



Inverse Echo Sounding: Using measured water depth to calculate water temperature and its variation over time

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Non-technical summary

Inverse echo sounding is a new method that, in this investigation, has been used to calculate average temperature difference in the water column over time using the difference in the recorded depth of points on the sea floor. The study took place over Cross Seamount, an inactive seamount, 300km southwest of the Islands of Hawaii and occurred between 27th December 2010 and 4th January 2011 on the *R/V Thomas G. Thompson*. The aim was to test the hypothesis that the method of inverse echo sounding is an accurate technique in being able to identify changes in average temperature of the water column over time. Depth data from a common area was acquired over time using seafloor mapping; this was then mathematically converted to temperature data which was analysed. An average water column temperature difference of 0.0044°C over a 22 hour time period was detected. The accuracy of the data was vital in determining the water column temperature and any errors in the equipment were analysed with respect to the processed data. The average temperature data calculated by inverse echo sounding was compared to Conductivity-Temperature-Depth (CTD) and expendable bathythermograph (XBT) averaged temperature with depth profiles taken at the Cross Seamount site and analysed for any discrepancies between the data. The technique provides rapid detection and calculation of the average temperature change in the water column over time allowing large scale ocean processes to be investigated and monitored. The method can also be used to track changes in global ocean temperature with respect to climate change to a high precision.

Abstract

The object of this investigation was to test the hypothesis that the method of inverse echo sounding is an accurate technique in being able to identify changes in average water temperature of the water column over time. The technique will provide a platform for monitoring large scale ocean processes over time with respect to temperature changes such as the El Nino Southern Oscillation, with frequent mapping of the area. The method will also allow the tracking of changes in global ocean temperature with respect to climate change. The method of inverse echo sounding has been used to detect a change in average temperature through the water column of 0.0044°C over a period of 22 hours. The technique uses multibeam mapping of the seafloor to measure depth, the level of the seafloor does not change and therefore any changes in depth must be due to the expansion or contraction of water induced by a change in temperature. The depth measurements were converted mathematically using the Mackenzie equation to temperature measurements and analysed. Comparisons of the technique with XBT and CTD data resulted in an underestimation of 5.5777°C for inverse echo sounding when calculating the average temperature of the water column, with an error of 0.4%. With further investigation, over a longer temporal scale, this technique provides a simple yet affective way to calculate water column temperature change.

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Temperature changes in the ocean vary both spatially and temporally. In the region of Hawaii, the Hawaiian Ocean Time Series (HOTS) has been recording temperature profiles near Station Aloha since 1988. Temperatures in the water column over the last 21 years range from minimum of 3°C at a depth of 1000m to a maximum of 27°C at the surface. The surface temperature ranges from 22 - 27°C due to the annual heating and cooling of the ocean, below 100m temperature remains relatively stable with a variation of no more than 1°C. Over a shorter time scale of 5 days temperature has been seen to fluctuate between 24.4°C and 24.6°C at a depth of 8m at the ALOHA station (Fujieki et al. 2010).

This investigation focused on the Cross Seamount; part of a seamount chain approximately 300km southwest of the Island of Hawaii. Cross is an inactive seamount approximately 4300m high with a summit 300m below the sea surface (Noble and Mullineaux 1989). It no longer expels hydrothermal fluids and therefore has a stable water column above the summit where the less dense water sits at the surface with colder denser water below (Keating et al. 1988).

In order to carry out the investigation the EM302 multibeam system, an XBT and a CTD were required. The *R/V Thomas G. Thompson's* bathymetric surveyor is the Simrad/Kongsberg EM302 multibeam system, which uses echo soundings to determine the bathymetry and depth of the seafloor. The EM302 has a frequency of 30 kHz, with a depth range of 10-7000m, up to 864 sound transducers and a maximum ping rate of 10Hz. The accuracy is 0.2-0.4% of the depth depending on the angle of the transducer (www.km.kongsberg.com/ks/web/nokbg0397.nsf). However on the sea trials for the EM302 on the *R/V Thomas G. Thompson* the error on the system was calculated to be 0.01% ± 0.39% of the water depth at the 95% confidence level in 2000 meters of water (TN-255 Cruise Report (in publication)). The accuracy of the data is important in this project as the research is investigating a method of detecting changes in the average temperature of the

water column and therefore any errors in the equipment being used are critical to take into consideration. The Seafloor Information System (SIS) automatically corrects for the roll, pitch and yaw of the ship (www.km.kongsberg.com/ks/web/nokbg0397.nsf). The system calculates depth using ray tracing as the sound wave propagates through the water.

Ray tracing is a function of sound velocity and is an important factor for the accuracy of depth measurement in water. The travel time of a sound ray is directly related to depth and temperature changes within the water column which cause the ray to refract towards and away from the normal. Minimum sound velocity generally occurs at 800-1000m; increases occur at the surface due to increased temperature and at depth due to increased pressure. An incorrect sound velocity profile can lead to errors in ray tracing in the water column and therefore the depth of the seafloor and bathymetry errors. Once the incoming angle of the signal is known the ray path can be traced using refraction laws, specifically Snell's Law:

$$\frac{\sin(\theta_z)}{C_z} = \frac{\sin(\theta_0)}{C_0} = k$$

Here θ_z = ray angle at depth z , θ_0 = ray angle at surface, C_z = sound velocity at z , C_0 = surface sound velocity and k = Snell-Descartes constant (Tonchia and Herve 1996). Acoustic ray tracing involves looking at how each ray's location, direction and intensity varies in the different stages of the water column. As sound velocity varies through the water column the angle of the acoustic ray is altered due to different water masses. Sound speed is a function of temperature, salinity and most importantly depth. Tracing an individual ray involves calculating its progression through the different water masses in the water column until it reaches an object which bounces the signal back to be detected by the receiver (Convey et al. 2008).

