**KESS Final Status Report -- DRAFT**
**For U.S. CLIVAR 2013 Summit / Process Study and Model Improvement Panel**

The **Kuroshio Extension System Study (KESS)** was undertaken by U.S. and Japanese scientists from 2002 to 2012, with the primary goal of identifying and quantifying the dynamic and thermodynamic processes governing the variability and interaction between the Kuroshio Extension (KE) and the recirculation gyre to the south, and a secondary goal of determining relationships between the KE system and the overlying atmosphere. Observations from the bottom of the ocean to the top of the troposphere were collected during the 2004-2006 field campaign (Donohue et al., 2008) that mapped the ocean structure over a full meander and across the jet from the southern anticyclonic recirculation gyre into the northern cyclonic recirculation gyre (Jayne et al. 2009). A surface mooring, referred to as the Kuroshio Extension Observatory (KEO) (Cronin et al. 2008), was launched during KESS, and continues today as part of the global network of OceanSITES reference stations and as part of more recent international process studies (HotSpot funded by Japan, Pacific MOVE: Mode-water Ventilation Experiment funded by China, and the Western North Pacific Integrated physical Biogeochemical Ocean observation Experiment (INBOX) funded by Japan).

The KESS field program fortuitously captured a regime transition in late 2004, due to a shift in the basin-scale wind forcing that occurred in 2002 associated with the Pacific Decadal Oscillation (PDO) (Qiu et al. 2007a). From 2001 through mid-2004, the KE exhibited the characteristic quasi-stationary meanders 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. Qiu et al. (2013) recently showed that this decadal modulation of the KE dynamical state can be predicted at lead times of up to ~6 years. This long-term predictability rests on two dynamic processes: (1) the oceanic adjustment is via baroclinic Rossby waves that carry interior wind-forced anomalies westward into the KE region, and (2) the low-frequency KE variability influences on the extratropical storm-tracks and surface wind stress curl field across the North Pacific basin (e.g., Nakamura et al. 2004; Kwon et al. 2010; Frankignoul et al. 2011). By shifting the storm-tracks and the large-scale wind stress curl pattern poleward (equatorward) during its stable (unstable) dynamic state, the KE variability induces a delayed negative feedback that can enhance the predictable of the KE dynamical state on the decadal timescales.

The regime shifts in the KE dynamic state bring about significant changes in the regional sea surface temperature, upper ocean heat content, and water mass properties of the Subtropical Mode Water (STMW), the Central Mode Water and the North Pacific Intermediate Water (see Kelly et al. 2010 for a review). For example, during the unstable period, eddies caused a 50% reduction in the thickness of STMW (Qiu et al. 2007b). The large convolutions in the KE path appear to form through interactions between the baroclinically unstable KE jet and deep eddies, with the upper ocean and deep eddies jointly intensifying (Bishop et al. 2013ab). In the process, a large divergent eddy heat flux is produced. When averaged over the water column and over the entire record which included both periods from the stable and unstable periods, these fluxes accounted for 0.05 PW of meridional eddy heat transport near 35°N and may account for ~1/3 of the total Pacific meridional heat transport at this latitude. In contrast to the Gulf Stream, the deep eddies that interact with the KE jet appear to originate as topographically controlled eddies formed outside the observational array, presumably near the Shatsky Rise ~ 160°E (Green et al. 2012). The relationship between the large-scale wind field/PDO and the deep eddy field needs to be explored further.

The KEO mooring observations showed that overall, horizontal heat advection helps maintain the upper ocean heat content in the presence of large wintertime surface heat loss, and also helps the seasonal thermocline restratify earlier than otherwise might be expected. Surface cooling and intense mixing are responsible for the erosion of the seasonal thermocline during the fall. Curiously due to the passage of warm season typhoons and winter storms, inertial oscillations are relatively energetic almost year-round and cause very high diffusivity values at the base of the mixed layer, particularly during winter when the mixed layer is hundreds of meters deep and stratification below it is weak (Cronin et al. 2013). Inertial oscillations were also observed in the deep ocean, with a factor of 5 increase in energy north of the jet (Park et al. 2010). Surface data from KEO are also being used as a reference time series to assess numerical weather prediction and satellite-based products (e.g. Kubota et al. 2008, Nui et al. 2010); its subsurface data, combined with data from the nearby subsurface KESS mooring, from Argo floats, and from satellite have been used to characterize the bottom depth and thickness of STMW, as well as the upper ocean heat content (Rainville et al. 2013). This combined dataset was then used to create regional maps of STMW thickness and upper ocean heat content that could be used for a wide-range of climate and ocean analyses.

