C. PROJECT DESCRIPTION

1 Introduction

The warm, northward-flowing waters of the Kuroshio western boundary current leave the Japanese coast to flow eastward as a free jet into the North Pacific – the Kuroshio Extension (KE) which forms a vigorously meandering boundary between the warm subtropical and cold northern waters of the Pacific. Water crosses this front in the surface wind-forced Ekman layer, in meander crests and troughs, and in warm or cold-core rings (Talley et al. 1995; Yasuda et al. 1996; Joyce et al. 2001).

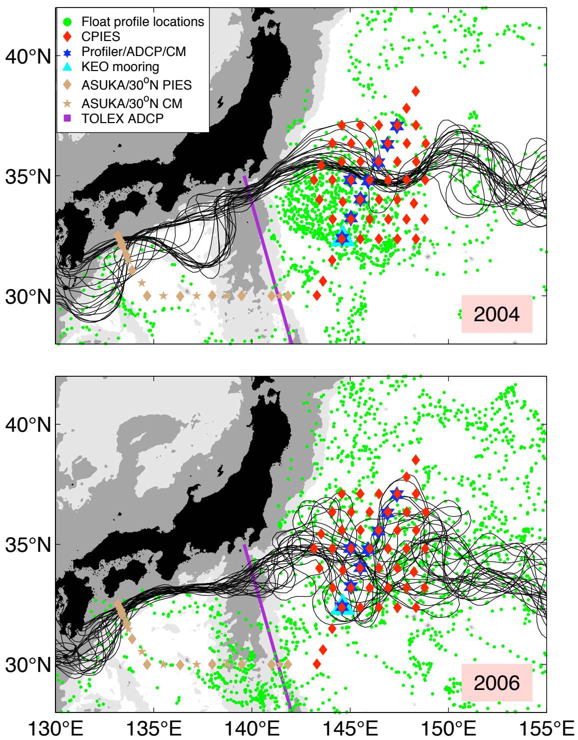

Figure 1: Maps of KE path defined by the 180 cm contours of sea surface height based on altimeter data for (top) 2004 and (bottom) 2006 (after Qiu and Chen 2005). The KESS array consists of CPIES (red diamonds), moored profilers (blue stars) and the KEO buoy (blue triangle). Profiling floats hydrocasts are denoted by green dots. The ASUKA and 30°N lines consisted of PIES (tan diamonds) and current meters (tan stars). ADCP data are collected along the TOLEX ferry route (purple). The 2000 and 4000 m isobaths are shaded gray.

Recirculation gyres exist south and north of the KE (Qiu et al. 1995; Qiu et al. 2008). Their size, strength and the intensity of meandering vary on decadal time scales and are thought to be coupled by the along-stream transports and cross-frontal exchanges of dynamical properties.

With support from the National Science Foundation a large, multi-institutional, international investigation of the KE was undertaken in the spring of 2004. Known as KESS – the Kuroshio Extension System Study – this was an ambitious deployment of modern instrumentation. Its goals were to understand the processes that govern the intense meandering and eddy variability of the KE, the recirculation gyres and subtropical mode water, and determine the role of air-sea interactions upon the underlying ocean and on the overlying atmosphere (Fig. 1). With the successful completion of the field program in 2006, analyses are underway and the data have been released through a centralized website (http://www.uskess.org). A related KESS analysis effort , a NSF-funded project from Rainville, Park, Bond, Farrar, and Jayne, focused on the ocean's response to atmospheric forcing. That project has a natural link with the NSF-funded CLIMODE experiment through their mutual goal to understand mode water formation.

Here we propose to complete the next level of analysis, evolved from the original KESS goals, and focussed upon understanding mesoscale processes in the KE. We will use observations from KESS and remote sensing, as well as three global ocean circulation models. Mechanisms that create mesoscale variability in the jet include barotropic and baroclinic instability, changes in upstream conditions, external forcing, the interaction of the jet and eddies with topography, wind forcing, and remotely-generated eddies propagating into the region. We postulate these to be the most influential processes acting in the KE, with important consequences: First, cross-frontal fluxes transfer water properties across the KE front. Second, potential vorticity (PV) flux divergences drive the recirculation gyres.Third, regime shifts arise from changes in the PV structure of the KE and recirculation gyre system.

The KESS field program fortuitously captured a regime transition in late 2004. The most recent weakly-meandering (so called "Stable") state, which had begun in 2001, exhibited the characteristic quasi-stationary meanders east of Japan (Fig. 1) and a strong zonally-elongated recirculation gyre. In December 2004 the KE switched into its strongly-meandering ("Unstable") state; its path became highly variable, eddy energy increased dramatically, and the recirculation gyre was obscured (Fig. 2). Qiu and Chen (2005) have shown that this switch between regimes has occurred on a multi-year time scale over the past 15 years.

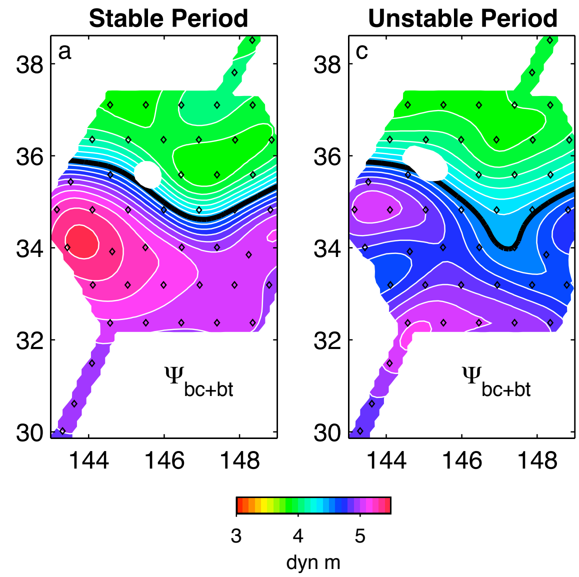

Figure 2: A strong recirculation gyre extended across the southern end of the KESS array during the weakly-meandering period (left) whereas the gyre was weaker, less extensive and fractured during the strongly-meandering period (right). Mean absolute streamfunction at the surface is contoured; the highlighted contour is used as the path indicator in Fig. 3

The change in eddy energy within the KESS array accompanied several dynamic processes: steep meander growth, ring formation, and ring-stream interaction. The increase in eddy energy was not limited to the upper ocean; it was also evident in the subthermocline ocean (Fig. 3).

Several mesoscale processes might account for the rapid change in the dynamic state of the KE. Qiu and Chen (2005) suggest that interannual variability in wind stress curl farther to the east over the central North Pacific and the resulting production of baroclinic Rossby Waves which carry this information westward: negative sea surface height anomalies impinging on the KE force it southward over a shallow segment of the Izu-Ogasawara Ridge, and this leads to large downstream meanders. Alternatively, Taguchi et al. (2005) show that in a numerical model, incident wind-curl-driven Rossby waves can change the potential vorticity (PV) structure and stability properties of the system.

