ASTRAL

*A*ll Atlantic Ocean **S**ustainable, Profi**T**able and **R**esilient **A**quacu**L**ture

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Evidence of accomplishment

Report

Contents

1 Summary

The main aim of task 5.1 is to identify the most immediate climate threats at ASTRAL's aquaculture sites, and along the Atlantic coast, using a combination of *in situ* observations and regionally optimized satellite data products. This is of great importance to ensure the sustained productivity of ASTRAL's IMTA value-chains as climate change affects the environmental conditions at the IMTA sites, which, in turn, could affect the organisms being cultured. Climate change induced environmental changes may lead to an IMTA site being less optimal for the productivity of specific organisms and more optimal for other organisms. It is therefore necessary to get an overview of changes in environmental conditions over the past several decades. Using this knowledge, we can better assess which environmental variables are most vulnerable to climate change and therefore may have the greatest impact on the organisms being cultured at ASTRAL's aquaculture sites.

Here we present results for climate trends in the Large Marine Ecosystems (LME) along the Atlantic coastline, as well as two regional studies (on the Southern Benguela Upwelling System and Beagle Channel) which are both important regions for ASTRAL IMTA sites. We perform the analysis in these relatively large regions to ensure the availability of climate-quality data. Climate trends occur on top of large natural variability and background noise due to short-term and/or local effects. Climate-quality data records thus need to cover a long enough temporal range (several decades), and have high enough measurement precision, to filter out the noise. Such data records are not available for the smaller regions around each individual IMTA-labs. However, the LMEs and two regional case studies are used because of their representativeness, and we are confident that climate trends identified for these larger regions are also valid locally at the IMTA sites.

Our analysis focusses on climate trends in sea surface temperature (SST), sea surface salinity (SSS), surface dissolved oxygen (O_2), chlorophyll-a, partial pressure of CO_2 (pCO_2), pH, and nitrate. We show that long-term trends exist in several climate related environmental variables, but that the limited data availability in some regions and for some variables, leads to large uncertainties around these trends and hence for the impacts these variables may have. To remedy the lack of *in situ* observational data, regionally optimized satellite data products have been developed for the Southern Benguela Upwelling System. Additionally, this report describes the invaluable efforts of ASTRAL to extend the available measurement data for the region around the (prospective) IMTA lab in the Beagle Channel. So far, data coverage is sparse here, and it is difficult to estimate climate-related trends in oceanic variables.

Our assessment shows that there is a clear long-term warming signal for the period 1957-2020 in all Large Marine Ecosystems associated with ASTRAL's IMTA sites. For the more recent period of 1980-2020, the calculated warming trend of 0.26 ± 0.05°C/decade for the Celtic-Biscay Shelf (surrounding ASTRAL's IMTA sites in Scotland and Ireland) is nearly twice as fast as the estimated global SST increase of 0.15 ± 0.04°C/decade (IPCC, 2019). The recent warming trend of 0.15 ± 0.04°C/decade of the South Brazil Shelf (adjacent to ASTRAL's IMTA in Brazil) is in line with the global SST-trend. Contrarily, the Patagonian Shelf (adjacent to ASTRAL's prospective IMTA in Argentina) and Benguela Current (adjacent to ASTRAL's IMTA in South Africa) experience the least warming of all 17 Atlantic LMEs with -0.01 ± 0.06°C/decade and 0.06 ± 0.05°C/decade, respectively. Our calculated SSS trends illustrate that SSS changes in our considered LMEs are so far small and are likely to not have a significant impact on IMTA-lab performance. We note, however, that the declining SSS-trend for the Patagonian Shelf recently accelerated, highlighting the need to monitor SSS at the prospective IMTA-lab in the Beagle Channel. A potential further acceleration might lead to a significant contribution of SSS to stratification changes. We detect no concerning O_2 trends for Celtic-Biscay Shelf, South Brazil Shelf or Patagonian Shelf. For the Benguela Current, we calculate a decreasing O_2 trend of 0.41 ± 0.17 mg L^{-1} for the period 1957-2020, which warrants close observation. Our results for nitrate reveal that the percentage of months represented by observations is less than 18% for each studied region. This challenges the veracity of our results and, therefore, we are unable to confidently identify trends for this variable. During the period 1980-2021, we find the strongest increases in pCO_2 and declines in pH for the South Brazil Shelf (93.97 ± 21.18 ppm and -0.11 ± 0.03 units, respectively) and Celtic-Biscay Shelf (91.64 ± 11.47 ppm and -0.11 ± 0.02 units, respectively). For the Benguela Current and the Patagonian Shelf we find a less pronounced pCO_2-increase and pH-decline (70.79 ± 14.18 ppm -0.07 ± 0.03 units, and 76.33 ± 14.01 ppm and -0.09 ± 0.02 units, respectively).

We note that our estimated trends give an Earth's system perspective into the vulnerability of ASTRAL's IMTA labs to climate change, i.e., we purely identify environmental changes and the speed of these changes. The vulnerability of an IMTA's production is not considered and is dependent on the sensitivity of the IMTA species to these environmental changes. Our report instead gives a first indication of the expected changes, which will help to create more resilient and productive IMTA value-chains. We are aware that there are many short-term (e.g., seasonal and interannual) and local environmental impacts, such as unusually heavy precipitation, drought, land run-off, which can affect the IMTAs more than long-term climate-induced trends. Studying such effects is not in the scope of this report. However, we want to stress that climate change happens on top of existing natural variability and acts to enhance extremes so that what was once a rare extreme event in the future might become a common feature.

2 Introduction

While weather describes the short-term atmospheric conditions over a specific region, climate is the weather of a specific region averaged over a long period of time. Since the industrial revolution in the mid-1800s, humans have begun to continuously emit large amounts of greenhouse gases. This causes global temperatures to rise, resulting in long-term changes to the climate. These long-term changes in the climate have already been noticed in the 1980s, leading to the establishment of the International Panel on Climate Change in 1988 by the United Nations Environment Programme (UN Environment) and the World Meteorological Organization (WMO) in 1988, with the goal to provide key input into the international negotiations to tackle climate change (Preface, IPCC, 1990). Since then, the impacts of climate change have become more noticeable and significant (IPCC, 2022).

More recently, it has become clear that climate change is starting to threaten the sustainability of food production systems, including aquaculture (IPCC, 2018; FAO, 2022). The effect of climate change on aquaculture varies depending on the region and its climatic zones, the production system, the cultured species and so forth (e.g., Bell et al., 2013; Barange et al., 2018). Some aquaculture systems are more suitable to adapt to changing conditions (Galappaththi et al., 2020). For example, some of the Integrated Multi-Trophic Aquaculture (IMTA) production systems in focus of ASTRAL, such as the abalone-Ulva IMTA in South Africa, are expected to be more resilient to a changing climate than monoculture (Osch et al., 2019) due to the oxygen production of the cultured seaweed, the ability of euryhaline species to tolerate wide ranges of salinity and of shellfish and seaweeds to tolerate large temperature variations (Ahmed and Glaser, 2016).

Despite certain advantages of IMTA value-chains in the face of climate change, IMTA labs can still be affected by climate change. Regionally, climate change induced changes in key variables for the IMTA production system can lead to these variables being out of the optimal physiological range of some the cultivated species but being more optimal for other cultivated species. In both cases, this will affect the production at the IMTA labs. In order to get first insights into some of the potential threats and benefits resulting from climate change, it is the goal of Task 5.1 to characterize emerging long-term environmental changes at a regional level in relation to climate change.

Specifically, it is the goal of this report to identify the most immediate climate changed induced changes at ASTRAL's aquaculture sites and along the Atlantic coast. Here, our approach is to collect quality controlled observational data for sea surface temperature (SST), sea surface salinity (SSS), surface dissolved oxygen, pCO_2, and surface nitrate at ASTRAL's IMTA labs and prospective sites, as well as on their adjacent areas, and to additionally calculate pH using pCO_2 and SSS where both are available. These data are then utilised to calculate trends in these key variables for the last 3-5 decades, if possible, given the availability of data. A special focus of our analysis is also set on the Southern Benguela Upwelling System in South Africa, where a set of regionally optimised remote sensing and *in situ* data products (including ocean colour, SST) are developed, made available and analysed. Based on these trend analyses for the Atlantic coast and the Southern Benguela Upwelling System, a first-order analysis will identify which variables are most sensitive to climate change and likely to have the greatest impacts on the IMTA sites.

Additionally, this report describes the invaluable efforts of ASTRAL to extend the available measurement data for the region around the (prospective) IMTA lab in the Beagle Channel. So far, data coverage is sparse here, and it is difficult to estimate climate-related trends in oceanic variables.

This report is organised as follows: Section 3: "Climate trends for Large Marine Ecosystems along the Atlantic Coast" focuses on climate trend in key oceanic variables (SST, SSS, dissolved oxygen, pCO_2, pH and nitrate) in Large Marine Ecosystems (LMEs) along the Atlantic Coast, with a specific focus on those LMEs that inhabit one of the IMTA labs, or the prospective IMTA lab, of ASTRAL. Section 4: "Climate trends for the Southern Benguela Upwelling System" focuses on the development of regionally optimized remote sensing datasets for SST and chlorophyll-a, as well as inter-annual and long-term climate trends for these variables, while Section 5: "Climate trends for the Beagle Channel" describes newly employed data collections and the problem of data sparsity. In Section 6: "The vulnerability of ASTRAL's IMTA labs to climate change", the results from Sections 3, 4 and 5 are summarised for each specific IMTA lab. Finally, Section 7 "Conclusions" summarises our findings and outlines the recommendations that we forward to Task 5.5 (Synthesis and monitoring recommendations).

3 Climate trends for Large Marine Ecosystems along the Atlantic Coast

This section focuses on climate trends in key oceanic variables (SST, SSS, dissolved oxygen, pCO_2, pH and nitrate) along the Atlantic Coast. We note that, due to the sparsity of data, it was not possible to determine climate trends without collating the available data into regions. Specifically, we have chosen

Large Marine Ecosystems for this goal. However, the sparse and collated data made it impossible to verify if a data point was an outlier due to a measurement error, sparse data or due to it being an extreme value. Therefore, out data analysis does not identify extreme values as originally planned for deliverable D5.1. We have instead performed a literature review on the occurrence of marine heat waves (MHWs) in the LMEs where there are IMTA-labs and have added this information to the newly estimated SST trends in Section 3.2.1.

3.1 Methods and data used for the trend estimation

3.1.1 Large Marine Ecosystems and collected observational data

We have analysed changes in Sea Surface Temperature (SST), Sea Surface Salinity (SSS), surface oxygen (O_2) and surface nitrate over the period 1957 to 2020, in addition to changes in surface pCO_2 and surface pH over the period 1980 to 2022 for the four Large Marine Ecosystems (LMEs) that include or are adjacent to an IMTA lab, or a prospective IMTA lab site (Table 1; Figure 1). We note that, for our results, "surface" corresponds to the first 11 meters of the water column. For SST, we extended our analysis to all seventeen LMEs of the Atlantic Ocean (their locations are displayed in Figure 1). The results of this extended analysis have been submitted to the Journal "Progress in Oceanography" where the manuscript ("Observation-based Sea Surface Temperature trends in Atlantic Large Marine Ecosystems") is currently under review.