The influence of the KE on the overlying atmosphere was investigated aboard the R/V Revelle KESS cruise during summer 2005. These observations showed that when the Baiu front was displaced north of the KE front, southwesterly winds advected warm, humid air from the subtropics over the cold water, producing a surface inversion favorable to fog formation. When the Baiu front was to the south, on the other hand, northerly winds across the KE front destabilized the marine atmospheric boundary layer, leading to the formation of a solid low-cloud deck beneath a strong capping inversion (Tanimoto et al. 2009). The influence of the KE on the atmosphere and climate system has also been the focus of the 1-billion yen HotSpot Experiment that began in 2010. Led by Dr. Hisashi Nakamura, member of the US CLIVAR working group on Western Boundary Currents, HotSpot involves more than 60 scientists, 10 postdocs, and 30 students throughout Japan. Intensive observations have been made from, among other platforms, aircraft, ships, floats, and an additional surface mooring deployed in the center of the KE jet, between KEO and J-KEO that span the KE jet. Since the conclusion of KESS intensive observations, JAMSTEC has deployed the J-KEO surface mooring north of the KE, and a biogeochemical subsurface mooring, S1, southeast of KEO in the center of the subtropical gyre. Japan has also initiated the Western North Pacific Integrated Physical-Biogeochemical Ocean observation Experiment (INBOX) that brings together physical oceanographers and biogeochemists to work collaboratively on processes such as the mode water sequestering of carbon. Interdisciplinary work is also occurring at KEO, which has recently been enhanced to monitor ocean acidification and various aspects of the carbon cycle. Mode water dissipation is the subject of the Chinese-funded

P-MOVE experiment led by Shang-Ping Xie that is set to begin in late March 2014. Together, the JKEO, KEO, and S1 moorings; and the HotSpot, INBOX and P-MOVE field programs form an effective observing system for mode water, from its formation and subduction, to its dissipation. Discussions are underway to combine these various activities into a larger international, interdisciplinary experiment.

KESS has followed all best practices for processes outlined in Cronin et al. (2009). In particular, all data are publically available and can be accessed through a central website: http://uskess.org While the KESS legacy lives on, there are no KESS-funded projects at this point. The KESS website has been paid for through the next few years. Eventually the website must be supported through US CLIVAR if it is to provide a resource for future scientists.

**References (not a complete list of KESS publications)**

Bishop, S. P., D. R. Watts, and K. A. Donohue, 2013a: Divergent eddy heat fluxes in the Kuroshio Extension at 144°–148°. Part 1: mean structure. *J. Phys. Oceanogr.*, (accepted).

Bishop, S.P., 2013b: Divergent eddy heat fluxes in the Kuroshio Extension at 144°-148°. Part 2: Spatiotemporal variability. *J. Phys. Oceanogr*, (accepted).

Cronin, M.F., N. A. Bond, J. T. Farrar, H. Ichikawa, S. R. Jayne, Y. Kawai, M. Konda, B. Qiu, L. Rainville, H. Tomita, 2013: Formation and erosion of the seasonal thermocline in the Kuroshio Extension recirculation gyre. *Deep Sea Res. II*, 85, 62-74, doi:10.1016/j.dsr2.2012.07.018

Cronin, M.F., S. Legg, and P. Zuidema, 2009: Best practices for process studies. *Bull. Am. Meteorol. Soc. Nowcast*, 90(7), 917-918.

Cronin, M. F., C. Meinig, C. L. Sabine, H. Ichikawa, H. Tomita, 2008: Surface mooring network in the Kuroshio Extension. *IEEE Systems Special Issue on GEOSS*, 2(3), 424-430.

