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Integration of passive acoustic monitoring data into OBIS-SEAMAP, a global biogeographic database, to advance spatially-explicit ecological assessments

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ABSTRACT

We successfully developed an extension of the OBIS-SEAMAP database, a global biogeographic database specializing in marine mammals, seabirds and sea turtles, to integrate passive acoustic monitoring (PAM) data with other commonly collected data types (i.e. line-transect visual sightings, animal telemetry, and photo-identification). As part of this effort, we made significant improvements in mapping and visualization tools for PAM data, including spatially and temporally interactive summary statistics, diel plots, temporal effort representation, and the unique rendering of PAM data to distinguish them from other data types. In this paper, we summarize technical challenges we overcame, report the methodologies and implementation of the integration, and conduct case studies using visual sightings and PAM data from bowhead whales and Risso's dolphins to demonstrate how the integrated database facilitates in-depth ecological assessments that form the foundation for spatially-explicit conservation efforts.

1. Introduction

Passive acoustic monitoring (PAM) is an increasingly important data collection method for spatially and temporally explicit assessments of the distribution, abundance and behavior of marine mammals. Biological assessments using PAM provide a wealth of information that supplements traditional visual line-transect data (Marques et al., 2009). PAM is able to collect data regardless of light or weather conditions and hence is capable of filling spatial and temporal gaps of data from visual surveys (Marques et al., 2009). PAM devices collect data continuously over extended study periods, allowing researchers to assess temporal variability in marine mammal calls at diel, seasonal, annual, or decadal scales (e.g. Johnston et al., 2008; Soldevilla et al., 2010a; Wiggins et al., 2005). Instruments can be deployed in remote locations or regions with consistently rough weather that are difficult or impossible to survey with visual methodologies (Mellinger et al., 2007). PAM is particularly well suited to record occurrences of species that are visually cryptic (Barlow and Taylor, 2005; Baumann-Pickering et al., 2012; Gedamke et al., 2001; Rankin et al., 2007). The technical capabilities of PAM devices are improving continually and the costs of deploying these instruments and analyzing data collected are being reduced (e.g. Wiggins and Hildebrand, 2007), so it is likely that PAM will continue to grow as a critical tool with which to study the spatial and temporal occurrence of marine mammals (Buxton and Jones, 2012; Rogers et al., 2013; Van Parijs et al., 2009).

Specialized data archiving and dissemination methods designed to facilitate information exchange among researchers and managers for marine megafauna are becoming more common, but to date these efforts have not extended to PAM data at a global scale. Data collectors and data aggregators face significant challenges that hinder the establishment of a platform to share PAM data. First, data storage and dissemination of raw PAM data require high server capacities with an increasing volume of data storage required for longer-duration, higher-frequency recordings (e.g. a single 1-month instrument deployment continuously sampling 16 bits at 200 kHz yields nearly a terabyte of data). Second, raw PAM data recordings require extensive data processing, including automated detection and classification with specialized acoustic software or manual analysis by trained acousticians with an understanding of the acoustic ecology of each species (Van Parijs et al., 2009). Further, new metadata standards are required to document information about the equipment used, data processing and analytical methods, and the detection, classification and localization (DCL) algorithms used in manipulating these large data sets. Finally, whereas processed data can be archived in a similar format to traditional visual sighting records (e.g. species occurrences with location, date/time, species identifier and count), the meaning of a PAM record is usually very different from that of a visual sighting record. For example, in a visual sighting record the count field typically represents the number of animals observed during a sighting event, while in a PAM record

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this field may indicate presence/absence of calls or numbers of detections within a given time period, or total number of detections within an encounter. On occasion, the number of animals may also be estimated, but this is not necessarily the case. To address these challenges, therefore, a biogeographic database incorporating PAM data must be flexible and include sufficient documentation on the survey design and methods, data processing and limitations to allow meaningful comparisons between datasets.

The Ocean Biogeographic Information System Spatial Ecological Analysis of Megavertebrate Populations (OBIS-SEAMAP; http://seamap.env.duke.edu; Halpin et al., 2006, 2009) is a thematic node of OBIS that specializes in marine megavertebrates (marine mammals, seabirds and sea turtles) and recently took up the challenge of integrating PAM data. OBIS-SEAMAP has been accumulating different data types, including traditional visual line-transect sightings, telemetry data, sea turtle nesting data and sighting histories of individual dolphins and whales from photo-identification catalogs (Fujioka et al., 2014). The spatio-temporal interactive tools available on the OBIS-SEAMAP data center allow these different types of data to be explored simultaneously in assessments of species occurrences across regions and time periods. The tools also allow users to associate occurrence data with oceanographic variables such as sea surface temperature for more detailed assessments (Halpin et al., 2009). The addition of PAM data to this integrated biogeographic database will fill data gaps and provide the opportunity to conduct ecological assessments of marine mammals over a broader range of spatio-temporal scales and research topics.

To pursue this integration effort, we addressed the following technical challenges: 1) how to extend the existing database to accommodate PAM data; 2) how to map and visualize PAM data along with other data types in a consistent, informative way; and 3) what additional tools are required to facilitate assessments of PAM data. We first summarize our integration methods and improvements to existing mapping and visualization tools for representing PAM data. Next, we present preliminary assessments using existing OBIS-SEAMAP data to discuss how the integration contributes to 1) improving our coverage of data gaps; 2) facilitating ecological assessments; and 3) enhancing conservation efforts. For these assessments, we develop two case studies combining and comparing visual sightings and PAM data. Finally, we critically evaluate the current capability and issues surrounding biogeographic databases with respect to PAM data and propose future directions for improvements.

2. Materials and methods

2.1. Database improvements to integrate PAM data

PAM data are provided by researchers to the OBIS-SEAMAP data manager who puts the data through a registration process. As for other data types, providers of PAM data are responsible for quality assurance on call detections, date and time of the detections, species identification and locations of the devices or localized positions of animals. Most of the PAM data and their originating surveys are described in peer-reviewed journal articles. Through the data registration processes, the OBIS-SEAMAP data manager may find inconsistency or errors and consult with the providers to correct the data. Given the large volume of raw PAM data, OBIS-SEAMAP cannot archive unprocessed data. Instead, providers summarize the PAM data in a way appropriate to the survey goals or research interests. These summaries result in data submitted in a similar format to other observation data types. From the standpoint of data interpretation and database management, however, significant differences exist between PAM data and previously integrated data types (e.g. data from visual line-transect surveys and satellite telemetry) as well as among PAM platforms and methodologies (e.g. fixed hydrophones versus towed-arrays).

A record in a visual survey dataset represents a species occurrence at a given location (i.e. a point along the trackline that the survey platform traveled) on a specific date and time with a quantified number of animals. In visual line-transect surveys, the horizontal or vertical angle to the group of animals relative to the survey platform heading is measured and can be used to calculate the location of the group. Raw PAM data are processed through manual analysis or with computer software to identify the detections of calls emitted by species of interest. The metrics that can be extracted from the data before being submitted to OBIS-SEAMAP include presence/absence or the number of detections of a species at a location within a given time period (e.g. per minute or hour; Soldevilla et al., 2010a), or total number of detections within an encounter. Methodologies to estimate group size from detections are still being developed (see Mellinger et al., 2007 for a review), so PAM data may not include an estimate of group size. In addition, the location of a detection can refer to point observations based on the instrument location (stationary or mobile), point localizations based on animal location estimated from array data, or tracks of animal/group movements based on consecutive localizations from array data or from tags attached to animals. Point and track localizations may include animal depth information in addition to latitude and longitude. Moreover, assumptions of independence of data points vary across study designs. For example, visual line-transect surveys typically assume independence of sighting events given the speed of the survey platform compared with the swimming speed of the marine mammal (Buckland et al., 1993; Thomas et al., 2010). The same assumption holds for mobile PAM transect surveys, but not for stationary PAM data or mobile approaches with slow moving recorders, such as buoys or gliders (e.g. animals may move away and back, or stay within the vicinity with an extended break in calling between events). Finally, different call types can be detected at various ranges, depending on frequency. For example, low frequency baleen whale calls can be detected over much greater ranges than high frequency odontocete calls. For point observations based on instrument location, this “point” may refer to a region as small as a 3 km radius for bottlenose dolphin whistles to hundreds of km radius for baleen whale calls (Jensen et al., 2012; Širović et al., 2007).

Knowledge of data collection methods and survey conditions that characterize the detection performance is critical for any ecological assessment using such data. Sighting effort from a visual line-transect survey is delineated as an assembly of transect segments followed by the survey platform (i.e. vessel or airplane), and associated with a set of attributes including platform locations with date and time, effort status (i.e. observers on or off effort) and survey conditions such as Beaufort sea state and glare (Barlow and Taylor, 2005). A similar spatio-temporal representation of effort is possible for PAM with towed hydrophone array surveys but this approach is not suited to PAM data collected from stationary instruments, because the monitoring takes place at a fixed location. The attributes logged during survey periods are different between a visual line-transect survey and a stationary or PAM line-transect survey. For example, instead of logging an observer's identifier, experience level, and watching status, PAM records log the device information such as sensor sensitivity, recording bandwidth and cycles, and other parameters to the device. Recording locations, depths, signal-to-noise ratio, and detection range are also important factors affecting the detection performance. Effort is a function of both the availability of quality recordings (duty cycles, appropriate frequency range for species of interest) and analysis effort (manual or automated).

