TEMPERATURE, SALINITY AND OXYGEN CLIMATOLOGY OF AFRICAN CONTINENTAL SHELF WATER, SOUTH OF THE EQUATOR, AND CHANGES SINCE 1945

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ABSTRACT

The first temperature, salinity and oxygen climatologies for waters of the continuous southern African continental shelf is presented. It is based on oceanographic data collected since 1945, sub-sampled at depths of 5, 50 and 100 m on a mixed-spatial grid with 0.25° to 0.5° resolution. The climatologies capture spatial heterogeneities and seasonal variability in key ocean variables for the southern African shelf in unique detail. The results correspond relatively well with biogeographic boundaries informed by classification schemes grounded in taxonomy, but questions the value of the Large Marine Ecosystem approach. Analysis of decadal trends demonstrates the inherent complexity and spatial heterogeneity associated with environmental variability, and suggest the possibility that decadal periodicities are in the process of being disrupted by a longer-term trend. The overall pattern is that southern African West and South coast shelf waters are becoming warmer, except for some upwelling areas, where cooling is evident. Benguela and Agulhas Bank shelf water are also becoming more oxygen depleted.

1. INTRODUCTION

Continental shelves account for only about 8% of the world's marine areas, but are host to more marine biodiversity, productivity and human activities than offshore waters, and provide ecosystem services comparable in magnitude to that of all terrestrial habitats (UNEP, 2006; Costanza et al., 1997). The African continental shelf is host to natural resources of particular and critical socio-economic value for coastal communities (Kainge et al., 2020). Understanding the significance of observed changes in ocean variables such as temperature and wind (Roualt et al., 2010; Leduc et al., 2010; Santos et al., 2012; Beal et al., 2016; Vizy et al., 2018; Malan et al., 2019), and ecosystem changes such as species range shifts and variability in species abundance (Cockcroft et al., 2008; Roy et al., 2007; Coetzee et al., 2008; Yemane et al., 2014; Blamey et al., 2015; Jarre et al., 2015a; Van der Linge et al., 2016; Kainge et al., 2017; Van der Linge and Hampton, 2018), have transdisciplinary significance (Potts et al., 2014; Augustyn et al., 2017; Hobday and Pecl, 2014; Kainge et al., 2020). Construction of climatological maps of key ocean variables, based on the calculation of mean fields from historical data sets, are valuable reference tools in this regard.

Only a limited number of climatologies have been constructed specifically for shelf areas, e.g. for the eastern seaboard of North America (Atkinson et al., 1983; Blanton et al., 2003; Bisagni, 2016; Richaud et al., 2016) and the Ross Sea off Antarctica (Russo et al., 2011). Most climatologies of key ocean variables exclude data from "land grid-boxes", i.e. coastal areas and portions of the inner continental shelf (Levitus, 1982; Levitus and Boyer, 1994; Ridgway et al. 2002; Boyer et al. 2005; Boyer et al. 2018). Large parts of the African shelf is relatively data poor (Boyer et al., 2018), and irregular and infrequent sampling presents unique challenges to the production of regional scale climatological maps. This study presents the first such climatological maps for waters of the southern African continental shelf, from the equator off the west coast of Gabon, to the equator and the east coast of Somalia.

Our knowledge of the morphology of the African continental shelf is much less advanced than for most other continents (Chiocci and Chivas, 2014). The shelves of the West, South and East African continental margins comprise passive continental margins characterised by thick sediment accumulations where fluvial supply is high, such as off the mouths of the Congo, Orange, Tugela, Limpopo, Save and Zambezi rivers (Scrutton, 1982). The coastline is dominated by lowland coasts with long unbroken sandy beaches (Orme, 1982); rugged mountainous coasts are rare, except along the most southern margin. The southern Africa continental shelf varies considerably in width, as defined by the offshore distance of the 200 m depth isobath (Fig 1A). In the south, the Agulhas Bank has a maximum offshore extent of about 270 km (Dingle et al., 1978). The shelf areas off Namibia and South Africa's west coast are also notably wider, compared to those off Angola (Bremner, 1981) and most of the East Coast (Schumann, 1998). The shelf regions off eastern South Africa and off northern Mozambique are particularly narrow, often less than 10 km wide, with steep offshore slopes (Schumann, 1998).

The southern Africa shelf is influenced by four surface ocean current systems, the Angola, Benguela, Agulhas and East African Coastal currents (Fig 1A). The warm southward flowing Angola Current derives primarily from the South Equatorial Under Current (SEUC) and the Guinea-Congo Under Current (GCUC) with additional austral winter inflow from the South Equatorial Counter Current (SECC) (Stramma and Schott, 1999; Mercier et al., 2003). The Angola Current forms the eastern boundary of the Angola Gyre, which is a large scale current field centered near 17°S, 5°E (Gordon and Bosley, 1991). Embedded in the gyre is the Angola Dome, centered at 10°S, 9°E (Mazeika, 1967). The Angola Current splits into two at the southern boundary of the Angola Gyre at ~ 16 to 17°S: a westward continuation, which closes the Angola gyre, and the Benguela Poleward Under Current (BPUC), which flows along the upper slope as far south as 27°S off Namibia (Mercier et al, 2003; Tchipalanga et al., 2018). At the confluence of the Angola Current and the cold northward flowing Benguela Current is a sharp thermal front, the Angola-Benguela Front (ABF, Fig 1A). The ABF migrates in an eastward and southward direction in response to the late austral summer (Feb - April) relaxation of equatorial easterly winds (Dias, 1983; Stramma and Schott, 1999; Ekau and Verheye, 2005). The cool Benguela Current flows northward off the west coast of South Africa and Namibia (Fig 1A), from approximately 35°S to just south of the ABF. It is driven by the prevailing South Easterly trade winds of the South Atlantic Ocean. Inshore of the Benguela Current, the south easterly winds cause inner shelf upwelling of cold nutrient-rich water (Olivar and Shelton, 1993; Shannon, 1995).

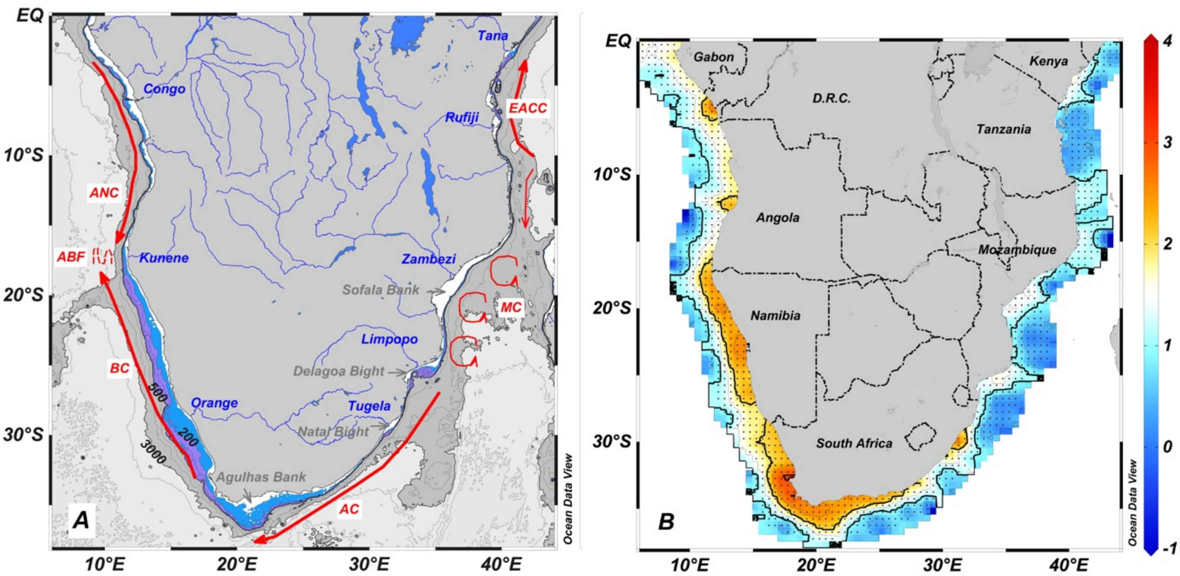

Fig 1. A: Bathymetric map of the study area; the coast to 100 m depth interval is filled in with white, 100 to 200 m blue, 200 to 500 m purple (thin solid lines indicate 300 and 400 m depth intervals); 500 to 3000 m dark grey (thin solid lines indicate depths at 500 m intervals), depths below 3 000 m are light grey (with thin solid lines indicating 500 m depth intervals). Also shown are the major continental river systems. B: Total number of sampling stations for which oceanographic data is publicly available (as WOD and SADCO datasets) for 1900 to 2020, plotted as log(#stations) per 0.5° latitude x 0.5° longitude bin. The black dots indicate the center points of the 0.5° x 0.5° degree bins used in this study.

The warm Agulhas Current dominates the shelf areas off the south and east coasts of South Africa (Fig 1A). The current originates near ~ 28°S off Mozambique and transports warm water in a south-westerly direction towards its retroflection area off the tip of Africa (Lutjeharms and van Ballegooyen, 1988; Lutjeharms and Cooper, 1996). The Agulhas and Benguela currents play a significant role in global ocean heat transfer between the Southern and the Northern Hemisphere (Duncombe Rae, 1991). The ocean area between ~ 10°S and 28°S along the east African coast is occupied by the Mozambique Current, a discontinuous current characterised by southward drifting anti-cyclonic eddies (Lutjeharms et al., 2012). The East African Coastal Current, or Zanzibar Current, flows northward from

~ 10°S along the east African coast (Swallow et al., 1991). There is close interaction in many cases between shelf and slope morphology and current movement, as has been described for south-eastern Africa (Lutjeharms 2006).

Several biogeographic divisions have been proposed for the southern Africa continental shelf and offshore ocean areas. The large marine ecosystem (LME) approach is widely used by regional scientists and resource managers (Sherman, 1993), despite its "amorphous" nature (Pauly, 1998). The study area hosts the Benguela Current Large Marine Ecosystem (BCLME), the Agulhas Current LME (ACLME) and the Somali Coastal Current LME (SCCLME) (Fig 2).

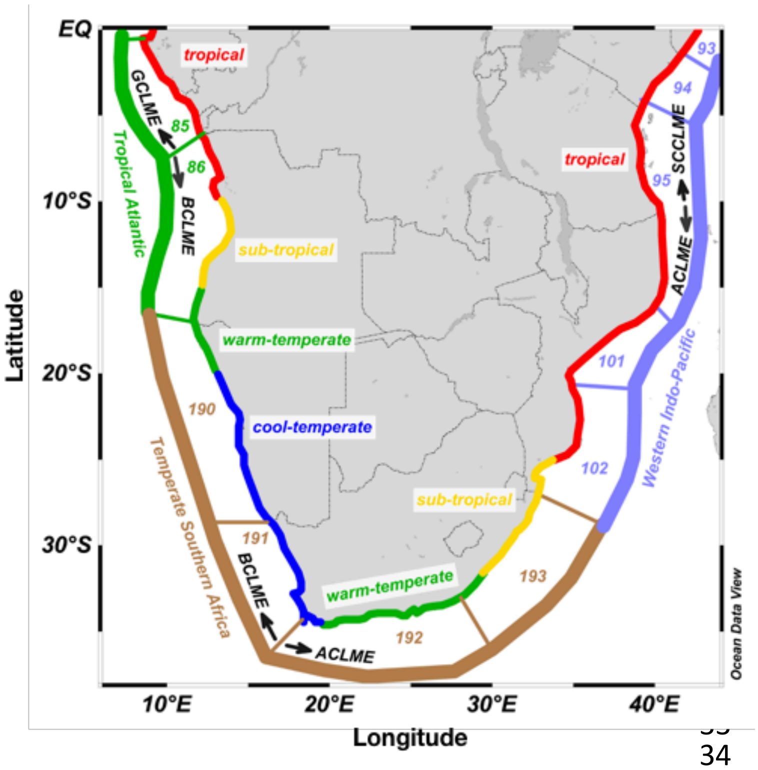

Fig 2. Map of the Tropical Atlantic (thick green line), Temperate Southern Africa (thick brown line) and Western Indo-Pacific (thick purple line) biogeographic Realms of Spalding et al. (2007), subdivided into these *Provinces* (and numbered ecoregion blocks): *Gulf of Guinea* (85 - Gulf of Guinea South, 86 - Angolan), *Benguela* (190 - Namib, 191 - Namaqua), *Agulhas* (192 - Agulhas Bank, 193 - Natal), *Western Indian Ocean* (102 - Delagoa, 101 - Bight of Sofala/Swamp Coast, 95 - East African Coral Coast, 94 - Northern Monsoon Current Coast), *Somali/Arabian* (93 - Central Somali Coast). Large marine ecosystems are indicated in black (LME's; Sherman, 1993): GCLME - Guinea Current LME, BCLME - Benguela Current LME, ACLME - Agulhas Current LME, SCCLME - Somali Coastal Current LME. Thin colored lines along the coastline indicate the biogeographical zones defined by Briggs and Bowen (2012) and Whitfield (2005), as modified by Potts et al. (2015).

The BCLME is one of the most productive ocean ecosystems in the world in terms of biomass production and fishery resources (Spalding et al., 2012). The relatively narrow Northern Benguela shelf, off Angola, is characterized by spatially extensive upwelling. The wide Central Benguela (off Namibia) and South Benguela (off South Africa) shelf areas, in contrast, host several discrete upwelling cells (Shannon, 1995). The hierarchical biogeographic classification system of Spalding et al. (2007) was developed specifically and uniquely for the benthic and pelagic biotas of coastal and shelf areas. This nested system describes three Realms, five Provinces and eleven biogeographic Ecoregions for the southern Africa continental shelf (Fig 2). Other classification systems that rely primarily on taxonomy (Briggs and Bowen, 2012; Potts et al. 2015) propose up to 7 biogeographic zones for the African shelf and coastline south of the equator (Fig 2).

Temperature has been proposed to be the key environmental variable correlating with the distribution of species and range shifts in shelf areas, as is the case for the open ocean (Spalding et al., 2007; Potts et al., 2015; Sunday et al., 2012; Cheung et al., 2013; Morley et al., 2018). It is also increasingly recognized that temperature extremes rather than average values determine population survival at the warm edge of a species' temperature range (Pinsky et al., 2019). Additionally, abrupt ecosystem change can be caused by extreme climatic events such as marine heatwaves, that is prolonged periods of anomalously warm seawater (Shannon et al., 1986; Gammelsrød et al., 1998; Mills et al., 2012; Cavole et al., 2016; Wernberg et al., 2016; Rouault et al., 2017; Jones et al., 2019; Smale et al., 2019). Globally, marine heatwaves have increased in frequency and duration since the early 20th century (Oliver et al., 2018), and global models project this trend to continue through the 21st century (Oliver et al., 2019). Temperature and dynamic temperature ranges, however, cannot be considered is isolation of other variables that influence marine species distribution, dissolved oxygen is also particularly important (Jarre et al., 2015b; Hamukuaya et al., 1998; Mbatha et al., 2019; Woodhead et al., 1997). This study presents annual and seasonal climatologies for temperature, salinity and oxygen for the continuous southern African continental shelf at depths of 5, 50 and 100 m. Interdecadal changes are also evaluated and discussed in the context of documented complex ecosystem changes that have been observed in the study area.

2. DATA AND METHODS

2.1. Study area, data sources and distribution

For the purpose of this study, data was extracted for the area 0 to 40°S, 5 to 45°E, from two open access online sources: WOD18 (World Ocean Database 2018, available at ncei.noaa.gov; Boyer et al., 2018) and SADCO (Southern African Data Centre for Oceanography, presently hosted at sadco.ocean.gov.za). The databases contain both high resolution CTD (i.e. Conductivity-Temperature-Depth data at 2 or 5 m depth intervals) and low resolution bottle (called OSD or Ocean Station Data in the WOD) data sets. WOD OSD data was retrieved at standard (as opposed to observed) depths of 0, 5, 50 and 100. The data sets were combined and stations with repeated timestamps removed. The consolidated WOD-SADCO data set comprises 77 259 individual stations within the 0 to 40°S, 5 to 45°E area. About 85% (65 852) of these stations are located within 3 degrees of the African coastline (Appendix 1).

An outlier filter (Richaud et al., 2016) was applied to this data set as a quality control measure. For this purpose, all data set values for temperature, salinity and oxygen were grouped into 1° x 1° bins, and the mean and standard deviation (σ) calculated for each variable at the surface (0 and 5), 50 and 100 m. All values more than 3 times the standard deviation away from the mean were considered outliers and removed, with the exception of surface salinity in bins adjacent to river mouths. Only one iteration of this procedure was carried out, no further data exclusion took place and less than 0.2% of the total data was removed through this procedure (listed in Appendix 2). The data set was also screened for spatial and temporal clustering (defined as multiple data points within a 24 h period and 5 km radius) as a precautionary measure. It is important to note that historical data, in particular biogeochemical data such as oxygen, "have been measured using a variety of manual and automated analytical techniques" (Boyer et al., 2018) and the details of these are often not contained in metadata. Comparison of measurement techniques and uncertainties fall outside the scope of the WOD and also this study.

The spatial and temporal coverage of the data set, excluding the above outliers, was then evaluated by counting the number of OSD and CTD casts in 0.5° x 0.5° bins (Fig 1B, Appendix 1), for a 3 degree distance away from the coastline. This was repeated for each of the variables (Appendix 1). Although the continental shelf is the focus of this study, it seemed sensible to include data from offshore of the 200 m depth isobath. The 0.5° x 0.5° bins closest to the coast, i.e. along the inner shelf, were termed H_{coast} (or $H_{0.5°}$). Successive bins further offshore ($H_{1°}$, $H_{1.5°}$, $H_{2°}$, $H_{2.5°}$ and $H_{3°}$) were aligned in an east-west direction for the West (west of 18.5°E) and East (east of 26.5°E) coast areas, and in a south-north direction along the South (18.5 to 26.5°E) coast. The H_{coast} bins all contain terrestrial land area, to different degrees. The distribution of data with depth (5, 50 and 100 m), time of day (four 6 hour intervals from 00:00-05:59 to 18:00-23:50) and time (5 year increments from 1945 to 2019) was established per 0.5°x3° bin, using temperature cast data (Appendix 1). In summary, 100% of the total casts contained temperature data, with equivalent values of 91% for salinity, 54% for oxygen. Additionally, 99% of the casts contained temperature data at the surface, 49% at 50 m and 37% at 100 m depth.

2.2. Analysis of intra-annual variability and seasonality in H_{coast} *bins*

Average monthly temperature values were calculated at depths of 5, 50 and 100 m for each H_{coast} bin, from 0 to 34.5°S along the West Coast, 18.5 to 26.5°E along the South Coast and 34.5 to 0°S along the East Coast (Fig 3). Constructing an annual profile consisting of monthly values (with n > 3) was possible for most of the H_{coast} bins, with minimal interpolation required, except for the East Coast and in particular north of 28°S along the East Coast (Table 1; Fig 3). In the latter instance, monthly data gaps were filled with the average of four values: that of the preceding and following month of the same bin, and values for the same month in the two adjacent H_{coast} bins. Temperature required the least amount of gap-filling, and typically up to a factor of two less than salinity and oxygen. In an offshore direction, i.e. H_{coast} towards $H_{3°}$, the amount of gap-filling required for the construction of annual profiles consisting of monthly values is excessive in most areas, even for temperature (Table 1). The method adopted by Ridgway et al. (2002) and Richaud et al. (2016), that is of assuming an annual profile and then using it to calculate monthly values for gap-filling purposes, and calculating an annual climatological average from that, was therefore not adopted in this study. This study, rather, constructed an annual climatology from four seasonal values. The choice of months to be grouped together to constitute a season, was based on the intra-annual variability observed in the H_{coast} bins, as detailed below.