Donohue, K.A., Watts, D.R., Tracey, K., Wimbush, M., Park, J.-H., Bond, N., Cronin, M., Chen, S., Qiu, B., Hacker, P., Hogg, N.B., Jayne, S.R., McClean, J., Rainville, L., Mitsudera, H., Tanimoto, Y., Xie, S.-P., 2008: Program studies the Kuroshio Extension. EOS Trans. AGU 89(17), 161–162.

Frankignoul, C., N. Sennechael, Y.-O. Kwon, and M.A. Alexander, 2011: Influence of the meridional shifts of the Kuroshio and the Oyashio Extensions on the atmospheric circulation. J. Climate, 24, 762-777.

Greene, A. D., D. R. Watts, G. G. Sutyrin, and H. Sasaki, 2012: Evidence of vertical coupling between the Kuroshio Extension and topographically controlled deep eddies. *Journal of Marine Research*, 70(5):719–747.

Jayne, S. R., N. G. Hogg, S. N. Waterman, L. Rainville, K. A. Donohue, D. R. Watts, K. L. Tracey, J. L. McClean, M. E. Maltrud, B. Qiu, S. Chen, and P. Hacker, 2009: The Kuroshio Extension and its recirculation gyres. *Deep-Sea Research I*, 56(12):2088–2099.

Kelly, K.A., R.J. Small, R.M. Samelson, B. Qiu, T.M. Joyce, Y.-O. Kwon and M.F. Cronin, 2010: Western boundary currents and frontal air-sea interaction: Gulf Stream and Kuroshio Extension. J. Climate, 23, 5644-5667.

Kwon, Y.-O., M.A. Alenxader, N.A. Bond, C. Frankignoul, H. Nakamura, B. Qiu, and L. Thompson, 2010: Role of the Gulf Stream and Kuroshio-Oyashio Systems in large-scale atmosphere-ocean interaction: A review. J. Climate, 23, 3249-3281.

Kubota, M., Iwabe, N., Cronin, M.F., Tomita, H., 2008: Surface heat fluxes from the NCEP/NCAR and NCEP/DOE reanalyses at the KEO buoy site. J. Geophys. Res. 113, C02009, doi:10.1020/2007JC004338.

Nakamura, H., T. Sampe, Y. Tanimoto, and A. Shimpo, 2004: Observed associations among storm tracks, jet streams and midlatitude oceanic fronts. Earth's Climate: The Ocean-Atmosphere Interaction, Geophys. Monogr., 147, Amer. Geophys. Union, 329-346.

Niu, X., R. T. Pinker, H. Wang, M. F. Cronin, 2010: Radiative fluxes at high latitudes. *Geophys. Res. Lett.*, 37, L20811, doi:10.1029/2010GL044606.

Park, J.-H., K. A. Donohue, D. R. Watts, and L. Rainville, 2010: Distribution of deep near-inertial waves observed in the Kuroshio Extension. *Journal of Oceanography*, 66(5):709–717.

Qiu, B., S. Chen, P. Hacker, 2007b: Effect of Mesoscale Eddies on Subtropical Mode Water Variability from the Kuroshio Extension System Study (KESS). *J. Phys. Oceanogr.*, **37**, 982–1000. doi: http://dx.doi.org/10.1175/JPO3097.1

Qiu, B., Schneider, N., Chen, S., 2007a: Coupled decadal variability in the North Pacific: An observationally constrained idealized model. J. Climate 20, 3602–3620.

Rainville, L., S. R. Jayne, M. F. Cronin, 2013: Variations of the Subtropical Mode Water in the Kuroshio Extension from direct observations. Submitted to J. Clim.

Tanimoto, Y., S.-P. Xie, K. Kai, H. Okajima, H. Tokinaga, T. Murayama, M. Nonaka, H. Nakamura, 2009: Observations of marine atmospheric boundary layer transitions across the summer Kuroshio Extension. *J. Climate*, **22**, 1360–1374.
doi: http://dx.doi.org/10.1175/2008JCLI2420.1