3-2 Remote sensing of coral reefs in Japan

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1 Introduction to remote sensing of coral reefs

Accurate, up-to-date and accessible information on the state of coral reef ecosystems is indispensable for informed and effective management of these important marine resources. Remote sensing holds a vital role in the science and management of natural resources since they provide a rich source of spatial information at synoptic scales and at different periods. For coral reefs, remotely-sensed images can be interpreted or analyzed to produce maps of various themes (presence/absence distribution, species composition, abundance) with degree, extent and detail at a rate that cannot be matched by field methods alone.

This chapter chronicles the contributions made by the Japan in the field of remote sensing applications to the science and management of coral reefs. To set the context, the topics contained herein include a brief background on coral reef remote sensing observation. The specific applications to benthic cover or habitat mapping, detection of coral health and bleaching, coral morphology estimation, bathymetry mapping, assessment of sedimentation, seagrass mapping, sea surface temperature monitoring are then presented with some other emerging applications. Each section in this chapter will first outline the recent efforts that were poured into the development of remote sensing technique and then will expound the specific methods and applications in Japan.

In Japan, most corals are located in the Ryukyu region, situated southwest of mainland Japan. Naturally, most of the study areas for coral reef studies are located in this region. The same is true for research topics that apply remote sensing techniques. In the entire Ryukyu Islands, the southeastern island of Ishigaki had received the most attention, particularly the east portion called Shiraho reef area not only because of its high degree of diversity which attract scientists but also for its accessibility and convenience for researchers. Shiraho reef is especially well-studied that much of the field data gathered by biologists and reef scientists are further utilized in performing validation of processed satellite image data. Although benthic cover mapping results are a popular fare among published reports, analysis of reef sedimentation and coral bleaching are increasingly becoming preferred topics of recent studies.

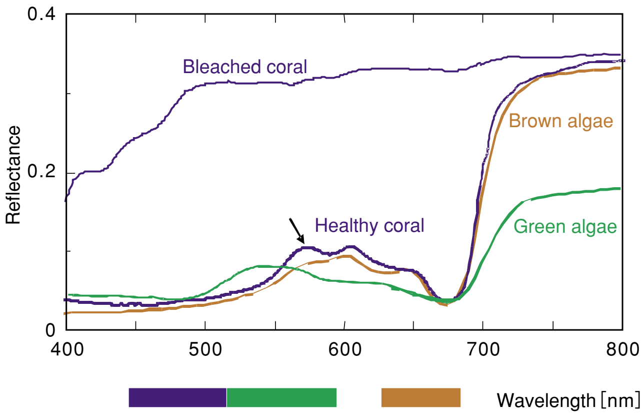


Fig. 1. Reflectance spectral of coral reef benthic organisms (coral and algae) and observation bands for Landsat TM. Spectral feature of coral is indicated by an arrow.

Remote sensing analysis attempts to develop methods by which imagery acquired from distant sensors can be related with that of existing physical conditions found on the earth's surface at the time of data acquisition. Images are grid array of signal data of varying intensity detected at different wavelength ranges. A key principle in remote sensing exploits the fact that objects exhibit spectral responses that vary with wavelength, known as spectral signatures (Fig. 1). The ability of optical sensors to "see" through the water column is an advantage for examining submerged objects like corals or seagrasses and the like. However, optical sensors are severely vulnerable to harsh weather conditions. Presence of clouds, haze and various forms of water vapor impede acquisition of clear scenes. Signal-to-noise ratio is likewise a key issue since water absorbs a large portion of the incoming energy rendering low contrast among submerged objects especially when the radiometric resolution of the sensor is low.

The techniques applied to interpret coral reef areas are rooted on traditional methods of visual interpretation commonly applied to aerial photography. Deduction of natural features is accomplished by examining image tone or color, scale, texture or pattern. Delineation of objects or detection of a certain phenomenon is usually carried out manually on printed images or digitized onscreen either by trained, experienced or knowledgeable interpreter.

Remote sensing of coral reefs is faced with three major difficulties. First, water column on coral reefs strongly absorbs wavelengths longer than 650 nm (approx), thus the use of light is limited to visible regions (400–650 nm). This aspect marks a significant difference from terrestrial vegetation remote sensing that makes extensive use of the near infrared sensors. Second, because of their symbiosis with zooxanthellae, corals show reflectance characteristics similar to that of algae (Fig. 1). This means that multispectral sensors with wavelength resolution of several tens of nanometers, such as Landsat TM, will find difficulty in distinguishing between corals and algae with precision. Third, because coral reefs are highly heterogeneous, the spatial resolution of currently available, widely used satellite imagery is considered to be too coarse to map reefs in detail due to spectral mixing in one pixel.

Nonetheless, current advances in remote sensing technology may circumvent or alleviate these limitations. The availability of digital imagery such as those obtained by sensors onboard satellite platforms enables implementation of numerical algorithms on computers to infer reef characteristics. The advent of sensors with multiple bandwidth detection capabilities made it possible to acquire multispectral (10 bandwidths or less) and hyperspectral data (more than 10 bands, e.g., airborne CASI and satellite-borne Hyperion). This development have vis-à-vis rendered analysis of images more complicated due to introduction of physics-based approaches, specifically radiative transfer models, but also presents greater potential for full extraction of object optical properties. At longer time scales, analysis of archived aerial photographs and satellites has been proven to be very effective in monitoring decadal changes in coral reefs at large spatial scale.

Japan enjoys a strong support and a solid infrastructure for conducting remote sensing research. This is primarily due to the presence of a national agency for space technology research and applications, the Japan Aerospace Exploration Agency (JAXA) (formerly called the National Space Development Agency - NASDA). Since 1978, Japan has launched about 5 (MOS-1, MOS-1b, Japan Earth Resource Satellite or JERS-1, ADEOS, and ADEOS II) earth observation satellites excluding the course-resolution Geostationary Meteorological Satellite (GMS) system, which is intended primarily for weather forecasting, and the Tropical Rainfall Measuring Mission (TRMM). Most satellite image datasets, including those produced by foreign missions are available from the Remote Sensing Technology Center (RESTEC), the distribution data distribution and technology promotion of NASDA.

Another organization in Japan that is involved in remote sensing activities is the Earth Remote Sensing and Data Analysis Center (ERSDAC), a non-profit foundation and now belongs, legally, to the private sector. The prime objective of ERSDAC is to accelerate the research and development of remote sensing technology to be applied to exploration for non-renewable resources as well as environmental monitoring on a global scale. ERSDAC currently acts as the data distribution center for ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), a sensor developed by Japan onboard the satellite Terra launched by the United States.

Often, the satellite images used in the analysis of coral reefs included ASTER, Landsat 7 ETM+, Landsat 3, 4 and 5 TM, ASTER, Ikonos and to a lesser extent, SPOT. An airborne hyperspectral sensor is also available from NASDA and has been used to acquire images over Kuroshima (Is.), Ishigaki Island and parts of the Okinawa and Kerama Islands.

2 Benthic cover classification of coral reefs

Remote sensing techniques allows for the investigation of wide area, including often inaccessible remote sites routinely, and thus is very effective for monitoring earth surface features including coral reefs. In reef areas, the most elementary biotic classes are coral, algae, and sand. Dead corals due to bleaching or infestation by crown-of-thorns starfish or COTS (*Acanthaster planci*) will be covered by algae, thus distinguishing corals and algae can be useful not only for mapping coral-reef elementary benthic organisms but also for monitoring coral reef health.