***Table 1**. List of the LMEs whose climate trends we analyze within this report, and their position relative to ASTRAL's (prospective) IMTA labs.*

LME name	Acronym	Position relative to ASTRAL's (prospective) IMTA labs
South Brazil Shelf	SBZ	Adjacent to Rio Grande do Sul, Brazil
Patagonian Shelf	PAT	Adjacent to Beagle Channel (prospective IMTA lab), Argentina
Benguela Current	BEN	Adjacent to Buffeljags Abalone, South Africa
Celtic-Biscay Shelf	CELT	Surrounding Port-a-Bhuiltin, Scotland as well as Bertraghnoy Bay, Ireland

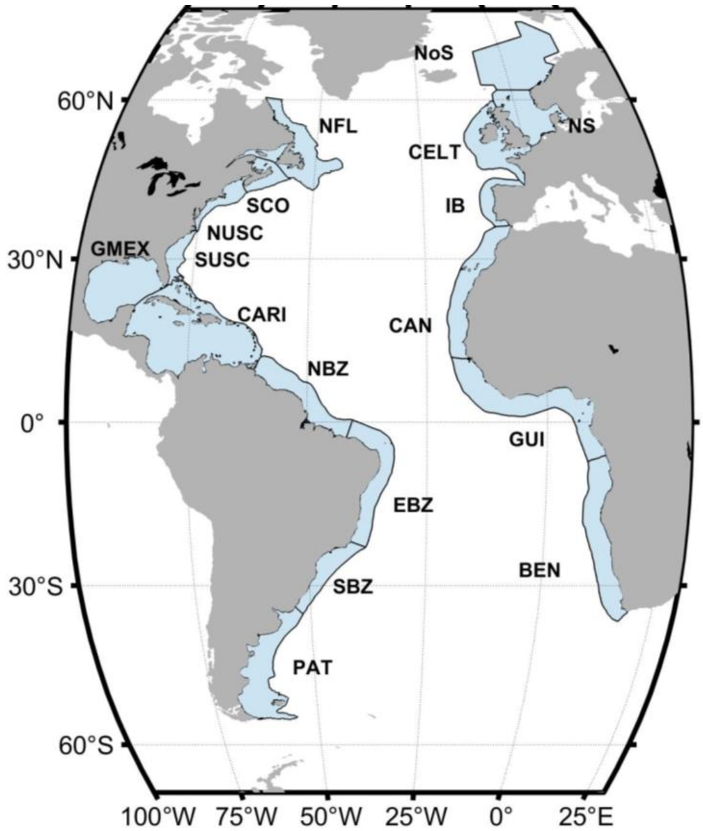

Figure 1. *Location of the 17 considered LMEs of the Atlantic ocean: Newfoundland-Labrador Shelf (NFL), Scotian Shelf (SCO), Northeast U.S. Continental Shelf (NUSC), Southeast U.S. Continental Shelf (SUSC), Gulf of Mexico (GMEX), Caribbean Sea (CARI), North Brazil Shelf (NBZ), East Brazil Shelf (EBZ), South Brazil Shelf (SBZ), Patagonian Shelf (PAT), Benguela Current (BEN), Guinea Current (GUI), Canary Current (CAN), Iberian Coastal (IB), Celtic-Biscay Shelf (CELT), North Sea (NS), Norwegian Sea (NoS).*

The *in situ* observational data collected for this deliverable comes from three main ocean data collections, which have been selected to maximize the size of our data collection over the period 1957-2020. Here, the World Ocean Database (Boyer et al., 2018) provides observations for the second half of the 20th century, while SOCAT version 2021 (Bakker et al., 2016) and GLODAPv2. 2021 (Lauvset et al., 2021) complete the dataset with observations mainly from the last two decades. We note, however, that observations of O_2 and Nitrate are not provided by the current version of SOCAT, whereas the World Ocean Database and GLODAPv2 do not provide observations of pCO_2. Yet, the newly updated version of the Surface Ocean Carbon Dioxide Atlas (SOCAT version 2022) provides one of the most complete open-source databases of pCO_2 and accounts for more than 40 million observations of pCO_2. As we calculate pH from, among others, observational data of pCO_2, both our calculation of pH and pCO_2 trends are solely based on observations from the SOCAT database. This leads to our trend estimates for pCO_2 and pH covering only the period 1980 to 2022.

Our data collection provides good data coverage in terms of SST and SSS observations, especially in the North Atlantic. However, the Brazilian coastlines suffer from less data coverage, though the level of data coverage is still acceptable. In our data collection, there is less observational data for pCO_2 available and much less observational data for O_2 and Nitrate. Among the four LMEs that include or are adjacent to an IMTA lab, 58% of months of the period 1957 to 2020 include at least one observation of O_2 data for the Benguela Current LME (BEN) while the other LMEs have less than 33% of months covered with observations of O_2 and Nitrate.

Table 2. *Total number of collected observations of SST, SSS, O_2, Nitrate and pCO_2, and of calculated pH values. The percentage of months that include observations is given in parentheses. Here, the reference period for SST, SSS, O_2 and Nitrate is 1957 to 2020 and 100% corresponds to 768 months or 64 years, while the reference period for pCO_2 and pH is 1980 to 2021, corresponding to 504 months or 42 years.*

	SST obs. (% months)	SSS obs. (% months)	O_2 obs. (% months)	nitrate obs. (% months)	pCO_2 obs. (% months)	pH (% months)
SBZ	27,620 (71.6%)	23,069 (43.2%)	4,454 (18.6%)	3,065 (10.2%)	18,108 (12%)	18,088 (11%)
PAT	171,168 (85.7%)	149,336 (64.8%)	2,394 (20.6%)	1,230 (10.0%)	153,470 (39%)	154,444 (38%)
BEN	95,573 (97.8%)	70,863 (81.0%)	20,158 (58.0%)	3,225 (15.6%)	42,450 (13%)	42,426 (12%)
CELT	719,157 (99.6%)	76,167 (88.54%)	10,731 (32,94%)	5,389 (17.32%)	718,333 (54%)	718,333 (48%)
17 LMEs [mill.]	8.21	5.94	0.22	0.08	7.10	7.10

3.1.2 Methods used for the trend estimation

Performing an analysis based on *in situ* observations has the advantage of providing real measurements of the climate states within each LME. However, it comes at the cost of irregular and infrequent sampling through time and space, which can induce a bias. This so-called “aliasing effect”, which has both a spatial and temporal dimension, therefore needs to be corrected. We overcome the two sides of the aliasing effect by using the methods of two peer-reviewed studies: Stendardo et al. (2012) and Fay and McKinley (2013). The method of Stendardo et al. (2012) corrects for the effect of spatial aliasing by adjusting available observations to the center of the considered region, while the method of Fay and McKinley (2013) removes the temporal dimension of the aliasing effect by mimicking the seasonal cycle with the fit of a sinusoidal curve to the available observations. This correction eliminates seasonal bias towards more frequently measured months. Here, the data is fitted to a curve of the form y = a + b*t + c*cos(2π*t+d), where "t" is the decimal year. We note that O_2 and nitrate data was too sparse to allow for a reasonable fit of the seasonal cycle such that the trend estimate for these variables is only based on a curve of the form y = a + b*t. Our reported trends correspond to the coefficient "b", which is given with a 95% confidence interval. We have calculated trends of SST, SSS, O_2 and nitrate in each LME over two time periods, 1957-2020 and 1980-2020. Thus, we are able to provide a long-term perspective for these climate-related variables but can also relate our results to more recent climate trends as, for example, the global ocean warming trend of 0.15 ± 0.04 ^{o}C/decade for 1980-2020 (Fox-Kemper et al., 2021). We note that trends for pCO_2 and pH are calculated for the time-period 1980-2022 only due to the available data.

3.2 Trend estimates

3.2.1 New estimates of long-term SST trends and their relation to marine heat waves

Changes in SST modulate spawning events and marine species abundances (Macleod et al., 2007; Halpern et al., 2008; Baird et al., 2009), and perhaps most importantly growth rates (e.g., Boltaña et al., 2017). Since 1850-1900, the global mean SST has increased by about 0.88^{o}C (possible range: 0.68 to 1.01^{o}C) with an evident acceleration of this warming since 1980, accounting for 0.60^{o}C (possible range: 0.44 to 0.74^{o}C) of this total sea surface warming (Fox-Kemper et al., 2021). The global warming imprint varies greatly from region to region, and some regions are experiencing larger thermal changes. As a consequence, temperature-driven shifts in fish populations have already been reported (Vollset et al., 2022; Pershing et al., 2015, Hastings et al., 2020). Hence, it is crucial to assess regional changes in SST to anticipate and foresee potential shifts in thermal conditions, leading to an environment being out of the optimal range for certain species while simultaneously entering the optimal thermal range for new organisms (Glibert et al., 2014; Baker-Austin et al., 2016; Collins et al., 2019).

Our calculated trends reveal that all 17 LMEs of the Atlantic show a significant warming trend for the period 1957-2020. Within the more recent time period (1980-2020), we find that these warming trends are accelerated in the North Atlantic and decelerated in the South Atlantic. The full report of these results ("Observation-based Sea Surface Temperature trends in Atlantic Large Marine Ecosystems") has been submitted to the scientific journal "*Progress in Oceanography"* and is currently under review.

When presenting our results, we classify the considered LMEs into five different warming categories based on those defined in the Transboundary Water Assessment Programme (IOC-UNEP and UNESCO, 2016): “cooling”: < 0ºC/decade, “slow”: 0 - 0.07ºC/decade, “moderate”: 0.07 – 0.14ºC/decade, “fast”: 0.14 – 0.21ºC/decade and “superfast”: > 0.21ºC/decade. Due to trend-uncertainties caused by sparse observational data, most of the calculated results have a large range in their warming rates such that they fit into several warming categories. Figure 2 shows these results for the four LMEs that include or are adjacent to ASTRAL’s IMTA labs. While all four regions show a clear long-term warming from 1957 to 2020 (CELT: 0.15 ± 0.03°C/decade; BEN: 0.10 ± 0.03°C/decade; SBZ: 0.15 ± 0.04°C/decade; PAT: 0.07 ± 0.04°C/decade), the results start to diverge in the more recent time-period (1980 to 2020 with CELT: 0.26 ± 0.05°C/decade; BEN: 0.06 ± 0.05°C/decade; SBZ: 0.13 ± 0.07°C/decade; PAT: -0.01 ± 0.06°C/decade). While the South Brazil Shelf (SBZ) experiences a slow-to-fast warming in line with the estimated global SST increase of 0.15 ± 0.04ºC/decade between 1980 and 2020 (IPCC, 2019), the Celtic-Biscay Shelf (CELT) shows a concerning acceleration of its warming trend resulting in a warming trend that is nearly twice as fast as the global average. This is consistent with the warming trend identified for this region by Alheit et al. (2014) between the mid-1980s and 2010. Contrarily, the Patagonian Shelf (PAT) and Benguela Current (BEN) experience the least warming of all 17 Atlantic LMEs. We note that the Benguela Current is characterized by important nearshore upwelling activities, which have been increasing over the past decades (Santos et al., 2012; Varela et al., 2015). This induces large cooling areas nearshore (Sweijd and Smit, 2020) that act against the global increase in temperatures. These findings are consistent with our calculated weakening of the warming in the Benguela Current (BEN) (Figure 2). Cooling trends identified offshore South Africa since the 1990s associated with increased wind-driven upwelling systems (Blamey et al., 2015), have been reported to generate a local shift of species (Mead et al., 2013).

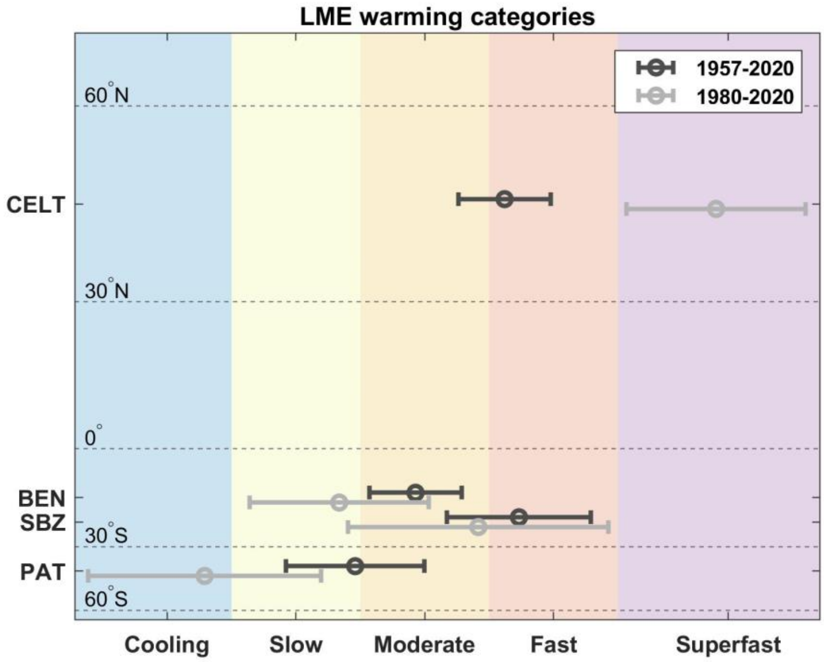

Figure 2. *Calculated warming rates for the LMEs that include or are adjacent to ASTRAL's IMTA labs. The categories follow those defined in the Transboundary Water Assessment Programme (IOC-UNEP and UNESCO, 2016), i.e., "cooling" (below 0°C), "slow" (0-0.07°C/decade), "moderate" (0.07-0.14°C/decade), "fast" (0.14-0.21°C/decade) and "superfast" (above 0.21°C/decade).*

While the long-term increase in SSTs is undoubtably changing marine living conditions, rapid increase in SSTs associated with marine heat waves (MHWs) often have a more severe impact on aquatic species as they occur on shorter timescales (Gaines and Denny, 1993). MHWs are defined as prolonged periods of anomalously warm seawater, typically a period of over 5 days where the seawater is warmer than the 90th percentile of the 30-year historical baseline (Hodbay et al., 2016). The impacts of MHWs on fisheries and aquaculture can be quite significant and increase mortality and generate shifts in marine populations (Oliver et al., 2017; Mills et al., 2012). An irreversible loss of kelp forest has, for example, been reported south of Australia after a MHW in 2015/16 (Thomsen et al., 2019). Since 1870, about 57% of the global ocean surface has experienced MHWs (Tanaka and van Houtan, 2022). Between 1925 and 2016, the duration of these events has increased by over 50% (Oliver et al., 2018). As global warming continues, the likelihood of these events is also increasing. Therefore, it is crucial to understand how MHWs have impacted the surface ocean temperature until now and how they are projected to continue.