To distinguish PAM data from other data types, we classified PAM datasets based on a combination of count type and platform. Count type is presence, estimated group size or the number of acoustic detections. The platform is either stationary or mobile. Therefore, in total, we added six new PAM data types (i.e. three count types by two platforms) to the OBIS-SEAMAP database. A collection of PAM data from either stationary or towed platforms was stored in a database table with each record representing a species occurrence composed of the location, date/time, identification of the hydrophone that detected the sound, species detected and count along with additional attributes provided by the providers. The count field was always 1 or 0 for a PAM dataset that presents species presence or absence, respectively. In cases where estimates of the number of calling animals were generated (e.g. Ward et al., 2012), the count field held those numbers. For other PAM datasets, the number of detections was included in the count field.

In the OBIS-SEAMAP data center, users can set criteria such as species and region of interest and extract data that meet the criteria. In response to the user's inputs, the site returns maps representing the data, a variety of charts and a summary of the data extracted (e.g. the number of records, the number of species and sum of the group size). These calculations need to account for differences in the meaning of data among data types and avoid misrepresentation of data. To address this challenge, we also amended the existing calculation methods, so the calculation is performed per data type before the results are combined (Fujioka et al., 2014). For example, when calculating the number of animals observed in an interactively selected study area, the count field of visual sighting records is regarded as the group size and summed under the assumption that each sighting observes a different group of animals (Buckland et al., 1993; Thomas et al., 2010). In the case of PAM data, OBIS-SEAMAP does not attempt to estimate a group size from the number of detections and those records without a group size are excluded from the calculation. PAM records indicating the presence or absence of the species are also dropped out from the calculation of the number of animals but those with an estimated group size are included. When such exclusion occurs, the interface clearly notifies that unquantified data records exist that are not included in the calculation.

Survey effort data from towed hydrophone arrays are processed in a similar way to visual line-transect survey data, in which a time series of vessel locations are connected to produce line segments traveled by the vessel. For PAM data from fixed sensors, we produced a set of records having the starting and ending time of the binned time period used for the detection analysis with the sensor locations. If the actual recording or effort time was reduced to a shorter time than the bin size due to the duty-cycle or recording problems, the reduced time was noted in a 'recording time' field. If duty-cycle was not accounted for in the analysis bin size, the proportion of available data per time bin was included when calculating effort.

2.2. Mapping and visualization of PAM detections and effort

From both stationary and mobile hydrophone arrays, PAM records are regarded as species occurrences and represented as points on a map, similar to other data types (e.g. visual sightings). One of the challenges in mapping PAM data along with other data types is to avoid misinterpretation of points while consistently mapping multiple data types. We represented PAM data points on a map with distinctive symbols according to the count type and platform (Table 1). We also added an option to include or exclude PAM data along with other data search criteria such as species, dataset or region.

Another challenge is implementing a spatio-temporal visualization of PAM survey effort for stationary hydrophone data types. We devised a symbol of non-filled ring that encircles the hydrophone location representing detections as a point (Fig. 1). Rendering of stationary PAM survey effort is designed so that the non-filled ring appears during on-duty periods and disappears during off-duty periods. Towed hydrophone array surveys share spatial similarities with visual line-transect surveys, so the same effort mapping methods were adopted for mobile platform effort data (Fig. 1).

OBIS-SEAMAP provides interactive graphing features to explore spatial and temporal changes for a variety of measures. To foster assessments of diel variation in the calls of vocalizing mammals, we developed diel plots that display an hourly summary of detections. In a diel plot for a certain PAM dataset, each species is represented as a series counting either the number of records or the number of detections aggregated over the study duration in one-hour bins from 0 to 23 hours (Fig. 2). Additionally, particular consideration is paid to distinguish different call types from the same species because they may represent different behavioral states or populations that occur within a same region (Oleson et al., 2007a, 2007b; Soldevilla et al., 2010b; Stafford et al., 2001). Previously, OBIS-SEAMAP was only able to represent a species by taxonomic identification codes by the Integrated Taxonomic Information System (http://www.itis.gov/). In cases of species represented by multiple call types, records in the PAM dataset were given a supplementary vocal type code, as highlighted in Fig. 2 that displays separate diel plot lines for different vocal types. Across temporal scales, we added a feature that allows visualization of effort alongside species occurrence to ensure changes in occurrence are understood in the context of when there was PAM effort. We also added the number of calls as an option for the y-axis measure to the graphing features.

Table 1
Classification of PAM data according to the count type and platform and their mapping symbols. Line and fill (for the count type of estimated group size) colors change according to the user's choice (e.g. color-coded by species or dataset).

Count type	Platform	
	Stationary	Mobile
Presence/absence		
Number of detections		
Estimated group size		

3. Results

3.1. Database improvements to integrate PAM data

An initial contribution of PAM data to OBIS-SEAMAP was made by the Density Estimation of Cetaceans from Passive Acoustic Fixed Sensors (DECAF) project led by Len Thomas at the University of St. Andrews. In extending the OBIS-SEAMAP database and improving the mapping and visualization tools to better represent PAM data, however, we have also incorporated PAM data collections from other contributors. As of May 2013, OBIS-SEAMAP has accumulated more than 147,000 PAM records of 12 marine mammal species from 18 datasets, 9 of which were provided by DECAF (Table 2). Fundamental information (i.e. location, date/time, species identification and count) from all PAM records were standardized and included in the database, so statistical calculations or ecological assessments from all data types are possible, under the condition that users understand implications and limitations of combining data across different survey methods and study goals that are presented in the metadata. This is particularly important as PAM data tend to cover spatial and temporal gaps that are difficult to fill with traditional visual surveys. For example, there are only two visual sightings of minke whales in Hawaiian waters from two visual surveys conducted in November 2010 and January 2012 (HDR, 2011, 2012) whereas there are more than 2600 sightings of other cetacean species from 15 surveys from 1913 through 2012 covering all months in effort within the US Exclusive Economic Zone (EEZ) around Hawaiian islands (the western edge was arbitrarily cut at 160.33 W; Table 3 and Fig. 3a and b). Incorporation of one of the PAM datasets from the DECAF project that detected minke whale "boing" vocalizations on hydrophones deployed north of Kaua'i (Mellinger et al., 2011; Martin et al., 2013; seamap.env.duke.edu/dataset/666) added more than 400 records of this species in the study area in February, March and April during the effort period from February through June in 2006. The detection range of minke whale vocalizations is typically ~25 km from the sensors (Martin et al., 2013) and thus the sensors used in the DECAF project did not cover the entire Hawaiian EEZ but the PAM data provide evidence of minke whale occurrences in a part of the Hawaiian waters.

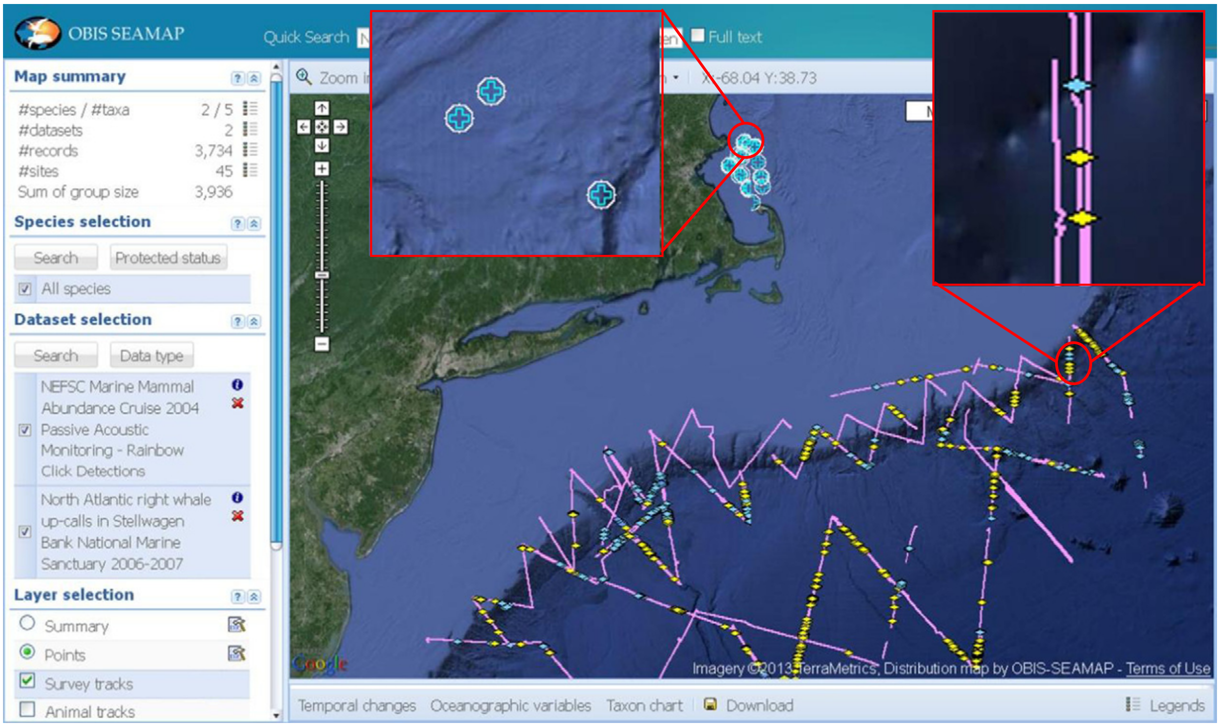


Fig. 1. Detections from towed and fixed sensors are represented as points with the diamond and cross symbols, respectively. Efforts of stationary hydrophones are given a symbol of non-filled circle and those of towed arrays of hydrophones are represented as lines that the platform followed. Point colors are based on species detected: yellow—*Delphinidae*; lighter blue (with cross symbol)—*Eubalaena glacialis*; darker blue (with diamond symbol)—*Physeter macrocephalus*.

