Looking Forward

NUMO expects to enter discussions with several volunteer communities before it decides on which site or sites to concentrate its detailed investigations. Potential volcanic impacts and rock deformation will need to be evaluated at some level right up to the point of selection and eventual license application of any site. At present, the emphasis is on avoidance, by excluding locations with a high likelihood of direct impacts in the next tens of thousands of years.

In the future, NUMO may (depending on location) need to assess the potential consequences associated with low probabilities for non-excluded sites, as well as look at indirect impacts, to decide whether the quantitative risks are acceptably low, meeting any regulatory requirements that will eventually be in place.

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MODIS Detects a Devastating Algal Bloom in Paracas Bay, Peru

PAGES 465, 472

The medium-resolution bands on NASA's Moderate-Resolution Imaging Spectroradiometer (MODIS) were successfully used to detect and map the distribution of a harmful phytoplankton bloom in the Paracas Bay, Peru, that caused economic losses worth millions of dollars. Routine application of MODIS data can be a valuable and cost-effective way to monitor harmful blooms and other turbid water plumes that cause disruption to the fishery and aquaculture operations of many coastal areas.

Paracas Bay

Paracas Bay is an area off the central coast of Peru (Figure 1). It is part of the Paracas National Reserve, but at the same time it is an important fishing area which is in close proximity to fishing industries in the port of Pisco. Around 130 fishing vessels are based in Pisco, and eight fisheries-related factories are located there. Fishing, fish meal manufacturing, and fish and shellfish farming are the region's most important economic activities. These activities are often disrupted by harmful algal blooms that can kill fish and shellfish both by producing toxins and causing anoxia (oxygen depletion) as a result of respiration and decay of the biomass.

In 2003, Pisco produced 8.4% of the Peruvian anchovy landings (5.165 million tons) but in 2004, mostly because of harmful phytoplankton blooms, its share decreased to 1.7%. The fish meal factories have a conversion rate of 5:1; i.e., for each 5 tons of anchovy, they produce 1 ton of fish meal worth $550 per ton. Between 2–4 April 2004, Pisco fish landings were between 10.6 and 11.4 thousand tons per day. After the episode of massive fish deaths in the bay, the maritime authority, DICAPI (Dirección General De Capitanías Y Guardacostas), closed the port on 4 April until April 27 in order to reduce the amount of effluents of the fish meal factories. At the same rate of landings, 22 days of port closure meant over 220,000 tons of anchovy and 50,000 tons of fish meal valued at about $27.5 million in lost revenue.

Another sector devastated by the algal bloom was local aquaculture, which reported losses estimated at $1 million. Social unrest such as roadblocks and other manifestations of protest by the population were reported by the press. The main source of conflict is the waste from the fish meal factories. The eight factories in the port have built a pipeline to dispose of huge amounts of the untreated waste outside the bay. However, it is widely believed that the disposal of the so-called "sanguaza" ("tail water") is not functioning properly and is still polluting the bay and its surroundings. In a study of a similar harmful bloom in 2000, *Cabello et al*. [2002] concluded that the organic matter from fishery effluents, together with the harmful algal bloom, generated a synergistic effect that caused the mass mortality of benthic species.

MODIS Medium-Resolution Bands

The medium-resolution (250- and 500-m) MODIS bands were designed for land applications, and their sensitivities are lower than those of the dedicated 1-km ocean bands. Recent work [*Hu et al*., 2003; *Li et al*., 2003] has shown that these bands have sufficient sensitivity to be useful in various aquatic applications such as detection and mapping of turbid plumes, oil slicks, and water quality in productive estuaries. Quantitative use of the medium-resolution MODIS bands in ocean applications is hampered by the inadequate sensor calibration, highly problematic

