2011

Quantitative ocean characterisation: Acoustically analogous environments

Reeder, D.B.

Journal of Operational Oceanography, Vol. 4, No. 1, 2011
http://hdl.handle.net/10945/45322

Quantitative ocean characterisation: Acoustically analogous environments

DB Reeder, CL Bryan, KR Everett, ML Batteen and AA Guest, Department of Oceanography, Naval Postgraduate School in Monterey, California, USA

Characterisation of the oceanic environment is of interest to many different scientific and engineering disciplines, including geologists, fisheries managers, marine mammal biologists, ocean resource managers, conservationists and ocean acousticians. Quantitative environmental characterisation requires a robust and efficient methodology to evaluate vast amounts of spatiotemporal environmental data. Presented here is such a methodology – flexible and robust enough to be used in multiple applications. The case presented is the determination of acoustically analogous environments in the ocean. A key element of this work is the construction of a set of acoustically relevant parameters which characterise acoustical properties of the water column, based on the sound speed profile. Results of this methodology demonstrate that this set of acoustically significant parameters accurately represent the acoustic propagation characteristics of the ocean environment.

LEAD AUTHOR'S BIOGRAPHY

D Benjamin Reeder is a Research Assistant Professor at the Naval Postgraduate School in Monterey, CA, USA. His research interests include shallow-water environmental characterisation, acoustic propagation through non-linear internal waves, acoustic scattering by marine organisms and ocean noise.

INTRODUCTION

Characterisation of the oceanic environment is of interest to many different scientific and engineering disciplines. Geologists search for environmental indicators which may contribute to successful exploration and exploitation. The alternative energy community seeks areas which show promise to support a particular type of alternative energy source, whether surface-riding mechanisms or surface wind-driven turbines. Fisheries managers seek to include environmental factors in fish population models. Marine mammal biologists are interested in the environmental factors which affect behaviour, foraging, communication and reproduction.

Concurrent mapping of animal distributions and environmental parameters has been helpful in understanding the temporal and spatial distribution of marine animals.[1] Ocean resource management and conservation efforts, as well as climate change research, have included the synthesis of spatial data on the distribution of human activities and their impact on marine ecosystems.[2] A fully ecological approach to ocean resource management requires mapping and correlating related datasets.[3] All such efforts require a robust and efficient methodology to quantitatively evaluate vast amounts of spatiotemporal data to characterise the ocean environment.

The purpose of this paper is to present such a methodology – one that is user-friendly and accurate, yet flexible and robust enough to be used for multiple applications. The particular application presented here is the determination of acoustically analogous environments in the ocean.

Determination of acoustically analogous ocean environments requires careful evaluation of the static (eg, bathymetry, seabed type, sediment thickness) and spatiotemporally dynamic parameters (eg, sea surface condition) which affect sound propagation through the ocean acoustic waveguide. Databases exist for a wide range of environmental parameters which describe various conditions above, within and below the ocean volume. Accurate determination of acoustically analogous environments consists of more than just a simple numerical correlation between matrices of data; it requires an understanding of the physics of acoustic propagation and how each environmental parameter contributes to the characteristics of the propagation.

The relative importance of any one parameter to the characterisation is application dependent. For example, the sediment type in a particular location in the deep ocean may matter more to a benthic biologist than it may to an ocean acoustician. The relative importance of the degree to which a single parameter varies is application dependent as well. For example, recent studies show that a decrease in ocean pH will matter more to an ocean geochemist than it will to an ocean acoustician.[4]

Attempts to find analogous environments have typically been carried out in an informal, non-quantitative manner. An early quantitative approach is the Environmental Site Analyzer (ESA), the motivation for which was the need to design acoustic systems to operate effectively in particular shallow water environments.[5] Conducting developmental testing in waters near the continental United States reduces costs and resources; evaluating system performance in environments analogous to waters in other parts of the world maximises the value of testing. The ESA grouped sound speed profiles (SSPs) into one of nine categories (isovelocity, upward refracting, channel, mildly/intermediately/steeply downward refracting, deep/intermediate/shallow layer), and combined with bathymetry, bottom characteristics, rainfall data, shipping density and wind speed, characterised several environments of interest.

At the heart of the ESA was a fuzzy-logic algorithm which used fuzzy entropy as the metric to measure the similarity of the parameters at two different sites, which is then followed by a set of heuristic rules to apply relative weights to each parameter in accordance with their respective importance. The likeness, or fuzzy entropy, of the two environments is determined from the sum of the individual fuzzy entropies from each parameter. The ESA employed a set of heuristic rules designed for a specific, shallow water acoustics application, thus limiting its usefulness.

The work presented here is a quantitative methodology for analogous environment determination which is user-friendly and accurate; flexible and robust enough to be tailored for a variety of applications; capable of global coverage; easily expanded with the addition of new databases; and which uses readily available software providing geo-rectified analysis. This work focuses on the specific application of the determination of acoustically analogous environments in the ocean, based on a thorough, acoustically-consistent characterisation of the sound speed profile.

The next sections provide a description of the data used in this particular application, a discussion of the proper characterisation of sound speed profiles, an explanation of the methodology, presentation of results, and conclusions.

DATA

The type and amount of data required to accurately characterise a particular environment varies with application. The ocean environment can be characterised by many different physical, chemical and biological parameters, which could be analysed as a function of time and space. Physical parameters include surface wind speed, sea surface wave height, temperature and salinity profiles, water depth and bottom sediment type. Acoustic parameters of interest include shipping density, ambient noise levels and SSPs. Nominally, more data means better characterisation; however, the ocean is extremely large and there will be a limit to the amount of data available. This study was intentionally limited to open-source, readily available, climatological oceanographic data; specifically, sea surface wave heights and wind speeds, SSPs (which include water depth, and temperature and salinity profiles), and bottom sediment type and thickness.