Oliver et al. (2018) used observation-based data reanalysis to identify MHWs over the period 1982-2016. Their results highlight that the Benguela Current (BEN) and South Brazil Shelf (SBZ) have experienced some of the strongest MHWs with SST anomalies of up to 5°C relative to the 1983-2012 climatological period. These strong and rapid variations in SSTs overshoot the warming induced by the long-term trends since 1980 (see above) indicating that MHWs are the dominant factor for climate induced SST-variations in both regions. Additionally, when comparing the periods 1982-1998 and 2000-2016, MHWs have become more frequent in these LMEs (by 5 to 6 counts per year) and more intense (up to 2.5°C warmer), suggesting an increasing risk for aquatic organisms with time. Contrarily, both the Patagonian Shelf (PAT) and the Celtic-Biscay Shelf (CELT) experienced a decrease of MHW-intensity between 1982-1998 and 2000-2016 and show a maximum warming of up to 2°C during MHWs in the period 1982-2016 (Olivier et al., 2018). Here, both the long-term SST-trend and MHWs lead to climate induced SST-variations of similar order.

3.2.2 New estimates of long-term SSS trends

Sea surface salinity (SSS) is a physical ocean parameter that reflects the amount of freshwater entering at the sea surface (e.g., from ice melting/formation, river runoff, air-sea exchange, and horizontal/vertical advection), which is commonly perceived to inhibit the vertical mixing of the water column, thus hindering the supply of nutrients to the surface (although runoff can also add nutrients to the surface layer). This variable strongly contributes to the global ocean circulation and Earth's climate (Siedler et al., 2001), and as part of the carbonate system, provides crucial information on ocean biogeochemistry (Land et al., 2015, 2019; Fine et al., 2017; Carter et al., 2021). Assessing long-term changes in SSS can help to foresee changes in ecosystems living conditions, not only in terms of salinity, but also in other parameters of the carbonate system that may be assessed through it.

Our results indicate only relatively small long-term trends in SSS in the four LMEs that include or are adjacent to an IMTA lab (Figure 3). Over both periods of time, our calculated SSS trends are very small for both the Celtic-Biscay Shelf (1957-2020: -0.013 ± 0.006 psu/decade; 1980-2020: 0.010 ± 0.012 psu/decade) and Benguela Current (1957-2020: 0.008 ± 0.005 psu/decade; 1980-2020: -0.007 ± 0.01 psu/decade). We are confident in these results as the data covers more than 80% of months for these two regions (Table 2). In the South Brazil Shelf (SBZ), the SSS-trend is positive over both periods (1957-2020: 0.048 ± 0.017 psu/decade; 1980-2020: 0.060 ± 0.030 psu/decade), although these results must be considered with care due to the relatively low data coverage in this region. The Patagonian Shelf is the only region showing a significantly decreasing trend in SSS for both periods of time (1957-2020: -0.077 ± 0.014 psu/decade; 1980-2020: -0.124 ± 0.021 psu/decade) and an acceleration of this negative trend over the more recent decades.

Yamaguchi and Suga (2019) show for the period 1960-2017 that changes that occurred in sea salinity had generally a relatively low impact on ocean stratification as compared to changes that occurred in sea temperature. Our calculated SSS trends show that SSS changes in our considered LMEs are so far small and will hence not have a significant impact on ocean stratification. We note, however, that the recent acceleration of the SSS-trend for the Patagonian Shelf is an indication that this trend might further accelerate with climate change and become an important contributor to stratification changes. Therefore, we highly recommend monitoring SSS at the adjacent possible IMTA site in the Beagle channel.

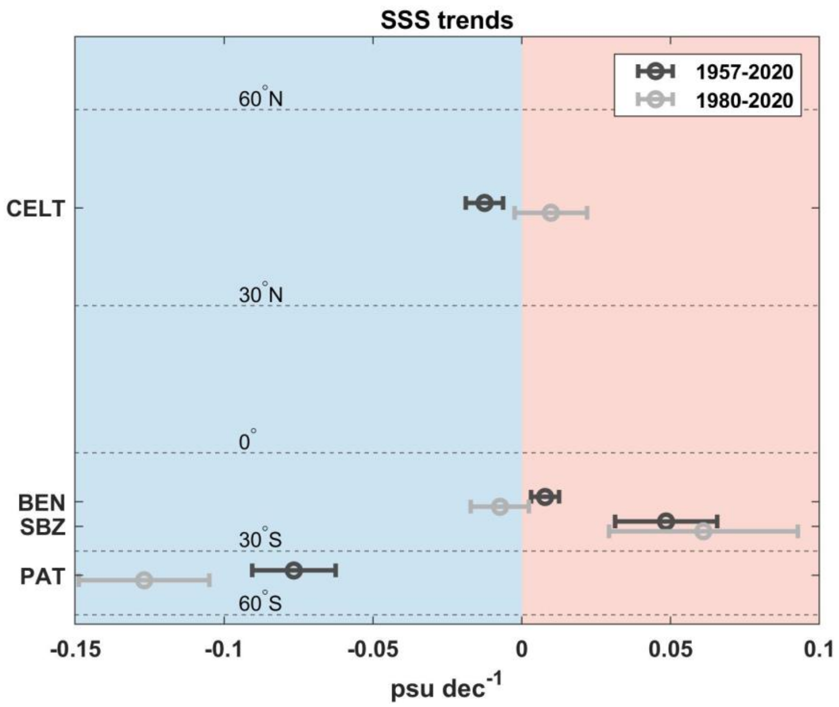

Figure 3. *Calculated SSS trends for the LMEs that include or are adjacent to IMTA labs.*

3.2.3 New estimates of long-term O_2 trends

The ongoing global warming affects the oxygen levels in the ocean through many processes. It directly reduces the solubility of oxygen in the water, alters the ventilation of oxygen by modifying the global ocean circulation, and changes the rates of absorption from organisms (Bindoff et al., 2019). A study investigating O_2 observations from 1958 to 2015 shows a widespread negative O_2 trend that begins to emerge from the envelope of interannual variations in the 1990s (Ito et al., 2017). This negative trend is projected to accelerate towards the end of the 21st century and further reduce the oxygen levels in the ocean, though there are regional differences (IPCC, 2019). Dissolved oxygen is one of the main factors that affect fish metabolism, welfare and growth (Claireaux and Lagardere, 1999). Fish growth and mortality are both directly and indirectly impacted by oxygen levels through hypoxia (Burnett, 1997) and stress generated when oxygen concentrations are outside the optimal organism's range leading to a vulnerability to diseases (Meyer, 1970; Snieszko, 1974). Hence, assessing O_2 trends in the physical environments of ASTRAL's IMTA labs is crucial.

Our calculations for O_2 in the South Brazil Shelf (SBZ) and Patagonian Shelf (PAT) show increasing trends with 0.74 ± 0.34 mg L^{-1} (0.12 ± 0.05 mg L^{-1}/decade) and 0.03 ± 0.28 mg L^{-1} (0.005 ± 0.044 mg L^{-1}/decade) for the period 1957-2020, respectively. However, due to the data sparsity in these two regions (Table 2), especially after 1990 (Figure 4), these results must be considered with care. For the Celtic-Biscay Shelf (CELT), our calculations show an overall O_2 decrease with a total trend of -0.17 ± 0.16 mg L^{-1} or -0.027 ± 0.025 mg L^{-1}/decade, but only 33% of the months considered have observations available. Only the Benguela Current (BEN) provides sufficient data coverage, with even a few years fully represented by observations (Figure 4, green stars). Here, we obtain a decreasing O_2 trend of -0.41 ± 0.17 mg L^{-1} during the period 1957-2020, corresponding to -0.064 ± 0.027 mg L^{-1}/decade. A study from Ito et al. (2017) for the period 1958 to 2017 confirms a noticeably declining trend in the Benguela Current (BEN), a small negative trend in the Celtic-Biscay Shelf (CELT), a negligible trend in the Patagonian Shelf (PAT) and a noticeably increasing trend in the South Brazil Shelf (SBZ) for O_2 at 100m depth. Due to the noticeable negative trend in O_2, we recommend monitoring the O_2 levels in the Benguela Current (BEN). We note that, in the other three LMEs, the O_2 levels remain relatively high, typically above 6 mg L^{-1}, which is well above the requirements for most aquatic species to thrive and we detect no concerning O_2 trends.

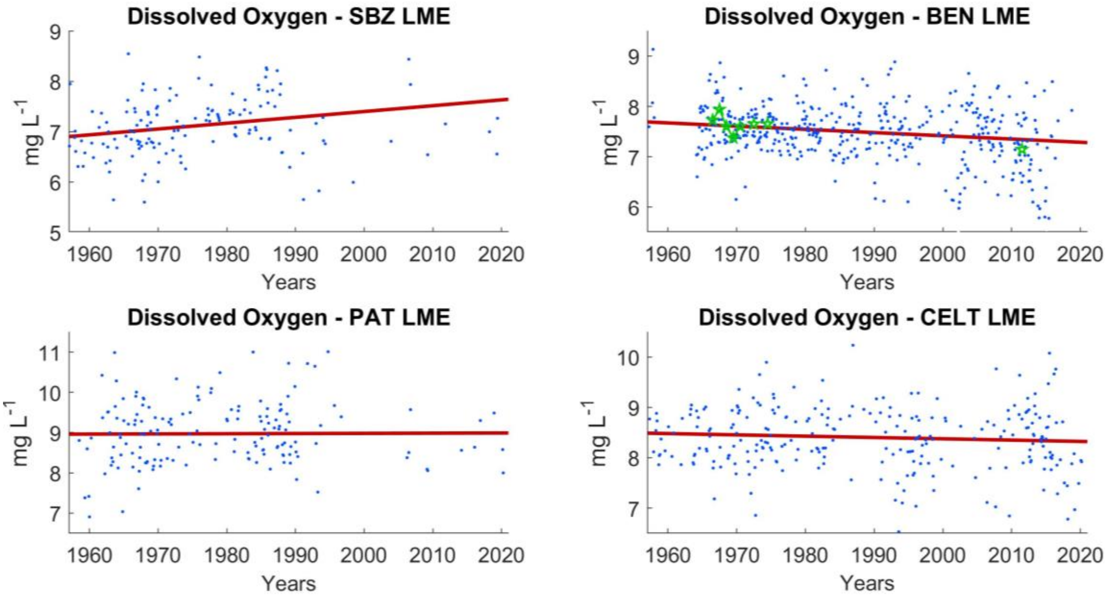

Figure 4. *Oxygen trends (red lines) based on monthly averages (blue dots). The green stars represent annual averages when all 12 months are represented by observations.*

3.2.4 New estimates of long-term nitrate trends

Nutrients such as phosphate, nitrate, silicate and iron, are required in high amounts for biological growth and development of phytoplankton and macroalgae (e.g., kelp). In coastal regions, recycling of phosphate is generally higher relative to nitrate (Howarth, 1988), which leads the ecosystems of these regions to often be nitrogen limited (Conley, 2000). Several studies show that nitrate is a critical limiting factor for kelp growth, especially in the North Atlantic (e.g., Schmid et al., 2020; Strong-Wright and Taylor, 2022). Increasing nearshore human activities such as agriculture and residential developments increases the input in nutrients from fertilizer and wastewater to groundwater, which is partly released to coastal surface waters (Valiela et al., 1990). The ongoing global warming also impacts the supply of nutrients at the surface through changes in stratification of the water column (Bindoff et al., 2019). These perturbations of the natural nutrient cycle have been recognized to play a key role in the frequency and intensity of Harmful Algal Blooms (HABs). As HABs have disastrous consequences causing death of fish, mammals, birds and even humans, monitoring the evolution of nitrate concentration in coastal regions is essential to understand the immediate impacts of human activities on primary production (phytoplankton). We note that monitoring of nitrate alone is not sufficient to predict and possibly prevent HAB episodes, but that it is also necessary to monitor phosphate and silicate (see Deliverable D5.2 of ASTRAL, “Biotic and abiotic conditions favouring HAB development and associated future risks”).

