Chapter 6
Remote Sensing of the Marine Environment: Challenges and Opportunities in the Galapagos Islands of Ecuador

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Abstract Analysis of marine and coastal systems is of fundamental importance to environmental scientists, engineers, and managers. Since the 1960s, remote sensing has played an important role in characterizing the marine environment, with particular emphasis on sea surface features, temperature, and salinity; mapping of shorelines, wetlands, and coral reefs; local fisheries and species movements; tracking hurricanes, earthquakes, and coastal flooding; and changes in coastal upwelling and marine productivity. This chapter reviews marine applications of remote sensing worldwide, exploring contemporary satellite systems, research themes, and analytical methods. In the Galapagos Islands of Ecuador, marine remote sensing has been limited to the use of large-scale daily image-gathering systems, such as CZCS, MODIS, SeaWiFS, and AVHRR, due to persistent cloud cover and constrained research budgets. Recent advances in satellite technology and availability, however, offer new opportunities for remote sensing in the Galapagos archipelago and beyond. Moderate-resolution sensors like SPOT and Landsat continue to be relevant for regional-scale evaluations of marine and coastal environments, identifying hotspots or focal areas for the use of more fine-grained imagery like QuickBird, WorldView-2, and aerial photographs. Radar systems like Aquarius and SAR show promise in new lines of oceanographic research, including sea surface salinity and the differentiation of mangrove subspecies. The use of ancillary or in situ data for calibration and validation of remotely-sensed image analysis can overcome the limitations of sensors used in bathymetric applications, while advances in cellular and GPS technology facilitate real-time

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reporting from citizen scientists for integrated monitoring of environmental and social change.

Introduction

Marine remote sensing is a broad field of study with a rich and expanding agenda. Applications include marine ecosystem characterizations, habitat mapping, and assessment of marine biodiversity, natural hazards management, oceanographic conditions, and cross-scale process models of seasonal and annual ocean circulation patterns. A diversity of satellite-based, remote sensing assets is available to generate views of ocean conditions around the globe. Remote observations and measurements of coastal margins, shallow seas, and deep oceans are generated at local, regional, and global scales and for historical and contemporary periods. Corrected spectral information and derived data products offer users considerable options to customize the selection and fusion of satellite remote sensing systems according to desired space-time scales. While historically the challenge was to match research questions to limited availability and iteratively negotiate the questions, data needs, and system availabilities, the challenge now is to select the most appropriate remote sensing systems that provide the optimum combination of spatial, temporal, spectral, and radiometric resolutions to address the defined problem. With these four resolutions, satellite remote sensing systems and associated data types can generate a more nuanced, scaled perspective of marine and coastal environments.

Some early optical systems have been the mainstay of marine, as well as terrestrial remote sensing, buoyed by their broad area reconnaissance capacities, spectral sensitivities, and spatial resolutions. Examples include the Coastal Zone Color Scanner (CZCS) that operated in the visible, near-infrared, and thermal infrared channels; and NOAA's Advanced Very High Resolution Radiometer (AVHRR) that extends the visible and infrared spectral regions into thermal infrared wavelengths of twice-daily imagery, used to assess sea surface temperature on a regional-global scale.

More contemporary systems have a broader range of applications for mapping and monitoring marine environments at a variety of resolutions: the Moderate-Resolution Imaging Spectrometer (MODIS) captures daily images around the globe for assessing ocean color in visible and near-infrared spectral regions at a 1,000 m spatial resolution. Hyperion and the Advanced Land Imager (ALI) have a 30 m spatial resolution and an extensive spectral range, finely sliced into over 200 spectral channels. WorldView-2 is a relatively new system for land and water remote sensing, with very high spatial resolution. TOPEX/Poseidon and Aquarius are altimeters and microwave radiometers, used for characterizing oceanographic parameters, such as sea surface height and salinity. These active systems emit pulses of energy that interact with earth surface features, whereas passive systems simply measure the spectral reflectivity of solar energy. Spectral regions are often associated with key surface properties, strongly influencing response patterns. For instance, the recently launched Landsat 8 is sensitive to plant pigmentation in the visible wavelengths, chlorophyll-a (Chl-a) in the near-infrared wavelengths, and moisture content in the middle-infrared wavelengths. WorldView-2 includes a spectral channel for characterizing bathymetry of marine environments, particularly the nearshore.

In short, marine remote sensing addresses a diverse range of oceanographic parameters, ecosystem conditions, and surface and near-surface features. Challenges imposed by ocean dynamics, the extensive geographic scale of marine settings, and the complex interactions of local, regional, and global processes continue to motivate new applications in marine remote sensing. This chapter is concerned with the following: (1) commonly used derived data products, research themes, and analytical techniques in marine remote sensing; (2) early and contemporary applications of marine remote sensing in the Galapagos Islands of Ecuador; and (3) ancillary data, especially bathymetric measures and local knowledge, and future opportunities for marine remote sensing in Galapagos and beyond, emphasizing data fusion and linking across terrestrial, marine, economic, and social systems.

Key Variables in Marine Remote Sensing

Some of the methodologies used in remote sensing of the marine environment are similar to those applied in terrestrial remote sensing (e.g., classification). However, many studies that utilize marine remote sensing resources rely on a set of variables that have specific application to marine environments. Robinson (2004) notes five primary observable quantities of the ocean environment, discussed below.

