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ABSTRACT. The science needed to understand highly migratory marine mammal, sea bird, and sea turtle species is not adequately addressed by individual data collections developed for a single region or single time period. These data must be brought together into a common, global map based on a coherent, interoperable, and openly accessible information system. This need was clearly articulated by the National Oceanographic Partnership Program (NOPP) and the Alfred P. Sloan Foundation when they co-sponsored a new effort to directly address this issue in 2002. The result is OBIS-SEAMAP: the world data-center for marine mammal, sea bird, and sea turtle information. OBIS-SEAMAP brings together georeferenced distribution, abundance, and telemetry data with tools to query and assess these species in a dynamic and searchable environment. In a second round of NOPP support that began in 2007, the National Science Foundation is helping expand this effort into new technologies and data types. To date, the OBIS-SEAMAP information system includes more than 2.2 million observation records from over 230 data sets spanning 73 years (1935–2008), and growth of this data archive is accelerating. All of these data are provided by a growing international network of individual and institutional data providers.

OVERVIEW

The first step toward more effective understanding and management of ocean animal species is to gather the available scientific data into a coherent, interoperable, and openly accessible information system. Without a common map of species observations, movement patterns, and behavior, we cannot begin to resolve the many difficult challenges our society faces in understanding and protecting these often threatened species. The science needed to understand highly migratory marine mammal, sea bird, and sea turtle species has not been adequately addressed by individual data collections developed for single regions and single time periods. The need for a common and accessible repository of high-quality, peer-reviewed, and professionally published data on protected marine species is absolutely fundamental to addressing future research and management needs. This critical need was clearly articulated by the National Oceanographic

Partnership Program (NOPP) and the Alfred P. Sloan Foundation when they co-sponsored a new effort to directly address this issue in 2002.

The result of this NOPP-sponsored initiative is OBIS-SEAMAP, the world data-center for marine mammal, sea bird, and sea turtle information. The OBIS-SEAMAP name is derived from a two-part acronym. OBIS refers to the Ocean Biogeographic Information System (Grassle and Stocks, 1999; Zhang and Grassle; 2002; Costello and Vanden Berghe, 2006), the worldwide information system for all marine taxa initiated by the Census of Marine Life (CoML; Ausubel, 1999). The second part of the acronym, "SEAMAP," refers to the specialized Spatial Ecological Analysis of Marine-megavertebrate Animal Populations node of this larger global ocean information system (Halpin et al., 2006). OBIS-SEAMAP (<http://seamap.env.duke.edu>) brings together georeferenced distribution and abundance data and tools to query and assess these

species in a dynamic and searchable environment (Figure 1). To date, the global OBIS-SEAMAP information system includes more than 2.2 million observation records from over 230 data sets spanning 73 years (1935–2008), and growth of this data archive is accelerating (Figure 2). All of these data are provided by a growing international network of voluntary individual and institutional data providers.

The OBIS-SEAMAP information system directly supports research into the ecology and management of important marine megavertebrates and augments the public understanding of the ecology of these species by: (1) facilitating studies of impacts on threatened species, (2) testing hypotheses about biogeographic and biodiversity models, and (3) supporting modeling efforts to predict distributional changes in response to environmental change.

To enhance the research and educational applications of this database, OBIS-SEAMAP provides a broad array of Web-based products and services, including rich species profiles, as well as compliant metadata and interactive mapping services. This system is taking advantage of recent technological advances in geographic information systems (GISs), Internet data standards, and content management systems to stimulate a novel community-based approach to the development of a data commons for biogeographic and conservation research. This publicly available biogeographic resource includes at-sea and colony-based counts and standardized metrics of relative abundance, standardized metadata describing survey and data processing methods, and species profiles with detailed ecological and

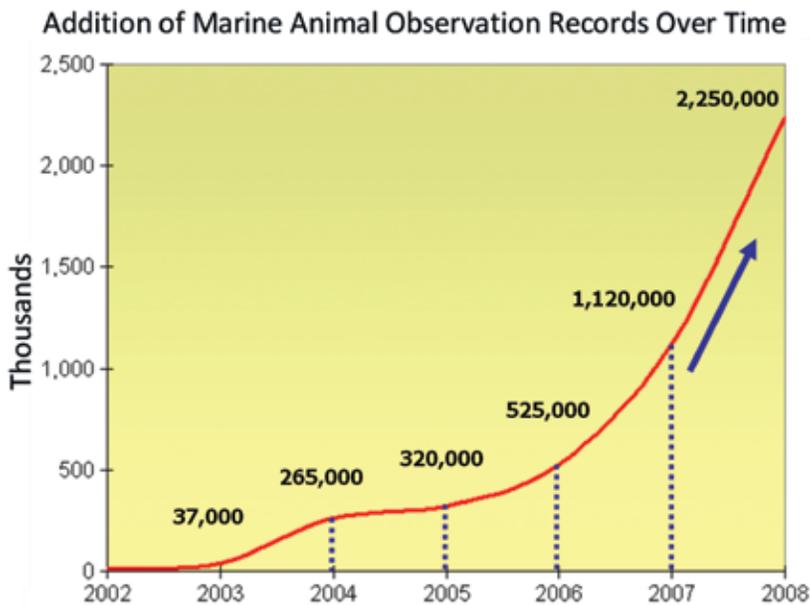


Figure 2. Exponential increase in marine animal observation data published through OBIS-SEAMAP with time.

taxonomic information.

The success of the OBIS-SEAMAP program can be attributed to an aggressive outreach program undertaken to attract potential data providers and system users by: (1) providing tools and services to data providers, (2) building and maintaining a critical online data archive, and (3) demonstrating the utility of the system through new research applications.

