HICO Observations of Biological and Sediment-Transport Processes in Monterey Bay, California

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Abstract: Coastal marine biological and sediment-transport processes are examined with HICO (Hyperspectral Imager for the Coastal Ocean) data and other remote sensing and in situ observations. The value of HICO spatial and spectral resolution is illustrated.

Summary

The Hyperspectral Imager for the Coastal Ocean (HICO) was built to demonstrate the utility of higher spatial resolution and hyperspectral imaging for ocean waters. HICO is flying on the International Space Station (ISS), has been operating since September 2009, and has collected over 5000 images of coastal ocean sites [1,2]. HICO data covers the 400-900 nm spectral range at 5.7 nm spectral sampling with a 93 m Ground Sample Distance (GSD). Earlier studies with airborne hyperspectral imagers demonstrated the utility of hyperspectral data for coastal ocean studies, particularly when the bottom is imaged or intense blooms of microscopic algae are present [3,4]. Using 10 m airborne hyperspectral data from Monterey Bay, [5] showed that 100 m GSD sampling was required to image oceanic fronts, blooms and other features. Utilization of spectral resolution to understand complex coastal environments has been well developed [6,7]. In this contribution, we examine HICO images of Monterey Bay, California, together with data from other remote sensing platforms (satellite, coastal HF radar) and autonomous underwater vehicles (AUVs) in a multi-scale, multidisciplinary study of complex coastal ocean phenomena.

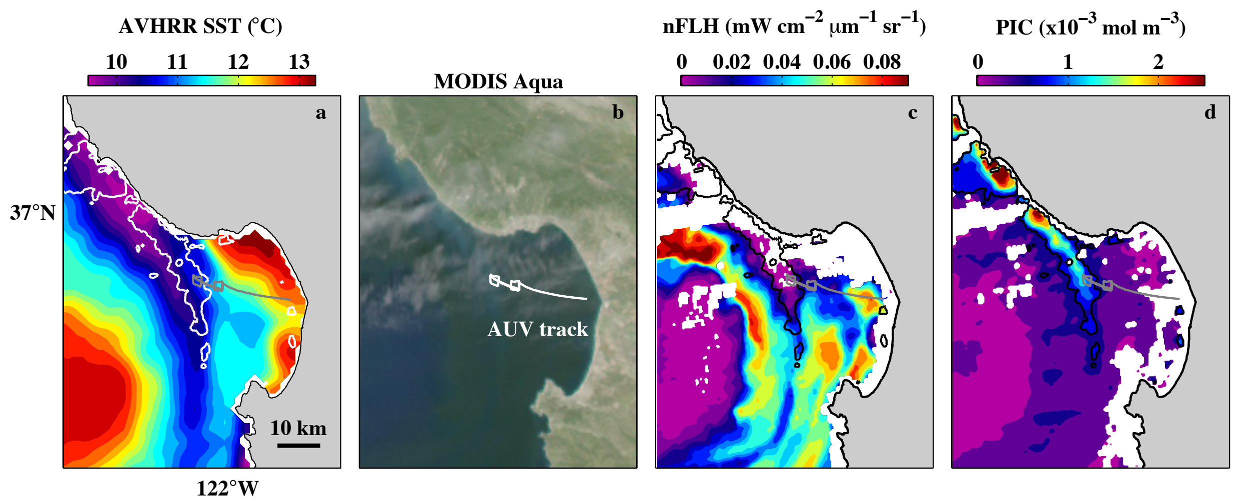

Figure 1. Regional conditions observed by satellite within a 7-hour period enveloping the HICO acquisition of Monterey Bay on 27 April 2011 (Figure 3). (a) Sea Surface Temperature (SST) from the Advanced Very High Resolution Radiometer, 27 April 2011, 21:50 PDT. (b-d) True color image and parameters derived from MODIS Aqua data acquired on 27 April 2011, 14:30 PDT. nFLH is normalized chlorophyll fluorescence line height, indicative of the abundance of microscopic algae; PIC is particulate inorganic carbon, indicative of resuspended sediments. The white contour in (a) and the black contours in (c,d) define the plume of resuspended sediments.

