Program Studies the Kuroshio Extension

PAGES 161–162

The Kuroshio Extension system links to North Pacific climate through its role in subtropical-subpolar exchange, the formation and distribution of mode waters, and the intensification of the extratropical storm track across the North Pacific. The Kuroshio Extension System Study (KESS) offers a window into these processes through integrated measurements of the ocean and atmosphere and through modeling efforts (Figure 1).

The northward flowing waters of the Kuroshio western boundary current leave the Japanese coast to flow eastward as a free jet—the Kuroshio Extension. The Extension forms a vigorously meandering boundary between the warm subtropical and cold northern waters.

Within its southern recirculation gyre, strong wintertime cooling deepens the mixed layer to form subtropical mode water, STMW [*Hanawa and Talley*, 2001]. The recirculation gyre, cross-frontal fluxes, and air-sea interactions each play an important role in the formation of STMW.

Intense air-sea heat exchanges occur where warm Kuroshio waters encounter the cold dry air masses that flow off the Asian continent. The time-varying strength and eastward penetration of the recirculation gyre and the Kuroshio Extension help maintain and steer storm tracks across the North Pacific.

The dynamic state of this system alternates on decadal timescales between weakly and vigorously meandering [*Qiu and Chen*, 2005]. The KESS field program—consisting of a moored array and deployment of profiling floats, intensive synoptic surveys, and atmospheric soundings—fortuitously captured this regime transition (Figure 1). The most recent stable pattern, which began in 2001, exhibited the characteristic pattern of two quasi-stationary meanders and a strong zonally elongated recirculation gyre. In December 2004, the Kuroshio Extension switched into its unstable state, its path became highly variable, eddy energy increased dramatically, and the recirculation gyre weakened. Observationally [*Qiu and Chen*, 2005] and numerically [*Taguchi et al.*, 2005], this regime shift has been connected to changes in central North Pacific wind stress curl. Baroclinic Rossby waves generated by this atmospheric forcing subsequently alter the stability of the Kuroshio through either a shift in upstream position or a change in the jet's structure.

KESS Program

We centered the KESS program's in situ instrument array on the first quasi-stationary meander crest and trough east of Japan and the region of highest eddy kinetic energy (Figure 1). The KESS array comprised inverted echo sounders (IES) equipped with current meters and bottom pressure gauges (known as CPIES) and a line of subsurface moorings including McLean moored profilers. The KESS array yielded 16 months (June 2004 to October 2005) of mesoscale resolving maps with complete array coverage.

As part of the KESS program, the Kuroshio Extension Observatory (KEO), a moored surface buoy deployed in the southern recirculation gyre, carries a suite of sensors to monitor air-sea fluxes and upper ocean temperature and salinity. In addition, 48 profiling floats were deployed on both sides of the Kuroshio. An atmospheric sounding component linked ocean observations with atmospheric processes; a total of 260 GPS-sondes were released (summer 2005 and 2006).

The KESS observations provide a means of evaluating numerical models. In particular, the global Parallel Ocean Program model with 0.1° horizontal resolution and