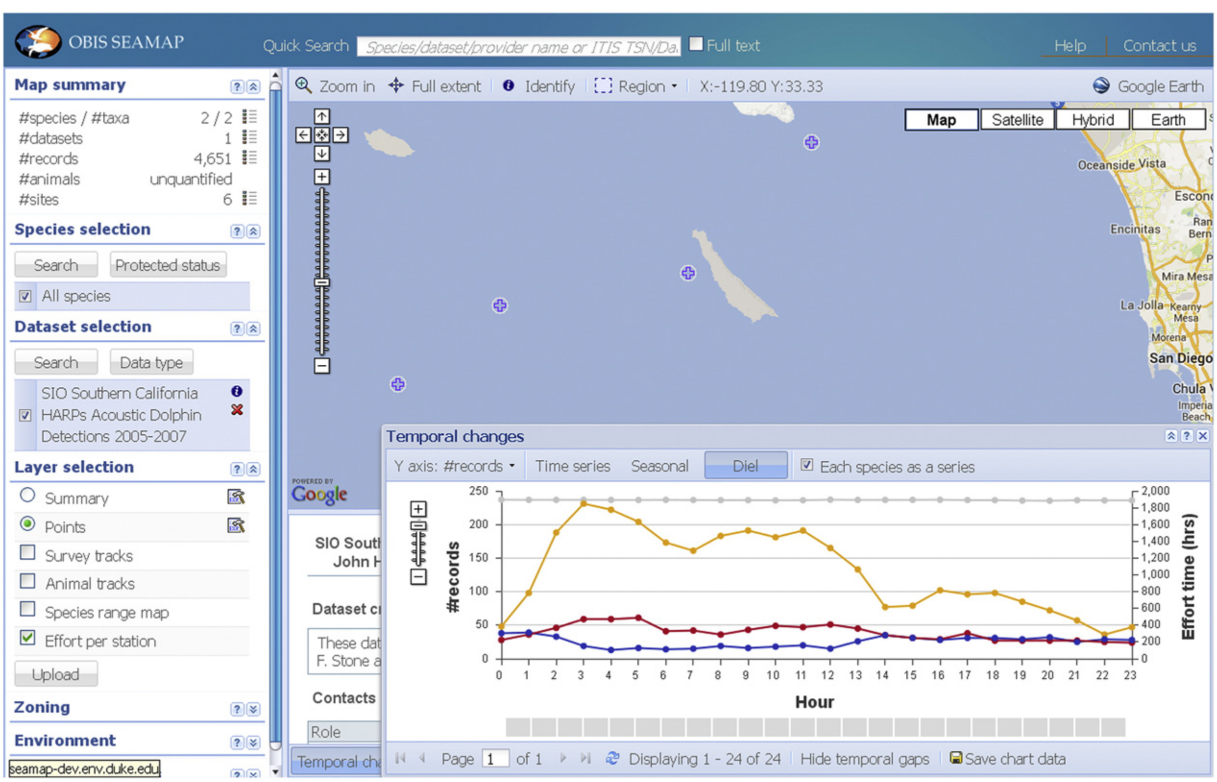


Fig. 2. Diel plots summarize hourly records of presence from 0 to 23 hours per species alongside recording and analysis effort (gray line) based on manual analysis of acoustic data. Two different click types emitted by Pacific white-sided dolphins are separated (Type A: red; Type B: blue). Yellow line is for Risso's dolphins. Hours are in UTC (local time is PST or UTC-8).

Table 2
Passive acoustic monitoring datasets registered and published in OBIS-SEAMAP as of May 2013.

Data source and link to the OBIS-SEAMAP web site	Data type	# of records	Citations or providers
DECAF—AUTEC Beaked whales—Multiple Sensors—Click counts http://seamap.env.duke.edu/dataset/677	Detections station	97,686	Marques et al. (2009)
DECAF—AUTEC Beaked Whales—Multiple Sensors—DTag Seafloor array presence http://seamap.env.duke.edu/dataset/722	Detections station	27,086	Marques et al. (2009)
DECAF—AUTEC Beaked Whales—Single Sensor case study http://seamap.env.duke.edu/dataset/720	Detections station	1	Küsel et al. (2011)
DECAF—AUTEC Sperm Whales—Multiple Sensors—Complete Dataset http://seamap.env.duke.edu/dataset/682	Detections station	675	Ward et al. (2012)
DECAF—AUTEC Sperm Whales—Multiple Sensors—Samples http://seamap.env.duke.edu/dataset/680	Group size station	49	Ward et al. (2012)
DECAF—PMFR Minke Whales—Multiple Sensor—Automated Boing Detections http://seamap.env.duke.edu/dataset/668	Detections station	192	Martin et al. (2013), Mellinger et al. (2011)
DECAF—PMFR Minke Whales—Multiple Sensor—Boing Associations http://seamap.env.duke.edu/dataset/664	Detections station	1067	Marques et al. (2011), Martin et al. (2013)
DECAF—PMFR Minke Whales—Multiple Sensor—Boing Localizations http://seamap.env.duke.edu/dataset/675	Detections station	23	Martin et al. (2013)
DECAF—PMFR Minke Whales—Multiple Sensor—Manual Boing Detections http://seamap.env.duke.edu/dataset/666	Detections station	408	Mellinger et al. (2011), Martin et al. (2013)
Duke Cherry Point PopUps 2005–2006 Bottlenose dolphin whistle presence http://seamap.env.duke.edu/dataset/567	Detections station	1026	Read et al. (2007)
Deep Panuke whale Acoustic 2003 http://seamap.env.duke.edu/dataset/651	Group size vessel	17	Potter et al. (2007)
Baltic Porpoise Acoustic Surveys 01–02 http://seamap.env.duke.edu/dataset/343	Group size vessel	462	Gillespie et al. (2005)
SIO Southern California HARPs Acoustic Dolphin Detections 2005–2007 http://seamap.env.duke.edu/dataset/533	Detections station	4651	Soldevilla et al. (2010a, 2010b, 2011)
Acoustic detections of Arctic mammals in the western Beaufort Sea 2010–2011 http://seamap.env.duke.edu/dataset/914	Presence station	5824	Stafford, K., University of Washington
NEFSC Marine Mammal Abundance Cruise 2004 Passive Acoustic Monitoring—Porpoise Detections http://seamap.env.duke.edu/dataset/537	Group size vessel	914	Gillespie et al. (2005); Van Parijs, S., NOAA
NEFSC Marine Mammal Abundance Cruise 2004 Passive Acoustic Monitoring—Rainbow Click Detections http://seamap.env.duke.edu/dataset/509	Group size vessel	1241	Van Parijs, S., NOAA
NEFSC Marine Mammal Abundance Cruise 2004 Passive Acoustic Monitoring—Whistle Detections http://seamap.env.duke.edu/dataset/535	Detections vessel	3195	Van Parijs, S., NOAA
North Atlantic right whale up-calls in Stellwagen Bank National Marine Sanctuary 2006–2007 http://seamap.env.duke.edu/dataset/892	Detections station	2743	Mussoline et al. (2012)

3.2. Mapping and visualization of PAM detections and effort

Integration of PAM data into the OBIS-SEAMAP database facilitates use of most of the mapping and visualization tools previously developed for other data types (i.e., overlays of oceanographic layers, display of seasonal/annual histograms). For example, using the OBIS-SEAMAP web site, a researcher can specify a region of interest using drawing tools, and extract, map or download the data that fall in the region and determine which species have been observed there (Halpin et al., 2009). The extracted data may include events from all data types, including visual sightings, acoustic detections, or tagged or photo-identified animals. Individual symbols distinguish PAM data from other data types in a map view. For example, points from a towed hydrophone are represented by a diamond symbol and those from a

Table 3
A list of species found in the US EEZ around the Hawaiian islands (the western edge was arbitrarily cut at 160.33 W) with the number of records of visual sightings, the number of datasets contributing to the sightings and the observed months.

Scientific name	Common name	# of records	# of datasets	Months
Balaenoptera acutorostrata	Minke whale	2	2	Jan, Nov
Balaenoptera borealis	Sei whale	1	1	Nov
Balaenoptera physalus	Fin whale	1	1	Dec
Feresa attenuata	Pygmy killer whale	45	4	All months except Mar
Globicephala macrorhynchus	Short-finned pilot whale	516	6	Year around
Grampus griseus	Risso's dolphin	8	1	Apr, May, Jul, Aug, Sept, Nov
Indopacetus pacificus	Longman's beaked whale	1	1	Aug
Kogia breviceps	Pygmy sperm whale	6	2	Jan, May, Jun, Aug, Nov
Kogia sima	Dwarf sperm whale	74	1	All months except Feb, Sept
Lagenodelphis hosei	Fraser's dolphin	2	1	Apr, May
Megaptera novaeangliae	Humpback whale	629	10	Jan through May, Nov, Dec
Mesoplodon densirostris	Blainville's beaked whale	48	2	All months except Feb
Orcinus orca	Killer whale	1	1	May
Peponocephala electra	Melon-headed whale	53	1	Year around
Physeter macrocephalus	Sperm whale	118	5	Year around
Pseudorca crassidens	False killer whale	47	3	All months except Jun
Stenella attenuata	Pantropical spotted dolphin	396	3	Year around
Stenella coeruleoalba	Striped dolphin	29	1	Apr through Oct, Dec
Stenella longirostris	Spinner dolphin	203	8	Year around
Steno bredanensis	Rough-toothed dolphin	174	2	All months except Feb
Tursiops truncatus	Bottlenose dolphin	196	5	Year around
Ziphius cavirostris	Cuvier's Beaked whale	64	1	All months except Feb, Mar, Jun