Intra-annual surface temperature variability in H_{coast} bins indicated that the warmest month of the year, along the entire southern African shelf, is most often February (55%), followed by March (34%) and January (11%) (Fig 3A, 4A). At the surface, the coldest month is most often August (46 %, blue line in Fig 3A; Fig 4B), followed by July (23%) and September (20%). At 50 and 100 m depths, however, the warmest and coldest monthly values were generally observed at different times of the year than at the surface and the seasonal pattern is more complex and geographically variable than at the surface (Fig 3, 4). February is the warmest month of the annual cycle for 20 % and 0% of the H_{coast} bins at 50 and 100 m, respectively, and August the coldest month for 24% and 22% of the H_{coast} bins, at these two deeper depths. The geographic complexicity in intra-annual variability were captured in shelf segment composites, consisting of the average of all the H_{coast} bin monthly values in that segment; Gabon-Angola or WC: 0 - 17°S, Central Benguela or WC: 17 - 28°S, Southern Benguela or WC: 28 - 34°S, Agulhas Bank or SC: 18.5 - 26.5°E and the southern East Coast or EC: 25 - 34°S (Fig 5). Based on the results of this evaluation, months were grouped together for the construction of seasonal average temperature, salinity and oxygen values, as follows: Jan-Feb-Mar (JFM) = summer; Apr-May-Jun (AMJ) = autumn; Jul-Aug-Sep (JAS) = winter; and Oct-Nov-Dec (OND) = spring.

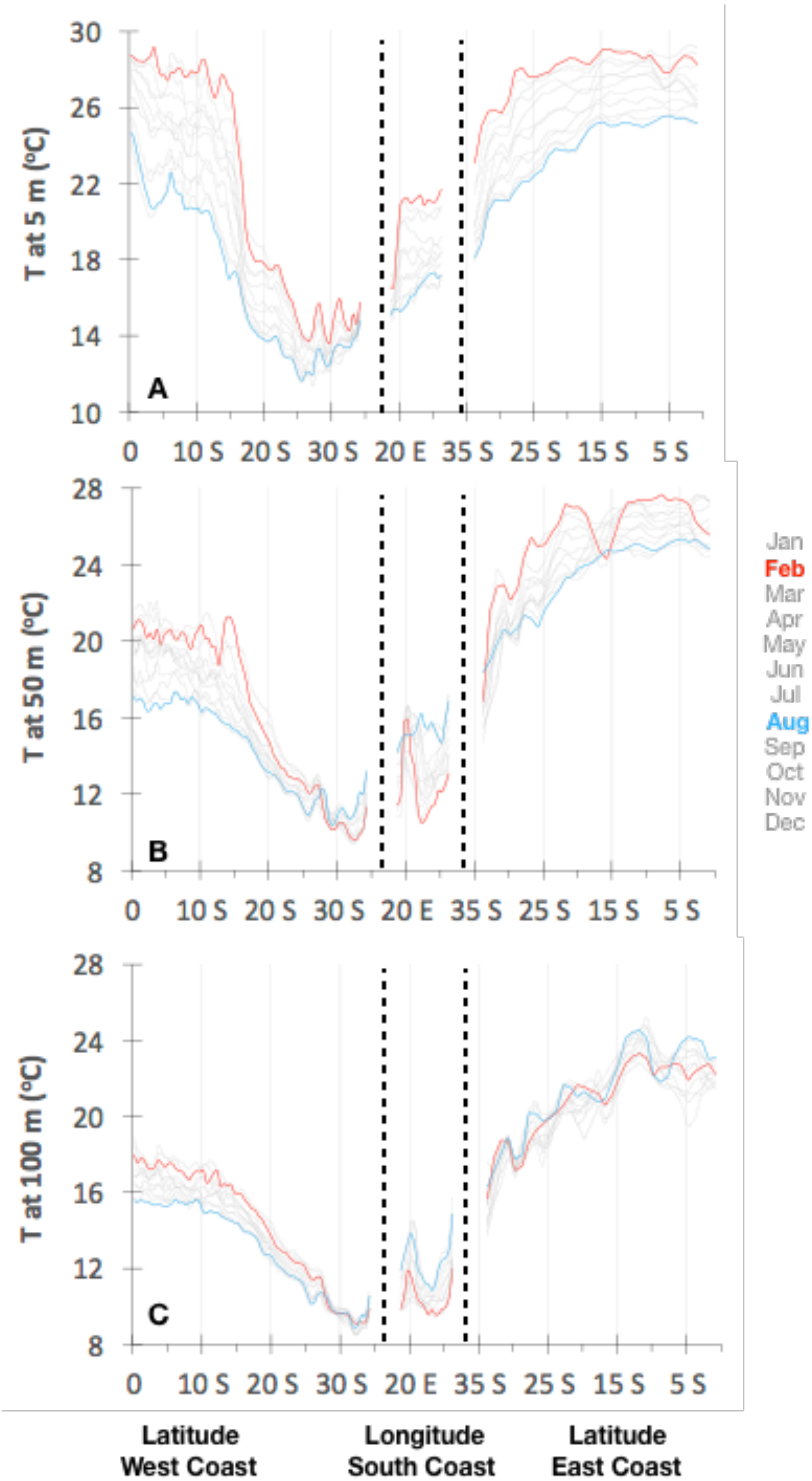

Fig 3. Comparative average monthly temperature values at depths of 5, 50 and 100 m (A to C) for H_{coast} bins, from 0 to 34.5°S along the West Coast, 18.5 to 26.5°E along the South Coast and 34.5 to 0°S along the East Coast. The red lines highlight values for February, most often the warmest month of the year in the study area, and the blue lines highlight values for August, most often the coldest month of the year. Grey lines indicate the other ten months of the year.

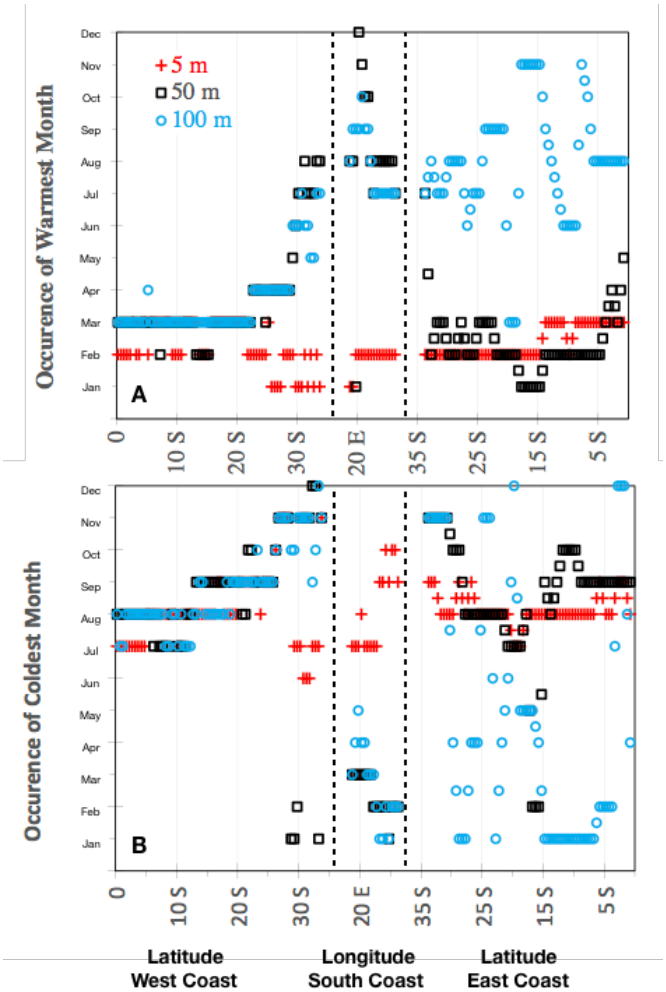

Fig 4. Months in which the highest (A) and lowest (B) monthly average T values are observed in H_{coast} bins.

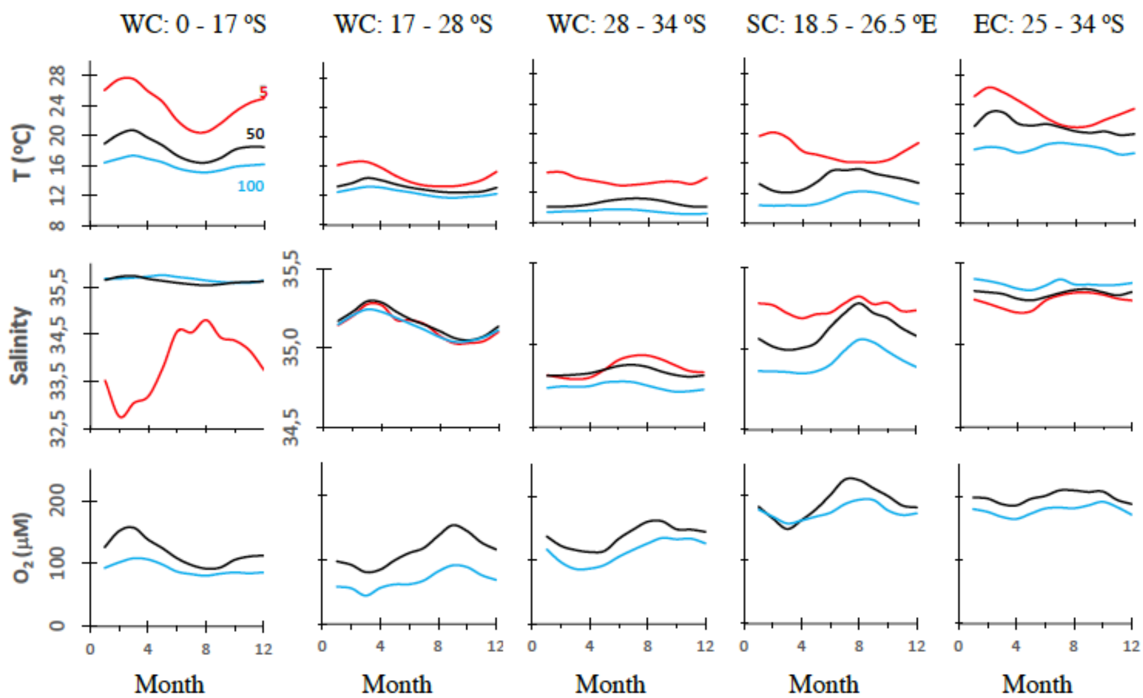

Fig 5. Composite temperature, salinity and oxygen annual profiles at depths of 5 m (red), 50 m (grey) and 100 m (blue), for all the H_{coast} bins within 5 degree sections.

Table 1 Percentage of grid boxes requiring gap-filling (n < 3), for calculation of temperature at 50 m depth.

AREA	H_{coast} Monthly %	Season	H_{coast} - $H_{1.5°}$ %	$H_{2°}$ - $H_{3°}$ %	Q1-Q6 %
West Coast: 0 - 17°S	7	JFM	10	51	29
		AMJ	6	32	29
		JAS	2	36	22
		OND	0	17	19
West Coast: 17 - 28°S	0	JFM	0	11	1
		AMJ	0	38	6
		JAS	2	41	6
		OND	2	27	7
West Coast: 28 - 34.5°S	4	JFM	0	14	0
		AMJ	2	33	2
		JAS	0	21	6
		OND	2	33	8
South Coast: 18.5 - 26.5°E	5	JFM	8	23	16
		AMJ	4	21	7
		JAS	2	26	10
		OND	4	17	6
East Coast: 27 - 34.5°S	8	JFM	19	> 50	56
		AMJ	15	> 50	30
		JAS	13	> 50	35
		OND	25	> 50	51
East Coast: 10 - 27°S	25	JFM	13	> 50	> 50
		AMJ	17	> 50	> 50
		JAS	17	> 50	> 50
		OND	36	> 50	> 50
East Coast: 0 - 10°S	33	JFM	18	> 50	> 50
		AMJ	20	> 50	> 50
		JAS	12	> 50	> 50
		OND	23	> 50	> 50

2.3. Analysis of potential sampling bias related to time of day or inter-annual trends

Evaluation of data distribution per time of day showed that 20% of the total casts were taken between 00:00 an 05:59 in the early morning, 32% between 06:00 and 11:59, 28% between 12:00 and 17:59 and 20% between 18:00 and 23:59 (Appendix 1). This fairly even distribution of sampling during the 24 hour cycle was further explored for potential bias, as follows: a diurnal surface temperature profile was constructed for each season, consisting of twelve 2-hour average values, for every H bin with a total of more than 400 casts (Appendix 3). The temperature average obtained from the diurnal profile ($T_{diurnal}$) was then compared to the average of all the values in the bin (T_{all}), for each season, without consideration of sampling time, and yielded the following relationship:

$$T_{all} = 0.9948*T_{diurnal} + 0.0827 \ (r^2 = 0.9988), \text{ and}$$

$$(T_{all} - T_{diurnal})_{average} = -0.003°C \ +/- \ 0.105 \ (1\sigma).$$

This analysis showed that there is no appreciable sampling bias related to the time of day, for surface temperature. It is also worth noting that the 12:00 to 17:59 period was the warmest time of the day (at the surface) in only 42.5% of the cases evaluated (Appendix 3). It is assumed that the time of day can also be ruled out as a potential appreciable source of sampling bias at 50 and 100 m depths, and for salinity and oxygen.

The uneven spatial and temporal distribution of data across the study area (Fig 1A; Appendix 1) presents a challenge to the analysis of the data for potential inter-annual or inter-decadal trends or periodicity. Even in the relatively small geographic area with the largest number of casts over the longest period of time, i.e. between 32 and 34°S on the West Coast, time series consisting of one or two year average values revealed no statistically significant monotic trends or periodicity in temperature, salinitiy or oxygen. As an alternative, time series consisting of decadal average values were constructed, for 1945-1953 to 2005-2014, for each season and depth interval. A Mann-Kendall test was then performed on each constructed time series that comprised of at least 4 decadal values, as a test for monotic trends. Only 3.5% of the H_{coast} to $H_{3°}$ bins contained enough data, over a long enough period and without too many sampling gaps, to satisfy this requirement. All significant monotic trends (>95% confidence level) are listed in Table 2 and the relevance of these trends are discussed in the text. All of the East Coast H bins north of 33°S contained inadequate data for inclusion in this analysis.

Although the available data was too sparse for the robust statistical analysis of periodicity using spectral analysis, the decadal time series data suggested potentially interesting periodicities in the data, generally consistent with the Atlantic multidecadal oscillation (AMO), i.e. alternating periods of warm and cold sea-surface temperatures with a period of 60 to 90 years (Kerr, 2000; Knudsen et al., 2011). This motivated the construction of three 25 year climatologies (detailed in the next sub-section), for the periods 1945 to 1969, 1970 to 1994 and 1995 to 2019, as an alternative evaluation of long-term variability. These 25 year periods approximate the timing of one cold (1970-1994) and two warm (1945-1969 and 1995-2019) phases of the AMO cycle. It also conveniently divided the data for the West and South coast areas into three equal 25 year periods, each with adequate data for the construction of climatologies at depths of 5, 50 and 100 m.

Table 2 Results of Mann-Kendall tests on decadal time series data for temperture and salinity. Trends shown are significant at the >95% level, positive values (bold) indicate increases over time and negative values decreasing trends.

Long	Lat	Type	Season	Data Period	T- 5	T-50	T-100	S-5	S-50	S-100
(± 0,25°)					°C/year			units/year		
11,25	-5,25	H2	JFM	1960-1988	-0,014		-0,026			
13,25	-12,25	H2	JFM	1961-1999	**0,050**					
12,25	-20,25	H3	JFM	1950-2002	**0,022**					
14,75	-25,75	H1	JFM	1966-1999	**0,033**	**0,037**		**0,007**	**0,005**	**0,007**
18,25	-33,75	H1	JFM	1951-2008			**0,016**			**0,002**
19,25	-34,75	H2	JFM	1948-2007		**0,079**			**0,006**	
19,75	-34,75	H1	JFM	1948-2007		**0,127**		**0,006**	**0,010**	
12,75	-20,75	H2	AMJ	1961-1999	**0,026**					
13,75	-23,25	H2	AMJ	1961-2018	**0,033**	**0,020**	**0,017**		**0,002**	
13,75	-23,75	H2	AMJ	1968-2018	**0,076**	**0,039**			**0,003**	**0,003**
17,25	-32,25	H3	AMJ	1948-2010	-0,027	-0,022	-0,016		-0,002	-0,002
17,75	-34,25	H2	AMJ	1954-2008	**0,049**	**0,035**	**0,030**		**0,003**	
23,25	-34,25	H1	AMJ	1958-2008	-0,040					
25,25	-34,25	H1	AMJ	1958-2008	-0,023					
13,25	-21,25	H2	JAS	1959-1998	**0,029**		**0,020**		**0,002**	**0,002**
16,75	-32,75	H4	JAS	1950-2011	**0,016**	**0,013**				
18,25	-33,75	H1	JAS	1950-2008	**0,027**	**0,061**	**0,020**			**0,002**
17,75	-33,75	H2	JAS	1949-2004	**0,022**	**0,053**	**0,034**	**0,003**	**0,005**	**0,004**
17,75	-34,25	H2	JAS	1950-2008	**0,020**				**0,002**	
13,25	-23,25	H3	OND	1964-1999	-0,039			**0,003**		
14,25	-23,75	H1	OND	1945-1999	-0,018					
19,25	-35,25	H3	OND	1948-2008			**0,024**			

2.4. Construction of seasonal and annual climatologies

The calculation of seasonal average values for H bins reduced the amount of gap-filling required considerably, compared to that required for monthly values (Table 1). The lower temporal sampling resolution (that is seasonal as opposed to monthly) then allowed for increased spatial resolution within the following data rich H bins, through their subdivisioning into 0.25° x 0.25° (or Q) bins: H_{coast} and H_{1° along the Gabon-Angola shelf, H_{coast} to $H_{1.5^\circ}$ along the Central and Southern Benguela shelf and the Agulhas Bank, and H_{coast} along the East Coast, from 34.5 to 28°S. Along the West and South coasts, seasonal average values were calculated for each of the three variables (T, S and O_2) at depths of 5, 50 and 100 m, for the Q bins inside these H bins, and for the appropriate H_{coast} to H_{3° bins along the shelf areas outside of these H bins. Along the East Coast, seasonal values were calculated for temperature only. The mixed spatial resolution grid used to construct climatologies took cognizance of the variable continental shelf width of the study area, data density and the observation that in most areas data availability decreases substantially offshore of the 500 m isobath. For gap filling purposes, mean values for "empty" data bins ($n < 3$) were calculated from the four nearest data bins, the pair of bins to the west and east, and that to the north and south. Along the West and South coasts "empty" data bins were usually isolated from each other and gap filling was straightforward. Along the East Coast, however, the larger proportion of "empty" data bins (Table 1) usually required an iterative process, starting with the filling of "empty" bins surrounded by at least 3 or 4 bins containing data, followed by the filling of empty bins surrounded by 2 bins containing data in addition to perhaps 1 or 2 gap-filled bins, and lastly empty bins surrounded by at least 1 data bin and 2 to 3 gap-filled data bins.

After construction of the seasonal climatologies, based on all data from 1945 to 2019 (Fig 6, 7, 8), annual climatologies consisting of the average of the seasonal values were constructed (Fig 9). Along the East Coast, the annual climatologies for salinity and oxygen represent the average of all available data. This procedure was then repeated to construct annual climatologies for the West and South coast areas, representing the 1945-1969, 1970-1994 and 1995-2019 periods mentioned earlier, but at a 0.5° scale, i.e. using H bins only. Differentials were calculated from the 25 year climatological averages, and mapped as follows for temperature, (Fig 10), and similarly for salinity (Fig 11) and oxygen (Fig 12).

A to C: $Avg_{[1970\ to\ 1994]} - Avg_{[1945\ to\ 1969]}$

D to F: $Av_{[1995\ to\ 2019]} - Avg_{[1970\ to\ 1994]}$

G to I: $Avg_{[1995\ to\ 2019]} - Avg_{[1945\ to\ 1969]}$

J to L: $Avg_{[1995\ to\ 2019]} - Avg_{[1945\ to\ 1969]}$#, with # indicating the exclusive plotting of H bins for which 25 year climatological values are available for each of the three 25 year periods, and that display monotonic trends (increasing or decreasing) from 1945 to 2019.