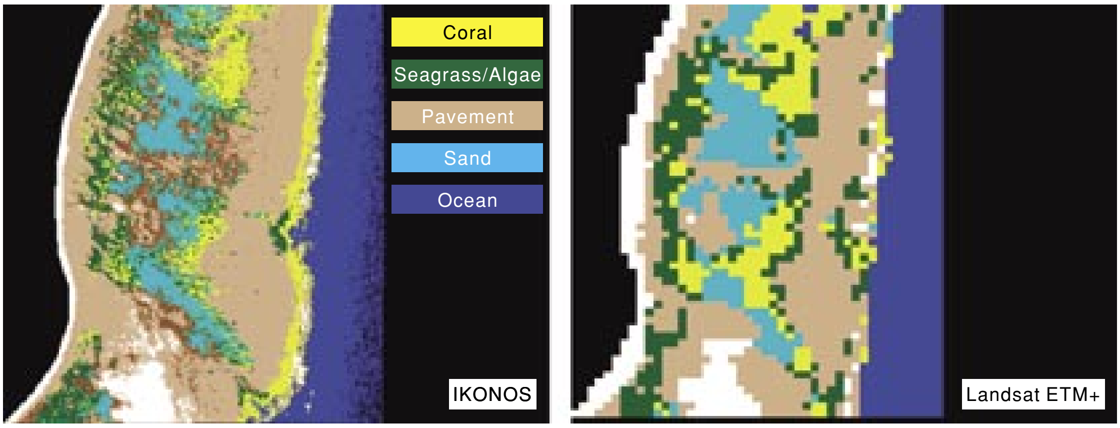


Fig. 2. Comparison of classification results by Ikonos and Landsat ETM+ (Shiraho Reef, Ishigaki Island).

In the Ryukyu Islands, classification of coral reefs using aerial photographs began in the late 1970's (Ohba and Aruga 1978). While most of these studies are rely on visual interpretation of the images, digital image classification was conducted by Nakamori and Sugai (1990) and Fujiwara *et al.* (1997). Kite photography was also used to detect bleached coral colonies (Hasegawa *et al.* 1999).

For classifying images, Landsat TM/ETM+ and SPOT HRV have been mainly used (Kato *et al.* 1992; Hasegawa 1993; Miyazaki *et al.* 1995, Nadaoka *et al.* 1997, 1998). Recently, high spatial resolution satellite sensor Ikonos, was used for classification, and an overall accuracy of 81% was achieved in Shiraho Reef, while the 64% overall accuracy was obtained by Landsat ETM+ (Andréfouët *et al.* 2003) (Fig. 2). Furthermore, the use of this first hyperspectral satellite-borne sensor, EO-1 Hyperion, for classification of coral reef benthic habitats situated at the eastern coast of Ishigaki Island is in progress (Matsunaga *et al.* 2003). They acquired and examined Hyperion data for diagnosing spectral features from shallow coral reef area and benthic classification (Matsunaga *et al.* 2001a). Furthermore, by simulating the top-of the atmosphere radiance as to be detected by Hyperion, Matsunaga *et al.* (2001b) showed that signal-to-noise ratio (SNR) and sensor spectral response may affect classification performance. It was also shown that spectral derivative analysis may pose potential for classifying sea bottom coverage.

As mentioned, although reflectance signatures of corals may be similar to other reef benthic habitats, their location within the reef may dictate their actual classification (Mumby *et al.* 1998). Paringit and Nadaoka (2004) used a contextual classification approach by morphology to constrain possible location of benthic classes. They have also introduced spectral unmixing approach for estimating the fractional coverage of benthic habitats. Instead of classification maps, the scheme produces fraction maps for every benthic habitat. If a classification map is desired, it can be derived by simple setting a threshold coverage for every benthic cover and combining the results.

Reflectance measurement by *in-situ* spectrometer has been conducted since 1990's (Hasegawa 1993; Matsunaga and Kayanne 1994; Miyazaki *et al.* 1995). Recently, the spectra obtained by hyperspectral sensors provide continuous data, and the analysis of reflectance spectra has successfully discriminated coral reef features (Holden and LeDrew 1999; Mumby *et al.* 2001; Hochberg *et al.* 2003). With radiative transfer simulation, the effectiveness of airborne hyperspectral remote sensing is believed to contribute to a much better classification results (Yamano *et al.* 2002). In the Ryukyu Islands, airborne hyperspectral sensor, CASI, was used to classify coral reef benthic features in Kuroshima and Akajima (Miyazaki *et al.* 1997, 1998; Yamano *et al.* 2003a).

The reflectance spectra as would be measured at the top of the atmosphere are substantially different from the *in-situ* spectra, due to differential attenuation by the water column and, most importantly, by atmospheric Rayleigh scattering. The result is that many of the spectral features that can be used to distinguish coral species from their surroundings or from one another, which have been used successfully with surface or aircraft data, would be obscured in spectral measurements from a spacecraft (Paringit and Nadaoka 2002a). However, above the atmosphere, the radiance contrasts between most coral species and mostly brighter non-coral objects remain noticeable for water column depths up to 20 m. Over many spectral intervals, the reflectance from dark coral under shallow water is smaller than that of deep water. The maximum top-of-atmosphere radiances, and maximum contrasts between scene types, occur between 400 nm and 600 nm. This supports the conclusions of recent satellite reef mapping exercises, which suggest that coral reef identification should be feasible using satellite remote sensing, but that detailed reef mapping (e.g., species identification) may be more difficult (Mumby *et al.* 1997). The measured and modeled hyperspectral reflectance spectra were examined separately to compare the degree to which different substrate types can be discriminated once the water column is "added" to the spectra. The classification accuracy assessment indicated that the ability to discriminate benthic habitat based on hyperspectral characteristics is limited when the effects of the water column are included as the kappa statistic drops from 0.70 to 0.49.

3 Evaluating coral health and detecting bleaching events

Remote sensing can be used for detecting stressed/bleached corals, as demonstrated by recent papers by Yamano and Tamura (2004) for bleached corals in Japan (see Section 7) and by Elvidge *et al.* (2004) for those in Great Barrier Reef of Australia.

Stressed corals show decreased physiological function, such as decreased photosynthetic activity and pigmentation, and changes in fluorescence spectra were detected prior to visible bleaching (Hardy *et al.* 1992). Yamano *et al.* (2003b) observed the reflectance spectra of naturally bleached corals and experimentally stressed corals by exposing them to high temperature and strong solar radiation, and analyzed changes in reflectance spectra, photosynthetic capacity, and zooxanthellae status. In response to stress, the corals became dominated by degraded, shrunken zooxanthellae, and their photosynthetic capacity decreased. In both experimentally stressed and naturally bleached corals, the red edge (maximum of the first derivative of a reflectance spectrum based on hyperspectral reflectance measurement) in the reflectance spectra shifted to a shorter wavelength (Fig. 3), suggesting the use of reflectance spectra as a potential tool for detecting stressed corals.

Bleached corals provide a strong optical signal that suggests that remote sensing investigations of major bleaching events are feasible using airborne or satellite sensors. However, patchy coral cover, varying intensities of bleaching, and water depths are likely to limit the application of remote sensing techniques in monitoring and mapping coral

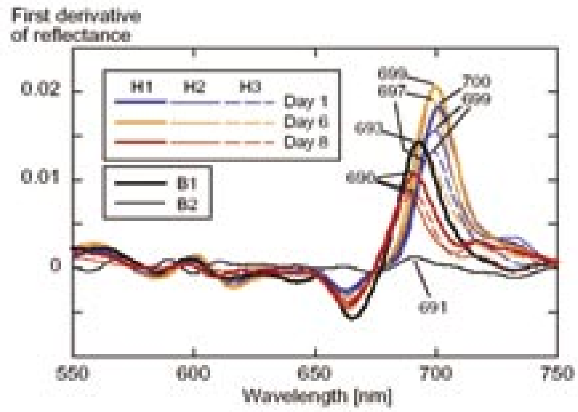


Fig. 3. First derivatives of reflectance spectra for *Montipora digitata* samples (H1 to H3) during the stress experiment and for naturally bleached *M. digitata* samples (B1 and B2). The location of the red edge is indicated.

bleaching. Analysis of scanned aerial photographs acquired during the 1998 bleaching event over the Great Barrier Reef (Australia) at various spatial resolutions, from 10 cm to 5 m showed that accuracy of mapping bleaching is highly sensitive to spatial resolution. Highest accuracy was obtained at 10 cm resolution for detection of totally bleached colonies. At 1 m resolution, as much as 50% of the 10-cm resolution signal is lost, though the spatial patterns remain correctly described (Andréfouët *et al.* 2002). Partially bleached (pale) corals are difficult to detect even in aerial surveys, leading to an underestimation of overall bleaching levels (total and partial bleaching) in aerial photos compared to *in-situ* surveys. If data volume and processing time are limiting factors, local variance analysis suggests that the optimal resolution necessary to capture spatial patterns of bleaching is in the range 40-80 cm.