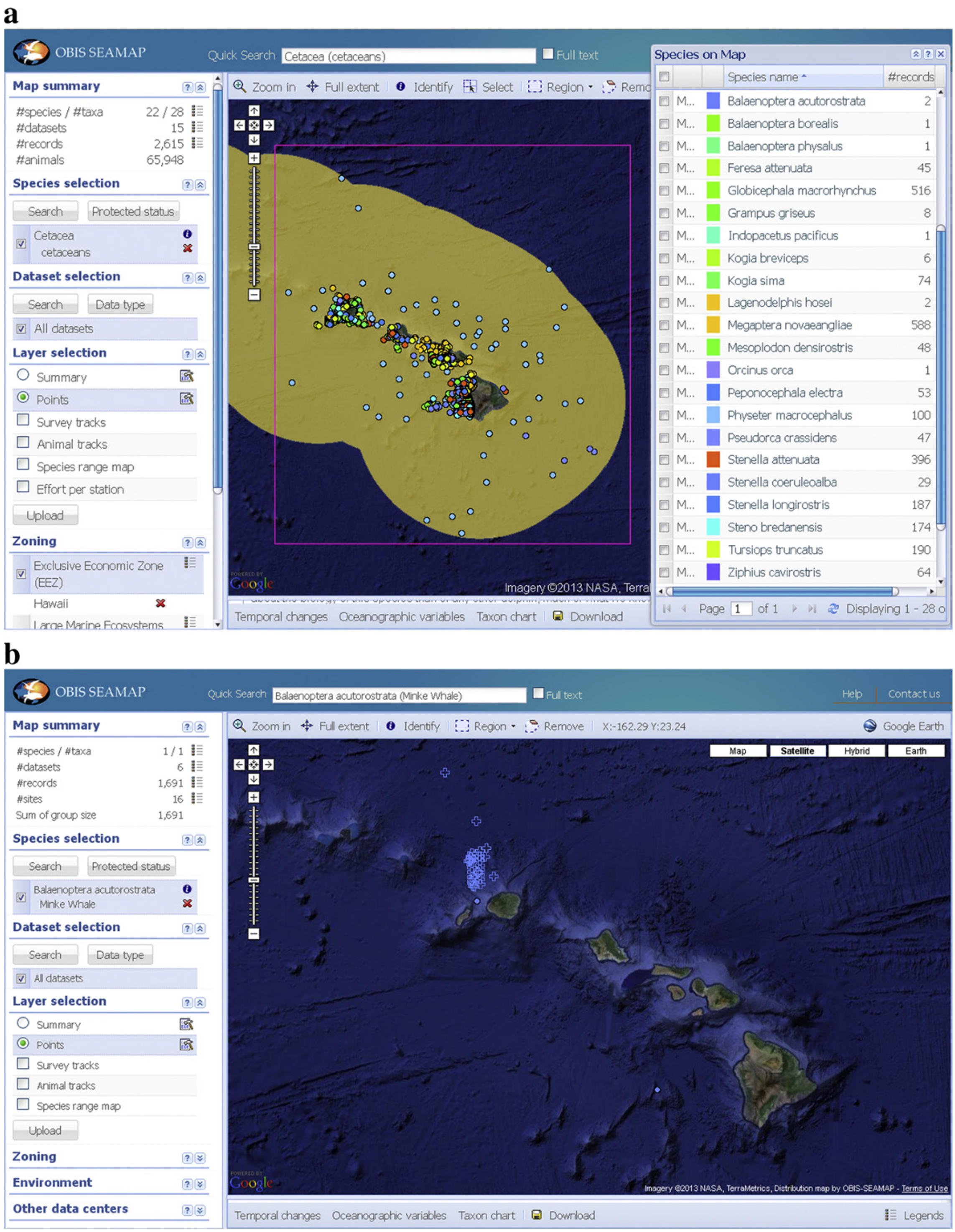


Fig. 3. Occurrences of cetacean species in US EEZ around the Hawaiian islands (yellow polygon; the western edge was arbitrarily cut at 160.33 W indicated by the pink bounding box) based on data from 15 visual surveys (a) and those of minke whales including the acoustic sensor locations (b). Points are color-coded by species.

fixed hydrophone are rendered with a cross (Table 1 and Fig. 1). Moreover, points representing the estimated number of animals are marked with filled symbols whereas those representing the number of detections are given non-filled symbols (Table 1 and Fig. 1). Presence-only detections are given different symbols (Table 1).

Effort data from PAM datasets are visualized differently depending on platform type (stationary or mobile). The locations of towed hydrophone arrays are displayed as survey lines, but those of fixed hydrophones are rendered with non-filled circles around hydrophone locations (Fig. 1). The temporal exploration features of OBIS-SEAMAP can be used in combination with the mapping features to find locations and periods when animals were vocally detected during the binned time period or the recording duration. For example, by selecting a day of interest, a researcher can identify locations with recording effort and acoustic detections as well as those with recording effort but no acoustic detections, which in turn helps assess behavior patterns from a spatial and temporal standpoint. If there is no recording effort on a chosen day, the query will yield neither effort nor detection symbols to denote that no effort was made on that day. Similarly, the addition of effort visualization capabilities to temporal charts allows researchers to account for differences in sampling intensity (e.g. duty cycle) that is particularly useful for PAM data from fixed instruments.

An additional enhancement to the temporal exploration features is the extended resolution of temporal charts to the hourly level allowing users to examine diel patterns and interactively select and filter PAM data by period of interest (e.g. in the morning or at night). This diel exploration feature can be combined with other temporal and spatial exploratory tools. For example, researchers can assess and compare diel patterns of vocal activities in different seasons and in separate regions (e.g. the East Pacific and the North Atlantic).

The ability to distinguish different call types from the same species further enhances in-depth assessments allowing researchers to examine the relationship between vocal activities and behavior patterns or identification of distinct populations (e.g. Soldevilla et al., 2010a, 2010b; Stafford et al., 2001; Oleson et al., 2007a, 2007b; Fig. 2). Different call types can be also selectively mapped which provides a useful tool to explore geographic variation in calling behavior.

3.3. Case studies

3.3.1. Risso's dolphins in the Southern California Bight

To demonstrate the new exploratory tools developed for PAM data, we used a dataset that includes acoustic detections of Risso's dolphins (*Grampus griseus*) at six stationary hydrophones deployed throughout the Southern California Bight between 2005 and 2007 (Soldevilla et al., 2010a, 2010b, 2011). Each record of the dataset represents the number of minutes with echolocation clicks present in one-hour time bins. Using this dataset, we explored diel variability in vocalizations with diel plots for the four hydrophones that recorded more than two detections (Fig. 4). In addition to visual assessments of online diel plots, we downloaded the source data represented in the diel plots (i.e. the numbers of minutes with detections and effort time over 24 hours) and normalized the detection rate by dividing the number of minutes with detections by hours of effort.

Diel plots of each of the four hydrophones assessed showed similar diel variability with three peaks just after sunset (ranging 00:46 to 03:20 in UTC), prior to sunrise (ranging 12:44 to 15:11 in UTC) and in mid-morning (Fig. 5). Overall, detections were more numerous at night times than day times across locations (Fig. 5).

3.3.2. Bowhead whales in the Western Arctic

In the second case study, we compared a visual sighting dataset and a stationary presence-type PAM dataset for bowhead whales (*Balaena mysticetus*) and explored seasonal and diel variation in sightings and acoustic detections to investigate how the PAM data could complement visual surveys and fill temporal gaps. For visual sightings of bowhead whales, we used a dataset from the Aerial Surveys of Arctic Marine Mammals project (Clarke et al., 2011; seamap.env.duke.edu/dataset/825) that focused on the fall migration of bowhead whales, with some additional surveys in spring. Visual survey effort occurred only during daylight hours. For PAM data, we used a set of detections recorded using a fixed hydrophone placed in the Beaufort Sea provided by Kathleen Stafford at the University of Washington. Acoustic monitoring was on during the first 15 minutes of every hour starting on 9/25/2010 and ended on 8/29/2011 and each record in this dataset represents a detection within an hour-long interval.

Bowhead whales make annual migrations back and forth between the Bering Sea and Beaufort Sea, so their occurrence along the north coast of Alaska is highly seasonal (Moore and Laidre, 2006). To make PAM data recorded at a single location comparable with sighting data covering broader areas, we arbitrarily limited our case study to a bounding box around the hydrophone location 4° (longitude) by 2° (latitude) that provided a wider area than the typical detection range of bowhead whale vocalizations (20–30 km; Moore et al., 2010). An arbitrary shape of a boundary can be also drawn, which might better represent a study area.