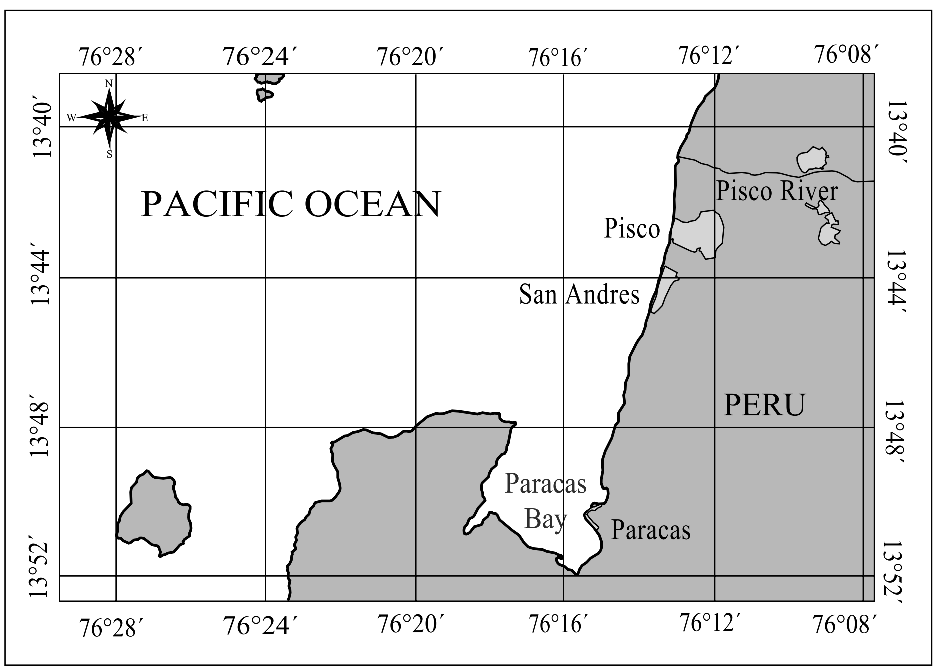

Fig. 1. Map of the Paracas Bay area.

By M. Kahru, B. G. Mitchell, A. Diaz, and M. Miura

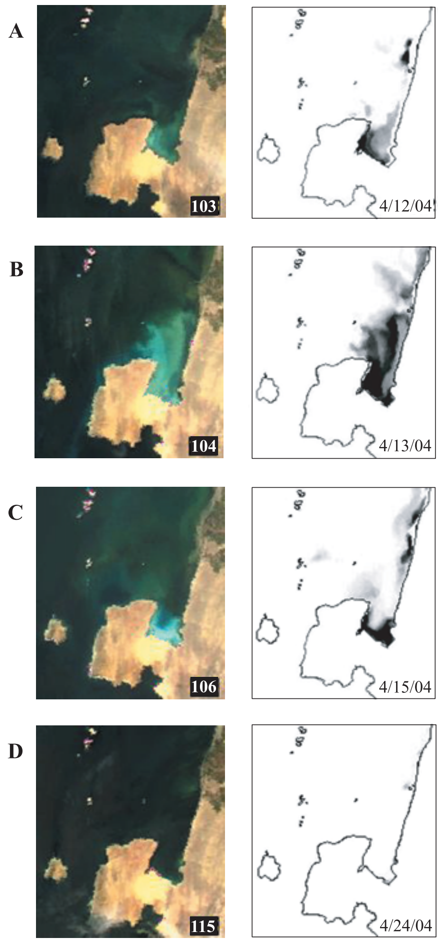

Fig. 2. Examples of the bloom using extracts of MODIS-Terra and MODIS-Aqua true-color (left column) and turbidity (right column; darker areas show higher turbidity) images of the Paracas area. Julian day is shown for the true-color images, and the corresponding month and day of 2004 are shown for the turbidity images. (A) The bloom (turquoise blue) is localized in the bay, and a separate turbidity area is seen near the Pisco River mouth. (B) Most extensive bloom, extending out of the bay. (C) Very concentrated bloom in the southern part of the bay. A separate turbidity center is near the Pisco River mouth. (D) The bloom has disappeared.