Surface parameters

Climatological wind speed and wave height values were extracted from the Surface Marine Gridded Climatology (SMGC v1.0) database maintained by the Fleet Numerical METOC Detachment Asheville Climatology Center in Asheville, North Carolina.[6] The database provides monthly climatological values of mean wind speed (MWS) and mean wave height (MWH, trough to crest) at 1 degree latitude and longitude spatial resolution.

Volume parameters

Sound speed profiles were extracted from the Generalised Digital Environmental Model (GDEM-V v3.0) database, which was developed and is maintained by the Naval Oceanographic Office (NAVOCEANO) at Stennis Space Center, Mississippi. GDEM-V provides gridded monthly means and standard deviations of global ocean temperature and salinity as a function of depth at a spatial resolution of 15 arc-minutes of latitude and longitude. The data span the global oceans with a latitude range of 82.0°S to 90.0°N and longitude range of 0° to 359.75°, including freshwater lakes and landlocked seas (eg, Great Lakes). The content for the GDEM-V database comes from data extracted from the Master Oceanographic Observation Data Set (MOODS), which contains nearly eight million profiles of temperature and salinity.[7]

Seabed parameters

Sediment type was taken from NAVOCEANO's Surface Sediment Type database, which assigns an integer value to each sediment type based upon grain size, origin and placement of the sediment.[8] The database contains both high and low resolution data, at 6 seconds and 5 minutes resolution, respectively. The high resolution data, restricted to selected geographical areas, were obtained from analyses of sediment grabs and cores collected by NAVOCEANO, National Geospatial Intelligence Agency (NGA) charts, side scan imagery, and from bathymetric and seismic publications. The 5 min low resolution data cover a majority of the global oceans and seas from a latitude of approximately 50°S to approximately 75°N, and were assembled from various high-level sources, including maps, atlases and regional ocean basins studies. Data are provided in four different schemes, each containing a different number of sediment categories: Enhanced (400), Standard (30), Reduced (15), and High Frequency Environmental Acoustics (23). The HFEVA data (Table 1) were used in this study because its categorisation scheme is based not only on physical properties, but also on acoustical properties.

HFEVA standard sediment type	HFEVA category
Rough rock	1
Rock	2
Cobble or gravel or pebble	3
Sandy gravel	4
Very coarse sand	5
Muddy sandy gravel	6
Coarse sand or gravelly sand	7
Gravelly muddy sand	8
Medium sand or sand	9
Muddy gravel	10
Fine sand or silty sand	11
Muddy sand	12
Very fine sand	13
Clayey sand	14
Coarse silt	15
Gravelly mud or sandy silt	16
Medium silt or sand-silt-clay	17
Sandy mud or silt	18
Fine silt or clayey silt	19
Sandy slay	20
Very fine silt	21
Silty clay	22
Clay	23

Table 1: NAVOCEANO's HFEVA Standard sediment types and integer category designation

Sediment thickness values were taken from the National Geophysical Data Center (NGDC) of the National Oceanic and Atmospheric Administration (NOAA).[9] The sediment thickness data are gridded at a resolution of five arc-minutes by five arc-minutes. The data were collected from three principal sources: isopach (lines of equal thickness) maps, ocean-drilling results and seismic reflection profiles maintained by NGDC. The values of the data are in metres (m) and represent the depth to the acoustic basement.

SSP CHARACTERISATION

The accuracy and reliability of the search for analogous environments very much depends upon the choice of data which are meaningful for the application. Selection of this data requires an understanding of the processes underlying the specific application. To illustrate the methodology, this paper specifically focuses on the problem of finding environments which are acoustically analogous, which are represented by sound speed profiles (SSP) as a function of depth.

Some analogous environment searches for some applications would require only point-by-point comparison of data. For example, if the goal were to find environments which contained bottom sediment of a type similar to the bottom sediment of the environment of interest, the analysis would involve simply finding environments which match (eg, 'sediment type #3'). A hydrographer looking for similar water masses could search for environments having similar temperature and salinity. Such a search could be described as finding the minimum difference between pixels in a raster image; however, finding acoustically-analogous environments is more like comparing vector images – there is a directional component which must be compared.

The goal is to find environments which support similar types of propagation regimes, and these regimes or characteristics depend upon the spatially-dependent physics of acoustic propagation through the environment, including factors such as the SSP, bottom characteristics and surface conditions. Refraction must be accounted for, which involves a spatially-dependent mechanism, not just a point-by-point comparison of numbers.

Acoustic propagation is driven largely by the index of refraction, represented by the sound speed as a function of depth (the SSP). To compare the refractive properties of two different water volumes, a point-by-point comparison of two profiles, in which the number of common points determines a match, is an ineffective method to characterise the SSP because small differences between similar profiles would deliver a poor match, yet be acoustically insignificant. Further, a point-by-point comparison with depth between two SSPs does not represent the properties of refraction. For example, two SSPs could have large differences in sound speed values for given increments in depth, but these differences are not necessarily acoustically significant. The index of refraction drives the characteristics of acoustic propagation in the ocean, so point-by-point values matter less than the gradients, which communicate the index of refraction in the water column. The point here is that the SSP must be described by those characteristics which communicate the manner in which sound propagates through the water.

Categorising SSPs as single entities (eg, 'isovelocity'), as in[5], begins to take into account the physics of propagation. A more complete approach (presented here) consists of generating a larger, more comprehensive set of parameters corresponding to key features in the profiles (not just the nature of the whole profile itself), which better represents the acoustical environmental characteristics. The similarity of the SSPs is then based upon those acoustically significant parameters.

