Kuroshio Extension System Study (KESS)

PROJECT SUMMARY

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. A recirculation gyre exists to the south of the Kuroshio Extension. Another may exist to the north. This is also one of the most intense air–sea heat exchange regions on the globe, where the warm Kuroshio waters encounter the cold dry air masses coming from the Asian continent. The Kuroshio Extension system exhibits variations which strongly affect North American climate. Among the diverse fields that will benefit from this work are fisheries and climate research, and understanding storm tracks.

Understanding the processes that govern the variability of and the interaction between the Kuroshio Extension and the recirculation gyre is the goal of this study. Processes coupling the baroclinic and barotropic circulations will be examined by case studies of the local dynamical balances, particularly during strong meandering events. The mechanisms by which water masses are exchanged and modified as they cross the front will be characterized. The objective is to determine the processes governing the strength and structure of the recirculation gyres in relation to the meandering jet.

Principal Investigators cooperating from three US institutions postulate dynamical and thermodynamical connections from mesoscale eddies to gyre-scale recirculations and to global climate variations and propose observations designed to test these hypotheses. They will deploy a state-of-the-art array consisting of moored-profiler and current-meter moorings and inverted echo sounders equipped with near-bottom pressure and current sensors. Shipboard surveys will conduct case studies of the water properties and currents throughout the water column. Profiling floats will monitor the temperature and salinity structure in the recirculation gyre south of the Kuroshio Extension. The proposed approach makes extensive use of satellite data (surface temperature and sea-surface height). They will also collaborate closely with Japanese scientists studying the overall Kuroshio system.

The Kuroshio Extension system is the right place to test hypotheses formulated from previous observational and modeling studies because of its distinct stratification, bathymetry, and thermohaline circulation. The time is right to conduct a study of the Kuroshio Extension system. Over the last several decades a number of substantial programs have been undertaken, focused on different parts of these western boundary currents, mostly in the Atlantic. These include studies of the Brazil-Malvinas Confluence, the Western Tropical Atlantic Studies, the Subtropical Atlantic Climate Study, and the North Atlantic Current Study. The program that is most closely related to this proposal and, arguably the most ambitious, was the Synoptic Ocean Prediction Experiment. These studies fundamentally changed the scientific community's understanding of the interconnected system of currents, recirculations, eddies, cross-frontal exchange mechanisms, and processes affecting the upper ocean heat budget. This improved dynamical understanding enables these scientists to pose new questions treating the western boundary current regime as a coupled system, linking eddy and gyre and global scales. Today's fundamentally improved remote-sensing, *in situ* observational, and computing abilities enable them to address these questions in a comprehensive manner.

Collaborative Proposal
Kuroshio Extension System Study
KESS
PROJECT DESCRIPTION

1 Introduction

Western boundary currents (WBCs) of the oceans are the principal conduits for communication between equatorial regions, where heat is added to the oceans and ambient potential vorticity (PV) is low, and the polar regions where heat is removed and PV is high. Understanding how these adjustments are made is fundamental to understanding the earth's global climate engine and of intrinsic interest in its own right. Over the last several decades a number of substantial programs focused on different parts of these WBCs have been undertaken, with a mostly Atlantic bias. These include studies of the Brazil-Malvinas Confluence, the Western Tropical Atlantic Studies, the Subtropical Atlantic Climate Study, and the North Atlantic Current Study. The program that is most closely related to this proposal and, arguably the most ambitious, was the Synoptic Ocean Prediction Experiment (SYNOP) which was jointly supported by the NSF and ONR in the late 1980s. This focussed on the Gulf Stream Extension region — that part of the Gulf Stream system between Cape Hatteras and the Grand Banks where heat loss to the atmosphere is high and transformation of the anomalously low potential vorticity carried from southern latitudes is made.

Although its *raison d'être* was to aid in the development of predictive models of detached WBCs and their environs, important new insights were gained into the workings of the meandering jet and its relationship to the surrounding ocean. A brief synopsis follows.

After separating from the coast, the narrow WBC is both barotropically and baroclinically unstable. Meanders result which grow and gradually spin up a deep eddy, slightly shifted in the downstream direction. This enhances exchange across the jet of both heat and PV. The PV flux removes the anomaly carried by the stream and forces oppositely rotating recirculation gyres to the north and south. In turn, these gyres trap fluid and become sites for deep wintertime convection, mode water formation and heat storage. Being reservoirs of both heat and anomalous PV, these gyres, like flywheels, can buffer high frequency change but have also been shown to permit low frequency internal oscillations of the system. The strong meridional SST changes that result and their associated interannual changes have been demonstrated in recent modeling and data analysis studies to influence midlatitude storm tracks and to generate internal feedbacks within the coupled ocean-atmosphere system.

The Gulf Stream/North Atlantic Current situation is distinctive in several respects. Even though the Gulf Stream separates at Cape Hatteras, it is never far from the coast until passing the Grand Banks. Most likely this is a result of the important additional circulation added by the meridional overturning circulation unique to the North Atlantic and the special geometry of the region. WBCs of other basins are quite different, separating once and for all, and having insignificant influence from the thermohaline circulation. In other respects, these WBC regimes are similar: heat loss to the atmosphere above them is generally large, potential vorticity is anomalous, and they are generally flanked by one or more recirculation gyres where mode water is formed. The Kuroshio with its Extension is the most important western boundary current of the Pacific and the one whose properties most impact the climate of North America.

Despite its obvious similarities to the Gulf Stream, the Kuroshio Extension is fundamentally different. In particular, it has distinct modes of variability, possibly different instability mechanisms, and potentially dissimilar physics governing its recirculation gyres. For these reasons, a comprehensive field campaign should be conducted to observe and characterize the dynamical and thermodynamical processes that control the Kuroshio Extension and its recirculation gyres.

The observational tools available for such a field program have improved greatly in recent years. Essentially all the instrumentation proposed herein – inverted echo sounders with pressure and current sensors, moored profilers, profiling floats, and altimetry – either did not exist or have been fundamentally improved since SYNOP.

The intense ocean-mesoscale variability in the Kuroshio Extension, and the slowly-varying strengths and structure of the recirculation gyres appear to be intrinsically coupled, with concomitant effects upon storm-tracks and climate-coupling. Building upon SYNOP and an emerging consensus based on recent modeling and observational findings, KESS has been designed to address and understand these dynamical issues.

2 Goal

The overall goal of KESS is to identify and quantify the dynamic and thermodynamic processes governing the variability of and the interaction between the Kuroshio Extension and the recirculation gyre.

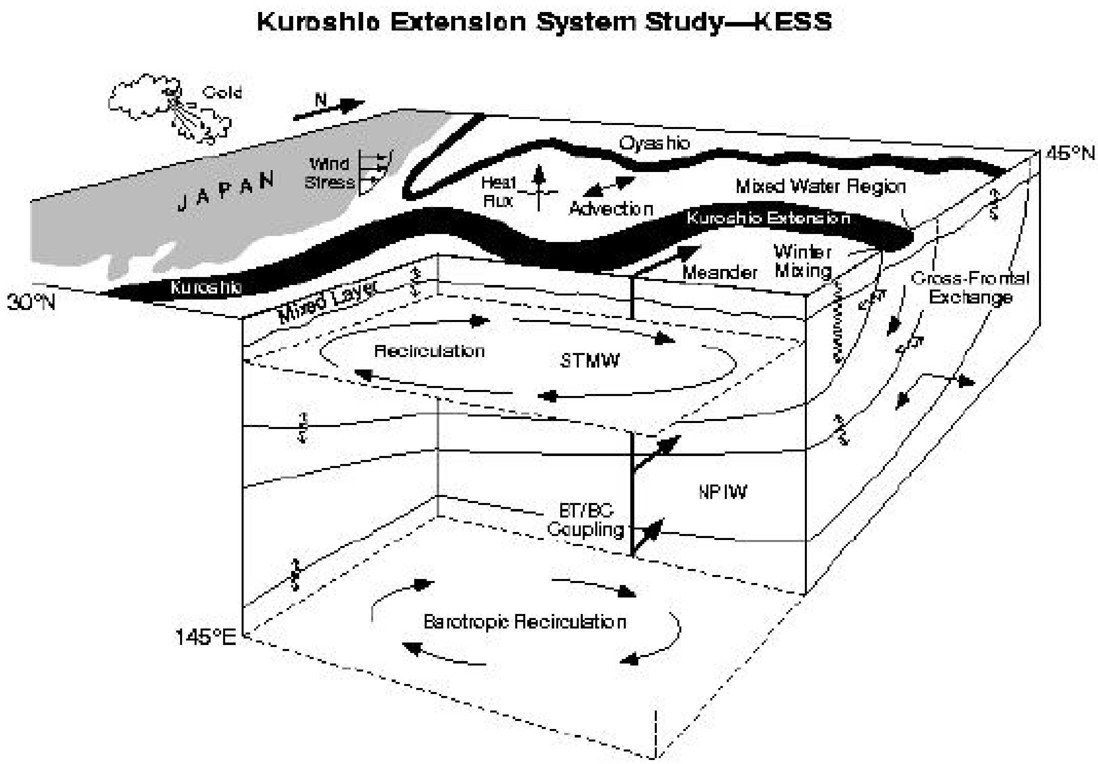


Figure 1: Dynamic and thermodynamic processes in the Kuroshio Extension System. Meanders of the jet couple with barotropic eddies to cause cross-frontal stirring and exchanges of heat, salt, and potential vorticity. These exchanges, along with surface heat fluxes and advection, alter the structure of the recirculation gyre and the upper ocean heat budget. Strong wintertime cooling deepens the mixed layer to form subtropical mode water, which recirculates in this region, retaining the memory of former winters. (courtesy B. Howe, APL)

3 Scientific background

The Kuroshio Extension is the region of the North Pacific Ocean occupied by the Kuroshio after it separates from the coast of Japan near 35°N and becomes a free inertial jet. Joining this region from the north, the cold waters of the Oyashio flow south along the east coast of Japan and depart the coast to flow as another eastward jet near 40°N. The paths of both fronts develop time-dependent meanders, which can grow steep and pinch off closed rings (*e.g.,* Mizuno and White 1983). The Kuroshio Extension is the major crossroads for the exchange of heat and fresh water between the subtropical and subpolar gyres in the North Pacific. North of the Kuroshio Extension, water within the Mixed Water Region mixes with water formed in the Okhotsk Sea in a complicated fashion to supply a large portion of the North Pacific Intermediate Water (NPIW) (Talley 1997; Talley et al. 1995) and produces a salinity minimum that spreads throughout the subtropical gyre of the North Pacific. The mixing also introduces heat and salt to the subarctic waters north of the Kuroshio, with influence extending into the Gulf of Alaska (Ueno and Yasuda 2001).

A tight recirculation gyre exists to the south, with structure and transport analogous to the Gulf Stream Extension region. By some accounts, a recirculation gyre also exists to the north of the Kuroshio Extension but its existence has not been decisively demonstrated; it is absent from the regional mean circulation derived from hydrography (Teague et al. 1990). A careful compilation of deep current meter records by Owens and Warren (2001) supports neither the presence nor the absence of such a gyre. We refer to this system of currents, fronts and recirculation gyre(s) as the "Kuroshio Extension System." Figure 1 schematically illustrates the circulation and processes.

The Kuroshio Extension region is one of especially high eddy kinetic energy (*e.g.,* Wyrtki et al. 1976, Qiu 2002). The highest mesoscale eddy variability occurs between the two quasi-stationary meanders which can be seen as a feature of the mean circulation (Teague et al. 1990, Figure 7). Processes responsible for the existence of these quasi-stationary meanders remain under dispute. Mizuno and White (1983) suggested that the Izu Ridge produces a standing Rossby wave, while Hurlburt et al. (1996) argued that a baroclinic instability process generates eddy-driven abyssal flows which steer the upper baroclinic front.