An expendable bathythermograph (XBT) measures temperature with depth of the water column up to 2000m (probe type dependent). The errors of the probe are $\pm 0.1^\circ\text{C}$ for

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temperature with an accuracy of $\pm 2\%$ for the depth measurement (www.sippican.com; Reseghetti et al. 2007; Georgi et al. 1980). For this investigation the T-5 probe was used as it can penetrate the deepest, the precise depth of the site is unknown. This probe requires a slow ship speed, therefore reducing the horizontal component of the deployment, an important factor in recording depth of the probe. They are primarily used by the US Navy for Under Sea Warfare, as they provide rapid surveying when high accuracy is not required (Heinmiller 1983). They can also be used by scientists to provide temperature profiles for climate studies (Boedeker 2001), The XBT probe is launched using a LM-3A Hand Launcher; a thin copper wire transmits temperature data to the onboard computer with a MK12 interface (www.km.kongsberg.com/ks/web/nokbg0397.nsf). The XBT measures temperature at a regular interval of 0.64m; this profile is used to calibrate the EM302 multibeam system for sound velocity at each level of the water column. The depth of the XBT is estimated using the fall rate equation: $Z(t) = At - Bt^2$, where Z is the depth at the time t , A is equivalent to the initial falling speed and B is a function of the density and viscosity of the medium the probe enters (Reseghetti et al. 2007). Sound speed is a function of temperature, salinity and depth, the XBT has a constant salinity which is input into the system and records temperature with depth this introduces a large amount of error into the data (Henigin. 2005).

Part of the aim of this investigation involves observing how XBT and CTD temperature profiles compare to the average temperature inferred by inverse echo sounding at Cross Seamount and to look for inaccuracies in the averaged data and suggest why these may occur. All three methods will be compared for individual accuracy and precision. The CTD is the most accurate method of measuring water properties to a large depth; it is relatively lightweight and has little drag thereby reducing horizontal motion in the water column resulting in accurate depth measurements (Steel et al. 2001). Temperature on the CTD is accurate to within 0.0018°C (Reverdin et al. 2009).

Many studies have found warm temperature errors in the XBT data: Henigin (2005) suggested that this is due to the fact that salinity can vary up to 1 psu from the surface to depth increasing upward refraction in the sound ray paths. Heinmiller (1983) found XBT temperature exceeded CTD temperature by 0.05- 0.31°C with a mean temperature difference of 0.17°C. Boedeker (2001) suggested XBT temperatures differed by -0.0117°C to +0.4398°C from CTD measurements with an average of 0.0882°C warmer. Whelan (2007) calculated XBT temperature ranges from -0.0271°C to +0.127°C than CTD's with an average of +0.0344°C and Roth (2001) calculated an average difference of +0.166 °C. The greatest temperature differences were found in the upper 80-125m and decreased with depth (Boedeker 2001; Roth 2001). These warm biases can affect the sound velocity in the water column with the sound profiles calculated from XBTs being 5.06m/s slower on average than those calculated from the CTDs (Reverdin et al. 2009).

Temperature in the ocean needs to be calculated to a high degree of accuracy as this system is sensitive to heat input. Uncertainty in the heat uptake by the deep ocean is a cause for concern with regards to climate change (Sokolov et al. 1998). A two layer box model would allow for deep ocean temperature to be monitored and assessed over time using the proposed method. The accuracy of the data collected would allow for the temperature to be closely observed with any abnormal increases in temperature being cause for concern.

The final outcome of this investigation hopes to show that the method of inverse echo sounding is an accurate yet rapid way to calculate the average temperature of the water column. The temperature change over the cruise period should be enough, based on HOTS data (Fujieki et al. 2010), to provide a small change in temperature over time. All the data from calculations of temperature using inverse echo sounding, the XBT and CTD to expected to correlate well with respect to each other.

Methods

Collection -Data was collected on the *R/V Thomas G Thompson* between 27th December 2010 and 4th January 2011 at Cross Seamount (18°42'16"N, 158°15'58"W). Using the onboard Simrad/Kongsberg EM302 multibeam system the summit of Cross Seamount was mapped for water depth. The passing of the vessel over the site occurred a total of four times with time intervals (Table 1). When over the summit before transect 1 took place; a XBT was deployed to record sound velocity

of the water column.

This sound velocity data

was then used to calibrate

the multibeam for the

collection of subsequent

data. CTDs were deployed

after transect 2, 3 and 4 to

get a detailed temperature

structure of the

water column for

comparison to the

inverse echo

sounding

calculations.

Table 1: Metadata for the date and time of the transects over the summit of the seamount. Time intervals will be used for change in temperature over time calculations

	Date	Time (UTC)	Time interval (between transect and previous transect) hh:mm
Transect 1	12/31/2010	2209	na
Transect 2	01/01/2011	0210	4:01
Transect 3	01/01/2011	1030	8:20
Transect 4	01/01/2011	2010	9:40
Total			22:01

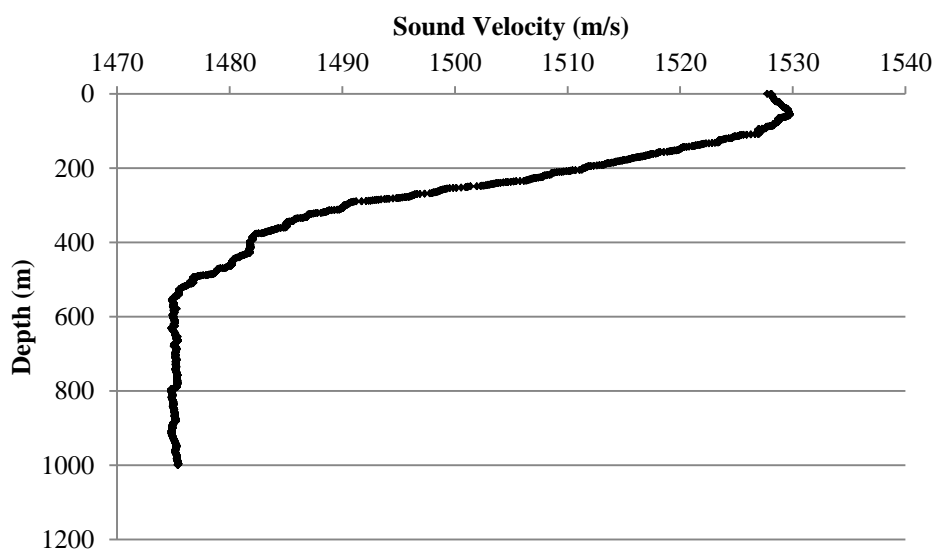


Fig. 1. Sound velocity profile at Cross Seamount, measured using a XBT.