Our results for nitrate reveal that the percentage of months represented by observations is less than 18% for each studied region. This challenges the veracity of our results and we are therefore unable to confidently identify trends for this variable. Here, we detect an urgent need for more monitoring efforts. This would also encourage more studies on climate trends in nitrate, which are currently rare. We note, however, that our calculated decreasing trend in Nitrate in the Benguela Current (BEN) is consistent with its increasing trend in SST as these two variables are inversely correlated (Waldron and Probyn, 1992) in that region.

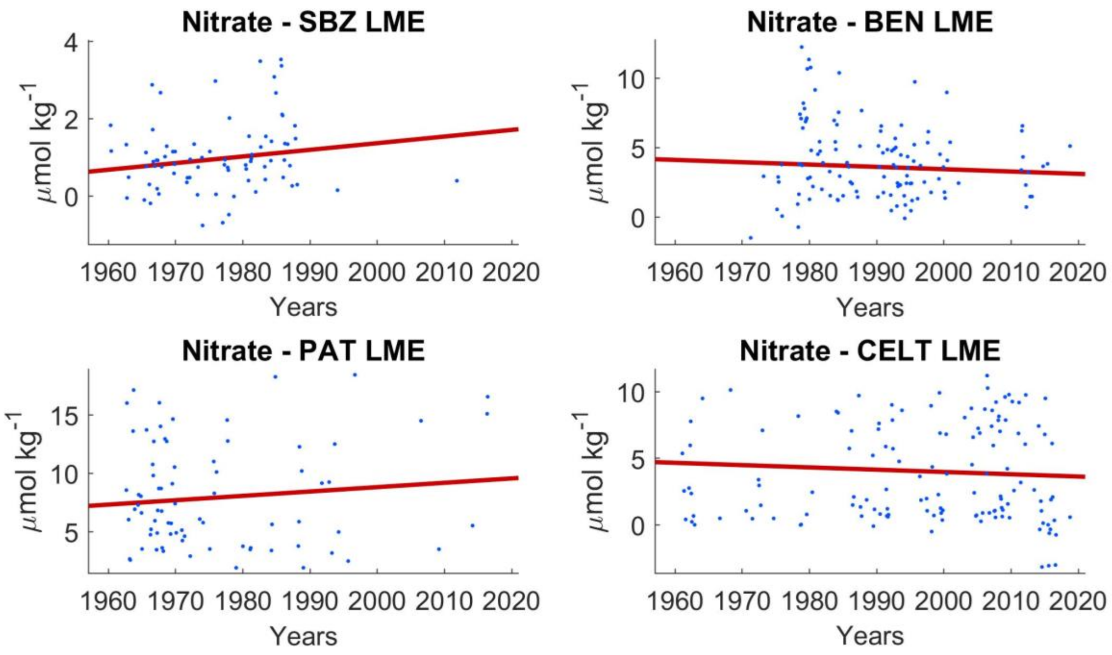

Figure 5. *Nitrate trends (red lines) based on monthly averages (blue dots). Due to data sparsity, we have no confidence in these trend-results.*

3.2.5 New estimates of long-term trends in pCO_2 and pH

In 2021 the global atmospheric CO_2 concentration reached ~416 ppm (http://www.esrl.noaa.gov/gmd/ccgg/trends/weekly.html), nearly double its pre-industrial value of ~280ppm in 1800. More than half of this increase has occurred since the 1980s. Human activities are mostly responsible for the atmospheric CO_2 accumulation by releasing tons of CO_2 into the atmosphere every year, ultimately driving the ongoing global warming and climate change. The ocean plays a crucial role in reducing this atmospheric CO_2 accumulation by currently absorbing ~25% of the anthropogenic emissions (Le Quéré et al., 2010), thus moderating global warming. However, this ocean uptake of anthropogenic carbon modifies the ocean chemical properties by increasing the partial pressure of CO_2 (pCO_2) at the ocean surface (Sabine et al., 2013). The ocean pCO_2 is an essential component of the carbonate system which can be used to retrieve other chemical properties of the waters like pH using the equations of the carbonate system (Millero, 1979). As more and more CO_2 is absorbed by the ocean and oceanic pCO_2 increases, pH declines in a process commonly referred to as "Ocean Acidification" (Haugan and Drange, 1996; Caldeira and Wickett, 2003). Ocean Acidification impacts e.g. marine calcifier species by making it more difficult to build shells and skeletal structures (e.g., corals, calcified algae, bivalves, crustaceans and echinoderms) and fish by having to perform more acid–base regulation which comes at some biological cost to the organism (Heuer and Grosell, 2014, Madhulika and Ngasotter, 2021, Gattuso et al., 2015, AMAP, 2018). According to the E.U. Copernicus Marine Service information (https://marine.copernicus.eu/), the current value of pH for the global surface ocean is estimated to be around 8.05. This is about 0.05 lower than in 1985, which represents a 15% more acid ocean and a global pH trend of about -0.0016 ± 0.0006 yr^{-1}. Monitoring and assessing the evolution of surface pCO_2 and pH is crucial to estimate the rate at which the ocean is taking up carbon and acidifying. Here, we analyzed the pCO_2 and pH trends since 1980. We note that our pH values are not based on direct observational estimates but are calculated with the CO2SYSv3 routine in Matlab (Lewis and Wallace, 1998; Sharp et al., 2020) as a function of pCO_2 (collected from SOCAT version 2022) and an SSS-based estimate of total alkalinity (Millero, 1997).

For surface pCO_2, our results show a clear increase in all four LMEs during the 1980-2021 period with pCO_2 trends of 76.33 ± 14.01 and 91.64 ± 11.47 ppm for Patagonian Shelf (PAT) and Celtic-Biscay Shelf (CELT), corresponding to an increase rate of about 18.17 ± 3.34 and 21.81 ± 2.73 ppm per decade. Although the data coverage in the Patagonian Shelf and the Celtic-Biscay Shelf (CELT) is not optimal before the year 2000, we are still confident in the results for the longer period because pCO_2 trend estimates starting 2000 provide comparable results (16.30 ± 4.41 ppm per decade for the Patagonian Shelf and 23.13 ± 4.37 ppm per decade in the Celtic-Biscay Shelf). The observational pCO_2 data for the South Brazil Shelf (SBZ) and Benguela Current (BEN) are even sparser such that our calculated trends for both regions are very uncertain (93.97 ± 21.18 ppm and 70.79 ± 14.18 ppm, respectively). Nevertheless, we note that our results indicate that the pCO_2 trends of Celtic-Biscay Shelf (CELT) and South Brazil Shelf (SBZ) are higher than those of the Patagonian Shelf (PAT) and Benguela Current (BEN). This is in line with a previous study using climate models (Tjiputra et al., 2014). Although the authors analyzed a slightly different period (1970-2011), they found stronger pCO_2 trends in the regions corresponding to the Celtic-Biscay Shelf (CELT) and South Brazil Shelf (SBZ) as compared to the Patagonian Shelf (PAT) and Benguela Current (BEN). We note that the South Brazil Shelf (SBZ) and Benguela Current (BEN) show higher initial values of pCO_2 than Patagonian Shelf (PAT) and Celtic-

Biscay Shelf (CELT). To conclude, we find the highest pCO_2 values with the strongest trend in the South Brazil Shelf (SBZ) yielding the highest present-day pCO_2 values.

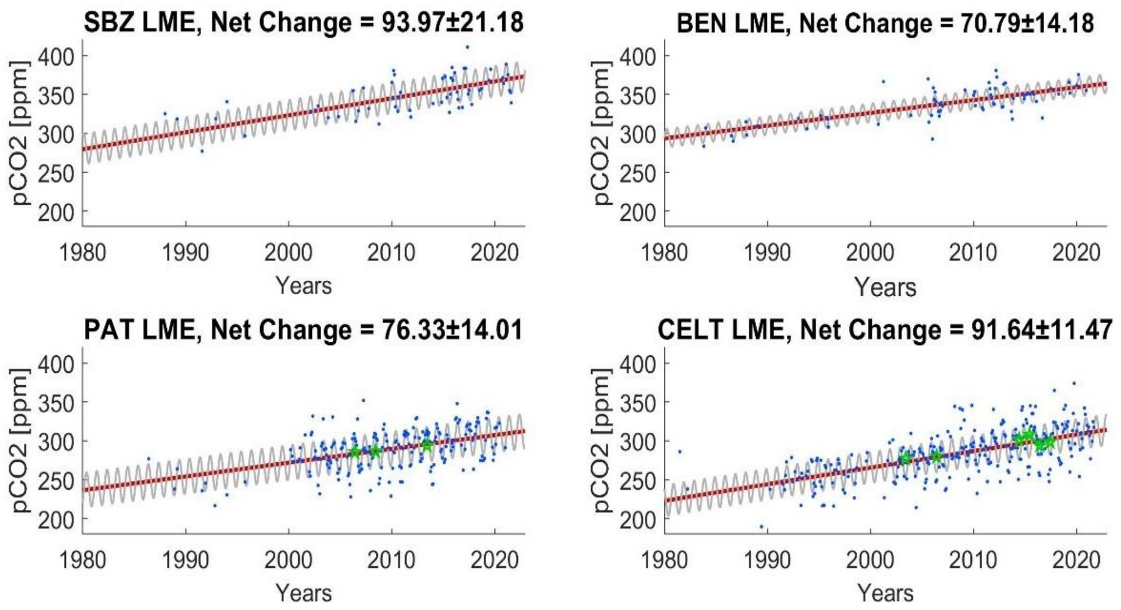

Figure 6*: pCO_2 trends (red lines) based on monthly averages (blue dots). The green stars represent annual averages when all 12 months are represented by observations. The harmonic component of the curve fit, which is mimicking the seasonal cycle, is shown as a solid grey line.*

Our results for surface pH are consistent with the observed increase in pCO_2. We find the strongest declines in pH for the South Brazil Shelf (-0.11 ± 0.03, corresponding to -0.0026 ± 0.007 units per year) and Celtic-Biscay Shelf (-0.11 ± 0.02, corresponding to -0.0026 ± 0.005 units per year). For the Benguela Current (BEN) and the Patagonian Shelf (PAT) we find a less strong pH-decline (-0.07 ± 0.03, corresponding to -0.0016 ± 0.007 units per year, and -0.09 ± 0.02, corresponding to -0.0021 ± 0.005 units per year, respectively). These trends are in line with the estimated global decline of pH between 1985 and 2020 estimated at -0.0016 ± 0.005 units per year (https://marine.copernicus.eu/). We note, however, that the uncertainties around those trends remain large.). We note, however, that the uncertainties around those trends remain large.