OBIS-SEAMAP has successfully developed a multifunction information system to provide critical data to scientists, managers, and educators under the NOPP program. Our ongoing efforts directly support the goals of CoML, the OBIS network, and the operational missions of multiple agencies, research efforts, and educational user communities. A recent example of applying OBIS-SEAMAP data to help resolve ocean management problems involves the use of marine mammal data sets to support ecological modeling of marine

mammal habitats to assist the US Navy in planning military readiness exercises in US coastal waters (Best et al., 2007). Other example projects include ongoing annual global assessments of the status of sea turtles and plotting the spatial and temporal trends of nesting data (Hutchinson et al., 2005; Mast et al., 2006). Further works is focused on developing a more technically advanced and fully interoperable marine animal information management system within the context of emerging Integrated Ocean Observing System (IOOS) efforts (e.g., <http://ioos.noaa.gov>).

ENCOURAGING DATA PUBLISHING

The creation of a data commons for biogeographic and conservation research is only feasible when a sense of community exists among researchers, data holders, administrators, and users of such a system. Sufficient benefits must be provided to encourage the different

participants to join the community. Most researchers recognize the value of expanding future scientific inquiry to questions covering larger spatial and temporal scales than an individual researcher can address in isolation. However, in addition to adding to the general progress of science, individuals also seek direct and tangible benefits. OBIS-SEAMAP has been developed with both of these goals in mind, and it includes a wide array of tools and services that are attractive to the research and conservation communities. More specifically, to enroll data providers into the system, we have devised three types of services: (1) data management, (2) value added, and (3) community development.

Data management services are designed to facilitate the integration of the various data sets into the OBIS-SEAMAP database. These services assist with: quality assurance and quality control (e.g., speed filters to identify erroneous locations along a survey track); dissemination (e.g., tools to share and disseminate research results with colleagues and founders); information technology benefits (e.g., data backup in the OBIS-SEAMAP server); and advertising (e.g., high visibility of individual data sets and supporting citations on the public OBIS-SEAMAP Web site as well as the OBIS portal and other metadata clearinghouses).

Value-added services enrich the data sets contributed to OBIS-SEAMAP in a variety of ways, including: providing additional ancillary data (e.g., automatic Integrated Taxonomic Information System—a taxonomic hierarchy for species recorded in contributed data sets); developing metadata to

enhance the long-term use of the data (e.g., automated creation of mandated Federal Geographic Data Committee [FGDC] metadata; and merging the biogeographic information with additional environmental data sets).

Community development services include the OBIS-SEAMAP Web tools designed to give data providers and users the ability to add content to the site, the right to manage their own data sets, and broad exposure to the public. In addition, users can provide access to groups of colleagues to promote collaborative efforts.

Persuading users to publish data requires devising approaches to protect proprietary data rights and to manage data access by the public and the scientific community. OBIS-SEAMAP has developed a “terms of data use” agreement that protects the rights of data contributors without restricting the applicability of the system for a wide array of educational and conservation applications. All data are made available as complete data sets with full citation of and contact information for the original data providers. Complete metadata and the terms of use are bundled with the download of data sets to further promote responsible usage and proper citation.

As ecological research becomes increasingly data intensive and global in scope, bio-informatics programs need to reconcile diverse national and international data access issues in a systematic fashion and in a policy arena that transcends national jurisdictions (Arzberger et al., 2004). As a data aggregator at this global scale, OBIS-SEAMAP continues to adapt to modern “community development” approaches and to encourage good practices by others in this field.

COMMON TOOLS – COMMON INTERFACE

The tools used for storing, distributing, and visualizing data in OBIS-SEAMAP leverage existing software, standards, and initiatives. Specific technologies evolve rapidly, but because the framework used by OBIS-SEAMAP relies on open standards and open-source products, the system can adapt quickly. Some of the most attractive aspects of these open-source technologies include their low cost, standards compliance, reusability, and customizable nature. The use of open standards, such as the Open GIS Consortium (OGC) standards, is especially important to promote the usage and interoperability of marine animal observation data among different software platforms and Web services applications. The use of common mapping interfaces such as Google Maps

and Google Earth provide an ease of use to people from a variety of backgrounds and disciplines (Figure 3).

A NODE IN A LARGER NETWORK

The OBIS-SEAMAP program, and the OBIS network in general, are examples of a larger community of emerging ecoinformatics programs and activities. To facilitate the discovery and exchange of data between programs, the central OBIS facility has adopted the use of the Darwin Core protocol using XML (Extensible Markup Language) and DiGIR (Distributed Generic Information Retrieval, <http://digir.sourceforge.net>) as a standard Internet exchange language and database access package for search and retrieval of records between participating network data nodes.