Processing - The first stage was to look at the metadata of the XBT, CTD and multibeam mapping to establish the times and locations of the collected data. The XBT and CTD metadata was then used to find out which multibeam transects corresponded with their deployments. The bathymetry transects of the summit of Cross Seamount were then visualised using Caris® software. An averaged sound velocity profile (Fig. 1) from the XBT data at Cross Seamount was then applied to the transects of the summit making the depth data comparable for analysis. The transects were then imported into ArcMap where the common areas to all four transects were clipped. The data was converted into a raster format with a resolution of 10m and the mean depth value of each pixel location on the transect was calculated. A stratified sample taken with relation to depth; a total of 25 points were selected in order to retrieve high accuracy data and to reduce errors (Fig. 2). The depth data from each transect at each stratified point was then extracted and exported into an excel spread sheet (Table 2). This allowed for quantification of depth change over time.

The Mackenzie Equation (Eq 1) (Mackenzie 1981):

$$C = 1448.96 + 4.591T - 5304 \times 10^{-2}T^2 + 2.374 \times 10^{-4}T^3 + 1.34 S - 35 + 1.63 \times 10^{-2}D + 1.675 \times 10^{-7}D^2 - 1025 \times 10^{-2}T S - 35 - 7.139 \times 10^{-13}TD^3$$

Here C=sound velocity (ms⁻¹), T=temperature (°C), S=salinity (psu), and D=depth (m). Eq 1 was used to calculate average temperature over time (Table 2) using Maple®

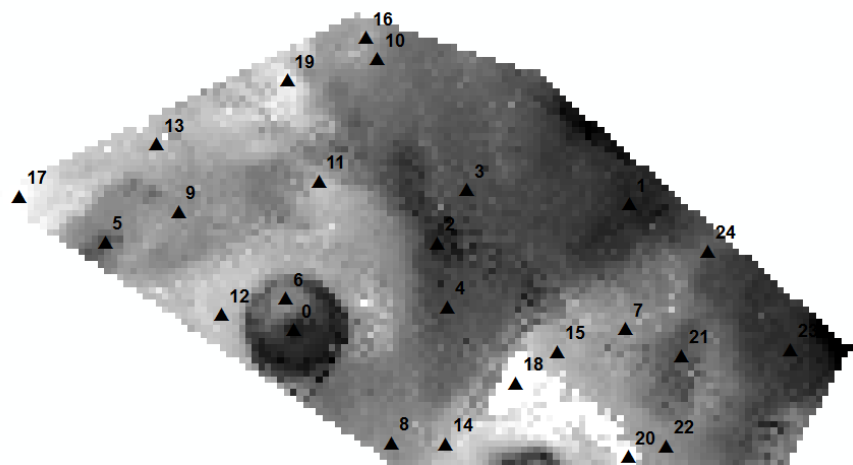


Fig. 2. The transect 1 multibeam image portraying where the stratified points were placed for sampling.

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software. The average sound velocity (C) from Fig. 1 was calculated to be 1508.146ms^{-1} . The salinity (S) used was 27.68 as this was input into the XBT and so is related to the sound velocity profile and therefore cannot be altered as this would affect values. Temperature was firstly calculated at the surface (D=0m) using Eq 1 and secondly at each depth shown in Table 2. This allowed for the range in temperature between the surface and seafloor to be found and allowed for comparison and analysis of change in depth over time.

Table 2. Extracted data from each transect showing depth at each point. The change in depth over time between transects and total depth change is also shown.

Point Number	Transect 1 - depths (m)	Transect 2 - depths (m)	Transect 3 - depths (m)	Transect 4 - depths (m)	depth change between transect 1 and 2 (4hours)	depth change between transect 2 and 3 (8.3hours)	depth change between transect 3 and 4 (9.7hours)	Total Depth Change over 22 hours
0	380.4235	380.0051	380.3586	380.4287	0.418335	-0.35345	-0.07013	-0.00525
1	381.051	380.5217	381.261	380.1657	0.529327	-0.73932	1.095276	0.885284
2	381.3183	380.8821	380.8409	381.1795	0.436157	0.04126	-0.33865	0.138763
3	383.1486	382.8688	383.7528	382.9888	0.279816	-0.884	0.764007	0.15982
4	383.2577	383.0237	383.2824	382.0294	0.234008	-0.2587	1.253021	1.228332
5	383.9359	383.6548	384.3667	383.6994	0.281159	-0.71191	0.667236	0.236481
6	386.9773	385.5753	387.3925	386.9339	1.401917	-1.81711	0.458527	0.043335
7	387.4268	387.8843	388.4982	387.183	-0.45743	-0.61392	1.315186	0.243836
8	387.2368	386.7242	387.3322	386.9704	0.512604	-0.60803	0.361847	0.266419
9	387.5291	387.5813	387.224	387.4253	-0.05225	0.357299	-0.20126	0.10379
10	386.8618	386.9396	387.2076	387.446	-0.07779	-0.26795	-0.23849	-0.58423
11	389.582	389.2872	390.1286	389.7676	0.294739	-0.84134	0.360992	-0.18561
12	390.0526	389.9979	390.4784	388.0073	0.054657	-0.48047	2.47113	2.045318
13	389.8205	389.4858	389.6881	390.6106	0.334687	-0.2023	-0.92252	-0.79013
14	389.9493	389.8803	390.4325	389.9327	0.069061	-0.55222	0.499756	0.016601
15	389.5829	389.9944	389.8385	389.7789	-0.41144	0.155853	0.059631	-0.19595
16	389.4076	388.8416	389.176	389.0933	0.565979	-0.33438	0.082764	0.314362
17	394.5662	393.8492	394.5799	393.9284	0.71701	-0.73074	0.65152	0.637787
18	400.9291	391.4908	398.3256	391.3473	9.438385	-6.83481	6.978302	9.581879
19	393.7493	391.5772	392.9918	391.4768	2.172089	-1.41458	1.515014	2.272522
20	405.8135	389.6656	389.6978	388.896	16.14792	-0.03223	0.801788	16.91748
21	383.838	384.3574	383.5799	384.3446	-0.51941	0.777466	-0.76465	-0.50659
22	387.1375	388.1533	387.4519	388.3794	-1.01578	0.701416	-0.92752	-1.24188
23	381.4378	381.688	381.5532	381.8621	-0.25015	0.134827	-0.3089	-0.42422
24	384.4348	384.0674	384.3463	383.4517	0.36734	-0.27893	0.894622	0.983032