Sea Surface Temperature

Sea surface temperature (SST) is the water temperature near the surface of the ocean and plays a critical role in the transfer of heat between the atmosphere and the oceans (Maurer 2002; Emery 2003). It is also tied to atmospheric and ocean circulation patterns, making it an important parameter in global climate models. Since the late 1960s, scientists have used satellite data for deriving regional or global SST measurements. Today there are several active satellites that have the ability to measure SST across a variety of spatial scales and resolutions, using both thermal infrared channels and passive microwave radiometry. Government sources often provide websites for searching and downloading raw and processed satellite data, while other organizations, such as the Group for High-Resolution Sea Surface Temperature (GHRSST), provide fused or value-added SST products. Data fusion is becoming popular as researchers attempt to leverage the benefits of each type of

SST sensor and diminish their weaknesses (Maurer 2002). These products are central to an understanding of oceanographic topics, such as the effects of upwelling on SST (Askari 2001), the relationship of SST and primary productivity (Kahru et al. 2012a), and the role that SST plays in algal blooms (Siegel and Gerth 2000).

Ocean Color and Derived Variables

Ocean color is a characteristic of seawater properties that are composed of phytoplankton, dissolved organic matter, suspended sediments, and, in certain areas, shallow seabeds (Robinson 2004). Many derived variables can be calculated from satellite-based ocean color measurements, including the concentration of Chl-a, which is a direct indicator of phytoplankton presence. Sensor-dependent empirical algorithms, such as those that require log-10 transformations of remote sensing radiance and transformed in situ measurements as inputs, are the basis for deriving Chl-a concentrations from raw images across multiple spatial and temporal scales (Kahru et al. 2012b). Such monitoring allows researchers to understand how physical processes affect biological distributions (Yoder 2000; Tang et al. 2009), such as the distribution of atmospheric aerosols, SST dynamics, inland flooding, and seasonal variances (Nezlin 2000; Siegel and Gerth 2000; Stegmann 2000).

Dissolved organic matter (DOM), like Chl-a, absorbs light in the blue part of the electromagnetic spectrum. It therefore competes with phytoplankton for light resources, and as the concentration of DOM increases, photosynthesis in the surrounding waters decreases. The presence of DOM makes it more difficult to accurately measure Chl-a concentrations via remotely sensed imagery, so much work has gone into developing algorithms that can separate out Chl-a concentrations from DOM and suspended sediments (e.g., Siswanto et al. 2011). DOM algorithms tend to be empirically based, as DOM concentration is seasonal and highly localized, most commonly found in coastal areas (Kowalczuk et al. 2005; Para et al. 2010). DOM has also been related to dissolved carbon from freshwater runoff, allowing for large-scale monitoring of this important indicator of climate change in nearshore environments (Matsuoka et al. 2012).

Suspended sediments and particulates, or total suspended matter (TSM), have similar effects as DOM in that they also inhibit light transmission and reduce phytoplankton growth. TSM is inorganic and has different spectral characteristics than Chl-a and DOM, and measuring the concentration of these elements can give researchers an indicator of water quality. TSM concentrations can be calculated with empirical, physical, or semi-analytical model algorithms, all of which require some level of in situ measurements for calibration of radiance values from passive multispectral sensors such as MODIS (Wang et al. 2012). Similar to DOM, TSM is more commonly found in coastal areas (Li et al. 2003; Binding et al. 2005; Surendran et al. 2006).

Ocean color can also play an important part in the classification of marine vegetation and seabed forms in coastal waters, as well as the creation of bathymetry layers. The reflectance of the sea bottom allows researchers to utilize similar methodologies to those in terrestrial remote sensing, where the water is shallow and transparent and contains little particulate matter (Robinson 2004). Reflectance can provide sufficient data for bathymetric mapping, typically to 20 m, although WorldView-2 imagery has shown the potential to register depths to 30 m (Tøttrup and Sørenson 2011), and various techniques have been developed for producing these maps (Philpot 1989; Stumpf et al. 2003; Haibin et al. 2008; Lyons et al. 2011).

Surface Roughness and Waves

Turbulence in the atmosphere is translated into increased wave activity, and as winds create waves, momentum and energy are transferred from the air to the ocean surface (Janssen 1996; Ly and Benilov 2003). Understanding this transfer of energy is important in properly parameterizing global climate models (Heimbach and Hasselmann 2000), and surface roughness can be directly observed using satellite imagery via both passive microwave radiometers and active microwave sensors (Robinson 2004). The magnitude of surface roughness has a direct effect on momentum transfer between the sea and the atmosphere, which itself influences other broad-scale processes such as atmospheric circulation, wave growth, and storm surges (Johnson et al. 1998; Taylor and Yelland 2001).

Wave spectra, or the combination of wave height and direction, can be derived from roughness variables. Satellite-based measurements of wave height using synthetic aperture radar (SAR) began in 1978 with the launch of Seasat (Heimbach and Hasselmann 2000). A number of current or recently decommissioned platform boast radar altimeters designed for capturing roughness and wave height, including TOPEX/Poseidon, ERS-2, Geosat-FO, Jason-1 and Jason-2, and Envisat. Data on wave heights provides critical information to industries involving shipping, oil exploration, fisheries management, and environmental protection of coastal resources.