OBIS-SEAMAP is participating in the

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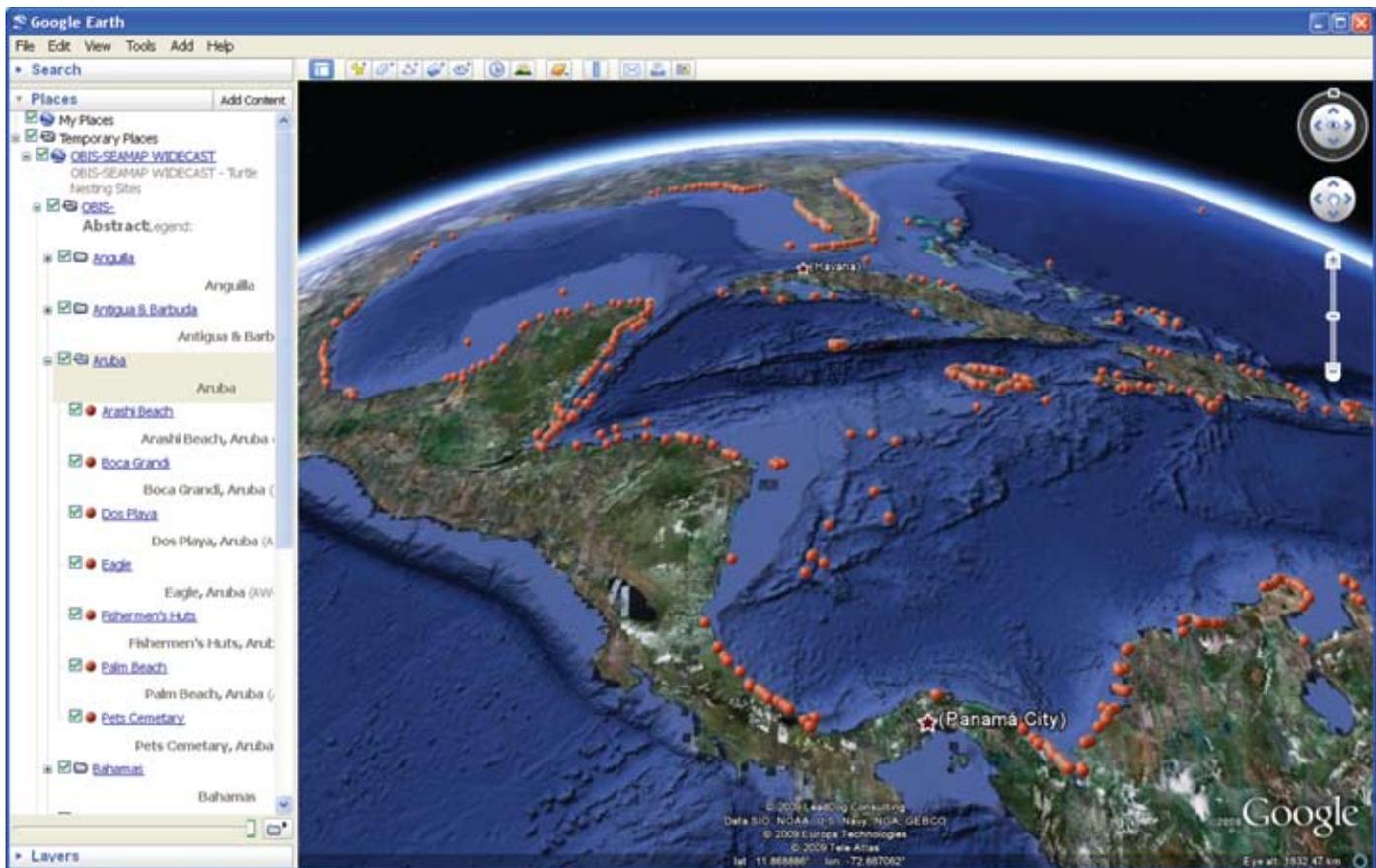


Figure 3. OBIS-SEAMAP allows users to view all data using common mapping interfaces such as Google Maps and Google Earth. This figure depicts a view of sea turtle nesting beach data from the Wider Caribbean Sea Turtle Conservation Network (WIDECAS; <http://www.widecast.org>). Data can be viewed directly or accessed through interoperable Web services.

OBIS network (<http://iOBIS.org>) through the use of DiGIR's client package, thus making its data available to the public through the central OBIS search interface. OBIS, in turn, is a data provider to the Global Biodiversity Information Facility (GBIF; <http://gbif.org>), which also uses DiGIR and XML transfer protocols. In addition to the OBIS and GBIF data centers, the Encyclopedia of Life (EOL; <http://EOL.org>) is developing descriptive species information pages and links to these observation data centers. OBIS-SEAMAP is a significant contributor to each of these global efforts. Emerging software technologies, such

as the next generation of OBIS/GBIF data exchange protocols, including the emerging Taxonomic Database Working Group (TDWG) TAPIR protocols (TDWG Access Protocol for Information Retrieval; <http://www.tdwg.org/activities/tapir/charter>), are being incorporated.

UNIQUE CHALLENGES FOR OBIS-SEAMAP

OBIS-SEAMAP data providers specifically require the ability to plot sampling effort and vessel track line information (for the sampling effort) along with their animal observation data. It is often just as useful to know where animals were

not observed as it is to know where they were observed. Many important statistical analyses and ecological models require the explicit sampling effort data (e.g., ship and aircraft track line data) and oceanographic condition (e.g., Beaufort sea state) for proper calculation. For aerial and ship surveys, data providers requested showing the cruise effort as line features, and for satellite-tracked animals, using an inferred track to depict travel between known locations. By moving beyond the display of simple point data, OBIS-SEAMAP encourages the larger biodiversity informatics community to provide