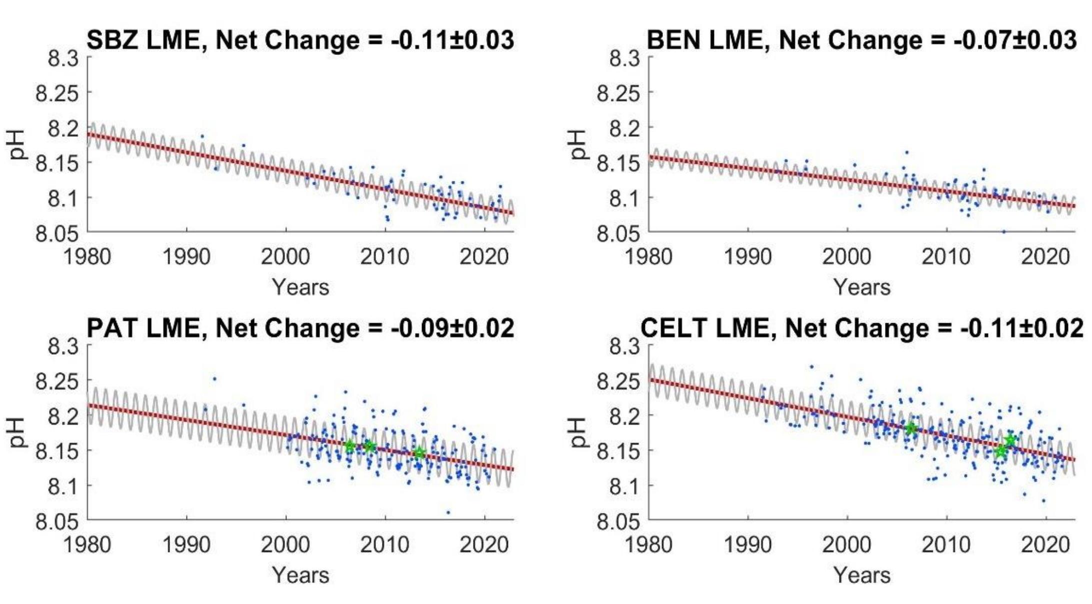

Figure 7: *pH trends (red lines) based on monthly averages (blue dots). The green stars represent annual averages when all 12 months are represented by observations. The harmonic component of the curve fit, which is mimicking the seasonal cycle, is shown as a solid grey line.*

4 Climate trends for the Southern Benguela Upwelling System

IMTA-locations are spatially very confined such that the spatial resolution of global earth system models is too coarse to properly resolve the dynamics of this specific location, while *in situ* observations in these locations are too sparse to be able to confidently determine climate trends and associated changes. This leads to the fact that our estimate of climate trends along the Atlantic coast with *in situ* observations (see Section 3) is based on relatively large areas. The availability of marine earth observation products (i.e., satellite products) represents the opportunity to examine recent inter-decadal coastal trends at high spatio-temporal resolution. As satellite data are only available since the 80s, it is still relatively challenging to use them for a long-term trend analysis as shorter time-series are more sensitive to decadal variability (Storto et al., 2019). Yet, the high-resolution is clearly of advantage when wanting to assess climate change induced environmental changes directly at the IMTA-locations. Here, we present a case study of regionally optimized satellite products for the Southern Benguela Upwelling System. This option has high value for ASTRAL's IMTA lab in South Africa as it allows to assess quality-controlled near-shore environmental change in its close surroundings. We note that similar applications in the environments surrounding the other IMTA labs of ASTRAL would be highly beneficial. Furthermore, the availability of a regionally accurate and validated high resolution satellite-derived SST product played a key role in identifying which reanalysis model and interpolated datasets are suitable for the examination of climate trends within the southern Benguela over longer time scales.

4.1 Methods

4.1.1 Regionally optimised Sea Surface Temperature and Chlorophyll-a products

High spatial resolution sea surface temperature data (~1 km) from satellites are susceptible to data gaps that result from the removal of pixels due to the presence of clouds and due to the removal of pixels mis-identified as clouds. These data gaps produce significant sampling errors when considering monthly or weekly binned data for the characterization of upwelling ecosystems from single sensor data. To resolve the temporal variability associated with upwelling events on the South African west and south coasts, it is thus necessary to combine information so that the highest possible valid pixel retrieval per sampling period is achieved. Therefore, we developed a sea surface temperature cloud flagging procedure that reduced cloud influence for data from the satellite instrument MODIS. The final product retains more sea surface pixels and retains the strong gradients associated with the edge of upwelling plumes. To improve the retrieval of valid SST data, a statistical method was employed whereby each pixel was tested for validity by confirming that the absolute value of the difference between the measured SST value and a 5-day average of all available MODIS SST pixels at that location was within 1.5 times its climatology monthly standard deviation. Except for upwelling locations, the Benguela optimized SST compared well to High Resolution Sea Surface Temperature Multiscale Ultra-high resolution (GHRSST MUR; Chin et al., 2010; Liu et al., 2017) data with absolute biases < 0.1 ^{o}C over most of the shelf and oceanic region. As it was demonstrated by Carr et al. (2021) that satellite SST products have the highest variance between products in dynamic regions such as upwelling ones, we used *in situ* data to validate our product in upwelling locations. Here, we compared a daily 5x5 pixel average extraction to *in situ* SST data at Oudekraal in the Cape Peninsula upwelling cell and found that the upwelling frequency observed in the Benguela optimized MODIS SST dataset is well-correlated with recorded *in situ* events.

Our regionally optimized satellite product for Chlorophyll-a (Chl-a) concentrations is based on the Benguela optimized switching algorithm developed for measurements of the satellite instruments MERIS and OLCI (Smith et al., 2018), which shows superior performance in the Southern Benguela compared to any single algorithm. However, due to the four-year gap between measurements of MERIS and OLCI, we also developed a regional switching algorithm for the MODIS instrument. The resultant Chl-a concentration retrievals were compared to *in situ* retrievals used by Smith et al. (2018), showing superior performance in the Southern Benguela compared to any single algorithm when compared to *in situ* data. These retrievals are thus suitable to accurately track high biomass values associated with harmful algal blooms.

4.1.2 Evaluation of reanalysis products for the determination of long-term trends

Previous studies have demonstrated a strong disagreement between satellite-derived SST products during the summer months at upwelling locations in the Southern Benguela Upwelling System (Smit et al., 2013; Carr et al., 2021). Global ocean reanalysis products, where various satellite and *in situ* ocean observations are assimilated into an ocean general circulation model, have the potential to provide more accurate estimates of the ocean state and its variability relative to estimates based solely on hydrodynamic models that exclude data assimilation (Verezemskaya et al., 2021). Here we evaluate four reanalysis products for the period 2000 to 2014. These are the Mercator Ocean's Global Reanalysis (GLORYS), Commonwealth Scientific and Industrial Research Organization's Bluelink Reanalysis (BRAN) and the Fleet Numerical Meteorology and Oceanography Centre's global Hybrid Coordinate Ocean Model (HYCOM) (Russo et al., 2022).

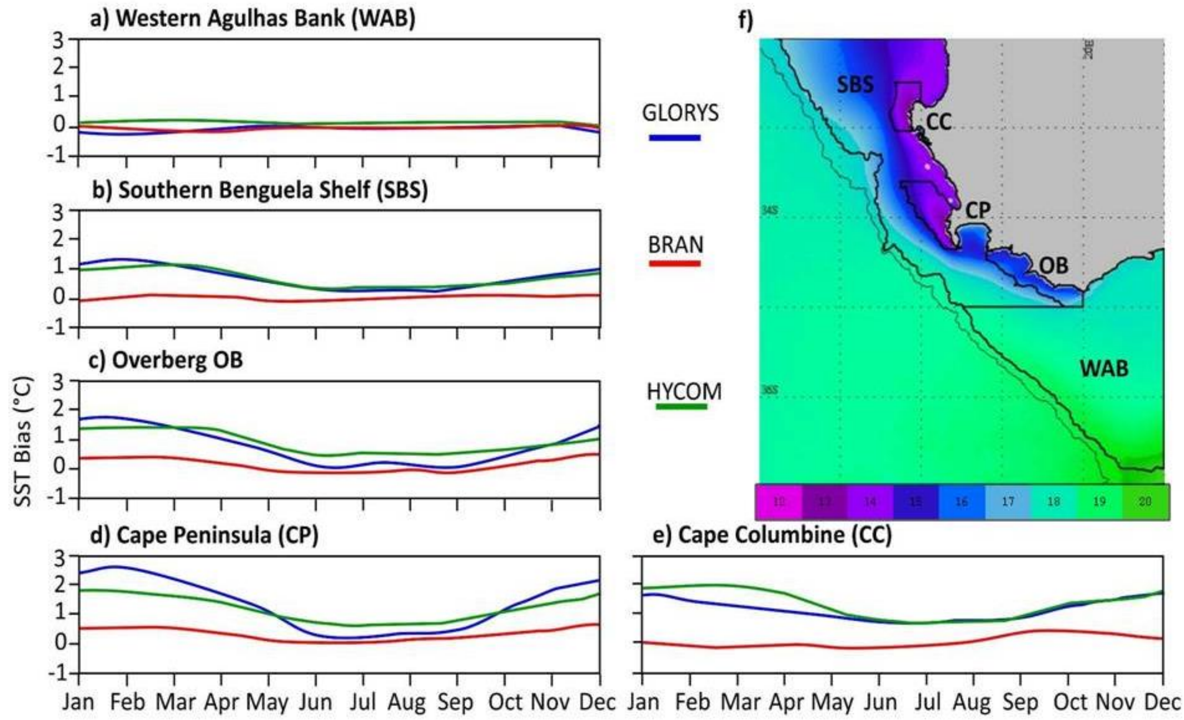

Figure 8. *A comparison of GLORYS, BRAN and HYCOM to our regionally optimized high resolution (1km) satellite sea surface temperature. Panels a)-e) illustrate the difference in SST between all three reanalysis products and the optimized SST in different locations and panel f) shows a summer climatology SST image, constructed from optimized SST product, representing the south-east Atlantic and southern Benguela Upwelling system.*

A comparison of these reanalysis products to the CSIR's regionally optimized high resolution (1km) satellite sea surface temperature allows for a closer investigation of shelf scale surface dynamics represented within the models. Since the regional SST product is not assimilated into the examined models, it serves as independent verification of model surface SST. We note that all three models reproduce the seasonal cycle accurately, with almost zero bias throughout the year over the Western Agulhas Bank (WAB); it is only over the Southern Benguela Shelf (SBS) between 32° and 35°S (Figure 8) where BRAN performs exceptionally well, whereas both HYCOM and GLORYS under-represent the seasonal upwelling signal. This relates to the fact that the mixed layer depth of GLORYS and HYCOM is deeper than what is observed *in situ* in the Southern Benguela Shelf and this results in the upwelled water having warmer temperatures. BRAN represents the mixed layer depth much more accurately, contributing to its good representation of coastal SSTs.

4.2 Results

4.2.1 Identifying upwelling events and high biomass frequency

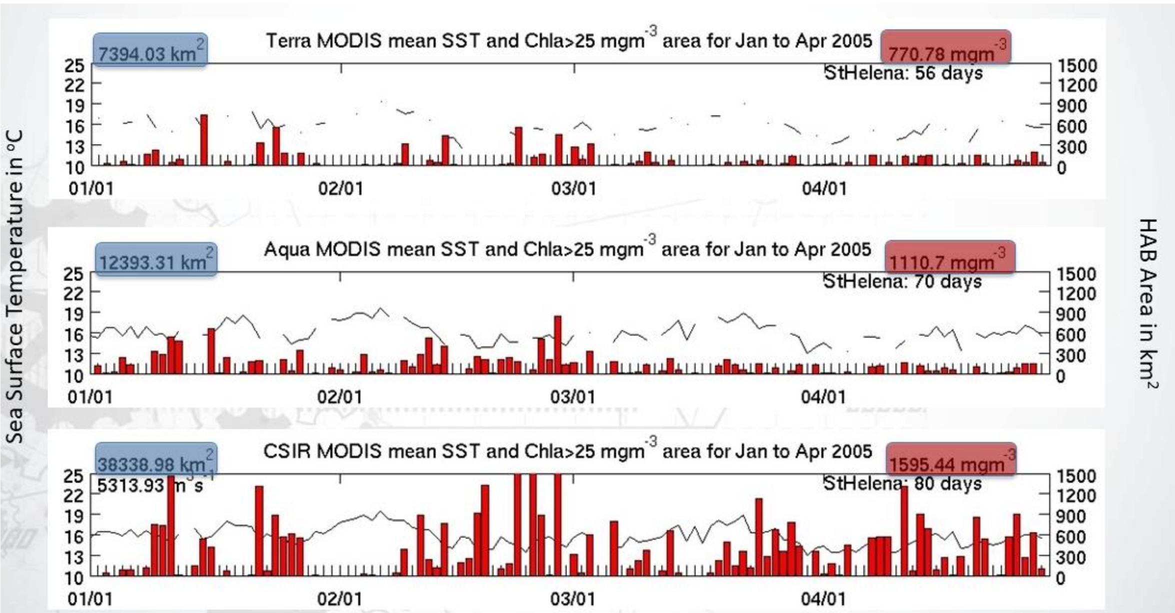

Figure 9 *All three panels show the daily area covered by pixels where the Chl-a concentration exceed 25 mgm^{-3} (red bars) and the associated mean SST (broken black line) within St Helena Bay for the summer and early autumn of 2005. Cumulative bloom areas for the season are represented in the blue boxes and the cumulative median Chl-a concentration for the season are represented in red boxes.*

When comparing the optimized MODIS SST and Chl-a product to the standard Terra Modis and Aqua MODIS products, it becomes apparent that the CSIR-MODIS product represents a considerable increase in spatial and temporal resolution for both variables (Figure 9). The regionally optimized products capture large areas of high biomass pixels at a higher frequency, and record bloom events on 80 of the 121 days and illustrate a more complete SST time series.