Observations of the vertical-coupling process associated with baroclinic instability have been acquired as a result of the SYNOP experiment in the Gulf Stream (Watts et al. 1995). A striking finding in that work was that strong deep eddies always spun up together with steep meanders of the upper jet, with the vertical phase-tilt characteristic of baroclinic instability (Shay et al. 1995; Watts et al. 2001a). Continuity of the vertical velocity, combined with rotational-stiffness, couples eddy processes throughout the water column. Meandering of the upper jet stretches the lower water column, spinning up nearly depth–independent eddies (Savidge and Bane 1999a,b; Howden 2000). While the Kuroshio Extension represents a dynamically simpler regime (*e.g.,* with no deep WBC and flatter topography), current meters under the Kuroshio Extension show energetic, nearly barotropic velocities (Schmitz 1987,1988). Intense abyssal flows were also detected by Hallock and Teague (1996) underneath the Kuroshio Extension path around 143°E. These measurements were separated incoherently, however. Analysis of currents measured near 35°N, 152°E reveal significant mean-to-eddy potential eddy conversion (Hall 1989,1991).

While strong velocities had previously been observed under the Gulf Stream, the association of these strong velocities with an organized deep flow field was not understood prior to the SYNOP observations. Maps of abyssal pressure and current fields revealed that the abyssal flows were organized into strong cyclonic and anticyclonic circulations (Figure 2). These fields, coupled with maps of upper-ocean velocity and temperature, provided insight into the dynamical connection between the deep barotropic eddies and the troughs and crests in the upper baroclinic jet. Since Cronin and Watts (1996) and Cronin (1996) demonstrated that Gulf Stream statistics (over two years) of eddy fluxes and their divergences were dominated by 6-8 major events, rather than an accumulation of many contributions spread more evenly over time, case-studies of large events proved particularly informative. For example, these revealed that meanders involve the whole water column as they steepen, abyssal eddies were nearly depth-independent, and Gulf Stream rings did not always have a deep influence.

In the Gulf Stream, the nearly barotropic eddies advect upper ocean water parcels along isopycnals, thus driving large-amplitude cross-frontal exchanges. In the Kuroshio Extension, mesoscale processes are also believed to play an important role in water-mass exchange and transformations between the subtropical and subpolar gyres of the North Pa-

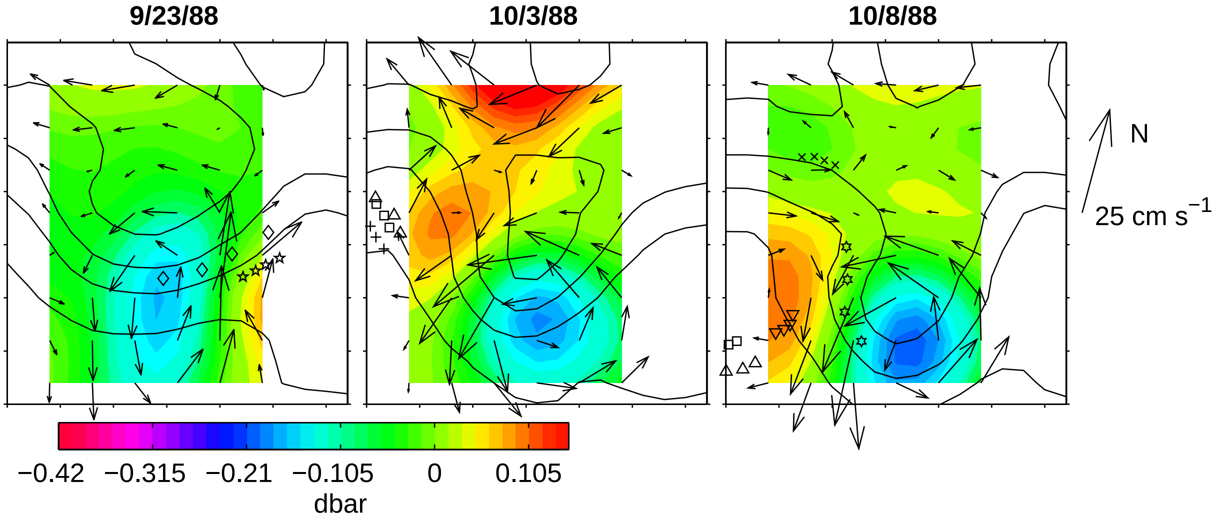


Figure 2: Case study of a Gulf Stream meander trough steepening over a two-week period. Four different measurements are superimposed: thermocline depth (thin solid lines, contour interval 200 m); the perturbation pressure field at 3500 m (in color); velocity vectors at 3500 m (speeds proportioned to the compass arrow); locations of several RAFOS floats (distinct symbols for each float, positions at 8-hour intervals centered on the map date). Tick marks are at 50 km intervals.

cific Ocean (Talley et al. 1995; Yasuda et al. 1996; Talley 1997; Yasuda 1997; Joyce et al. 2001). For example, low salinity NPIW undoubtedly comes from North Pacific Subarctic regions where the fresh water flux into the ocean is positive. Recent studies suggest that NPIW formation begins in the Okhotsk Sea (Talley 1991), where low PV water forms in the Kuril Basin (Yasuda 1997) by convective processes associated with sea-ice formation (Kitani 1973) and from the dense water that exits the Japan Sea (Watanabe and Wakatsuchi 1998). The low-PV water enters the open Pacific where it mixes with East-Kamchatka Current Water to form Oyashio water (Yasuda 1997; Kono and Kawasaki 1997) whose coastal part retains the low-PV. The Oyashio flows southward along the east coast of Japan (Yasuda et al. 1996) and a portion of the Oyashio merges with the Kuroshio Extension. Hydrographic observations suggest that further modification occurs as the low-PV waters of the Oyashio mix with the older, high-salinity water. A large part of the NPIW is thought to form in this region (Yasuda et al. 1996; Talley et al. 1995; Talley 1997). Further modification is observed after it has crossed the Kuroshio front, and the end-product NPIW is observed throughout the subtropical gyre.

The cross-frontal exchange process has also been interpreted in terms of dynamical systems theory of chaotic exchange (Lozier et al. 1997; Rogerson et al. 1999) and is believed to be inhibited at shallow levels where there is a significant PV front (“barrier”) (*e.g.*, Bower and Lozier 1994). At intermediate levels hydrography confirms there is partial exchange of water parcels (“stirring”), and deeper levels appear well-mixed (“blender”) (Bower et al. 1985). In the Gulf Stream, cross-frontal exchanges at intermediate depths occur preferentially in propagating and growing steep meanders (Bower and Rossby 1989; Howden 2000; Song and Rossby 1995). Intermediate depth waters tend to be injected south of the frontal zone in the region entering meander troughs. Lagrangian observations demonstrate the permanent crossing of water parcels across the Gulf Stream front. Moored mesoscale-mapping observations quantified the large cross-frontal transports (Lindstrom et al. 1997). Because this stirring process injects waters into a laterally-sheared field, the straining is postulated to form thin streamers that are left behind at intermediate depths, reminiscent of the streamers commonly seen in satellite SST images near meander crests. Significant transfer across the Gulf Stream is also associated with the shedding and decay of cold-core rings (Richardson 1983; Cheney and Richardson 1976).

Like other inertial western boundary currents in subtropical gyres, the Kuroshio carries anomalously low levels of PV, as well as enormous quantities of heat, poleward. On separating from the western boundary, the Kuroshio Extension behaves as a meandering eastward jet; one of the major functions of the meandering jet is to dissipate the PV anomaly so that the water can reenter the interior subtropical gyre. This dissipation process is characterized by instabilities of both baroclinic and barotropic origin which are manifested by vigorous meandering.

The flux of PV anomalies away from the detached jet erodes the ambient PV field in the interior, creating plateaus upon which nearly inertial recirculation gyres develop (Cessi et al. 1987; Jayne and Hogg 1999). Spall (1996) has shown that this process can lead to natural internal oscillations (*i.e.*, even without atmospheric coupling). Specifically, meandering of the jet causes PV fluxes that spin up the recirculation gyre. Moreover, the (slowly evolving) PV distribution across the jet determines its stability properties and its consequent intensity of meandering. A cyclic process arises because the low PV anomaly carried into a strong recirculation gyre from the deep western boundary current tends to reduce the instabilities, thus weakening the recirculation. The gyre retracts, which is followed by stronger instability and gyre spin-up again, with a decadal time scale. In addition, if there are other sources of variability in the PV anomaly distribution supplied by the western boundary current, due to changes in the thermohaline circulation for example, these will also lead to a modulation of the recirculation gyre.

In the Kuroshio Extension, the existence of a southern recirculation gyre is well demonstrated by lowered ADCP measurements from the WOCE P10 cruise across the Kuroshio Extension southeast of Japan (Figure 3). The volume transport of the eastward-flowing Kuroshio Extension, denoted in Figure 3 by the unshaded area, is about 140 Sv (Wijffels et al. 1998). This is three times as large as the maximum Sverdrup transport of about 45 Sv in the subtropical North Pacific (*e.g.*, Hautala et al. 1994; Huang and Qiu 1994). This inflated eastward transport is largely due to the existence of the southern recirculating flow. Though weak in its surface speed, the lowered ADCP measurements show that this westward recirculating flow has a strong *barotropic* component and has a total volume transport exceeding 90 Sv (Wijffels et al. 1998, their Figure 6).

That the recirculation gyre is an inseparable part of the Kuroshio Extension system is also seen from the T/P satellite altimetric measurements (SSH). Over the past 8 years, the Kuroshio Extension evolved gradually from an elongated state to a contracted one from late 1992 to 1996. This modal transition reversed after 1997 and the Kuroshio Extension re-

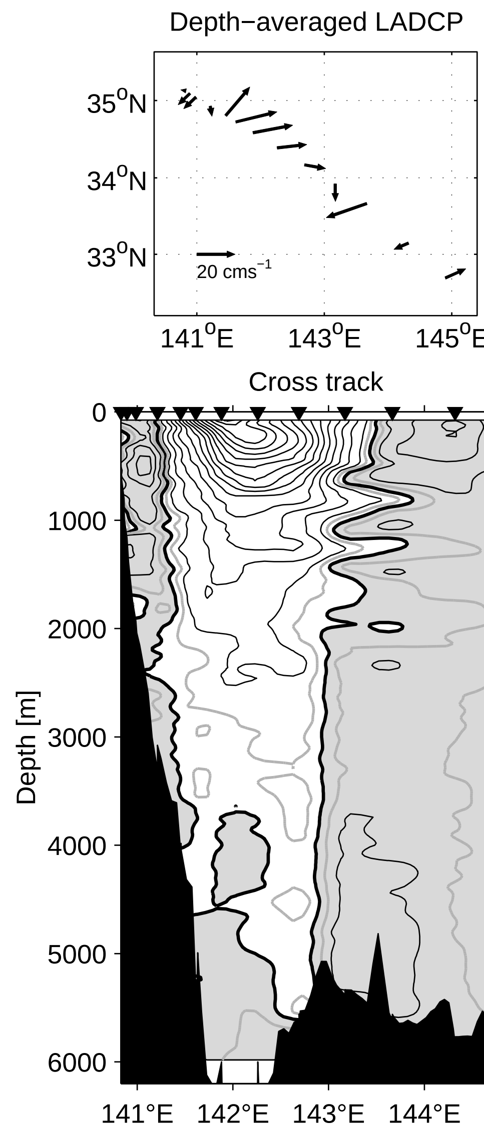


Figure 3: Lowered acoustic Doppler current profiler velocities from World Ocean Circulation Hydrographic Program section P10 where it crossed the Kuroshio Extension close to Japan (Wijffels et al. 1998). Velocities are positive to the northeast. Velocities are contoured at 10 cm s^{-1} intervals, with an additional gray contour at ± 5 cm s^{-1}. Shaded regions are negative. Note strong deep recirculation (shaded) south of the Kuroshio Extension.