4 Detection of coral morphological features

It is widely known that key remote sensing factors such as direction of the sun, reflection, refraction, scattering and shading control the angular distribution of light in coral. The quality of the optical spectrum that reaches the bottom of shallow waters is influenced by the sequential layers of enveloping atmosphere, the water column starting from the water surface state and along depth (Fig. 4). These influences repeatedly alter light as it exits upward from the bottom and subsequently detected by the sensor. Various forms of the radiative transfer model are used to quantitatively describe the effects of the optically-active constituents present on these layers to the sun radiance as it enters the environment and its eventual capture by remote sensors. As explained in the previous section, spectral mixture models provide a way to quantify proportion of different benthic cover within a pixel.

The remaining gap thus lies in the morphological aspect of coral reflectance modeling. Previous mapping attempts for example, do not consider them as volume-occupying and bulk-filled entities as they are in reality. Therefore, the actual quantitative aspects governing the spectral response changes at different observation angles and various coral structural attributes must be clarified since morphologic variations within coral assemblage further results in unequal distribution of light within the canopy. The dependence of light intercepted by coral with viewing geometry and morphology forms the basis for defining the bidirectional reflectance distribution function (BRDF) for corals. While previous studies have identified various factors contributory to bidirectionally-reflecting nature of corals (Joyce and Phinn 2002), Paringit and Nadaoka (2002b,c,d) proceeded to develop a directional reflectance model specific for analyzing coral reef areas, which may be called also "3-D coral canopy model" or "coral BRDF model", emphasizing the importance of shape, form and shadowing of coral canopies as main factors in influencing their appearance in images or real scenes.

Here, coral "canopies" are treated as an assemblage of three-dimensional objects that vary with certain coral component characteristics. To explain the radiance distribution within the coral, a mathematical description for the structure of the coral was devised as a function as total area occupied by branches or facets per area of substrate called the facet area index (FAI). The branch number density and the height, of a single branch of coral, determine FAI. Utilizing this concept of FAI, which is analogous to the notion of leaf area distribution (LAI) in terrestrial vegetation, the reflectance directly from the top of the coral can be computed. We may also generalize the geometry of the coral-covered heap as a turbid medium of an inclined area with a specific volume density and vertical canopy thickness or height to be incorporated in our model simply by the FAI.

The objective of remote sensing analysis is to relate the set of reflectance measurements represented either as *in-situ* spectra or in arrayed image form tiled according to spectral bandwidth, with that of the independent parameters (Paringit and Nadaoka 2002c). It is the exact opposite of

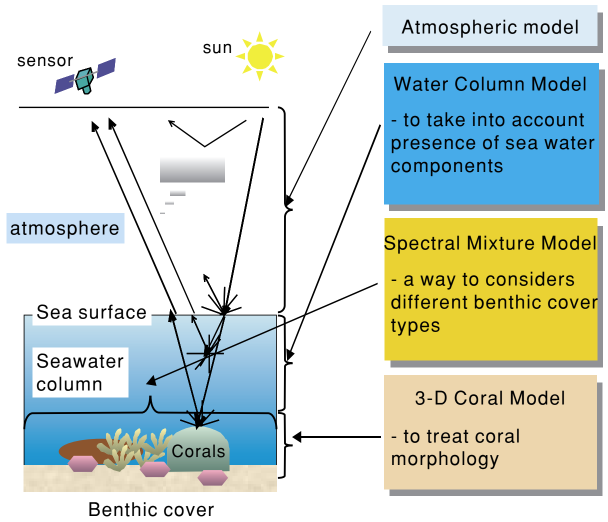


Fig. 4. Coupling of atmospheric, water column, cover and morphology reflectance models.

doing the reflectance modeling and thus called the inverse problem. The inverse problem seeks to test the reflectance, computed based on a set of input geometric and optical parameters by the coral reflectance model against a set of measured coral multidirectional, multiview reflectance values by means of a merit function. The inversion process estimates the inherent optical property (IOP) of the coral components (branches), its structural configuration, the qualitative condition of the seawater at a certain observation time. Since the forward problem cannot be inverted directly, an iterative error minimization scheme is employed instead. The difference between the estimated spectral curve and measured (e.g., from the image) is minimized by adjusting the model values in a predictor-corrector scheme. When the difference reaches a minimum, or the set of variables is optimized, absorption coefficients and bottom depths along with other properties are derived simultaneously.

Use of the inverted coral BRDF model for a transect in 4-band Ikonos image, now masked to contain the coral cover only, resulted in the computed FAI shown on Fig. 5 (b). Maximum FAI values reached up to 3.4 m2/m2 while a minimum was fixed at 1. No exact protocols exist to verify these results. To make reasonable comparisons, we utilize the coral coverage survey from Kayanne *et al.* (2002), which shows the distribution of coral species namely *Heliopora, Porites* (massive), *Porites* (branching), *Montipora* (branching), *Acropora* (branching) and *Pavona* along five (1 km approximate) transects in the Shiraho Reef. Some extrapolations based on the computed morphological characteristics of the corals (e.g., branching or not, if branching, how dense?) are then made in relation to coral

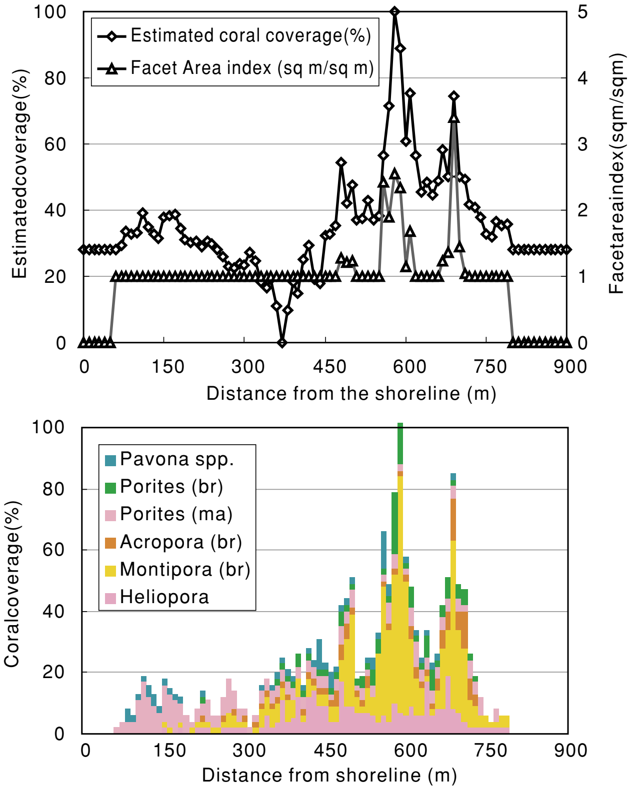


Fig. 5. (a) Coral coverage and facet area index calculations based on the coral layer model applied to Ikonos March 2001 image and (b) coral cover data from field survey in 2001. Note the striking similarities between estimated and actual coverage.

type distribution. To demonstrate, Fig. 5 (b) plots show the actual coverage. It shows a reasonable agreement between presence of coral and FAI, by correctly assigning a value of 1. Furthermore, when branching corals are present (e.g., *Montipora* and *Heliopora*), peaks in FAI occur along the transect. Maximum computed FAI also occurred in a point along the transect where full coral coverage was found. On the other hand, the tendency to underestimate is also apparent. This may be due to the initial threshold step where aerial mixture of substrate (e.g., sand) and coral could result in lower FAIs.