Here we suggest additional mechanisms, motivated by the KESS observations. During the Stable period, frontal waves persistently propagated along the KE axis, facilitating cross-frontal exchange especially within intermediate layers as noted by Kouketsu et al. (2007). The interaction between these frontal waves and preexisting deep eddies may steepen the meander trough and initiate ring separation. Another mechanism follows from observation that a warm-core eddy absorbed in the first crest was followed by a steep 'reverse-S' shaped meander and formation of a cold-core eddy downstream. Perhaps the Unstable state reflects a readjustment of the KE after it merges with the warm-core eddy, and rings beget more rings and meanders.

Finally, the well-documened recirculation gyre to the south of the KE has interannual modulation (Qiu 2003; Qiu and Chen 2005). The existence of one to the north now has confirmation from the KESS observations (Qiu et al. 2008). The Kuroshio Extension differs from the Gulf Stream where gyres of almost equal strength flank the stream (Hogg 1992). Eddy forcing is likely to be present in the KE, as it is in the Gulf Stream, but how this works where the topographic setting is quite different and the KE configuration downstream of the separation point is so different, as well, motivates additional topics that we propose below to study.

2 Observations

The KESS array, deployed in summer 2004 and recovered summer 2006, comprised inverted echo sounders equipped with bottom pressure gauges and current meters (CPIES) and tall subsurface moorings deployed across the jet (Fig. 1). The moorings, equipped with upward-looking acoustic Doppler current profilers (ADCP), McLane moored profilers (MMP), and current meters resolved the fluctuations in the density and velocity fields through most of the water column. The KESS collaboration also deployed profiling floats and conducted shipboard hydrographic surveys.

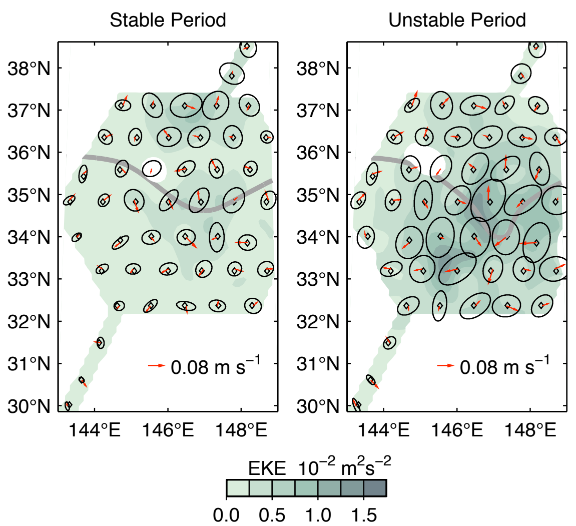

Figure 3: Weaker EKE (color-shaded) nominally at 5300 dbar during the Stable period (left) compared with the Unstable period (right). Mean currents and standard deviation ellipses are shown. The mean path of the KE is indicated (gray).

The Kuroshio Transport and Surface Flux Group lead by Dr. H. Ichikawa at JAMSTEC maintains a website, http://www.jamstec.go.jp/iorgc/ocorp/ktsfg/, that consolidates many Japanese efforts in the Kuroshio. We highlight the most relevant projects. An array of PIES/current meters deployed along the ASUKA line and 30°N (Fig. 1) during October 2004 - September 2006 measured the Kuroshio through-flow south of Japan. In addition, repeat shipboard ADCP data were collected along the TOLEX ferry line from September 1997 to January 2005 (Hanawa et al. 1996).

A surface flux buoy, the Kuroshio Extension Observatory (KEO) deployed in the southern recirculation gyre, funded by NOAA as part of the OceanSITES network continues today. J-KEO, a comparable buoy deployed in 2007 north of the KE, is part of a joint US-Japan collaboration. In addition, an atmospheric sounding component released 260 GPS-sondes. While not the focus here, we mention these programs for completeness.

For the tall moorings, the current meters at 1500, 2000, 3500, and 5000 m, and the ADCP (0 to 250 m) yielded almost complete time series at all sites (>80% data return), while the MMPs had problems. Typically the MMPs worked after deployments in 2004 and 2005, but stopped profiling in strong currents and some had mechanical failures in winter months. For sites occupied for two consecutive years, the MMPs returned measurements at any given depth (250–1500 m) and any given day 55% of the time, with rates as high as 72% for a given site.

The CPIES array maps the velocity and density structures through the full water column. A CPIES measures round-trip acoustic echo time from sea bed to sea surface, allowing estimates of vertical profiles of temperature and density at each CPIES, utilizing empirical relationships established with regional hydrography. Time-series profiles of geopotential thickness are estimated at each site, and through geostrophy baroclinic shears are determined. Additionally, CPIES pressures and currents provide referencing to make the baroclinic velocity profiles absolute. This method has been successfully used in many frontal regions, for example the North Atlantic Current (Meinen and Watts 2000), and the Kuroshio (Andres et al. 2008). A manuscript by Donohue et al. (2008) documents the KESS application and quantifies errors.

The array has sufficient lateral spacing to estimate mesoscale dynamical quantities. Battery failures and shorts in the current meter cables caused many data records to stop early. Only one CPIES was lost, yet those data were downloaded by telemetry.We map current and density for the entire region for 16 months (June 2004–October 2005) and for subregions until May 2006.

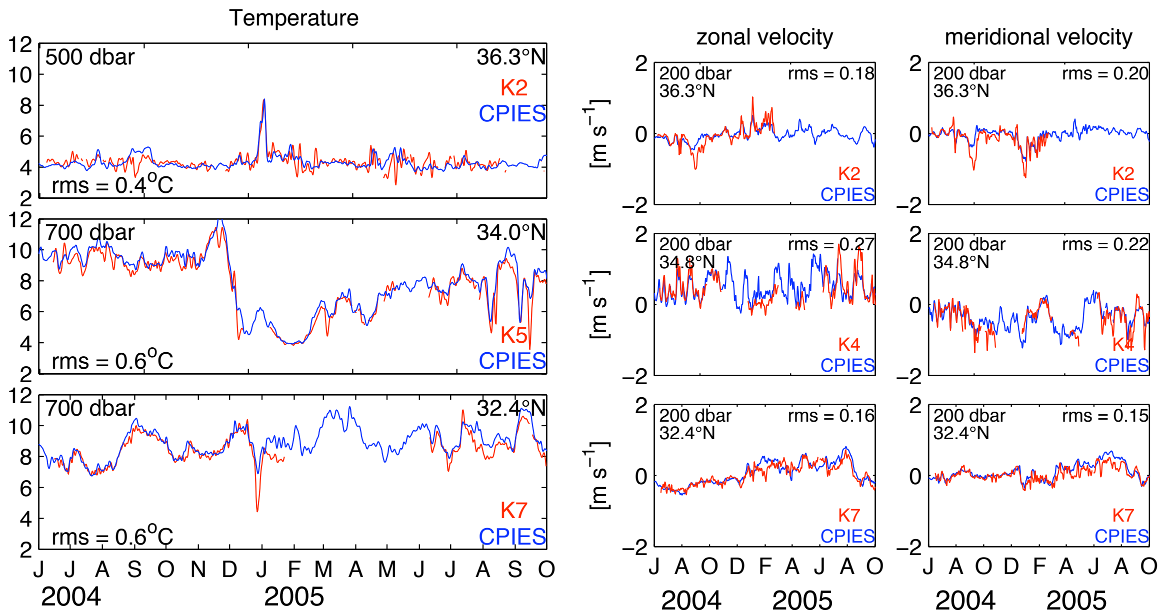

Figure 4: CPIES-estimated temperatures (left) and velocities (right) compare well to MMP-measured temperatures and ADCP-measured velocities.