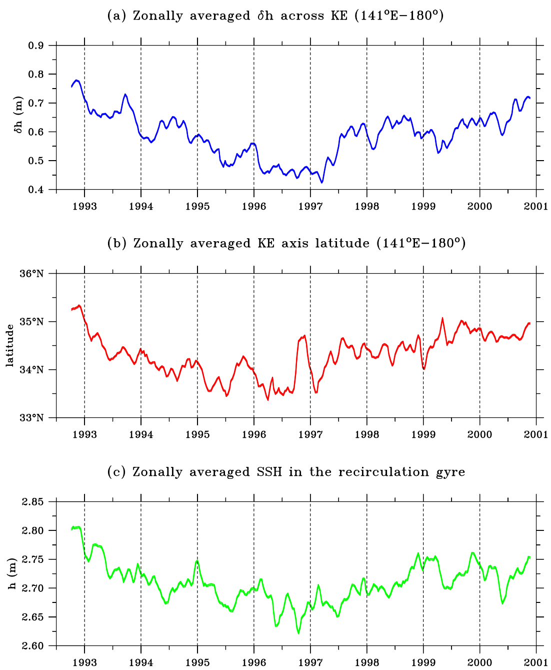


Figure 4: Time series of (a) the zonally averaged SSH difference across the Kuroshio Extension, (b) the zonally averaged axis position of the Kuroshio Extension, and (c) the zonally averaged SSH in the recirculation gyre. Here, the zonal average is from 141°E to 180°E. Examples of the SSH fields are given in Figure 5.

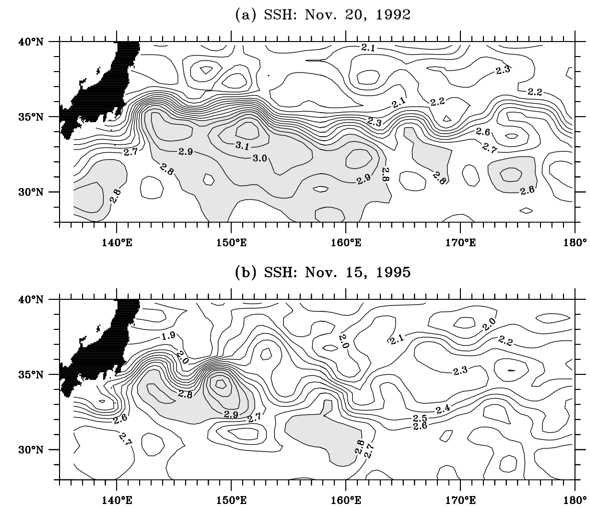


Figure 5: Sea surface height fields on (a) 20 November 1992 and (b) 15 November 1995. Compared with 1995, the Kuroshio Extension in 1992 is accompanied by a recirculation gyre with greater zonal and meridional extent.

turned to the elongated state after 1999 (Figure 4). As indicated in Figure 5, in the elongated state, the Kuroshio Extension has a larger eastward surface transport, a greater zonal penetration, and a more northerly zonal-mean path. All these characteristics are closely connected to the presence of an intense, zonally-elongated southern recirculation gyre. In its contracted state, the Kuroshio Extension has a smaller eastward surface transport, a more southerly mean path, and is accompanied by a weaker southern recirculation gyre.

In the Kuroshio Extension region, the average heat flux from ocean to atmosphere (DaSilva et al. 1994) is among the highest in the world, and is particularly strong in winter when cold dry continental air encounters the warm waters advected northward from low latitudes by the Kuroshio. South of the Kuroshio Extension, this strong cooling results in convection, forms a deep mixed layer, and is the primary source of Subtropical Mode Water (STMW), a water with anomalously low PV (Hanawa and Talley 2001). This deep, weakly stratified water mass is in contact with the atmosphere in late winter, and its enormous heat capacity is able to moderate upper-ocean water temperatures (Warren 1972).

The Kuroshio Extension region exhibits strong interannual to interdecadal sea surface temperature (SST) variability, and is considered to be one of the key areas of Pacific climate variation (Miller et al. 1994; Deser and Blackmon 1995; Latif and Barnett 1996; Nakamura et al. 1997). Averaged annually, the net heat flux from the ocean to the atmosphere over the Kuroshio Extension region ranges from 50 to 150 $\mathrm{W\,m^{-2}}$ (DaSilva et al. 1994). In order to maintain the thermodynamic equilibrium in the surface ocean and the atmospheric boundary layer, this net heat loss must be balanced by heat advection of the ocean circulation. Indeed, a recent study by Qiu (2000) using altimeter and other available *in situ* data found that the Kuroshio Extension upper layer is *not* simply a well-mixed layer passively responding to heat flux anomalies forced by the atmosphere. He showed that the large-scale changes in the Kuroshio Extension system (Figures 4 and 5) influence the surface ocean heat balance and can generate the wintertime SST anomalies through anomalous geostrophic heat advection.

Over the midlatitude North Pacific Ocean, the preferred paths of wintertime extratropical storms parallel the eastward-flowing Kuroshio Extension (Figure 6) and correspond to the region where the heat

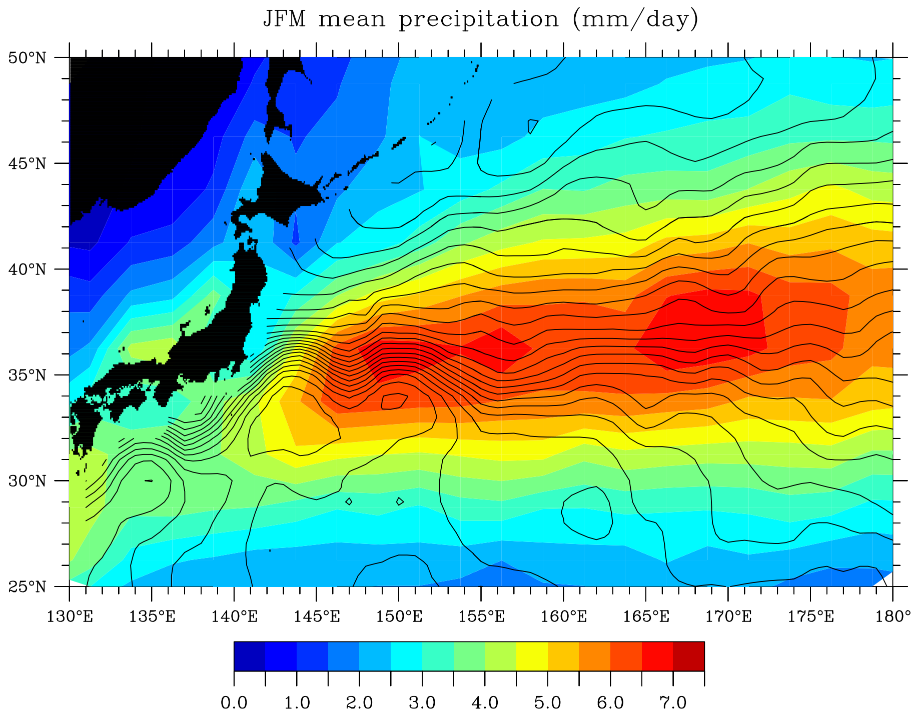


Figure 6: Wintertime (JFM) mean precipitation over the North Pacific Ocean. Based on Xie and Arkin (1997). Contours: Sea surface dynamic height (0/1000 db) climatology from Teague et al. (1990).

loss from the ocean to the atmosphere is largest. Given the proximity of the areas of maximum air-sea heat exchange, atmospheric storm tracks, and maximum oceanic variability, it is conceivable that the large-scale fluctuations occurring in the Kuroshio Extension system could change the upper ocean heat balance and modify the atmospheric circulation at long time scales by altering the baroclinicity and positions of the wintertime storms (*e.g.*, Nakamura and Izumi 2002; Joyce et al. 2001). Although KESS does not address the issue of midlatitude ocean-atmosphere coupling, a better understanding of the dynamics and thermodynamics of the time-varying Kuroshio Extension and its recirculation gyre clearly contributes to our goal of unraveling the coupled ocean-atmosphere system as a whole.

Numerical models of ever-increasing resolution are being applied to western boundary current systems, generally in the context of full basin models, given today's computer capabilities and the need to avoid open boundary conditions. As they achieve grid spacings of about 6 km or less, a threshold seems to be reached where the models simulate realistic deep eddy variability, and with concomitant vertical coupling between the upper meandering jets and deep flows, and realistic paths and separation (Hurlburt and Hogan 2000; Hurlburt and Metzger 1998; McClean et al. 2002). Ever more powerful and fine resolution models are becoming accessible (*e.g.*, NLOM, HYCOM, POP, JAMSTEC). This modeling community recognizes the essential role played by mesoscale processes for the models to realistically simulate the circulation (see letters of collaboration from Drs. Hurlburt and McClean in Section I). Mesoscale eddies and meanders play a crucial role in driving and modulating the broader scale circulation through its defining influence on volume transport and poleward heat transport of the WBC system. However, there are important differences between the Atlantic and Pacific Oceans in terms of the topography, stratification / PV structure, neighboring subarctic circulation, wind curl and thermohaline forcing. Therefore, it would be unwise to assume that models should seek to replicate in the Kuroshio the same processes that are at work in the Gulf Stream. New observational process-studies are required in the Pacific and particularly in the Kuroshio Extension, tailored to address these issues and to use as measures of model fidelity.

4 Objectives

Objective 1

To understand processes coupling the baroclinic and barotropic circulation and variability.

Working Hypotheses

- As in the canonical baroclinic instability process, meandering of the Kuroshio Extension couples the baroclinic front to deep eddies, that, in turn steer the baroclinic front.
- The baroclinic and barotropic coupling differ in the Kuroshio compared to the Gulf Stream due to differing topography, stratification and PV.
- The background PV field favors mixed baroclinic/barotropic instability.
- Mesoscale processes are punctuated by episodic large-amplitude events, which dominate the statistics of eddy fluxes and their divergences.

What's needed

Density and velocity time series, with mesoscale resolution to calculate the horizontal derivatives of velocity and density and their time-tendency terms. Sufficient vertical resolution is necessary to quantify the structure of the upper-jet baroclinic front and the deep nearly barotropic fields. "Case-studies" of the local dynamical balances, particularly of large-amplitude events.

Objective 2

To determine and quantify cross-frontal exchange processes in the Kuroshio Extension.

Working Hypotheses

- Mesoscale processes including meanders, rings, and barotropic eddies drive cross-frontal fluxes of heat, salt, momentum, and PV.
- Meander crests and troughs play symmetric roles in the cross-frontal exchange process.
- Stirring processes strain waters injected across the front into thin streamers and facilitate the final mixing process.

What's needed

In situ, mesoscale-resolving observations of density and velocity to quantify and characterize cross-frontal transport and its variablity. Hydrographic surveys with high spatial resolution through steep meanders and their associated streamers to understand the mixing process and the final outcome. Time series of density and velocity to estimate tendencies and place the synoptic survey in a temporal context.

Objective 3

To determine the processes that govern the strength and structure of the recirculation gyre – its position, elongation, stratification, and subtropical mode water formation within the gyre.

Working Hypotheses

- Meanders and mesoscale instabilities result in PV-fluxes that drive recirculation.
- Modulation of the recirculation gyre is due to changing PV structure of the Kuroshio Extension (Spall (1996) hypothesis).
- SST changes are moderated by the enormous heat capacity of STMW lenses which are sequestered reservoirs of heat.
- Mean and eddy fluxes of heat by the Kuroshio Extension play a role in the variation of SST in the Kuroshio Extension region.

What's needed

High spatial resolution current and density measurements to study the evolving structure of the Kuroshio Extension and eddy-mean flow interaction. Direct measurements of density and velocity to determine the vertical stucture of the recirculation gyre. Concurrent analyses of longer-term satellite SSH and surface temperature observations to combine with *in situ* measurements to observe the strength and horizontal structure of the recirculation. Simultaneous *in situ* measurements of thermocline, mixed layer, and integrated heat content.

5 Program plan

Here we present an overview of the field work specifically designed to quantify the interlinked processes discussed in Section 3 and test the hypotheses in Section 4. The suite of observations builds upon recent advances in instrumentation and data analysis. Figure 7 is a map view of the proposed observing array.

The moored array is designed to measure the time-varying density and velocity fields with the 4-D mesoscale resolution required to determine dynamical balances and cross-frontal exchanges of heat, salt, momentum, and PV. We center a high-resolution *in situ* instrument array on the first quasi-stationary meander trough east of Japan and in the region of highest eddy kinetic energy (Figure 7). The array comprises inverted echo sounders equipped with bottom pressure gauges and current meters (C-PIESs), and moored profilers (MPs) equipped with upward-looking acoustic Doppler current meters (ADCPs) and deep current meters (CMs). CTD/shipboard acoustic Doppler profiler (SADCP) surveys will measure the broad-scale density and velocity structure and conduct highly resolved feature-studies to examine the ultimate mixing processes of water parcels that cross the front.