The standard deviation associated with the average of all of the data (1945 to 2019) within each H or Q was mapped, as well as the standard deviation asssociated with the average of the seasonal values (Appendix 4). These statistics represent different types of variability within the data set, i.e. the total variability in the data and the variability around the seasonal average, and are not equivalent. All climatologies were plotted using the ODV free software package (Schlitzer, 2018). The "quick gridding" display option was used, since it produced the most realistic and least distorted data displays. The construction and visualization of the climatologies presented in this study are purposefully simplistic, in order to encourage its use, reproduction and modification.

3. INTRA-ANNUAL VARIABILITY ALONG THE SOUTHERN AFRICA CONTINENTAL SHELF

3.1. Gabon to Angolan shelf, from the equator to ~ 17°S on the West Coast

Along the southern Africa shelf, the largest seasonal surface temperature fluctiations are observed on the shelf area between Gabon and Angola (or the Northern Benguela) (Fig 3A, 5). It is also only along the Gabon-Angola and the Central Benguela shelf areas that similar seasonal temperature profiles are observed at depths of 5, 50 and 100 m (Fig 5). These two adjacent areas also display similar temperature seasonality, or occurrence of the warmest and coldest periods of the annual cycle, and at all depths (Fig 4). During summer, the shelf area north of ~ 12°S is characterized by water temperatures exceeding 28°C, and very strong temperature gradients are present south of that towards the 20°C isotherm (Fig 3A, 6A). Apart from this, > 28°C surface water temperatures are observed on the shelf only in autumn (Fig 6B). The inner Angolan shelf area is dominated by 24 to 26°C surface water in autumn and spring, and 20 to 22°C in winter (Fig 6C, 6D). At 50 m depth an intrusion of warm water (> 20°C) is evident along the Gabon-Angola shelf, that appears to initiate near the equator in spring, and penetrates as far south as 12°S in summer, before it retreats or dissipates in autumn (Fig 6E-H). A similiar seasonal intrusion of warm water ((> 16°C) is observed at 100 m (Fig 6I-L). The seasonal incursion of warmer water observed in the climatologies, supports the proposed strengthening of the Gabon-Congo Undercurrent (GCUC) during spring (Stramma and Schott, 1999). The GCUC flows southwards along the African coast and derives primarily from the Equatorial Under Current between 1°S and 6°S (Stramma and Schott, 1999).

Surface water on the Gabon-Angola shelf is significantly influenced by fresh water outflow from several large rivers, most notably the Congo River, the largest river along the southern Africa coastline (Fig 1A, 5). This results in large seasonal variability, and pronounced salinity gradients at the surface and between the surface and water at 50 and 100 m (Fig 5). The surface salinity climatologies show that the Congo river plume influences a very large part of the shelf in summer (Fig 7A) and reaches its smallest extent in winter (Fig 7C). This is consistent with Congo river seasonal flow fluctuations (Sonwa et al., 2020). Similar seasonal changes in salinity, but of smaller magnitude, just south of the equator and at ~8°S, presumably reflect the influences of the Ogooué river in Gabon and the Cuanza river in Angola, respectively.

The Gabon-Angola shelf area is also characterized by pronounced spatial and seasonal changes in dissolved oxygen, particularly at depths of 50 and 100 m (Fig 5, 8E-L). The oxygen climatologies show generally decreasing values from the equator towards the Angolan shelf. At 100 m depths, low oxygen water (< 100 μM O_2) water dominates the shelf between 5°S and 17°S throughout the year (Fig 8I-L). At both 50 and 100 m depth there is a westward and northward expansion of < 100 μM O_2 water from summer (Fig 8E, 8I) to winter (Fig 8G, 8K). During summer, < 100 μM O_2 water is situated offshore of the Angola shelf at 50 m depth (Fig 8E), as is the case for < 50 μM O_2 water at 100 m depth (Fig 8I). This climatological observation of a minimum in the westward and northward extension of low oxygen water in summer, and a maximum extension of this water in winter, is consistent with previous reports for this area (Chapman and Shannon, 1987; Mohrholz et al., 2008).

3.2 Central and Southern Benguela shelf, from ~ 17°S to 35°S on the West Coast

Along the southern African shelf area, the smallest seasonal temperature ranges, at all depths, are observed in the climatologies of the Southern Benguela (28 to 36°S) inner shelf, and the Central Benguela (17 to 28°S; Fig 3, 5). At ~ 27°S and 32°S, where the shelf is at its broadest (Fig 1A), summer surface temperatures are higher and the seasonal temperature range larger, compared to adjacent shelf areas (Fig 3A). A notable feature of seasonal temperature variability in the Southern Benguela is that temperature moves out of phase with increasing depth (Fig 4, 5). At 50 and 100 m depths, temperature is higher during the winter than during spring and summer, the opposite to what is observed at the surface. This result is consistent with the seasonal Southern Benguela upwelling season, which peaks in spring and summer (Hutchings et al., 2009) and is associated with the upwelling of colder (and lower salinity) water onto the shelf. Upwelling processses in the Central and Southern Benguela have been extensively studied and there are numerous publications and reports that can be consulted for much more detail than the space in this manuscript allows for (Hutchings et al., 2009, and reference therein; Jarre et al., 2015b; Lamont et al., 2018).

Seasonal climatologies show that surface temperature values below 16°C (as an example) is a persistent feature along the inner shelf along the Central and Southern Benguela in spring and autumn (Fig 6B, 6D). During summer, however, this 16°C surface isotherm contracts towards the coast and is absent from the northern half of the Central Benguela (Fig 6A). During winter, in contrast, < 16°C water extends much further westward, as well as further north and south than is observed in spring and autumn (Fig 6C). During winter, in fact, the surface 16°C isotherm extends beyond the Southern Benguela, in an eastward direction along the shelf to ~ 22°E on the Agulhas Bank (Fig 6C). Similarly, 16 to 18°C surface water is present in a continuous band that extends from the Central Benguela shelf to the eastern Agulhas Bank in spring and autumn (Fig 6B, 6D). In contrast, 16 to 18°C surface water is restricted to the Central and Southern Benguela and absent from the Agulhas Bank in summer, (Fig 6A), but absent from the Central and Southern Benguela, and present on the Agulhas Bank, in winter (Fig 6C). These seasonal contractions and expansions in the areal extent of water within specific temperature envelopes are also observed in the 50 and 100 m climatologies. At 100 m depth, for example, < 12°C is present on the shelf in a continous band than extends from the Southern Benguela, all the way to the eastern edge of the Agulhas Bank, in summer and autumn (Fig 6I, 6J). In winter (Fig 6L) and spring (Fig 6L), however, the < 12°C extends into the Central Benguela, at a depth of 100 m. Also, in winter and spring, < 12°C water does not occur in a continous band from the Souther Benguela to the eastern Agulhas Bank at 100 m, due to the presence of warmer water between ~ 20 and 22°E during these seasons.

In the Central Benguela, seasonal salinity climatologies (for 5, 50 and 100 m) suggest a southward shift in the position of the salinity isolines in the northern part of the Central Benguela shelf (~ 17 to 22°S, Fig 7), consistent with the southward migration of the ABF, and the higher salinity and low oxygen water associated with it, from February to April (Dias, 1983; Stramma and Schott, 1999; Ekau and Verheye, 2005; Mohrholz et al., 2008). The Southern Benguela shelf is characterized by the lowest salinity waters on the southern African shelf, with the obvious exception of surface water on the Gabon-Angolan shelf (Fig 5). The surface salinity climatologies show a freshwater influence at the Orange river mouth (~28.5°S) and at the Berg river mouth (~ 32.5°S) (Fig 7A-D). This is more pronounced in summer and winter respectively, consistent with the peak runoff seasons of these rivers (de Villiers and Thiart, 2007). Apart from these river influences, the lowest salinity waters are found at 100 m depth, and during summer (Fig 7I) and autumn (Fig 7J). Enhanced freshening of water during summer and autumn are also observed at 50 m at ~ 32°S in the Soutern Benguela. The seasonal salinity changes evident in the 50 and 100 m climatologies, are consistent with the seasonal upwelling of low salinity water onto the shelf (Hutchings et al., 2009).

Composite graphs of intra-annual variability in dissolved oxygen show that the Central Benguela is characterized by the lowest oxygen levels in the study area (Fig 5). In both the Central and Southern Benguela, oxygen levels decline during the summer and autumn, at both 50 and 100 m depths, and reach a seasonal high in winter. The seasonal oxygen climatologies show that the presence of low oxygen water (< 100 μM O_2) is widespread along the inner shelf at 100 m depth (Fig 8I-L) in both the Central and Southern Benguela. The areal extent of this low oxygen water is more widespread in summer and autumn, than in winter and spring. In the Central Benguela, these seasonal changes are more pronounced, and low oxygen water extends ~ 2° further south and futher offshore during summer and autumn. These seasonal changes are consistent with the seasonal incursion of low oxygyen water form the Angola Gyre into the Central Benguela, mentioned earlier (Dias, 1983; Stramma and Schott, 1999; Ekau and Verheye, 2005; Mohrholz et al., 2008) and documented seasonality in the Southern Benguela (Hutchiings et al., 2009; Jarre et al., 2015b). At 50 m depth, low oxygen water is less widespread than at 100 m (Fig 8E-H). In the Southern Benguela, low oxygen water is evident at 50 m in the summer, and at the ~29°S and ~ 32.5°S upwelling cells only (Fig 8E). There is some indication of its presence, at 50 m, at the ~29°S upwelling cell in autumn (Fig 8F) and the ~ 32.5°S cell in spring (Fig 8H), but it is entirely absent from the Southern Benguela in winter (Fig 8G). Surface ocean oxygen levels (Fig 8A-D) vary seasonally in response to primarily changes in primary productivity and temperature, and a discussion of these complex processes and interpretation of these changes are beyond the scope of this manuscript.

3.3 South Coast or Agulhas Bank, from 18.5°E to 26.5°E

A prominent commonality between the South Coast and the Southern Benguela, is the contrasting temperature seasonalities of surface and deeper waters (Fig 5). On the Agulhas Bank, as also observed in the Southern Benguela, water temperature at 50 and 100 m depths reaches a seasonal high in winter, and not in summer as is observed at the surface. On the Agulhas Bank, this difference in seasonality between surface and deeper waters is more pronounced than in the Southern Benguela. Temperature climatologies show that along the South Coast, surface temperature generally increases in an easterly direction (Fig 6A-D). Along the inner shelf, this general trend is disrupted in areas of coastal upwelling, for example between ~23° and 24°E in autumn (Fig 6B). During summer, the Agulhas Bank is dominated by surface water temperatures in the 20 to 22°C range (Fig 6A). From autumn to spring, however, the 20°C surface isotherm is situated along the eastern shelf edge of the Agulhas Bank, and the shelf is dominated by 16 to 20°C surface water (Fig 6B-D). The 16°C surface isotherm migrates from its spring/summer inner shelf position at Cape Point (~ 18.5°E) to just west of Cape Agulhas (~ 20°E) in autumn and Cape Infanta (~ 21°E) in winter (Fig 6C). At 100 m depth, cold (< 16°C) water is present along the inner shelf throughout the year, but it is more prominent and present in a continous band than extends into the Southern Benguela, in summer (Fig 6I) and autumn (Fig 6J), as mentioned previously. Temperature climatologies suggest similar seasonalities are present at 50 m (Fig 6E-H).

Seasonal salinity climatologies (Fig 7), mirror that of temperature, with lower salinities coinciding with colder temperatures, and higher salinities with higher temperatures. Seasonal oxygen climatologies (Fig 8) show that cold, lower salinity waters also typically have lower oxygen values, with similar seasonal variations to that observed for temperature and oxygen. Although Agulhas Bank water has higher O_2 levels than that of the Southern Benguela shelf, ranging from 125 to 200 μM at 100 m compared to 75 to 175 μM, it displays similar seasonality, with generally lower values in summer and autumn and to a lesser extent spring. The upwelling features and gradients across the Agulhas Bank, evident in the temperature, salinity and oxygen climatologies are consistent with previous observations of wind-driven coastal upwelling and shelf-edge upwelling induced by the southward flowing Agulhas Current (Probyn et al., 1994; Lutjeharms et al., 1996). The seasonal climatologies presented here provide new insight into the spatial extent of intra-annual variability and the connectivity with the Southern Benguela.

3.4 East Coast, from the equator to 36°S

Despite the limitations resulting from relative data scarcity along the East Coast, some patterns are evident. Along the East Coast, there is a decrease in temperature, but a general increase in the seasonal surface temperature range from the equator towards the pole (Fig 3), which is opposite to the trend observed along the West Coast. Seasonal temperature profiles appear complex, particularly along the inner shelf and at 100 m depth (Fig 5). This may be an artefact of the relative scarcity of data on the East Coast, but it can also reflect high variability associated with the incursion of offshore waters onto the shelf, which is very narrow in some areas compared to the West and South Coast shelf areas. East Coast shelf water is consistently warmer than that of the West Coast at similar latitudes (Fig 3). For example, between 0 and 10°S, East Coast shelf water is approximately 6 to 8°C warmer than that of the West Coast, at all three depths. Between 25 and 35°S, this offset is 8 to 10°C at each of the three different depths.

It is evident in the seasonal surface climatologies that > 28°C water is much more common on the the East Coast, than on the West Coast, and it is present as far south as at least 25°S in summer (Fig 6A) and 15°S in autumn and spring (Fig 6B, 6D). In winter, however, the East Coast shelf is characterized by average surface temperatures below 26°C (Fig 6C). The 24°C surface isotherm intersects the coastline at a relatively narrow latitudinal range of 25 to 27°S from autumn to spring, but extends much further south in summer. This southward summer shift coincides with the westward shift of the 20°C isotherm along the southern margin of the East Coast and the Agulhas Bank, and an apparent shelf-ward shift of offshore warm surface water during this season, possibly related to seasonality in the position of the Agulhas Current. An interesting feature of the temperature climatologies is the temperature maximum between 10 and 15°S along the East Coast, particularly noticeable at deeper depths (Fig 6D-H). The warmer shelf water between these latitudes is also characterized by lower salinity values, compared to shelf water further north and south.

Freshening of surface water is evident offshore of river mouths, for example the Tugela, Limpopo, Zambezi, Rufiji and Tana rivers (Fig 1, Fig7A-D). The geographic extent of the influence of these river outflows on the salinity of shelf surface water, however, is not as pronounced as that of the Congo river on the Angolan shelf area. Data scarcity impedes capture of such features in a climatology. The warm waters of the East Coast contain high oxygen levels with apparently low seasonal variability; the scarcity of oxygen data along the East Coast, however, precludes a more detailed discussion and evaluation of these observations.

4. ENVIRONMENTAL CLIMATOLOGIES AND ECOLOGICAL CONSIDERATIONS

4.1 Biogeographic zone boundaries in comparison to key climatological map features

The approximate boundaries of biogeographic Realms and ecoregions blocks (Spalding et al., 2007), LME's (Sherman, 1993) and coastal biogeographic zones (Potts et al., 2015), were superimposed on the annual climatologies of temperature, salinity and oxygen, to qualitative evaluate biogeographic boundaries in the context of environmental spatial patterns (Fig 9). It is difficult to find qualitative agreement between the temperature, salinity and oxygen climatologies, and the large scale biogeographic zones, that is the Realms and LME's. If the Temperature Southern African Realm (Fig 2) extended ~5° further north, with its boundary with the Tropical Atlantic Realm positioned just north of the ABF, it would capture alll southern African shelf water with average surface temperatures < 24^{o}C. The smaller ecoregion blocks within these Realms (numbered in Fig 9 according to Spalding et al., 2007), however, also display poor qualitative agreement with environmental climatologies. An exception to this is the "Namaqua" ecoregion block (#191 in Fig 2 and 9), which corresponds to the Southern Benguela (Fig 9). The LME divisions (Sherman, 1993) show the poorest relationship with environmental variables. The coastal biogeographic zones (Potts et al., 2015), overall, agree the best with features of the environmental climatologies. This classification scheme uniquely transends national boundaries, and also rely primarily on taxonomy (Briggs and Bowen, 2012; Potts et al. 2015; Whitfield, 2005). The tropical coastal zone corresponds with average surface water temperatures >25^{o}C on both the West and East Coast, the sub-tropical coastal zone with average surface values between ~ 23 and 25^{o}C on both the West and East Coast, and the warm-temperate coastal zone with surface values between ~ 17 and 23^{o}C, on the West and South Coast (Fig 9A). The construction of climatologies for key ocean variables, and at the surface as well as deeper depths, can be used as a guide to refine the boundaries of biogeographic zones, or possibly to evaluate the usefulness of the concept of such boundaries in a highly variable environment.

4.2 Decadal changes in environmental climatologies, compared to marine species range shifts

Differences between the three 25 year climatologies, representing changes and trends from 1945 to 2019, demonstrate the complexity and spatial heterogeneities inherent in environmental change, that have been the bugbear of efforts to understand increasing evidence for ecosystem change (Fig 10 to 12). For the sake of brevity, only the most prominent changes are summarized below, followed by a synopsis of documented environmental and ecosystem changes, that correspond to changes and trends evident in the environmental climatologies (Table 2; Fig 10-12):

• The Gabon-Angola shelf was generally cooler in 1970-1994 compared to both the 1945-1969 and 1995-2019 periods.

• Temperature change in the Central and Southern Benguela were generally out of phase with that on the Gabon-Angola shelf in 1970-1994, compared to 1945-1969, while the Agulhas Bank was in phase with the Gabon-Angola shelf during these periods.
• There is a general warming trend along the entire West Coast shelf area, at all depths; the only exceptions to this warming trend are observed at some of the upwelling areas, most notably parts of the Angolan shelf and the central part of the Southern Benguela.
• Warming is more pronounced in the Northern Benguela, than in the Central Benguela.
• There is a warming trend on the western Agulhas Bank, that contrasts with a cooling trend on the eastern Agulhas Bank; these trends are more prominent at deeper depths around the shelf edge.
• Increasing temperature trends are generally accompanied by increasing trends in salinity, and cooling trends with decreasing trends in salinity.
• Dissolved oxygen levels are generally decreasing in the Central and Southern Benguela, and the Agulhas Bank, but there is evidence for increasing oxygen levels in the Northern Benguela.

The above climatological trends are consistent with documented changes in the environment, such as:
• Increasing trends in sea surface temperature off Angola over the past three decades, with above global average values (Hobday and Pecl, 2014; Bindoff et al., 2019) of between 0.23°C (Jarre et al., 2015a) and 0.8°C (Potts et al., 2014) per decade.
• Southward shifts of warm Angola-Benguela Front water by about 2°, in response to changes in the position of the South Atlantic High-Pressure Cell (Vizy et al., 2018).
• A decline in upwelling favourable winds in the Central Benguela, but increases in the Southern Benguela (Hutchings et al., 2009; Jarre et al., 2015; Van der Lingen and Hampton, 2018).
• A decline of upwelling off Namibia (Santos et al., 2012; Lamont et al., 2018) and coastal temperature increases of between 0.2 and 0.5°C per decade in the northern part of the Central Benguela (Jarre et al., 2015a).
• Cooling of inshore waters along South Africa's west and south coast by 0.1 to 0.2°C per decade over the past four decades, in contrast to warming of Agulhas Current water by up to 0.6°C per decade (Rouault et al., 2010; Blamey et al., 2015).
• Increased cooling and upwelling in the Southern Benguela (Rouault et al., 2010; Lamont et al., 2018; Leduc et al., 2010; Santos et al., 2012).
• Broadening of the Agulhas Current (Beal and Elipot, 2015). Differences between the 25 year climatologies suggest that long-term cooling of the eastern Agulhas Bank is taking place (in areas of wind-induced coastal upwelling and along the shelf edge), with a contrasting warming trend on the western Agulhas Bank, that is on the "lee" side of the Agulhas Bank in relation to the flow direction of the Agulhas Current. The results suggest that the Agulhas Bank may be significantly impacted by the reported broadening of the Agulhas Current.

The climatological trends are also consistent with documented ecosystem changes, such as:
• Decreased pelagic fish catches off Angola from the late 1970's to 1990's, with recoveries since the mid-2000's (Kainge et al., 2020). Oxygen has been shown to be a key determinant of species such

as juvenile deepwater hake in the Northern Benguela (Kainge et al., 2017) and the climatologies document warmer temperature and higher oxygen levels, coinciding with the recovery of fisheries.