CPIES-derived fields compare well with the tall mooring data (Fig. 4). CPIES mapped velocities account for about 80% of the signal overall across the KE, with rms error in geostrophic velocity only 10 cm s^{-1} at 200 dbar depth, and additional differences due to submesoscale variability. Importantly, the mooring-CPIES comparisons have verified our error estimates of temperature, specific volume anomaly and velocity. Mapped temperature and velocity rms differences decrease with depth and are typically less than 1°C (6 cm s^{-1}) at 500 m and 0.25°C (3 cm s^{-1}) at 800 m depth. These low error levels enable us to address the original KESS objectives and more, as proposed below.

3 Fine-resolution Global Ocean Simulations

POP In support of KESS goals (Rainville et al. 2007) used output from a 0.1°, 40-level global simulation of the Parallel Ocean Program (POP), forced with mainly synoptic atmospheric fluxes for 1979-2003 (Maltrud and McClean 2005; McClean et al. 2006; McClean et al. 2008), to examine the formation and variability of the North Pacific Subtropical Mode Water (STMW) over a three year period. Analysis conducted in parallel with the KESS field program demonstrated the role of explicitly resolved eddies to the representation of STMW in the KE region. Jayne et al. (2008) investigated the existence and strength of recirculation gyres in KE with this model.

Recently, improvements have been made to the POP model. These include the implementation of a global 0.1° tripole grid configuration which provides a much more isotropic grid in the KESS region than the previous displaced pole grid. Additionally, partial bottom cells (Pacanowski and Gnanadesikan 1998) improve the presentation of the flows over the ocean floor. A marked improvement in the representation of the Northwest Corner in the North Atlantic and the path ways of Agulhas eddies has resulted (Maltrud et al. 2008). Currently, the simulation has been run for 32 years; it is forced with repeating monthly-averaged normal-year atmospheric fluxes constructed by Large and Yeager (2004) for the Common Ocean-Ice Reference Experiments (CORE). Normal year forcing consists of single annual cycles of all atmospheric data needed to force an ocean model and is representative of climatological conditions over 43 years of interannually varying atmospheric state. Synoptic variability *i.e.* atmospheric storms) is retained with a seamless transition from 31 December to 1 January (Large and Yeager, 2004). The forcing uses the NCEP/NCAR reanalysis corrected with scatterometer data that in particular improves the representation of the tropical circulation. Here we propose to conduct a 5-year global tripole 0.1° POP simulation forced with interannually-varying synoptic CORE forcing for the years 2000–2006 initialized from this spun-up ocean state. Another NSF project, if funded, would provide resources for a 5-year interannually varying simulation for 1994-1999 initialized from the 32-year spun-up state. If funded we would continue on from that simulation for 2000–2005.

Both state variables and cross-terms for flux calculations will be archived on a high-frequency basis (daily) in the northwest Pacific for the period of the KESS experiment to permit consistent comparisons with KESS data. We will then move beyond straightforward assessments by implementing a vorticity diagnostic package developed by Spall (1992) for the Community Modeling Effort (CME) model and used by McClean and Klinck (1995) to understand 50-day oscillations in the North Equatorial Countercurrent. The package calculates all terms in the full vorticity budget from model output including a truncation error term to assess the misrepresentation of spatial derivatives in the vorticity equation that arises from the model discretization. This diagnosis will complement results from the observational analysis and extend the vorticity analyses into space-time domains beyond the KESS window.

HYCOM We aim to complement model studies with the global 1/12° Hybrid Coordinate Ocean Model (HYCOM) hindcast simulation that includes the Navy Coupled Ocean Data Assimilation system (NCODA). The hindcast is forced with daily fields from the Navy Operational Global Atmospheric Prediction System (NOGAPS) for Nov 2003 to Aug 2008. State variables and atmospheric fluxes are archived daily, however cross-terms for complete ocean property flux calculations and budgets are not (http://hycom.coaps.fsu.edu/dataserver/index.html). We particularly hope that the assimilative run will improve the understanding of KE regime shifts. A non-data assimilative simulation using the same grid and forcing is available for Jan 2003 through Apr 2007.

OFES The JAMSEC Ocean General CIrculation Model for the Earth Simulatar (OFES) based on MOM3 is configured for the region 75° S to 75° S, excluded the Arctic and has 0.1° horizontal grid spacing and 54 vertical levels (Sasaki et al. 2008). The model is forced by daily-mean NCEP/NCAR reanalysis wind stress and surface tracer fluxes for the period 1950 to 2006 from the last condition of the 50-year climatological spin-up integration as the initial state (see http://www.jamstec.go.jp/esc/research/ AtmOcn/ofes/index.en.html). Drs. Nonaka and Sasaki, will provide us daily hindcast data. Our interest in this model draws from the opportunity to collaborate with Japanese colleagues and a recognition of the breadth of analysis in the KE region.

4 Mechanisms that create mesoscale variability in the KE

4.1 Jet Path Variability

Mesoscale variability arises from local instability of the KE jet and external forcing. We propose the following analyses to identify and quantify mechanisms that produce mesoscale variability:

1. Diagnose the eddy-mean energy and PV budgets.
2. Determine wavenumber and frequency spectra and associated growth of waves.
3. Compare the observed PV structure against criteria for instability.
4. Evaluate fluxes in case studies of strong events, addressing the quantitative role of features that arise locally and from external forcing.
5. Determine coherence and linear-response with upstream variability.

6. Determine the extent to which Rossby-wave dynamics explain the mesoscale variability.

In the Gulf Stream, meander troughs steepen and spin up deep eddies (Savidge and Bane 1999a; 1999b; Howden 2000). This shallow–deep coupling is thought to occur through baroclinic instability (Rossby 1987; Dewar and Bane 1989; Cronin and Watts 1996). Studies implicate both baroclinic and barotropic instability (*e.g.* Hall 1986; Holland and Haidvogel 1981). Although from just one mooring (at 35°N, 153°E) in the Kuroshio, Hall (1991) found that baroclinic processes dominate. She showed that the barotropic conversion process feeds energy from the mean flow to eddies on the south side of the current, but in the opposite direction on the north side (Qiu 1995; Adamec 1998). The KESS MMP moorings and CPIES array can provide more complete vertical and lateral information beyond what was available in both these studies.