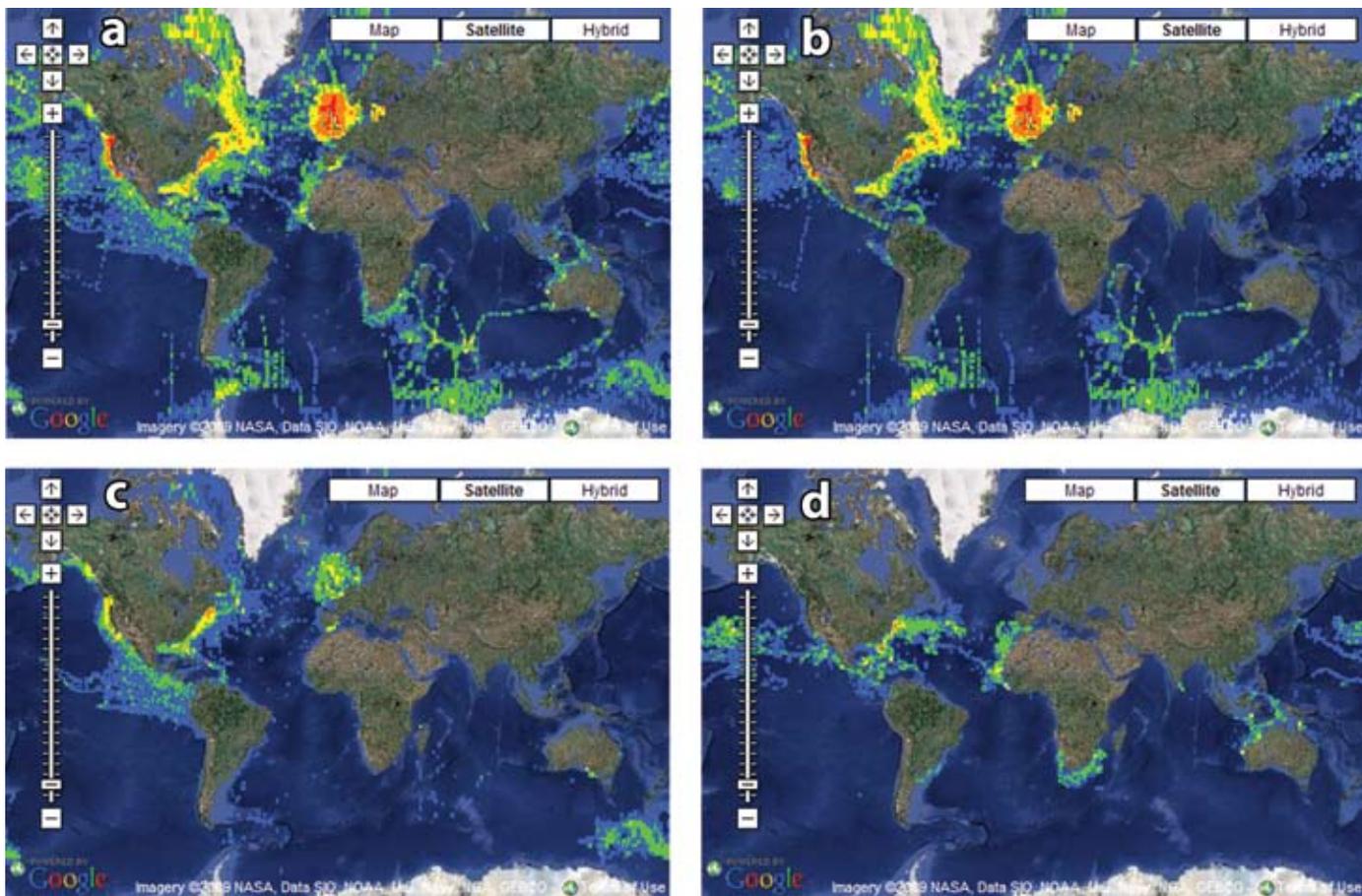


Figure 4. Geographic distribution of species observations. (a) All taxa. (b) Sea birds. (c) Marine mammals. (d) Sea turtles. Significant geographic gaps are apparent in the current data holdings due to biases in existing observation effort and data availability. A formal gap analysis is underway to target future data acquisitions.

the necessary standardized effort data required to estimate the distribution and abundance of marine animals.

NEW DEVELOPMENTS: OBIS-SEAMAP2.0

Recently, the NOPP program, in partnership with the National Science Foundation, sponsored a second round of support to fund the second-generation development of our program, OBIS-SEAMAP2.0. Under this second round of NOPP support, we are in the process of developing more advanced applications to support the needs of our user community. These applications

include a spatial and temporal “gap analysis” of existing data holdings, exploration of new data types, and development of new technologies and partnerships.

Spatial and Temporal Data Gap Analysis

The distribution of high-quality data sets of marine animal observations is highly uneven in both time and space. Some areas have been surveyed extensively, but there are critical gaps in the coverage of species, geographic regions, and time periods. The spatial distribution of data collected in the initial phase of this program reflects existing biases in the

density of sampling and data acquisition in North American and European waters (Figure 4a–d). In this second phase of the project, we are conducting a formal gap analysis to identify and prioritize data acquisition for underrepresented regions and species. We are targeting new data acquisitions to fill these critical gaps, and we are developing a direct reporting process with primary data collection agencies to provide feedback for future data collection efforts.

Analysis of marine mammal distribution must directly consider the temporal dimension of data representation because of the dynamic nature of the

ocean environment and the mobile nature of these species. OBIS-SEAMAP provides new tools to allow users to view data holdings through time as well as through space (Figure 5). For predictive modeling and statistical analysis, our ability to provide data coverage depicting marine animal distributions in relation to oceanographic conditions at precise seasonal and subseasonal time steps is especially critical.

An important difference between the OBIS-SEAMAP geodatabase archive and other biogeographic data services (i.e., iOBIS, GBIF, EoL) is that we record and distribute the original survey effort to allow analysis of the spatial and temporal coverage of the surveys themselves, not just the resulting observations.

These types of data are critical in accounting for potential survey bias so that we can look at gaps in both species observations and survey effort.