Multi-platform satellite remote sensing describes the conditions present within a period of repeated HICO acquisitions of the Monterey Bay region of central California. The characteristic signal of coastal upwelling in this region is evident in the sea surface temperature (SST) image (Fig. 1a) as a cold filament originating from the coastal boundary north of the bay, and extending southward across the bay mouth. This wind-driven coastal upwelling draws deep nutrient-enriched waters into the shallow sunlit layer, thereby supporting the growth of microscopic algae, phytoplankton. In patterns of blue, green or reddish coloration, RGB images qualitatively describe distributions of phytoplankton (Fig. 1b), and fluorescence of phytoplankton chlorophyll can be quantified (Fig. 1c). While nutrient supply is essential to support ocean life through algal primary production, some algal blooms can harm marine life and people [8,9]. Three quarters of all harmful algal bloom (HAB) species are dinoflagellates [10], motile microalgae that typically aggregate near the surface during the day, where they are detectable by remote sensing due to the intensity and spectral character of their reflectance [11,12].

In addition to nutrients, coastal upwelling can bring to the surface turbid fluid from the bottom boundary layer of the continental shelf. This too is a highly visible to remote sensing. In the Monterey Bay region, this sediment signal may be evident as milky coloration within cold upwelled waters (Figs. 1a,b), and it is quantifiable (Fig. 1d). Comparison of the patterns in SST, chlorophyll fluorescence, and suspended sediments in Fig. 1 indicates a sediment plume extending southward within waters of low phytoplankton abundance, along the inshore edge of the upwelling filament. Sediment transport can influence the ecology of benthic zooplankton having pelagic larval stages [13], its constituents may influence the toxicity of certain microalgae [14], and it has been hypothesized as an important link in mercury cycling in coastal waters [15]. Thus, the focus of this paper is upon ecologically significant pelagic features that can be effectively characterized by high-resolution hyperspectral remote sensing, augmented by additional remote sensing and in situ data.

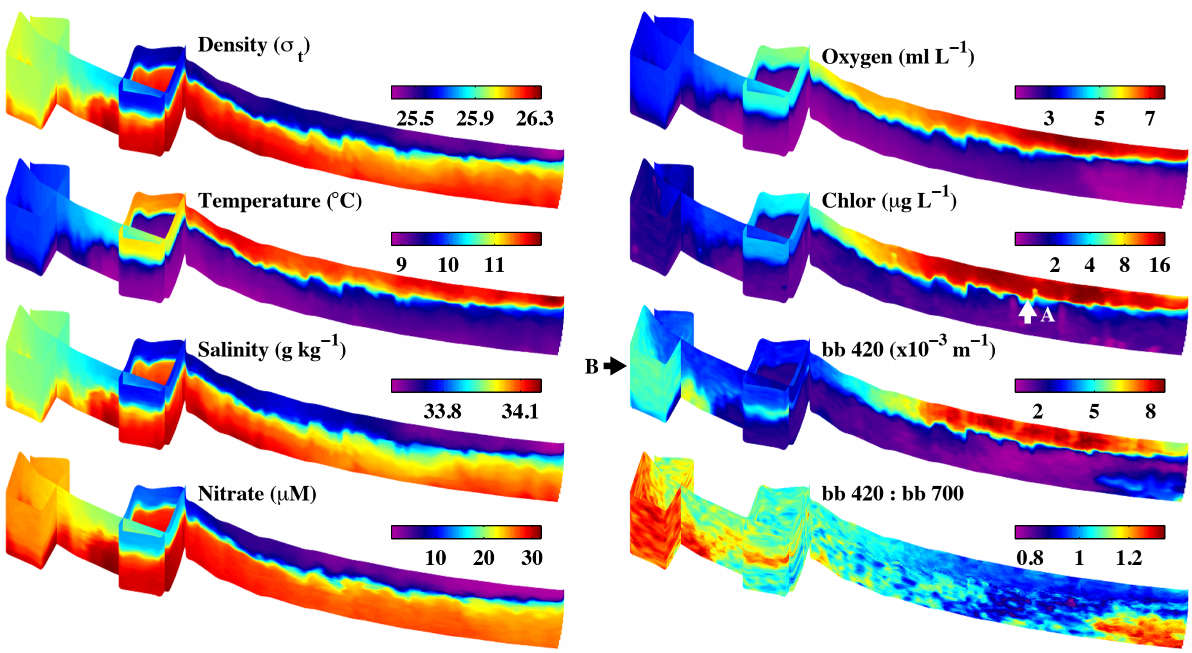

Figure 2. Vertical sections of properties measured by the *Dorado* AUV along the track shown in Fig. 1, between 14:00 and 23:00 on 28 April 2011. The depth range shown is 2 to 40 m. Arrows indicate near-surface features examined with remote sensing data: (A) a phytoplankton bloom patch, and (B) sediments transported from an upwelling center (Fig. 1). The property bb 420 is optical backscattering at 420 nm.