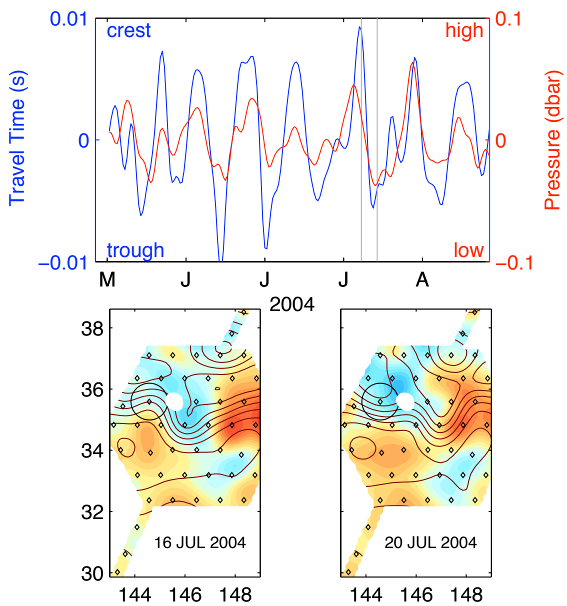

Figure 5: Frontal waves in travel time (blue) and pressure (red) at circled CPIES in maps. High pressure (orange) occurred under a frontal wave crest (bottom left) and low pressure (blue) under a trough (bottom right).

Statistical studies of the energy fluxes and PV fluxes will be used to quantify eddy-mean interactions. The methods of Bryden (1979) and Phillips and Rintoul (2000) will guide analyses of the pointwise MMP measurements and Cronin (1996) and Bower and Hogg (1996) the two-dimensional analyses that will utilize all data. In particular, we will identify and characterize cases of up-gradient and down-gradient fluxes, and quantify the role of episodic events in the context of the time-average observed fluxes. Stephanie Waterman, a Ph.D. candidate in MIT/WHOI Joint Program (KESS funded), showed a downstream evolution of eddy-to-mean conversion in idealized numerical models. Upstream (downstream) of the jet stabilization point eddies flux energy and PV downgradient (upgradient). Additionly, her work points to mixed barotropic and baroclinic instability.

We propose to determine these fluxes in state-of-the art numerical models which provide a more extensive spatio-temporal depiction of the KE. First we will conduct consistent data-model comparisons. We will examine how well the models reproduce mean, eddy and eddy-to-mean conversion quantities within the KESS region. In order to assess how well such terms as the baroclinic and barotropic eddy-to-mean conversion, (*e.g.* $-\overline{v'T'}\frac{\partial\overline{T}}{\partial y}$ and $-\overline{u'v'}\frac{\partial\overline{u}}{\partial y}$) are determined from the CPIES-array alone, we will compare the results of a Bryden (1979) analysis from the MMPs to those estimated from the CPIES array.

Frontal waves and longer meanders are part of the continuum of path perturbations on the KE, and several mechanisms may trigger them. Local instability mechanisms may draw upon available mean potential and kinetic energy, and our diagnoses will quantify by frequency and wavelength the growth rates and associated fluxes. The KESS array observed a recurrent train of frontal waves propagating downstream. They exert influence through the whole water column, with deep pressure perturbations typically leading the upper layer waves. (Fig. 5). High-resolution hydrographic observations reveal that low-salinity water intrusions across the Kuroshio are associated with intermediate-depth frontal waves propagating downstream with 100–200 km wavelength and 0.2–0.3 m/s phase speed (Kouketsu et al. 2005; 2007), and their properties have been investigated in idealized numerical simulation (Kouketsu and Yasuda 2008). These closely resemble short meanders in the Gulf Stream (Tracey and Watts 1986; Kontoyiannis and Watts 1994) and are also prevalent in the POP model. A URI senior physics major will investigate the wavenumber and frequency of these waves using daily AMSR/TMI SST.

Also we will investigate a number of external forcing mechanisms. As the current separates from the southern coast of Japan, shifts in the inflow transport or path may force frequencies that grew upstream, and atmospheric-forcing may perturb the current as it crosses the Izu Ridge. Frontal waves exist upstream in the East China Sea (James et al. 1999) at non-negligible amplitudes and generally propagate downstream. Coastal sea level data reveals that wind-induced coastal trapped waves with several-day periods are dominant south of Japan (Kitade and Matsuyama 2000), and those coastal fluctuations can generate small meanders of the Kuroshio (Nagano and Kawabe 2005). We will utilize concurrent data sets such as coastal and island tide gauges along Izu Ridge south of Japan, the concurrent array of PIES along the ASUKA line south of Japan, and NCEP atmospheric forcing data to examine coherence with frontal displacements within KESS. Notably, these all have at least daily sampling, as required to apply cross-spectral analyses to these energetic 5–20 d waves. We will tailor cross-spectral analyses to quantify the response to this suite of external forcing mechanisms that may generate mesoscale variability in KESS.

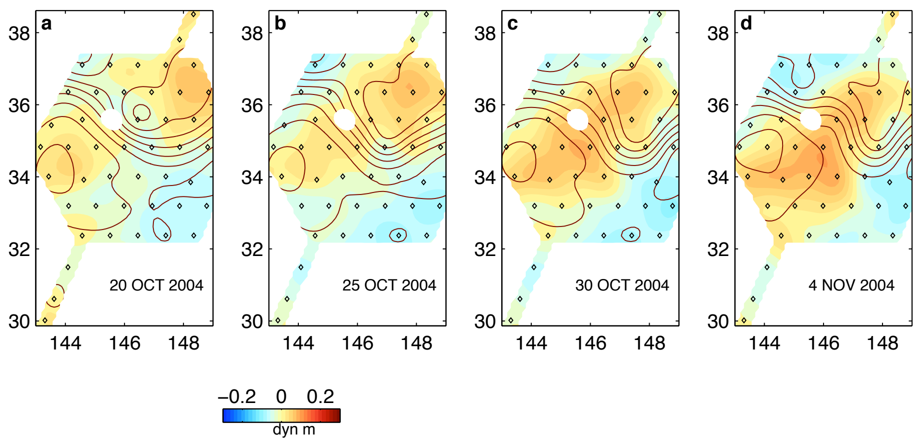

Figure 6: A deep anticyclone in the northeast corner propagates to the southwest where it encounters an anticyclone associated with a frontal wave. The deep anticyclone intensifies and the upper KE meander steepens. Deep streamfunction is color-shaded; upper streamfunction is contoured.