New Data Types

Most data sets archived in the current OBIS-SEAMAP portal are derived from scientific surveys based on ship, aerial, and telemetry platforms. We are actively extending the visualization and analytical capacity of OBIS-SEAMAP2.0 to support: (1) acoustic location data, (2) photo-ID data, (3) advanced telemetry (three-dimensional dive behavior), and (4) integrated model outputs. The inclusion of these new data types into the OBIS-SEAMAP information system will significantly enhance the capabilities of

marine mammal scientists and managers to meet the challenges of critical species management.

Acoustic Location Data

To date, the OBIS-SEAMAP project has been very successful in attracting high-quality marine mammal line transect visual survey data sets. These surveys are conducted primarily during periods of excellent visibility and good sea conditions—typically during summer months, particularly in high latitudes. To augment these surveys, we are expanding the OBIS-SEAMAP data archive to include marine mammal location data generated from passive acoustic monitoring systems. Acoustic location data can provide observations of marine mammals

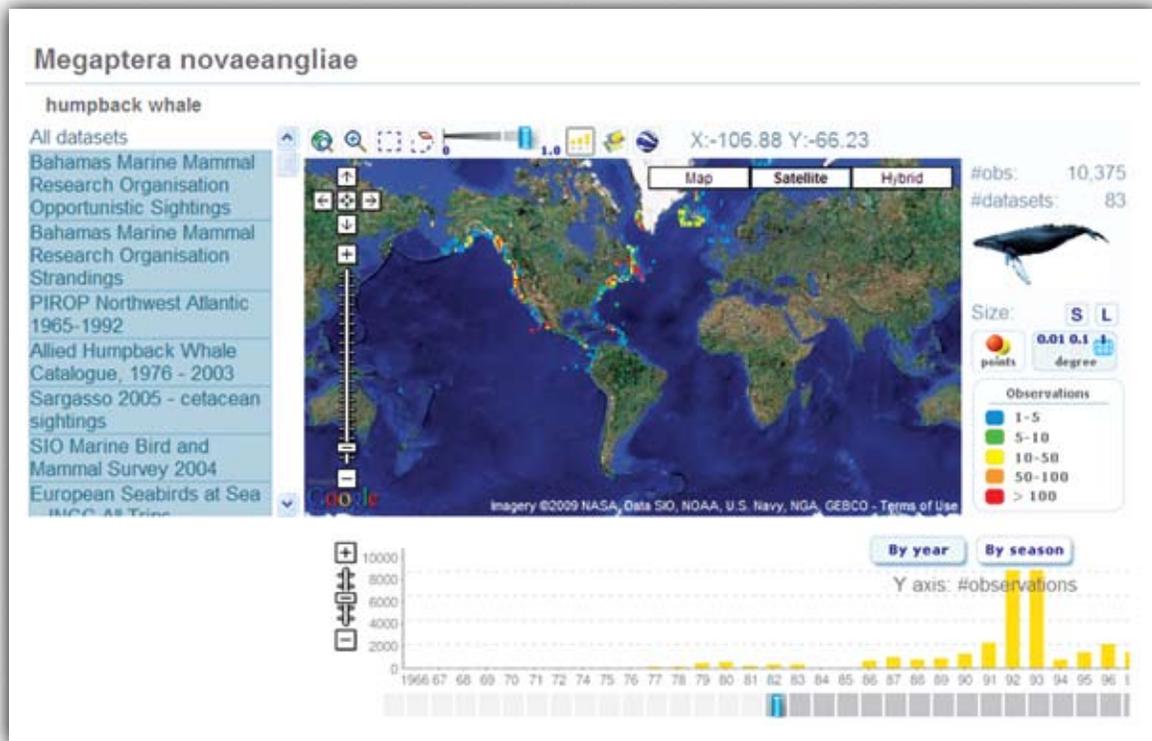


Figure 5. OBIS-SEAMAP features the ability to query data through time as well as space. The slider bar at the bottom of the page depicted in this figure allows the user to select different time periods to view animal observations. This selection tool also permits assessment of temporal gaps in data coverage for different species by years and by seasons.

in times and areas where traditional survey methods are not possible.

We are expanding the OBIS-SEAMAP archive to include observations of marine mammals collected by the following types of acoustic monitoring systems: moored single stations, such as pop-up ocean bottom recorders, for example, the Acoustic Recording Package and High-Frequency Acoustic Recording Package; bottom-mounted fixed arrays; towed arrays; and autonomous gliders. To make this archive useful, we are addressing the following issues: (1) how to visualize long-term records obtained from a single monitoring site, (2) how to reflect uncertainty in two- and three-dimensional position estimates derived from listening arrays, (3) how to deal with both archival and real-time monitoring systems, and (4) what novel types of metadata are required to describe these systems and their limitations.

Interactive Photo-ID Data Systems

Photographic identification (photo-ID) data sets are important for understanding the behavior and migratory movements of individual marine mammals. These data are different in many respects from traditional line transect surveys and are unique in their association with digital photographs. OBIS-SEAMAP includes a growing number of data sets that are derived from photographic identification research. At the present time, however, standard biodiversity information system architectures are not able to display the identity of individual animals from these types of records. We are expanding the capabilities of OBIS-SEAMAP to include this individual-based information and are developing a series of new tools that

will enhance the functionality of the archive for researchers using photo-ID methods. We are also developing Web-based tools that will facilitate cooperative research across institutional and geographic boundaries.

