# Altimetric Observations and Model Simulations of Coastal Kelvin waves in the Bay of Bengal

Matthew J. Nienhaus[1], Bulusu Subrahmanyam[1,2]

[1]Marine Science Program, University of South Carolina, Columbia, SC 29208.
[1,2]Department of Earth and Ocean Sciences, University of South Carolina, Columbia, SC 29208.

## Abstract

Kelvin waves originating in the equatorial Indian Ocean propagate along the equatorial wave guide until reaching the Sumatra coast and follow the coastal waveguide counter clockwise around the perimeter of the Bay of Bengal. We observed these coastal Kelvin waves using altimetry as well as model simulations from the HYbrid Coordinate Ocean Model (HYCOM) and Simple Ocean Data Assimilation (SODA) reanalysis for the period from 1993-2006. The wavelet analyses revealed the period and extent of these waves. The altimeter observations and model simulations have similar cycles of an upwelling Kelvin wave propagating during January - April of each year, and a downwelling Kelvin wave propagating during May - August of each year. The beginning phase of the upwelling (downwelling) Kelvin wave is followed by strong currents flowing in the opposite (same) direction of the propagation. Wavelet analysis of these coastal Kelvin waves shows a dominant semiannual period off the coast of Sumatra, and transitions into an annual period as it continues around the perimeter of the Bay of Bengal.

## Altimetry data and Model simulations

- HYCOM, SODA and altimetry sea surface height anomaly (SSHA) data were analyzed to detect the signatures of upwelling and downwelling Kelvin waves along the equatorial and coastal waveguides of the Indian Ocean, Bay of Bengal (BoB) and southeastern Arabian Sea. We have considered SODA and altimetry data for the time period from January to August for the years 1993 to 2006, and HYCOM data covering the same time period from 2002 to 2006. HYCOM model simulation SSHA was calculated and displayed from daily averages, SODA model simulation SSHA was calculated and displayed from five day averages, and altimetry data was collected and displayed from weekly averages.
- The zonal (U) and meridional (V) currents data from HYCOM, SODA and altimetry data were used to plot average sea surface current speed and direction anomalies during the same time period as SSHA was measured in order to track the surface patterns of the Kelvin waves as they propagate. Altimetry current anomalies were measured from geostrophic currents, while HYCOM and SODA current anomalies were measured from absolute currents.
- Wavelet analyses were constructed using the SODA and altimetry data in order to determine Kelvin wave period and energy at three different points in the Indian Ocean (1° N 96° E, 15° N 92° E, and 18° N 85° E). These three points correspond to three different regions in the Indian Ocean/BoB; the equatorial region off the coast of Sumatra, the eastern edge of the BoB near the Andaman Sea, and the western edge of the BoB near the east coast of India.

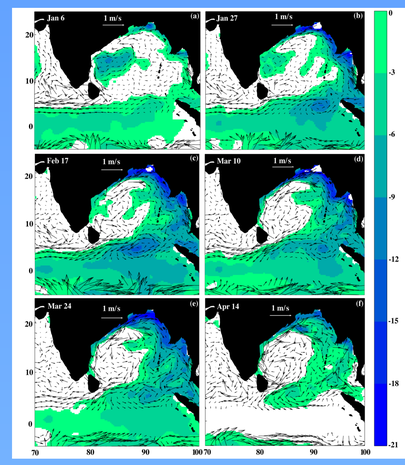

Figure 1

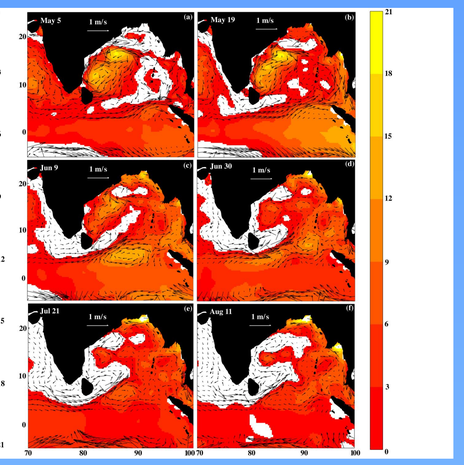

Figure 2

Kelvin waves in the Indian Ocean detected with weekly average sea surface height anomalies (SSHA) data (cm) using altimetry, at 2-3 week intervals from January-April (Figure 1) and May-August (Figure 2), averaged from 1993-2006. In Figure 1, negative values of SSHA are displayed to show the propagation of the upwelling Kelvin wave, whereas positive values are displayed in Figure 2 to show the propagation of the downwelling Kelvin wave. Overlaid are the weekly averaged geostrophic sea surface current vectors calculated using U and V from altimetry data. Geostrophic currents from 3°N to 3° S were removed.