Some of the largest frontal waves, meanders, and ring-formations in the KE appear to have been triggered by external features, deep synoptic eddies, warm and cold rings, and other, possibly wind-driven eddies, arriving from the east. Common examples in the CPIES dataset find incoming deep cyclones and anticyclones arriving from NE along the northern edge of the KE. They encounter a small amplitude frontal wave, and they can lock together with proper phasing to release energy which in turn steepens the wave crest and trough (Fig. 6). Warm and cold core ring interactions in the Gulf Stream and KE jets are known to cause steep mesoscale crests and troughs, develop S paths, and pinch off new rings of either or both sign. We will start with a comprehensive census that will include a wavenumber-frequency spectra for deep mesoscale processes, an estimate of the fraction of upper and deep cyclones and anticyclones that develop locally from infinitesimal disturbances versus grow from external preexisting disturbances, and a list of major events. Case-studies will build upon daily maps and evaluate the dynamical balances (*e.g.* Howden 2000) by diagnosing relative vorticity and planetary vorticity and isopycnal layer-thickness vorticity, and their respective tendency and advection terms. This will also help us examine whether external disturbances self-propagate or advect with the recirculation gyres.

The mean streamcoordinate velocity and PV structure of the KE for the stable period has been evaluated by Penelope Howe, a URI student who recently finished her Master's thesis. She found that the gradient of PV changed sign in the horizontal and in the vertical. We aim to extend that study and determine the mean PV structure during the unstable period. Given these different PV structures we will examine their implications for instability to various wavelength meanders — for example testing simple instability model predictions of mixed baroclinic/barotropic instability like Johns (1988), James et al. (1999), and Koutetsu and Yasuda (2008). We hypothesize that some of the growing meanders within KESS may not match the predicted fastest growing wave properties, because forcing from upstream (*e.g.* coastal modes along southern Japan or atmospherically driven) variability may introduce non-negligible perturbations at other frequencies.

Using output from the 0.1° POP simulation of Maltrud and McClean (2005), we have repeated some of the analysis of Bower and Hogg (1992), in particular examining the Reynolds stress at 2000 m in frequency bands from days to about a year for evidence of wave radiation in the polarization of current ellipses and the sign of the velocity covariance. This work is in its preliminary stages, however the main result so far is strong convergence of the meridional flux of zonal momentum towards the KE (in agreement with Qiu et al. 2008 model analysis) from both sides. We propose to continue this analysis, and additionally to evaluate the wave activity and wave activity flux of Plumb (1986) as in Nakamura and Kagimoto (2006) for the North Atlantic. Plumb (1986) notes that the wave activity flux definition is not unique and suggests an alternative alternative form requiring the evaluation of the ageostrophic part of the flow (feasible in a high-resolution model), with the advantage that the conventional component of wave energy flux appears explicitly in the wave activity flux. Chester et al. (1994) evaluated Plumb's (1986) wave activity flux within a tomographic array centered at about 35°N, 55°W just south of the Gulf Stream, and found results consistent with a flux of wave activity away from the Gulf Stream. We will evaluate wave activity quantities within different frequency bands as in by Bower and Hogg (1992) and Miller et al. (2007).

4.2 Cyclogenesis generated by the interaction of deep eddies with seamounts.

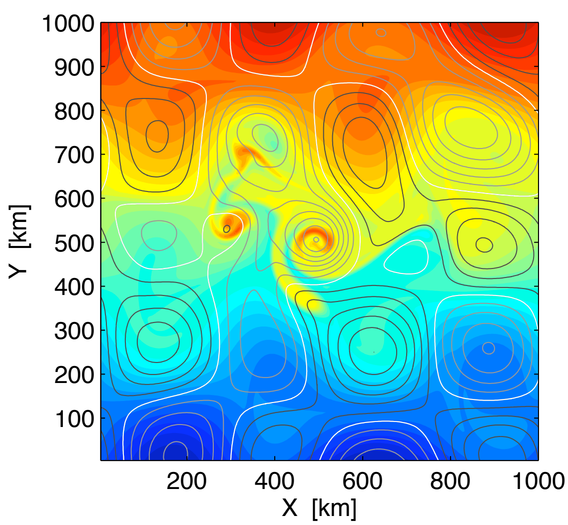

Figure 7: Barotropic model shows a cyclonic eddy (300, 500) reorganizes from filaments that shed from a seamount (500,500) when the incident current field exceeds a threshold. Quasi-geostrophic PV color-shaded (positive red). Deep streamfunction contoured (anticyclonic, gray; cyclonic black; zero contour, white.)

Many strong cyclonic and anticyclonic deep eddies enter the region from the east with diameters around 250 km. They often strengthen to $|\zeta| \approx 0.1 f_0$ by instability mechanisms when they encounter the baroclinic jet. Recently submitted work by Andrew Greene, a URI PhD student, used KESS deep currents and pressures and a barotropic model to show that the strongest deep cyclones spin up by advecting water columns off isolated seamounts. These locally-generated cyclones have vorticity as large as $0.2 f_0$. While lower layer stretching due to meandering of the baroclinic jet accounts for many observed deep eddies, the magnitude of vorticity produced by this process is limited to about $0.1 f_0$ because relative stretching is small in the 6000-m deep KE. Stronger deep eddies require more stretching, as provided by topographic interactions. The initial value problem of uniform flow over a topographic bump has been the focus of earlier numerical investigations (Huppert and Byran 1976, Verron and Le Provost 1985). Both baroclinic and barotropic models demonstrate that cyclonic vorticity generated on the seamount flank can be advected downstream to form a cyclone if the incident flow is sufficiently strong. Greene et al. (2008) lets the incident flow be non-uniform and time-varying Rossby waves, with amplitude and properties similar to the KESS observations. This cyclogenesis mechanism generated filaments with width L_R =O(20 km). The high PV filaments detach from the seamount, advect with the synoptic current, and subsequently reorganize into coherent cyclones, resembling the observations in location, timing, and scales (Fig. 7).

We propose the following analyses that are closely tied to those of the previous section but with an emphasis on cyclogenesis due to interaction with topography.

1. Account for the number and intensity of deep eddies generated locally by topographic processes.
2. Assess this mechanism in the GCMs.

Before we can determine the role these eddies play in the KE system we need to compile a careful accounting of their strength and prevalence. The Greene et al. (2008) study provides only preliminary data analysis. Moreover, we aim to assess whether the state-of-the-art GCMs reproduce this process. If they do, we hope to make further progress towards determining their impact upon the dynamic balances, PV fluxes, and form drag. This topographic mechanism for generating strong deep cyclones motivates not only new directions for KESS analysis but also collaborative modeling efforts being proposed by Sutyrin and Flierl (see attached letter).