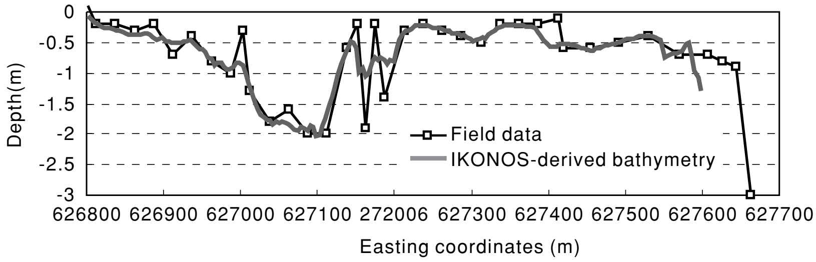
5 Bathymetry Mapping

Earlier studies of passive remote sensing in shallow-water indicate empirical regression as the most common method of extracting bathymetry. This approach provides rapid data processing, but it requires knowledge of a few true depths for the regression parameters to be determined, and it cannot reveal in-water constituents. Bathymetric mapping by remote sensing techniques is possible only down to 25 m in the clearest natural waters due to natural absorption, and the ability to estimate depth remotely deteriorates considerably less in turbid waters. Traditionally, existing methods (Lyzenga 1978; Benny and Dawson 1983; Jupp 1988) are heavily reliant on the diffuse attenuation coefficient of the water column, supposing that water quality does not vary within the area covered by the image, and makes the unrealistic assumption that bottom albedo is constant and exhibits a Lambertian reflectance. Prevailing practices suggest measurements at different depths and creation of a log-liner regression line against the satellite data values (DNs, reflectance or radiance) where the gradient equals the site-specific attenuation coefficient. An examination of the depths versus DN plots for the first 3 bands of Landsat in the Shiraho Reef, however, suggests that the negative exponential relationship is not quite obvious. Therefore, a more sophisticated technique must be developed to derive bathymetry from optical satellite imagery. This is where the coral reflectance model (Paringit and Nadaoka 2002b, c, d) may again come into promising use.

The process of estimating depth starts by modeling remote-sensing reflectance spectrum by plugging in set of values of absorption, backscattering, bottom albedo, and bottom depth. Then the estimated reflectance spectrum is compared with the spectrum from measurements until the error is minimized or a convergence is reached. This time however, the depth parameter, z is included as one of the unknowns to be estimated. Instead of relying on the diffuse attenuation coefficients based on depth measurements, the proposed method computes attenuation based on absorption, and backscattering coefficients as light passes in and out of the water column. These coefficients can be computed from previous bio-optical model that require concentrations of various optically-active constituents and sea surface state.

A constrained linear mixture model was first employed to determine relative proportion of different benthic cover types. The resulting seabed fractional map served as a basis for assigning proper substrate albedo for each pixel in bathymetry extraction for all methods examined. Note that unlike three previous methods, the albedo value of coral-laden regions for each satellite band examined through the present model undergoes further re-computation by the BRDF model iteratively to achieve underwater top-of-the-coral reflectance until such time that the error tolerance for the inversion is achieved.

Figure 6 shows the results of depth estimation in the case of Ikonos image estimated for portions along two of the five permanent transect lines (Kayanne *et al.* 2002) using the



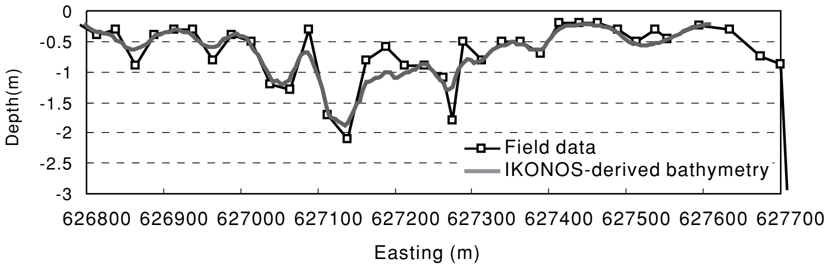


Fig. 6. Comparison of depth estimates derived from Ikonos data processing using the inverted layer model with field bathymetry data along CL permanent transect lines in Shiraho Reef (RMS=0.24). Surveyed depth data is from Kayanne *et al.* (2002).

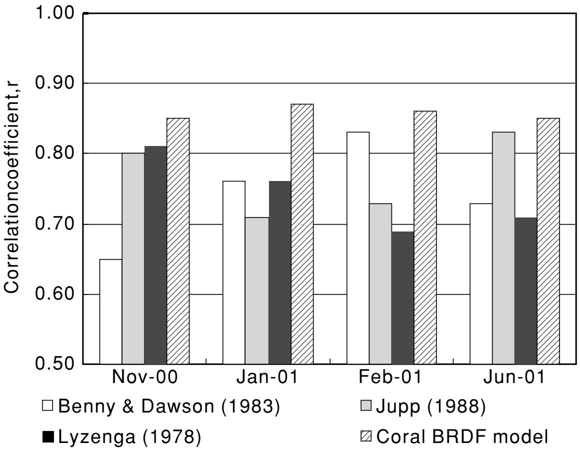


Fig. 7. Comparison of bathymetry mapping algorithms.

proposed model by (Paringit and Nadaoka 2002c; Paringit 2003). With the four meter resolution of multispectral Ikonos, a remarkable improvement in the topographic detail is seen. This quality even exceeds those yielded by sounding devices aboard survey vessels which can sample at slower rate relative to boat speed.

Another positive feature of the method is found in the consistency of its results. For example, although the satellite passes over a certain area in the earth's surface about the same time during the day (10:00 AM JST as in the case of Ishigaki), tidal variations would influence reflectance and alter depth estimates (Fig. 7). The different bathymetry mapping methods as mentioned above, including that of the present model (coral BRDF model) were applied to Landsat ETM+ images acquired in four different dates (November 2000, January 2001, February 2001, June 2001). All of the images were corrected for tidal fluctuations and were referred to a common vertical datum. Obviously, as shown in Fig. 7, the proposed model indicated as "coral BRDF model" gives the highest performance in the bathymetry mapping, regardless of the difference in the time of the image data acquisition.

With the high-resolution bathymetry data for Shiraho reef area and its surroundings obtained by applying the method described above to Ikonos imagery, Tamura *et al.* (2003) succeeded in numerically simulating currents and other hydrodynamic quantities in excellent agreements with field data.

6 Sedimentation mapping applications

The problem of sedimentation is a serious threat to the coral reefs in Japan. Fringing coral reefs suffer from substantial sediment inflows of red silt, called *akatsuchi* discharged from rivers due to intensive agricultural and infrastructure activities prevalent in inland areas surrounded by the reefs. A powerful and relatively simple method to assess seabed conditions is to come up with an index to quantify the levels of sedimentation (Nadaoka and Tamura 1992; Nadaoka *et al.* 1998) by applying an optical theory. The premise is that the differences in the degree of the sediment deposition at the seabed may affect the characteristics of the light reflectivity at the sea bottom. Nadaoka and Tamura (1992, 1993) derived an index, which may be called "sedimentation index *SI* ", and would be sensitive to the seabed reflectivity, without appreciable dependence on the water depth.

Figure 8 shows the results of the *SI* analysis, which gives good agreement with the field survey data. Results of the analysis show that among related factors such as precipitation, land slope and vegetation, red-silt outflow and its deposition in the reef area are most influenced by vegetation cover.