To understand the dynamic and thermodynamic changes in the recirculation gyre (heat content, temperature advection, subduction, and PV), we need measurements of adequate resolution within the recirculation gyre (Figure 7). Satellite observations of SSH and SST will provide the large-scale context for KESS. Profiling T, S floats deployed within the recirculation gyre will monitor the temporal evolution of the temperature and salinity in the near-surface mixed layer, the STMW, and the intermediate waters. They are well suited for observing such processes as the mixed-layer evolution during winter storm events. Heat content and absolute velocity structure in the recirculation gyre will be measured by the combination of C-PIESs, MPs, and profiling floats.

The *in situ* observations will span a two-year period. Our experimental objectives are to accurately characterize the state of the Kuroshio Extension/recirculation gyre(s) system within this time-frame; to quantify the key exchange processes; and to relate these processes to satellite observations. Historical satellite and moored observations from the Kuroshio Extension suggest that in two years we should observe several large meander and ring-formation events, the slowly evolving mean state of the southern recirculation gyre, and its short-term response to a variety of winter storm conditions. Statistics of the eddy fluxes and their divergences are expected to be dominated by a few major events, consequently the KESS observation plan is tailored to provide informative case-studies. While the planned *in situ* array will not observe pentadal/decadal climatic variations, it offers valuable insight into the dynamical processes which are fundamental to climatic variability. Additionally the array will provide improved interpretation of the satellite SSH fields, which have been measured since 1992 by Topex/Poseidon and will continue with Jason 1 (launched December 2001).

Figure 8 gives the experiment schedule. The field experiment will begin in Summer 2004 and will be maintained for two years. During Summer 2004 a cruise will be required to deploy the MPs and C-PIESs. In Summer 2005, after the first year of deployment the MPs will require servicing and C-PIES data will be collected by acoustic telemetery to the ship (without disturbing the pressure leveling). All moored instrumentation will be recovered during Summer 2006. On the 2004 and 2005 cruises, 20 floats will be deployed in the recirculation gyre. Hydrographic surveys will be conducted on these cruises.

Data from the MPs, C-PIESs, and floats will become available in 2005 and again in 2006. The PIs will thus be able to address data and scientific issues in concert. After the initial processing of the substantial data set, we will have over two years for analysis.

Modeling collaborations. The large data set consisting of *in situ* and satellite observations will be crucial for the evaluation of ocean circulation models particularly as the resolution improves and mesoscale fields become ever more realistic. While no modeling efforts are explicitly included in this program, we have already initiated collaborations with several modeling groups. These on-going efforts are described in Section 6 and letters of intent from the modelers are included in Section I.

Program management. URI will provide program coordination for the KESS PIs. A web site will be established to facilitate inter-PI communication including data exchange and to provide project information to peers and to the public. Two workshops are planned: *Fall 2003,* at the AGU meeting for cruise coordination and *Fall 2005,* at URI for sharing initial results from the mid-experiment data recoveries. A special Kuroshio Extension session will be organized for a 2007 AGU meeting.

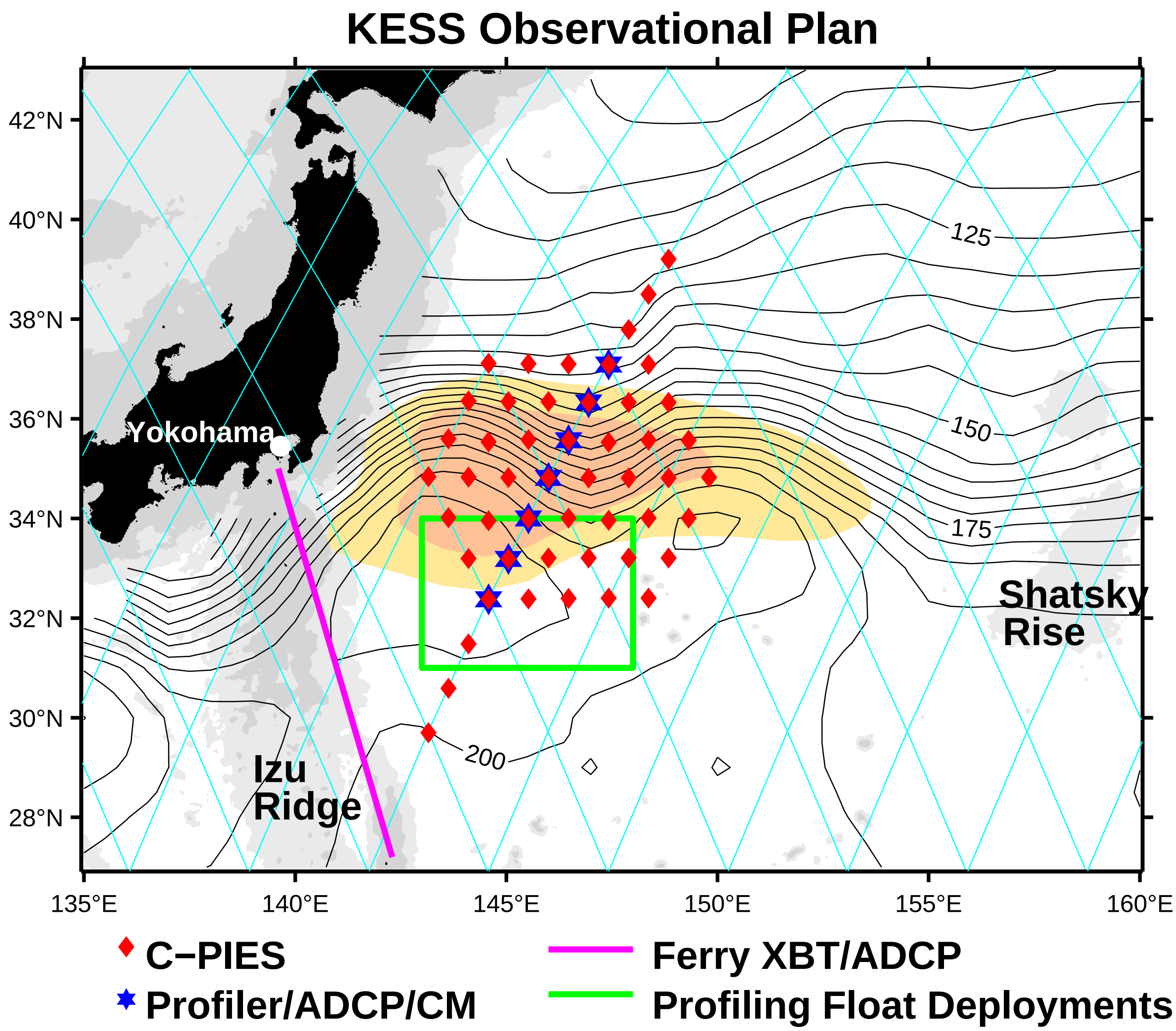


Figure 7: Proposed KESS array of C-PIESs (red diamonds) and MPs (blue stars). Profiling T,S floats will be deployed within the green boxed region. Thin blue lines indicate T/P-Jason 1 ground tracks, the magenta line indicates the TOLEX Ogasawara ferry route. Solid lines are the GDEM mean surface dynamic height contours in dyn cm from Teague et al. (1990). The 2000 and 4000 m isobaths are shaded dark and light gray, respectively. Eddy kinetic energy > 0.18 and $0.24\ \mathrm{m^2 s^{-2}}$ is color shaded yellow and orange, respectively. CTD/SADCP observations will be made at all C-PIES sites and in three feature studies.

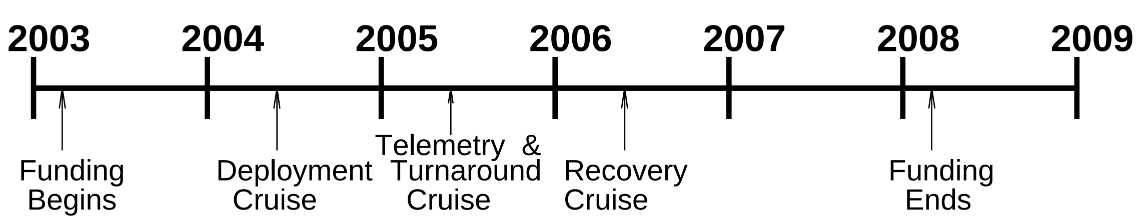


Figure 8: Timeline of the KESS experiment

The URI, WHOI, and UH components draw their individual and common Goals from the preceeding tightly integrated set of Objectives. The next three subsections propose for each institution observations and tasks, which are jointly tailored to meet our common Objectives.

5.1 URI component

Principal Investigators: D. Randolph Watts and Kathleen Donohue

Goals. We aim (a) to understand the dynamics of the vertical coupling intrinsic to baroclinic instability, (b) to quantify the exchange of waters as a function of depth across the baroclinic zone associated with steep meanders and rings, (c) to understand the interactions between the mesoscale eddies and the recirculation gyres, and (d) to estimate the time-varying strength of circulation on $\sim$ 300 km transects crossing the recirculation gyre to the south and the mixed-water regime to the north.

The KESS C-PIES array design is motivated by the need identified with all three Objectives (Section 4) to map the velocity and density structure both vertically and horizontally. Previous experiments in other strong current systems illustrate that a mesoscale resolving array of PIES and deep current meters provides the information needed to accurately diagnose vertical and ageostrophic motions (*e.g.*, Lindstrom et al. 1997; Howden 2000). With the WHOI and UH components we have complementary programs to address our joint goals. The C-PIES array lateral spacing is designed as discussed below to produce mapping accuracy sufficient to estimate mesoscale dynamical quantities such as advection of vorticity. This is complemented by the high vertical resolution of the MPs and profiling floats. The satellite altimeter data provides the larger-scale context for the array.

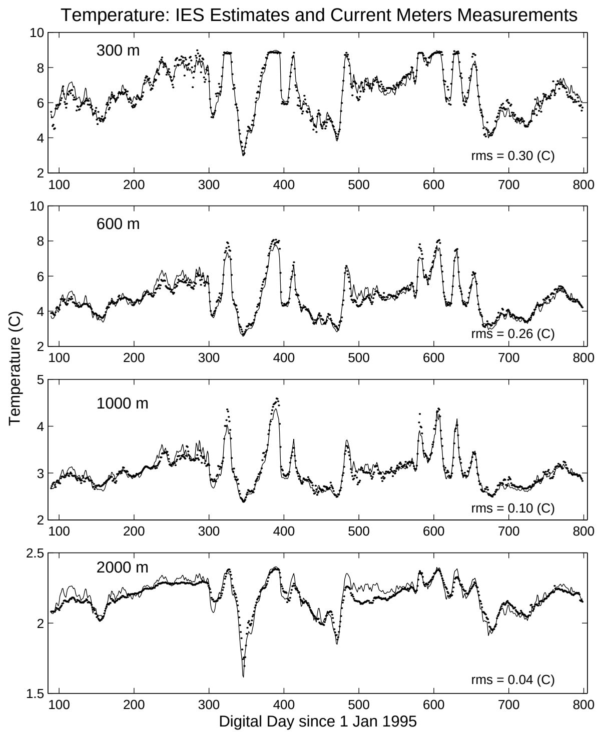
C-PIES. The inverted echo sounder (IES) measures acoustic echo time (τ) from the sea bed to the sea surface. The "PIES" is an IES with a bottom-pressure sensor. The "C-PIES" is an IES with added sensors to measure both current (tethered 50 m above the sea floor to avoid the bottom boundary layer) and bottom pressure. The instruments sample hourly and have telemetry systems that enable us to download data to a computer on a nearby ship.