Currents and General Circulation

Currents have a direct impact on climate, biodiversity of the oceans, and ocean-related industries. While there are many different means of understanding currents at the local scale, satellite imagery allows us to gather this data along entire coastlines and across oceans. Satellite imaging of currents is calibrated with in situ measurements of moored and floating buoys and ocean drifters. Thermal infrared sensors are one source of data on currents as they provide measurements on SST, which can define current boundaries and be tracked to determine the path and velocity of the current. Ocean color sensors can additionally allow scientists to track the movement of visible features, such as Chl-a plumes, along a current. SAR is used to identify spatiotemporal variations in oceanfronts, allowing for the creation of current tracks, and satellite altimetry has been used to derive ocean height dynamics, improving tidal charts and increasing scientific knowledge of tides and circulation variability (Garzoli and Goni 2000; Klemas 2012).

El Niño-Southern Oscillation (ENSO) events lead to altered currents, rises in sea level, increases in sea surface temperature and salinity, and changes in the thermocline. The Tropical Ocean-Global Atmosphere (TOGA) program, a component of the World Climate Research Programme that ran from 1985 to 1994, facilitated a richer understanding of ENSO events, and since then the use of remote sensing in ENSO research has gradually increased (McPhaden et al. 1998). Numerous studies link ENSO to fisheries (Carr and Broad 2000), surface circulation (Cai and He 2010), SST (Ballabrera-Poy et al. 2002), physical and biogeochemical processes (Hong et al. 2011), seasonal upwelling (Hong et al. 2009), sardine recruitment (Gomez et al. 2012), eastern Pacific leatherback turtle foraging (Saba et al. 2008), Chl-a concentration (Sasaoka et al. 2002; Yamada et al. 2004), and coral bleaching (Carriquiry et al. 2001).

Sea Surface Salinity

Sea surface salinity has strong effects on circulation in coastal zones, and it impacts energy exchange in the air-sea interface (Le Vine et al. 2000). Measurements of salinity can also be used to better understand the impacts of freshwater runoff, ice melt, and large-scale meteorological events such as hurricanes and monsoons (Lagerloef 2000). As recently as 2000, the ability to map salinity with satellite imagery was still beyond the capabilities of current technology. Some L-band microwave systems have been used over the past decade to derive measurements of salinity, though those instruments were not designed with this goal in mind (e.g., Burrage et al. 2008; Martin et al. 2012; Yueh and Chaubell 2012). Promising early results have been derived from NASA's 2011 Aquarius satellite mission, the first designed to specifically measure salinity from space (Le Vine et al. 2013).

Table 6.1 summarizes the specifications for some of the key satellite systems from the 1970s on that have been widely used in marine applications. Even for systems no longer acquiring information, historical archives remain a valuable informational asset.

Table 6.1 Summary of satellite systems, sensors, and data products commonly used in marine remote sensing

Satellite system	Sensors	Country	From	To	Sensor type	Designed for
GOES-1 to GOES-7	VISSR	USA	1975	Mid-1990s	P	SST
Meteosat (1–7)	VISSR	Europe	1977	Current	P	SST
Seasat	SMMR, Scat, SAR, RA	USA	1978	1978	A	SSH, WS, SST
TIROS-N	AVHRR	USA	1978	1981	P	SST
Nimbus-7	CZCS	USA	1978	1986	P and O	OC
NOAA (6–17)	AVHRR/2, AVHRR/3	USA	1978	Current	P	SST
Geosat	RA	USA	1985	1990	A	SSH
MOS-1A/1B	MESSR, MSR, VTIR	Japan	1987	1992	A and P	SST
ERS (1 and 2)	ATSR, ATSR-2, AMI, RA	Europe	1991	2011	A	WH, WS, OC
TOPEX/ Poseidon	POSEIDON-1, TOPEX	USA/ France	1992	2006	A	SSH
GOES-8 to GOES-15	GOES-IM Imager	USA	1995	Current	P	SST
ADEOS 1	OCTS, NSCAT	Japan	1996	1997	A and P	OC, WS
IRS-P3	MOS	India	1996	2006	P	OC
SeaStar	SeaWiFS	USA	1997	2010	P and O	OC
TRMM	TMI	USA/Japan	1997	Current	A	SST
QuikSCAT	SeaWinds	USA	1999	2009	A	WS
IRS-P4/ OceanSat-1	OCM, MSMR	India	1999	2010	A and P	OC, SST, WS
KOMPSAT-1/2	OSMI	S. Korea	1999	Current	P	OC
Aqua	MODIS, AMSR-E	USA	2000	Current	A, O, and M	SST, OC
Jason-1	Poseidon-2	USA/ France	2001	Current	A	SSH, WH, WS
ADEOS II	AMSR, GLI, SeaWinds	Japan	2002	2003	A and P	OC, WS, SST
Envisat	ASAR, AATSR, MERIS	Europe	2002	2012	A and P	SST, OC, WS
Jason-2	Poseidon-3	USA/ France	2009	Current	A	SSH
SAC-D	Aquarius	USA	2011	Current	A and P L-band	SSS

A active, *M* microwave, *O* optical, *P* passive, *OC* ocean color, *SSH* sea surface height, *SSS* sea surface salinity, *SST* sea surface temperature, *WH* wave height, *WS* wind speed

Key Themes in Marine Remote Sensing

Technologies and analytical methods for marine remote sensing have improved greatly in just the last decade, with greater abilities to detect oceanic and nearshore properties at a variety of scales. The growing number of sensors combined with advances in data telemetry and processing algorithms makes the marine application of remotely sensed data virtually limitless. The following sections describe key themes and analytical techniques in marine remote sensing that have emerged in tropical and island settings worldwide, presenting opportunities for more comprehensive and interdisciplinary research in the Galapagos.