• An increase in the latitudinal range of demersal species off Angola, with an overall southward tendency and an expansion into deeper water (Yemane et al., 2014).
• A southward shift in the distribution of some Angolan coastal fish species (Potts et al., 2014)
• A southward shift for round herring in the Southern Benguela (Blamey et al., 2015).
• An eastward shift for adult anchovy (Roy et al., 2007; Fairweather et al., 2006) and sardine (Coetzee et al., 2008) since the mid-to-late-1990's (Augustyn et al., 2017).
• An eastward migration of rock lobster (Cockcroft et al., 2008).

There are several important caveats associated with the choice of 25 year periods for the construction of climatologies, that need to be emphasized. The choice of periods were primarily informed by the availability of data, for both the West and South Coast shelf areas. It is not the intention of this study to propose that these are the best or most ideal periods for the evaluation of decadal periodicities or long-term trends, or that the entire southern African shelf area is subject to decadal periodicities with similar amplitudes or periods. The choice of periods may not even be ideal for the evaluation of Gabon-Angola shelf waters, despite climatological evidence for AMO periodicities on the adjacent continental shelf and the ocean areas further north (Kerr, 2000; Knudsen et al., 2011; Sonwa et al., 2020). The most appropriate choice of time period for the study of trends or periodicities can only be informed by the availability of more data. These caveats, however, make the correspondence between changes observed in the climatologies, compared to documented and anticipated (Bakun et al., 2015; Bindoff et al., 2019) environmental and ecological changes, all the more remarkable. A speculative observation, based on the results of this study, is that decadal periodicities are in the process of being interrupted by a longer-term trend, possibly as the result of global warming.

5. CONCLUSIONS

This study raises several important issues in regards to marine species range shifts, in response to environmental change, and the definition of biogeographic zone boundaries. Ecological changes can only be fully understood and interpreted in an environmental context, if the environmental tolerances and ranges of species are known. Environmental climatologies, such as those presented here, can be used to guide the design of laboratory and field studies, for the optimal collection of data aimed at better understanding the environmental tolerance limits of species. The climatologies also shed important light on the geographic complexity of environmental change, that can be used to guide management decisions about geographic areas to prioritize for monitoring and conservation purposes. The climatologies also demonstrate that ecoregion or biogeographic boundaries cannot be assumed to occupy similar geographic locations for species that occupy different depth zones, and that changes observed at the surface cannot be assumed to apply to deeper depths.

Data availability is a concern, most obviously for the East Coast shelf area. There are two specific areas that appear curiously under-studied and under-sampled, given their oceanographic significance in the region: the Agulhas Current source region off southern Mozambique on the East Coast, and the large Lüderitz upwelling at ~ 27°S on the West Coast. The Agulhas Bank has been more extensively studied than these two areas, but not nearly as extensively as the Southern Benguela; the magnitude of change evident for the Agulhas Bank in the climatologies should motivate more studies and monitoring in this important transition zone. The most significant concern around data availability, however, is that only 0.33% of the data used in this study represent sampling carried out since 2010 (Appendix 1). In some instances this reflects an actual reduction in ocean monitoring activities, but it also reflects changing attitudes towards the placement of data in the public domain, even when data collection is publicly funded. There is evidence for accelerated global environmental change since 2010, (Bindoff et al., 2019), that is not captured in the climatologies of this study, because of the dearth of recent data in the public domain for the southern African shelf area. It remains to be seen, therefore, to what extent the decadal changes presented in this study over- or under-represent present and on-going change in the region.

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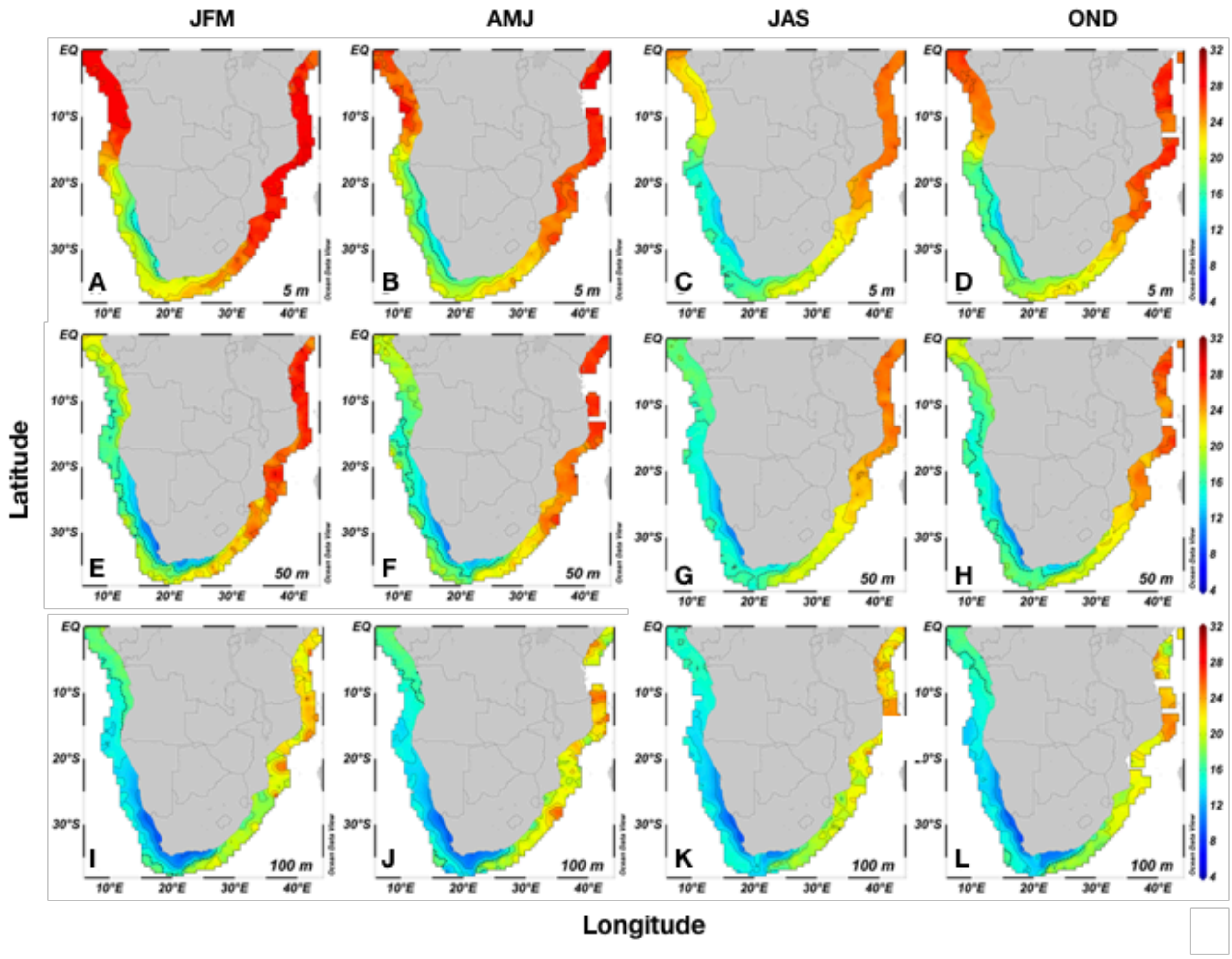

Fig 6. Seasonal temperature climatologies at depths of 5 (A to D), 50 (E to H) and 100 m (I to L) for summer (JFM), autumn (AMJ), winter (JAS) and spring (OND). Contour intervals are 2°C, with 16°C indicated with a dashed line.

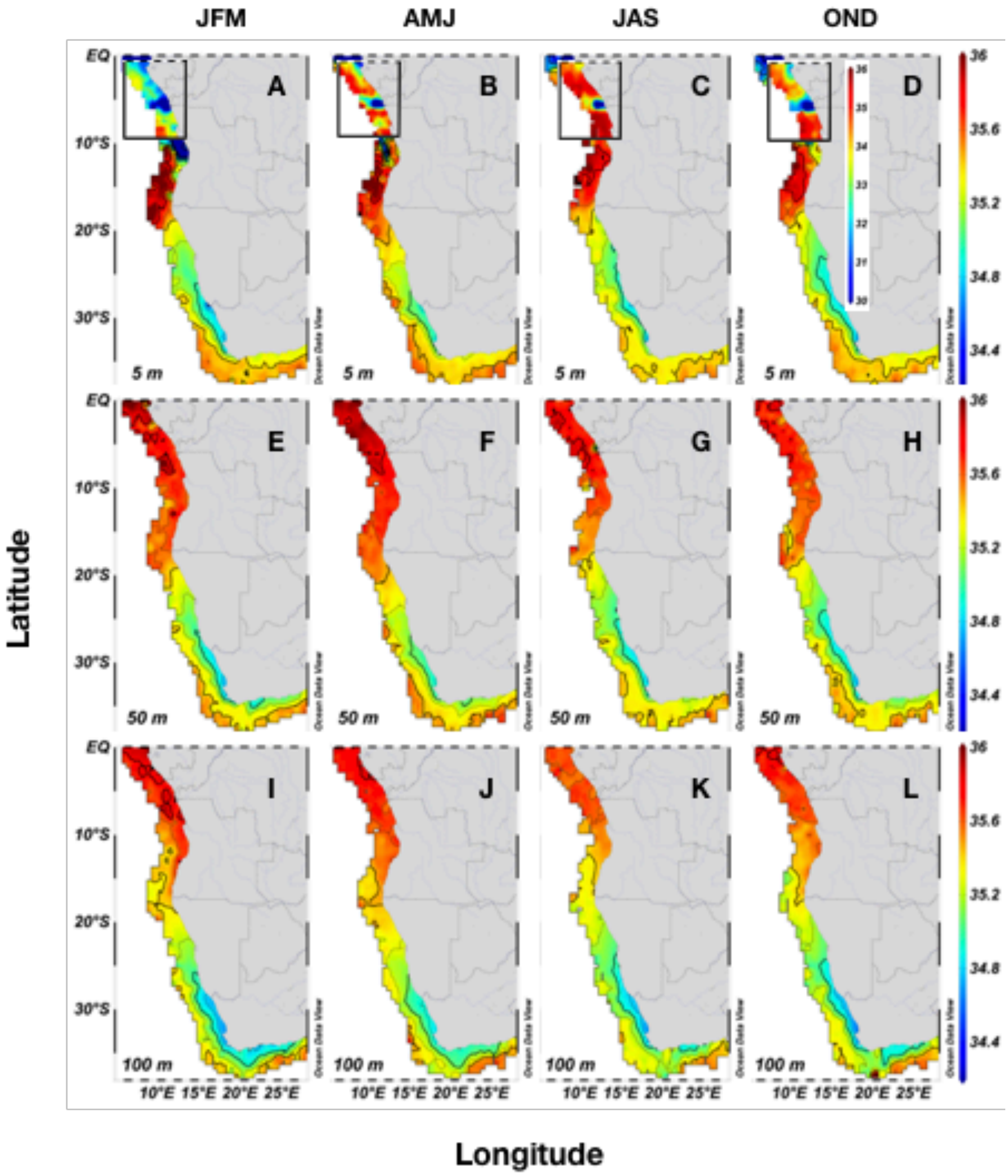

Fig 7. Seasonal salinity climatologies at depths of 5 (A to D), 50 (E to H) and 100 m (I to L) for summer (JFM), autumn (AMJ), winter (JAS) and spring (OND). Contour intervals are 0.2, with 34.6, 35.0 and 35.4 indicated with thicker lines.

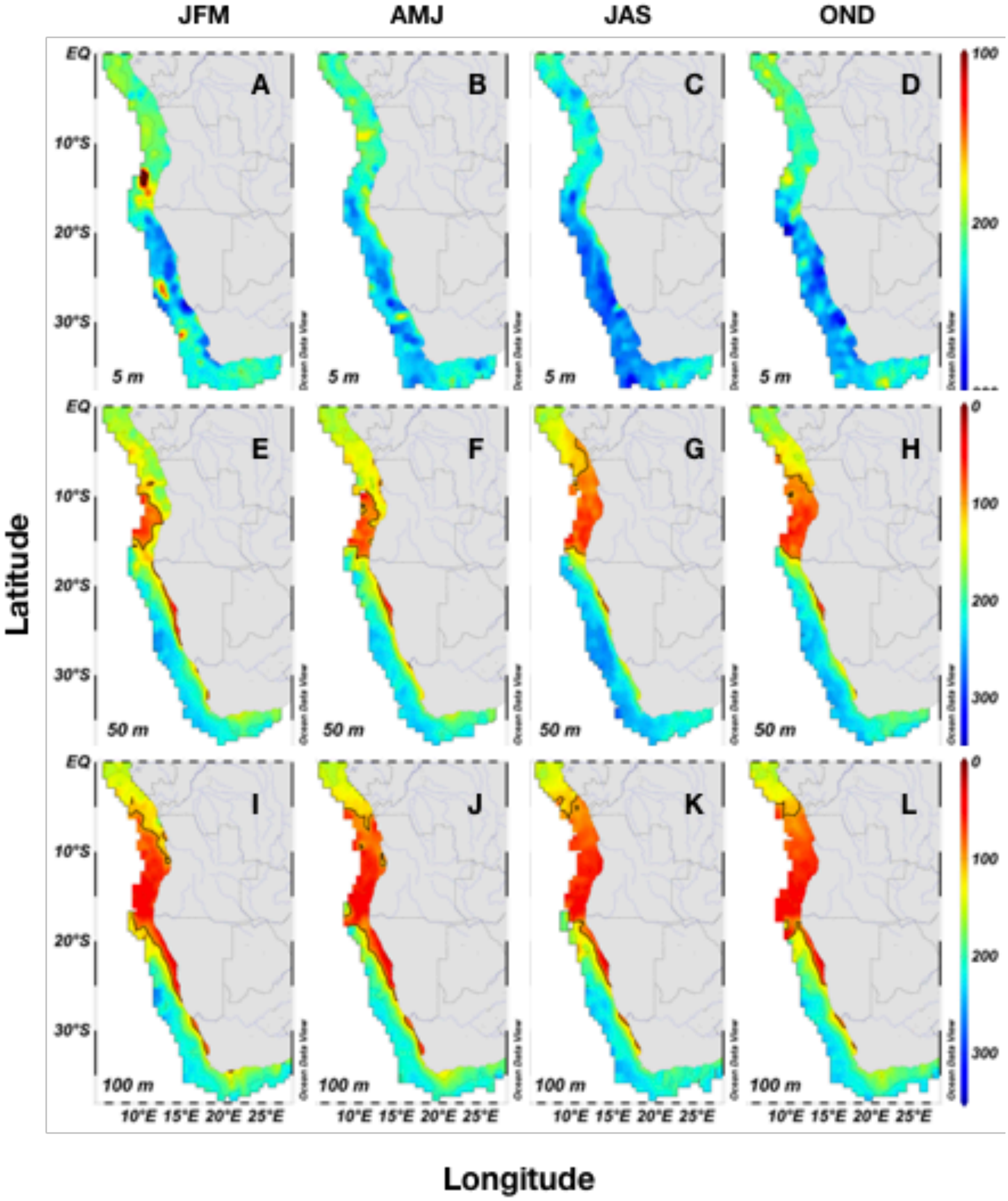

Fig 8. . Seasonal oxygen climatologies at depths of 5 (A to D), 50 (E to H) and 100 m (I to L) for summer (JFM), autumn (AMJ), winter (JAS) and spring (OND). Contour intervals are 50 µM, with 100 µM indicated with a thicker line.

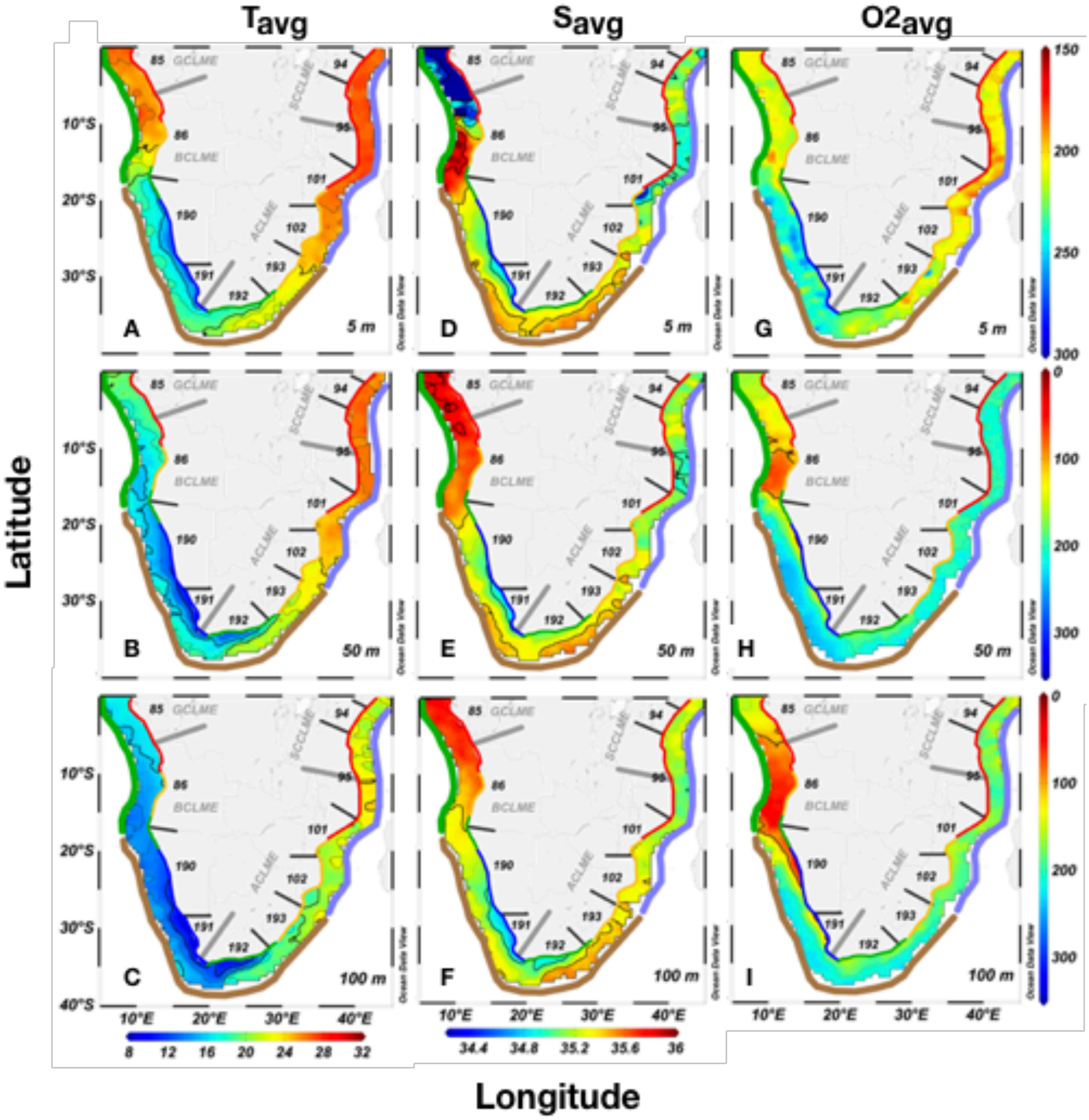

Fig 9. Annual climatologies for temperature (A to C), salinity (D to F) and oxygen (G to I), at depths of 5, 50 and 100 m depths. Temperature contour intervals are 2°C, with 16, 20 and 24°C indicated with thicker lines. Salinity contour intervals are 0.2, with 34.6, 35.0 and 35.4 indicated with thicker lines. Oxygen contour intervals are 50 μM and 100 μM is indicated with a thicker line. The biogeographic boundaries of Fig 2 are superimposed on the climatologies.