SSP parameters

The speed of sound in the ocean is a function of temperature, salinity, and pressure and varies with location and time of year. Water temperature is the dominant factor in sound speed; its dominance diminishes with depth as the water temperature reaches a constant minimum below about 1000m. Below approximately 1000m, pressure becomes the dominant factor such that sound speed increases linearly with depth at a rate of approximately –0.016 s^{-1}. Salinity is a minor contributor except in the vicinity of freshwater sources (eg, polar regions, river run-off) or in environments of very high salinity (eg, Mediterranean and Arabian Seas). Empirical sound speed formulas have been developed from laboratory and at-sea experiments over the past 50 years. The equation by Del Grosso is used in this work.[10]

Fig 1 displays the parameters extracted or derived from the SSP to describe the acoustic propagation characteristics supported by a particular water mass. The GDEM-V SSPs were processed to generate two sets of parameters:

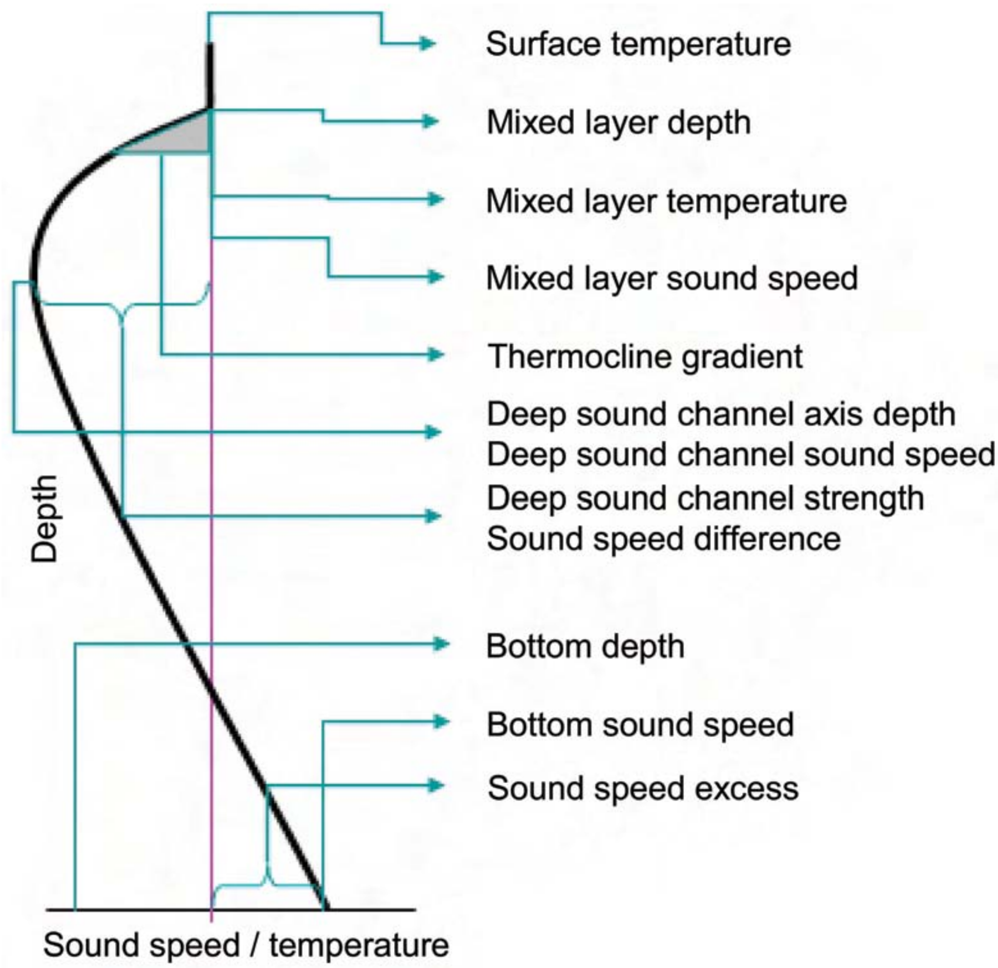

Fig 1: A canonical SSP and the acoustically significant parameters used to characterise the acoustic propagation conditions supported by the water mass

SST	Sea surface temperature	Water temperature at surface (°C)
MLD	Mixed layer depth	Depth of maximum near-surface temperature (m)
MLT	Mixed layer temperature	Mean temperature within the ML (°C)
MLc	Mixed layer sound speed	Mean sound speed in the ML (m/s)
Γ	Gamma at the thermocline	Max gradient in the SSP below the MLD (1/s)
DSCA	Deep sound channel axis	Depth of minimum sound speed (m)
DSCAc	DSCA sound speed	Sound speed at the DSCA (m/s)
SSD	Sound speed difference	Difference in sound speeds at two depths (m/s)
DSCS	DSC strength	DSCAc – Bc, or SSD, whichever is smaller (m/s)
BD	Bottom depth	Depth of bottom (m)
Bc	Bottom sound speed	Sound speed at the bottom (m/s)
SSE	Sound speed excess	Bc – MLc (m/s)

Table 2: Non-binary parameters extracted or derived from the SSP to describe the acoustic propagation characteristics supported by the water mass

1. A set of binary parameters which describe the general nature of the SSP;
2. A set of non-binary parameters which specify specific values within the SSP.

The binary descriptors are ‘Isovelocity’ (ISO), ‘Upward Refracting’ (UR), ‘Downward Refracting’ (DR) and ‘No Deep Sound Channel’ (NoDSC).

SSPs are considered isovelocity if the sound speed standard deviation is less than 0.8. SSPs having positive and negative gradients along the entire profile are defined as upward refracting and downward refracting, respectively. SSPs having a negative gradient only for all depths below the mixed layer depth (MLD) have no DSC. Table 2 lists and defines each non-binary parameter.

The MLD defines the bottom of the acoustic surface duct, and often equals the sonic layer depth (SLD), the depth of maximum near-surface sound speed. The mixed layer is composed of well-mixed, isothermal water, and creates an important, near-surface acoustic waveguide. Within the mixed layer, sound speed increases with depth due to increasing pressure. This creates an upward-refracting acoustic waveguide that effectively traps acoustic energy and provides extended ranges of acoustic propagation. MLD changes with season and responds to surface forcing (winds and waves).

The gradient of the thermocline (Γ) is the dominant near-surface acoustic characteristic in the SSP. Acoustically, it separates the surface duct from the DSC and quantifies the ‘strength’ of the layer.