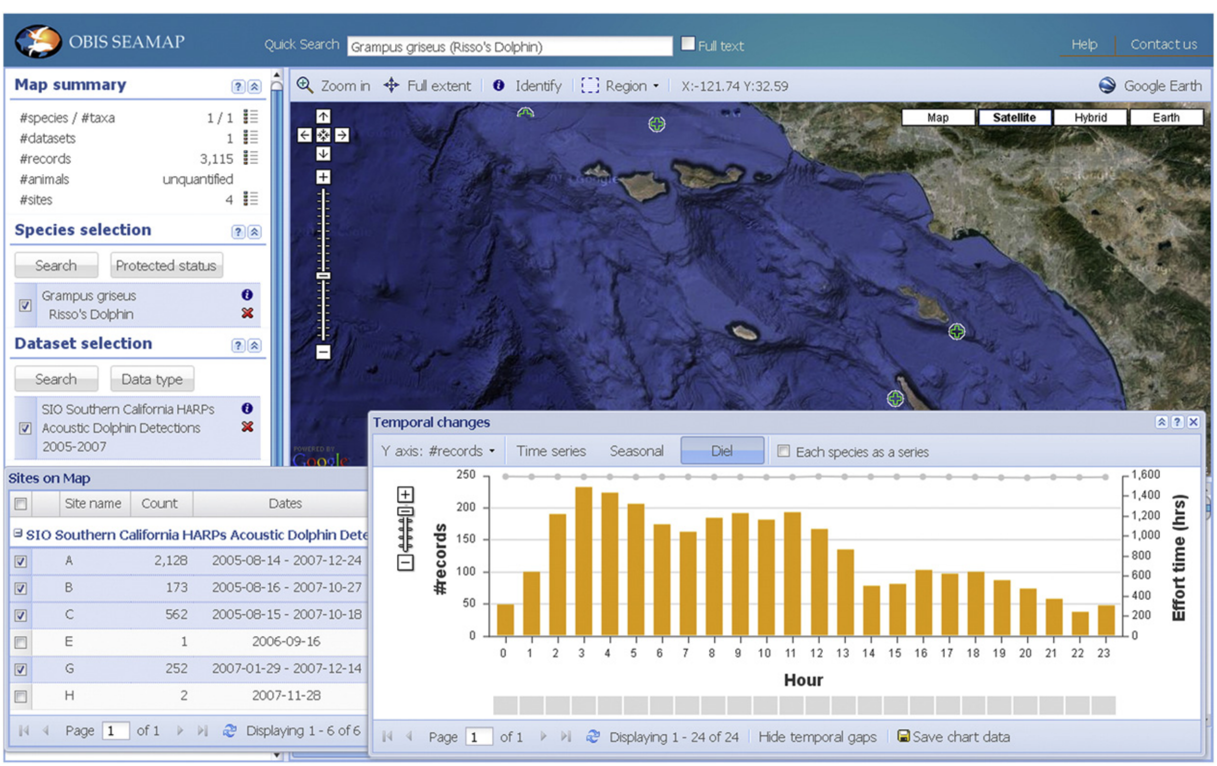


Fig. 4. Locations of the four hydrophones having more than two detections and diel plots summing up detections from the hydrophones along with total effort hours (gray line) from "SIO Southern California HARPs Acoustic Dolphin Detections 2005–2007." Four hydrophones on the map are identified as Sites C, B, A, G in a clockwise circle from the top left (just below [Identify] button). Hours are in UTC (local time is PST or UTC-8). Note: OBIS-SEAMAP uses tiling technology to map a large area. Due to this, a portion of the two northern hydrophone location symbols are not visible where two tiles line up.

Out of 6151 sightings of bowhead whales from the aerial survey dataset, 1074 fell in the bounding box. The PAM data added 1859 records of hourly presence. The diel plots of visual sightings and acoustic detections showed that the number of records roughly followed hourly variation in effort (Fig. 6). The larger numbers of records in daytime are attributable to visual sightings, but acoustic detections occurred at a relatively uniform rate throughout the day and night (Fig. 6).

The seasonal changes of the number of visual sighting records showed two peaks in spring (i.e. April and May) and fall (i.e. September and October; Fig. 7a). This trend remained when the record numbers were divided by effort hours to normalize sighting rates (Fig. 7b). The seasonal detections of bowhead whales at the hydrophone exhibited a broader increase from April through July with a peak in June (Fig. 8a). However, a fall peak comparable with the one from visual sightings

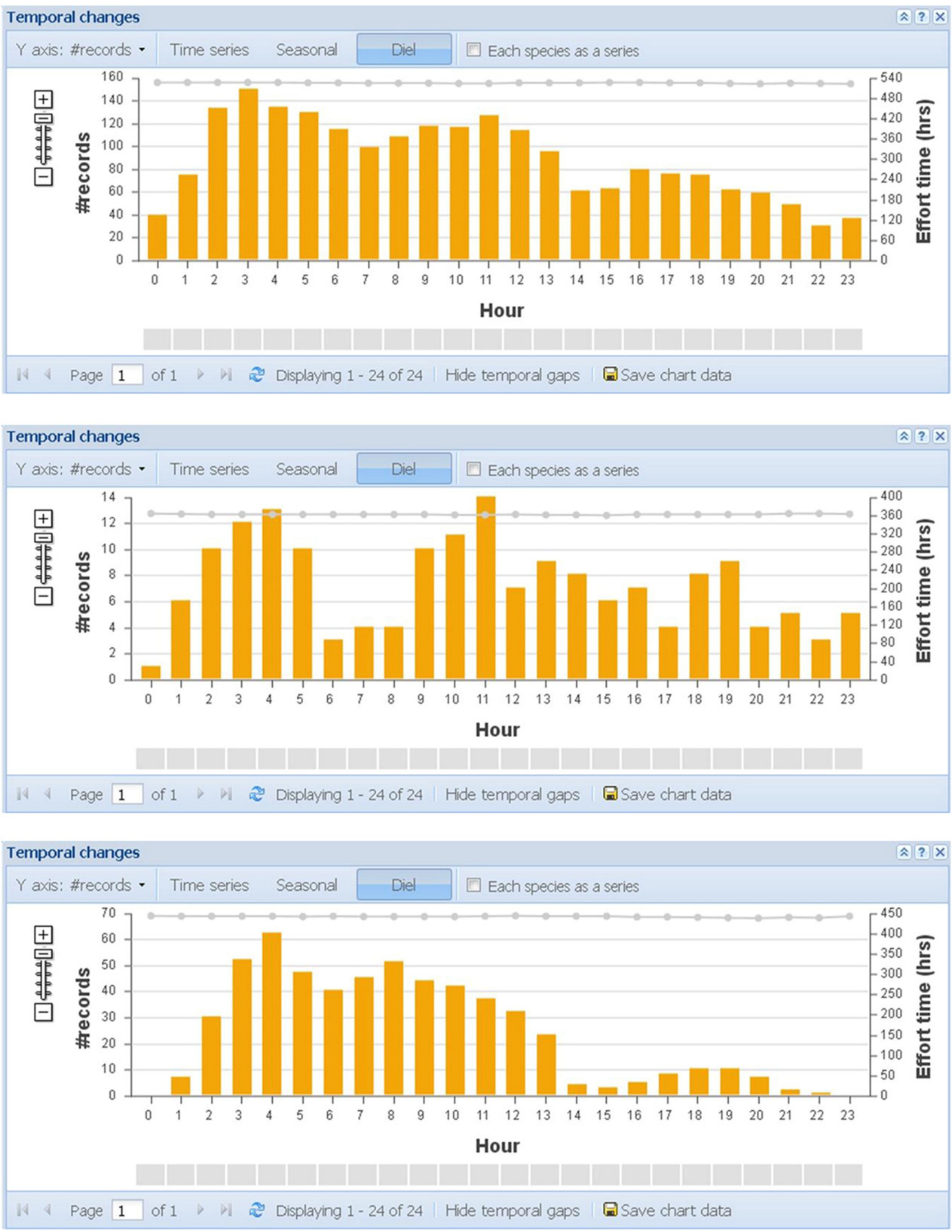
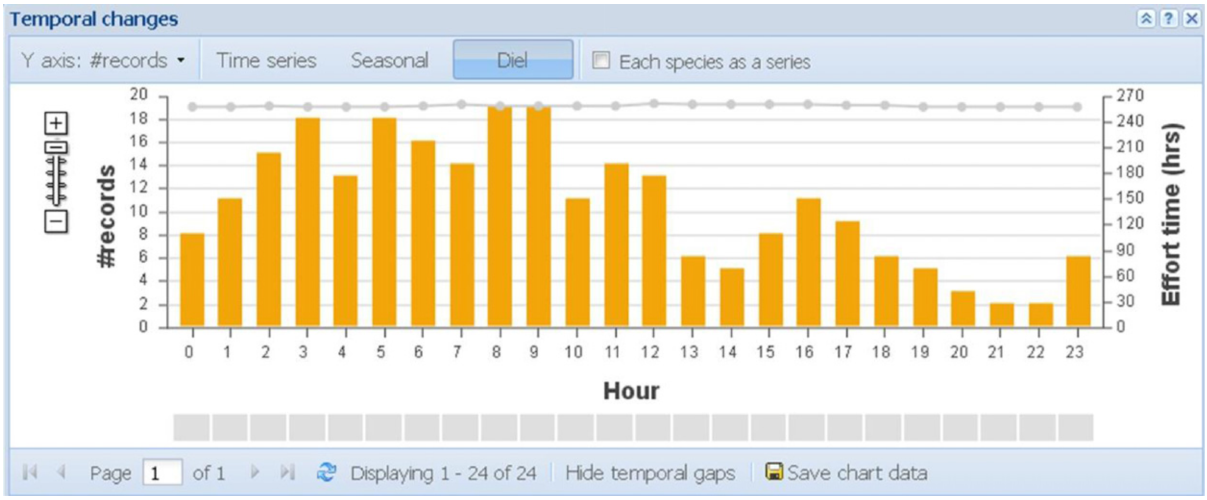


Fig. 5. Diel plots of four hydrophones A, B, C and G (from top to the fourth chart) with normalized detection rates (bottom). The hours at the x-axis are in UTC (local time is PST or UTC-8).