5 Consequences of mesoscale variability

5.1 Cross-frontal fluxes

The exchange of passive and dynamical water properties across the "barrier" presented by the upper Kuroshio occurs along pathways opened by meso- and smaller-scale processes, which in turn cause isopycnal and diapycnal mixing. Significant bulk transfer across the front accompanies the formation and decay of warm- and cold-core rings (Richardson 1983; Cheney and Richardson 1976; Qiu et al. 2007). In meanders and frontal waves, exchange is believed to be inhibited at upper levels where there is a significant PV front ("barrier") (e.g., Bower and Lozier 1994) while deeper levels appear well-mixed ("blender") (Bower et al. 1985). At intermediate levels, hydrography confirms that water parcels partially exchange along isopycnals ("stirring"), where cross-frontal exchanges occur preferentially in propagating and growing steep meanders (Bower and Rossby 1989; Lindstrom et al. 1997; Howden 2000; Song and Rossby 1995; Sainz-Trápaga and Sugimoto 2000; Kouketsu et al. 2007). Ultimately, mixing occurs at small scales where cabbeling and double diffusion can be important (Talley and Yun, 2001). In the KE, intrusions and their associated mixing play an important role in the lateral transport of heat and salt across the front, and in setting the downstream properties of North Pacific Intermediate Water, which is an integral component of the Pacific and global circulation (Joyce et al. 2001; Talley 1993).

We propose the following analyses:

1. Quantify eddy and mean cross-frontal exchange of mass, temperature and PV.
2. Determine the role of mesoscale processes in this cross-frontal exchange.

We will examine the role of mesoscale processes. The KESS array observed at least five potential cross-frontal processes: 1) the quasi-stationary meander east of Japan, 2) steep strong meandering, 3) ring formation, 4) ring-meander interaction, and 5) frontal wave propagation.

We propose to carefully quantify the temperature and thickness fluxes associated with these processes, which preliminary analyses indicate all contribute substantially: The mean cross frontal

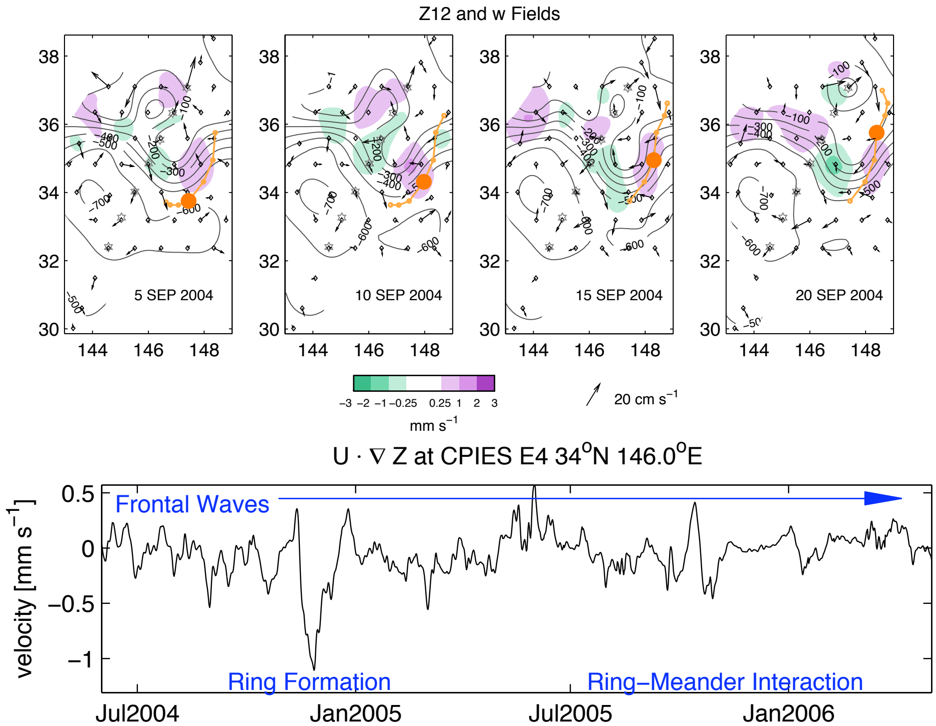

Figure 8: Top panels: Thermocline depth from the CPIES array (black contours) shows downwelling (green hues, moving from cold-to-warm side) occurring from crest-to-trough and upwelling (purple hues, moving from warm-to-cold side) occurring trough-to-crest. An Argo float (orange dot daily location, 35-day piece-wise trajectory) fortuitously crossed the KE, providing direct estimates of T and S and their cross-frontal exchange during the wave's passage. Bottom panel: Time series of $\vec{U} \cdot \nabla Z$ (along-isopycnal advection contribution to vertical velocity) at a mid-array site illustrates the event-driven nature of cross-frontal fluxes.

exchange entering the first trough of the quasi-stationary meander within a 400 m lens at intermediate depths is 1–2 Sv. Larger rates of exchange occur in steep meander and ring-interaction events but only episodically. Initial estimates for the frontal waves illustrated below indicate intermediate-level exchanges ~ 2 Sv, equal-and-opposite entering trough and crest. While the net transport is zero, streamers are left behind and the net heat flux is northward. The line of MMPs is well suited for measuring the structure of T, S, and PV anomalies associated with these processes and quantifying the exchange, while the CPIES array resolves the mesoscale density and flow fields.

An illustration of the dominant role played by mesoscale processes is shown in the time series of vertical velocity at a mid-array location (Fig. 8). Here, isopycnal vertical velocity is diagnosed, following Howden (2000) by $w = \frac{\partial Z}{\partial t} + \vec{U} \cdot \nabla Z$, where Z is the depth of an isotherm within the thermocline and $\vec{U}$ is the horizontal velocity vector. The terms on the right are respectively the isopycnal tendency and along-isopycnal advection. Lindstrom et al. (1997) demonstrated that vertical motions of isopycnal Rafos floats in Gulf Stream meanders agree well with w diagnosed in this adiabatic manner. The record in Fig. 8 is dominated by events such as a cold-core ring formation and ring-meander interaction. While the cross-frontal fluxes in individual frontal waves are weaker compared to these strong events, their influence could be large due to their prevalence. The quantitative role of frontal waves in cross-frontal exchange will be examined by case-studies like that illustrated in Fig. 8.

We will analyze the MMP and mapped-CPIES mean and eddy temperature and thickness fluxes, and in parallel we will evaluate the comparable model fields. Again, the models provide the larger spatial and temporal context to guide our understanding of the regional and time-integrated role of these exchange processes.

Within the POP model, T and S variations along isopyncal surfaces across the KE will be evaluated with emphasis on constructing the 3-dimensional temporal residual mean circulation (TRM) in and near the model KE (Gent and McWilliams, 1996; McDougall and McIntosh, 2001). The implementation of diagnostics for the TRM from the POP output is not a trivial task, we (IC and JM) have proposed similar work in the Antarctic Circumpolar Current so that the same programming effort serves more than one project. Construction of the TRM flow will require evaluation of model fluxes corresponding to the observed cross-front fluxes. If possible, tracer studies will be included in the POP model runs; cross-front transfer of tracers will complement the proposed eddy flux studies.