4.2.2 Long term trend analysis in the Southern Benguela

Using the BRAN dataset, which is available as daily fields for the period January 1993 to December 2019 at 1/10° (~11 km) resolution, and our newly developed regionally optimized 1 km dataset we examine the surface SST trends within the southern Benguela Upwelling System over a 15-year period (Figure 10). Additionally, we also compare the results to the recently updated and extended version of the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) product (Good et al., 2020), developed by the UK MetOffice.

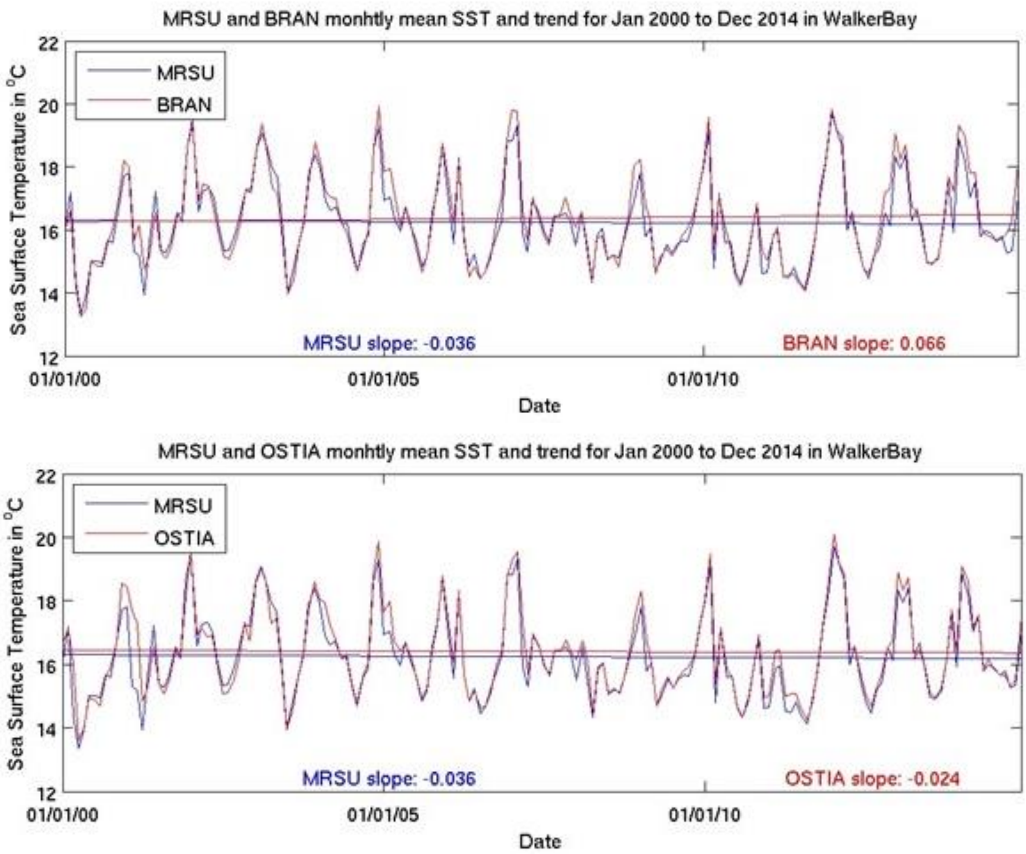

Figure 10: *The upper panel shows a comparison of our regional optimised data product (MRSU) and BRAN monthly mean SST data extracted within Walker Bay for the period 2000 to 2014. The lower panel shows the same dataset, except for that the MRSU-product is compared to the OSTIA-product.*

Monthly anomalies generated from the monthly climatologies of BRAN, OSTIA and our regionally optimised SST product are strongly correlated with an almost zero bias. While a cooling trend is evident in the regionally optimised SST dataset for the period, as well as in the OSTIA product, BRAN shows a warming trend. We note, however, that the SST-trends of all three products are small, resulting in an SST trend of -0.026°C/decade (regionally optimised product), -0.017°C/decade (OSTIA) or 0.047°C/decade (BRAN), such that all three trend-estimates are way below the estimated global SST increase of 0.15 ± 0.04°C/decade between 1980 and 2020 (IPCC, 2019). Similar results were found at key upwelling and retention zones along the southern Benguela Upwelling System (not shown). The results do indicate that the general intra- and interannual SST variability are well represented by BRAN, although the amplitude of upwelling events could be under-represented. Since the OSTIA dataset covers an extensive period (1981 to the present), it might prove to be the ideal product for examining not only climate trends in SST in the southern Benguela System, but also variability in upwelling event frequency and intensity within a 40-year period. We note that a 15-year time series is too short for interpreting climate-related trends.

5 Climate trends for the Beagle Channel

5.1 Climate-related variables in Beagle Channel, past and present

Climate change is evident in Argentinean Patagonia, as in the rest of the world. Air temperature has increased by over 0.5°C in the last 60 years (Gutiérrez et al., 2021; Iturbide et al., 2021) and climate models predict that it will continue to increase and reach *ca.*+3°C by 2100. Nevertheless, according to the last IPCC report (Gutierrez et al., 2021; Iturbide et al. 2021), there is limited data or literature on the Southern Patagonia region and therefore observed changes, modelling and related trend estimates are of low confidence. In fact, the short time span of *in situ* data collection results is insufficient for climate trends analysis. This highlights the need for long-term monitoring programs and data acquisition in the region.

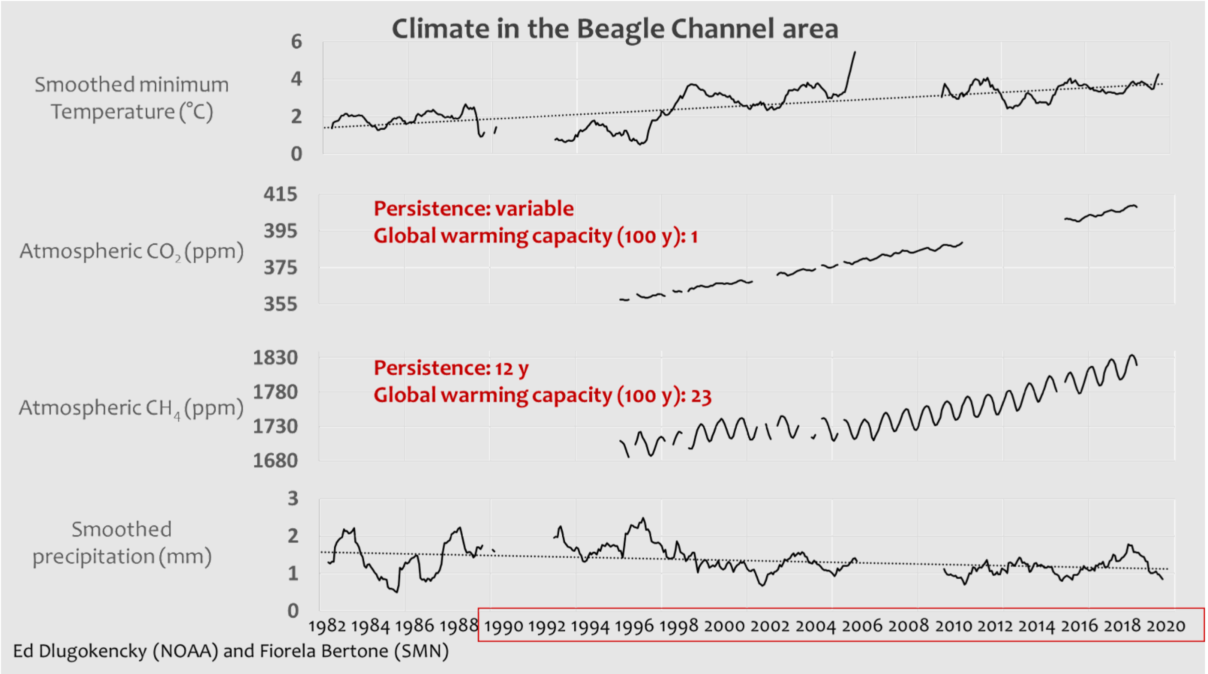

Figure 11. *Changes in minimum air temperature (°C), atmospheric CO_2 and CH_4 and precipitation (mm) for the Beagle Channel area in the last 40 years. Data sources: Ed Dlugokencky (NOAA) and Fiorela Bertone (National Meteorological Service)*

As evidenced in Figure 11, there is a lack of continuity in the environmental-meteorological data, which renders the estimation of long-term trends difficult. The available data does, however, show that in the Beagle Channel, the minimum air temperature has increased *ca.* 2°C in the last 40 years (Argentinian National Meteorological Service). Figure 12 shows that the available *in situ* SST data are also limited in this region.

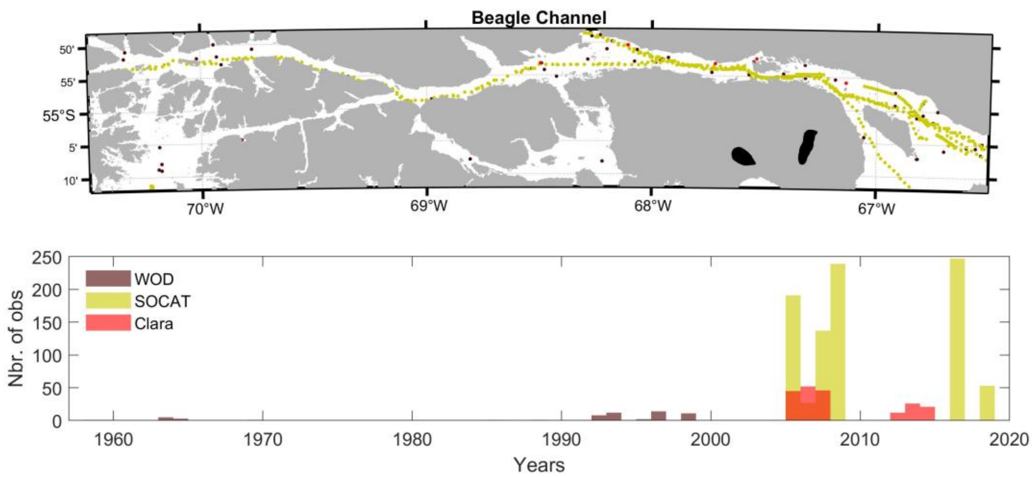

Figure 12. *Distribution of SST observation data in the Beagle channel. The illustrated data set gathers the observations from the World Ocean Database (WOD), SOCAT version 2021 and unpublished, locally collected data.*

5.2 *In situ* data registration: moorings

Figure 13. *Illustration of the locations of ASTRAL's measurement sites in the Beagle Channel.*

Within ASTRAL, we have begun to monitor water temperature, conductivity, salinity and light (PAR) at the site which has potential to be used for IMTA production. In detail, two lines carrying an array of sensors for temperature, conductivity and light were deployed at the mouth and inlet of Brown Bay (Figure 13). These sensor lines are continuously monitored by fishermen of Almanza Port from the coast and by personnel of the Secretary of Fisheries of the Province, who clean the sensors periodically, check the conditions of the moors, rope and the extent of fouling. In addition to recording environmental parameters in the Bay, a sensor (HOBO Water Level (13 ft) Data Logger - U20L-04) was placed to record temperature and water level in the Almanza River, which is the main freshwater outflow to the Bay. The registration of environmental variables is carried out in collaboration with the activities of WP2, but some preliminary results are presented here.

The sensor line inside Brown Bay (54°51'47.06"S; 67°30'29.76"W) was fitted with two sensors for conductivity and temperature, and two sensors for temperature only (Figure 14). The line with the sensors was deployed at a water depth of 20 m, hanging from a mussel raft as shown in Figure 14.