Habitat and Migration

Ocean color and temperature remote sensing have been widely used in studies to characterize large-scale ENSO events in the tropical Pacific, employing passive optical sensors for detecting SST and Chl-a concentrations (Vialard et al. 2002; Baker et al. 2008; Lo-Yat et al. 2011; Boyce et al. 2012) and active altimeters for calculating surface winds and ocean topographic anomalies (Quilfen et al. 2000; Contreras 2002; Karnauskas et al. 2008). Some studies in the tropics linking migrating species with satellite-derived habitat variables are largely qualitative, simply overlaying track data on maps of oceanographic characteristics, without considering how physical parameters might influence migration routes (Hays et al. 2001; Lander et al. 2013). More recent maritime habitat research has applied remotely-sensed parameters to the study of tropical storm impacts and eddy formation (Dong et al. 2009; Han et al. 2012), global current systems as maritime navigation aids (Cervone 2013), coral bleaching (Baker et al. 2008; Krug et al. 2012), changes in submerged aquatic vegetation in sea grass-dominated settings using a Landsat-TM and Landsat-ETM image time series and change detection approaches (Gullstrom et al. 2006; Ferwerda et al. 2007), and the hydrologic impacts of volcanic eruptions within oceanic archipelagos (Mantas et al. 2011). Such analyses can span the full breadth of available spatial, spectral, temporal, and radiometric scales.

The availability of very fine spatial resolution imagery has also led to straightforward, nonanalytical applications in remote locations: a small number of studies have used aerial photography and QuickBird and Worldview panchromatic scenes, combined with simple visual analysis or object-based classifications to detect the presence and abundance of individuals or species colonies in glacial and aquatic environments (Barber-Meyer et al. 2007; LaRue et al. 2011; Lynch et al. 2012; Groom et al. 2011).

Fisheries

Closely linked to species migration research, fisheries science frequently applies a fusion of quantitative and qualitative data, remote sensing platforms, and analytical techniques (Mellin et al. 2009; Stuart et al. 2011). Numerous studies have linked remotely sensed variables such as sea surface height, salinity, SST, and wind speeds to the presence of pelagic species in tropical and subtropical marine environments (Maul et al. 1984; Klimley and Butler 1988; Herron et al. 1989; Zainuddin et al. 2008). Shipboard surveys, where feasible, more accurately predict species presence and abundance, but in the absence of in situ biotic information and particularly across large spatial and temporal scales, remotely sensed data have been instrumental in marine research (Murphy and Jenkins 2010; Chassot et al. 2011).

Vulnerability and Hazards

Vulnerability assessments for coastal regions apply remotely-sensed data to derive indices or generate risk scenarios based on geomorphological or biophysical parameters. Typically these studies are concerned with populated areas located along coastlines, and their vulnerability to climate change impacts (Cazenave and Llovel 2010; Rankey 2011; Scopelitis et al. 2011; AlRashidi et al. 2012) hurricanes and tsunamis (Dall'Osso et al. 2009; Eckert et al. 2012; Kumar and Kunte 2012; Romer et al. 2012), drifting contaminants such as oil spills (Helzel et al. 2011; Leifer et al. 2012), shoreline changes due to coastal sediment dynamics and ENSO events (Shaghude et al. 2003), or a set of the above factors commonly faced by island states or territories (Narayana 2011; Farhan and Lim 2012). A much smaller subset of the hazards literature focuses on man-made impacts to marine systems, such as land use change, runoff, and pollution (Nicholls et al. 2008; Ceia et al. 2010).

Hazards research draws on a wide range of resolutions within the optical sensors, finding that daily coverage satellites like MODIS, SeaWiFS, and MERIS support rapid response to disasters or susceptibility at regional scales, while fine-resolution and hyperspectral imagery prove useful in post-disaster interpretation and adaptive planning (Maina et al. 2008; Leifer et al. 2012). Trebossen et al. (2005) demonstrated that in tropical regions characterized by high cloud cover, continuous collection of radar imagery from satellites like ERS-1, ERS-2, and Envisat can provide frequent updates on shoreline evolution and response to sedimentation and erosion events.

Mangroves

Because mangroves provide shelter from tsunamis and storm events to inland ecosystems (Alongi 2002) and function as nurseries and feeding grounds for fish (Mumby et al. 2004; Nagelkerken et al. 2008), they are frequently described in the hazards and fisheries remote sensing literature (Omo-Irabor et al. 2011; Liu et al. 2013). The proximity of mangroves to human settlements and their availability as an economic resource have prompted some research to apply traditional land use/land cover change scenarios to link livelihood decisions with mangrove use and change in a sustainability framework (Walters et al. 2008; Conchedda et al. 2011). Medium resolution sensors are typically applied to mangrove monitoring at regional to large scales, including SPOT, Landsat, and SAR (Gang and Agatsiva 1992; Aschbacher et al. 1995; Green et al. 1998; Conchedda et al. 2008; Bhattarai and Giri 2011). These studies typically focus on characterizing the spatial extent of mangroves or their increase/decrease over time with respect to climate change impacts, disasters, and anthropogenic processes. Aerial photography has been utilized in mangrove research since the 1990s, particularly before the more widespread availability of high spatial resolution sensors (Chauvaud et al. 1998; Manson et al. 2001). More recently, fine- and very fine-resolution imagery like QuickBird, Worldview-2, GeoEye-1, and IKONOS has been exploited for evaluating mangrove habitat complexity at the smallest scales (Kovacs et al. 2005; Proisy et al. 2007; Heumann 2011a; Satyanarayana et al. 2011; Liu et al. 2013).