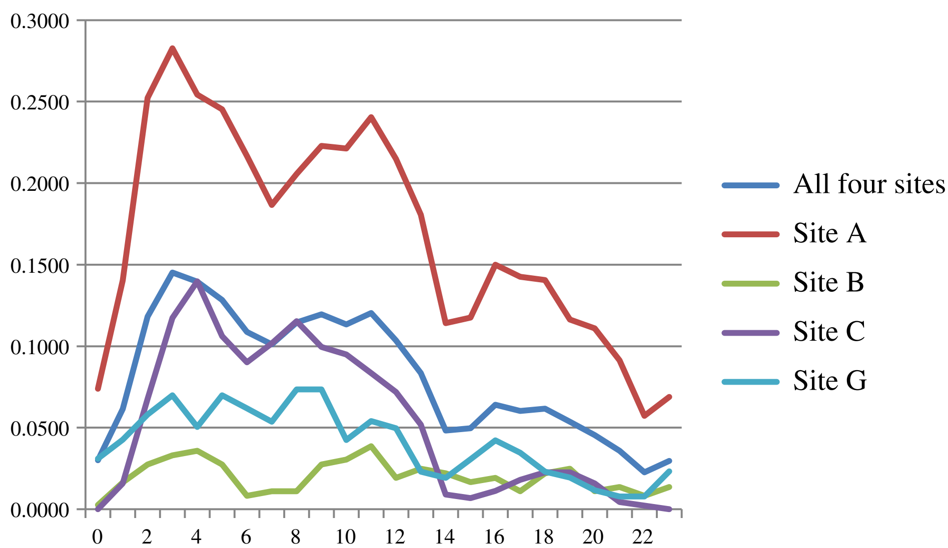


Fig. 5. (*continued*).

was not obvious even when these acoustic data were normalized by effort (Fig. 8b).

4. Discussion

4.1. Database improvements to integrate PAM data

By integrating PAM data into a biogeographic database, researchers can complement traditional visual survey data, advance the types of analysis possible, improve the accuracy of their outputs and reduce uncertainty. For example, an increasing number of studies combine visual sightings and PAM detections to improve detection probabilities and to estimate density of the target species (e.g. Barlow and Taylor, 2005; Gerrodette et al., 2011; Oleson et al., 2007a, 2007b). It is also possible to combine multiple data types collected from different surveys conducted in broader areas and longer time periods than any single project could cover.

The analysis of minke whale occurrence in Hawaiian waters clearly illustrates the complementarity of visual and PAM data. Minke whales are known to occur in low-latitudes globally while breeding (Gedamke et al., 2001), but the paucity of sightings in Hawaiian waters led to suggestions that the species is rare there (Shallenberger, 1981). However, recent PAM studies suggest that minke whales are more common in Hawaiian waters than previously believed (Oswald et al., 2011; Rankin et al., 2007). The discrepancy between visual and acoustic records is due, at least in part, to the difficulty of observing minke whales in poor weather conditions (Rankin et al., 2007). In one study, 88% of minke whale sightings were recorded in calm sea states (i.e. Beaufort 0 or 1) that comprised less than 4% of survey effort (Rankin et al., submitted for publication).

To allow better understanding of PAM data from individual projects and meaningful comparisons of data sets from different projects, it is crucial to include metadata detailing descriptions of survey goals, monitoring equipment, monitoring methods, the DCL algorithms or manual analytical processes, and the assumptions and limitations of the summarized data published in a data center. In the case of the PAM data from the DECAF project, existing OBIS-SEAMAP metadata standards, that adopt those described by the Federal Geographic Data Committee (FGDC) and Global Change Master Directory (GCMD), provide space for brief descriptions of data processing, references to the peer-reviewed articles addressing the surveys and resulting data, and a link to the project web site (http://www.creem.st-and.ac.uk/decaf/) which provides in-depth documentation of the project with links to original data. These standards, however, do not include elements that explicitly address attributes specific to PAM data such as sensor's bandwidth, monitoring cycles, or parameters used for DCL processes. We are currently extending metadata standards to accommodate such elements as part of a project funded by the US National Oceanographic Partnership Program (NOPP) and National Science Foundation. OBIS-SEAMAP will, therefore, incorporate the extended metadata standards for PAM,

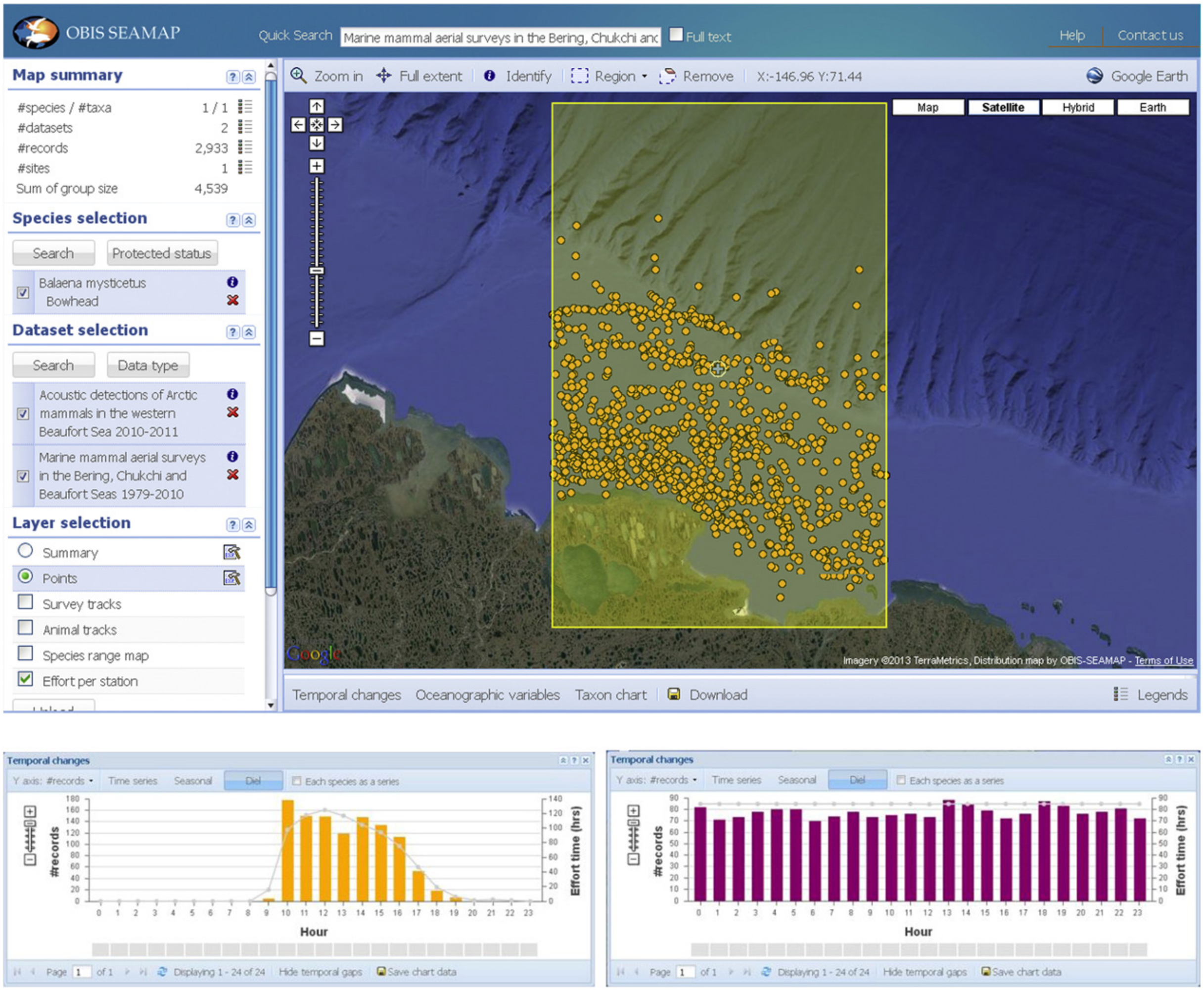


Fig. 6. Bowhead whale visual sightings (yellow points) and the location of the hydrophone (blue cross with a gray circle representing sampling effort) with diel plots of the number of records from visual sightings (left) and PAM detections (right). Gray lines in the plots represent effort hours.

collaborate with data providers to refine and present the metadata, so that users understand the nature of the PAM data and their limitations.

Analysis of biometric quantities (e.g. the number of animals) derived from a biogeographic database requires a clear understanding of the metrics incorporated and any normalization method used in the database. Multiple records of detections could be consolidated to one presence record per unit time (e.g. day) but this treatment could still lead to an overestimate of abundance as the records could have been generated from a single animal. An underestimate is also possible as sensors could detect only a single caller from a group of animals. For a more justifiable estimation of the density or abundance of the species from PAM detection data, specialized statistical methods are required—such methods are still in development (Marques et al., 2009; Martin et al., 2013). Due to these complexities, we excluded PAM data representing presence or the number of detections from summary calculations (e.g. the number of animals in a study area) and marked them as 'unquantified', resulting in limits to our knowledge of species abundance. Further improvements in incorporating PAM data are required to produce more justifiable biometric quantities for abundance or density analyses.

4.2. Mapping and visualization of PAM detections and effort

While integrating PAM data into OBIS-SEAMAP, we classified six count and platform type combinations and implemented different rendering for each of these. However, raw PAM data recordings can be processed to produce various types of outputs depending on research questions, study design, and processing methods. In the case of the minke whale detections from a stationary array, we produced four datasets with similar sets of data analyzed with different objectives and methods (i.e. manual detections, automated detections, call associations across an array, and localizations). One of the four datasets, for example, represents associations of the same "boing" call received on multiple hydrophones, which is necessary to estimate the density of these sounds using spatially explicit capture-recapture methods (Marques et al., 2011). Records in each of the four datasets have different meaning and are suitable for different applications, but they are currently classified as the same data type in the OBIS-SEAMAP database and hence rendered with the same symbol. These datasets partially overlap, so mapping them together could lead to misinterpretation (e.g. an overestimate of abundance of minke whales). To distinguish them more clearly and avoid confusion, we will need to develop and implement more appropriate classification and mapping and visualization methods.