Paringit and Nadaoka (2003c, 2004) proposed another approach to detect red silt sediments in sea bottom surface by use of the spectral mixture algorithm, in which the red

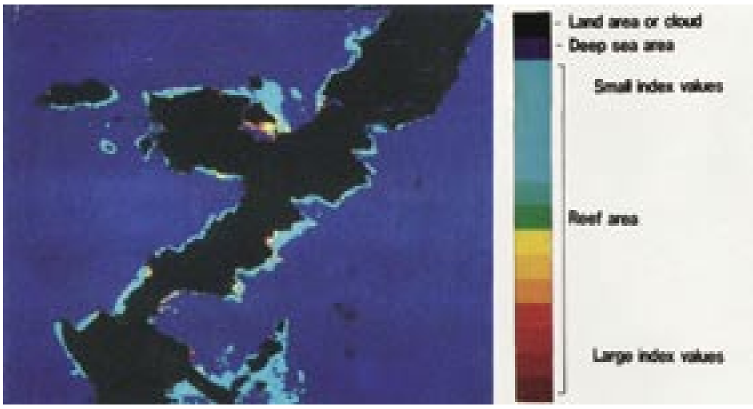


Fig. 8. Classification of the sea-bottom conditions based on the sedimentation index *SI*.

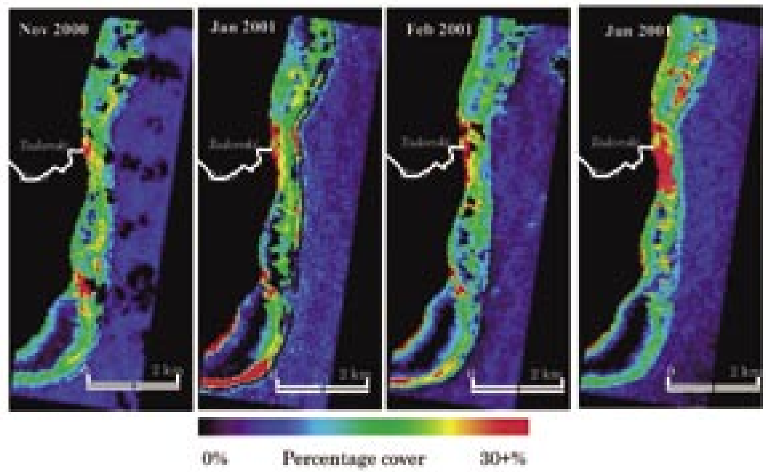


Fig. 9. Satellite-derived sediment deposition distribution map based on mixture analysis (Paringit and Nadaoka 2003c).

silt sedimentation at the bottom surface is estimated as a spatial fraction covered with the red-silt in a pixel together with all other benthic cover element fractions. The method assumes that the composite reflectance of every element in an image can be deconvolved into its components, in terms of cover, usually by assuming a linear model for the occurring spectrally mixed signal. In shallow benthic environments, spectral mixing is considered to occur either by 1) proportional mixing which occur when spectra from contiguous benthic cover combine according to their relative size or area (e.g., when corals and sand occupy the sea bed) or by 2) fusion-type mixing which happens when materials that have different composition blend with one another, the resultant product of which renders the components indistinguishable (e.g., suspended particles and chlorophyll-*a* mixed with seawater). Linear mixing assumes that there is no significant amount of multiple scattering between the different surface covering entities, i.e., every photon reaching the sensor, has interacted with only one surface covering entity.

The sequence of processed images (Fig. 9) reveals abrupt spread in high sediment coverage southward from the Todoroki River after May 31 rainfall event. Over-estimation of sediment coverage occurring on the reef crest found on southern portion in the Jan 2001 map maybe attributed to reduced organic activity in winter season. Concurrent with lower tide conditions which exposed the carbonate materials in the reef pavement surfaces, caused this portion to be confused as sediment deposits. It is noted that this does not occur on the results from other images since tide conditions were relatively higher than that of the November 2000 image.

The spread in sedimentation south of Todoroki River was well-attributed to the meteorological conditions at the time of the sediment discharge in the river mouth. As opposed to the prevalent northerly direction, wind was headed in southerly direction just after the storm event deflecting the sediment-laden river plume from Todoroki River to flow southwards (Nadaoka and Paringit 2002). The outline of the derivation procedure of the sedimentation index *SI* in English is given in Nadaoka *et al.* (1998).

7 Change detection techniques and long-term monitoring

Change detection by an analysis of multitemporal aerial photographs and satellite data have also been conducted. Using Landsat TM data and aerial photographs, Hasegawa (1993, 1998, 2001) and Matsunaga and Kayanne (1997) visually detected changes in seagrass and coral patches at Shiraho and Kabira reefs in Ishigaki Island, respectively. By analyzing aerial photographs taken from 1973 to 1994 and relating to meteorological data, Yamano *et al.* (2000) suggested the changes in coral patch distribution in Kabira Reef (Fig. 10) was due to frequency of typhoon occurrences.

A straightforward comparison between satellite images acquired on different dates is however not reliable since image signals are strongly influenced by tide level at the time of acquisition (e.g., 10:15 ± 10 AM for Landsat) and the magnitude of solar radiation. Variabilities in recorded radiance arising from these factors affect application conventional classification algorithms to multidate satellite images resulting in misclassification. Based on a similar approach to derive the sedimentation index *SI* by Nadaoka and Tamura (1992, 1993), Matsunaga *et al.* (1997) developed a Bottom Index *BI* algorithm based on Lyzenga (1978) to minimize the water depth effect on satellite data. *BI* is a modified reflectance ratio between two bands in satellite data and corresponds to the proportion of benthic community cover in a pixel. *BI* can be computed as the log ratio between two band minus the reflectance at a nearby deep area. The *BI* algorithm was applied to Landsat TM data of Ishigaki coral reefs, Japan acquired from 1984 to 1996 and tested as a method to separate sand and coral/algae/seagrass habitat. The extinction coefficient ratio between two TM bands that is necessary for *BI* algorithm was basically constant there. Temporal variations of the sea floor cover type in Ishigaki from 1984 to 1996 were produced by *BI* maps (Matsunaga *et al.* 2000; Fig. 11). Sea truth survey was conducted in August 2000 to validate the *BI* maps. Matsunaga *et al.* (2001c, 2001d) further tested the adeptness of the *BI* algorithm by combining Landsat TM and data generated from by ASTER VNIR (Visible and Near Infrared) sensor and yielded a 12% precision classification accuracy. The depth limits of both ASTER VNIR and Landsat TM images were investigated using radiative transfer models. The results show that the depth limits depend on variable solar conditions at the time of observation and on the type of sea bottom. Application of the *BI* on the combined ASTER VNIR and Landsat ETM+ result in a more detailed distribution of sea bottom in the shallow waters that becomes more uncertain towards deeper waters.