Results

The exported and calculated data for depth and temperature can be seen in Table 2 and Table 4 respectively. Temperature calculated from water depth data from the multibeam correlates well over time with only a small amount of temperature change being seen (Fig. 3). Points 17, 18 and 20 are however more erratic; they are all situated on the deepest parts of the common area. The highest temperature variation over time had a maximum change of 0.811°C between transects 1 and 2 at point 20. The remaining points all fluctuate slightly in temperature change over time indicating a change in temperature over time is present. However the changes are minimal between -0.0091°C and $+0.0124^{\circ}\text{C}$ (Fig. 3C). Mean change in calculated temperature range is shown in Table 4 and results show that the overall change in temperature over 22 hours to be 0.0044°C . Errors in the data with the different instruments and methods used indicates that the inverse echo sounding technique and range values are much lower than those values measured with instruments (Table 3), however this is dependent on the depth being measured. The averaged temperatures for all of the methods vary significantly (Fig. 4). The average temperatures of the water column using reverse echo sounding vary by 0.0044°C and are also up to 5.5777°C lower than the corresponding measurements with XBT and CTD instruments which vary in average temperature from $16.0276 - 20.2072^{\circ}\text{C}$. Instrument errors are small and in the case of the CTD casts, negligible (Table 3). Visualisations of how depth changes with time and the difference in depth between each transect can be found in Appendix 1 and Appendix 2 respectively.

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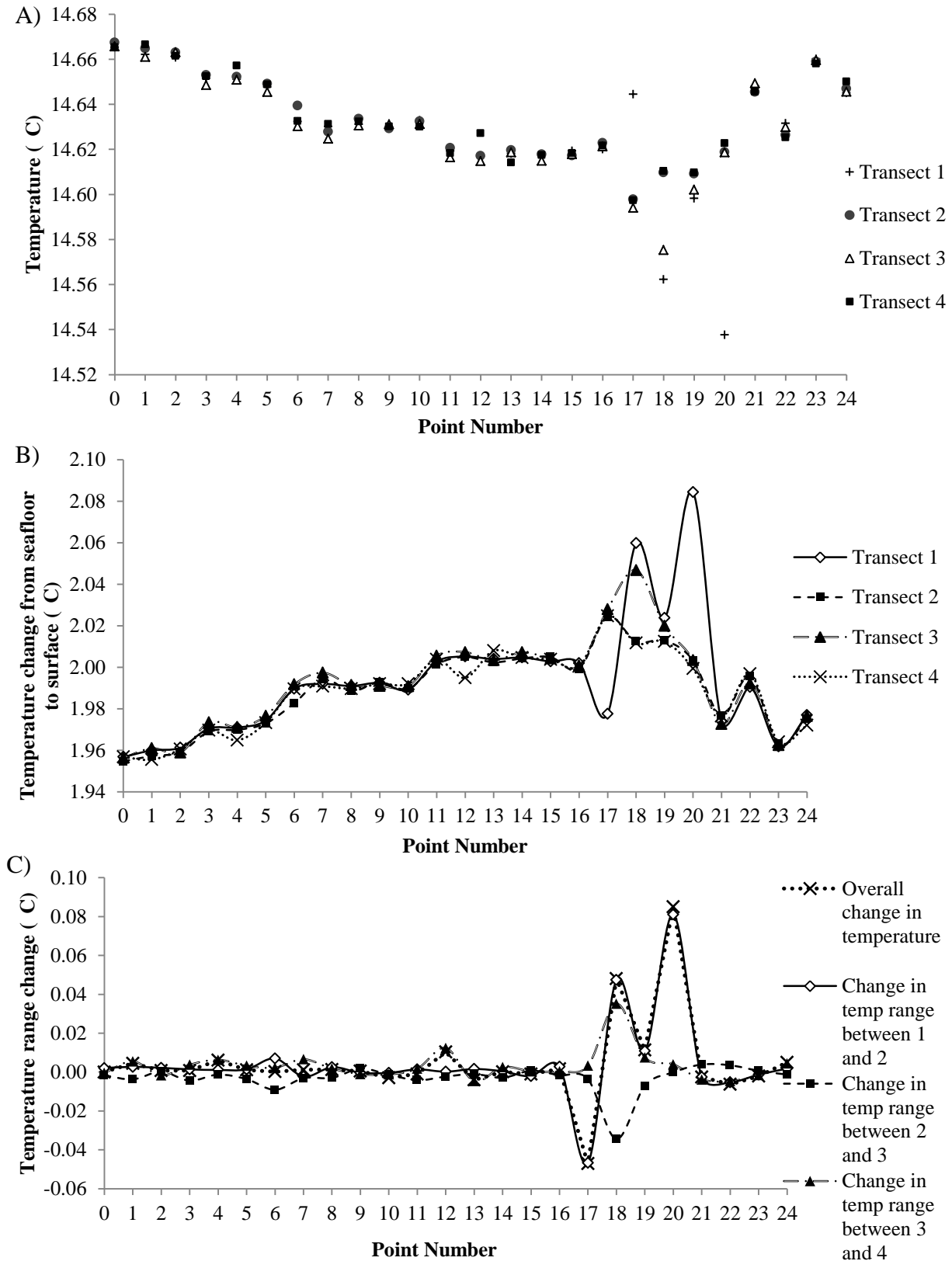


Fig. 3. Plots of temperature against point numbers (see Fig 2). A) Temperature changes over time for each transect, temperatures were calculated using Eq 1. B) Temperature range has been calculated between the sea surface and seafloor. C) Change in temperature range over time cumulating in the overall change in temperature over the investigation.