We realize that the representation of PAM detections as points at the locations of devices on the map needs further improvement. Call detection ranges differ among species, vocal types, monitoring equipment and environmental conditions (e.g. ambient noise from wind or shipping, sound propagation effects). For example, bottlenose dolphin whistles in the 5–20 kHz frequency range can be detected up to 3 km but baleen whale calls in the 20–100 Hz frequency range propagating through the SOFAR channel can be detected

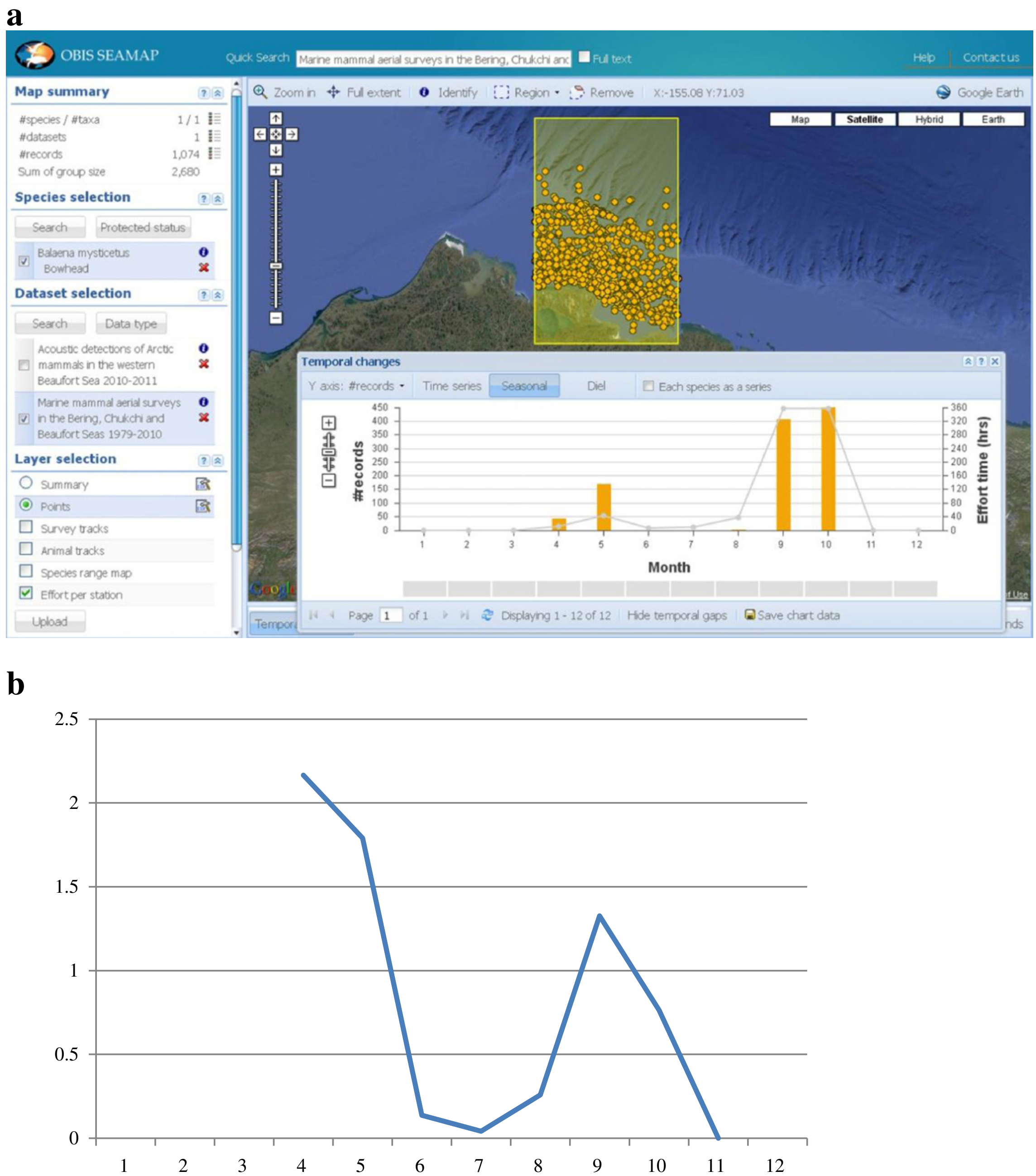


Fig. 7. Seasonal changes of bowhead whale sightings from "Marine mammal aerial surveys in the Bering, Chukchi and Beaufort Seas 1979–2010" within the bounding box of the case study: a) the number of records each month along with effort hours (gray line); b) normalized sighting rate (no effort in January through March and December).

at hydrophones located hundreds of kilometers away (Jensen et al., 2012; Širović et al., 2007). Thus, mapping species occurrences at the device locations can inaccurately represent species' distributions. It might be possible to resolve this problem by adding a radial boundary of an estimated detection range to mapped device point locations or to replace points with polygons as detection ranges of the devices for the target species are the fundamental information to estimate the population density (e.g. McDonald and Fox, 1999).

Species classification from acoustic records can be difficult, and geographic variability in call types may occur (McDonald et al., 2006). Ideally, PAM data would be presented with records of the vocal sounds themselves. Due to the large storage requirements to store raw sound data, however, we found it more reasonable to establish links to external sound data repositories (e.g. MobySound [http://www.mobysound.org/] and Macaulay Library [http://macaulaylibrary.org/]) rather than storing them in the biogeographic data center. Another possibility is to archive sample spectrograms and recording clips of representative calls and associate them with the corresponding PAM records in the database. These images or sounds can be presented online using a similar mechanism implemented for images of photo-identification catalogs (Fujioka et al., 2014).

Diel plots are often used in analyses of PAM data to assess temporal patterns of call detections that may result from foraging and movement behaviors (e.g. Soldevilla et al., 2010a, 2010b), but our integration efforts made them available for visual sightings as well, so it is possible for researchers to combine visual sightings and PAM data into a diel plot. It is also worth noting that the capability of presenting each species as a time series in a temporal chart is particularly helpful as PAM oftentimes records multiple species at the same location. This capability allows for an ecological comparison among detected species.

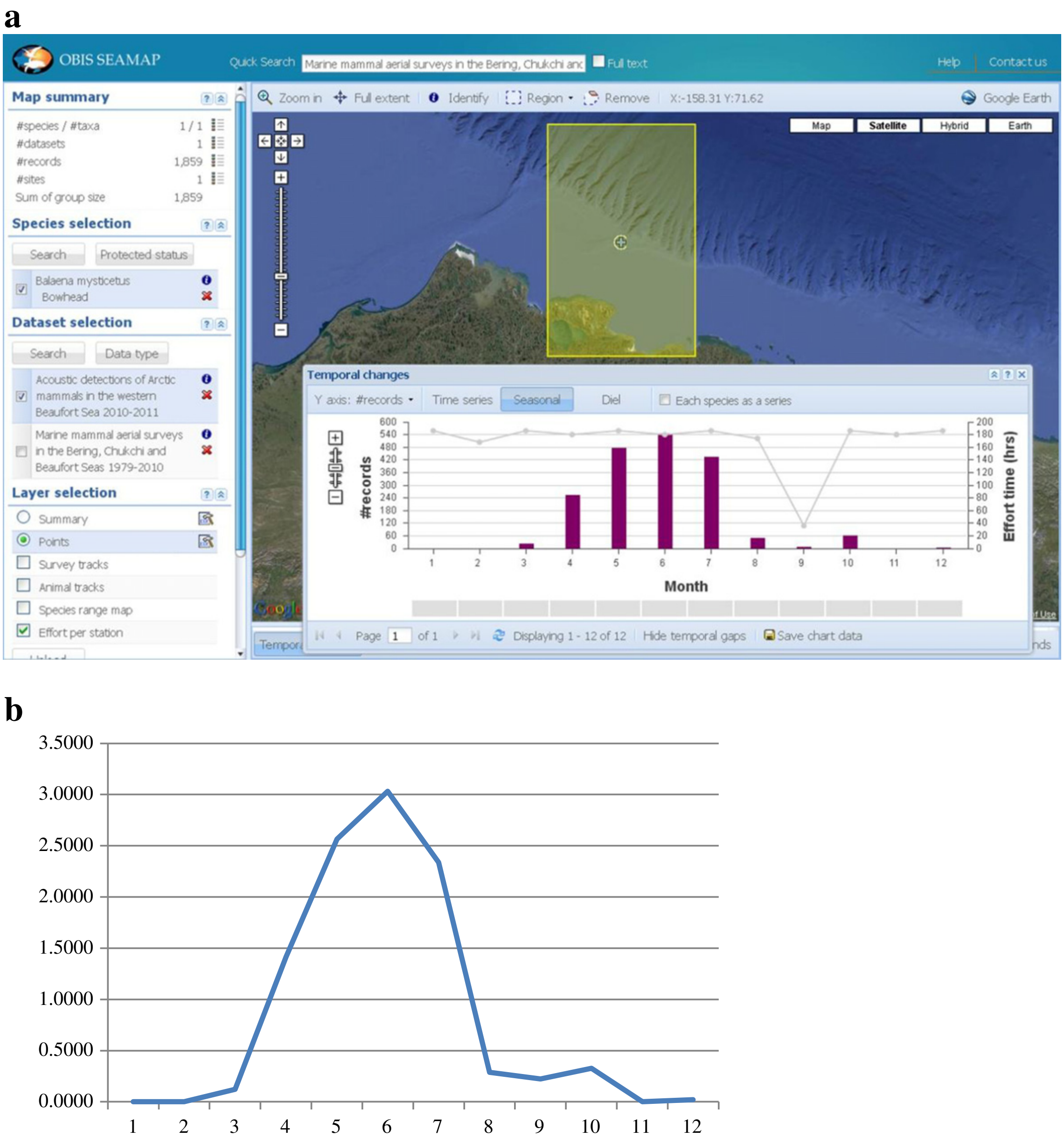


Fig. 8. Seasonal changes of bowhead whale detections from “Acoustic detections of Arctic mammals in the western Beaufort Sea 2010–2011”: a) the number of detections each month along with effort (recording) hours (gray line); b) normalized detection rate.

