KESS and CLIMODE observations into the ECCO 1 degree ocean model. The planned analysis will be first to compare the mooring observations to the the ECCO climatology that has already been developed. Secondly a comparison of the KESS and CLIMODE STMW formation regions will be conducted. Despite the large spatial coverage of the CPIES array, the fine vertical resolution of the subsurface moorings, the large number of float profiles, and the high quality of atmospheric measurements at KEO, the data set cannot resolve all the scales needed to address some of the fundamental questions in this proposal. The scope of our observations will be expanded by using high-resolution numerical models. For example, studying STMW in the POP model, Rainville et al. (2007) were unable to determine where and how the mode water was destroyed. New POP simulations are being run with additional outputs saved to specifically understand these processes. In particular, the POP and ECCO simulations will used to calculate regional heat balance in the Kuroshio Extension. Guided by the observational results from the work proposed here, we will collaborate with the PIs, students, and postdocs involved in the model development and analysis to specifically examine the vertical processes in the model creating and destroying STMW in the context of both the meso- and large-scale dynamical state of the Kuroshio and episodic atmospheric forcing.

7 Work plan

This proposal emphasizes the need for a collaborative study, where the different components of the KESS field program and data from other sources will be combined and applied to understand the ocean response to atmospheric forcing in the Kuroshio Extension region. Our main objectives and the tasks of the different PIs are described here.

Rainville will focus on the propagation of near-inertial waves, their impact on the mixing at the base of the mixed layer and in the main thermocline, and on the STMW studies. He will be responsible for the processing and distribution of the KESS sub-surface mooring and KEO data. Near-inertial currents and isopycnal displacement will be isolated from the different instruments, the mixed-layer depth will be inferred from vertical shear and acoustic return intensity from the ADCP when no direct measurements are available. Rainville will calculate the (subsurface) energy fluxes and describe the vertical and horizontal propagation along the KESS mooring array. He will coordinate with Farrar and Bond to link the vertical inertial propagation with the mixed-layer studies. Rainville will work with Jayne to determine the impacts episodic near-inertial waves for the erosion of STMW.

Farrar will focus on the mixed-layer response to wind forcing, working with Rainville, Park, Cronin, and Bond. He will use the observations to diagnose terms in the near-inertial kinetic energy budget, including, for the first time, direct estimates of the contribution of interaction with a strong mesoscale flow and of vertical and horizontal energy propagation in such a budget. The kinetic energy budget of mixed-layer near-inertial oscillations is intimately linked to the mixed-layer heat budget, and he will work with Cronin and Rainville to coordinate these analyses. He will work with Rainville to link the surface energy input to the subsequent subsurface energy flux associated with near-inertial waves. This analysis of the observations will be supported by numerical modeling studies using a high-resolution three-dimensional primitive equation ocean model.

Bond will focus on specification of the atmospheric forcing. Forcing fields will be produced from reanalysis products, with validation of the winds from these products from scattterometers, for times when the latter data are available. He will also provide high-resolution NWP model simulations of air-sea fluxes for selected cases. He will collaborate with the other investigators in the selection of cases for intensive study, and in the interpretation of results.

Jayne will concentrate on analysis of numerical model output from POP and ECCO. He will coordinate with J. Marshall and the MIT group to compare and contrast the Gulf Stream (CLIMODE) and the Kuroshio (KESS) utilizing the ECCO assimilation products, combined with satellite products (SST, altimetry, OSCAR) and examine the Kuroshio regional thermodynamic budgets. He will combine the KESS observations with satellite data to obtain the synthesis fields. A portion of his time will be devoted to the continuing development and maintenance of the KESS website.

Park will primarily work on the interaction between background large- and meso-scale flow fields with near-inertial motions through full water column. He will be responsible for the processing and distribution of CPIES bottom current meter and acoustic-echo-time data for output at hourly intervals. Park will conduct case studies to interpret vertical and horizontal energy propagation of near-inertial waves responding to episodic tropical storms (typhoons) and winter storms. He will compute optimal-interpolated 3-D potential vorticity maps, and relate them to the episodic near-inertial wave energy distribution to look at its advection, reflection or trapping. Park will estimate low-mode near-inertial wave energy distribution using the acoustic-echo-time data and relate them with large- and meso-scale circulation patterns as well as the mixed layer near-inertial motions.

8 Broader impacts

This study is motivated by the need for a better understanding of the ocean response to atmospheric forcing and its central role in mixing the upper ocean. The current implementations of mixing in climate models are generally parameterizations based on a generic continuous spectrum of internal waves (Garrett and Munk, 1975). We believe, however, that mixing might be more event-driven. A major fraction of the energy in the ocean is contained in motions near the inertial frequency, but the generation of these near-inertial internal waves is temporally and spatially variable. The relative contribution of wind forcing and other mechanisms for generation of near-inertial variability in the deep ocean (e.g., parametric subharmonic instability and other wave-wave interaction or topographic generation) is poorly constrained. Understanding how these waves are generated, how they propagate, and how mesoscale currents affect their dissipation is crucial to our ability to include their important role in general circulation models. As global ocean models and wind fields achieve increasingly high resolution allowing direct simulation of near-inertial waves (e.g. Zhai et al., 2007), it will be important to have documented examples of the behavior of actual near-inertial waves in a strong mesoscale flow field.