The deep sound channel axis (DSCA) can vary from 1300m in the mid-latitudes to near-surface depths at high latitudes. The sound speed gradient is zero at the DSCA, where temperatures decrease with depth from the warmer surface water temperatures (thermocline), giving way to a negative temperature and sound speed gradient. Below the DSCA, the temperature is nearly isothermal and sound speed increases as pressure increases, resulting in a positive sound speed gradient. Thus, the DSCA is an inflection point in the SSP, where the gradient transitions from negative to positive. The sound essentially becomes trapped and undergoes little transmission loss, particularly at low frequencies, as losses from surface and bottom interactions are avoided. In the deeper oceans, the DSC plays a significant role in sound propagation and the DSCA is, therefore, a valuable parameter to use in analogous environments determination.

The sound speed difference (SSD), for deep-water cases, is the difference between the mixed layer sound speed (MLc) and deep sound channel sound speed (DSCc), and characterises the strength of the DSC. If there is no DSC, as in shallow water environments, then SSD is the difference between MLc and the bottom sound speed (Bc), and characterises the strength of the shallow water waveguide’s upward or downward refraction.

The deep sound channel strength (DSCS) gives an indication of the maximum sound speed change that a given sound ray may encounter in the DSC. Mathematically, the DSCS is either the difference between the bottom and DSC sound speeds or is equal to the SSD as defined above, whichever is smaller. In shallow water the sound speed at the bottom can be less than the ML sound speed. In this situation, the DSCS is the difference of the bottom and DSC sound speeds. In deep-water where the bottom sound speed is larger than the MLc, the DSCS is the SSD.

Seabed parameters (eg, BD, SedTh, SedTy) are very important in the shallow water environments, as acoustic propagation characteristics are driven by bottom interaction mechanisms which contribute to much greater transmission loss. Bottom characteristics are less important in deep-water environments. These differences in importance can be accounted for in the parameter weighting.

The sound speed excess (SSE) is a key acoustic parameter because it is an indicator as to whether or not Convergence Zone (CZ) propagation is possible. Sufficient depth excess or sound speed excess for CZ propagation is needed to minimise bottom interaction. Depth excess is the difference between the critical depth and the bottom, where the critical depth is defined as the depth of the equivalent Mixed Layer sound speed located below the DSCA. Depth excess and sound speed excess are used interchangeably when discussing CZ propagation. For a near-surface source, a minimum depth excess of ~366m (200 fathoms) or sound speed excess of 6.7m/s is required for a 50% probability of CZ propagation. The probability increases to 80% if depth excess is greater than 300 fathoms (548.6m) or sound speed excess is greater than 10.1m/s.[11]

It is important to note that any algorithm used to process and characterise data in an automated fashion will require some quality control and verification, and will be source and application dependent. Unfiltered data or data which has not been averaged can be very noisy or contain a significant amount of natural variability. Ideally, the automated algorithm is sufficiently robust to mitigate the need for extensive manual quality control. Data for this work were taken from climatological databases which provide relatively smooth profiles and required relatively little effort to ensure that the parameters extracted from the SSP accurately represented the acoustical characteristics of the environment. However, certain heuristic controls were put in place to ensure accuracy. For example, if the SSP contained multiple thermoclines in a certain depth zone, the algorithm was constructed to choose the largest gradient as the main thermocline.

METHODOLOGY

An ideal analogous environment determination methodology would be:

1. Easily accessible and user-friendly,
2. Robust and reliable for a variety of applications.

First, the methodology presented here is accessible and user-friendly by its use of the widely-used ArcGIS software, produced by the Environmental Systems Research Institute (ESRI). The ArcGIS Desktop suite is a complete GIS software package that allows users to analyse spatial patterns, trends and relationships that are not apparent in other software spreadsheets and databases. The software has the capability of displaying data on a map and allowing users to perform advanced geospatial analysis on the data and display the results.[12] ArcMap is the main application in ArcGIS used in mapping, editing, analysis and querying. Geographic information is represented as a collection of layers that can be displayed simultaneously or individually.

Secondly, the methodology presented here is robust and reliable because the capabilities of the GIS software allow the user to preferentially weight the most important parameters over others for a particular application. Each scenario or application, besides relying on different types of data, would dictate differing relative values of various parameters. Instead of ‘hard-wiring’ a rigid set of application-specific weights into the process, the approach taken here grants the user the ability to adjust the relative importance of each parameter to allow flexibility and support sensitivity studies. This setting of the relative importance of the various parameters occurs inherently in the process, and will be described in this section.

Each parameter described in the previous section is displayed as a layer within ArcMap as a function of latitude and longitude, one layer for each month. In the case described in this paper, there are 158 layers (12 monthly layers for each SSP and SMGC parameters and one layer each for bottom sediment type and bottom sediment thickness). Once all parameters are imported and available in ArcMAP (the shapefile [.shp] format is most convenient), the similarity function is used to perform the analysis. The process consists of finding the locations that first meet the query criterion of one layer's descriptors and then using those environments to begin the selection of the next layer's descriptors. The details of importing data files into ArcMap and the standard steps in the analysis process within ArcMap are detailed in the ArcMap user's guide and[13]. The major components of the process are discussed next.

First, the application-specific parameters in the environment of interest (EOI) to be used are identified. For the deep-water acoustics example discussed in the next section, the most significant SSP descriptors are MLD, Γ, DSCA, DSCc, DSCS, SSE and BD. Other parameters used are wind speed, wave height, sediment thickness, and sediment type. Incidentally, important acoustic parameters for a shallow water environment would include SST, MLD, MLc, BD, Bc and SSD.