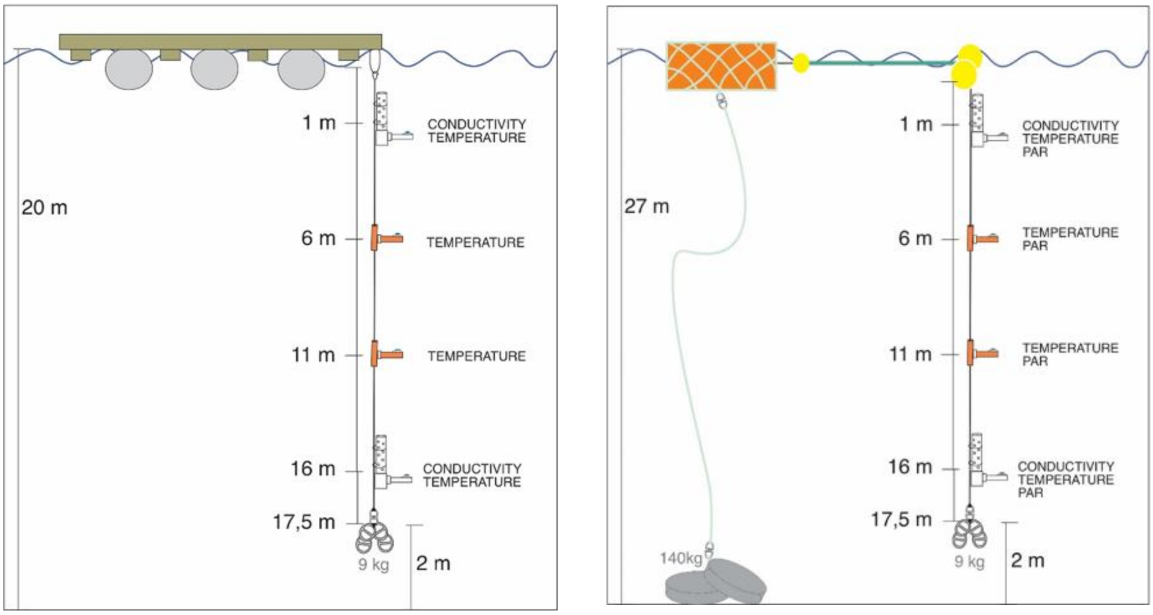

Figure 14: *Left panel: Line of sensors attached to a mussel raft inside Brown Bay (54°51'47.06"S; 67°30'29.76"W). Right panel: Line of sensors mooring with a double-buoys system out of Brown Bay (54°52'23.60"S 67°32'36.71"W).*

The system deployed at the mouth of Brown Bay (54°52'23.60"S 67°32'36.71"W) was designed by CONICET. It consisted of a fixed-line moored at a water depth of 27 m and has a weight of 140 kg attached to a rectangular Styrofoam buoy (80x40x40 cm). A plastic pipe of 2 m connects this buoy to two circular hard plastic buoys from where the sensor line was fixed (Figure 14). In this way, the line rises and falls following the tide behavior, recording the data at the same depth from the surface. This line was fitted with two sensors for conductivity and temperature and four sensors for light and temperature. The light sensors were fixed to ensure that they remain parallel to the surface of the water. The tow hitch on top of the conductivity sensor's protective housing and the threaded tube where the light sensors attached allowed for easy retrieval and facilitated work with the sensors.

Almanza River is the nearest freshwater inlet to Brown Bay. For this area, there is no previous data recorded about its flow dynamics and temperature. Therefore, a temperature and water level sensor was deployed and data is recovered or supervised monthly. In addition, manual measurements of the flow were made with a current meter to allow the data obtained by the sensor to be transformed later into flow data.

5.2.1 Preliminary observational results

Up to the beginning of June 2022, we have already recorded *ca.* 6 months of continuous data. The mooring "inside BB" started recording on the 23rd of November 2021, while the mooring at "mouth BB" was deployed on the 1st of December 2021. The water level sensor, located in the Almanza River, was the first sensor to be deployed (October 2021).

For both moorings, the temperature is recorded at four different depths (Figure 15). Observations of temperature range so far between 6.4 and 12.5°C, with generally higher values recorded from the "inside BB" than for the "mouth BB" mooring.

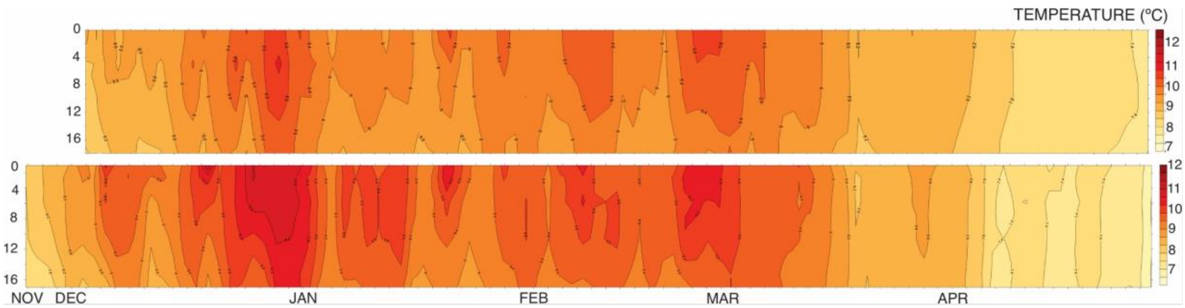

Figure 15. *Water column temperature (°C) records from Nov 2021 to Apr 2022. Upper panel: data for the "mouth Brown Bay" mooring, lower panel: data for the "inside Brown Bay" mooring.*

Salinity (S) was recorded at two depths at both moorings (Figure 16). For both moorings, "inside BB" (30.3 ppt) and "mouth BB" (30.6 ppt), salinity maxima were recorded at the beginning of the recording period, in November and December 2021, respectively.

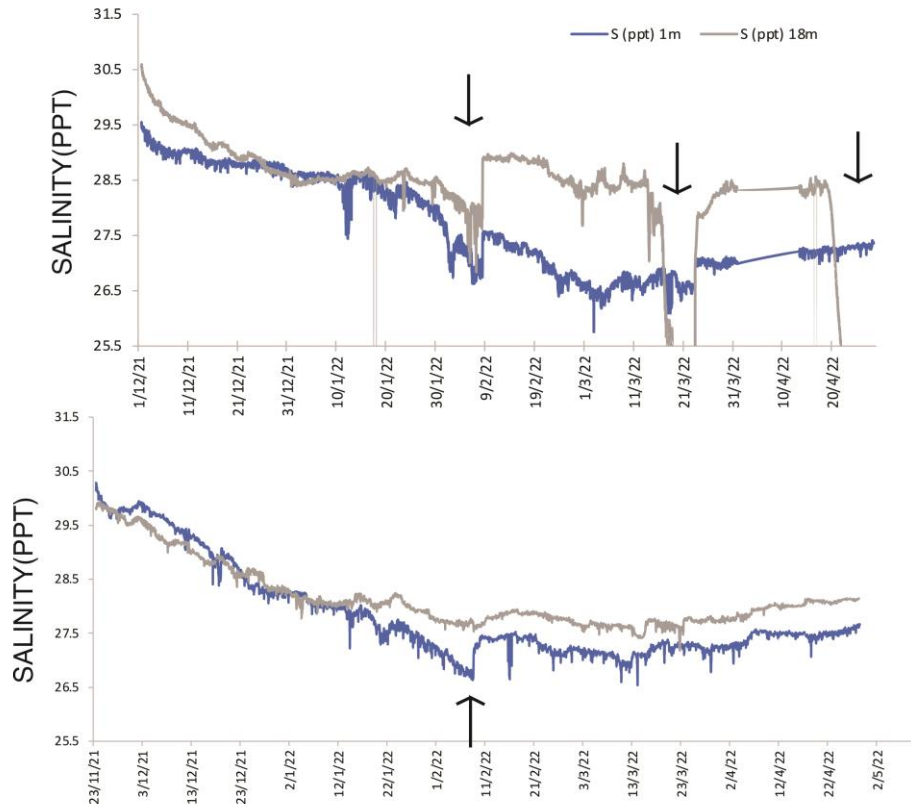

Figure 16. *Salinity (ppt) records in the water column from November 2021 to April 2022. Upper panel: data for "mouth Brown Bay" mooring, lower panel: data for "inside Brown Bay" mooring. Grey, near bottom (ca. 17 m) sensor. Blue, subsurface (1 m) sensor. Black arrows indicate potential fouling affecting our salinity estimation.*

These are the first 6 months of continuous S and T data for the region, which are very important for understanding its freshwater inputs (together with the water level probe in Almanza River, see below) and stratification. Additionally, circulation models have recently been developed for the region (Cucco et al., 2022). Therefore, with time and continuous data recovery, a more complete dynamical description on the possible IMTA site will be obtained. We note that after analysing the S data, we realised that fouling during spring-summer can be intense on the chosen measurement site, therefore *in situ* calibration with an external CTD is crucial for a more accurate salinity determination. Therefore, periodical (weekly) cleaning and supervising of the sensors, has been performed since June 2022.

PAR (irradiance) values measured at 1 m and 11 m were used to calculate the diffuse attenuation of photosynthetic active radiation (K_d, a measure commonly used to quantitatively assess the light availability). These K_d estimations were performed for all PAR-measured periods and changes in the optical conditions of the water column (up to 11m) could be seen. Nevertheless, the PAR sensor located at 16m failed during the first acquisition period and was broken with no solution in December 2021. Moreover, when we went to recover the data on February 2022, the 6m PAR sensor was broken, and measurements only reached mid-January 2022 (Figure 18). Both sensors were replaced in the next campaign, in July 2022.

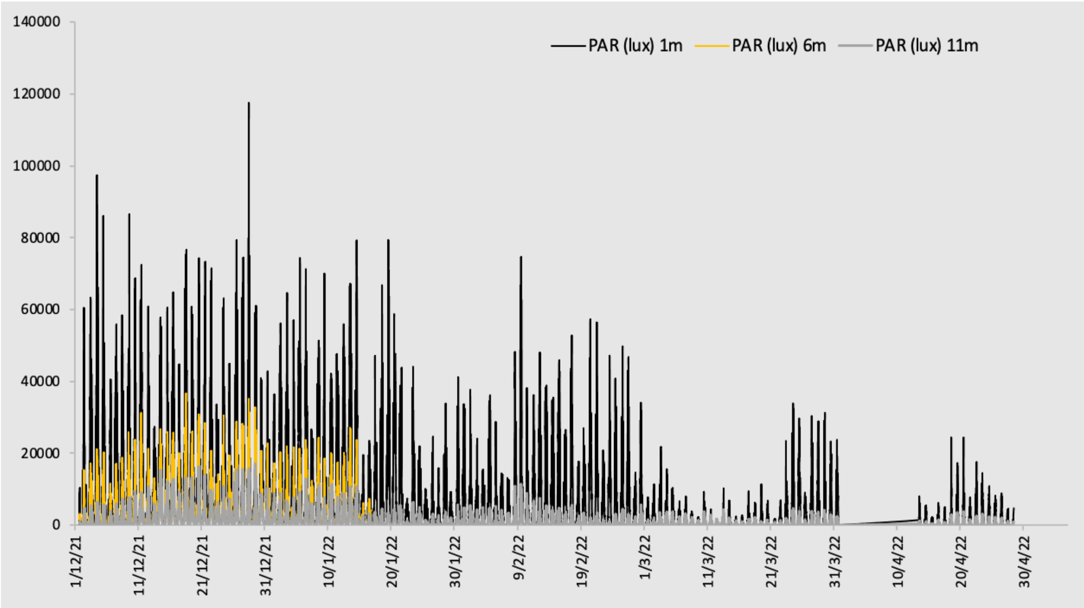

Figure 17. *PAR readings at the different depths on "Mouth Brown Bay" mooring, for all sampled periods.*

Almanza River's water level was registered as pressure (KPa) and measurements of flow speed and river depth were also recorded. Here, we only present the pressure data (Figure 18), nevertheless the rest of the parameters will be available soon. Water temperature was also recorded by the sensor, showing the highest values, as expected, during the austral summer months of January through to March.