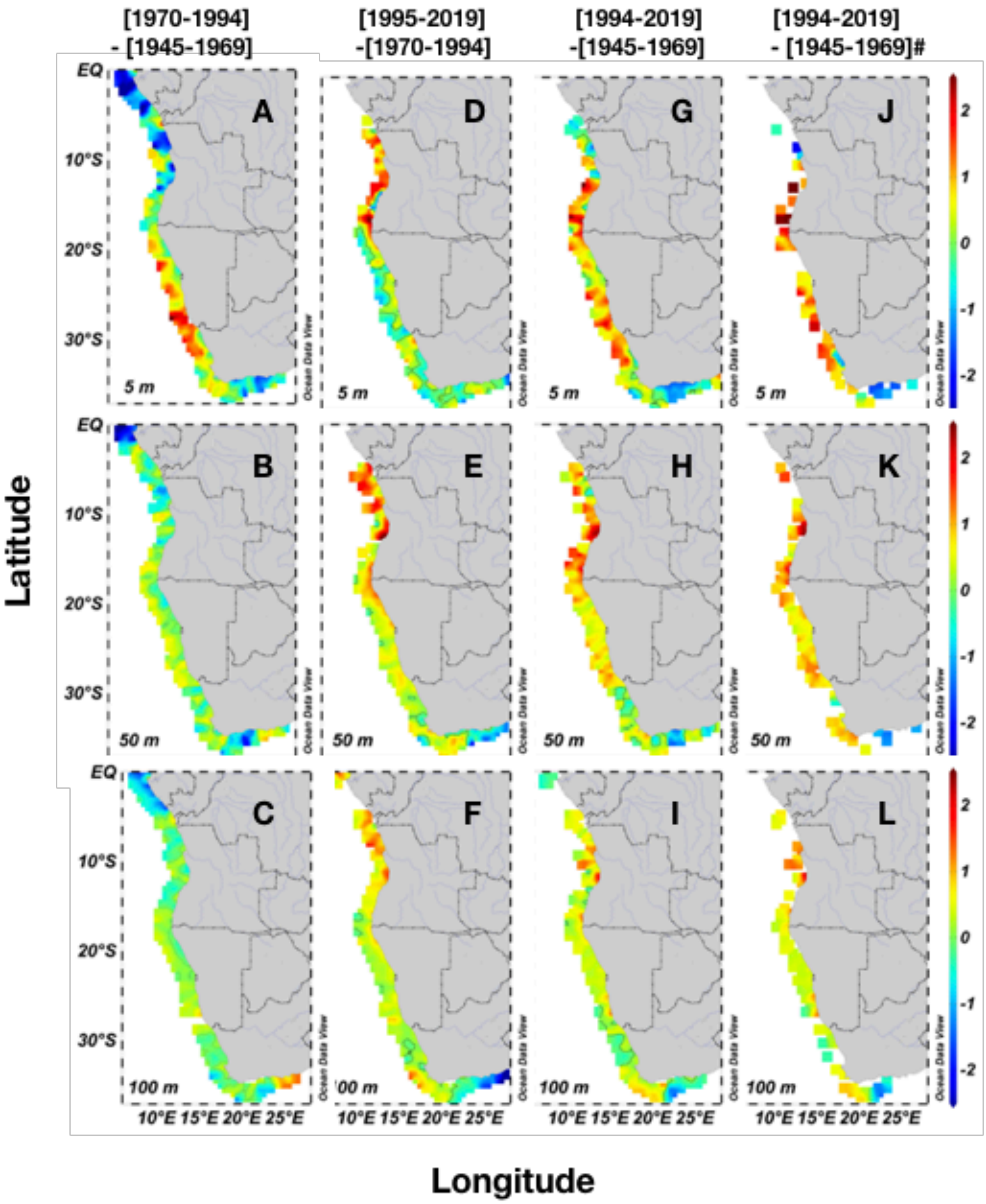

Fig 10. The difference between 25 year climatological average annual temperature values ($T_{25yr\ period}$) at depths of 5, 50 and 100 m, for the following periods: A to C: $T_{[1970\ to\ 1994]}$ - $T_{[1945\ to\ 1969]}$; D to F: $T_{[1995\ to\ 2014]}$ - $T_{[1970\ to\ 1994]}$; G to I: $T_{[1995\ to\ 2014]}$ - $T_{[1945\ to\ 1969]}$; J to L: $T_{[1995\ to\ 2014]}$ - $T_{[1945\ to\ 1969]}$#, with # indicating the exclusive plotting of H bins for which 25 year climatological values are available for each of the three 25 year periods, and that display monotonic trends (increasing or decreasing) from 1945 to 2014. The zero contour line is shown.

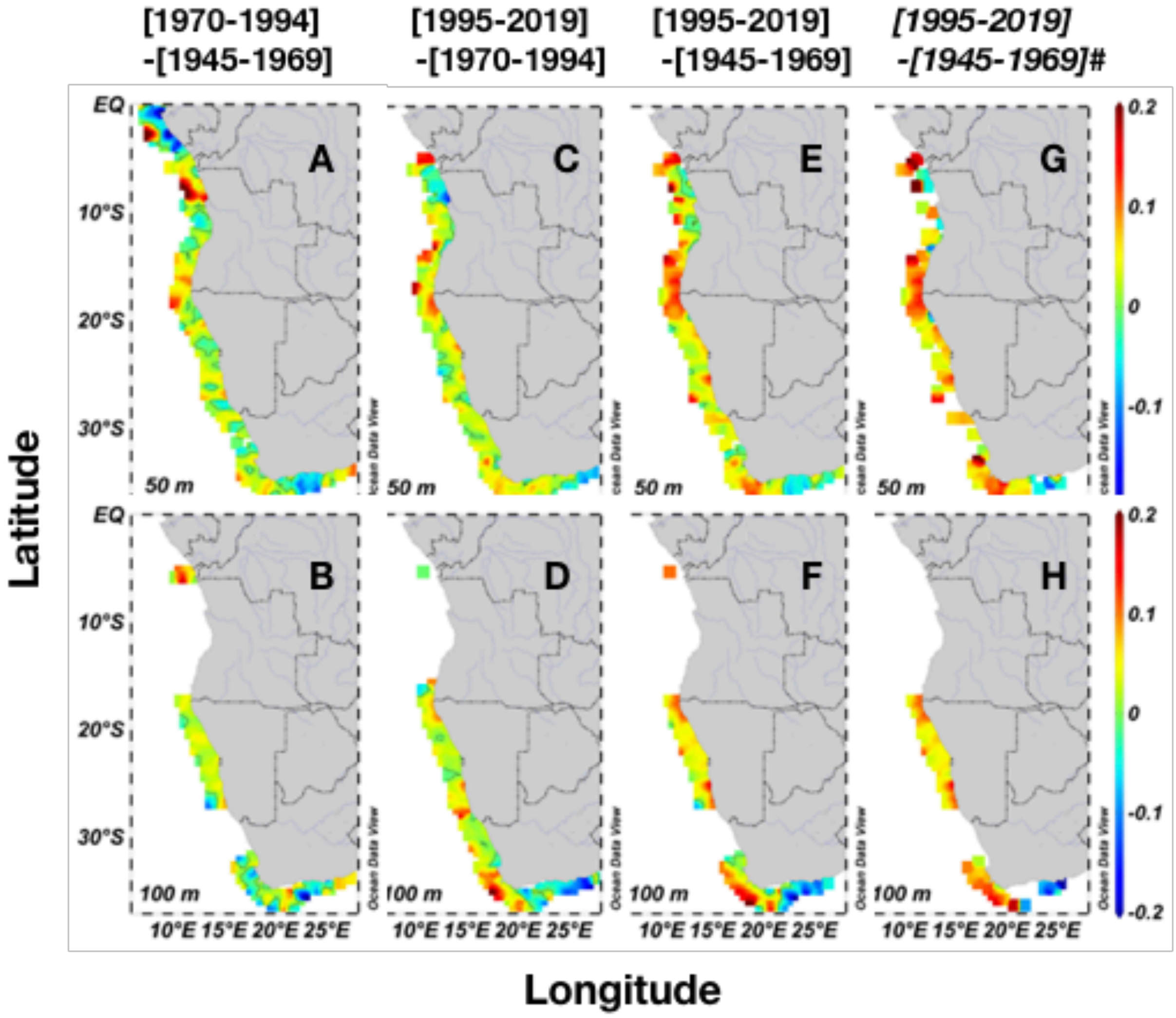

Fig 11. The difference between 25 year climatological average annual salinity values ($S_{25yr\ period}$) at depths of 5, 50 and 100 m, for the following periods: A to C: $S_{[1970\ to\ 1994]}$ - $S_{[1945\ to\ 1969]}$; D to F: $S_{[1995\ to\ 2014]}$ - $S_{[1970\ to\ 1994]}$; G to I: $S_{[1995\ to\ 2014]}$ - $S_{[1945\ to\ 1969]}$; J to L: $S_{[1995\ to\ 2014]}$ - $S_{[1945\ to\ 1969]}$#, with # indicating the exclusive plotting of H bins for which 25 year climatological values are available for each of the three 25 year periods, and that display monotonic trends (increasing or decreasing) from 1945 to 2014. The zero contour line is shown.

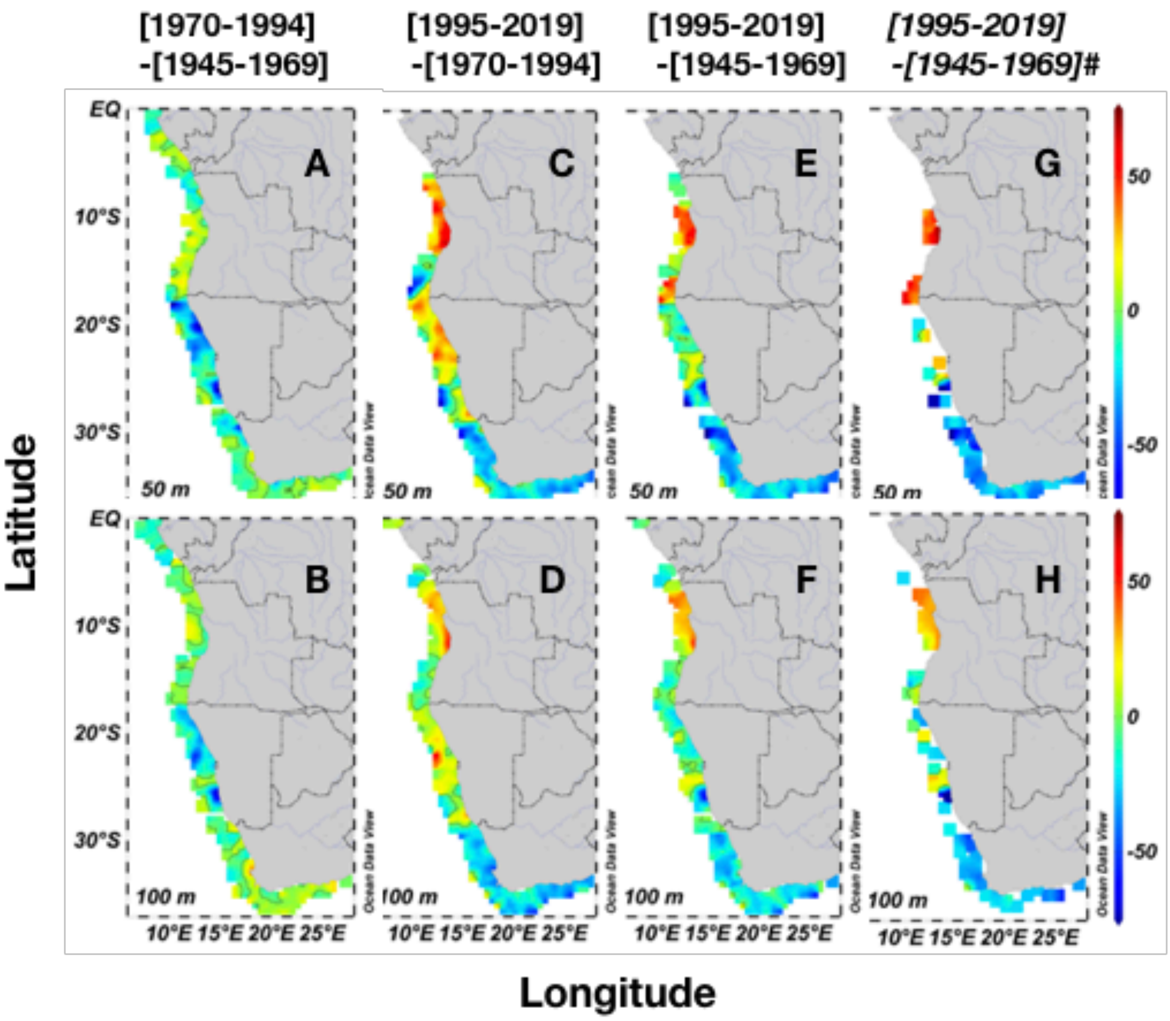

Fig 12. The difference between 25 year climatological average annual oxygen values ($O_{25yr\ period}$) at depths of 5, 50 and 100 m, for the following periods: A to C: $O_{[1970\ to\ 1994]}$ - $O_{[1945\ to\ 1969]}$; D to F: $O_{[1995\ to\ 2014]}$ - $O_{[1970\ to\ 1994]}$; G to I: $O_{[1995\ to\ 2014]}$ - $O_{[1945\ to\ 1969]}$; J to L: $O_{[1995\ to\ 2014]}$ - $O_{[1945\ to\ 1969]}$#, with # indicating the exclusive plotting of H bins for which 25 year climatological values are available for each of the three 25 year periods, and that display monotonic trends (increasing or decreasing) from 1945 to 2014. The zero contour line is shown.

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Appendix 1 Summary statistics for OSD and CTD data extracted from the WOD-18 database for the period 1945 to 2019. The first letter in the "ID" refers to either the west (W), south (S) or east (E) coast of Africa. It is followed by a number representing the latitudinal or longitudinal centre of a 0,5°x0,5° data box. The midpoint of H+1° grid boxes (0.5° x 0.5°) are listed in columns 2 and 3. H_{coast} grid boxes extend to the coastline, and their dimensions vary to accomodate the changing shape of the coastline. The total number of OSD and CTD casts (#OSD-casts and #CTD-casts) for the period 1945 to 2019 and H_{coast} to H+3° boxes, are listed, as well as the total number of casts containing temperature, salinity, oxygen, phosphate, silicate and nitrate data. This is followed by the percentage of temperature casts per depth interval (5, 50 and 100 m), six hour sampling period (from 00:00-05:59 to 18:00-23:59) and five year sampling period (from 1945-1949 to 2015-2019).