In strong-current regions of the global ocean, the IES vertical acoustic echo time measurements have been used to estimate, with remarkable accuracy, entire *profiles* of temperature $T(p)$ and specific-volume anomaly $\delta(p)$ (or equivalently density $\rho(p)$). From hydrographic data, two-dimensional τ-parameterizations of these fields, $T_G(\tau, p)$ and $\delta_G(\tau, p)$, can be computed. We call each of these a "gravest empirical mode" (GEM) representation of the vertical structure. IES measurements of τ, combined with the GEM interpretation, produce estimated $T(p)$ and $\delta(p)$ time series at each site. Time-series profiles of geopotential thickness, $\phi(p) = \int_0^p \delta(p')\, dp'$, can then be estimated above each IES. Pairs of IESs give $\phi(p)$ lateral differences, which, through geostrophy, determine profiles of average baroclinic shear between the two sites (normal to the sites' separation vector). An L-shaped group of three IESs determines estimates of both velocity components. A 2-D array of appropriately spaced IESs can map out the 3-D structure of the horizontal velocity field. Additionally, the deep pressure and current measurements provide referencing to make the velocity profiles absolute. This method has been succesfully used in the North Atlantic Current (Meinen and Watts 2000), the Antarctic Circumpolar Current (Watts et al. 2001b) and the Kuroshio (Book et al. 2002) and is currently being employed in experiments in the Agulhas Retroflection Region and the Japan Sea.

Here we show an example from the Antarctic Circumpolar Current (Figures 9 and 10). Both temperatures and velocities determined from PIES measurements interpreted via the GEM technique are in excellent agreement with measurements from nearby moorings and a hydrographic survey.

GEM fields for temperature, salinity, specific volume, and potential vorticity have been calculated for the KESS region (Willeford 2001). The KESS GEM temperature field enables an IES to estimate temperature at 500 dbar in the thermocline with rms error of 0.4–0.5°C (not shown). The rms error decreases with depth, and at 2500 dbar is less than 0.04°C. Hence we expect accuracy comparable to Figure 9 (with T(500dbar) ranging from 4–14°C).

C-PIES Array Design. Figure 7 shows the proposed locations of the C-PIES array consisting of 50 C-PIESs. The design of this array is based on the following considerations. (1) The array is in the region of maximum Kuroshio Extension eddy kinetic energy. (2) The 525 km (32.4° – 37.11°N) meridional extent of the main array is sufficient to ensure that it almost always fully encompasses the Kuroshio Extension front and extends meridionally into the adjacent waters. (3) The zonal width of the KESS C-PIES array encompasses the typical meander wave-



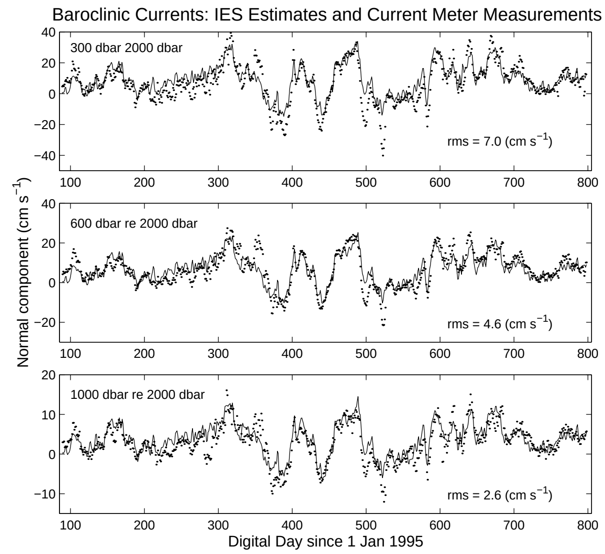


Figure 9: Temperatures obtained by two methods in the Subantarctic Front south of Australia: estimates from τ measurements of a single IES using the GEM method (solid) at the same site as temperatures measured by four current meters (dotted) at the different depth levels shown. Note changes in the ordinate scales between panels. From Watts et al. (2000b).

Figure 10: Current velocities obtained by two methods in the Subantarctic Front. Velocities respectively at nominal levels 300, 600, and 1000 dbar relative to 2000 dbar were estimated from a pair of adjacent IESs about 90 km apart (solid) and determined from measured currents on a mooring midway between the IESs (dotted). The current component along 107°True is shown. The ordinate changes scales between panels. Note that most of the difference between the IES- and the CM-determined currents can be attributed to the former being a horizontal average of the flow between the IESs, while the latter is a point measurement. From Watts et al. (2000b).

length. (4) The mesoscale resolution is sufficient to enable a study of dynamical balances. According to Koblinsky et al. (1984, Fig.4), the correlation length scale of the spatial autocorrelation function for temperature at 300 m in the region is 90-100 km, in both N-S and E-W directions. In designing a coherent mesoscale-mapping C-PIES array, we have chosen a spacing of 85 km. Throughout the region, errors associated with the mapped fields will be only about twice that of the measurements themselves and will be robust in case isolated instruments fail. (5) Of the 50 C-PIES sites, 32 are chosen along T/P Jason-1 altimeter tracks of which 9 coincide with cross-over points and 18 resolve the region within the "diamonds".

The hexagonal arrangement and spacing of sites in the array is dictated by the altimeter ground-tracks and the above requirements for areal coverage. Figure 11 demonstrates that to achieve accurate mesoscale resolution, two C-PIES sites are required between the cross-over points, both along the tracks and through the diamond centers. The predicted mapping error for the meridional barotropic velocity component is illustrated for the array configuration. These errors were predicted by optimal interpolation (Bretherton et al. 1976) using both the bottom pressure and lower level gradients (deep currents) that would be measured at the C-PIES sites as inputs and specifying a correlation length of 90 km. The error fields shown are also representative of those obtained for barotropic streamfunction and zonal velocity, and error fields approximately double for vorticity estimates. The errors within the proposed hexagon are less than 15% everywhere, consistent with the required accuracy. By contrast, the right panel of Figure 11 indicates for a sparser array, where a single C-PIES instead of two was placed between the cross-over points, that mapping errors would be unacceptable for dynamical analyses (exceeding 25% in nearly two-thirds of the region).

While it could be argued that this sparser array is

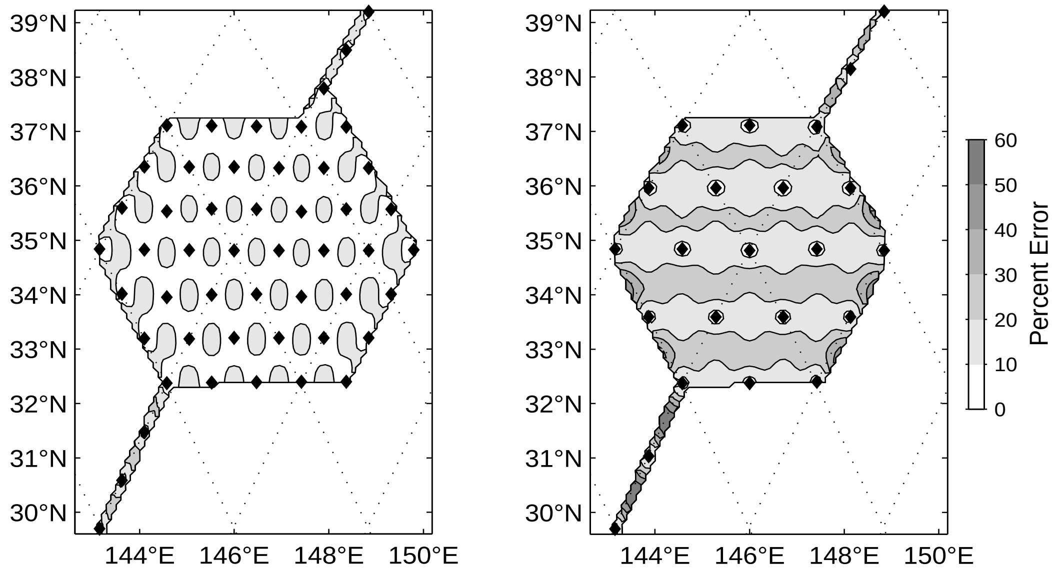


Figure 11: Estimated mapping errors in v (percent variance) for two array configurations predicted by optimal interpolation using a correlation length scale of 90 km. The meridional barotropic component is illustrated because of its key role in cross-frontal exchanges. The left panel is for the proposed KESS array, and the right panel is for a sparser array. Solid diamonds denote C-PIES locations and dotted lines indicate T/P Jason-1 groundtracks. Contour interval 10%.

sufficient to estimate mesoscale features of the temperature and density fields (acceptable for pattern recognition), the lateral gradient estimates required for dynamical analyses have unacceptable errors. For example, errors for relative vorticity estimates are twice those shown. While the proposed array serves our goals, estimates for the sparser array would have errors exceeding 50%. For the baroclinic fields, the errors are larger (in approximate ratio 8/5) since upper level gradients are not directly measured. Furthermore, the sparser array would not be robust to even a single instrument loss. While excellent success rates were achieved on previous deployments of PIES (90–95%), it is unrealistic to assume there will be no failures during KESS. Consequently, we argue that the proposed grid spacing, which requires 50 C-PIESs, is necessary to meet our objectives stated in Section 4.

Analyses. The pressure measurements will be used to map the deep streamfunction fields. If the mean abyssal currents were zero, it would be adequate to set the mean pressure gradients equal to zero as well in order to level the pressures. In this region, however, mean currents of ~ 5 cm s^{-1} and instantaneous currents as high as 40 cm s^{-1} were observed below 4000 m (Schmitz 1987; Schmitz et al. 1982; Hallock and Teague 1996; Owens and Warren 2001). Thus, referencing the measured pressures to the same absolute geopotential is required and will be accomplished by following the technique described in Watts et al. (2001a) using the mean current vectors measured directly by the C-PIESs. This enables us, for example, to estimate the absolute current structure crossing the two 'antennae' that extend nearly 300 km south across the recirculation gyre and north across the mixed water regime.

The C-PIES measurements interpreted *via* the GEM method will be used to estimate time series of full-water-column profiles of the typical T, S, and PV structure in streamfunction coordinates as it flows through the region. Optimal interpolation will be used to produce 4-D maps of these quantities and the velocity field. From daily maps we will be able to evaluate the dynamical balances, with particular focus on episodic extreme events. In the Gulf Stream, eddy statistics were dominated by steep meander events; this case-study approach has proven particularly informative (*e.g.*, Cronin 1996; Howden 2000).

We will be able to estimate cross-frontal advection, using the property gradients along isopycnals, mapped on a day-by-day basis. In individual events, however, water properties and PV will deviate from the typical conditions as they are advected *across* the baroclinic zone. This acts to enhance the cross-frontal exchange above that obtained by the advection of GEM-estimated quantities. An important aspect of our combined MP/ADCP/CM and C-PIES investigation is to characterize the nature of cross-frontal exchange (*e.g.*, are the statistics comprised of a few thick fresh bolusses or many small streamers with small anomaly?). The combined C-PIES and MP measurements will make complementary estimates of the cross-frontal fluxes – from the advection of typical property gradients throughout the C-PIES mapping region, and from the full covariances of property anomalies at all the MP/ADCP/MP sites. The line of MPs is well suited for measuring the detailed structure of these T, S, and PV anomalies, and the C-PIES array provides data for interpreting them in relation to the pertinent mesoscale features.

We will work closely with the UH component to investigate the relationship between the sea surface height and the subsurface signals. The C-PIES data will be used to separate the baroclinic and barotropic components of the SSH variation (Hendry et al. 2002; Teague et al. 1995). Modelers have expressed interest in understanding the dynamical components of altimeter SSH in order to improve model simulations which assimilate SSH (such as Hurlburt et al. 2000). We will be able to enhance the altimeter data in four ways. First, we can absolutely reference the SSH anomaly and we can provide estimates of the geoid along the 6 T/P Jason-1 tracks coincident with our array (Teague et al. 1997). Second, we can determine the relative contributions of baroclinic and barotropic components of the SSH anomaly – distinguishing steric and non-steric contributions. Third, we can resolve mesoscale features in the regions between tracks, the "diamonds". Fourth, by comparing our C-PIES measurements with altimeter measurements we will test a scheme whereby the GEMs can be used to infer, from altimeter data, subsurface temperature and velocity fields in the KESS region – important results which can be applied to times before and after the KESS array deployment.