The features detected by remote sensing were observed in situ by multiple AUVs. Multidisciplinary observations from one of the AUVs are shown in Fig. 2 (surface track shown in Fig. 1). The bloom patch in central Monterey Bay observed by MODIS (Fig. 1c) was transected by the AUV (label A in Chlor section of Fig. 2). The low-chlorophyll, sediment-enriched waters observed by satellite (Fig. 1c,d) were evident in situ (Fig. 2). They exhibited elevated salinity, density, nitrate (nutrient) concentrations, and optical backscattering (label B in the bb420 section), and depressed temperature and oxygen concentration. The color of particles in the sediment plume sampled at the western edge of the AUV survey was distinct from the color of phytoplankton (backscattering ratio in the last panel of Fig. 2 relative to Chlor). These coastal features were observed by additional sensors on the *Dorado* AUV, including a sensor that measured the particle size distribution and a particle imaging device, and they were repeatedly observed and autonomously tracked for two days by the *Tethys* AUV. Autonomous localization of the moving front by *Tethys*, using onboard algorithms, provided targeting information required by *Dorado* and its water *Gulper* sampling system. The time-series from both AUVs illustrate temporal variability across the central bay.

HICO images of Monterey Bay were acquired on 25 April, 27 April, and 3 May 2011. During this period, Monterey Bay experienced significant changes in wind-driven upwelling and upper-ocean water properties. Of particular interest was intensification of upwelling that resulted in a diminishing signal of phytoplankton chlorophyll fluorescence (Figure 3) and variation in the signal of suspended sediments. Using time-series of moored environmental observations, HF radar measurements of surface currents, and AUV characterization of the water column, we describe the influences of advection and mixing on the environment of the bay, and on the signals detected by the HICO time-series.

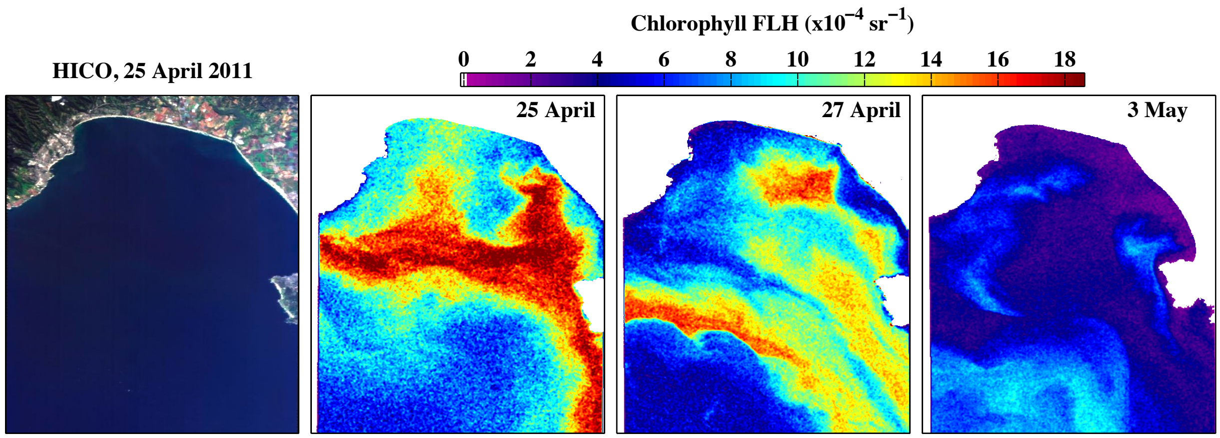

Figure 3. Images derived from atmospherically corrected HICO data. (a) An RGB image is shown only for the first acquisition in the time-series. (b-d) Chlorophyll fluorescence line height (FLH) derived from remote sensing reflectance, using bands centered at [663, 686, and 749 nm].