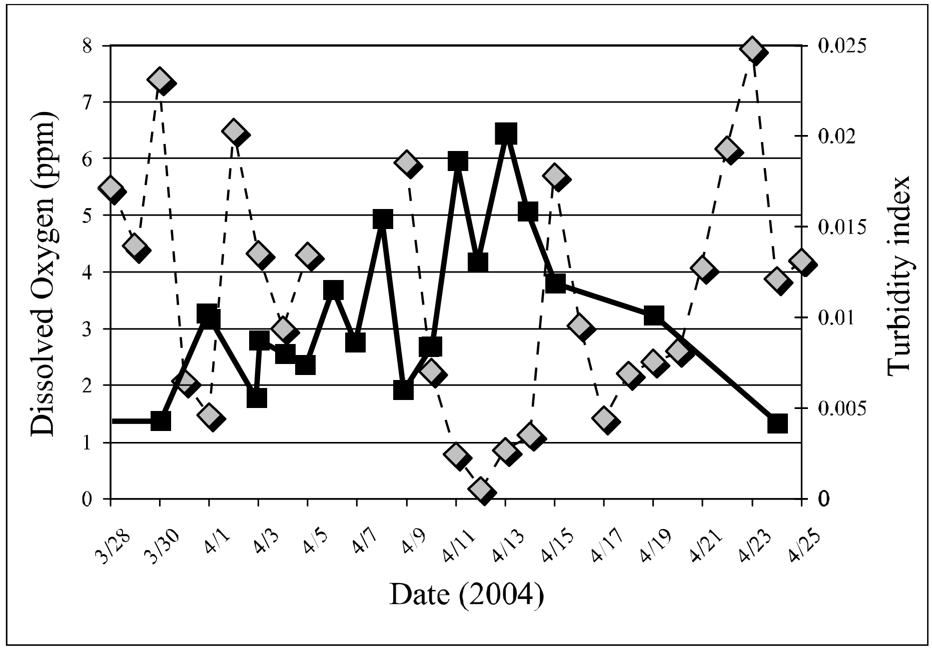

Fig. 3. Time series of the turbidity index (black squares, dimensionless) and oxygen concentration (gray diamonds, ppm) during the massive phytoplankton bloom in the Paracas Bay in March-April 2004. Turbidity is averaged over the bay, but oxygen concentration is from a single station within the bay.

atmospheric correction, and bio-optical inversion procedures [*Hu et al.*, 2004].

Considering these problems, we took an empirical approach and did not try to estimate the water-leaving radiance that is the traditional input to bio-optical models. Instead, a simplified atmospheric correction algorithm by J. Descloitres of the MODIS Rapid Response Project (http://rapidfire.sci.gsfc. nasa.gov) was used. This algorithm uses top-of-the-atmosphere level-1B radiance data to calculate a first approximation to surface reflectance by removing the gross effects of the Sun and sensor geometry, molecular path reflectance, and absorption by O_2, O_3, and H_2O.

The corrected reflectance data of the MODIS bands 1 (620–670 nm), 2 (841–876 nm), 3 (459–479 nm), and 4 (545–565 nm) were then used to create two image products for detecting and mapping the algal bloom. First, true-color (red-green-blue) images using, respectively, bands 1, 4, and 3 showed a color signature (turquoise blue) that clearly identified the distribution of the bloom (Figure 2, left column).

Second, as a semiquantitative measure of the amount of particulate material in the near-surface water, the turbidity index was calculated by subtracting band-2 reflectance from band-1 reflectance. Reflectance at longer wavelengths is known to be influenced mostly by scattering in the atmosphere because of the larger water absorption, and the subtraction removes most of the residual atmospheric component due to aerosols. While turbidity is not specific to algal blooms, it is a quantitative estimate of the intensity of the bloom once the existence of the bloom is detected by the true-color images. We have no in situ measurements of the total suspended mass (TSM) in the water, and therefore the reflectance data cannot be converted to TSM. In Figure 2 (right column), a gray scale is used to show relative turbidity. Various modules of the Microsoft Windows-based software WIM Automation Module (http://www.wimsoft.com) were used throughout this study to process MODIS imagery.