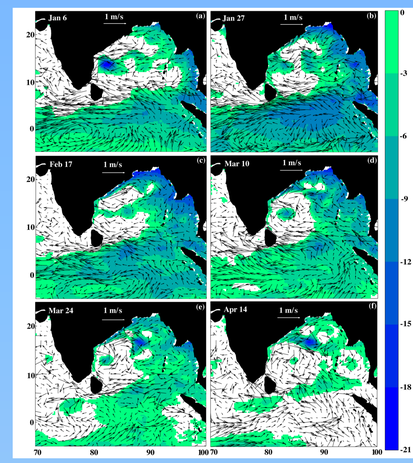

Figure 3

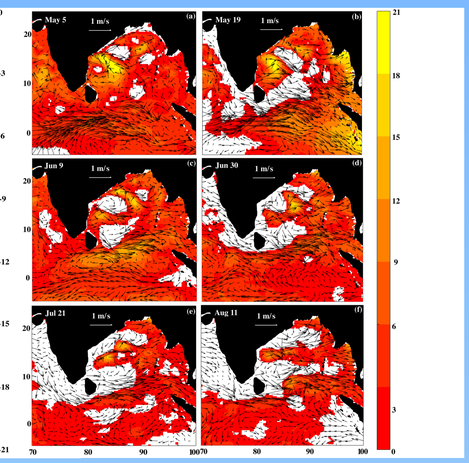

Figure 4

Kelvin waves in the Indian Ocean detected with weekly average sea surface height anomalies (SSHA) (cm) using HYCOM, at 2-3 week intervals from January-April (Figure 3) and May-August (Figure 4), averaged from 2003-2006. In Figure 3, only negative values of SSHA are displayed to show the propagation of the upwelling Kelvin wave, whereas positive values are displayed in Figure 4 to show the propagation of the downwelling Kelvin wave. Overlaid are the weekly averaged absolute sea surface current vectors calculated using U and V from HYCOM data.

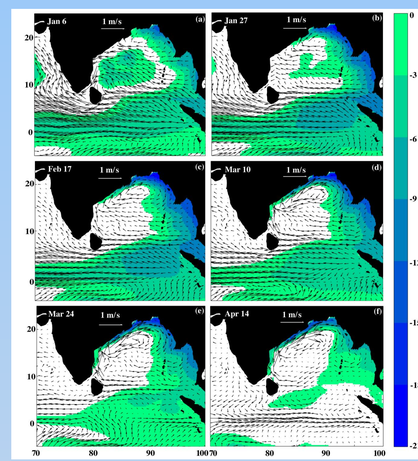

Figure 5

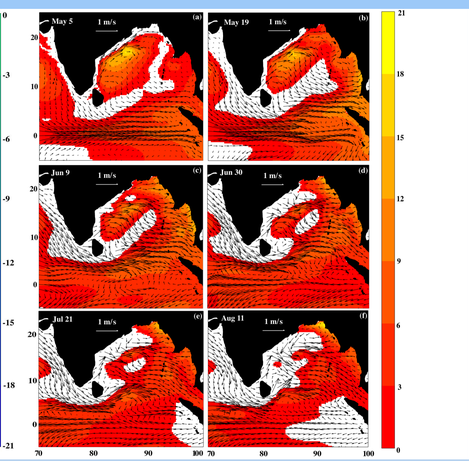

Figure 6

Kelvin waves in the Indian Ocean detected with weekly average sea surface height anomalies (SSHA) (cm) using SODA, at 2-3 week intervals from January-April (Figure 5) and May-August (Figure 6), averaged from 1993-2006. In Figure 5, only negative values of SSHA are displayed to show the propagation of the upwelling Kelvin wave, whereas positive values are displayed in Figure 6 to show the propagation of the downwelling Kelvin wave. Overlaid are the weekly averaged absolute sea surface current vectors calculated using U and V from SODA data.