Hydrographic Case-Studies. We also propose small-scale intensive CTD/SADCP surveys in order to provide case studies of cross-frontal exchange. These surveys will describe small-scale features and aspects of the flow that are not laterally resolved by other measurements, for example streamers that are hypothesized to result when intermediate water is carried across the Kuroshio Extension by meander processes. Hydrographic surveys will be taken on the C-PIES array deployment, telemetry, and recovery cruises. Initially, a larger-scale survey will be conducted by taking CTD profiles at each C-PIES site, which will also serve as part of the instrument calibration. From these initial surveys, along with near-real-time SST imagery and altimeter SSH data, we will select a location for the high-resolution survey. For example, in a 6 day feature survey we can expect to take 80 casts to 1500-m depth covering a 120-130 km region with an average 15-km station spacing. Based upon recent 2-D surveys in the Kuroshio region these small-scale surveys can provide robust estimates of horizontal gradients of temperature and salt (Joyce et al. 2001). Direct velocity measurements combined with the hydrography enable the calculation of geostrophic and ageostrophic property fluxes, yielding case studies of cross-frontal exchange in Kuroshio meanders. A UNOLS vessel with deep-reaching SADCP such as the R/V *Revelle* is requested because it has a shipboard acoustic Doppler system with 1000 m depth capability. This shipboard dual frequency "Hydrographic Doppler Sonar System" will continue to be operational at the time of the KESS experiment (R. Pinkel, pers. comm.). The system consists of two sonars, a long-range 50 kHz unit and a high-resolution 140 kHz device. The long-range unit is presently achieving depths of 700-1000 m with 12-m depth resolution. Data are recorded every two minutes. The high-resolution system penetrates to 200-350 m, with 3.5 m depth resolution. Data are recorded every minute.

5.2 WHOI component

Principal Investigators: Steven Jayne and Nelson Hogg

Goals. We aim to (a) quantify the partition between barotropic and baroclinic instability mechanisms within the Kuroshio jet, (b) investigate the role of eddy processes in forcing the recirculation(s), (c) quantify the exchange of North Pacific Intermediate Water (NPIW) across the Kuroshio and (d) contribute toward an improved understanding of the upper ocean heat balance.

Baroclinic/Barotropic Instability. In the Gulf Stream, Howden (2000) has described six events in a 2-year period in which meander-troughs steepen and spin up a co-rotating deep eddy (Figure 2, see also Savidge and Bane 1999a, 1999b). This shallow–deep coupling is thought to happen through baroclinic instability, a belief supported by a number of other studies (Dewar and Bane 1989; Rossby 1987; Cronin and Watts 1996). However, this is not a universal conclusion (*e.g.,* Hall 1986) and numerical models generally implicate the barotropic energy conversion process (*e.g.,* Haidvogel and Holland 1978; Holland and Haidvogel 1980). In contrast with the Gulf Stream, Hall (1991) found that baroclinic processes dominate in the Kuroshio, although her analysis was restricted by the availability of just one mooring (at 35°N, 153°E). Both she and Qiu (1995) and Adamec (1998), who worked with sea surface height data, 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. What is missing from both these studies is the more complete vertical and lateral information that will be provided by MP/CM/ADCP and C-PIES arrays, as well as the supporting satellite altimeter observations. The profiler array will also allow us to map out the PV field in the cross-stream direction. The structure of this field, in particular the location of its extrema, is crucial to the identification of the dominant mode of instability.

The repeated ADCP/XBT transect that is made by the Ogasawara-maru ferry (Figure 7 and Section 7) will provide a very useful time series of upper ocean currents and temperature with which we will be able to compare our moored section and investigate the manner in which properties such as PV evolve.

Recirculation physics. A variety of mechanisms have been offered for producing the intense recirculation zones found in the vicinity of western boundary currents. Our working hypothesis is that they result from the need of the quasi-inertial current to rid itself of low PV that it acquired at more southern latitudes. The signature of the anomalous PV is a minimum in its cross-stream distribution from which instabilities result. Simplified barotropic and reduced-gravity numerical models (Cessi et al. 1987; Jayne and Hogg 1999) have been able to model this process and predict recirculation strengths quite accurately in spite of their reliance on the barotropic instability mechanism. Parameterizations for the spatial covariance function for the streamfunction have also been used to model the interaction between eddies and the mean flow. Satellite altimeters measure sea surface height which, with the geostrophic approximation, is a proxy for streamfunction and therefore can be used to assess the appropriateness of the statistical formulation of Hogg (1993). With the MP measurements through the thermocline we will be able to obtain a better parameterization for the vertical dependence and, thereby, assess the importance of thickness fluxes in the eddy–mean flow vorticity balance.

North Pacific Intermediate Water exchanges. From synoptic surveys NPIW has been found south of the Kuroshio, although its route and transformation across the Kuroshio Extension is not well understood. Experience within the Gulf Stream would suggest ring formation, barotropic/baroclinic coupling (Lindstrom et al. 1997) and chaotic exchange (Lozier et al. 1997) as the primary processes. The MPs will allow us to quantify the average exchange of NPIW in the region of the array and will determine the exact depths and water properties in events mapped by the surrounding C-PIES array.

The upper ocean heat budget. The upper ocean heat budget depends on many factors and will be primarily determined through use of satellite measurements of sea surface variability (SST and SSH) and profiling floats (Section 5.3). The primary balance is between advection of warm water from the tropics and the loss of heat through the sea surface. Cooling in the wintertime is sufficiently strong that penetrative convection takes place in the weakly stratified region to the south of the Kuroshio, and this results in the formation of Subtropical Mode Water (STMW). Given that the annually-averaged heat flux through the air–sea interface in the Kuroshio Extension region is strongly upward, it is clear that horizontal heat advection must play an important role in the regional upper ocean heat balance and will be measured by the MPs, along with the seasonal STMW formation process.

The Moored Profiler/Current Meter Array. Seven deep moorings will be deployed along a line in the C-PIES array, across the axis of the Kuroshio Extension and extending south into the southern recirculation gyre (see Figure 7). The moorings will consist of 3 deep Aanderaa RCM-11 acoustic current meters at 2000 m, 3500 m, and 5000 m. Above the RCM-11s will be a moored profiler that will travel from 1500 m up to 200 m and back again once a day. Finally, at the top of each mooring will be an upward-looking ADCP which will cover the near-surface velocity field (see Figure 12). The moorings themselves will be collocated with C-PIESs so as to permit the validation of the temperature and salinity structure estimated by the C-PIESs against direct measuremetns from the MPs. With simultaneous measurements of temperature and salinity we will also be able to estimate the cross-frontal flux of heat and salt and, with the 2-year time series and C-PIES maps of the velocity field, expect to observe a number of occasions when NPIW is exchanged across the Kuroshio front.

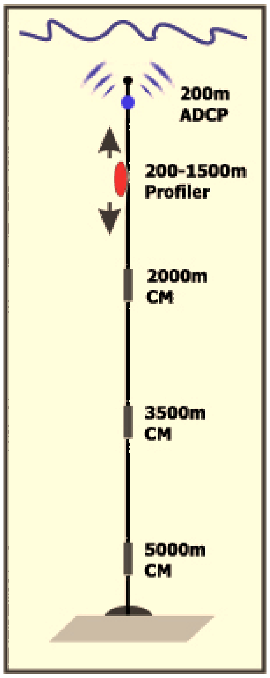


Figure 12: Schematic of the deep-sea mooring design.

The design of the array is a compromise between the need to cover the full meridional extent of the Kuroshio Extension, including steep meander crests and troughs in which major exchanges are most likely to occur, and the need to be able to resolve the structure adequately. With the full width of the Kuroshio Extension being about 200 km, the spacing proposed (100 km) in Figure 7 is barely adequate. However, we anticipate using the method pioneered by Hall and Bryden (1985) and extended by Hogg (1991) and Johns et al. (1995) to reconstruct the cross-stream structure by assuming that it is being horizontally profiled as the Kuroshio Extension meanders over the moorings. An advantage of this array, over the single mooring used by Hall and Bryden (1985), is that additional degrees of freedom are available (from the moorings and the inverted echo sounders) to relax the frozen structure assumption – in particular, to determine the lateral position and path of the current independently of the observed vertical structure.

The southern end of the profiler array will be in the recirculation gyre except when a very large trough occurs in the region. In the upper part of the MP profile we should also observe the deep convection of newly forming STMW and be able to contribute to the calculation of the heat budget for the recirculation gyre, capitalizing on the mapping information to distinguish whether each profile is in the gyre, in a ring core, or along the periphery of the Kuroshio. The array extends northward into the Mixed Water region where it is uncertain as to whether or not the time-averaged circulation contains a recirculating component. Theory and experience in the Gulf Stream suggests that it should. However, it has never been decisively demonstrated that it does, in fact, exist.

The instrument package within the MP contains both a CTD and a 3-axis acoustic current meter, and through use of a traction drive system, climbs up and down a mooring line (Doherty et al., 1999; Toole et al. 1999). Its power and recording capacity give it capability to cover a total distance of 1 million meters (*e.g.*, one up and down trip per day over 1.3 km for 365 days). The great advantage over conventional mooring systems, even those containing doppler profiling instruments, is that profiles of velocity, temperature and conductivity are obtained. Use of a mooring design program with parameters appropriate to the Kuroshio gives us confidence that the strong currents should give no difficulties. The WHOI Moored Profiler has been developed over the past 5 years (Doherty et al. 1999). The first generation used a closed-shell design that has since been modified to an open-shell, where the drive wheels are exposed to the seawater flowing by them to reduce the potential for biological fouling. Four successful deployments of MPs, so equipped, have been made to date including one that made 500 round trips between 500 m and 1500 m in the Kuroshio Extension region (Y. Yoshikawa, pers. comm.).

5.3 UH component

Principal Investigators: Bo Qiu, Peter Hacker, and Humio Mitsudera

Goals. We aim to (a) quantify the horizontal structure and temporal variability of the Kuroshio Extension and the recirculation gyre using altimetric data, (b) quantify the temporal evolution of the upper ocean temperature and salinity fields (STMW and intermediate waters) in the recirculation gyre using profiling T/S floats, and (c) evaluate the upper ocean heat and salt budgets in the recirculation gyre region.

Satellite altimetric data. The Jason-1 altimeter satellite was successfully launched in December, 2001. It will provide us with the high-quality sea surface height information over the 5-year period of the KESS project. The mean SSH inferred from the altimetric data (Qiu 1995) will be used in conjunction with the anomalies to estimate fields of absolute SSH, whose accuracy can be directly validated within the C-PIES array. The broad-scale SSH maps thus created (see Figure 5, for examples) will put in perspective meandering events observed by the regional, intensive dynamics array of KESS. The SSH fields will also be useful to determine the location of the Kuroshio Extension over the broad region, helping us in identifying the extent of the recirculation gyre and in deploying the profiling T/S floats. Many of the C-PIESs and MP/ADCP/CMs (Figure 7) are located along six Jason-1 groundtracks providing an opportunity to examine the relationship between the altimetrically measured SSH signals and the subsurface oceanic signals (*e.g.,* Teague et al. 1995).

Profiling T/S floats. During each of the first two cruises (2004, 2005), 20 profiling T/S floats (Argo-type such as APEX, Webb Research Corporation, or SOLO/UCSD) will be deployed within the recirculation gyre to the south of the Kuroshio Extension. The purpose of these floats is to monitor the temporal evolution of the temperature and salinity fields near the center of the recirculation gyre, both on the high-resolution scale (100-200 km) and, as they disperse, on the regional array scale, over two annual cycles. The floats will provide information on SST, SSS, the seasonal mixed layer above the top of the pycnocline, and the deeper mode and intermediate waters, as well as drift velocity estimates at the parking depth of 1000 m (Figure 13). From 1000 m the floats will profile temperature and salinity to the near-surface every 5 days with 5-meter vertical resolution. The choice of a 1000 m parking depth will allow up to 300 profiles (assumes ARGOS "multisatellite service"). Thus, the floats can be preprogrammed to provide 5 day profiling for 2 years from 1000 m, and an extended "Argo" mission of 10 day profiling from 2000 m, when the floats are likely to have dispersed to the Ago spacing of 300 km. (Two-way and high-data-rate communications may be commercially available by the time of KESS, providing additional sampling options.) Although a 10-day sampling interval would be sufficient temporal resolution for thermocline processes, the 5-day interval is desirable to resolve mixed-layer evolution in winter, such as changes resulting from individual storms, and for reduced noise in the heat and salt budget calculations especially within the seasonally evolving mixed layer.