Beaches

Aside from particular ecosystems and habitats such as mangroves and coral reefs, marine management relies on having accurate habitat maps across coastal regions to identify areas for zoning and protection (Mumby et al. 1999). Shoreline monitoring via remotely sensed imagery may encompass very small areas, such as individual beaches and dunes, to entire coastlines or islands (Gould and Arnone 1997; Stockdon et al. 2002; Kelle et al. 2007; Fonseca et al. 2010). Historically, the most common shoreline detection technique was subjective visual interpretation (Boak and Turner 2005). At the very local level, Argus video imaging has been used for long-term optical shoreline observation of storm response, seasonal cycling, bathymetric surveys, and anthropogenic processes at individual sites where cameras can be located (Turner et al. 2006; Kroon et al. 2007; Holman and Stanley 2007).

Image Analysis

Classification

There is a broad literature on marine remote sensing classification, the process of categorizing distinct shoreline and seascape features through spectral response patterns. With few exceptions, optical sensors have been the predominant data source in classification studies. Analytical techniques applied to multispectral imagery in mangrove research range from supervised/unsupervised classification, object-based classification, and more sophisticated methods like support machine vectors and fuzzy classifications (Bhattarai and Giri 2011; Long and Giri 2011; Heumann 2011b). The classification of coral reefs is fairly common, with studies using a combination of medium-resolution public imagery and high-resolution commercial imagery to compare and contrast the benefits of each product (Mumby and Edwards 2002; Andréfouët et al. 2003) and hyperspectral airborne imagery to study the effects of scaling up from species-level data to community-level classifications (Andréfouët et al. 2004).

Other classification studies include automated (Steimle and Finkl 2011) and manual (Chauvaud et al. 1998) mapping of marine environments, identification of biological hot spots (Palacios et al. 2006), and habitat mapping for tracking fin whales and striped dolphins (Panigada et al. 2008). Recent work has focused on improving feature classification accuracy and process assessments at the land-water boundary, using fine-resolution sensors to compare and contrast analytical techniques (Fonseca et al. 2010; Collin and Hench 2012). As a cost-effective alternative to Light Detection and Ranging (LiDAR) data, Knudby et al. (2011) verified the utility of optical, object-based models for classifying reef benthos and geomorphology from fine-resolution satellite images. Spatially explicit modeling scenarios utilize both fine- and coarse-grained imagery, but the high costs of QuickBird, IKONOS, WorldView-2, and other sources frequently preclude analysis at the habitat level (Andréfouët et al. 2005; Hamel and Andréfouët 2010).

Indices and Derivatives

There have been few tropical marine studies in which the derivation of indices from remotely sensed imagery was a major component. The multivariate ENSO index was used along with derived net primary productivity to aid in leatherback turtle conservation management (Saba et al. 2008), while the creation of a temperature index was used to better understand the migration patterns of sei whales (Kimura et al. 2005). Improvements in tagging and geo-location technologies have facilitated rigorous statistical analyses of physical characteristics, from bootstrapping techniques (Tremblay et al. 2009), to generalized additive mixed models (Gremillet et al. 2008; Panigada et al. 2008; Peery et al. 2009; Shillinger et al. 2011), and randomization testing (Kobayashi et al. 2011). Complex two-dimensional modeling scenarios have been developed to predict marine habitat use and movement typically at large (1 km pixel resolution or more) spatial scales; while at smaller scales, contemporary research using three-dimensional models that integrate remotely sensed bathymetry and vertical temperature stratification finds that seafloor characteristics explain more variability in habitat use decisions and hot spot formation (Nur et al. 2011; Palamara et al. 2012).

Change Detection

The mapping and change detection of landforms, beach deposition, and erosion at regional scales have been widely achieved using low-cost Landsat and SPOT imagery (Siddiqui and Maajid 2004; Kelle et al. 2007). Photogrammetry and topographic data collection have provided additional opportunities for geomorphological and bathymetric shoreline analysis. For bathymetry at fine resolutions, stereo aerial photography provides a higher resolution complement to optical and LiDAR sensors (Boak and Turner 2005), where over large areas NASA's Airborne Topographic Mapper (ATM) facilitates three-dimensional shoreline characterization and change detection (Stockdon et al. 2002; Sallenger et al. 2003). Two studies used Landsat imagery to map spatial and temporal changes in sea grass distribution (Gullstrom et al. 2006; Ferwerda et al. 2007), while Shaghude et al. (2003) manually identified sediment dynamics in Zanzibar. Tang et al. (2009) used low- to moderate-resolution marine remote sensing platforms to investigate changes in Chl-a distribution and other biophysical variables following the 2005 tsunami. The temporal extent of aerial photography has also proven useful in change detection studies: Fromard et al. (2004) traced 50 years of mangrove habitat transitions using a combination of historic aerial photographs and SPOT imagery, but the spectral limitations of aerial photography preclude complex analyses of environmental characteristics.