Our new tools allow researchers to exchange images and data and to identify individual animals using a Web browser interface. To achieve this goal, we have developed an initial prototype photo-ID portal within OBIS-SEAMAP using the Mid-Atlantic Bottlenose Dolphin Photo-ID Catalog (MABDC). This OBIS-SEAMAP prototype photo-ID system (Figure 6) allows researchers to search for particular individuals, select individuals to be matched, establish search criteria, search for potential matches, and review and circulate potential matches.

This system provides sighting location and photographic images of individual marine mammals linked through centralized photo-ID catalogs. Data contributors can match images and then examine temporal and spatial movement patterns of individual animals that occur across sites. We plan to expand this system to other collaborative photo-ID catalogs using a common Web-based catalog browser. Curators of all contributing catalogs will continue to be responsible for the data and images contributed to OBIS-SEAMAP, and individual researchers will continue to maintain ownership of all contributed records and images.

Advanced Telemetry Data

The OBIS-SEAMAP data archive currently maintains an expanding collection of satellite telemetry data that describe the movements of individual

marine mammals, sea birds, and sea turtles (Figure 7). These data sets form an important supplement to observations of the same species derived from traditional surveys. Telemetry tracking data allow us to answer a variety of different questions concerning the environmental response and migratory behavior of different animal species (Stone et al., 1999). In addition to accepting direct publication of animal telemetry data sets, we also maintain a partnership with the Satellite Tracking and Analysis Tool (STAT) system (<http://www.seaturtle.org/stat/>), which provides a common suite of open-access, platform-independent tools for data parsing and integration with oceanographic data sets (Coyne and Godley, 2005). OBIS-SEAMAP acts as the default portal through which STAT data are shared with the larger iOBIS and marine research communities. Finally, a significant proportion of the data in STAT are collected and processed in near-real time. The integration of “live” data streams (currently averaging more than 1,000 locations per day) enhances the predictive power of ongoing modeling activities through OBIS-SEAMAP.

In addition to satellite tracking data, we are developing our capacity to absorb large and complex data sets generated by the latest generation of digital archival tags (DTAGs). We are focusing particularly on the current generation of DTAGs and new medium-term digital GPS tags being developed by researchers at the Woods Hole Oceanographic Institution (Johnson and Tyack, 2003). Incorporation of three-dimensional telemetry dive data with time into OBIS-SEAMAP allows for the direct exchange and analysis of animal

behavior in response to environmental gradients. Developing common protocols and methods for exchanging these data is increasing the analytical opportunities to assess animal movement in four dimensions.

OCEANOGRAPHIC DATA AND ECOLOGICAL MODELS

Analysis of marine animal distributions often requires analysis of the underlying oceanographic conditions at the time of the observations. The OBIS-SEAMAP system permits direct linkage to

common ocean data layers selected to match user-defined time periods (Figure 8). This linkage allows for the seamless fusion of observation, effort, and ocean environment data for further analysis and modeling.