The 40 floats will be deployed within a 300x400 km domain centered near the southern MP/ADCP/CM mooring, so as to seed the center of the recirculation gyre identified in Figure 7 and the area of high winter heat flux. The floats complement the mooring by providing essential temperature and salinity data above the reach of the mooring. The dispersion of the floats will result from both eddy motion within the gyre and the larger-scale gyre circulation. We expect some fraction of the floats to remain within the central portion of the gyre (within 300 km of the southern mooring), and the remaining floats to disperse within the larger-scale recirculation gyre (140°E–155°E). We plan to deploy the floats at a 100 km spacing near and south of the eastward flowing Kuroshio Extension using the pre-cruise SSH maps and NRL's Global NLOM Nowcast/Forecast as guides. Figure 3 indicates that the westward flow in the southern branch of the recirculation gyre is nearly barotropic below 800 m with speeds of 0-10 cm s^{-1}. The few Argo float data from the region suggest net displacements of 200-600 km in a year for floats not trapped in the Kuroshio Extension. From these data we estimate that the initial deployment of 20 floats will disperse to Argo spacing in 1-2 years. We plan to deploy the additional 20 floats in 2005 to maintain the high-resolution profiling T/S array for the second year near the southern MP/ADCP/CM mooring to ensure that the recirculation gyre remains well sampled for the second year by this high-resolution profiling T/S suite of floats. Thus, after the second deployment both the central region and the larger-scale regions should be populated with profiling floats. The deployment strategy clearly has an exploratory aspect because of the scarcity of existing Argo data from the recirculation gyre region. We plan to monitor and analyze data from the Japanese Argo deployments during the first year of KESS to refine our deployment strategy.

Upper-ocean budget analysis. Several dynamic and thermodynamic processes contribute to changes in the upper ocean heat budget. They include advection by geostrophic and Ekman flows, heat exchanges through the air-sea interface, entrainment of subsurface STMWs, and smaller-scale eddy heat fluxes (Wunsch 1999). We aim to quantify the contributions of dynamic and thermodynamic processes that cause seasonal and year-to-year variations in the upper ocean heat budget and the associated SST in the recirculation gyre region. In addition, the salt budget in the upper ocean will also be analyzed because the formation and seasonal and interannual evolutions of STMW could be affected by the salinity. At deeper levels relatively fresh NPIW is exchanged across the Kuroshio Extension. Budget

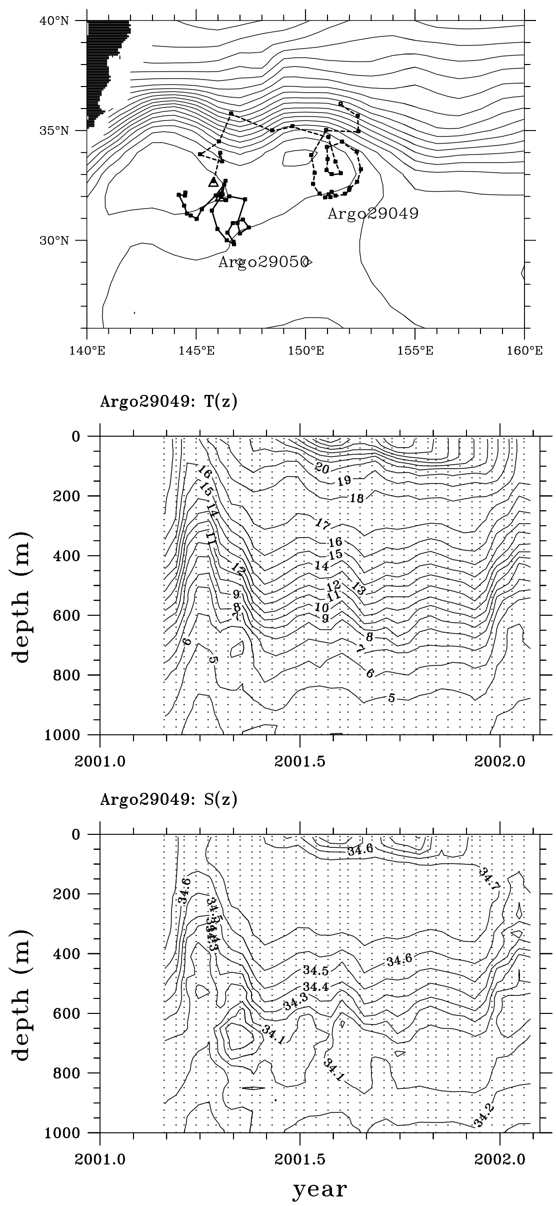


Figure 13: (top) Trajectories of two Japanese Argo floats (for 11 and 9 months) deployed in February, 2001. Triangles denote the deployment sites; squares are at ∼10-day intervals. The 2 floats took significantly divergent paths: one being trapped in the recirculation gyre and the other interacting actively with the Kuroshio Extension and its recirculation. The bottom 2 panels show the vertical T and S distributions measured by Argo 29049. The STMW and the NPIW can be respectively identified at ~ 200 m depth where $\partial T/\partial z$ is minimum and at ∼750 m depth where salinity is minimum.

calculations will be conducted using profiling T/S floats, altimetrically derived SSH field, and other concurrent Eulerian measurements from the Intensive Dynamics Study (see Sections 5.1 and 5.2). The primary domain of the calculation will be centered at the southernmost MP/ADCP/CM mooring site (at 144.5°E and 32.5°N, see Figure 7) in the recirculation gyre, extending over a horizontal scale of 400 – 800 km depending on the evolution of the profiling float distribution. We intend to conduct the budget calculations using two complementary approaches.

The local budget analysis focusing on the profiling T/S float data and the southern MP will closely follow the procedure used in the Coupled Ocean Atmosphere Response Experiment (COARE) as described in Feng et al. (1998). For the advective terms in the heat and salt budgets, we will use the upper ocean horizontal velocity data, $u(z)$ and $v(z)$, from the ADCP and the Profiler on the MP/ADCP/CM moorings. In addition, the absolute velocity profile (from the C-PIES and MP line that transects the recirculation gyre), heat-content estimates from the C-PIESs array, and all other measurements of temperature, salinity and velocity within the domain can be used. Data from successive 5-day periods are analyzed, using simultaneous least-square fits, to determine domain-mean quantities (T and S), their time rate of change, and their linear gradients as a function of depth across a sampling domain. Our choice of O(100 km) float spacing stems from the need to resolve the horizontal gradient structure within the recirculation gyre. Vertical velocity $w(z)$ along sloping isopycnals is estimated from the conservation of density equation (assuming no mixing). The results of the analysis are time-series of $T, S, u, v,$ and w, as functions of depth, the time-derivative terms for each variable, and the spatial gradients of T and S within the measurement domain. These variables are then used to evaluate the time-derivative and advection terms in the heat and salt budget equations. The absorption of shortwave radiation as a function of depth can be estimated as in Feng et al. (1998). With the assumption of zero vertical fluxes at the base of the budget layer, the upper ocean budget calculations provide a direct estimate, subject to the error estimates of the calculations, of the air-sea fluxes. Although we propose a different suite of instrumentation in KESS in order to calculate budgets over 2 years, the methodology used in COARE (Feng et al. 2000) demonstrated the power of the analysis technique with error estimates, the importance of the advective terms, and the ability to close the heat budget to 10 W m s^{-2} on a monthly time-scale (at least for COARE). Our estimates in KESS will be compared with the air-sea fluxes from operational weather and satellite derived products to check for consistency and to identify problems. Although KESS will not make direct measurements of vertical turbulent fluxes, this term can be roughly estimated in the budget calculations using the MP/ADCP/CM data and the methods presented in Gregg (1989) and Polzin et al. (1995).

The profiling T/S float data will be made available in real-time on the GTS. Delayed mode data (and products) will be quality controlled according to US Argo calibration procedures (Wong et al. 2001) and in coordination with Greg Johnson at PMEL, who is responsible for US Argo delayed-mode data.

As the second approach, we propose to use a 3-dimensional model of the upper ocean from the surface to 1000 m depth, which includes the STMW and the NPIW. The model's mixed layer dynamics will follow that proposed by Price et al. (1986, hereafter PWP) in which the evolution of the mixed layer depends crucially on the bulk Richardson number, or the vertical velocity shear and the density stratification at the base of the mixed layer. The original formulation of the PWP model (1-D vertical) will be extended to three dimensions, covering the Kuroshio Extension from 140°E to 170°E and 25°N to 40°N. Following Qiu and Kelly (1993) and Kelly and Qiu (1995), we will use the altimetrically-derived SSH field to specify the time-dependent, surface geostrophic velocity field. In the subsurface water, the thermal-wind relation will be used to infer the flow field using the model-predicted T/S fields. Careful comparison will be made between the model and the available T/S measurements (from the floats and the moored profilers) so as to improve model physics and parameters. Near the sea surface, additional advection due to Ekman fluxes will be included. The forcing fields for the model include the surface wind stress and heat fluxes, which will be taken from the daily NCEP reanalysis results. In this second approach, much of the advective flow field will be inferred from the large-scale SSH and point observations, rather than dynamically predicted. The thermodynamics of the models, on the other hand, will retain their complexity. In particular, we will take advantage of new insights regarding the horizontal eddy fluxes gained from the measurements of the intensive dynamic array. Given the historical difficulties in realistically simulating the KESS region with full-fledged ocean GCMs (OGCMs) in terms of zonal penetration scale, bifurcation latitude, and appropriate eddy kinetic energy level, we believe that this process model will provide a synthesis of all available KESS data to quantify the upper-ocean heat and salt budget – and will thereby serve as a crucial check of the corresponding terms in OGCMs.

Through both the local budget analysis and the regional upper ocean modeling, we intend to address questions such as: (1) How does the winter mixed layer respond to the atmospheric synoptic (*i.e.,* storm) time scales? (2) How important is buoyancy forcing to the structure of the recirculation gyre? (3) Does the STMW lens serve as a sequestered reservoir from year to year, and to what degree are subsequent-year SST changes moderated by its enormous heat capacity?

6 Program synopsis

The Kuroshio Extension and its recirculation are important components of the Earth's climate system, particularly in the Pacific Basin. Its influence on Pacific storms, both their intensity and tracks, and their impact on the west coast of the U.S. should not be underestimated. However, to better understand the dynamics and thermodynamics that govern the Kuroshio Extension and its recirculation gyres, an extensive observational campaign must be mounted, and KESS is meant to do this. The observation tools that have been developed in the two decades since SYNOP, *i.e.,* altimetry, C-PIES, MPs, and profiling floats, will allow us to do this. The KESS array is designed to use these tools synergistically to observe the Kuroshio Extension in a more complete way than any one of them could do alone. In particular, the C-PIES will map features of the jet as they evolve and, in combination with the MPs, will quantify the cross-frontal fluxes, while the profiling floats will monitor the upper ocean structure around the Kuroshio Extension and its recirculation gyres. KESS will use these combined observations 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 measurements from the KESS array will guide future planning for a longterm observational program as part of CLIVAR.

7 Related projects

Ogasawara-maru (ferry) ADCP/XBT measurement: Upstream of the KESS Intensive Dynamics Array and over the Izu Ridge (Figure 7), a commercial ferry, *Ogasawara-maru*, shuttles between Tokyo and the island of Chichi-jima (Hanawa et al. 1996). The ferry is equipped with an ADCP, which can be used to determine the upstream condition to the KESS region. Since the ferry makes a round trip across the Kuroshio 50 times a year, we can obtain 100 velocity sections of the upper 400 m in a year. The ADCP data have been accumulating since 1992 and the XBT measurements have also been conducted every 2 months since 1988. As shown by his Letter of Intent attached to this proposal, Prof. Hanawa and the KESS PIs will collaborate with regard to this measurement.