5.2 Recirculation gyre dynamics

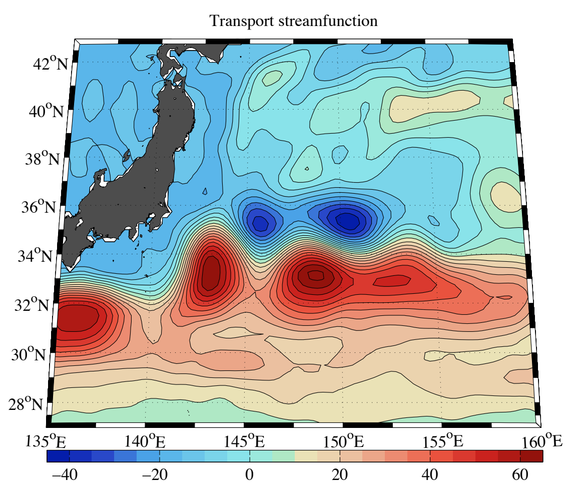

Figure 9: Evidence of recirculation gyres north and south of the KE. Transport streamfunction from the POP model exhibiting strong recirculations to both the north and south of the jet. Transport is contoured in units of Sverdrups.

Strong western boundary currents, such as the Gulf Stream and KE, are often flanked by recirculation gyres which greatly enhance the transport of the jet. Furthermore by providing quasi-stable regions where water can be trapped for long periods, they are sites for deep wintertime convection, formation regions of mode waters, and reservoirs of heat and PV. A hypothesis is recirculation gyres result because the quasi-inertial, baroclinic western boundary current rids itself of low PV that it acquired at more southern latitudes. The anomalous PV signature is a minimum in its cross-stream distribution, which satisfies necessary conditions for instability. Simplified barotropic and reduced-gravity numerical models (*i.e.* Cessi et al. 1987; Jayne et al. 1996; Jayne and Hogg 1999) have been able to model this process and produce recirculation strengths quite accurately, despite their reliance on the barotropic instability mechanism. S. Waterman expands these ideas to include a baroclinic part.

Recirculation gyres flank the Gulf Stream after it separates from the coast of North America both to the north and south of jet (Worthington 1976; Richardson 1985; Hogg et al. 1986; Hogg 1992). They enhance the transport of the Gulf Stream from approximately 85 Sv at its separation point at Cape Hatteras to 150 Sv at 60°W (Hogg 1992). In the case of the Kuroshio, the situation prior to KESS was less clear. A westward recirculation has been observed south of the jet in the P10 WOCE section using a lowered ADCP (Wijffels et al. 1998). The southern recirculation gyre is also clear in altimetry observations of the Kuroshio (Qiu and Chen 2005) and in subsurface drifting float observations (Qiu et al. 2008). However to the north of the current, the presence or absence of a recirculation was not firmly established prior to KESS. It is absent from the regional mean circulation derived from hydrography (Teague et al. 1990) and a careful compilation of deep current meter records by Owens and Warren (2001) supports neither the presence nor the absence of such a gyre. Utilizing float observations from KESS and the OFES model output, Qiu et al. (2008) find recirculation gyres to both the north and south of the KE.

Jayne et al. (2008) further discuss the recirculation gyres and find evidence for them in the KESS observational data from current meters, CPIES, and floats, and a POP model simulation.

Imawaki et al. (2001) estimated that the Kuroshio carries 42$\pm$1.6 Sv through the ASUKA line south of Japan. The transport estimated across the KESS mooring array is 123.2 Sv from the stream-averaged current meter data and assuming that the ASUKA-line transport gives the inflow transport of the jet before it develops recirculation gyres, we estimate that there is 63.9 Sv. of transport in the southern recirculation gyre and 17.3 Sv in the northern recirculation gyre. This can be compared to the POP 1/10° model simulation (Fig. 9), in which the transport increases from 41.7 Sv as the jet detaches from the coast at 140°E south of Japan to 101.5 Sv across the first quasi-stationary meander crest (where the KESS array was located) and 109.9 Sv across the second meander crest.

We propose the following analyses:

1. Test simple theoretical models of recirculation dynamics agree with the KESS observations.
2. Utilize the high-resolution POP output to diagnose the PV and momentum budgets in the KE.

The same mesoscale processes that drive the recirculation gyres in the Gulf Stream are likely active in the KE, however, the presence of the semi-permanent meanders in the KE complicates the dynamical picture. With the KESS data set we have the opportunity to understand the dynamics of the jet and its recirculation gyres. Using the observations and model output we will explore the dynamics of the recirculation gyres to both the south and north of the KE. There is promise in this endeavor as a variety of new observations and model output are available for the KE region. We propose to analyze the PV balance in the KE, and in particular to derive the thickness flux of PV from the CPIES and mooring observations to test if the simple theoretical models agree with the KESS observations. Further we plan to analyze the 1/10° POP output, and in particular carefully examine the PV budget to further test our theoretical model of recirculation gyre dynamics.

5.3 Regime Shifts of the Kuroshio Extension/Recirculation Gyre system

One hypothesis is that regime shifts in the KE/RG system arise from changes in the PV structure that effect the stability properties and consequent production of eddy variance. These changes, in turn, may arise from processes generated locally or that enter from upstream or from downstream, including wind-generated perturbations. The thrust of this section will be to use the longer time and larger spatial windows provided by models and remote sensing data (mainly SSH) to gain an understanding of the shift between stable and unstable states of the KE.

Under this topic we propose the following analyses:

1. Using satellite derived SSH track eddies as in Chelton et al. (2007) and determine more completely their structure and importance to the KESS observing period.
2. Attempt to relate the PV structure change between the stable and unstable regimes (as in Section 4.1) with PV anomalies transported in from the east by a train of eddies and waves.
3. Compare quantitative aspects of the regime shift with models.

Using a simple linear model Qiu and Chen (2005) show, rather convincingly, that modulation of the windstress over the central Pacific by the Pacific Decadal Oscillation propagates westward as modulated baroclinic Rossby waves. The resulting times of enhanced cyclonic and anticyclonic energy in the KE/RG region lead to alterations of the KE position, RG strength, the eddy kinetic energy in the region, and transitions between stable and unstable states. Taguchi et al. (2007) explore this mechanism further a high resolution model (OFES) for a much longer period: 1950 to 2003. Their analysis, using empirical modes, supports Qiu and Chen's (2005) assertion. They further suggest that this energy upon reaching the KE also excites intrinsic modes of the KE jet which are much more tightly trapped to the jet than the broadscale forcing alone would suggest.

Long distance baroclinic Rossby wave propagation has been well revealed by altimetric sea surface height observations (*e.g.* Chelton and Schlax 1996). By high pass filtering the AVISO SSH fields in the zonal direction to remove heating and cooling effects and then smoothing in space and time, Chelton et al. (2007) show that abundant smaller scale, more-or-less circular eddies dominate the resulting SSH. These eddies propagate almost due west from the central Pacific with the linear baroclinic Rossby wave phase speed but are nonlinear: their estimates for the KE region show particle to phase speed ratio on the order of 2–3.