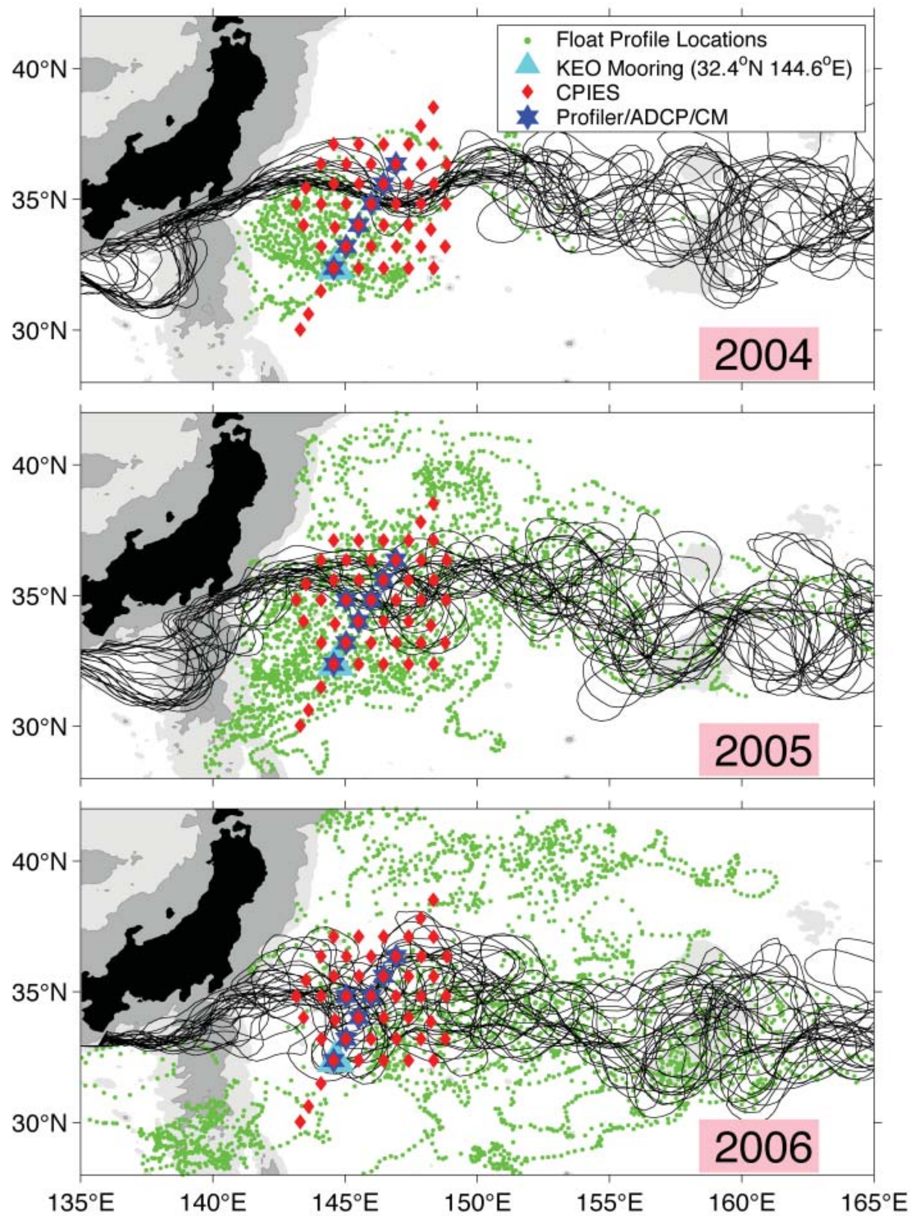

*Fig. 1. Maps of the biweekly Kuroshio Extension path defined by the 170-centimeter contours of sea surface height based on combined hydrographic [*Teague et al., *1990] and altimeter data [*Qiu and Chen, *2005] for 2004, 2005, and 2006. The Kuroshio Extension System Study (KESS) array consists of inverted echo sounders equipped with current meters and bottom pressure gauges (CPIES, red diamonds), moored profilers and current meters (blue stars), and the Kuroshio Extension Observatory (KEO) buoy (blue triangle). Locations of profiling float hydrocasts are denoted by green dots. The 2000- and 4000-meter isobaths are shaded gray.*

40 vertical levels forced by synoptic fields allows for the evaluation of interbasin, interhemisphere, and intergyre transfers.

Cross-Frontal Fluxes

Cross-frontal fluxes strongly influence the characteristics of STMW and North Pacific Intermediate Water, two integral components of the North Pacific circulation. Initial analyses of KESS data reveal at least three potential cross-frontal mesoscale processes: Frontal waves nearly always propagate along the current, steep crests and troughs develop intermittently, and rings detach episodically after the regime transition. While cross-frontal fluxes associated with frontal waves are weakest from event to event compared with the other processes, their influence could be large due to their prevalence. Frontal waves are aliased in altimeter sea surface height owing to their rapid propagation (25 kilometers per day) and short wavelengths (160 kilometers).

Subtropical Mode Water Formation and Evolution

STMW forms during winter when the surface mixed layer cools and deepens. As summer progresses, a seasonal thermocline forms and isolates STMW from the atmosphere. Subsequent erosion occurs. Air-sea fluxes are important; yet ocean preconditioning also affects STMW formation. The stable regime's low eddy energy level and strong recirculation gyre facilitated this formation [*Qiu et al.*, 2007].