JAMSTEC/IPRC OGCM and data assimilation: The JAMSTEC high-resolution global ocean model and a Kuroshio/Oyashio regional model will be continually upgraded at JAMSTEC and IPRC. The global model has 0.25° resolution with 55 levels, forced by the ECMWF wind. The Kuroshio/Oyashio regional model is based on the Princeton Ocean Model with curvilinear coordinates varying from 1/12° to 1/6°. This model has recently succeeded in simulating pathways for subpolar water that subducts below the Kuroshio Extension, is finally redistributed to the subtropical gyre and transforms to NPIW. Impacts of the subpolar water intrusion on the circulations in the Kuroshio Extension and the recirculation regions will be further investigated during the KESS period. This model will also be used to investigate the effects of low-PV input by buoyancy forcing, as well as the effects of remote forcing due to large-scale circulation changes. Further, a reduced Kalman filter will be inplemented to the regional model, and analysis using assimilated data will also be conducted. The regional model is going to be upgraded using a variable coordinate that covers the entire North Pacific Ocean. The Hybrid Coordinate Ocean Model (HYCOM) is planned to be implemented. A letter of collaboration from Dr. H. Misudera at IPRC/Frontier Research System for Global Change is attached.

Post-SAGE project: Japan's Subarctic Gyre Experiment (SAGE) will be ending this fiscal year. At present, the Japanese SAGE PIs are in the process of formulating observational plans and submitting proposal(s) to the Ministry of Education, Culture, Science and Technology of Japan in October, 2002. The research areas of the post-SAGE project include: upper ocean heat budget, Kuroshio variations south of Japan, the Kuroshio Extension, subducton processes, deep ocean circulation, and large-scale ocean modeling. Professor Kimio Hanawa, who will lead this Japanese effort, has shown strong interest in possible bilateral collaboration with the KESS PIs (see attached letter of intent in Section I).

ARGO program: The international ARGO plan calls for deployment of ARGO floats to achieve 3 degree spacing. In particular, the Japanese ARGO program is underway, so that a substantial number of profiling floats will be seeded in the KESS area according to the ARGO specifications. KESS will coordinate with the Japanese ARGO team to attempt deployment of ARGO floats in the KESS domain. KESS plans to use the ARGO data to augment project analyses such as the upper ocean budget study.

Other Japanese programs: There are two Japanese programs in which PIESs will be used to study the Kuroshio system upstream of the KESS area. One of them is called the Kuroshio Observation Program (KOP) in which Dr. Ichikawa and other scientists from the Japanese Marine Science and Technology Center (JAMSTEC) are deploying PIESs and current moorings east of Okinawa across the Ryukyu Current, in conjunction with Wimbush and Watts (at URI) who will be deploying C-PIES and PIES instruments west of Okinawa across the Kuroshio in the East China Sea (with ONR support). In another JAMSTEC program, led by Dr. Yoshikawa, PIESs and current moorings will be deployed on either side of the Izu-Ogasawara Ridge at the latitude of Okinawa. (See attached letter of support from Dr. Hiroshi Ichikawa of the KOP program in Section I.)

Naval Research Laboratory modeling effort: The Naval Oceanographic Office (NAVO) is already running the first operational eddy-resolving (1/16°) nearly-global ocean model with assimilation of satellite altimeter SSH and other data. Dr. H. Hurlburt and his group at the Naval Research Laboratory are eager to obtain data to assess the accuracy of this model and its data assimilation skill in the dynamically active KESS region. The KESS array's mesoscale spatial resolution and meander-wavelength extent, together with its fine temporal resolution and long duration, make the KESS data set especially valuable to such a modeling effort. (See attached letter of collaboration from Dr. Hurlburt in Section I.)

Naval Postgraduate School modeling effort: As part of a Department of Defense High Performance Grand Challenge Grant, Drs. J. McClean and M. Maltrud et al. are performing a 0.1°, 40-level global POP simulation of ocean circulation using realistic surface forcing. This increased resolution is expected to provide unprecedented improvements in their eddy variability. Dr. McClean at the Naval Postgraduate School is proposing a POP model-output study whose goal is to quantify and understand in particular the mesoscale processes. She attended the KESS planning meeting where we jointly identified the value of KESS observational mesoscale process studies for validation of model dynamics. (See attached letter of collaboration from Dr. McClean in Section I.)

U.S. CLIVAR/PBECS: The U.S. CLIVAR Program seeks a better understanding and more realistic simulation of phenomena involving coupled ocean-atmosphere-land processes on seasonal-to-decadal time scales. For the Pacific sector under this program, the Pacific Basin Extended Climate Study (PBECS) was recently established and it has identified understanding the midlatitude Pacific Decadal Oscillation as one of its three scientific foci (Davis et al. 2000). In order to achieve this understanding and in conjunction with the basin-scale observing network, PBECS has recommended a process study of the Kuroshio-Oyashio Extension, including its deep recirculation and air-sea interactions. Given the importance of climate to the Pacific-rim countries and the interest among them, PBECS has also urged development of international partnerships. The KESS project is highly compatible with the U.S. CLIVAR/PBECS objectives and recommendations.

8 Broader impacts

Results from KESS will further our understanding and quantify the processes at work in the Kuroshio Extension region. This knowledge has direct relevance to both climate and fisheries research and prediction. For climate, KESS will bring about an improved assessment of the role of the region on storm track evolution over the northwest Pacific and on the role of the ocean in the evolution of the Pacific Decadal Oscillation. The latter has significant implications for North American climate. For fisheries research, KESS results will improve our understanding and ability to predict the location and evolution of the north wall of the Kuroshio Extension and the regional evolution of the SST structure, two features closely associated with fish-catch.

KESS will result in an unprecedented data set for the evaluation of realistic ocean general circulation models required for climate studies, and for the design of an efficient and effective monitoring strategy in the Kuroshio Extension region for eventual achievement of CLIVAR goals.

Undergraduate and graduate students will be active participants in KESS. Undergraduate engineering students will assist in instrument development and construction. Undergraduate physics majors will participate on research cruises and in the data analyses, primarily during the summer months. Graduate students will participate on reasearch cruises and attend national meetings to present their research findings.

Recognizing the great value of the KESS data set, we plan to make these available to other analysis and modeling groups. A web site will be maintained to facilitate communication and data exchange. Data will be distributed to the broad community via the national data libraries, such as NODC.

9 Results from prior NSF support

P. Hacker/UH and K. Donohue/URI (OCE-9413172) November 1, 1994 – October 31, 1998 $644,691 [US co-PI: E. Firing/UH] **Title: Acoustic Doppler Current Profiling on the U.S. WOCE Hydrographic Program Expedition to the Indian Ocean**

During the WOCE Hydrographic Program (WHP) Indian Ocean cruise of the R/V Knorr, we obtained shipboard (SADCP) and lowered (LADCP) acoustic Doppler current profiler data throughout 6 major cruise legs. During the entire Indian Ocean Expedition, including WHP cruises on which Mike Kosro and Teresa Chereskin were the velocity PIs, the same instrument suite, setup, and software were used successfully.

Preliminary analysis of the R/V Knorr Indian Ocean data sets has included a description—the first ever based on direct measurements—of currents in the Bay of Bengal (Hacker et al. 1998); a note on the Indonesian throughflow (Gordon et al. 1997); a preliminary calculation of geographically varying mixing rates inferred from fine structure in velocity profiles (Polzin and Firing 1997); a study of deep circulation south of Australia (Hufford et al. 1997); and a note on the nearly barotropic current along the Kerguelen Plateau (Donohue et al. 1999). Repeat surveys of the Agulhas Current and Agulhas Undercurrent show that information in the hydrography is not adequate to distinguish unambiguously recirculating components in the velocity field or the vertical extent of the Agulhas Current; velocity measurements such as the LADCP profiles are essential (Donohue et al. 2000).

N. G. Hogg, W. B. Owens, and K. G. Speer (OCE-9911148) March 1, 2000 – February 28, 2001 $600,000 [US co-PI: W. B. Owens/WHOI, and K. G. Speer/FSU] **Title: Deep Basin Experiment Synthesis**

The Deep Basin Experiment was a large international investigation of the intermediate and deep circulation in the Brazil Basin — a contribution to the World Ocean Circulation Experiment. The most intense observational period spanned most of the last decade with some French neutrally floats still in operation, as of this writing. We have been working on various topics in an attempt to improve our understanding of how the deep circulation works. Estimation of the transport of Antarctic Bottom Water across the southern boundary into the basin has been updated and improved (Hogg et al. 1999; Zenk et al. 1999). These estimates, combined with calculations of the outflow at the equator and an analysis of the deep climatology has permitted estimation of the basin averaged diffusivity at the bottom water level (Morris et al. 2001). A description of the experiment in the context of the global deep circulation was published in the WOCE volume *Ocean Circulation and Climate* (Hogg, 2001). Zonally banded flows are a prominent feature of the deep flow and these have become the subject of a paper (Treguier et al. in prep.) discussing their origin. We are presently in the final year of this 2-year grant and anticipate completing analysis of an inverse model which will combine all available hydrographic data with neutrally buoyant float data to provide an improved scheme for the sub-thermocline circulation. We are also engaged in an analysis of the low frequency (annual and longer) motions within the basin using the neutrally buoyant float data and have a draft manuscript (Hogg, in prep.).

B. Qiu (OCE99-11268) June 1, 2001 - May 31, 2003 $210,000 Title: Dynamics of the Low-Frequency Variability of the Kuroshio Current System

Supported by this grant, Qiu and Miao (2000) investigated the bi-modal path variations of the Kuroshio south of Japan on the interannual-to-decadal time scales. By analyzing observational data and by running a primitive-equation OGCM, we showed that the observed Kuroshio path oscillation since 1975 could result from a self-sustained internal mechanism involving the instability of the Kuroshio and its recirculation. The topographic constraint by the Japan coast to the north is found to be important for the oscillation mechanism. In the Kuroshio Extension region, Qiu (2000) described a large-scale structural change associated with the zonal penetration of the Kuroshio Extension jet. Causes for this structural change are explored, and it is argued that the basin-wide wind forcing and the nonlinear dynamics involving the inertial recirculation gyre are both important factors (Qiu 2002). Finally, support of this grant has also helped the PI to contribute a full article, entitled "Kuroshio and Oyashio Currents", to *Encyclopedia of Ocean Sciences* published by Academic Press (Qiu 2001).

D. R. Watts/URI (OCE 92-04041) June 1, 1994 - May 31, 2000 $939,244; (OCE 99-12320) June 1, 2000 - May 31, 2002 $218,000 [US co-PI's: Alan Chave, WHOI; Jean Filloux, SIO; Douglas Luther, U. Hawaii; James Richman, OSU]
Title: U.S. Australian Cooperative Study of the Northern Branch of the ACC

In the Subantarctic Fluxes and Dynamics Experiment, moored observations were collected by a line of horizontal electric field recorders (HEFR) in between two parallel lines of IESs south of Tasmania near 143°E (Luther et al. 1997). Additionally, a small local dynamics array consisted of 7 current meter moorings. Observations of vertically-averaged barotropic and gravest baroclinic mode structure of the (u, v) and T fields throughout the water column were made with mesoscale resolution. Data from eight CTD sections were used to estimate temperature and density as a function of pressure and vertical acoustic travel time in order to parameterize our gravest empirical mode interpretation for the IES data (Watts et al. 2001b). Using this interpretation, daily maps of T and (u, v) tracked the SAF. The synoptic front width is ~70 km. The mean position is 51°S, and the r.m.s. amplitude of meandering is 60–70 km. Steep meanders with amplitude $\sim$ 300 km formed episodically; two cases of ring-interaction were observed. At times the SAF nearly joined with the Polar Front at the southern end of the array, while at others, the SAF was more than 300 km farther north. Meinen et al. (2002) describe the method for obtaining profiles of absolute velocity from the combined HEFR+IES measurements. The currents at 3500 m often exceeded 10-15 cm s^{-1} and speeds higher than 30 cm s^{-1} were observed.

This grant supported the thesis work of Che Sun (Ph.D., 2001). Sun and Watts (2001) showed that gravest empirical mode projections for the Antaractic Circumpolar Current slowly evolve with longitude, especially in the upper 200 m and in the subtropical waters.

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