4.3. Ecological and technical considerations of case studies

4.3.1. Risso's dolphins in the Southern California Bight

Diel variability in vocalizations can represent a change in behavior, leading to higher calling rates at a given time of day, or movements into and out of the detection ranges of the hydrophones (Mellinger et al., 2007). The similarity between diel plots across the four hydrophones revealed in this case study suggests the diel variability represents a behavioral change in Risso's dolphin vocal activity throughout the Southern California Bight rather than diel movements toward or away from the hydrophones. If this variation is due to diel movement patterns, such as those exhibited by Hawaiian spinner dolphins (Norris et al., 1994), diel patterns of vocal detections would likely vary by site. Risso's dolphins produce echolocation while foraging, so the higher detection rates at night likely reflect increased foraging activity as the deep-scattering layer migrates to the surface (Soldevilla et al., 2010a). This case study demonstrates the advantages of being able to examine both spatial and temporal aspects of PAM data to draw comparisons across sites that, in turn, improves our understanding of the ecology of the species of interest.

4.3.2. Bowhead whales in the Western Arctic

The use of PAM to observe bowhead whale presence is particularly important in the harsh environment of the Arctic, where visual surveys are limited by weather and lighting conditions and whales often migrate under ice (Raftery and Zeh, 1998). This case study demonstrates the advantage of combining visual sighting and PAM data to extend temporal coverage on both annual and diel time scales. The PAM dataset included bowhead calls throughout day and night in all months but January, February and November, whereas the visual sightings were constrained to periods of daylight when observers were on effort. These constraints severely limited the duration of visual monitoring to the hours of 09:00 to 22:00 h and the months of April through October.

The two seasonal peaks of bowhead whale sightings from the visual data coincided well with prior knowledge of the timing of seasonal migrations passing off Barrow, Alaska (Clarke et al., 2011), but the PAM data indicate that the fall migration may not be well detected by the acoustic recorder. This could be attributed to the tendency of individual whales taking routes closer to the coast in fall than in spring (Braham et al., 1980; Treacy et al., 2006). In fact, a qualitative assessment of the visual sightings in spring and fall demonstrated that the recorder was appropriately located to detect the spring migration, but visual sightings in fall occupied a broader area that extended beyond the bowhead whale call detection range for the PAM instrument (Fig. 9). The estimated detection range of the hydrophone was 20–30 km (Moore et al., 2010), so whales migrating near shore in fall were likely outside this range, although the estimated detection range may not be applicable to near shore environments. Alternatively, the whales may not have been as vocally active in the fall as in the spring.

Aerial survey coverage within the case study bounding box in June and July was extremely limited, with only 6.1 and 9.5 hours spent surveying, respectively and resulted in no sighting of bowhead whales. However, the PAM data exhibited the highest detections in June. The limited visual survey efforts in June and July and lack of overlap between visual and acoustic survey years (except September and October 2010) hinder further investigation to assess the seasonal

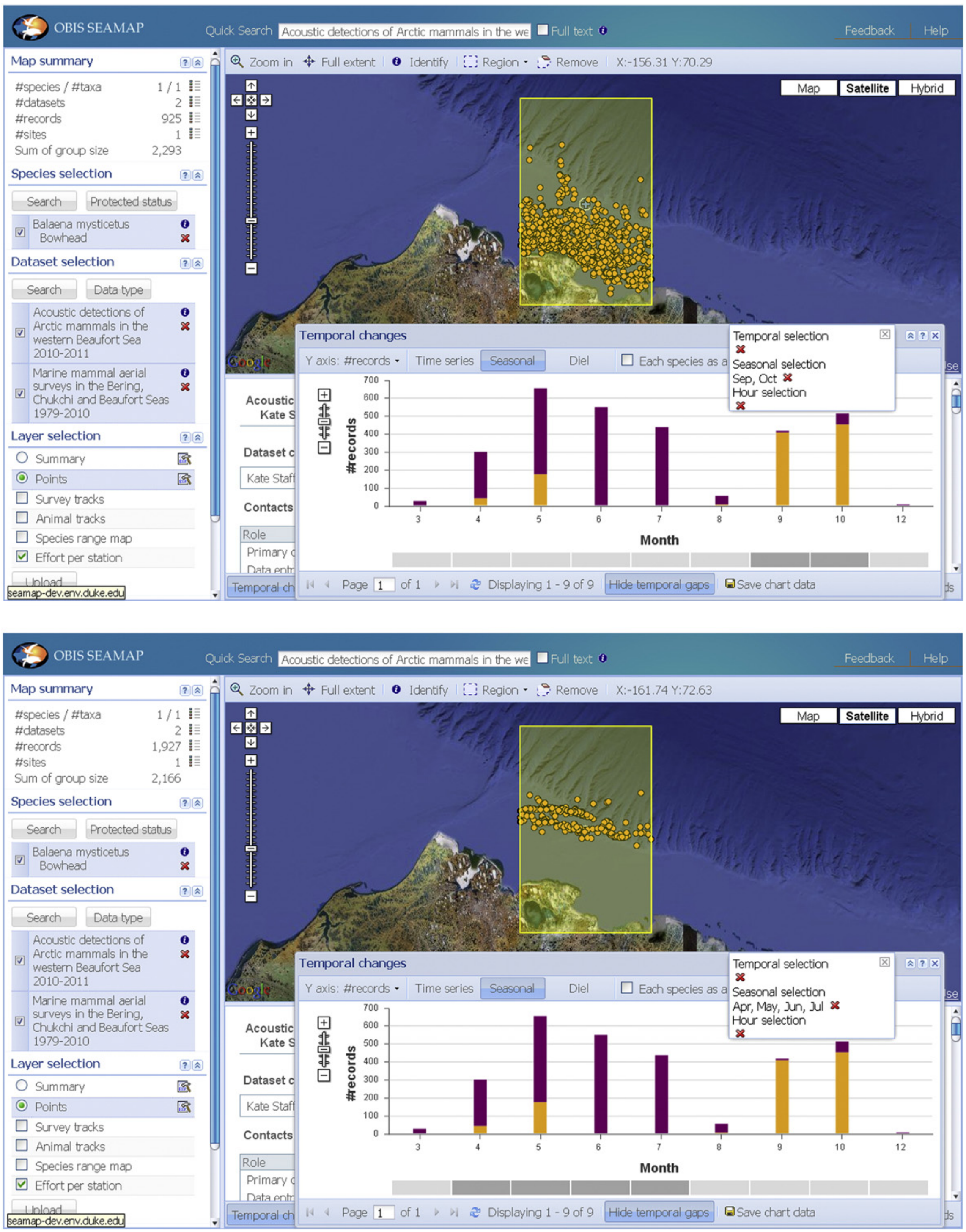


Fig. 9. Bowhead whales tend to migrate closer to the coasts in September and October (above) than in April through July (below). The hydrophone was located right on spot for the spring migration.

shift of peak detections between visual and PAM data. The difference could be caused by an inter-annual shift in the timing of migration, variation in detectability based on behaviors (e.g. if whales spend more time at depth and vocalizing when feeding) or anthropogenic impacts on their distribution (e.g. Moore and Laidre, 2006; Moore et al., 2010). The ability to conduct these comparisons using the OBIS-SEAMAP mapping and visualization tools and generate ecological questions for further study demonstrates the advantage of integrating PAM data with other data types in a biogeographic database. This case study also emphasizes the importance of effort data, which are critical for comparisons across different locations in a single dataset or among different datasets.

4.4. Conclusions

Visual sighting surveys, telemetry records, photo-identification catalogs and PAM data represent different views into the ecology, distribution and behavior of marine mammals. Sometimes these different types of data are complementary and strengthen the results of a study, but in other cases they can produce seemingly contradictory outcomes (e.g. Rogers et al., 2013). Nevertheless, the integration of these data types into a biogeographic database provides new views of and tools to assess the ecology of marine mammals and global-scale biodiversity. For example, while quantitatively combining different data types into environmental niche models to predict species density remains a significant modeling challenge (Aarts et al., 2008; Louzao et al., 2009), such an approach will provide more reliable inputs for the delineation of marine protected areas for marine spatial planning.

Growing realization of useful applications of PAM data leads to higher demands on PAM data in national and international conservation-oriented projects. For example, in 2011, the U.S. National Oceanic and Atmospheric Administration (NOAA) initiated several efforts to improve methods to manage cumulative impacts of human activities on marine mammals. One of such efforts is the Cetacean Density and Distribution Mapping Group (CetMap) in which PAM data are being used to improve presence maps for various marine mammal species. OBIS-SEAMAP has contributed a significant amount of visual survey data to CetMap and we expect to contribute PAM data as well.

We hope that the improvements of the OBIS-SEAMAP database and features and the case studies presented here will provide a common framework to facilitate the wider use of PAM data and encourage acoustic researchers and data centers to accelerate data sharing of PAM data.

Acknowledgments

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