Our understanding of STMW erosion continues to be refined. Internal wave breaking and lateral eddy advection are likely suspects contributing to enhanced mixing [*Rainville et al.*, 2007]. Whether internal wave energy is driven by regular predictable internal tides or by episodic storm-driven inertial energy, as well as how background circulation traps, focuses, or refracts internal wave energy, remains to be determined by KESS investigators.

This article highlights two facets of the KESS program. The Web site http://uskess.org offers a comprehensive program description. KESS scientists work closely with the U.S. CLIVAR Western Boundary Current Ocean-Atmosphere Interaction Working Group.

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References

Hanawa, K., and L. D. Talley (2001), Mode waters, in *Ocean Circulation and Climate*, edited by G. Siedler et al., pp. 373–386, Academic, San Diego, Calif.
Qiu, B., and S. Chen (2005), Variability in the Kuroshio Extension jet, recirculation gyre, and mesoscale eddies on decadal time scales, *J. Phys. Oceanogr., 35,* 2090–2103.
Qiu, B., S. Chen, and P. Hacker (2007), Effect of mesoscale eddies on subtropical mode water variability from the Kuroshio Extension System Study (KESS), *J. Phys. Oceanogr., 37,* 982–1000.
Rainville, L., S. R. Jayne, J. L. McClean, and M. E. Maltrud (2007), Formation of Subtropical Mode Water in a high-resolution ocean simulation of the Kuroshio Extension region, *Ocean Modell., 17,* 338–356.
Taguchi, B., S. Xie, H. Mitsudera, and A Kubokawa (2005), Response of the Kuroshio Extension to Rossby waves associated with the 1970s climate regime shift in a high-resolution ocean model, *J. Clim., 18,* 2979–2995.
Teague, W. J., M. J. Carron, and P. J. Hogan (1990), A comparison between the generalized digital environmental model and Levitus climatologies, *J. Geophys. Res., 95*(C5), 7167–7183.

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MEETINGS

Geodetic Observations Help Scientists Understand Geohazards and Mitigate Disasters

The GGOS Contribution to GEOSS and an Observing System for Geohazards and Disaster Prevention; Frascati, Italy, 5–6 October 2007

PAGE 163

Modern space-geodetic observations have revolutionized our understanding of geohazards, and these observations have a great potential for further scientific discovery and applications, including early warning.

To discuss this, about 50 scientists from the geodetic and geohazards communities took part in a workshop organized by the Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) as a contribution to the intergovernmental Group on Earth Observations (GEO). Highest-level representatives of space agencies (European Space Agency, NASA, and Agenzia Spaziale Italiana) emphasized the fundamental importance of the geodetic reference frames for satellite missions and Earth observation. Although high, the present accuracy of these reference frames still is a key limitation in quantifying global change processes such as changes in ice sheets and sea level. Improvements of the reference frame are a pivotal step toward a better understanding of these processes and their impact on society. The representative of GEO identified GGOS as a core element in the Global Earth Observation System of Systems (GEOSS), which aims to integrate Earth observations in order to better serve users in a number of societal benefit areas, including disasters.

Several speakers emphasized that major scientific and technological challenges for GGOS are consistency across the three areas of geodesy (geometry, gravity, and rotation) and consistency between observations and models. At seasonal timescales, mass redistribution in the fluid envelope of the Earth is well constrained by geodetic observations, but understanding the driving processes requires a combination of different parameters (surface displacements, gravity changes, Earth rotation perturbations). Global change and geohazards phenomena are inherently linked with the reference frame, and meeting attendees proposed that the integration of physical models with geodetic observations may be required for a better understanding of these phenomena.

Systems aimed at prediction of geohazards and early warning systems work best if they are mutually informed and consistent. GGOS has the necessary bandwidth to cover both roles and for scientific and practical reasons should play both roles. Speakers illustrated the versatility of interferometric synthetic aperture radar (InSAR) for the early detection of hazardous areas, thus providing a basis for informed decisions on where to invest in dedicated monitoring systems. GPS has revolutionized the understanding of tectonic processes. Other speakers noted that remote sensing of newly discovered seismic waves in the atmosphere and ionosphere, and of tsunamis, from space seems possible with geodetic techniques and