Table 3. Data from all four transects indicating the instrument used and error present in the methods. Errors are in °C for the instruments and % for the inverse echo sounding as this is the depth error of the multibeam system. Visualised in Fig. 4.

	Instrument	Average temperature (°C)	Range (°C)	Error (°C)	Error (%)
Transect 1	XBT	16.0276	17.0300	0.1	
	Inverse echo sounding				0.4
Transect 2	CTD Downcast	19.8441	17.2848	0.0018	
	CTD Upcast	20.1633	17.3200	0.0018	
	Inverse echo sounding	14.6336	1.9885		0.4
Transect 3	CTD Downcast	19.8856	16.4446	0.0018	
	CTD Upcast	20.2072	16.4718	0.0018	
	Inverse echo sounding	14.6305	1.9916		0.4
Transect 4	CTD Downcast	19.8643	17.1307	0.0018	
	CTD Upcast	20.0339	17.1324	0.0018	
	Inverse echo sounding	14.6338	1.9883		0.4

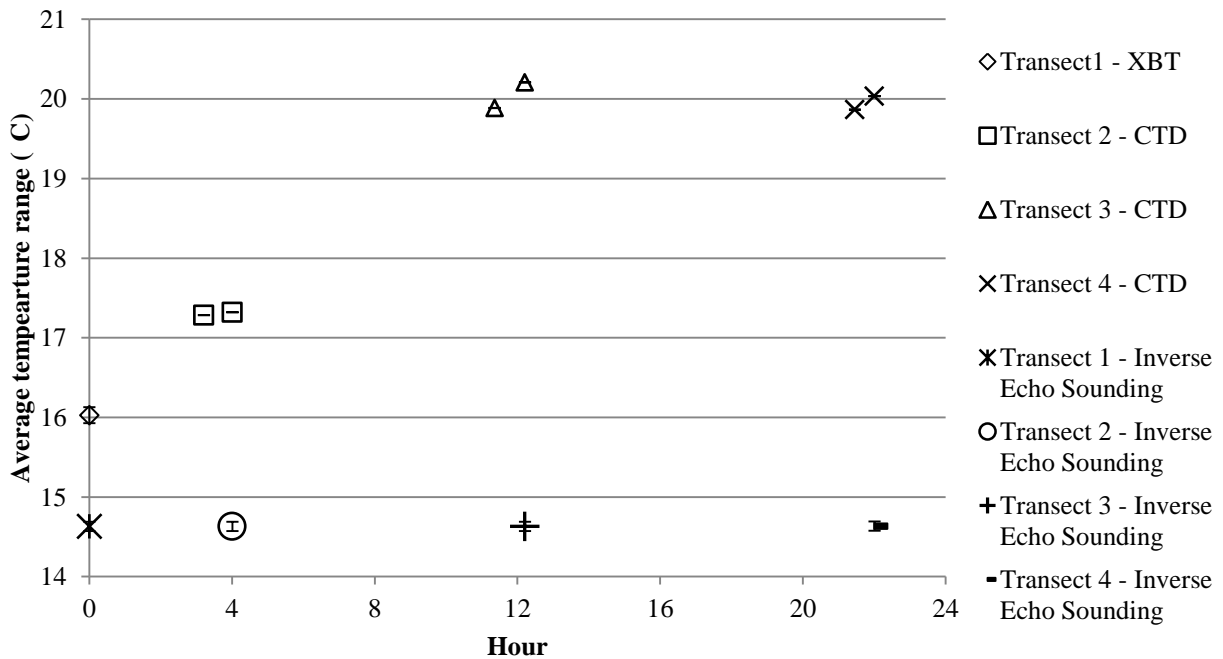


Fig. 4. Demonstrating how average temperature changes over time looking at the instruments and methods used in Table 3. Hour on the x axis refers to the number of hours into the investigation, to a total of 22.01. Error bars have been included for the data.

Table 4. Calculated data for temperature using Eq 1 and depth measurements. Range is calculated between the surface temperature (bottom left) and temperature at the seafloor, see Table 2 for depths. The change in temperature range is also calculated between transects signifying data over time.