References

[1] R.L. Lucke, M. Corson, N.R. McGlothlin, S.D. Butcher, D.L. Wood, D.R. Korwan, R.R. Li, W.A. Snyder, C.O. Davis and D.T. Chen, "The Hyperspectral Imager for the Coastal Ocean (HICO): Instrument Description and First Images", Applied Optics, V. 50 (11): 1501-1516, doi:10.1364/AO.50.001501 (2011).
[2] M. Corson and C.O. Davis, "The Hyperspectral Imager for the Coastal Ocean (HICO) provides a new view of the Coastal Ocean from the International Space Station", AGU EOS, V. 92(19): 161-162 (2012).
[3] C.O. Davis, K.L. Carder, B-C Gao, Z.P. Lee and W.P. Bissett, "The Development of Imaging Spectrometry of the Coastal Ocean", IEEE Proceedings of the International Geoscience and Remote Sensing Symposium, V. 4: 1982-1985 (2006).
[4] J.P. Ryan, A.M. Fischer, R.M. Kudela, J.F.R. Gower, S.A. King, R. Marin III and F.P. Chavez, "Influences of upwelling and downwelling winds on red tide bloom dynamics in Monterey Bay, California", Continental Shelf Research, 29: 785–795 (2009).
[5] C.O. Davis, M. Kavanaugh, R. Letelier, W.P. Bissett and D. Kohler, "Spatial and Spectral Resolution Considerations for Imaging Coastal Waters", Proceedings of the SPIE V. 6680, 66800P:1-12 (2007).
[6] Z. P. Lee and K. L. Carder, "Effect of spectral band numbers on the retrieval of water column and bottom properties from ocean color data", Applied Optics, V. 41: 2191-2201 (2002).
[7] Z. P. Lee, K. Carder, R. Arnone and M. X. He, "Determination of Primary Spectral Bands for Remote Sensing of Aquatic Environments", Sensors, V.7: 3428-3441 (2007).
[8] C. A. Scholin. F. Gulland, G.J. Doucette S. Benson and 22 others, "Mortality of sea lions along the central California coast linked to a toxic diatom bloom", Nature 403:80–84 (2000).
[9] D.A. Jessup, M.A. Miller, J.P. Ryan, H.M. Nevins, H.A. Kerkering, A. Mekebri, D.B. Crane, T.A. Johnson and R.M. Kudela, "Mass Stranding of Marine Birds Caused by a Surfactant-Producing Red Tide", PLoS ONE 4(2): e4550. doi:10.1371/journal.pone.0004550 (2009).
[10] A. Sournia, "Red-tide and toxic marine phytoplankton of the world ocean: an inquiry into biodiversity", in Harmful Marine Algal Blooms, P. Lassus, G. Arzul, E. Erard-LeDenn, P. Gentien, and C. Marcaillou-LeBaut, eds. Lavoisier, Paris, France (1995).
[11] J. Gower, S. King, G. Borstad, and L. Brown, "Detection of intense plankton blooms using the 709 nm band of the MERIS imaging spectrometer", Int. J. Remote Sens., 26, 2005– 2012 (2005).
[12] J.P. Ryan, J.F.R. Gower, S.A. King, W.P. Bissett, A.M. Fischer, R.M. Kudela, Z. Kolber, F. Mazzillo, E.V. Rienecker and F.P. Chavez, "A coastal ocean extreme bloom incubator", Geophysical Research Letters, 35, L12602, doi:10.1029/2008GL034081 (2008).
[13] J.P. Ryan, S.B. Johnson, A. Sherman, K. Rajan, F. Py, H. Thomas, J.B.J. Harvey, L. Bird, J.D. Paduan and R.C. Vrijenhoek, "Mobile autonomous process sampling within coastal ocean observing systems", Limnol. Oceanogr. Methods 8: 394–402 (2010).
[14] J. Ryan, D. Greenfield, R. Marin III, C. Preston, B. Roman, S. Jensen, D. Pargett, J. Birch, C. Mikulski, G. Doucette and C. Scholin, "Harmful phytoplankton ecology studies using an autonomous molecular analytical and ocean observing network", Limnol. Oceanogr., doi:10.4319/lo.2011.56.4.1255 (2011).
[15] P.S. Weiss-Penzias, C. Ortiz Jr., R.P. Acosta, W. Heim, J.P. Ryan, D. Fernandez, J.L. Collett Jr. and A.R. Flegal, "Total and monomethyl mercury in fog water from the central California coast", Geophys. Res. Lett., 39, L03804, doi:10.1029/2011GL050324 (2012).