Significant bleaching event, probably due to anomalously high Sea surface temperature (SST), was occurred in the summer of 1998. Attempt to detect bleaching corals was made by Yamano and Tamura (2004) as described before. Using a radiative transfer simulation and an analysis of multitemporal Landsat TM images, they showed that Landsat

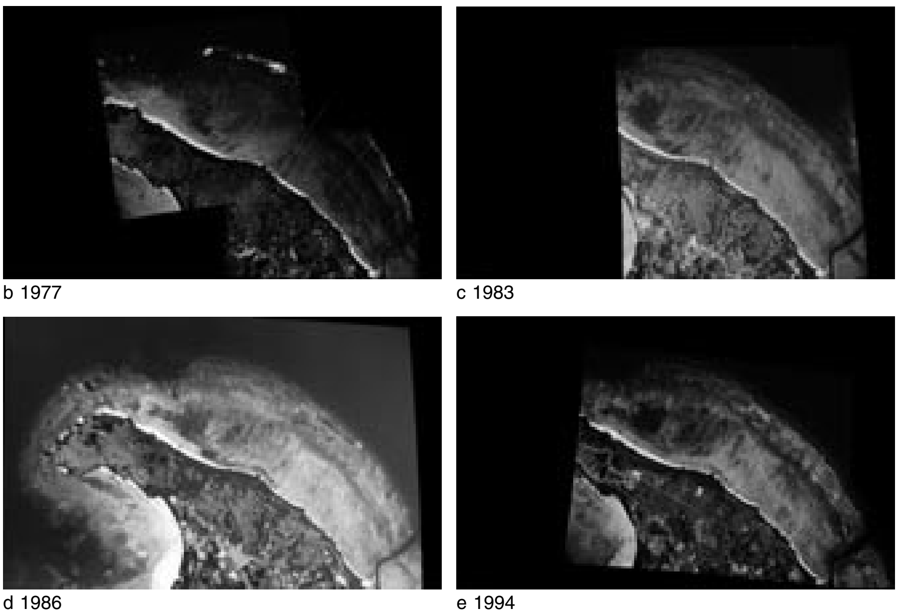


Fig. 10. Change in coral reef patch distribution as revealed by historical aerial photographs (Yamano *et al.* 2000). (Kabira Reef, Ishigaki Island).

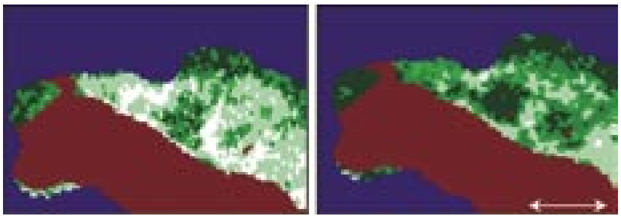


Fig. 11. Change in coral reefs as revealed by Landsat TM. (Kabira Reef, Ishigaki Island). Provided courtesy of Dr. Matsunaga.

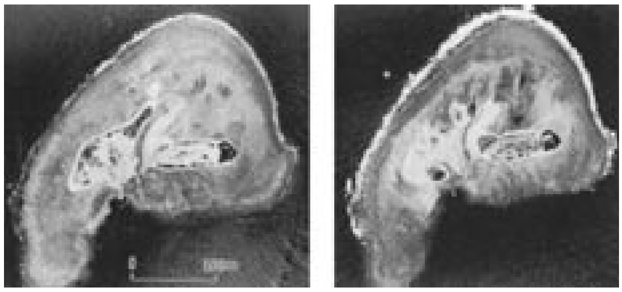


Fig. 12. Change in coral sand cays as revealed by historical aerial photographs (left: 1970, right: 1984, Chiibishi, Okinawa).

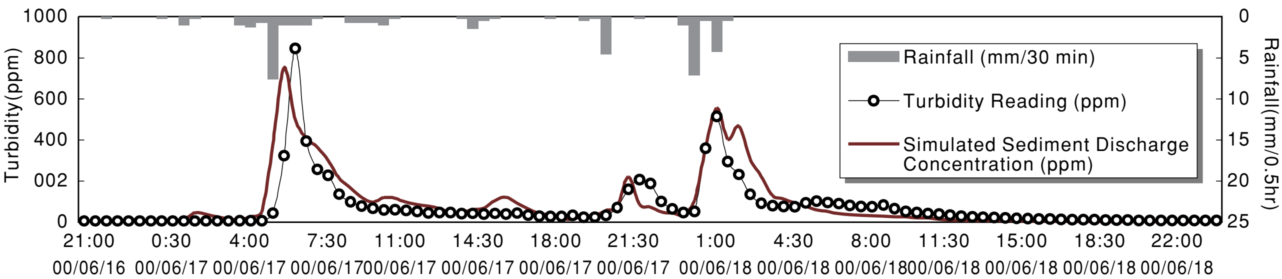


Fig. 13. A comparison of the simulated and measured sediment discharges watershed for a rainfall events in the Todoroki River, Ishigaki Island.

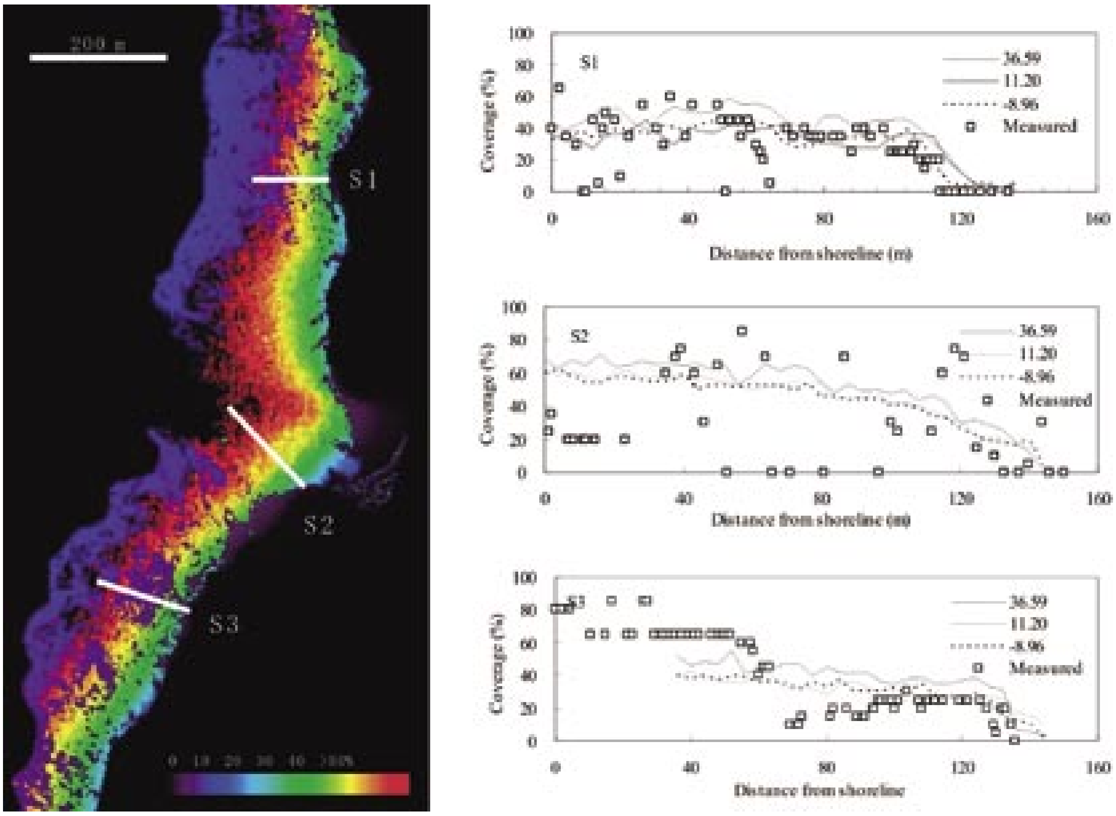
TM could detect bleaching if at least 23 % of the coral surface in a pixel has been bleached at Ishigaki Island. They also succeeded in detecting sites where 25 to 55% of coral coverage was bleached by analyzing Landsat TM data obtained from 1984 to 2000.

In addition to monitoring changes in coral reef benthic organisms, changes in reef-associated topography were detected by analyzing historical aerial photographs. Hasegawa (1990a, b) showed the changes in sand cays in Kume Island and near Okinawa Main Island (Fig. 12). The changes in the cay of Kume Island were attributed to typhoons.