Points	Transect 1		Transect 2		Transect 3		Transect 4		Change in temp range (°C)			
	Temperature (°C)	Range (°C)	Temperature (°C)	Range (°C)	Temperature (°C)	Range (°C)	Temperature (°C)	Range (°C)	Transects 1 and 2	Transects 2 and 3	Transects 3 and 4	Overall
0	14.6653	1.9568	14.6674	1.9547	14.6657	1.9564	14.6653	1.9568	0.0021	-0.0017	-0.0004	0.0000
1	14.6621	1.9600	14.6648	1.9573	14.6611	1.9610	14.6666	1.9555	0.0027	-0.0037	0.0055	0.0045
2	14.6608	1.9613	14.6630	1.9591	14.6632	1.9589	14.6615	1.9606	0.0022	0.0002	-0.0017	0.0007
3	14.6516	1.9705	14.6530	1.9691	14.6486	1.9735	14.6524	1.9697	0.0014	-0.0044	0.0038	0.0008
4	14.6511	1.9710	14.6522	1.9699	14.6509	1.9712	14.6572	1.9649	0.0011	-0.0013	0.0063	0.0061
5	14.6477	1.9744	14.6491	1.9730	14.6455	1.9766	14.6488	1.9733	0.0014	-0.0036	0.0033	0.0011
6	14.6324	1.9897	14.6394	1.9827	14.6303	1.9918	14.6326	1.9895	0.0070	-0.0091	0.0023	0.0002
7	14.6301	1.9920	14.6278	1.9943	14.6247	1.9974	14.6313	1.9908	-0.0023	-0.0031	0.0066	0.0012
8	14.6311	1.9910	14.6336	1.9885	14.6306	1.9915	14.6324	1.9897	0.0025	-0.0030	0.0018	0.0013
9	14.6296	1.9925	14.6293	1.9928	14.6311	1.9910	14.6301	1.9920	-0.0003	0.0018	-0.0010	0.0005
10	14.6329	1.9892	14.6325	1.9896	14.6312	1.9909	14.6300	1.9921	-0.0004	-0.0013	-0.0012	-0.0029
11	14.6193	2.0028	14.6207	2.0014	14.6165	2.0056	14.6183	2.0038	0.0014	-0.0042	0.0018	-0.0010
12	14.6169	2.0052	14.6171	2.0050	14.6148	2.0073	14.6272	1.9949	0.0002	-0.0023	0.0124	0.0103
13	14.6181	2.0040	14.6197	2.0024	14.6187	2.0034	14.6141	2.0080	0.0016	-0.0010	-0.0046	-0.0040
14	14.6174	2.0047	14.6178	2.0043	14.6149	2.0072	14.6175	2.0046	0.0004	-0.0029	0.0026	0.0001
15	14.6193	2.0028	14.6172	2.0049	14.6179	2.0042	14.6183	2.0038	-0.0021	0.0007	0.0004	-0.0010
16	14.6201	2.0020	14.6229	1.9992	14.6213	2.0008	14.6217	2.0004	0.0028	-0.0016	0.0004	0.0016
17	14.6445	1.9776	14.5978	2.0243	14.5941	2.0280	14.5974	2.0247	-0.0467	-0.0037	0.0033	-0.0471
18	14.5623	2.0598	14.6097	2.0124	14.5753	2.0468	14.6104	2.0117	0.0474	-0.0344	0.0351	0.0481
19	14.5983	2.0238	14.6092	2.0129	14.6021	2.0200	14.6097	2.0124	0.0109	-0.0071	0.0076	0.0114
20	14.5377	2.0844	14.6188	2.0033	14.6187	2.0034	14.6227	1.9994	0.0811	-0.0001	0.0040	0.0850
21	14.6481	1.9740	14.6455	1.9766	14.6494	1.9727	14.6456	1.9765	-0.0026	0.0039	-0.0038	-0.0025
22	14.6316	1.9905	14.6264	1.9957	14.6299	1.9922	14.6253	1.9968	-0.0052	0.0035	-0.0046	-0.0063
23	14.6602	1.9619	14.6589	1.9632	14.6596	1.9625	14.6581	1.9640	-0.0013	0.0007	-0.0015	-0.0021
24	14.6451	1.9770	14.6469	1.9752	14.6456	1.9765	14.6501	1.9720	0.0018	-0.0013	0.0045	0.0050
							mean		0.0043	-0.0032	0.0033	0.0044
	Depth (m)	Temperature (°C)										
Surface	0.0000	16.6221										

Discussion

The results suggest that inverse echo sounding is a method by which water temperature can be calculated over time. However this investigation cannot show conclusively that this method is any more or less accurate than other methods. This study is an original idea of which no published data or literature can be found, preventing any data comparison with other studies. The results do show that change in the water column temperature over time does occur, however, over the 22 hour study period an average change of only 0.0044°C was recorded. The value is considered to be a positive value inferring an increase in water temperature. Three points (17, 18 and 20) did change dramatically, with a 0.811°C difference between transects 1 and 2. These points were all found on the deepest parts of the common study area but were not grouped in one location; the multibeam errors suggested below may provide some insight into why these anomalous temperature changes occurred.

When processing the depth data using Caris® the mean of the depth data was taken as this was considered the most accurate way to sample the depth. To measure depth, individual sound ‘pings’ are transmitted to the seafloor, the time it takes for the sound to be reflected back to the receiver is used to calculate depth. For each of the pixels seen in the visualisation (Appendix 1) there are hundreds of individual ‘pings’. Averaging the ‘ping’ depths removed the minimum and maximum depth recorded, settling for the mean depth measurement. There is uncertainty if this mean depth is representative of sea floor depth at this time. The temperature change over time calculation is very sensitive to accurate depth measurements; therefore an error in the depth data produces an error in the temperature data. It is unclear whether these errors may large enough to conclude the change in temperature measurement over time as being void and due to errors not actual temperature change. The transducers from the multibeam themselves have errors of 0.4% in their depth measurements, averaging

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the depth for the locations could have produced the anomalies seen especially in deeper areas where the scattering of the sound beam may have occurred.

The Mackenzie equation (Eq 1, Mackenzie 1981) was used to calculate temperature and is the basis for the method of inverse echo sounding. For this investigation the parameters of salinity and sound velocity were set values with depth being the variable used to calculate the temperature. The two set values in this equation were average data from the XBT. When plotting temperature against depth a linear relationship is present due to the set salinity and sound velocity values. The XBT's metadata showed that the salinity had been set at 27.68 when the sound velocity profile was taken and this value was used in the equation. The sound velocity had a set value of 1503.146ms^{-1} . The salinity affects the sound velocity and so changing it to a more expected value of around 35 for seawater would have resulted in errors in the sound velocity data. Due to the salinity values, when temperature was calculated it was calculated with a freshwater bias and this therefore skewed the results making the comparison of inverse echo sounding to the XBT and CTD data very difficult. The same is true for the sound velocity measurement; sound velocity is faster at the surface and decreases with depth to a minimum at approximately 800-1000m. Averaging the parameters did not allow for the presence of a thermocline in the temperature calculations which is present in the Hawaii region (Fujiieki et al. 2010). Neither did it account for faster sound velocities at the surface. If the salinity is set to the measured surface salinity of 34.5 and the sound velocity at the surface to 1527.74ms^{-1} , the temperature calculated is 22.5719°C . This value is more representative of the measured temperatures from the XBT and CTD. It is the constraints of the method and calculation used that therefore caused the surface temperature measurement to be approximately 9°C lower than the actual surface temperature as measured by the CTD and XBT. This also accounts partially for the inverse sounding temperatures being up to 5.5777°C lower.