ID	Lon-H+1°	Lat-H+1°	#OSD-casts	#CTD-casts	# Temp	#Salinity	#Oxygen	% 5m	% 50m	% 100m	% 00:00-05:59	% 06:00-11:59	% 12:00-17:59	% 18:00-23:59	% 1945-49	% 1950-54	% 1955-59	% 1960-64	% 1965-69	% 1970-74	% 1975-79	% 1980-84	% 1985-89	% 1990-94	% 1995-99	% 2000-04	% 2005-09	% 2010-14	% 2015-19
W-0,25	8,25	-0,25	225	17	240	236	162	100	43	26	18	29	28	24	1,9	0,6	6,8	11,1	42,6	13,6	13,0	6,2	0,0	0,0	0,0	0,0	3,1	1,2	0,0
W-0,75	8,25	-0,75	164	12	173	171	100	99	30	22	17	26	32	25	3,1	0,0	3,1	14,2	37,8	18,9	11,8	7,9	0,8	0,0	0,0	0,0	1,6	0,8	0,0
W-1,25	8,25	-1,25	372	37	392	391	313	100	42	22	18	22	27	32	0,9	0,0	0,0	9,6	54,3	4,7	24,8	4,3	0,0	0,0	0,0	0,0	0,9	0,3	0,0
W-1,75	8,75	-1,75	196	9	204	201	143	100	44	14	23	20	22	35	0,0	0,0	1,8	7,2	74,9	5,4	4,8	5,4	0,0	0,0	0,0	0,0	0,6	0,0	0,0
W-2,25	8,75	-2,25	161	3	164	162	121	100	47	26	21	32	30	17	0,0	0,7	5,1	8,8	27,0	8,0	41,6	8,0	0,0	0,0	0,0	0,0	0,7	0,0	0,0
W-2,75	9,25	-2,75	120	8	128	128	81	100	39	23	18	25	35	21	0,0	0,0	3,0	15,8	43,6	18,8	6,9	11,9	0,0	0,0	0,0	0,0	0,0	0,0	0,0
W-3,25	9,75	-3,25	199	7	206	208	158	100	45	25	26	32	25	17	1,2	0,0	5,4	12,0	35,5	4,2	31,9	9,6	0,0	0,0	0,0	0,0	0,0	0,0	0,0
W-3,75	10,25	-3,75	134	4	138	140	111	100	44	25	16	26	34	24	0,9	0,0	3,6	15,2	40,2	4,5	22,3	12,5	0,0	0,0	0,0	0,0	0,9	0,0	0,0
W-4,25	10,75	-4,25	141	3	144	147	119	100	41	23	18	28	31	23	1,6	0,0	2,4	14,4	20,8	7,2	33,6	15,2	0,0	4,8	0,0	0,0	0,0	0,0	0,0
W-4,75	11,25	-4,75	3777	24	3799	3797	3481	100	5	1	2	91	5	2	0,1	0,1	0,8	1,8	6,5	31,8	40,0	18,2	0,1	0,2	0,0	0,2	0,1	0,1	0,1
W-5,25	11,25	-5,25	505	9	513	511	363	100	43	28	21	25	33	21	0,4	0,4	0,4	13,9	33,3	18,1	24,6	5,4	1,5	0,0	0,0	0,4	0,2	0,9	0,2
W-5,75	11,25	-5,75	293	16	305	299	240	100	34	24	19	31	27	24	5,7	4,4	2,6	11,0	28,6	4,0	20,3	11,0	11,0	0,0	0,0	1,3	0,0	0,0	0,0
W-6,25	12,25	-6,25	236	38	274	264	216	100	41	30	17	35	28	20	6,9	3,0	1,3	1,3	12,4	2,6	43,8	8,2	5,2	0,0	15,5	0,0	0,0	0,0	0,0
W-6,75	12,25	-6,75	147	32	179	177	140	100	51	32	19	22	35	25	4,7	5,6	0,0	0,0	14,0	3,7	22,4	13,1	8,4	0,0	28,0	0,0	0,0	0,0	0,0
W-7,25	12,25	-7,25	139	28	164	163	122	100	62	41	21	27	26	26	3,4	0,7	5,4	0,7	12,1	4,0	24,8	11,4	18,8	0,0	18,1	0,7	0,0	0,0	0,0
W-7,75	12,75	-7,75	131	45	169	170	139	100	65	30	20	18	20	41	4,3	0,0	0,0	1,1	11,8	5,4	25,8	3,2	3,2	0,0	45,2	0,0	0,0	0,0	0,0
W-8,25	12,75	-8,25	208	26	233	229	158	100	62	44	18	28	30	25	1,9	0,0	0,9	0,0	12,6	3,7	25,6	26,0	18,1	0,0	11,2	0,0	0,0	0,0	0,0
W-8,75	12,75	-8,75	130	21	151	141	92	100	71	40	22	25	35	18	2,4	8,1	7,3	1,6	22,8	4,1	15,4	6,5	17,9	0,0	13,8	0,0	0,0	0,0	0,0
W-9,25	12,25	-9,25	89	66	155	152	116	99	59	45	19	32	22	28	1,4	0,0	2,1	2,1	15,4	4,2	18,2	6,3	6,3	0,0	44,1	0,0	0,0	0,0	0,0
W-9,75	12,75	-9,75	143	38	180	162	112	100	61	39	14	38	26	22	3,4	0,0	0,0	0,0	25,3	3,4	16,1	8,0	2,3	0,0	41,4	0,0	0,0	0,0	0,0
W-10,25	12,75	-10,25	180	38	218	203	123	100	57	36	21	30	28	21	0,5	0,0	0,0	2,0	10,2	2,5	16,8	31,5	19,8	0,0	16,8	0,0	0,0	0,0	0,0
W-10,75	13,25	-10,75	144	70	214	211	165	96	77	38	12	25	35	28	4,4	0,0	3,0	0,0	11,1	1,5	10,4	2,2	20,7	0,0	32,6	0,0	0,0	14,1	0,0
W-11,25	13,25	-11,25	147	52	199	188	122	97	51	34	15	25	29	30	0,6	0,0	0,0	1,8	13,9	0,6	23,5	13,9	12,7	13,9	18,1	0,0	0,0	1,2	0,0
W-11,75	13,25	-11,75	359	46	405	380	216	100	76	52	14	39	25	21	2,0	5,4	0,0	1,4	25,9	1,4	10,9	3,4	22,4	2,0	25,2	0,0	0,0	0,0	0,0
W-12,25	13,25	-12,25	826	86	912	885	492	100	55	29	17	36	30	17	0,2	0,7	0,5	0,4	8,4	40,3	11,6	14,5	14,5	0,0	8,9	0,0	0,0	0,0	0,0
W-12,75	12,75	-12,75	322	9	331	328	138	100	49	22	51	16	16	18	0,3	1,0	0,3	0,3	12,3	56,8	12,6	5,2	8,7	0,3	2,3	0,0	0,0	0,0	0,0
W-13,25	12,25	-13,25	91	12	103	101	51	100	54	38	19	26	26	29	6,0	0,0	2,4	1,2	33,3	3,6	27,4	10,7	9,5	0,0	6,0	0,0	0,0	0,0	0,0
W-13,75	12,25	-13,75	121	28	149	148	103	100	73	51	13	34	38	15	1,6	5,4	0,0	0,0	20,9	14,0	13,2	7,0	19,4	0,0	17,8	0,8	0,0	0,0	0,0
W-14,25	11,75	-14,25	104	12	116	113	72	100	59	42	27	32	19	22	1,0	0,0	1,0	2,9	23,1	15,4	31,7	14,4	0,0	0,0	10,6	0,0	0,0	0,0	0,0
W-14,75	11,75	-14,75	86	20	106	105	59	99	57	38	15	28	33	24	1,3	1,3	0,0	2,5	25,0	25,0	18,8	8,8	0,0	0,0	12,5	5,0	0,0	0,0	0,0
W-15,25	11,75	-15,25	116	31	146	144	95	100	60	44	23	28	32	17	0,8	1,5	0,0	2,3	22,7	14,4	17,4	8,3	12,9	0,0	13,6	6,1	0,0	0,0	0,0
W-15,75	11,25	-15,75	126	59	184	184	137	100	68	50	22	28	22	29	1,3	4,7	2,0	2,0	26,0	12,7	8,7	5,3	8,7	0,0	22,0	6,7	0,0	0,0	0,0
W-16,25	11,25	-16,25	156	67	222	215	153	100	54	31	14	25	31	31	0,5	0,0	0,0	1,1	12,5	9,2	21,7	11,4	8,7	7,6	25,5	1,6	0,0	0,0	0,0
W-16,75	11,25	-16,75	185	121	306	293	237	100	55	42	27	27	24	23	1,3	2,2	0,0	3,1	22,1	12,8	8,4	3,1	6,6	4,0	34,1	2,2	0,0	0,0	0,0
W-17,25	11,25	-17,25	388	134	522	496	328	100	63	46	25	29	24	22	0,0	3,7	4,5	4,5	17,8	11,0	10,8	5,1	7,1	5,7	28,6	1,1	0,0	0,0	0,0
W-17,75	11,25	-17,75	543	213	755	700	456	100	48	45	21	27	29	24	0,0	0,0	0,0	3,1	20,0	3,6	7,4	4,5	34,8	6,9	19,2	0,4	0,0	0,0	0,0
W-18,25	11,25	-18,25	475	198	672	598	380	99	64	49	28	30	19	24	0,0	0,0	0,0	4,1	8,6	3,4	2,9	1,1	36,7	9,8	26,1	0,5	0,0	0,0	6,8
W-18,75	11,75	-18,75	582	211	788	699	496	100	54	46	19	29	28	24	0,0	0,4	0,8	3,6	18,2	8,7	4,9	5,5	32,8	7,8	16,1	1,1	0,0	0,0	0,0
W-19,25	12,25	-19,25	511	186	696	617	417	99	69	56	20	28	28	24	0,0	0,2	2,1	0,4	15,2	4,2	1,1	1,5	37,9	8,0	29,5	0,0	0,0	0,0	0,0
W-19,75	12,25	-19,75	595	269	864	751	571	100	56	46	22	27	27	24	0,2	2,4	0,0	2,6	19,4	5,0	1,6	1,4	40,2	7,8	19,0	0,4	0,0	0,0	0,0
W-20,25	12,75	-20,25	558	307	865	757	562	100	67	54	20	29	28	24	0,0	0,3	0,0	1,2	12,3	2,9	8,6	3,2	29,1	9,6	32,0	0,8	0,0	0,0	0,0
W-20,75	12,75	-20,75	486	228	714	645	477	100	55	48	28	27	25	20	0,0	0,4	0,2	1,2	17,6	6,0	9,5	5,4	31,3	7,0	20,9	0,4	0,0	0,0	0,0
W-21,25	13,25	-21,25	499	238	737	675	478	99	72	58	23	30	24	22	0,0	0,4	2,6	4,7	15,1	5,1	0,9	1,8	29,5	6,1	33,0	0,9	0,0	0,0	0,0
W-21,75	13,25	-21,75	500	381	879	817	583	100	62	51	26	25	25	25	0,0	0,0	1,1	1,3	6,0	3,8	1,1	3,2	36,2	15,6	31,8	0,0	0,0	0,0	0,0
W-22,25	13,75	-22,25	632	325	955	885	714	100	63	44	22	26	26	26	0,0	0,3	0,6	2,4	12,5	2,7	17,5	1,8	24,1	4,2	33,4	0,5	0,0	0,0	0,0
W-22,75	13,75	-22,75	567	530	1096	1017	845	100	65	51	22	31	25	22	0,6	1,3	4,1	9,1	17,0	4,3	1,1	1,4	27,2	5,7	26,7	1,4	0,0	0,0	0,0
W-23,25	13,75	-23,25	545	499	1044	965	720	99	69	58	22	24	28	26	0,1	0,8	0,6	4,1	8,4	2,4	4,1	2,9	24,2	4,1	43,4	0,3	4,5	0,0	0,1
W-23,75	13,75	-23,75	392	406	798	751	562	100	51	45	20	32	24	24	0,8	1,6	1,3	1,6	3,9	1,8	1,0	3,9	35,2	6,8	32,8	0,0	6,0	0,0	3,1
W-24,25	13,75	-24,25	353	377	730	659	513	99	76	64	19	32	26	23	0,5	0,3	0,5	1,4	7,8	2,3	0,5	0,8	29,0	11,1	45,9	0,0	0,0	0,0	0,0
W-24,75	14,25	-24,75	309	198	507	452	344	100	61	52	24	32	27	17	2,4	0,6	3,5	6,8	2,9	3,5	8,5	0,9	32,9	5,6	32,1	0,3	0,0	0,0	0,0
W-25,25	14,25	-25,25	352	166	518	434	307	100	58	46	17	31	30	22	11,5	1,6	0,0	1,6	7,1	2,1	6,0	1,6	32,8	3,9	29,1	2,8	0,0	0,0	0,0
W-25,75	14,25	-25,75	379	191	570	407	264	100	42	38	16	32	33	19	25,1	0,5	0,0	0,5	1,9	2,1	4,8	0,3	35,0	9,1	19,0	1,6	0,0	0,0	0,0
W-26,25	14,25	-26,25	452	214	666	504	350	100	50	44	16	34	34	15	21,9	0,3	0,2	0,7	7,8	3,1	9,3	0,2	25,3	9,7	20,7	1,0	0,0	0,0	0,0
W-26,75	14,25	-26,75	305	196	501	444	340	99	57	51	20	37	28	16	6,2	0,5	3,7	6,4	10,1	3,7	6,4	0,2	27,6	4,4	25,9	4,9	0,0	0,0	0,0
W-27,25	14,75	-27,25	207	129	335	300	203	100	70	59	24	31	25	19	0,0	0,0	0,0	0,0	5,8	7,1	8,5	2,2	34,4	4,5	34,8	2,7	0,0	0,0	0,0
W-27,75	14,75	-27,75	188	64	251	218	138	99	57	46	17	34	28	20	0,0	1,1	0,0	0,0	5,4	4,9	14,7	9,8	40,2	6,0	17,9	0,0	0,0	0,0	0,0
W-28,25	15,25	-28,25	144	107	250	204	143	99	66	53	17	31	31	21	0,0	0,0	0,0	0,6	6,9	0,6	0,6	0,6	38,7	17,9	30,1	4,0	0,0	0,0	0,0
W-28,75	15,75	-28,75	271	218	245	199	140	99	52	41	26	29	28	16	3,1	2,8	5,3	6,5	2,2	2,2	0,6	9,3	26,1	11,5	16,8	9,9	3,1	0,6	0,0
W-29,25	16,25	-29,25	206	323	468	375	303	99	48	39	20	43	29	8	3,7	0,2	0,0	0,0	0,0	0,2	0,2	12,7	21,1	18,9	14,0	19,1	9,8	0,0	0,0
W-29,75	16,25	-29,75	194	391	585	462	350	99	54	46	24	41	28	7	3,1	0,2	0,0	0,7	3,5	0,2	0,4	7,5	23,4	16,3	9,1	24,9	10,6	0,0	0,0
W-30,25	16,75	-30,25	250	412	662	521	387	96	51	46	22	36	34	8	3,6	0,0	3,4	4,0	0,0	0,6	0,0	9,6	17,4	25,5	9,0	18,4	8,4	0,0	0,0
W-30,75	16,75	-30,75	152	401	552	441	340	100	53	48	20	40	29	10	4,6	0,0	0,0	0,5	1,6	0,9	0,0	8,7	13,3	14,0	14,0	28,2	14,2	0,0	0,0
W-31,25	17,25	-31,25	160	365	525	419	311	100	47	42	26	39	27	8	5,6	0,2	0,0	0,5	0,5	0,7	3,3	10,5	16,4	14,5	8,0	24,4	15,5	0,0	0,0
W-31,75	17,75	-31,75	254	461	714	526	378	99	46	38	20	40	29	11	7,7	0,0	0,2	0,2	0,8	0,4	3,2	6,2	17,3	19,6	7,3	23,4	13,6	0,2	0,0
W-32,25	17,75	-32,25	2539	1137	3675	3406	1627	100	73	56	19	39	31	10	1,3	20,0	19,0	16,7	6,0	0,6	1,1	3,0	3,4	3,7	2,0	13,9	9,2	0,1	0,0
W-32,75	17,75	-32,75	2786	1045	3830	3594	1408	100	49	42	18	28	29	25	1,3	12,4	12,1	21,9	16,0	2,7	0,9	3,0	1,6	3,8	1,8	12,8	9,6	0,0	0,0
W-33,25	17,75	-33,25	2631	305	2935	2726	712	100	57	52	20	34	29	17	0,9	11,3	15,3	32,9	20,4	5,1	1,4	2,6	1,8	2,0	0,7	3,7	1,9	0,0	0,0
W-33,75	17,75	-33,75	2583	287	2870	2578	1070	100	47	38	17	36	28	19	0,1	1,8	7,0	40,2	23,2	9,9	3,6	3,2	3,1	1,9	0,9	2,4	2,6	0,0	0,0
W-34,25	17,75	-34,25	1499	1009	2508	2289	1386	100	54	44	22	30	31	17	0,4	0,6	4,2	28,1	18,1	1,6	2,0	1,5	2,6	4,3	3,5	12,8	19,6	0,0	0,8
W-34,75	17,75	-34,75	608	128	736	687	351	99	47	44	15	39	30	16	0,0	0,4	2,4	46,7	26,3	0,6	2,4	2,7	4,8	4,4	1,5	3,4	3,7	0,0	0,0
W-35,25	17,75	-35,25	284	28	312	303	181	100	58	57	21	37	33	9	0,4	0,4	1,7	36,4	49,0	0,8	1,3	0,0	2,5	2,9	0,8	1,3	2,5	0,0	0,0
W-35,75	17,75	-35,75	83	12	95	94	77	100	84	81	19	8	66	7	0,0	1,5	3,1	35,4	41,5	0,0	3,1	9,2	0,0	6,2	0,0	0,0	0,0	0,0	0,0
S-18,75	18,75	-34,75	1120	481	1599	1405	748	100	37	24	21	38	28	13	2,8	0,6	7,1	29,6	20,6	1,5	1,4	1,9	16,7	4,9	2,0	6,2	4,6	0,1	0,0
S-19,25	19,25	-34,75	1001	359	1357	1208	622	100	45	31	23	36	31	10	4,7	0,2	3,1	32,8	22,8	1,0	1,4	2,6	12,2	6,3	2,0	5,5	5,5	0,0	0,0
S-19,75	19,75	-35,25	846	300	1145	1044	563	99	43	35	22	38	31	10	2,0	0,0	3,4	36,8	21,7	1,4	4,3	1,0	12,3	3,9	1,5	5,8	6,0	0,0	0,0
S-20,25	20,25	-35,25	862	376	1237	1162	653	100	43	34	22	34	30	13	1,8	0,4	1,8	31,1	23,5	1,7	1,4	0,5	8,5	10,2	3,5	5,6	10,1	0,0	0,0
S-20,75	20,75	-34,75	600	359	958	843	475	100	50	11	25	39	27	9	1,4	0,0	0,6	36,9	16,1	0,3	2,4	0,5	10,3	9,0	3,6	7,8	11,1	0,0	0,0
S-21,25	21,25	-35,25	480	449	929	831	501	100	57	23	20	38	32	10	3,1	0,0	0,6	14,2	22,5	0,1	1,6	0,1	16,1	12,4	4,7	10,0	14,7	0,0	0,0
S-21,75	21,75	-34,75	142	425	566	513	338	100	54	32	23	43	25	9	0,0	0,0	0,7	2,3	2,0	0,0	0,2	0,0	26,0	21,9	9,0	13,8	24,0	0,0	0,0
S-22,25	22,25	-34,75	189	509	698	624	387	100	53	27	24	33	30	13	0,0	0,0	1,6	2,1	4,2	1,1	0,0	0,3	25,7	22,8	7,0	14,2	20,9	0,0	0,0
S-22,75	22,75	-34,75	100	244	344	309	199	99	59	36	24	22	31	22	0,0	0,0	2,4	1,0	2,0	0,3	1,4	1,7	22,5	25,9	8,2	12,6	21,8	0,0	0,0
S-23,25	23,25	-34,75	137	237	374	333	231	100	61	41	24	42	25	8	0,0	0,0	1,8	8,3	3,0	2,1	0,6	1,2	14,2	25,7	5,9	13,0	24,3	0,0	0,0
S-23,75	23,75	-34,75	110	225	335	295	213	100	63	43	18	39	32	11	0,0	0,0	0,7	5,7	2,7	2,3	0,7	0,0	20,1	24,7	4,7	13,0	25,4	0,0	0,0
S-24,25	24,25	-34,75	100	221	321	268	151	100	71	55	21	33	30	16	0,0	0,3	0,7	0,0	8,3	4,2	0,7	1,4	10,1	33,7	15,3	9,7	15,6	0,0	0,0
S-24,75	24,75	-34,75	88	153	241	200	136	97	50	37	26	33	30	11	0,0	0,0	0,0	1,4	3,7	6,5	2,8	0,0	11,2	36,3	11,2	13,5	13,5	0,0	0,0
S-25,25	25,25	-34,75	117	222	339	282	180	98	58	36	19	29	32	20	0,0	0,0	0,0	0,7	4,9	5,9	5,6	0,7	11,8	34,2	7,6	11,5	17,1	0,0	0,0
S-25,75	25,75	-34,25	144	160	303	278	191	100	46	35	17	41	28	14	0,4	0,0	2,7	8,4	4,2	5,0	6,1	0,0	16,4	22,5	5,0	10,7	18,7	0,0	0,0
S-26,25	26,25	-34,25	116	139	253	219	150	100	42	34	20	34	42	4	1,3	0,0	0,0	4,7	9,9	1,3	3,0	0,0	21,5	24,5	3,9	6,0	22,3	1,7	0,0
E-35,25	27,25	-35,25	12	4	16	17	13	100	100	43	71	14	14	0	0,0	25,0	12,5	25,0	25,0	12,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
E-34,75	27,25	-34,75	21	8	29	26	23	80	16	20	24	24	20	32	3,8	0,0	3,8	7,7	11,5	7,7	7,7	0,0	0,0	0,0	0,0	0,0	0,0	57,7	0,0
E-34,25	27,25	-34,25	44	55	99	81	57	94	62	62	26	18	33	24	0,0	0,0	3,4	3,4	3,4	4,5	12,5	0,0	3,4	27,3	10,2	6,8	8,0	17,0	0,0
E-33,75	27,25	-33,75	103	161	264	234	138	97	50	15	16	34	30	20	0,0	0,0	0,0	2,3	0,0	3,3	5,7	0,0	9,4	28,3	9,0	9,4	15,6	10,2	0,0
E-33,25	28,25	-33,25	88	61	149	178	80	100	30	16	27	27	24	22	0,7	3,5	7,8	6,4	3,5	6,4	13,5	0,0	2,8	7,1	12,8	3,5	23,4	5,7	2,8
E-32,75	28,75	-32,75	43	27	71	79	27	100	46	29	10	25	31	34	1,6	0,0	20,6	7,9	6,3	7,9	9,5	0,0	3,2	15,9	6,3	3,2	17,5	0,0	0,0
E-32,25	29,25	-32,25	49	19	68	68	32	100	64	42	26	38	19	17	0,0	0,0	21,7	33,3	5,0	3,3	0,0	0,0	10,0	11,7	0,0	5,0	10,0	0,0	0,0
E-31,75	29,75	-31,75	114	29	142	127	53	100	29	23	5	40	35	20	35,4	0,0	20,7	15,9	3,7	1,2	9,8	0,0	2,4	0,0	2,4	0,0	8,5	0,0	0,0
E-31,25	30,25	-31,25	684	54	738	733	99	100	16	12	12	33	36	18	6,5	0,0	1,0	0,3	0,7	15,9	61,2	1,8	2,5	0,0	4,3	3,6	2,3	0,0	0,0
E-30,75	30,75	-30,75	128	5	133	93	14	100	28	17	10	40	38	12	17,8	0,0	5,0	2,0	42,6	7,9	18,8	0,0	4,0	0,0	1,0	0,0	1,0	0,0	0,0
E-30,25	31,25	-30,25	1390	35	1425	1122	60	100	37	33	9	48	33	10	1,0	0,0	0,8	15,2	42,8	29,5	9,8	0,3	0,6	0,0	0,0	0,0	0,0	0,0	0,0
E-29,75	31,75	-29,75	820	122	940	667	71	100	27	19	10	54	21	14	1,4	0,2	1,2	38,3	29,2	20,0	4,0	0,1	4,5	0,0	0,0	1,1	0,0	0,0	0,0
E-29,25	31,75	-29,25	188	36	224	179	92	100	16	6	8	42	36	14	16,0	0,0	4,2	5,7	38,7	6,6	9,4	0,0	17,0	0,0	0,0	1,9	0,5	0,0	0,0
E-28,75	32,75	-28,75	103	11	114	76	10	100	18	11	6	34	47	13	19,5	0,0	0,0	5,3	5,3	4,4	55,8	0,0	9,7	0,0	0,0	0,0	0,0	0,0	0,0
E-28,25	33,25	-28,25	54	1	55	23	0	100	13	11	5	42	34	18	6,0	0,0	0,0	0,0	10,0	8,0	74,0	0,0	0,0	0,0	0,0	0,0	2,0	0,0	0,0
E-27,75	33,25	-27,75	38	1	39	8	3	100	23	23	9	50	23	18	0,0	0,0	0,0	2,6	5,3	10,5	76,3	0,0	0,0	0,0	0,0	0,0	5,3	0,0	0,0
E-27,25	33,75	-27,25	37	0	37	9	3	100	4	4	4	40	36	20	0,0	0,0	0,0	0,0	8,6	2,9	88,6	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
E-26,75	33,75	-26,75	17	1	18	11	6	100	33	33	8	42	25	25	0,0	0,0	0,0	5,9	11,8	11,8	58,8	0,0	0,0	11,8	0,0	0,0	0,0	0,0	0,0
E-26,25	33,75	-26,25	63	3	65	56	33	100	47	47	25	29	22	24	0,0	0,0	0,0	3,6	16,4	1,8	61,8	12,7	0,0	3,6	0,0	0,0	0,0	0,0	0,0
E-25,75	33,75	-25,75	125	4	129	121	66	99	60	53	18	24	35	24	0,0	0,0	2,1	14,4	61,9	8,2	9,3	1,0	0,0	3,1	0,0	0,0	0,0	0,0	0,0
E-25,25	34,25	-25,25	144	6	150	133	51	100	62	51	21	31	29	19	0,0	0,0	0,0	3,0	59,3	6,7	23,0	5,2	0,0	3,0	0,0	0,0	0,0	0,0	0,0
E-24,75	35,25	-24,75	86	34	110	99	64	97	38	28	17	30	35	18	0,0	0,0	0,0	5,7	16,0	17,9	16,0	4,7	0,0	2,8	15,1	21,7	0,0	0,0	0,0
E-24,25	36,25	-24,25	19	2	21	20	10	100	24	24	18	18	41	24	0,0	5,9	0,0	17,6	11,8	0,0	52,9	0,0	0,0	5,9	0,0	5,9	0,0	0,0	0,0
E-23,75	36,25	-23,75	22	2	24	22	11	100	28	22	17	33	17	33	0,0	0,0	0,0	11,1	11,1	0,0	66,7	0,0	0,0	5,6	0,0	0,0	5,6	0,0	0,0
E-23,25	36,25	-23,25	29	3	32	28	24	100	50	54	25	32	18	25	0,0	3,6	0,0	0,0	3,6	0,0	53,6	28,6	0,0	10,7	0,0	0,0	0,0	0,0	0,0
E-22,75	36,25	-22,75	17	2	19	18	14	100	8	8	17	42	25	17	0,0	0,0	0,0	8,3	8,3	0,0	75,0	0,0	0,0	0,0	0,0	0,0	8,3	0,0	0,0
E-22,25	36,25	-22,25	13	1	14	13	10	100	23	23	15	38	15	31	0,0	0,0	0,0	0,0	7,7	0,0	84,6	0,0	0,0	7,7	0,0	0,0	0,0	0,0	0,0
E-21,75	36,25	-21,75	22	3	25	21	12	100	45	40	30	35	15	20	0,0	0,0	0,0	0,0	10,0	0,0	75,0	5,0	0,0	10,0	0,0	0,0	0,0	0,0	0,0
E-21,25	35,75	-21,25	38	1	39	38	28	100	40	37	3	33	37	27	0,0	3,3	0,0	6,7	10,0	0,0	46,7	30,0	0,0	3,3	0,0	0,0	0,0	0,0	0,0
E-20,75	35,75	-20,75	50	0	50	48	23	100	29	18	18	35	24	24	0,0	2,9	2,9	11,8	20,6	0,0	8,8	50,0	2,9	0,0	0,0	0,0	0,0	0,0	0,0
E-20,25	35,75	-20,25	77	1	77	73	39	100	34	13	21	20	34	25	0,0	11,1	1,6	12,7	25,4	0,0	19,0	28,6	0,0	1,6	0,0	0,0	0,0	0,0	0,0
E-19,75	36,25	-19,75	93	4	96	89	45	100	48	12	23	28	29	20	0,0	0,0	0,0	9,8	22,0	0,0	35,4	28,0	0,0	3,7	0,0	0,0	0,0	0,0	1,2
E-19,25	36,25	-19,25	99	3	102	98	30	100	30	5	23	36	21	20	0,0	0,0	0,0	3,0	10,0	0,0	54,0	30,0	0,0	2,0	0,0	0,0	0,0	0,0	1,0
E-18,75	37,25	-18,75	116	3	119	108	70	100	44	31	26	29	33	13	0,0	0,0	0,0	0,9	17,9	0,0	11,6	67,9	0,0	1,8	0,0	0,0	0,0	0,0	0,0
E-18,25	37,25	-18,25	64	2	65	62	21	100	21	5	12	43	21	24	0,0	0,0	1,7	1,7	25,9	0,0	13,8	53,4	0,0	3,4	0,0	0,0	0,0	0,0	0,0
E-17,75	37,75	-17,75	79	3	82	75	19	100	18	5	15	45	25	15	0,0	0,0	0,0	0,0	28,8	0,0	15,1	52,1	0,0	4,1	0,0	0,0	0,0	0,0	0,0
E-17,25	38,75	-17,25	44	4	48	43	13	100	24	16	16	38	38	8	0,0	0,0	2,6	0,0	12,8	0,0	15,4	64,1	0,0	5,1	0,0	0,0	0,0	0,0	0,0
E-16,75	40,25	-16,75	30	4	34	32	25	100	62	57	19	24	24	33	0,0	0,0	4,8	19,0	19,0	4,8	9,5	38,1	0,0	0,0	0,0	0,0	4,8	0,0	0,0
E-16,25	40,75	-16,25	34	7	41	40	23	100	71	61	21	29	21	29	0,0	0,0	0,0	28,6	3,6	7,1	28,6	14,3	0,0	3,6	0,0	3,6	3,6	7,1	0,0
E-15,75	41,25	-15,75	44	4	48	48	31	100	42	37	5	16	58	21	0,0	5,3	0,0	5,3	15,8	5,3	26,3	36,8	0,0	0,0	0,0	0,0	0,0	5,3	0,0
E-15,25	41,25	-15,25	32	8	40	40	26	97	52	39	35	26	16	23	0,0	6,5	6,5	16,1	19,4	9,7	6,5	16,1	0,0	0,0	0,0	3,2	0,0	16,1	0,0
E-14,75	41,75	-14,75	24	3	27	27	16	100	63	53	26	37	32	5	0,0	0,0	10,5	10,5	21,1	5,3	10,5	36,8	0,0	0,0	0,0	0,0	5,3	0,0	0,0
E-14,25	41,25	-14,25	35	1	36	36	29	97	65	53	9	26	32	32	0,0	2,9	0,0	11,8	26,5	2,9	20,6	35,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0
E-13,75	41,75	-13,75	23	1	24	24	12	100	27	33	47	40	7	7	0,0	0,0	0,0	5,3	36,8	10,5	42,1	0,0	0,0	0,0	0,0	0,0	5,3	0,0	0,0
E-13,25	41,25	-13,25	22	1	23	23	19	100	88	71	29	29	18	24	0,0	0,0	0,0	17,6	11,8	11,8	0,0	58,8	0,0	0,0	0,0	0,0	0,0	0,0	0,0
E-12,75	41,25	-12,75	9	0	9	9	3	100	100	100	0	67	33	0	0,0	0,0	0,0	33,3	0,0	0,0	0,0	66,7	0,0	0,0	0,0	0,0	0,0	0,0	0,0
E-12,25	41,25	-12,25	39	0	39	39	27	100	63	69	22	22	31	25	0,0	0,0	0,0	15,6	6,3	15,6	12,5	50,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
E-11,75	41,25	-11,75	26	0	26	26	19	100	70	70	0	30	30	40	0,0	0,0	0,0	50,0	10,0	20,0	0,0	20,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
E-11,25	41,25	-11,25	35	5	40	40	28	100	29	32	32	21	26	21	0,0	0,0	0,0	5,9	14,7	20,6	35,3	23,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0
E-10,75	41,25	-10,75	20	1	21	21	14	100	11	11	33	22	33	11	0,0	0,0	0,0	11,1	44,4	22,2	22,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
E-10,25	41,25	-10,25	22	1	23	23	19	100	74	68	16	32	5	47	0,0	0,0	0,0	0,0	21,1	26,3	15,8	36,8	0,0	0,0	0,0	0,0	0,0	0,0	0,0
E-9,75	40,75	-9,75	17	0	17	17	14	100	71	71	29	14	57	0	0,0	0,0	0,0	14,3	14,3	57,1	14,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
E-9,25	40,75	-9,25	13	11	24	24	11	100	24	24	0	41	29	29	0,0	0,0	0,0	11,8	5,9	64,7	5,9	5,9	0,0	5,9	0,0	0,0	0,0	0,0	0,0
E-8,75	40,75	-8,75	10	5	15	15	5	100	40	20	20	30	20	30	0,0	0,0	0,0	40,0	0,0	20,0	40,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
E-8,25	40,75	-8,25	8	0	8	8	8	100	0	0	33	17	17	33	0,0	0,0	0,0	0,0	0,0	66,7	0,0	33,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0
E-7,75	40,75	-7,75	19	2	21	21	16	100	40	40	13	47	20	20	0,0	0,0	0,0	20,0	6,7	26,7	33,3	6,7	0,0	6,7	0,0	0,0	0,0	0,0	0,0
E-7,25	40,75	-7,25	9	0	9	8	7	100	40	20	40	20	0	40	0,0	0,0	0,0	20,0	0,0	20,0	20,0	20,0	0,0	20,0	0,0	0,0	0,0	0,0	0,0
E-6,75	40,25	-6,75	21	0	21	19	18	100	78	56	11	39	33	17	0,0	0,0	0,0	15,8	0,0	21,1	52,6	5,3	0,0	5,3	0,0	0,0	0,0	0,0	0,0
E-6,25	40,25	-6,25	8	0	8	8	5	100	60	40	0	80	0	20	0,0	0,0	0,0	20,0	0,0	80,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
E-5,75	40,25	-5,75	16	0	16	14	12	100	60	30	30	30	30	10	0,0	0,0	0,0	50,0	0,0	20,0	30,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
E-5,25	40,25	-5,25	18	2	20	17	13	100	55	55	9	27	36	27	0,0	0,0	0,0	9,1	9,1	9,1	27,3	0,0	45,5	0,0	0,0	0,0	0,0	0,0	0,0
E-4,75	40,25	-4,75	40	2	42	38	30	100	51	46	32	20	20	29	0,0	0,0	0,0	4,9	2,4	7,3	26,8	4,9	53,7	0,0	0,0	0,0	0,0	0,0	0,0
E-4,25	40,25	-4,25	57	46	103	102	72	100	13	5	20	38	26	16	0,0	1,2	0,0	5,8	8,1	2,3	15,1	7,0	9,3	39,5	11,6	0,0	0,0	0,0	0,0
E-3,75	40,75	-3,75	29	15	44	44	16	100	11	4	30	33	15	22	0,0	0,0	0,0	0,0	24,1	3,4	27,6	0,0	44,8	0,0	0,0	0,0	0,0	0,0	0,0
E-3,25	40,75	-3,25	30	33	63	63	57	100	12	9	19	22	45	14	0,0	0,0	0,0	3,4	0,0	1,7	16,9	0,0	0,0	78,0	0,0	0,0	0,0	0,0	0,0
E-2,75	41,25	-2,75	37	16	53	52	39	91	20	11	20	27	24	29	0,0	0,0	0,0	0,0	0,0	2,2	26,7	15,6	0,0	55,6	0,0	0,0	0,0	0,0	0,0
E-2,25	41,75	-2,25	25	19	44	44	33	100	21	16	37	32	11	21	0,0	0,0	0,0	10,3	0,0	5,1	25,6	10,3	0,0	48,7	0,0	0,0	0,0	0,0	0,0
E-1,75	42,25	-1,75	22	22	44	43	21	100	60	53	23	27	17	33	0,0	0,0	0,0	16,7	13,3	6,7	43,3	0,0	0,0	20,0	0,0	0,0	0,0	0,0	0,0
E-1,25	42,75	-1,25	16	18	34	38	7	100	80	77	23	20	30	27	0,0	0,0	0,0	0,0	13,3	26,7	60,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
E-0,75	43,25	-0,75	6	18	24	24	3	100	96	96	22	17	30	30	0,0	0,0	0,0	4,3	8,7	13,0	73,9	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
E-0,25	43,25	-0,25	17	20	37	37	15	97	59	55	34	31	14	21	0,0	0,0	0,0	6,9	3,4	20,7	44,8	0,0	24,1	0,0	0,0	0,0	0,0	0,0	0,0
			47033	19218	65852	59736	35657	99	49	37	20	32	28	20															
						91	54																						