Second, a numerical weight is applied to the parameters to account for their relative importance quantitatively, since some of the chosen parameters will be more important than others in finding analogous environments. The numerical weight of a specific parameter is effectively established in ArcMap by adjusting the range of values for which the parameter is queried. A higher weight is applied to a more important parameter by decreasing the range of values for which the parameter is queried: the smaller range of values limits the results to environments which more closely match the value in the EOI. Conversely, a less important parameter would be queried using a larger range of values to allow the results to include environments which are relatively less similar to the EOI. For example, the search could begin by querying parameters for values within 10% of the EOI values. Repeating the process for values within 20%, 30%, 40%, etc, of the EOI values provides a scaled search and produces scaled results. If DSC depth is more important than bottom depth, then querying for DSC depth values within 10% of the EOI's DSC depth and bottom depth within 20% of the EOI's bottom depth would generate weighted results.

Third, once each of the parameters has been weighted, ArcMap's ability to rapidly query a multitude of data points can be utilised. Each data layer is searched sequentially, the optimal order of which is determined by the user. When the query is complete, any locations meeting the query criteria will be displayed on the map, as shown in the next section.

RESULTS

The capability of this methodology to find acoustically similar environments is illustrated for the case of a deep-water environment located north of the Philippines at 20°N, 119°E during the month of January. Three queries were performed to assess the differences in the results due to changes in parameter weighting, from more restrictive (Query A) to less restrictive (Query C).

Table 3 provides a summary of the EOI's values for the SSP descriptors during the chosen month of January, SMGC wind speed and wave height, sediment type and sediment thickness, as well as the query criteria and parameters used. Query A used the '10% criteria' for MLD, Γ, DSCc, DSCA, DSCS and SSE, while the '20% criteria' was used for BD, MWS, MWH, SedTh and SedTy. Query B used the '20% criteria' for MLD, Γ, DCSc, DSCA, DSCS and SSE, and the '30% criteria' for BD, MWS, MWH, SedTh and SedTy. Query C used the '20% criteria' for DSCc, DSCA, DSCS and SSE, the '30% criteria' for MLD and Γ, and the '40% criteria' for BD, MWS, MWH, SedTh and SedTy. All binary parameters return positive results for exact matches.

Query A produced results for 12 locations (Table 4) during the months of January, February and March, based on the criteria shown in Table 3. Panel A of Fig 2 shows four

EOI parameters	*EOI values*	*Query A*	*Query B*	*Query C*
ISO	0	Exact	Exact	Exact
UR	0	Exact	Exact	Exact
DR	0	Exact	Exact	Exact
NoDSC	0	Exact	Exact	Exact
SST	23.9	-	-	-
SSD	47.8	-	-	-
MLD	45	10%	20%	30%
MLT	23.9	-	-	-
MLc	1530.9	-	-	-
Γ	–0.2012	10%	20%	30%
DSCc	1483.2	10%	20%	20%
DSCA	1100	10%	20%	20%
DSCS	26.1	10%	20%	20%
SSE	–21.7	10%	20%	20%
Bc	1509.2	-	-	-
BD	3178	20%	30%	40%
MWS	18.3	20%	30%	40%
MWH	1.9	20%	30%	40%
SedTh	2001	20%	30%	40%
SedTy	clay	Exact	Exact	Exact

Table 3: EOI parameters and values during the month of January, and search criteria used for each of the queries

	Query A	*Query B*	*Query C*
January	5	94	277
February	3	134	378
March	4	168	435
April	0	88	475
May	0	22	176
June	0	27	65
July	0	10	62
August	0	10	42
September	0	5	54
October	0	21	66
November	0	14	104
December	0	64	179
TOTAL	12	657	2313

Table 4: Summary of monthly analogous environments returned for Query A, B & C

locations during the month of March which are closely analogous to the conditions in the EOI during the month of January. Only 12 analogous environments were returned for the EOI in January using Query A, which may not provide the user with a sufficient number of analogous environments, depending upon the application. Panel B of Fig 2 indicates locations for the results of Query B during the month of March. Query B uses a wider range of values for certain parameters, as shown in Table 3, resulting in 657 analogous environments for all 12 months of the year (Table 4). The month of March provides the largest number of acoustically analogous environments for Query B. As expected, a greater number of analogous environments were returned for Query C than for Query B or A (Table 4). Panel C of Fig 2 displays the locations for the results of Query C during the month of April, which returned the largest number of acoustically analogous environments. As the range of values are increased