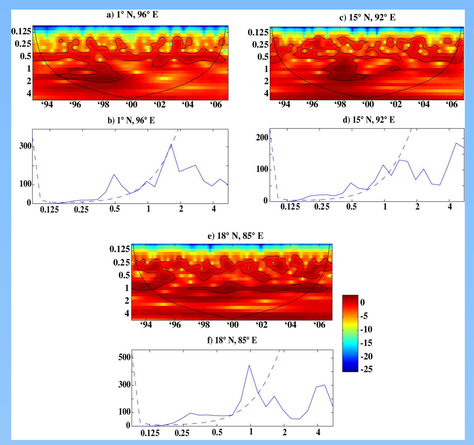

Figure 7

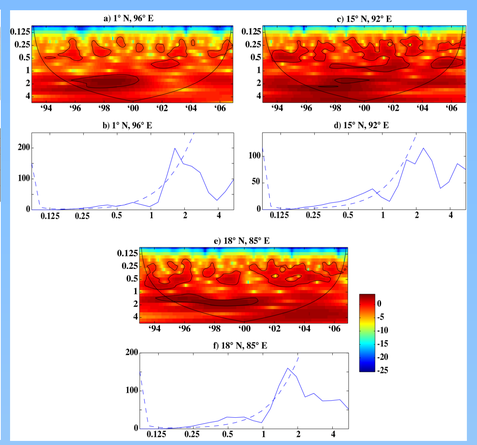

Figure 8

Wavelet analyses of altimetry (Figure 7) and SODA (Figure 8) SSHA from three locations in the Bay of Bengal. Figures 7 & 8a, c and e have axes of elapsed time in years and wave period in years (horizontally and vertically, respectively), and Figures 7 & 8b, d and f have axes of period in years and power in $cm^2$ (horizontally and vertically, respectively). The dashed line is the 95% significance level cone of influence, where anything above the line is significant.

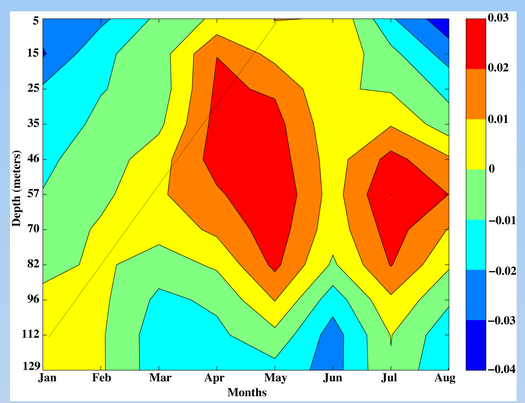

Figure 9

Figure 9: Time series of alongshore velocity anomalies (m/s) averaged from 1993-2006 from SODA layer profiles at 2° N, 94° E (near the Sumatra coast). The top 12 layers of SODA correspond to a level of depth and extends to a depth of about 130 m. The upwelling and downwelling Kelvin wave is visible in the depth profile, with the downwelling wave breaking the surface in April before sinking again in July. The dotted line shows the coastal Kelvin wave propagation.

## Discussions and Conclusions

- The observations of average SSHA, current speed and direction, and wave period and energy in the equatorial and coastal northern Indian Ocean over the course of the 13 eight-month periods reveal several important features of planetary waves in the region. A clearly recognizable upwelling Kelvin wave occurs from January to April, and a clear downwelling wave occurs from May to August. Throughout each year, the Kelvin waves follow a predictable and similar path along the Indian Ocean waveguide. They start from the east coast of Africa and follow the equator through the Indian Ocean until splitting at the coast of Sumatra. Upwelling Kelvin waves propagate north along the coastal waveguide of the Andaman Sea, around the northernmost point of the BoB, and tail off on the east coast of India, just before passing Sri Lanka. The winter monsoon current is well developed in March and April and flows into the coastal Bay of Bengal as the northward flowing EICC. At the same time there will be upwelling Kelvin wave propagation from the northern coast. The upwelling wave is followed by the downwelling Kelvin wave along a similar path, continues along the coastal waveguide, and instead dissipates along the northern BoB.
- Observations of the coastal Kelvin waves in the BoB show the typical paths that Kelvin waves follow when propagating along the coastal waveguides, and which areas experience larger variability in SSHA when the Kelvin waves pass directly through them. The surface currents follow a pattern of flowing against the upwelling waves and the downwelling waves, which correspond to both wind speed and direction from atmospheric circulation as well as seasonal currents and circulation patterns in the BoB. The wavelet analyses show the average wave period and wave energy over the entire 13-year period, with decreasing wave period and increasing wave energy as the Kelvin wave propagates. This demonstrates that Kelvin waves speed up as they continue propagating along the coastal waveguide, and likewise more energy shifts from the lower period waves to the higher period waves. Coastal Kelvin waves have a propagating horizontal speed of ~2.5 m /s and a vertical speed of ~1.2 m/day. By having long-term altimetric and salinity observations, further studies can be done to determine additional effects on the BoB circulation and salt transport.

**Acknowledgements**

Matthew Nienhaus is supported by the Office of Naval Research (ONR) Award# N000141110700 awarded to BS. We would like to thank NOAA and Oregon State University for the travel support to attend the 5CA-WS and OSTST meetings. We thank Benjamin Giese for making available the Simple Ocean Data Assimilation (SODA) reanalysis and Jay F. Shriver for providing HYCOM simulations. The altimeter products were distributed by AVISO.