Appendix 2 WOD-18 data points excluded from the climatology, for each of the variables studied. The unique WOD Station ID can be used to find ancillary data for the particular station, at ncei.noaa.gov.

WOD StationID	Depth	Temperature	Salinity	Oxygen
18681	0	3,13		
167237	100		36,24	
178684	0		32,39	
355657	50			32
404741	0		32,30	
406622	0		33,06	
415965	0		33,49	
454521	0			26
465504	50			
532511	0		31,99	
598804	0	2,47	3,43	
717517	0			61
730626	0	7,44		
794626	0			
855259	0			
1323552	50		32,85	
6624740	0			676
6695714	0	3,02	2,69	
6737152	50	4,80		
6768833	0	2,64		
6794839	50	1,81		
6794839	100	1,81		
6796221	50	3,37		
6875195	0		37,78	
6887273	0		33,12	
7067809	0	35,01		
7213009	50		2,09	
7213009	100		1,80	
8337232	100		31,92	
8552259	0		33,35	
8552354	100			
8552370	100			
8552384	100			
8552597	0			
8552597	100			
8552597	0			
8552598	0			
8552691	0			
8552692	0			
8552693	0			
8552694	0			
8552696	0			
8552697	0			
8552698	0			
8552699	0			
8552748	0			
8552752	0			
8552754	0			
8552780	0			
8552794	0			
8552800	0			
8552994	0		34,01	
8553007	50			
8553010	50			
8553011	50			
8553012	50			
8553013	50			
8553014	50			
8553022	50			
8556262	0			
8556263	0			
8556264	0			
8556265	0			
8589195	100	4,06		
8589484	50			
8589485	50			
8589486	0			
8589486	50			
8589486	100			
8589487	50			
8589487	100			
8589488	50			
8589489	50			
8589490	50			
8589490	100			
8589491	50			
8589491	100			
8589558	0		30,59	
8589636	0	1,28		
8589671	50			
8589671	50			
8749324	50			1520
8749324	100			1517
8754127	50	0,90	0,90	
8754222	50		2,48	
8758038	100		38,32	
8758038	50		40,46	
9921458	0	2,48		
9921975	0	4,98		
10474743	0		15,09	
10474744	0		24,52	
10474745	0		27,99	
10474746	0		22,79	
10474747	0		11,58	
10474748	0		13,32	
10474749	0		22,06	
10474750	0		6,49	
10474751	0		24,98	
10474752	0		14,69	

Appendix 3 Surface temperature 2-hour averages for all H bins with n > 200, for each of the four seasons, with the average of these 2-hr averages, $T_{diurnal}$, the average of all surface temperature values for that season, T_{all}, and the difference between these averages. Also shown are the total number of casts for each season, and the distribution of these casts between the four daily 6-hour periods as shown. Temperature averages in brackets are bins with n <3.