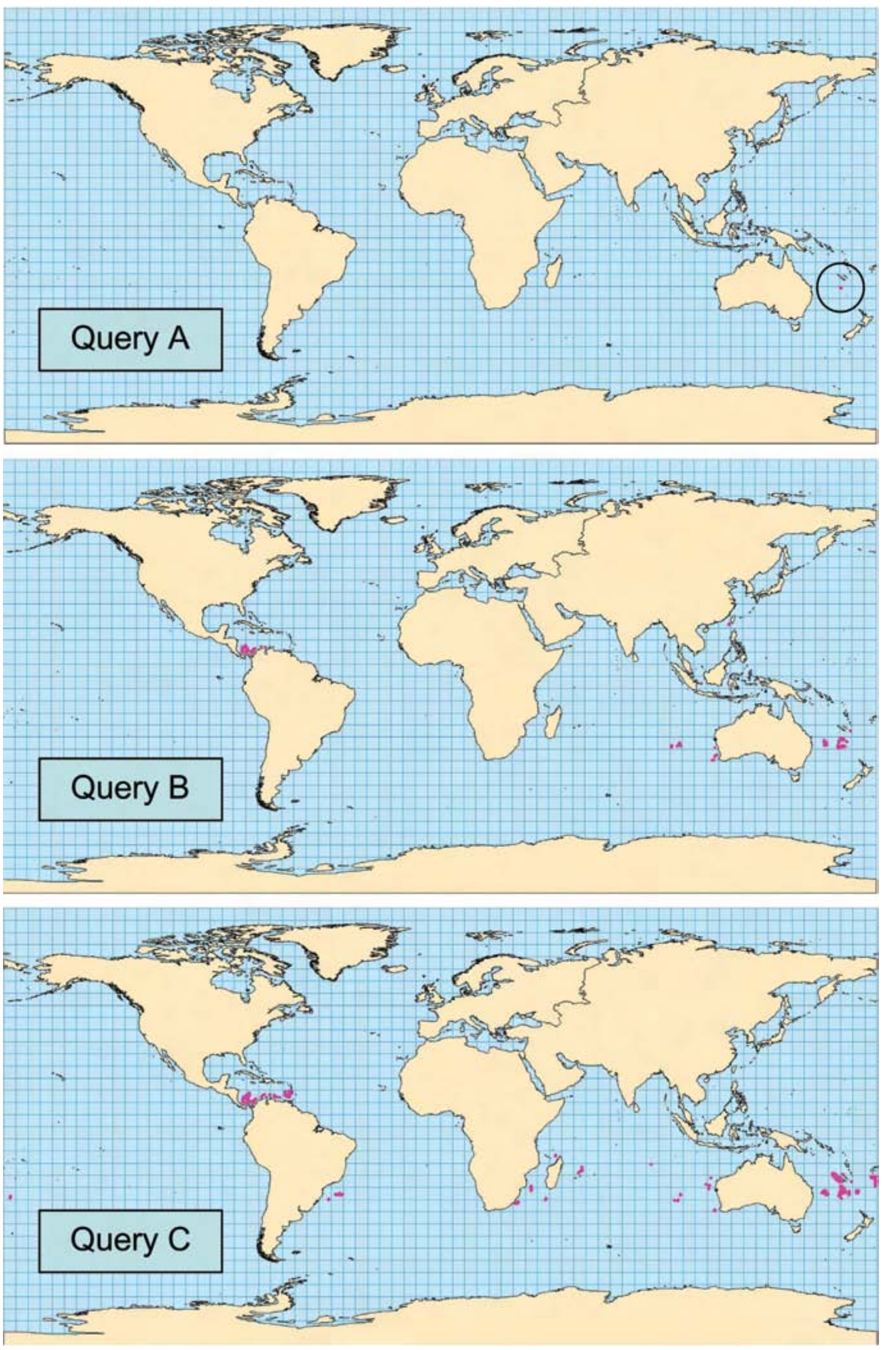

Fig 2: Locations of the results for Query A (a), Query B (b) and Query C (c). Panel (a) shows four locations during the month of March which are closely analogous to the conditions in the EOI during the month of January. Panel (b) indicates 168 locations for the results of Query B during the month of March. Panel (c) displays 475 locations for the results of Query C during the month of April

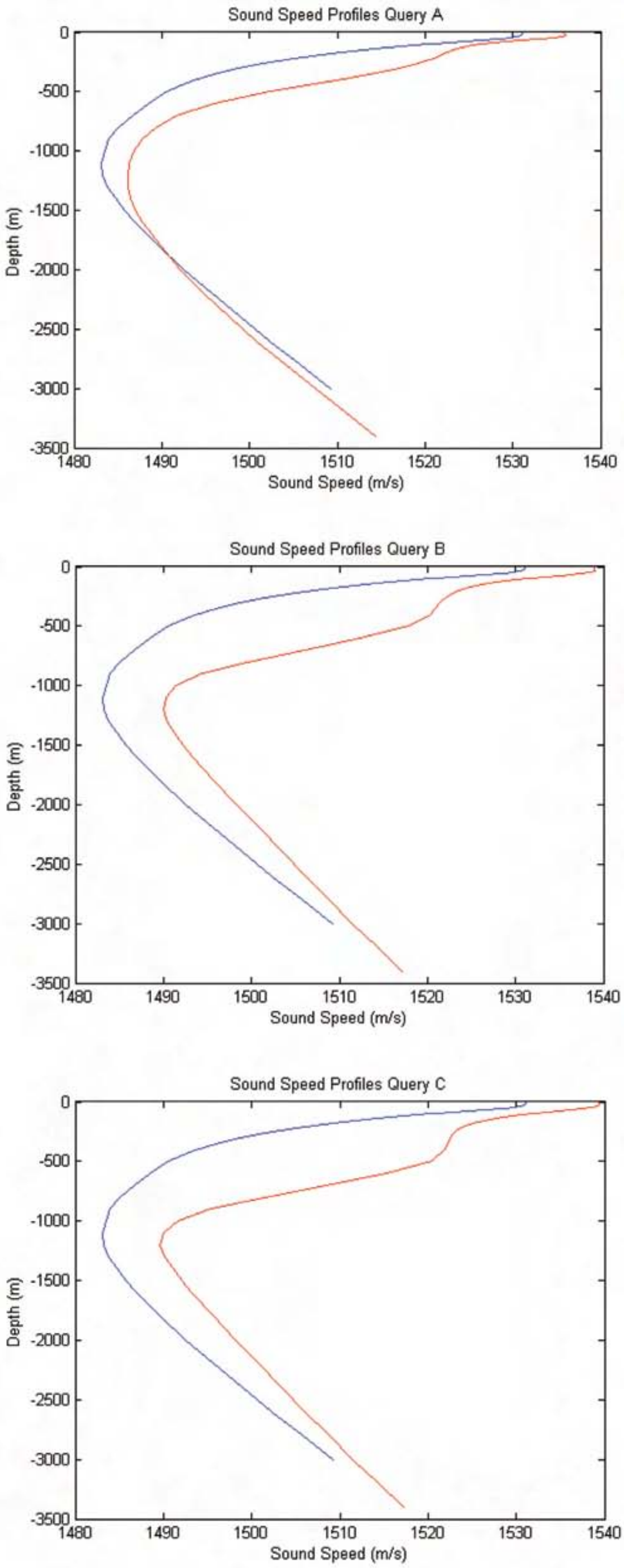

Fig 3: SSPs for the EOI and selected analogous environments. This shows the SSPs for the EOI in January (in blue in all panels) and an analogous environment in March (located at 25.75°S, 165.25°E) from Query A (a), an analogous environment in October (located at 31°N, 76°W) from Query B (b), and an analogous environment in October (located at 30.75°N, 76.5°W) from Query C (c). Comparison of the EOI SSP to the analogous environments' SSPs shows decreasing similarity from Query A to Query C

from Query A to Query C, the areas analogous to the EOI spread geographically into areas quite distant from the EOI, such as Australian and Caribbean waters.