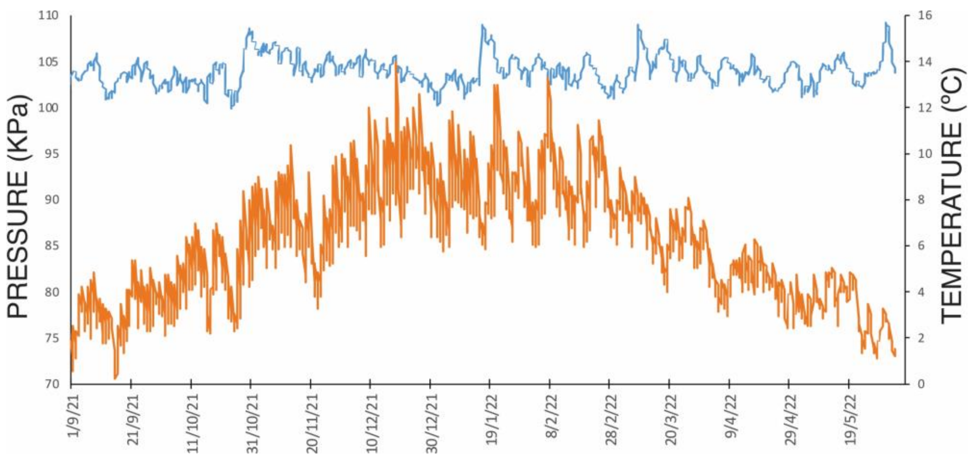

Figure 18. *Water level (pressure, in blue) and temperature records (in orange) for Almanza Bay from Oct 2021 to Apr 2022.*

5.3 Trend estimates

No trends could be estimated for key oceanic variables in the Beagle Channel. Nevertheless, climate change is evident from the increase observed in the minimum air temperature in the area; suggesting that extreme events and other global change related processes will affect this area (Moreau et al., 2014; Nahuelhual et al., 2019; Helbling et al., 2022).

6 The vulnerability of ASTRAL's IMTA sites to climate change

We note that our calculated trends give an Earth's system perspective into the vulnerability of ASTRAL's IMTA labs to climate change, i.e. we purely identify environmental changes and the speed of these changes. The vulnerability of an IMTA's production to these environmental changes is not considered and is dependent on the sensitivity of the IMTA species to these environmental changes. Our results give a first indication of the expected changes, which will help to create more sustainable IMTA value-chains.

6.1 IMTA Lab Scotland and IMTA Lab Ireland

Our climate trend estimates identify that the Large Marine Ecosystem surroundings ASTRAL's IMTAs in Ireland and Scotland (the Celtic-Biscay Shelf) is very vulnerable to climate change (in terms of our selected variables). It experiences:

- a clear long-term warming (1957-2020)
- an alarming warming acceleration during 1980-2020 with a "superfast" trend of 0.26 ± 0.05°C/decade
- only small trends in salinity
- data sparsity does not allow for a confident trend estimate in oxygen, but our estimated trend of -0.41 ± 0.17 mg L^{-1} during the period 1957-2020 is in line with literature (Ito et al., 2017)
- no confident trends in nitrate can be estimated due to data sparsity
- a strong increase in pCO_2 and a strong decline in pH during the period 1980-2021 (91.64 ± 11.47 ppm and -0.11 ± 0.02 units).

6.2 IMTA Lab South Africa

Our climate trend estimates identify that the Large Marine Ecosystem adjacent to ASTRAL's IMTA in South Africa (the Benguela Current) is vulnerable to climate change (in terms of our selected variables). It experiences:

- a clear long-term warming trend of 0.10 ± 0.03°C/decade (1957-2020), categorized as "moderate"
- a deceleration of the warming resulting in a trend of 0.06 ± 0.05°C/decade for 1980-2020
- only small trends in salinity
- a decreasing O_2 trend of -0.41 ± 0.17 mg L^{-1} during the period 1957-2020
- No confident trends in nitrate can be estimated due to the data sparsity
- A less strong pCO_2-increase and pH-decline (70.79 ± 14.18 ppm and -0.07 ± 0.03 units) between 1980 to 2021

6.3 IMTA Lab Brazil

Our climate trend estimates identify that the Large Marine Ecosystem adjacent to ASTRAL's IMTAs Rio Grande do Sul (South Brazil Shelf) is vulnerable to climate change (in terms of our selected variables). It experiences:

- a clear long-term warming trend of 0.15 ± 0.04°C/decade (1957-2020)
- a warming trend of 0.13 ± 0.07°C/decade between 1980 and 2020 in line with the estimated global SST increase of 0.15 ± 0.04°C/decade
- insignificant trends in salinity
- an increasing trend in O_2 of 0.74 ± 0.34 mg L^{-1} for the period 1957-2020, respectively. Due to the data sparsity, these results must be considered with care but a study from Ito and co-authors (Ito et al., 2017) confirms the increasing trend
- No confident trends in nitrate can be estimated due to data sparsity
- a strong increase in pCO_2 and decline in pH (93.97 ± 21.18 ppm and -0.11 ± 0.03 units) between 1980 to 2021

6.4 Future IMTA Lab Argentina

Even though climate change affects all ecosystems on Earth, our climate trend estimates identify that the Large Marine Ecosystem adjacent to ASTRAL's IMTAs in Argentina (Patagonian Shelf) seems to be weakly affected by climate change (in terms of our selected variables). It experiences:

- a clear long-term warming trend of 0.07 ± 0.04°C/decade (1957-2020)
- signs of a warming deceleration and possibly even a cooling trend of -0.01 ± 0.06°C/decade for 1980-2020
- a significantly decreasing trend in SSS for both periods of time (1957-2020: -0.077 ± 0.014 psu/decade; 1980-2020: -0.124 ± 0.021 psu/decade) that is accelerating with time

- an increasing trend in O_2 of 0.03 ± 0.28 mg L^{-1} for the period 1957-2020, respectively. Due to the data sparsity, these results must be considered with care but a study from Ito and co-authors (2017) confirms the negligible trend
- No confident trend in nitrate can be estimated due to data sparsity
- a less strong pCO_2-increase and pH-decline (76.33 ± 14.01 ppm and -0.09 ± 0.02 units, respectively) for the period 1980-2021

This is one of the regions on Earth with the least amount of observed data. New data acquired in the frame of ASTRAL will allow for further insight into oceanographic conditions, which are the most needed. To aid this, an initiative from the Argentinian National Ministry of Science is further constructing a series of lander-type devices to be placed along the Argentinian coast, including one in the Beagle Channel. This network (ROMA, in Spanish: Red de Observatorios Marinos Argentinos) will further contribute to fill current gaps in data coverage.

7 Conclusions

Due to the known threat and opportunities that climate change brings to the sustainability of aquaculture (FAO, 2022), it is highly important to identify climate change related challenges and options at ASTRAL's IMTA sites. As the effect of climate change varies depending on the region and its climatic zones, it was the goal of Task 5.1 to characterize emerging long-term environmental changes at a regional level in relation to climate change. Specifically, we focussed on climatic trends in physical and biogeochemical key ocean variables, that is SST, SSS, surface dissolved oxygen, surface pCO_2, surface pH, surface inorganic nutrients and chlorophyll-a. For our calculation of climate trends, we focussed on collecting and analysing climate trends of quality-controlled observational data as well as on satellite data for the Southern Benguela Upwelling System.

In order to identify climate trends, it is necessary to have long-term observations of the variables in question so that a climate trend can unambiguously be distinguished from natural variability. There is long-term and frequent observational sampling for land surface air temperature, such that warming trends can be detected in most continental regions. However, *in situ* observations of the ocean are sparse in both space and time, such that a determination of a long-term trend is much more challenging for these variables. Data sparsity hinders a climate trend estimate for key oceanographic variables in the Beagle Channel, ASTRAL's prospective IMTA site in Argentina. Here, ASTRAL is helping to establish continuous measurements of temperature, conductivity and light at the mouth and inlet of Brown Bay. The data sparsity in Argentina is confirmed when checking collections of *in situ* data, where the South Brazil Shelf Large Marine Ecosystem has the least data coverage of all ecosystems adjacent to ASTRAL's prospective IMTA site. While the Large Marine Ecosystems surrounding the other IMTAs of ASTRAL (Patagonian Shelf, Benguela Current, South Brazil Shelf and Celtic-Biscay Shelf) have enough *in situ* data of SST and SSS to allow for confident climate trend-estimates, *in situ* data of nitrate and oxygen are too sparse in all regions to allow for a confident trend estimate. The coverage of i*n situ* data of pCO_2 and the confidence in calculated trends in pH and pCO_2 is strongly dependent on the region and the time-period considered. It was planned to make use of large-scale scenarios on climate change impacts on Atlantic coastal ecosystems from H2020 project TRIATLAS to confirm the calculated trends, but the model output was not available in time. Instead, we confirmed our trends with published estimates, whenever possible. For the Southern Benguela Upwelling System, a set of regionally optimized remote sensing data products are developed and evaluated with *in situ* data. Due to their high spatial (1 km) and temporal resolution, these allow for analysis of trends and variability in smaller regions, but only over a 15-year period (2000-2014), which is too short to capture climate trends. An examination of the regionally optimized SST data for 2000 to 2014 showed a coastal cooling trend throughout the southern Benguela Upwelling System for that period. The availability of a regionally accurate and validated high resolution satellite-derived SST product played a key role in identifying surface temperature products from the BRAN reanalysis model and OSTIA dataset as suitable for the examination of climate trends within the southern Benguela over longer time scales.

Confident climate trend estimates identify that the Large Marine Ecosystem surroundings ASTRAL's IMTAs in Ireland and Scotland (the Celtic-Biscay Shelf) seems to be most vulnerable to climate change (in terms of our selected variables), as it experiences a clear long-term warming (1957-2020) and an alarming warming acceleration during 1980-2020 categorizing the warming of this LME as “superfast”. The long-term warming signal is accompanied by a moderate decline in surface oxygen during the period 1957-2020 (confirmed with Ito et al., 2017) and by a strong increase in pCO_2 and a strong decline in surface pH during the period 1980-2021. The Large Marine Ecosystem adjacent to ASTRAL's IMTA site in South Africa is vulnerable to climate change. Though it has experienced only a moderate long-term warming (1957-2020), and even a deceleration of the warming for 1980-2020, it still experiences a decreasing trend in O_2 during the period 1957-2020 and a pH decline between 1980 to 2021. Similarly, the Large Marine Ecosystem adjacent to ASTRAL's IMTA site in Brazil is vulnerable to climate change as it experiences a sustained moderate warming for both periods (1957-2020 and 1980-2020) and a strong increase in pCO_2 and decline in pH between 1980 to 2021. Yet, it also shows an increasing trend for O_2 for the period 1957-2020, confirmed by Ito and co-authors (2017). For all of ASTRAL's IMTA-labs, it would therefore seem to be beneficial to produce species that tolerate a wide range of temperature- and oxygen-values or species that benefit from the occurring changes. Even though no climate trends could be established for the Beagle channel (i.e., the prospective IMTA lab in Argentina), we note that the adjacent Patagonian Shelf Large Marine Ecosystem shows only a very slow warming over the long-term period 1957-2020 and results suggest that this region has experienced a cooling over the more recent period (1980-2020). It also experiences a significantly decreasing trend in SSS for 1957-2020 that is accelerating with time. The slow warming and freshening at surface are consistent with our trend-estimates for pCO_2, pH and O_2 which suggest a less strong pCO_2-increase and pH-decline for the period 1980-2021 and a negligible trend in O_2 for the period 1957-2020. Due to the data sparsity, these results must be considered with care, but they are in line with results of Ito and co-authors (2017) for oxygen as well as Tjiputra and co-authors (2014) for pCO_2. We hence assume that the prospective IMTA lab in Argentina might be less vulnerable to climate change. However, this assumption has to be confirmed when longer time-series of the new ASTRAL measurement lines are available. This site may also be vulnerable to increases in freshwater input, as evidenced by the decrease in salinity over the past four decades.

7.1 List of climate-related variables to monitor

- At all sites temperature should be monitored at the minimum on the surface, but additionally a sample at depth will be worthwhile in order to capture changes in stratification.
- At the prospective site in the Beagle Channel, salinity measurements have been set-up. This is of importance to follow up on the indications of decreasing sea surface salinity in the surrounding Large Marine Ecosystem. At this IMTA site there is a general lack of data for all climate related variables so a good monitoring system that covers all is necessary. Given that this is a prospective site there is opportunity to develop a fit-for-purpose monitoring system here.
- At all sites dissolved oxygen should be monitored. Dissolved oxygen should preferably be measured both at the IMTA site and upstream/downstream of the site to catch changes over a larger area.
- There is almost no data on inorganic nutrients at the IMTA sites or in the surrounding Large Marine Ecosystems. We recommend that at least nitrate is regularly measured for monitoring and trend assessment as it is of importance for kelp growth.
- For the Southern Benguela Upwelling System regionally optimized satellite data products have been shown to be very informative. Developing such regionally optimized data products also for other regions where there are IMTAs would be very useful.

Note: The results of the analysis of climate trends in Sea Surface Temperature have been submitted to the Journal "Progress in Oceanography" where the manuscript ("Observation-based Sea Surface Temperature trends in Atlantic Large Marine Ecosystems") is currently under review.

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