Data Fusion

Sensor fusion has gained widespread acceptance for the study of terrestrial and marine environments by integrating data acquired from remote sensing systems of varying spatial, spectral, temporal, and radiometric resolutions. With the vast array of space-based systems, the challenge is to select the most optimum systems to characterize key features of the phenomena under consideration. Underwater topography for coastal areas was mapped through a combination of TerraSAR-X data to characterize ocean waves and QuickBird optical data to map bathymetry in shallow, coastal settings (Pleskachevsky et al. 2011). Askari (2001) developed indicators of upwelling identification caused by eddy interactions with bottom topography by fusing AVHRR, ERS-1, TOPEX/Poseidon/ERS-2, and OrbView/SeaWiFS imagery to integrate measures of SST, ocean color, sea height anomalies, and the appearance of striations that formed along the boundaries of the eddy. MODIS and SeaWiFS have also been integrated to examine changed in the pattern of Chl-a content and sea surface temperature related to the 2004 South Asian tsunami.

The vulnerability and hazards literature currently offers the most comprehensive synthesis of social, marine, and terrestrial data sources, because of the proximity of human communities to vulnerable coastal zones. Coastal inundation presents particular risk to communities, and integrated observation strategies are needed to monitor associated processes such as erosion, flooding, tidal anomalies, and changes in nearshore geomorphology by combining radar and moderate-resolution imagery with data sources on terrestrial rainfall, ocean surface winds, and cloud cover (Morris et al. 2005; Tralli et al. 2005; Brock and Purkis 2009).

Marine Remote Sensing in Galapagos

In the Galapagos Islands, with their unique geographic and geologic configurations in the tropical Pacific, the application of remote sensing in the terrestrial and marine environments has been relatively sparse. Part of the reason for this is the persistent cloud cover and masking effects on data sets acquired by optical sensors. Often, multi-temporal composites are constructed that cover a 10- to 14-day period to reduce the aerial effects of clouds over land and water. Data acquired by radar systems reduce the impact of clouds and water vapor on spectral response patterns. The fact that the Galapagos archipelago is composed of numerous small islands and rocky outcrops has also minimized the relevance of coarse-grained systems, although several islands, including the populated islands, are sufficiently sizeable for the application of data from AVHRR and MODIS.

The earliest remote sensing applications in the Galapagos archipelago began in the 1980s, with the use of the CZCS and AVHRR satellite data for evaluating oceanographic trends in primary productivity, ocean color, and SST during the severe 1982–1983 ENSO event that affected nearly every aspect of plant, animal, and marine life in the islands (Feldman et al. 1984; Legeckis 1986). Subsequent work linked longer-term, larger-scale data sets from sensors like SeaWiFS and MODIS to describe the unique and seasonal oceanographic characteristics of the Galapagos (Palacios 2002; Sweet et al. 2007) and their relationships to corals (Wellington et al. 1996), phytoplankton blooms and biological hot spot formation (Palacios et al. 2006; Pennington et al. 2006; Dasgupta et al. 2009), and ENSO events of varying severity (Leonard and McClain 1996; Wellington et al. 2001; Ryan et al. 2002; Wolff et al. 2012). Calibration of oceanographic and atmospheric models has been facilitated by the use of satellite data records and augmented by in situ data collected within the tropical Pacific (McClain et al. 2002; Sweet et al. 2009; Montes et al. 2011; Karnauskas and Cohen 2012). The fusion of remote data sources enabled Schaeffer et al. (2008) to identify key hotspots for diversity within the archipelago.

There have been two maritime applications of remotely sensed data to link species migrations and habitat use within and around the Galapagos archipelago (Awkerman et al. 2005; Seminoff et al. 2008), and one study employed SeaWiFS data to link productivity to regions affected by the 2001 *Jessica* oil spill, as a measure of toxicity (Banks 2003). Contemporary utilization of imagery from hyperspectral/hyperspatial remote sensing platforms like QuickBird and WorldView-2 to analyze coastal vegetation has yielded promising results for identifying key habitats in Galapagos intertidal ecosystems, such as mangrove forests (Song et al. 2011; Heumann 2011a, b).

Ancillary Data to Calibrate/Validate Marine Remote Sensing

Bathymetry

The generation of accurate oceanographic, hydrographic, biological, and ecological data models is of extreme importance to conservation efforts and the sustainability of marine resources. Detailed bathymetric information is a key variable for coastal and marine modeling, but mapping the seafloor is difficult because it usually represents areas of nonstationarity and complex structures, such as small channels with varying orientations, coastal heterogeneity, and deep canyons within regions of gentle slopes (Magneron et al. 2010). Figure 6.1 shows three-dimensional seafloor and terrestrial surfaces for the Galapagos Islands, based on surveys conducted by the Ecuadorian Oceanographic Institute of the Army (INOCAR) and Geographic Military Institute (IGM).

Traditional bathymetric calculation involves the measurement of ocean depths using shipboard echo sounding (SONAR). Novel techniques include the use of airborne LiDAR and optical data, including spectral and hyperspectral imagery and pixel and/or object-based image processing approaches. With the support of geographic information systems (GIS), SONAR and LiDAR systems allow the generation of digital terrain models (DTM). LiDAR-derived seafloor topography also proves to be a particularly strong predictor for fish and coral richness when utilized in machine learning algorithms like maximum entropy modeling (MaxEnt) and Boosted Regression Tree methods (Pittman et al. 2009; Pittman and Brown 2011). Unfortunately, the use of boat-mounted SONAR and airborne LIDAR systems is limited by their very high cost and the constraints imposed by geographic accessibility.