The calculated temperature was compared to the HOTS data from Cruise 216 using data from 11th May 2009 and Cruise 217 using data from 12th September 2009 (www.soest.hawaii.edu/HOT_WOCE/ftp.html). The two data sets are 124 days or 2976 hours apart. The average temperature of the water column, down to the relative depth of cross seamount (378m) were 17.6450°C and 17.4106°C respectively for the dates above. This gave a difference of 0.2344°C over 2976 hours. When scaling up the temperature measurement calculated in this investigation, 0.0044°C over 22 hours, to being equivalent in time to the HOTS data, a temperature difference of 0.5952°C is established. The calculated temperature is over double the HOTS data temperature however it is in a range that would warrant further investigation. HOTS data from the same dates as the cruise was not available but, when available, could be used to find the precise temperature differences relevant to the cruise. Summer and autumn months generally have warmer sea surface temperatures due to preceding increased solar insolation. The temperature rise calculated could be representative during certain months of the year however to fully establish this further research is required.

Many studies including Henigin (2005), Boedeker (2001) and Whelan (2007) have all found warm temperature errors in their XBT data when compared to the CTD data from the same site. In this study however, the average temperature from the XBT was on average 4.1072°C lower than the CTD measurements (Table 3, Fig. 4). The temperature error on the XBT is 0.1°C (www.sippican.com; Reseghetti et al. 2007; Georgi et al. 1980) and the CTD error is 0.0018°C (Reverdin et al. 2009) indicating that instrument error does not explain the difference. Only one XBT was taken with workable results for this study, thus the temperature anomaly could be due to the salinity differences as stated previously or could be due to a technical error in the data.

Spatial and temporal errors are also present in the data. The metadata shows that the XBT and CTDs were not deployed directly over the common area identified (Fig. 2). They

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may have been deployed in areas where other water masses may have been present therefore recording inaccurate results for the location. Temporally there were differences in time between the transect and the instrument deployment; again this could allow for a different parcel of water to enter the area and skew the results.

Another way to process the data would have been to use a two layer box model. This method was not used in this investigation as the exact depth of the mixed layer was unknown, however this could be determined in future studies using an Acoustic Doppler Current Profiler (ADCP). This way the average temperature of the mixed layer and the deep ocean could have been calculated and a more significant difference in the temperature over time, especially in the mixed layer, may have resulted.

Temperature differences over time of the ocean are becoming a widely known topic due to global warming. Sea surface temperatures have risen by 0.4°C over the last 30 years (IPCC 2007). Due to ocean circulation the interior of the ocean will also experience a rise in temperature. Sokolov et al. (1998) expressed concern with the heat of the deep ocean, this method and a two box model, could allow the deep ocean to be monitored. With frequent passing over the same location the multibeam will be able to detect the depth and therefore temperature change over time. The technique requires less personal than the CTD casts to detect interior ocean temperature and allows temperature to be calculated to four decimal places, resulting in precision calculations. A multibeam system is required, however this is present on most vessels and an XBT is required for multibeam calibration but the method removes the need for any further equipment to be carried or deployed.

This investigation did not come to a definitive conclusion; further research into the technique is required. Future studies would look at different temporal scales; this study looked at 22 hours which is not long enough to get an accurate picture of water column changes over time. Seasonal and annual time scales could be investigated where a common

area is mapped at regular intervals to see if water column changes can be detected by the technique. Alternative sites with different water column structures such as a site of hydrothermal venting where buoyant plumes rise from the seafloor producing different temperature structures could be investigated. Two locations would provide a contrast in water column stability, allowing the method of inverse echo sounding to be tested under diverse water column structures which will help to determine reliability and accuracy in the technique. Application to a real world scenario could involve predicting El Nino and how it affects water temperature. Water temperatures during El Nino events are well documented and can provide informative tests of the method as the water temperature difference data in this area is well documented.

Conclusions

The data indicate that the method of reverse echo sounding is a possible method for investigating how water column temperature changes with time. It is probable that the time scale over which the investigation was carried out was too short to see significant changes in the water column structure which has resulted in data which does not support my original hypothesis. A temperature change of 0.0044°C was found over the 22 hour time period. This is a low value relative to the overall temperature at depth; however with a longer study time this temperature range would increase as the water column structure changes seasonally. It is unclear whether the temperature change is present or if depth and averaging errors on the multibeam data are large enough to hide the real temperature change. However, when 0.0044°C is scaled up to temperature change over a longer time period and compared with the HOTS data the measurements, a promising result occurs as temperatures are within the same order of magnitude. It was also proposed that the average temperature data calculated by inverse echo sounding will not be significantly different from XBT and CTD averaged

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temperature profiles. This has been proved a null statement as there is no correlation between the inverse echo sounding technique, the XBT and CTD (Fig. 4). The errors in the Mackenzie Equation have shown that the method used to calculate temperature is probably at fault not the data itself. Further investigation, on a longer time scale, with an updated and improved methodology is required into the technique in order to retrieve a definitive conclusion.