8 Monitoring adjacent land area

Reefs around the Ryukyu Islands suffer from extensive sedimentation. In Ishigaki Island, e.g., the red-soil-dominated watersheds contribute substantial sediment discharge to fringing coral reefs. This is caused mainly by intense agricultural activity in the inland area. Surface soil removed by tillage are carried by surface runoff contributing to severe soil erosion. There have been efforts to examine this relationship between coral reef degradation and remote sensing. For example, Miller and Cruise (1995) describes a study wherein remote sensing technology is integrated with a hydrologic model to analyze possible linkages between land processes and coral reef growth rates in an area on the west coast of Puerto Rico. However, assessment of erosion levels utilize the USLE (Universal Soil Loss Equation) technique. A drawback of this method is that it is highly empirical and would need extensive field surveys to parameterize properly.

Paringit and Nadaoka (2001, 2003a) demonstrated the application of remote sensing techniques in the retrieval of vegetation and soil parameters from combined aerial photography and Landsat TM data to implement a distributed soil-loss modeling in small agricultural catchments. Using numerical solutions of overland flow simulations and sediment continuity equations, an analysis of the variation in erosional patterns and sediment distribution during rainfall events was performed. To account for the spatial as well as temporal variability of selected parameters of the soil-loss equations, they proposed use of Leaf Area Index and land cover component to account for the variability of associated vegetation cover based on their spectral characteristics as captured by remotely sensed data. To allow for complete spatial integration, modeling the movement of sediment is accomplished under a loose-coupled GIS (Geographical Information Systems) computational framework. With the model indicating general agreement with field data for sediment concentration (Fig. 13), this study lends an important theoretical support and empirical evidence to the role of vegetation as a potential agent for soil erosion control.



(a) (b)

Fig. 14. (a) Estimates of seagrass coverage showing distribution, and (b) modeled versus measured seagrass canopy coverage.

9 Seagrass mapping

A method (Paringit and Nadaoka 2003b) to process high-resolution multispectral satellite data for seagrass mapping has been implemented based on an inversion of a bidirectional reflectance distribution function (BRDF) developed particularly for seagrass beds (Paringit *et al.* 2003). The BRDF simulates radiative transfer from seagrass canopies approximated by assuming certain principles of geometric-optics and photon transport. Reflectance from seagrass canopies are considered to be linear mixtures of leaves and background signatures, which are moreover influenced by parameters of such as seagrass leaf architecture and transmittance, seawater column inherent optical properties and substrate reflectance. To validate results of model estimates, transect line surveys along seagrass meadows were conducted to obtain actual seagrass percentage cover, species distribution, shoot density and abundance. Likewise, spectral profiles of the bottom cover, together with pigmentation and turbidity through the water column were obtained by field underwater spectrometer and *in-situ* instruments. High-resolution satellite (Ikonos) data taken at multiple angles were processed according to the inversion model protocol. Results from model simulations show reasonable agreement between values of modeled and observed spectral reflectance from *in-situ* and space sensors (Fig. 14). Comparison of modeled versus *in-situ* reflectance data reveals that a relatively parsimonious set of variables is enough to assess seagrass biophysical properties with reasonable accuracy.

10 Sea surface temperature applications

Data products from processed satellite-based imagery are finding complimentary roles in coral reef applications. For example, sea surface temperature (SST) product derived from the NOAA AVHRR (National Oceanic and Atmospheric Administration Very High Resolution Radiometer) was used to determine the extent of decrease in water temperature after the onset of a typhoon in relation to the hydrodynamic and thermal environments of a fringing reef (Nadaoka *et al.* 2001a). They found that the decrease in SST before and after a typhoon event, measured seven days apart, is almost identical to the value observed at one measurement station

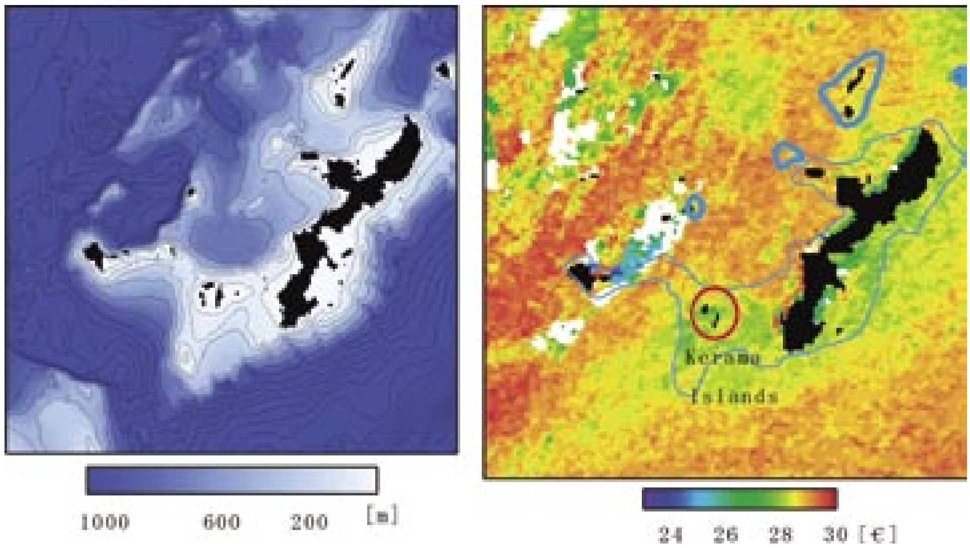


Fig. 15. Left: bathymetry of the Okinawa Islands showing prominence of the shallow shelf region around the island. Right: A NOAA/SST plot taken June 24, 1999 depicting relatively lower temperature on the shelf area.

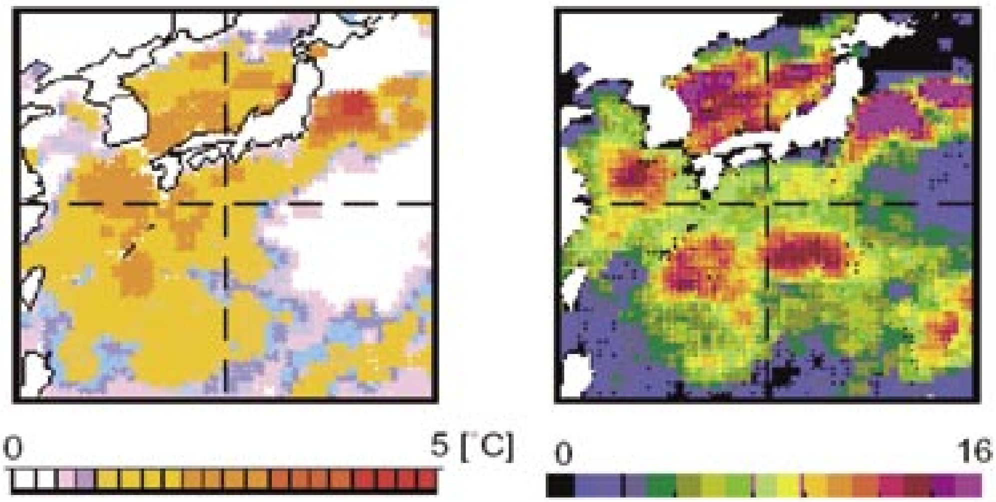


Fig. 16. Chart of composite indices of bleaching related thermal stress around the Ryukyus Islands in the summer of 2001. Hot Spots (left) and Degree Heating Weeks (right). Provided through the courtesy of U.S. NOAA Coral Reef Watch Program.

just outside the reef and gave clues to vertical mixing process in the surface layer.

In another study, NOAA-SST and SeaWiFS data, in aid to numerical modeling techniques, were used to clarify the relationship between the regional variability of water temperatures and spatial non-uniform appearance of coral mass bleaching and consequent mortality (Nadaoka *et al.* 2001b) around the Okinawa mainland and adjacent islands. A series of SST/NOAA images revealed that portions of the image with lower SST nearly coincide with the shelf region west of the Okinawa mainland where the Kerama Islands are located (Fig. 15). From the result of the numerical experiment and others, they suggested that this presence of shelf around the Kerama Island caused relatively cool water in the area by blocking incoming warm water from the Kurushio current.