Harmful Bloom in April 2004

Visual observations of brownish-red discoloration of the water in the bay were made on 26–29 March. This was probably the beginning of the algal bloom. The Peruvian Marine Research Institute (IMARPE) registered a red tide (algal bloom) in the Paracas area starting on 2 April. The bloom was dominated by the dinoflagellate *Gymnodinium sanguineum*, with other dinoflagellate and diatom species present in high numbers (Lourdes Carbajo, Pisco Coastal Laboratory, IMARPE, personal communication, 2004). Concentrations of up to 3200 cells/mL were reported just before the massive death of phytoplankton between 9–11 April. The toxicity of *G. sanguineum* is not well established, but the species is associated with fish and shellfish kills around the world [*Faust and Gulledge*, 2002].

For a 25-day period from 30 March to 24 April, including the bloom, 20 cloud-free Terra and Aqua images of the Paracas Bay, including 3 days with both Terra and Aqua images in the same day, were obtained. Some of these images are shown in Figure 2.

Figure 3 shows the rise and fall of the bloom as measured by the mean MODIS-detected turbidity in the bay. The bloom resulted in the accumulation of phytoplankton biomass that subsequently sunk to the bottom of the bay and caused oxygen depletion. The water turbidity index calculated from the 250-m MODIS data was inversely correlated with oxygen concentration measured in situ in the water column. Because of strong and variable water exchange between the bay and the surrounding ocean areas, the oxygen concentrations are quite variable (Figure 3). During the short period of 11–14 April 2004 that coincided with the peak of the dinoflagellate bloom, oxygen concentration in the bay may be decreased to below the "alert" level. Oxygen concentration was close to 0 on 12 April; fish kills were reported that day. Previous reports of fish kills were on 2 April when oxygen concentration was still relatively high.

Potential for Monitoring

Global MODIS data are available for downloading shortly after the satellite overpass (http://daac.gsfc.nasa.gov/MODIS/data_access.

shtml). Although the volume of the data files is quite large, with improved network speeds this will be less of an issue even in remote locations. With simple processing on a low-cost personal computer, it is possible to cost-effectively monitor bays and other coastal areas where harmful algal blooms and/or water masses with increased turbidity present an environmental problem. Clouds are the main obstacle in using visible remote sensing imagery. It was probably lucky for this study to obtain, as an average, 0.8 cloud-free scenes per day using both Terra and Aqua. The frequency of cloud-free imagery in other areas and other time periods may be lower. Government agencies as well as local fishing, oil, and gas companies have shown interest in the satellite data used here. Currently, the true-color images like those in Figure 2 are being distributed commercially by a local company, GeoMap Digital S.A.C.

Acknowledgments

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Geomagnetic Observatory Operates at the Seafloor in the Northwest Pacific Ocean

PAGES 467, 473

The need to establish seafloor observatories has been important for decades. Multidisciplinary efforts aimed at establishing such observatories [e.g., *Beranzoli et al.*, 1998] are now culminating the ongoing Ocean Observatories Initiative [*Copley*, 2004].

This article reports on how the world's first seafloor geomagnetic observatory NWP (North-Western Pacific) is producing data that are compatible with those obtained by satellite Ørsted and the existing geomagnetic observatory network. In particular, the article reports on the remarkable agreement between the satellite-predicted and actual secular variation, which ensures the accuracy of the geomagnetic measurements both in space and at the seafloor.