Air-sea exchanges play a central role for water-mass formation and transformation. The focus of the present study is on STMW, but the same processes and feedbacks are likely to be important for ventilating and mixing the deep ocean everywhere that strong winds blow over an ocean full of fronts and mesoscale eddies, such as around the Southern Ocean. The understanding gained in this study will be applicable in many areas.

This proposal includes significant support for 3 early-career scientists (Farrar, Rainville, Park).

9 Data Management Plan

To encourage the broadest possible collaboration between the KESS investigators and to ease the access of data between institutions and the community at-large, we have established a centralized KESS website and a web server for all of the observational data (http://uskess.org). We are guided by the “best practices” that have been set forth by the CLIVAR Process Studies and Model Improvement Panel (PSMIP). The purpose of the website is multifold: beyond just hosting the raw data for community access, it also serves to describe the experiment and the observational program, provide ready access to all publications related to KESS, and hosts “value-added” data products such as movies of the data, mapped fields and derived fields. Our goal is to serve “off-the-shelf” products that would enable model-data comparisons. In its final form all of the information on the website could be written to storage media (DVDs) and would be handed off to an outside entity for archiving and future distribution. It is envisioned that some numerical model output will be hosted on the website, but due to its sheer volume, it is impractical to serve significant pieces of it from a website. It is most important that there be descriptions of what simulations are available (e.g. NRL/NLOM, ECCO, SODA and OFES), what model output is available from each simulation, and the steps necessary to access the output.

Results from Prior NSF Support

Collaborative Proposal: Kuroshio Extension System Study (KESS) OCE-0220161: $2,116,287, 02/01/2003 to 1/31/2008 N. G. Hogg and S. R. Jayne

In the collaborative KESS project, this award supported the subsurface mooring component, equipped with upward-looking ADCPs, moored profilers, and current meters. We have presented initial results at national and international meetings and KESS web site. Rainville et al. (2007) diagnosed the formation of subtropical mode water in the POP model. Studies in preparation and near completion include evidence for a northern recirculation gyre (S. Jayne lead author) and an interpretation of deep currents within a linear Rossby wave context (N. Hogg lead author).

Rainville, L., S. R. Jayne, J. L. McClean, and M. E. Maltrud, 2007: Formation of subtropical mode water in a high-resolution ocean simulation of the Kuroshio Extension region. *Ocean Modelling*, **17**, 328–356.

Analysis of full-depth profiles of mixing observations across the Arctic Ocean ARC-0612342: $136,485, 07/01/2006 to 06/30/2007 P. Winsor and L. Rainville

We analyzed a set of microstructure profiles collected in 2005 to estimate the turbulent dissipation rate and its spatial distribution across the Arctic. Results have been presented at conferences and two papers have been submitted with Rainville as lead author.

Internal Tides and Inertial Oscillations: Analysis of Observations in the Gulf Stream south of New England OCE-0453681: $174,251, 03/15/2005 to 02/29/2008 J.-H. Park and D. R. Watts

This project relates near-inertial and super-inertial internal gravity waves to the sub-inertial mesoscale processes using an array of PIESs and tall current moorings in the Gulf Stream. Results has been presented at the 2006 AGU Fall Meeting. In addition to the originally proposed study, we discovered a basin-scale nonisostatic response to the 5-day-period Rossby-Haurwitz atmospheric pressure wave using bottom pressure.

Park, J.-H. and D. R. Watts, 2006: Near 5-day nonisostatic response of the Atlantic Ocean to atmospheric surface pressure deduced from sub-surface and bottom pressure measurements. *Geophys. Res. Lett.*, **33**, L12610,doi:10.1029/2006GL026304.

US-GLOBEC NEP Phase IIIb-CGOA Environmental Influences on Growth and Survival of Southeast Alaska Coho Salmon in Contrast with Other Northeast Pacific Regions OCE-0627247: $70,918 (University of Washington component), 03/15/2006 to 30/04/2009 N. A. Bond

This project involves a combination of retrospective and field work related to coho salmon and their habitat. The PI is characterizing the regional oceanographic conditions encountered by the salmon and relating them to climate-scale variability. The early results indicate the adult returns from individual stocks exhibit less coherent fluctuations than originally supposed, and these returns are more controlled by predation than food availability. Generally, the quality of habitat for these salmon does not appear to be simply related to the basin-scale climate.

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