As described above, since the 1980s, SST has been monitored globally by NOAA AVHRR, and has served as an early warning tool for bleaching (Strong *et al.* 1997). In addition to 1998, bleaching occurred in the summer of 2001 around the Ryukyu Islands, though the damage was small relative to that of 1998. As with that of 1998, the bleaching in 2001 was attributed to anomalously high SST indicated by Strong *et al.* (2002) who showed anomalously high SST around the Ryukyu Islands by analyzing *in-situ* temperature and NOAA AVHRR data (Fig. 16).

Fig. 17. Aerial photograph of coral slicks near Tokashiki Island in the Kerama Islands (Nadaoka *et al*. 2002a).

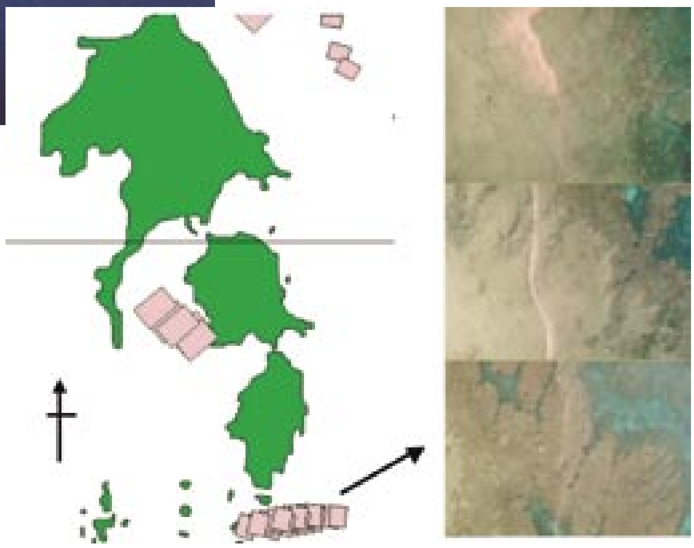


Fig. 18. Modsic photo of coral slicks (Nadaoka *et al*. 2002a).

In addition to SST, significant wave heights in oceans have been monitored by the TOPEX/POSEIDON satellite altimeter (Fu *et al*. 1994), and relationship between coral reef development and significant wave heights was examined (Yamano *et al*. 2003c). Flow line patterns in a backreef moat were extracted from aerial photographs based on an arrangement of coral patches (Yoshida *et al*. 2004).

11 Other remote sensing applications

For purposes of defining conservation measures, the environmental aspects of coral reproduction have attracted significant attention. A notable effort along this query is how remotely-sensed data can be used in tracking coral larvae dispersal (Nadaoka, *et al*. 2002a, b). Oblique and nadir-looking photographs taken with small-format aerial cameras on low-altitude airplanes captured the linear-like patterns of coral larvae slicks in Kerama Islands during the period of mass spawning in summer of 2001(Fig. 17). By co-locating the photographs using the GPS onboard the plane, exact location of the slicks were determined (Fig. 18). Relating slick occurrences with other environmental parameters such as current and meteorological conditions, improved the understanding of larvae distribution over large areas.

Novel forms of remote sensing have also been explored to determine features coral larval transport. Small drifting devices (0.3 m in diameter) installed with a custom-made GPS and mobile phone were deployed in areas where slicks were initially found. Calling up the drifters telephone numbers results in answering back their geographic positions. This provides a low-cost system, as compared with a satellite communication system, to locate the current drifter s position and to enable the retrieval of the drifters. GPS log data gives the detail of drifters routes (Fig. 19). Simultaneous with the investigation of larval transport with GPS drifters, Nadaoka *et al*. (2002b) attempted to monitor broad-scale distribution sea surface flow velocity by use of an HF ocean radar system. Figure 20 shows an example of HF radar data. It can be seen that although the flow in the Kerama region varies and corresponds to the trajec-

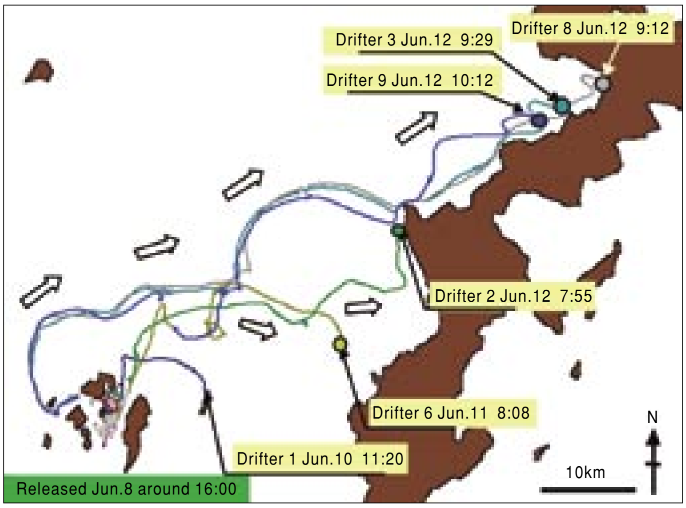


Fig. 19. Trajectories of drifters released in the Kerama Islands (Nadaoka *et al.* 2002b).

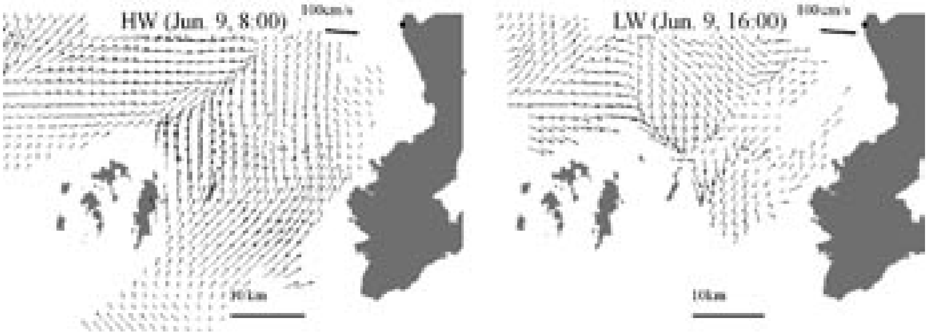


Fig. 20. Examples of sea surface flow observed by an HF ocean radar system.

tory of the above-mentioned drifters, it turns out that it actually drifts east or in generally, northeast. The effect of topographic feature has been a crucial factor. The presence of the continental shelf southwest of the Okinawa main island causes this eastward flow, suggested by the result of numerical simulation analysis performed by Nadaoka and others (Suzuki *et al.* 2004). Concurrent with these field surveys, indoor experiments were conducted to observe the crawling rate of coral larvae, which was found to show its peak around four days after spawning and fertilization. The trajectory plots shows not only that a sea surface particle may be conveyed to the Okinawa main island west coast region from the islands, but also that a living thing such as a coral larvae may be transported from Kerama Islands in four days to the main island. The latter is consistent in the period with that for coral larvae to show the peak crawling rate. These results prove that the Kerama Islands act as a source area of coral larvae for coral reefs of the west coasts in Okinawa main island and give a scientific basis for protecting the coastal region of the Kerama Islands as a preservation zone.

12 Concluding remarks

As described in the previous sections, remote sensing has a great potential to contribute to coral reef science and management. Despite the advances that have been made with regards to remote-sensing analysis methods and the accessibility of imagery data notwithstanding, the scientific community at large may still hesitate ot use remote sensing. This is supported by the fact that at present, there are only a handful of specialists which directly utilize processed remote sensing datasets to support their scientific findings from data gathered by other means. Besides, some sectors still prefer to do traditional field surveys over image processing to obtain coral or benthic cover. The remote sensing community should exert effort to reach out to the management sector by explaining the practical benefits as well as laying down proper guidelines and reasonable expectations in use of the technology.