Ecological models predicting the

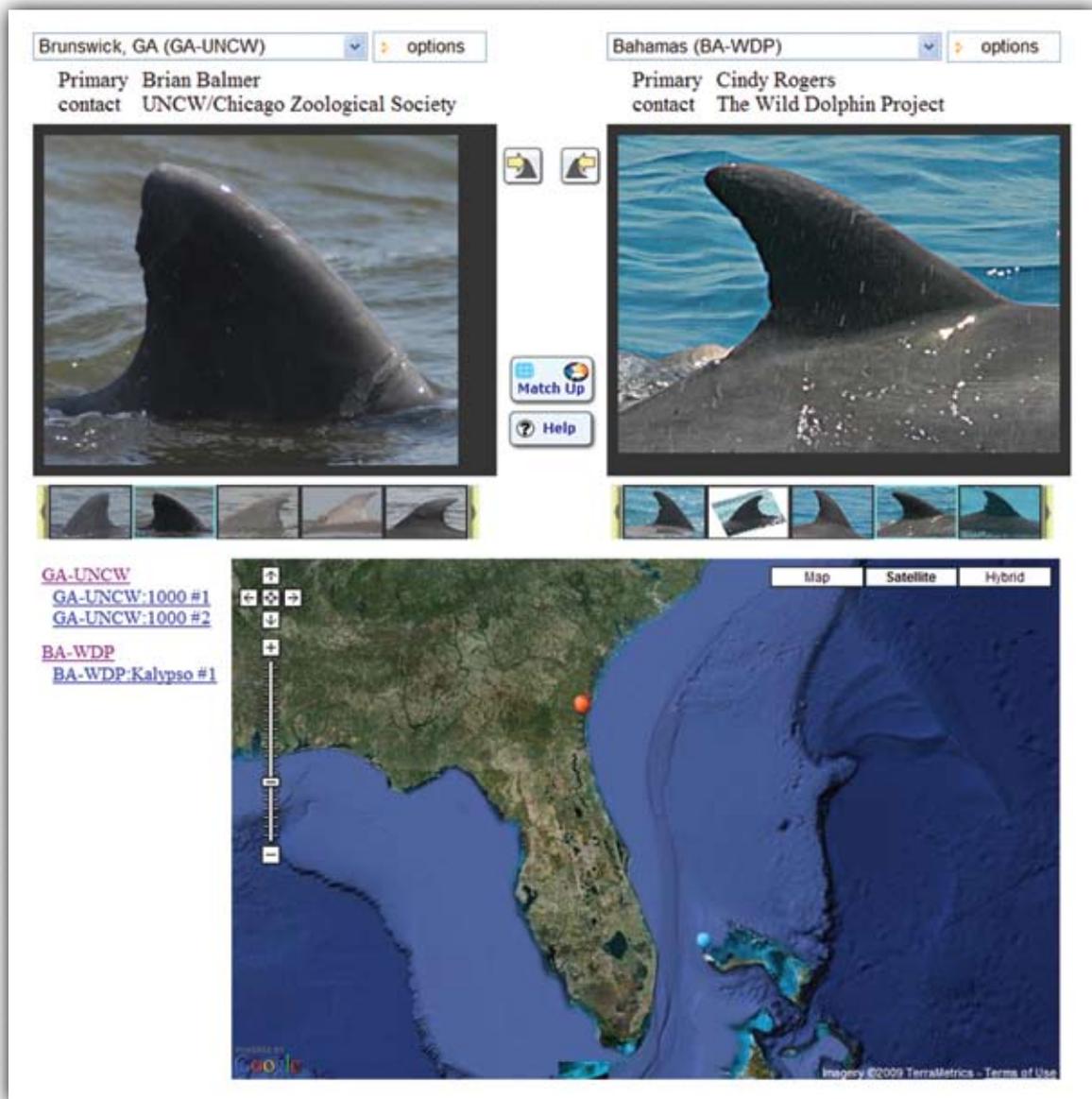


Figure 6. OBIS-SEAMAP features an advanced photo-id matching system designed for tracking the reoccurrence of individual animals by linking photos to geographic locations. This figure depicts data from the Mid-Atlantic Bottlenose Dolphin Photo-ID Catalog (MABDC). This tool allows a group of users to submit photos for reidentification by other members of the network and track the movement of individual animals.

distribution and environmental relationships for individual species are in increasing demand for environmental planning and environmental impact assessments. We are building tools to publish continuous surfaces of density and habitat based on empirical models

that can be updated with the addition of new data and improved modeling techniques (Redfern et al., 2006). We are expanding the capabilities of OBIS-SEAMAP to display the results of environmental model outputs along with detailed methodological and statistical

metadata so that users can interpret and appropriately use model outputs in a responsible manner.

Given the complexity and variety of model outputs and methods, we will develop a metadata structure for fully describing the methods used as well

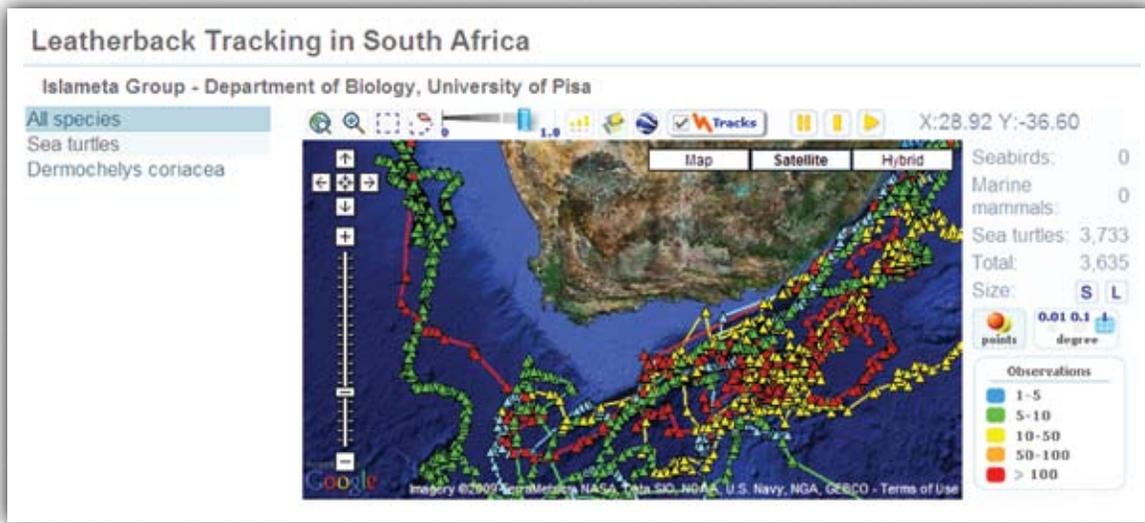


Figure 7. OBIS-SEAMAP is expanding the functionality to store and disseminate advanced telemetry animal tracking data. This figure depicts leatherback turtle tracks off the coast of South Africa submitted by researchers from the University of Pisa. The different color track lines indicate individual animals.

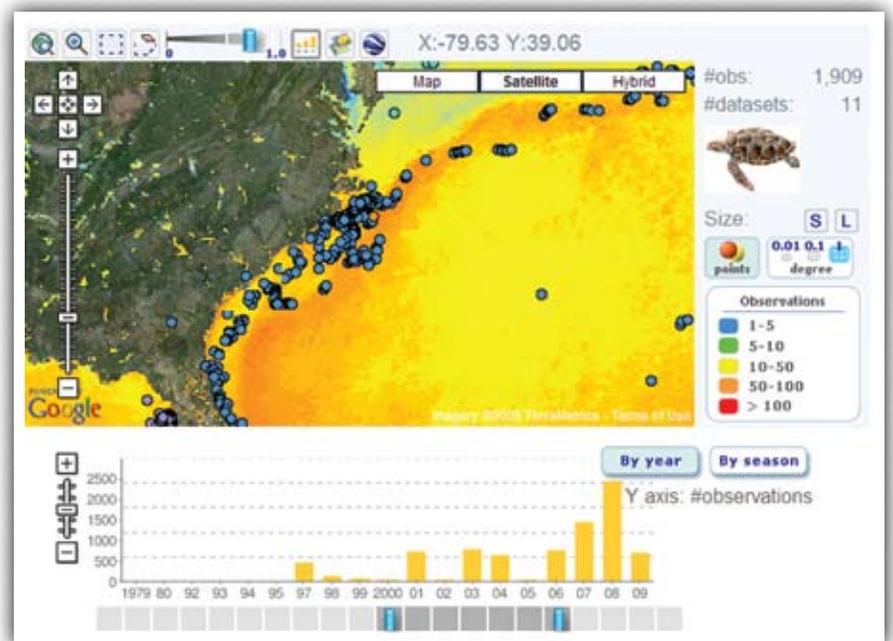


Figure 8. Interactive fusion of oceanographic data and models with animal observation data. Sea surface temperature, sea surface height, and ocean color (Chl *a*) imagery can be selected by time period to match the animal observation data being displayed and queried in OBIS-SEAMAP.