H type	Longitude	Latitude	Season	#casts	%casts 00:00-05:59	%casts 06:00-11:59	%casts 12:00-17:59	%casts 18:00-23:59	Tavg 00:00-01:59	Tavg 02:00-03:59	Tavg 04:00-05:59	Tavg 06:00-07:59	Tavg 08:00-09:59	Tavg 10:00-11:59	Tavg 12:00-13:59	Tavg 14:00-15:59	Tavg 16:00-17:59	Tavg 18:00-19:59	Tavg 20:00-21:59	Tavg 22:00-23:59	$T_{diurnal}$	T_{all}	T_{all} - $T_{diurnal}$
H_{coast}	11,75	-4,75	JFM	926	2	93	4	1	(27,25)	27,210	26,669	27,219	27,332	27,847	28,362	28,517	28,299	27,710	27,742	27,280	27,619	27,479	-0,140
			AMJ	921	3	91	5	1	nodata	nodata	26,579	24,849	24,433	24,331	25,443	26,420	25,086	(26,55)	nodata	(26,84)		24,828	
			JAS	888	1	93	4	1	20,900	(20,71)	20,528	21,427	21,240	21,543	22,512	22,329	22,407	22,210	21,747	(21,01)	21,547	21,391	-0,156
			OND	858	1	95	3	1	26,210	(25,45)	24,696	25,183	25,199	24,998	25,002	24,764	25,727	26,223	25,787	(26,02)	25,439	25,168	-0,271
H1°	11,25	-17,75	JFM	171	23	29	15	33	19,531	19,058	18,436	18,296	19,295	20,274	20,108	19,506	18,941	19,185	18,899	19,815	19,279	19,288	0,009
			AMJ	87	23	28	30	20	17,104	16,592	17,186	16,981	17,629	17,575	17,369	16,190	16,040	16,256	16,710	16,766	16,867	16,915	0,049
			JAS	59	13	34	38	16	14,684	(14,45)	(14,27)	14,382	14,340	15,018	15,014	15,556	15,053	15,103	14,890	15,427	14,849	14,891	0,042
			OND	108	23	20	29	28	16,234	15,809	16,164	16,551	14,944	15,632	16,582	16,305	15,795	15,761	16,045	16,181	16,000	16,046	0,046
H_{coast}	12,75	-19,75	JFM	111	18	10	37	35	19,461	18,863	17,806	(18,005)	18,146	19,361	19,248	17,491	17,752	17,302	18,041	18,928	18,367	18,183	-0,184
			AMJ	82	18	38	18	26	16,753	16,189	15,568	15,524	15,886	16,041	16,655	14,453	15,470	15,627	15,370	16,122	15,805	15,763	-0,042
			JAS	46	15	32	43	11	13,528	(14,03)	14,533	(13,930)	13,490	14,217	14,051	14,004	14,670	(14,610)	14,550	13,883	14,125	14,003	-0,122
			OND	63	28	25	22	26	14,130	13,867	13,722	(13,848)	13,974	14,058	14,960	14,963	14,735	14,672	15,747	14,366	14,420	14,512	0,092
H1°	12,25	-19,75	JFM	125	18	23	32	27	18,427	18,651	18,988	18,084	19,841	20,421	19,403	19,763	19,546	18,383	19,001	19,537	19,170	19,297	0,127
			AMJ	66	23	27	27	24	17,087	17,180	16,548	17,175	17,674	17,093	17,059	16,346	(16,705)	17,064	16,362	16,281	16,881	16,940	0,059
			JAS	63	14	38	29	18	14,190	(14,46)	14,735	15,492	14,803	14,866	14,820	14,985	14,557	14,662	14,543	14,230	14,695	14,753	0,058
			OND	71	16	24	36	23	15,964	16,487	(15,786)	15,086	15,529	16,074	15,560	15,724	15,302	15,690	15,345	15,180	15,644	15,665	0,021
H_{coast}	14,25	-22,75	JFM	154	29	38	11	22	16,890	16,258	17,020	16,848	16,929	16,682	15,964	17,006	18,178	18,117	17,608	17,127	17,052	17,043	-0,009
			AMJ	98	23	30	32	15	16,016	15,682	15,225	14,010	14,439	14,748	15,140	13,850	14,036	14,323	14,433	15,318	14,768	14,822	0,054
			JAS	79	29	25	28	19	12,709	12,730	12,472	12,617	12,899	13,206	13,178	12,494	12,972	13,668	13,153	12,527	12,885	12,943	0,058
			OND	43	16	47	23	14	14,137	(16,01)	15,910	14,439	14,140	13,480	14,014	(14,087)	14,160	13,943	13,727	(12,27)	14,193	14,181	-0,012
H_{coast}	18,25	-32,25	JFM	345	26	24	36	14	14,724	13,879	13,956	14,139	14,777	14,510	14,798	14,841	14,431	14,113	14,391	14,557	14,426	14,339	-0,087
			AMJ	258	29	22	33	16	13,552	13,469	13,327	12,945	13,762	14,053	13,808	13,788	13,501	13,423	13,440	13,559	13,552	13,509	-0,043
			JAS	226	28	37	27	9	13,107	12,898	12,994	13,054	13,384	13,521	13,469	13,256	13,354	12,765	12,660	12,743	13,100	13,177	0,077
			OND	199	33	23	31	13	13,797	13,057	13,037	13,079	13,140	13,554	13,635	14,078	14,737	14,020	13,114	13,413	13,555	13,532	-0,023
H1°	17,75	-32,25	JFM	359	12	46	32	10	15,549	15,088	14,969	14,439	14,883	15,261	15,179	15,365	15,483	15,033	15,628	14,603	15,123	15,103	-0,020
			AMJ	278	12	51	27	10	14,223	14,323	13,907	14,115	14,519	14,508	14,386	14,151	14,055	14,183	14,104	13,578	14,171	14,257	0,086
			JAS	304	15	49	30	7	(13,48)	13,644	14,051	13,878	13,989	13,919	14,166	14,106	13,99	14,053	13,514	13,320	13,843	13,992	0,149
			OND	258	20	43	25	12	14,631	14,450	13,959	13,923	14,461	14,711	14,759	15,030	14,490	14,289	15,733	15,603	14,670	14,549	-0,121
H1.5°	17,25	-32,25	JFM	248	16	50	30	5	15,831	16,853	16,547	16,27	15,825	16,245	16,961	16,871	16,951	16,766	(17,27)	17,772	16,680	16,516	-0,164
			AMJ	154	10	59	28	2	14,203	15,495	15,557	15,497	15,279	15,461	15,873	15,437	15,528	(15,200)	15,375	(15,58)	15,374	15,406	0,032
			JAS	170	13	57	26	4	14,547	14,782	14,901	14,896	14,741	14,878	14,862	14,469	14,523	(15,540)	(14,85)	14,160	14,762	14,816	0,054
			OND	151	12	60	25	3	16,445	15,605	15,637	15,728	15,415	15,347	15,508	15,767	15,902	(15,175)	(15,86)	16,547	15,745	15,505	-0,240
H2°	16,75	-32,25	JFM	214	28	40	25	6	17,951	17,531	17,921	18,340	18,406	18,758	19,308	18,535	18,043	17,762	18,224	17,672	18,204	18,370	0,166
			AMJ	127	21	30	43	7	(17,25)	17,444	16,884	16,905	17,045	16,572	17,275	17,87	16,903	17,270	16,983	(17,06)	17,121	17,072	-0,049
			JAS	136	26	35	31	8	14,873	15,495	15,400	15,179	15,261	15,158	15,271	15,895	15,511	15,146	14,873	(14,87)	15,245	15,410	0,165
			OND	110	25	24	45	6	(16,82)	16,530	16,190	16,082	16,425	16,578	16,837	16,759	16,728	15,812	16,380	(16,60)	16,478	16,574	0,096
H_{coast}	18,25	-32,75	JFM	279	17	13	16	54	13,397	14,127	14,208	14,515	14,518	14,432	13,62	14,418	14,158	13,871	13,578	13,678	14,043	13,844	-0,199
			AMJ	298	14	10	25	51	13,355	13,758	13,101	13,884	14,05	13,935	13,705	13,509	13,703	13,393	13,527	13,513	13,619	13,561	-0,058
			JAS	305	11	9	28	52	13,020	12,898	(12,66)	12,414	13,298	13,672	14,346	13,475	13,386	13,318	13,262	13,269	13,251	13,348	0,097
			OND	235	15	11	22	53	13,365	12,996	(12,97)	12,94	13,906	14,469	14,268	14,336	13,198	13,413	13,428	13,403	13,558	13,561	0,004
H1°	17,75	-32,75	JFM	292	22	28	34	16	14,479	14,312	14,154	14,041	14,599	14,670	14,527	14,548	14,551	14,371	14,002	14,953	14,434	14,490	0,056
			AMJ	253	18	33	35	15	13,723	14,183	14,077	14,439	14,013	14,241	14,475	14,852	14,639	14,448	13,707	13,500	14,191	14,299	0,108
			JAS	269	17	40	34	9	12,897	13,858	13,966	13,852	13,827	14,229	13,905	13,553	13,437	13,877	13,960	13,002	13,697	13,815	0,118
			OND	246	23	29	32	16	12,872	13,807	13,671	13,606	14,155	14,660	14,117	13,390	14,344	13,991	14,329	14,016	13,913	13,990	0,077
H1.5°	17,25	-32,75	JFM	254	20	37	33	10	17,735	17,21	16,949	17,346	17,111	17,062	17,223	17,157	16,887	17,091	17,951	17,100	17,235	17,276	0,041
			AMJ	201	15	40	37	8	14,993	15,611	16,102	16,053	16,626	16,604	16,268	16,593	16,350	15,630	16,150	17,444	16,202	16,349	0,147
			JAS	236	15	41	30	13	15,390	15,379	15,215	15,229	15,333	15,256	15,392	15,175	15,378	15,323	15,250	15,333	15,304	15,320	0,016
			OND	217	17	37	31	15	16,084	16,265	15,472	16,388	16,593	16,716	16,458	16,849	16,586	16,358	15,975	15,891	16,303	16,398	0,095
H2°	16,75	-32,75	JFM	207	27	39	28	6	19,206	18,787	18,731	18,676	18,540	18,472	18,773	18,888	18,494	19,412	18,110	(18,66)	18,729	18,761	0,032
			AMJ	158	28	36	30	6	17,047	16,915	17,070	16,878	17,656	17,247	17,290	17,229	16,965	17,890	17,878	17,133	17,267	17,157	-0,110
			JAS	164	28	29	32	11	15,680	15,910	15,668	15,505	15,536	15,691	16,123	16,007	15,899	15,746	15,995	15,865	15,802	15,845	0,043
			OND	168	29	35	28	8	17,327	16,995	17,069	16,919	17,263	17,571	17,526	17,177	17,029	16,912	(17,38)	17,857	17,252	17,235	-0,017
H1°	17,75	-33,25	JFM	446	26	29	22	24	17,064	15,631	14,718	15,165	14,956	15,107	15,338	15,441	15,828	17,033	17,679	17,305	15,939	15,909	-0,030
			AMJ	358	21	27	28	25	14,194	13,941	14,829	14,953	14,972	15,340	14,938	14,785	14,378	14,231	14,280	14,316	14,596	14,598	0,002
			JAS	434	21	25	30	23	13,641	13,973	14,281	14,695	14,444	14,544	14,639	14,421	14,112	13,793	13,631	13,661	14,153	14,176	0,023
			OND	354	25	22	27	26	15,811	14,884	14,269	14,930	15,460	15,293	14,958	15,335	15,290	15,843	15,652	15,554	15,273	15,285	0,012
H1.5°	17,25	-33,25	JFM	228	20	46	29	5	19,640	19,331	18,469	17,752	18,379	18,140	18,512	19,153	19,384	18,437	18,497	20,330	18,835	18,699	-0,136
			AMJ	169	15	46	33	7	(17,10)	17,429	17,746	17,229	17,026	17,175	17,073	17,427	17,230	17,909	(17,74)	(17,60)	17,390	17,317	-0,073
			JAS	191	17	46	28	9	15,592	15,738	15,174	15,546	15,788	15,608	15,570	15,609	15,203	15,450	16,245	15,293	15,568	15,592	0,024
			OND	205	23	39	30	9	16,498	17,245	16,732	16,606	16,708	16,798	17,287	16,791	16,991	17,758	17,938	17,852	17,100	17,016	-0,084
H_{coast}	18,25	-33,75	JFM	298	15	31	29	26	13,117	13,482	13,128	13,864	13,696	13,930	14,721	14,963	13,987	13,366	12,961	12,860	13,673	13,782	0,109
			AMJ	361	17	29	21	32	13,057	13,367	13,579	14,147	14,521	14,634	14,575	14,394	13,619	13,544	13,365	13,254	13,838	13,797	-0,041
			JAS	286	15	29	23	34	13,450	13,638	13,578	14,226	14,133	14,110	13,878	14,069	13,973	13,638	13,586	13,692	13,831	13,840	0,009
			OND	312	19	26	22	33	13,778	13,412	13,235	13,736	13,773	13,357	14,407	14,261	13,698	13,617	13,076	13,265	13,635	13,569	-0,066
H1°	17,75	-33,75	JFM	338	23	40	30	8	17,918	15,820	16,395	16,57	16,939	16,462	16,711	16,887	15,956	16,79	18,221	17,824	16,874	16,692	-0,182
			AMJ	199	15	44	36	6	(15,94)	16,036	16,213	16,003	16,701	16,023	16,082	15,667	16,153	16,167	14,773	(15,85)	15,968	16,108	0,140
			JAS	204	16	39	33	11	15,982	15,513	15,516	15,508	15,582	15,320	15,350	15,052	14,855	15,146	15,503	14,922	15,354	15,377	0,023
			OND	185	17	40	31	11	16,112	15,099	14,473	15,157	15,612	15,161	15,445	16,114	15,641	16,32	16,439	15,752	15,610	15,500	-0,110
H_{coast}	18,25	-34,25	JFM	254	20	27	38	15	17,728	15,031	15,714	15,110	13,706	15,843	15,424	16,767	17,448	16,102	16,793	15,316	15,915	15,879	-0,036
			AMJ	210	20	36	35	10	16,583	15,666	16,224	15,030	14,418	14,824	15,254	16,328	16,103	16,735	(16,27)	(15,80)	15,769	15,472	-0,297
			JAS	195	15	30	40	16	(14,14)	14,231	15,222	15,146	14,870	15,032	15,229	15,096	15,293	15,220	15,164	14,649	14,941	15,044	0,103
			OND	294	21	26	37	16	14,693	13,291	13,743	13,854	13,734	13,774	15,399	15,484	14,235	14,005	14,337	14,530	14,257	14,346	0,089
H1°	17,75	-34,25	JFM	271	26	38	20	16	20,601	19,406	19,511	19,316	19,442	19,304	20,119	20,213	20,118	20,237	21,093	21,065	20,035	19,938	-0,097
			AMJ	161	26	34	22	18	19,220	17,400	17,114	16,362	16,730	16,876	17,765	17,668	18,015	17,942	18,550	17,585	17,602	17,364	-0,238
			JAS	209	26	31	25	17	16,376	16,283	16,145	16,413	16,405	15,876	16,653	16,578	16,051	16,067	15,730	16,062	16,220	16,225	0,005
			OND	239	23	28	25	25	18,237	17,386	17,523	17,551	17,96	17,729	18,084	17,380	19,262	19,443	18,337	18,287	18,098	18,024	-0,074
H_{coast}	18,75	-34,25	JFM	237	19	43	28	10	17,973	17,758	16,493	15,992	16,236	17,165	17,226	18,086	18,353	17,559	16,934	15,483	17,105	17,043	-0,062
			AMJ	309	20	26	36	18	13,682	14,640	14,339	13,894	14,110	15,128	14,815	14,926	14,748	14,631	14,485	14,629	14,502	14,549	0,047
			JAS	189	21	42	32	5	15,016	15,241	15,214	15,062	14,937	15,191	15,250	14,825	14,744	14,646	14,742	14,435	14,942	14,991	0,049
			OND	182	25	40	23	12	15,024	16,396	16,137	16,448	16,450	16,901	16,650	17,426	16,601	15,935	14,807	14,306	16,090	16,320	0,230
H1°	18,75	-34,75	JFM	131	28	35	33	4	20,583	18,553	19,195	20,052	18,845	20,209	20,528	20,458	20,818	20,783	(20,95)	(21,11)	20,173	20,011	-0,162
			AMJ	74	24	35	28	13	(17,32)	14,390	16,132	16,571	17,666	17,340	17,212	15,912	15,833	15,767	15,723	(16,98)	16,404	16,413	0,009
			JAS	66	26	41	29	5	(16,01)	15,456	15,852	15,86	15,794	16,124	16,488	16,310	(17,13)	16,415	(15,70)	(14,90)	16,003	15,955	-0,048
			OND	116	24	32	28	17	17,896	17,413	18,129	17,742	18,238	17,985	17,678	18,447	17,933	17,500	17,062	16,932	17,746	17,837	0,091
H1°	19,25	-34,75	JFM	167	27	27	39	7	20,303	18,174	18,866	18,36	18,374	18,298	18,892	18,253	18,056	17,907	18,813	19,720	18,668	18,530	-0,138
			AMJ	122	33	26	33	8	16,913	16,672	16,115	15,507	16,460	16,355	17,082	15,933	15,81	15,937	16,037	(17,070)	16,324	16,263	-0,061
			JAS	124	25	26	37	12	(15,60)	15,921	15,605	15,426	15,616	15,096	15,629	15,498	15,479	15,219	15,435	15,260	15,482	15,555	0,073
			OND	177	26	30	33	12	17,479	16,853	16,778	16,767	17,642	17,609	17,382	17,216	17,571	17,911	16,860	17,468	17,295	17,271	-0,024
H1.5°	19,25	-35,25	JFM	147	22	43	29	7	21,324	21,25	21,268	20,616	20,644	20,431	21,456	21,217	21,045	20,694	(21,47)	20,590	21,000	20,972	-0,028
			AMJ	80	15	55	24	6	18,900	(15,62)	18,038	17,804	17,636	18,009	18,031	17,966	17,367	18,135	(18,87)	17,76	17,845	17,833	-0,012
			JAS	83	24	39	27	11	(16,01)	16,478	16,488	15,939	16,35	16,105	16,411	16,612	16,66	16,808	15,583	15,54	16,249	16,296	0,047
			OND	142	25	30	26	19	18,220	18,469	18,182	18,402	18,439	19,104	18,608	17,994	18,001	17,901	18,449	18,04	18,317	18,315	-0,002
H1°	19,75	-35,25	JFM	116	17	33	37	13	21,083	21,124	21,073	21,216	20,486	21,017	20,211	21,038	20,723	20,636	20,094	20,130	20,736	20,791	0,055
			AMJ	78	10	43	29	18	(17,99)	18,377	16,645	16,684	18,077	18,640	17,702	17,918	17,088	16,843	17,943	17,598	17,625	17,711	0,086
			JAS	79	25	51	19	5	(15,97)	16,218	15,869	15,925	16,035	15,829	16,316	15,896	16,252	15,570	15,580	(15,77)	15,936	15,975	0,039
			OND	99	24	38	22	17	18,515	18,611	18,754	18,419	18,133	18,100	17,741	18,055	18,654	17,884	18,545	18,662	18,339	18,279	-0,060
H_{coast}	20,25	-34,75	JFM	86	20	29	34	18	(21,33)	21,138	(21,660)	21,176	20,511	21,542	21,691	21,288	20,773	20,138	21,218	21,530	21,167	20,980	-0,187
			AMJ	99	31	23	34	11	(18,70)	17,846	17,549	17,122	17,330	17,230	17,492	17,437	17,866	17,459	16,240	(17,47)	17,478	17,432	-0,046
			JAS	91	24	29	29	18	(15,19)	14,965	15,288	15,527	15,369	15,45	15,303	15,284	15,338	15,104	15,063	(15,42)	15,275	15,253	-0,022
			OND	109	20	28	35	17	(18,04)	17,395	17,906	17,527	17,19	18,398	18,595	18,074	18,745	18,656	18,587	18,135	18,104	18,057	-0,047
H1°	20,25	-35,25	JFM	77	27	40	21	12	20,770	20,983	21,086	21,202	21,366	21,031	20,991	20,923	20,94	20,92	20,435	20,602	20,937	21,074	0,137
			AMJ	129	18	49	26	7	(17,59)	18,130	18,188	17,473	17,860	17,570	17,639	18,425	18,039	18,845	17,872	17,060	17,891	17,899	0,008
			JAS	88	19	44	26	11	(15,70)	16,053	15,605	15,783	15,237	15,546	15,967	15,941	15,451	15,938	15,123	15,411	15,646	15,592	-0,054
			OND	116	25	35	21	18	18,263	18,285	17,478	17,796	17,934	18,393	18,898	19,061	18,526	18,276	17,950	18,220	18,257	18,095	-0,162
H1°	20,75	-34,75	JFM	61	27	33	24	16	(20,54)	21,820	21,042	20,391	20,757	21,484	21,627	21,814	21,580	20,657	21,348	(20,94)	21,167	21,142	-0,025
			AMJ	127	16	43	34	7	(17,93)	17,630	17,029	16,423	16,929	17,184	17,679	17,719	17,390	16,286	16,998	17,710	17,242	17,209	-0,033
			JAS	98	11	47	34	7	(15,56)	16,120	15,844	15,748	15,987	15,836	15,903	16,048	15,231	15,562	15,398	(15,24)	15,706	15,811	0,105
			OND	87	22	39	28	11	17,670	18,363	18,520	18,981	18,783	18,654	18,468	20,706	19,083	20,060	18,995	(18,16)	18,871	18,840	-0,031
H_{coast}	21,25	-34,75	JFM	53	23	40	19	17	(21,49)	21,329	21,735	21,004	20,900	19,989	20,738	20,763	21,467	21,188	20,920	(21,65)	21,098	21,064	-0,034
			AMJ	108	23	46	26	6	(17,32)	17,768	17,868	17,332	17,600	17,892	17,416	17,832	18,777	18,200	17,535	(16,87)	17,701	17,683	-0,018
			JAS	91	35	34	16	14	(16,03)	15,572	15,828	15,515	15,965	16,225	16,644	16,754	16,037	16,403	15,207	15,724	15,992	15,862	-0,130
			OND	61	24	46	22	8	(18,12)	18,169	18,905	18,26	18,442	18,549	18,001	17,872	17,933	17,995	17,700	(17,91)	18,155	18,236	0,081
H1°	22,25	-34,75	JFM	80	27	22	29	22	19,800	19,303	19,543	20,240	20,216	20,35	20,793	20,389	19,457	17,650	19,830	20,187	19,813	19,820	0,007
			AMJ	71	15	49	28	8	18,490	(16,870)	17,037	17,528	17,491	17,693	18,373	18,602	17,347	16,873	16,490	18,600	17,616	17,564	-0,052
			JAS	48	10	45	33	12	16,547	(16,595)	15,890	16,960	16,810	16,566	17,044	16,763	16,847	16,690	16,520	16,500	16,644	16,664	0,020
			OND	46	19	25	31	25	18,432	(17,859)	17,287	17,407	17,342	18,073	18,782	18,379	19,187	18,412	18,398	19,240	18,233	18,282	0,049
H1°	30,25	-31,25	JFM	208	14	29	31	26	25,267	25,182	25,190	24,990	25,509	25,945	25,525	25,699	25,228	24,961	25,301	25,284	25,340	25,338	-0,002
			AMJ	134	2	26	57	15	(22,75)	(22,65)	nodata	22,504	22,465	22,822	23,425	23,306	22,935	21,709	22,135	(22,44)		23,012	
			JAS	173	18	24	37	21	20,752	20,837	20,820	20,994	21,010	21,204	21,512	21,302	21,170	20,815	21,027	20,755	21,017	21,061	0,045
			OND	32	6	27	52	15	nodata	nodata	(22,09)	22,047	(23,30)	22,314	23,000	22,735	21,937	21,397	(21,14)	nodata		22,233	
H1°	31,25	-30,25	JFM	273	14	36	33	16	26,371	26,692	26,200	26,116	26,286	26,190	26,118	26,273	25,863	26,518	26,632	26,845	26,342	26,544	0,202
			AMJ	424	10	43	38	9	23,143	22,980	23,169	23,145	23,071	23,062	23,885	23,814	23,894	23,736	23,439	23,098	23,370	23,543	0,173
			JAS	199	9	44	37	11	20,975	20,670	20,948	20,984	21,292	21,52	21,576	21,258	20,999	20,843	20,973	21,014	21,088	21,276	0,188
			OND	108	2	58	38	2	nodata	(22,85)	(21,40)	21,805	22,991	23,095	22,614	22,191	21,550	(25,49)	(24,59)	(25,12)		22,687	
H_{coast}	31,25	-29,75	JFM	274	12	49	25	15	26,543	25,242	25,989	25,773	24,798	25,177	25,439	25,351	25,511	25,426	25,399	25,548	25,516	25,302	-0,214
			AMJ	276	8	54	23	15	22,565	21,240	22,525	23,124	23,324	23,328	23,236	23,060	23,198	22,945	22,673	22,985	22,850	23,069	0,219
			JAS	152	14	47	20	20	21,566	21,447	21,745	21,169	21,362	21,274	21,718	21,500	20,708	20,884	20,765	20,998	21,261	21,263	0,002
			OND	137	1	76	13	10	nodata	nodata	(22,17)	23,409	23,188	24,038	(24,63)	(23,13)	21,801	22,153	21,443	(20,60)		23,069	

Appendix 4 The standard deviation associated with the average of all available temperature data, and the standard deviation associated with the average of the the four seasonal climatological averages, at depths of 5, 50 and 100 m.