The eddies, being nonlinear, transport different water properties, such as thickness PV, into the region. Qiu et al. (2006) speculate that rings formed from meanders of the KE help to erode the subtropical mode water. It seems likely that this steady train of eddies carrying anomalous water from farther east could do so, as well. The amplitudes of both the baroclinic Rossby waves and the eddies have comparable SSH displacement (20 cm) which implies that the horizontal velocities of the eddies are much larger given their much smaller spatial scales. It is unknown how they originate or what their influence is on the KE/RG system. We would like to explore these topics.

The KESS data set gives us the opportunity to study these features more completely and to investigate their interaction with the KE and the RG. Although it seems likely that their vertical structure is approximately first baroclinic mode, given the close correspondence to the linear phase speed, this has not been demonstrated and can be with our data. We will employ the technique of Chelton et al. (2007) to track eddies to help us understand their relationship with events observed in the KESS observations. The KE rather quickly adjusted from a stable to an unstable state after November 2004. Did the incoming Rossby waves or the impinging eddies have anything to do with this transition as has been suggested by Qiu and Chen (2005)? In this regard, the PV structure of the KE for the periods before and after the transition will be of interest.

A train of strong deep eddies traveled through the KESS from NE to SW at the time of the stable to unstable transition. It is unknown what impact they had on the KE or what role they might have played in the transition. One possibility is that they were locally generated by instability and are merely a reflection of the transistion. Another is that they were remotely forced and aided the transition through an alteration of the PV. Through use of altimetry and the upper ocean instrumentation we will explore both their vertical structure and attempt to discover their origin.

Initial analysis of the POP 1999–2000 simulation indicates dispersionless westward propagation within the southern recirculation gyre, similar to that reported by Chelton and Schlax (1996) in the Pacific and by Osychny et al. (2004) in the Atlantic; somewhat as in Chelton et al. (2007) the variance consists of westward drifting eddies rather than Rossby waves. In the model, this signal is also visible at the 2000 m level where the mean flow is influenced by the Shatsky Rise at about 158°E. Ikeda and Yamada (2006) have suggested that this feature may trap much shorter period (tens of days) topographic Rossby waves. This trapping was not evident in our preliminary analysis of the 2000 m velocities, but a meridional Hovmöller diagram at that longitude suggests northward phase propagation at about the annual period — as though the rise were scattering energy into Rossby waves. The longer model runs described in Section 3 should give us the opportunity to investigate these processes more thorougly and their possible relationship to regime shifts.

6 Broader Impacts

Western boundary currents are one of the foremost processes in global heat transport and regulating the climate. The work proposed here in collaboration with other projects will advance our understanding of the decadal changes observed in the state of the current, which is believed to play a major role in steering and intensifying extra-tropical storms, controlling the strength of the recirculation gyre and the formation of mode water.

The moored array data are served directly from the website http://www.uskess.org, and shipboard ADCP and bathymetric data can be retrieved from links to centralized archives. The purpose of the website is multifold: hosting the raw data, describing the experiment, providing access to publications, and hosting data products. Our goal is to serve products that would enable model-data comparisons.Eventually, the information on the website will be archived by an outside entity.

Students play key roles in KESS. Graduate students receive broad training that includes proposal preparation, data analyses, and publication and presentation at national meetings. One, possibly two, female URI undergraduates will work on KESS for their senior projects. During the summer, undergraduates participating in the URI SURFO program (NSF-funded REU) will conduct data analyses. In addition, a post doc (Elizabeth Douglass, WHOI) and a project scientist (Ivana Cerovečki, Scripps) join this analysis effort. McClean will participate in a teachers workshop held at San Francisco State University.

We will conduct joint analyses with Japanese scientists. Data collected by the Japanese provide valuable upstream measurements of the Kuroshio which coincide with the KESS experiment, and the daily fields produced by the OFES provide an opportunity to investigate a larger region.

7 Results from prior NSF support

Collaborative Proposal: Kuroshio Extension System Study (KESS). OCE-0220161: $2,116,287, 02/01/03 to 1/31/08, N. G. Hogg and S. R. Jayne. OCE-0221008: $3,667,404, 12/01/2002 to 11/30/07, D. R. Watts and K. Donohue.

These awards supported the tall moorings and CPIES components of the KESS project to-date. We have disseminated initial results to the community via more than 15 presentations at national and international meetings, a KESS website, and through published results. Qiu et al. (2006) documented the properties and seasonal evolution of the Subtropical Mode Water during the stable period. Rainville et al. (2007), diagnosed the formation of Subtropical Mode Water in POP, gave evidence for a northern recirculation gyre (Qiu et al. 2008), provided an overview of the KESS experiment (Donohue et al. 2008), determined the KE structure in stream coordinates (masters thesis of Howe at URI 2008), compared KESS bottom pressure to Grace (Park et al. 2008), and showed that deep cyclogenesis can result from synoptic eddies interacting with a seamount (Greene et al. 2008). The CPIES data processing is documented in Kennelly et al. (2008).

Studies near completion include: the methodology for the 4D mapping of circulation from CPIES (Donohue lead author), a technique to estimate climatological hydrographic properties from ADCP velocity sections (Greene lead author), a comparison between CPIES-derived SSH to altimeter products (Park lead author), an interpretation of deep currents within a linear Rossby wave context (Hogg lead author), and a documentation of the statistics within KESS (Watts lead author).

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Jayne, S. R., N. G. Hogg, S. N. Waterman, L. Rainville, K. A. Donohue, D. R. Watts, J.-H. Park, J. L. McClean, M. E. Maltrud, B. Qiu, S. Chen, and P. Hacker, 2008: Recirculation in the Kuroshio Extension. *J. Phys. Oceanogr.*, submitted.

Internal Tides and Inertial Oscillations: Analysis of Observations in the Gulf Stream south of New England. OCE-0453681: $174,251, 03/15/05 to 02/29/08, 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 PIES and tall current meters in the Gulf Stream. The near- to sub-inertial current fluctuations interaction with deep cyclonic eddies has been presented. In addition, we discovered a basin-scale nonisostatic response to the 5-day-period Rossby-Haurwitz atmospheric pressure wave using bottom pressure (Park and Watts 2006).

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.

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Mesoscale Variability and Processes in an Eddy-Resolving Global POP Simulation. OCE-0221781/0549225: $391,168, 09/01/2002-08/31/2008, J. L. McClean.

The mean and variability of the upper ocean circulation of global 0.1° POP was compared with data from altimetry, current meters, time series of temperature profiles, and published volume transports and meridional heat transports (Maltrud and McClean 2005; McClean et al. 2006; McClean et al. 2008). A 0.1° North Atlantic configuration of POP was compared with tide gauges and altimetry using wavelet transforms (Tokmakian and McClean 2003). Interannual processes in the Indo-Pacific as depicted by POP were examined (McClean et al. 2005; Prasad et al. 2004). Mesoscale properties were studied in the Agulhas Retroflection (Bryne and McClean 2008) and off Japan in the KESS region (Rainville et al. 2007). Output was provided upon request.

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