as summarizing subsets of results in a meaningful way. The environmental modeling field is experiencing rapid advances in data exchange standards coincident with the emergence of enabling technologies (Argent, 2004; Frehner and Brandli, 2006; Raskin and Pan, 2005). We are using emerging XML standards, such as the Ecological Metadata Language and Semantic Web, for this task.

FUTURE TECHNOLOGY TRENDS

We are developing innovations in six focus areas at this time:

1. Improving accessibility and utility of geospatial and taxonomic services to browsers, servers, and desktop clients via **Web services** technology.
2. Promoting visibility of data sets by translating metadata into various formats and **populating metadata clearinghouses**.
3. Encouraging participation and collaboration of data providers for multiple uses with refined **access control** for users and groups to control additional data fields.
4. Facilitating broader applications with the addition of more relevant **background layers**, such as fishing effort, vessel traffic, and protected area boundaries.
5. Increasing the volume of OBIS-SEAMAP holdings with **nonredundant data harvesting** from OBIS and GBIF and other data portals.
6. Refining the transparency and effectiveness of the **development environment** through the use of bug tracking, version control, milestones, and content management software.

INCREASED USE OF WEB SERVICES

Increased access and automation of data feeds to and from OBIS-SEAMAP will increase its utility and effectiveness. We will expand the Web services offered by OBIS-SEAMAP to include more geospatial, environmental, and taxonomic services. Data exchange will be formatted with XML and Simple Access Object Protocol (SOAP) using the latest standards (Smiatek, 2005; Frehner and Brandli, 2006). Client libraries for the most common analytical programs, such as ArcGIS, MATLAB, and the R statistical package, will be created to consume these services directly from desktop applications.

The further development of Web service architectures based on common standards (e.g., OPenDAP [Open-source Project for a Network Data Access Protocol], OGC, SOAP, Marine XML, digital object identifiers) will permit increased interoperability between the marine biogeographic observation community and the marine oceanographic observation community. The development of modular scripts for scientific workflow modeling programs (e.g., Kepler, JPL SciFlo, ESRI ModelBuilder) and semantics to intelligently exchange across data schemes will facilitate easier, more comprehensive analysis of marine animals and their dynamic environments.

INTEROPERABILITY WITH IOBIS/IOOS/GEOS

The tools used for storing, distributing, and visualizing data in OBIS-SEAMAP leverage existing software, standards, and initiatives. The use of open standards, such as the OGC standards, is especially

important to promote the use and interoperability of marine animal observation data between different software platforms and Web services applications. New developments in OBIS-SEAMAP data transfer, Internet mapping, and marine metadata will be conducted in close coordination with iOBIS and the IOOS Data Management and Communications Steering Committee (<http://dmac.ocean.us/index.jsp>). All OBIS-SEAMAP data are currently listed in the NASA Global Change Metadata Directory (GCMD) to permit seamless compliance with other federal programs. Automatically populating metadata to other portals could save much of the advertising and processing burden on the end user. Relevant metadata portals include GeoData.gov, NBII.gov, KNB.Ecoinformatics.org, ConservationMaps.org, and GeographyNetwork.com. Each has its own metadata standard (DIF for GCMD, FGDC for GeodData, FGDC with Biological Profile for NBII, and EML for KNB). We are building XML style sheet language translators (XSLT) to convert stored metadata into the necessary formats, and we regularly update these metadata clearinghouses.

IMPROVING DATA QUALITY

Recent reviews of marine fish data found in global information systems have highlighted the need to develop better methods for data quality control in contributed information systems (Robertson, 2008). The OBIS-SEAMAP program strives to provide the highest-quality data available in the most objective and transparent manner possible. A fundamental quality-control design built into OBIS-SEAMAP is very basic: instead of pooling data from potentially

uneven sources, our system emphasizes the selection of complete data sets of known quality and also emphasizes direct communications and collaboration with the original data providers. Because data are published by individual data providers, the final responsibility for data quality resides with the original data collector. However, proactive steps can be taken to develop useful feedback systems to help continuously improve data quality. OBIS-SEAMAP is implementing a feedback system to return information to data providers on quality control issues and publish updated changes to data sets when errors are detected. Our first examples of interactive data correction and revision are helping to guide the way for continuous data improvement.

CONCLUSIONS

The creation of a seamless biogeographic information system specifically highlighting marine mammal, sea bird, and sea turtle species of our ocean is essential for us to better understand these animals and to develop better management decisions. This interoperable information system will place species distribution data coupled with oceanographic information at the fingertips of researchers, students, managers, and policy decision makers worldwide. This program is the direct result of two rounds of NOPP support that have provided the catalyst. The continued success of the OBIS-SEAMAP program will only be achieved by continued participation, collaboration, and data sharing among researchers, managers, and educators throughout the globe.

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