Comparison of the EOI SSP to the analogous environments' SSPs (Fig 3) validates the results of the process. The SSPs for the EOI in January and an analogous environment in March (located at 25.75°S, 165.25°E) from Query A (Panel A) are very similar in shape, with key features at almost identical depths. A significant feature is the lack of sufficient depth excess for CZ propagation, indicating that seabed interaction is important in these environments. Given the similarity of the SSPs, it is reasonable to expect the acoustic propagation characteristics in both environments to be very similar. The SSPs for the EOI in January and an analogous environment in October (located at 31°N, 76°W) from Query B (Panel B) are not as similar as the SSPs for Query A; however, the SSP descriptors used in Query B criteria match well. For example, the DSC Depth for both profiles is approximately 1200m and the MLD is approximately 45m. The SSPs for the EOI in January and an analogous environment in October (located at 30.75°N, 76.5°W) from Query C (Panel C) are nearly identical to the SSPs for Query B, with only a slight difference in the depth of the upper portion of the deep sound channel.

The ray traces (Fig 4) for the EOI in January (Panel A) and the analogous environments from Queries A, B and C indicate the propagation conditions for each environment based on the SSPs. The rays shown are depictions of sound rays from a source at 100m launched at 21 different degree angles (−10:1:10), with the surface and bottom boundaries modelled as perfectly reflecting planar interfaces. The nearly identical ray traces in Panels A and B indicate that the two environments are acoustically analogous. The small shift of the analogous environment ray trace pattern to the right by approximately 2–3km in Query B (Panel C) and Query C (Panel D) can be attributed to the difference in bottom depth between the two environments: the analogous environment bottom depth is several hundred metres deeper. These ray traces further confirm the chosen analogous environments to be representative of the EOI in January, to varying degrees based upon the search criteria.

In summary, the analogous environments identified by the queries are consistent with expectations – deep-water environments which support DSC propagation for sufficiently deep sources and surface duct propagation for near surface sources, but which do not support CZ propagation due to the strong downward-refracting nature of the SSP above the DSCA and insufficient SSE. The number of analogous environments returned in each month for the three different queries differs due to the varying parameter weighting. The number of analogous environments produced by Query C is more than three times that of Query B, which is more than 54 times that of Query A. A comparison of the SSPs shows decreasing similarity with each query, while maintaining certain features such as MLD and DSCA. A comparison of the ray traces shows strong similarity, with shifts in the pattern of less than 3km. These results for this particular scenario reveal that relaxing the search criteria from Query A to Query C sacrificed little in terms of the analogous environments' acoustic propagation