The seafloor geomagnetic observatory has been in operation since 1 August 2001. So far, 718-day-long time series of seafloor electromagnetic fields have been obtained. Very precise attitude data make the seafloor data treated equivalently to those on land. Moreover, the absolute scalar geomagnetic measurement is now possible even at the seafloor by an Overhauser scalar absolute magnetometer taking advantage of nuclear magnetic resonance. The state-of-the-art technology is now utilized not only in space but also at the seafloor. A main point of this article is how well the slow and smooth temporal variation of the magnetic field coincides at both locations. Close agreement with satellite data collected more than 500 km above the seafloor is clearly demonstrated.

By H. Toh, Y. Hamano, M. Ichiki, and H. Utada

Now that there is a miniconstellation of magnetic satellites [Ørsted, CHAMP (Challenging Mini-Satellite Payload), and SAC-C (Satelite de Aplicaciones Cientificas-C]) in space, this topical report will have an impact on space physics as well as on geomagnetism.

Development of the SeaFloor ElectroMagnetic Station (SFEMS)

A new SeaFloor ElectroMagnetic Station (SFEMS; *Toh et al.* [1998]) has been developed in conjunction with the Japanese Ocean Hemisphere Project. This new instrument provided its first data in July 2002 at 41°07'03"N, 159°55'43"E, 5570 m, a site henceforth referred to as NWP (Figure 1). The geoelectromagnetic data in the northwest Pacific consist of the absolute geomagnetic total force measured by an Overhauser scalar absolute magnetometer, a three-component geomagnetic field measured by a fluxgate magnetometer, and a horizontal

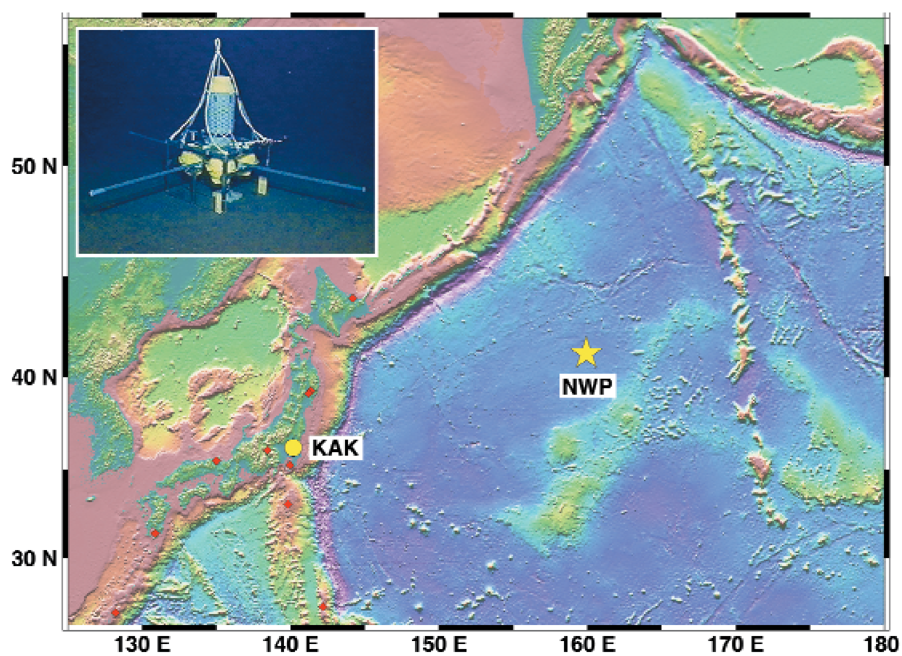

*Fig. 1. Topography of the northwestern Pacific and a photograph of the Seafloor Electro-Magnetic Station (SFEMS) operating at the deep seafloor (inset). NWP as well as Kakioka Magnetic Observatory (KAK) are shown by the star and circle, respectively. Smaller red diamonds are existing geomagnetic observatories around Japan. The photo was provided courtesy of the Japan Agency for Marine Science and Technology, and the bathymetric map was drawn using Generic Mapping Tools [*Wessel and Smith, *1998].*