Compared to traditional shipboard echo sounding, optical remote sensing methods offer more flexibility, efficiency, and cost-effective means of mapping bathymetry (Gao 2009). Newer optical systems like WorldView-2 and the

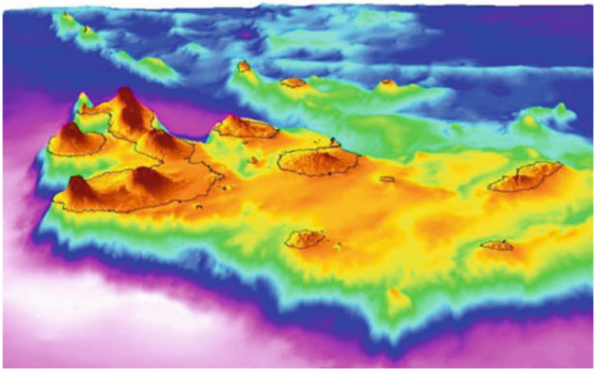

Fig. 6.1 Digital terrain model of the bathymetry and topography of the Galapagos archipelago

Hyperspectral Imager for the Coastal Ocean (HICO) have been used to characterize the seafloor, opening a new frontier in the generation of bathymetric models for coastal areas (Lee et al. 2011; Lucke et al. 2011). Optical and nonoptical remote sensors can detect submerged terrain conditions down to 30 m (Gao 2009), but environmental factors affect the ability of sensors to accurately assess ocean depth, including atmospheric conditions, water turbidity, bottom material, and waves. Because of these uncertainties, the validation of remote sensing data with oceanographic surveys has been deployed with good success. Deidda and Sanna (2012) used the coastal channels in a stereoscopic pair of WorldView-2 images to generate a basic model of depth that was calibrated using a traditional bathymetric survey. Ohlendorf et al. (2011) and Cerdeira-Estrada et al. (2012) used all eight multispectral channels of WorldView-2 to map bathymetry and benthic seafloor, validated with traditional bathymetry data. For the Galapagos Islands, the use of remote sensing for benthic habitats and detailed bathymetry mapping has great potential. Bathymetric surveys can be used to calibrate models that are applied to other areas, where there are gaps in the information needed to characterize coastal features (Fig. 6.2).

Local Knowledge and Citizen Science

Finally, the use of community knowledge and citizen science is now being linked to marine remote sensing data as a complementary source of information about key species. Jaine et al. (2012) integrate data collected by dive operators off the Great Barrier Reef into complex additive, spatially explicit models to successfully predict seasonal manta ray use of a coral reef. In terms of management applications and marine spatial planning, spatial analytical approaches can also integrate fishery demands and local knowledge sources. Howell et al. (2008) report that Hawaii's Turtle Watch program features input from fishers, loggerhead turtle tracking data, and remotely-sensed parameters in three dimensions to maintain a sustainable