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Appendix 1

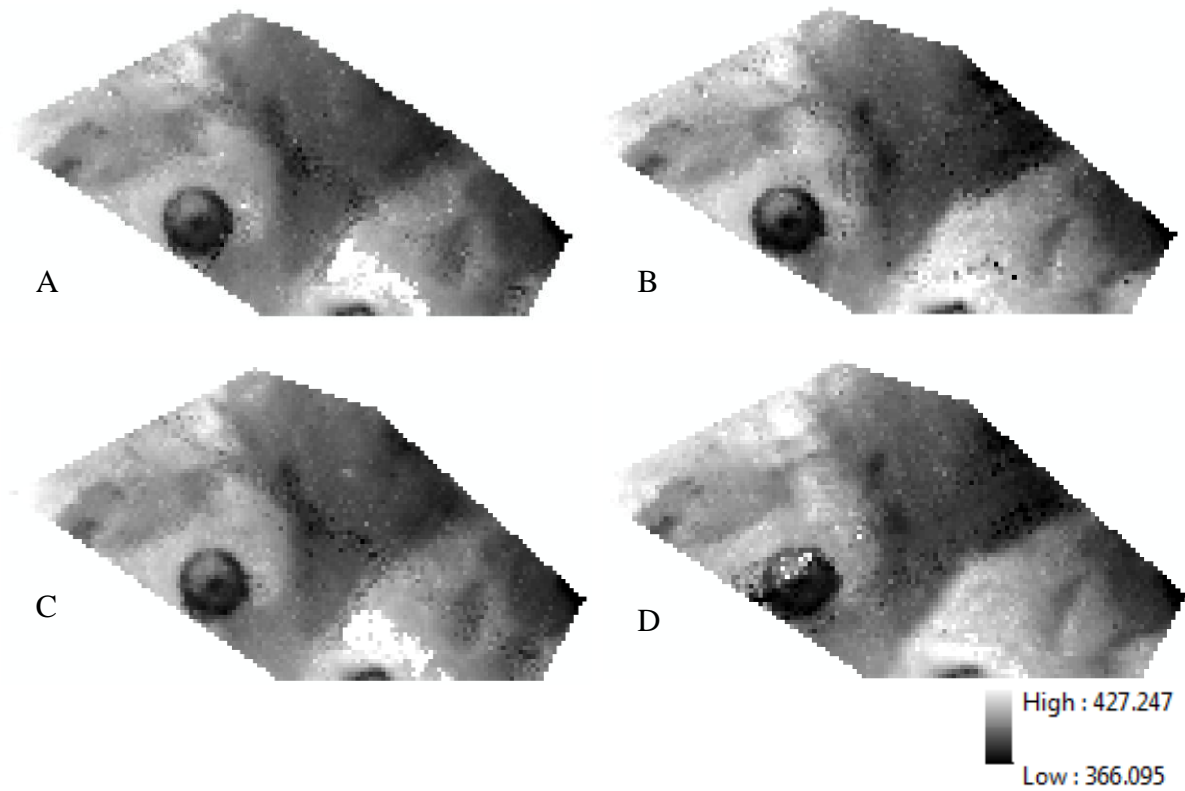


Fig. 1. Illustrations of how depth changes over time. Values in the key are in metres and measured from the sea surface therefore low values are closer to the surface and high values are deeper. A) corresponds to transect 1; B) transect 2; C) transect 3 and D) transect 4. Images were produced using Caris® software.

Appendix 2

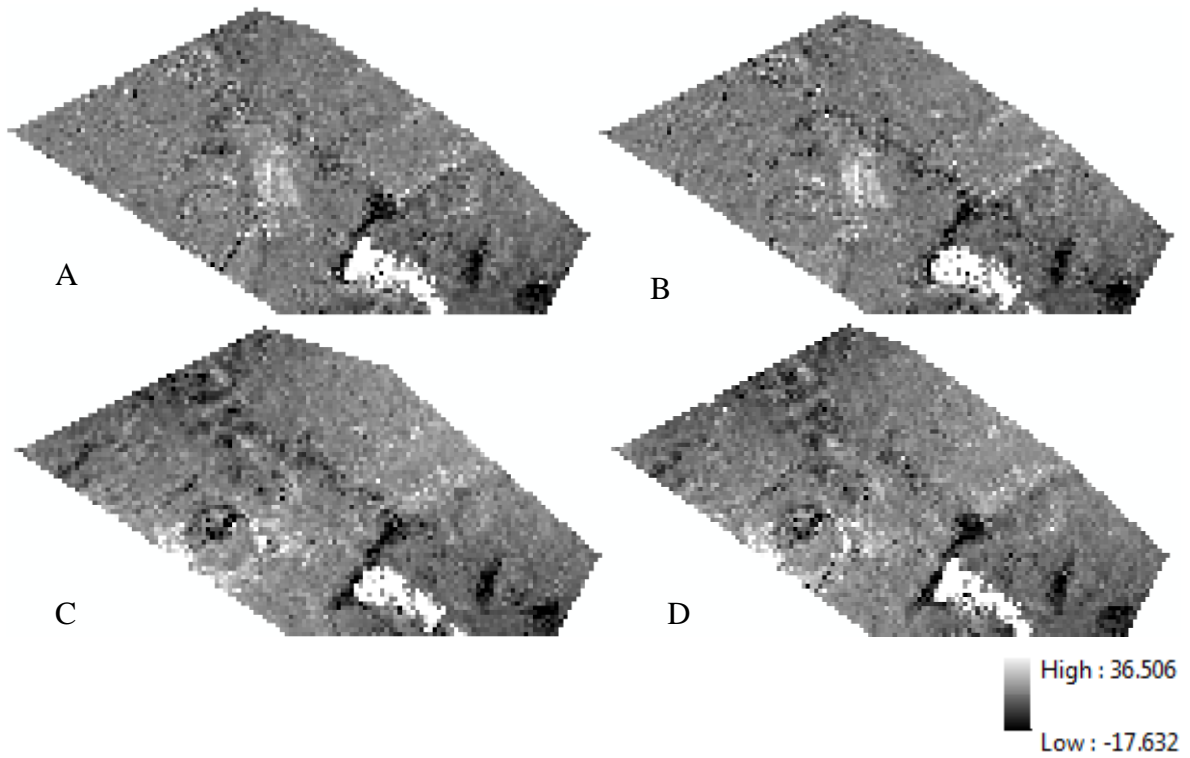


Fig. 2. Visualisations of the change depth of the common area between each transect. A) Depth change between transect 1 and transect 2; B) between transect 2 and transect 3; C) between transect 3 and transect 4; D) overall change in depth between transect 1 and