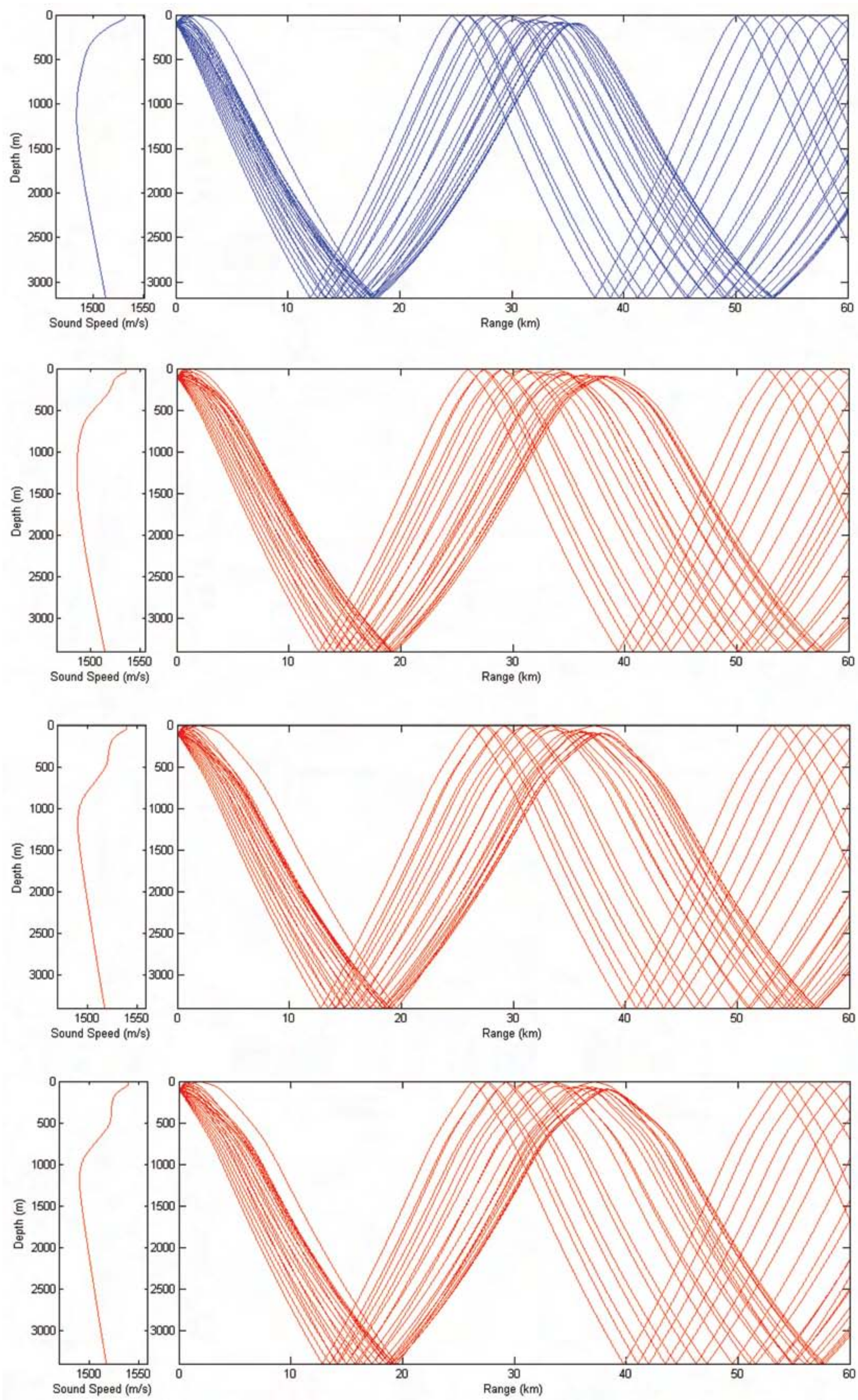

Fig 4: Ray traces for the EOI (blue in panel (a)) and selected analogous environments indicate the propagation conditions for each environment based on the SSPs in the Fig 3. The panels show the ray traces for the EOI in January (a), and the analogous environments from Query A (b), Query B (c) and Query C (d). The rays shown are depictions of sound rays from a source at 100m launched at 21 different degree angles (–10:1:10), with the surface and bottom boundaries modelled as perfectly reflecting planar interfaces. These ray traces further confirm the chosen analogous environments to be representative of the EOI in January, to varying degrees based upon the search criteria

characteristics, while providing more matches for the user to consider for a particular application.

The purpose of this study was to demonstrate potential for the proposed methodology. While a full statistical characterisation is outside the intended scope of the paper, future work should focus on a statistical characterisation of the environment of interest, followed by the application of automated tools, such as decision trees, neural networks and clustering techniques, to provide the proper set of ranked parameters and analogous environments.

CONCLUSIONS

Previous approaches to analogous environment determination have had limited applicability. A robust methodology should allow the user to select those parameters which are most important to the user's specific application, and should be user-friendly, flexible and expandable. The analogous environment methodology presented here was developed based on an assessment of acoustically relevant parameters of the undersea environment. Climatological data representative of those parameters (sound speed profiles, wind speeds and wave heights, and sediment thicknesses and types) were accessed via publicly available databases. Additional data can be easily included in the process to complement the climatological data used here which may not adequately represent the environment at a specific time or location due to variability occurring on shorter time and smaller space scales.

A deep-water acoustics example was used to test the approach. The resulting analogous environments for each month were variable, yet centred on the query criteria. A key element of this work was the construction of a set of acoustically significant parameters that characterises the acoustic propagation conditions supported by a particular ocean environment. These parameters were derived from the SSP and represent the refractive properties of the environment. The methodology was validated by comparing sound speed profiles and acoustic ray traces of the analogous environments and the EOI. The results validate this methodology and confirm that this set of acoustically relevant parameters accurately represents the acoustic propagation characteristics of the ocean environment.

ACKNOWLEDGEMENTS

The authors express their sincere appreciation to Dennis Krynen for his insight and assistance in the development of acoustically relevant parameters from sound speed profiles, and to the reviewers for their thoughtful and helpful comments.

REFERENCES

1. Walli A, Teo SLH, Boustany A, Farwell CJ and Williams T. 2009. *Seasonal movements, aggregations and diving behaviour of Atlantic bluefin tuna* (Thunnus thynnus) *revealed with archival tags*. PLoS ONE 4(7): e6151. doi:10.1371/journal.pone.0006151.

2. Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'Agrosa C, Bruno JF, Casey KS, Ebert C, Fox HE, Fujita R, Heinemann D, Lenihan HS, Madin EMP, Perry MT, Selig ER, Spalding M, Steneck R and Watson R. 2008. *A global map of human impact on marine ecosystems*. Science, 319, 948.

3. Greene CH, Block BA, Welch D, Jackson G, Lawson GL and Rechisky EL. 2009. *Advances in conservation oceanography: New tagging and tracking technologies and their potential for transforming the science underlying fisheries management*. Oceanography, 22(1).

4. Reeder DB and Chiu CS. 2010. *Ocean acidification and its impact on ocean noise: Phenomenology and analysis*. J. Acoust. Soc. Am. EL, 128(3): 137–143.

5. Miyamoto R. 1999. Environmental site analyzer Version 3.1, Technical Report, Applied Physics Laboratory, University of Washington.

6. FNMOC. Fleet Numerical METOC Detachment Asheville. 2000. Database description for the Surface Marine Gridded Climatology (SMGC) database upgrade Version 2.0. Technical Report, Naval Oceanographic Office Systems Integrated Division.

7. NAVOCEANO. Naval Oceanographic Office, Oceanographic Data Bases Division (2003), Database description for the Generalized Digital Environmental Model (GDEM-V) (U) Version 3.0. Naval Oceanographic Office, Stennis Space Center, MS.

8. NAVOCEANO. Naval Oceanographic Office, Acoustics Division (2003). Database description for Surface Sediment Type (U) version 2.0. Naval Oceanographic Office, Stennis Space Center, MS.

9. Divins DL. 2008. NGDC total sediment thickness of the world's oceans & marginal seas. [http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html]. Retrieved: 4 Jan 2008.

10. Del Grosso VA. 1974. *New equation for the speed of sound in natural waters (with comparisons to other equations)*. J. Acoust. Soc. Am., 56(4), pp.1084–1091.

11. NAVOCEANO. Naval Oceanographic Office. 1999. Fleet Oceanographic and Acoustic Reference Manual, Naval Oceanographic Office, Stennis Space Center, MS.

12. ESRI. Environmental Systems Research Institute. 2008. ArcGIS Desktop, [http://www.esri.com/software/arcgis/about/desktop_gis.html]. Accessed: 21 Feb 2008.

13. Bryan CL. 2008. A quantitative approach to determine analogous areas using environmental parameters. MS Thesis, Naval Postgraduate School, Monterey, CA.