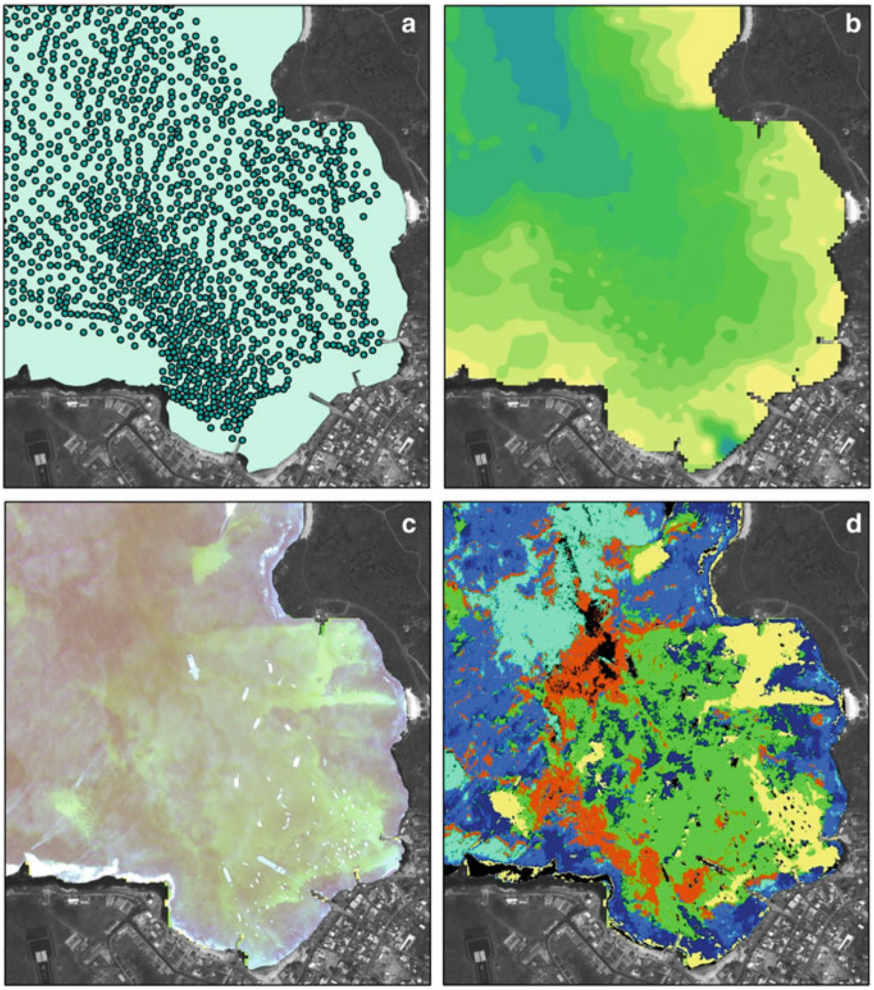

Fig. 6.2 Bathymetric characterizations of Wreck Bay, San Cristobal Island: (**a**) traditional bathymetric survey generated by INOCAR; (**b**) a continuous surface created by interpolating depths of the bathymetric survey, where darker shading represents greater depths; (**c**) a WorldView-2 scene that shows the combination of the coastal, green, and yellow channels, indicating landscape features; and (**d**) an unsupervised classification of the WorldView-2 scene to show different types of conditions at different depths

swordfish fishery, while "ground truth" data using habitat knowledge from resource users can aid in the interpretation of remotely-sensed data (Kloser et al. 2001). One innovative study involved the use of indigenous ecological knowledge to aid a supervised classification of a marine lagoon (Lauer and Aswani 2008). Given the large number of tourism and fishing boats operating in the relatively small Galapagos Marine Reserve, there is great potential for online and real-time mechanisms that support continuous and spatially explicit reporting from tour guides, boat captains, and tourists alike.

Summary and Conclusions

Large area applicability, multi-resolution capacity, repetitive orbits, archival collections, and digital representations for fusion with other satellite assets and disparate spatial data are among the many benefits afforded by remote sensing of marine and coastal environments. The limited remote sensing analyses that have been conducted over the Galapagos marine environment typically employ coarse-grained satellite systems for the study of archipelago-wide attributes (e.g., ENSO events and oil spills). Nevertheless, borrowing from preliminary work in Galapagos and contemporary marine remote sensing literature around the world, marine science and management can benefit from incorporating the following:

Taking advantage of higher resolutions and increasing satellite system options. Marine remote sensing has traditionally utilized active and passive sensors across a wide range of spatial resolutions to capture and analyze data related to biophysical aspects of the oceanic and nearshore environments, as well as climatological phenomena. New systems now provide an opportunity to push the limits of what we can discover from space as sensors with finer spatial resolution, larger spectral resolutions, and shorter temporal resolutions are being launched every year, enabling researchers to interpret marine and coastal environments at scales previously unimaginable. In 2014, for example, WorldView-3 will be launched with improved resolution across all scales. Additionally, there is a growing trend of satellite constellations that work towards a single purpose. In 2016, NASA will launch their Cyclone Global Navigation Satellite System (CYGNSS) that will consist of eight microsatellites that monitor oceanic and meteorological dynamics related to cyclone development. As satellites continue to be launched by government agencies and private companies around the world, researchers can anticipate more affordable, accessible imagery and derived data products.

System fusion (e.g., optical and nonoptical data systems, fine- and coarse-grained resolutions, contemporary and historical periods) and the assembly of data products operating at the pixel and object levels. Operationally, the fusion of multiple systems into single analyses is now the rule rather than the exception as satellite assets are pooled or integrated to more effectively represent space-time scales, with the local being nested within the regional and an assembled image or time series contextualized through annual and/or decadal observations. Field data collection campaigns need to be coordinated to calibrate and validate remote sensing products, using tools and techniques for geo-locating observations. Advanced field electronics and specialized devices, such as data loggers, can also be employed to assess marine variables, such as salinity, temperature, and sediment deposition.

Prioritization of process over pattern. Increasingly, the goal is not only to assess marine patterns but a more complete process understanding that involves spatial organization and variable responses. The movement away from pattern to a richer understanding of marine processes has involved the upscaling of observations and measurements from fine-grained imagery and downscaling from coarse-grained imagery, as well as the extension in time through image time series and the compression in time of short-term marine processes. In coastal areas, satellite assessment of linked terrestrial and marine subsystems acknowledges the integration of, for instance, sedimentation due to deforestation and urban development, beach degradation, and habitat alteration caused by the destruction of fringing mangroves and coral reefs.

Linking to the human dimension. Populated island and coastal environments are increasingly being viewed as coupled human-natural systems, necessitating the union of terrestrial, marine, and social sciences in research. Linking remote sensing systems to the human dimension is vital to discerning the human imprint across the landscape (Crews and Walsh 2009) as well as the importance of human agents and actions. In Galapagos as in other similar settings, residents in coastal and highland communities rely upon a complex household strategy of livelihood diversification in agriculture, tourism, and fisheries to manage economic and environmental uncertainty. They are tied to the onset of ENSO events that comparatively advantage terrestrial systems at the expense of marine conditions, global economic crises, and public policy that impacts the service sector. Changes in ocean temperature and primary productivity create feedbacks from the marine to the social systems through threats to livelihoods and community sustainability.

Remote sensing assets are expanding in number and capacity, and spatial patterns are increasingly being explicitly linked to social and ecological processes. Marine remote sensing will continue to be of pronounced interest and should be implemented as an approach for monitoring high priority variables, processes, and environments. In the Galapagos archipelago and beyond, the integration of increasingly available data derived from fixed-point sensors, floating instruments, aerial photography, local knowledge, and satellite systems will facilitate both discrete and continuous assessments in support of scientific research and management efforts.

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