3.1 The use of Copernicus Marine Service products to describe the State of the Tropical Western Pacific Ocean around the Islands: A case study

3.1 The use of Copernicus Marine Service products to describe the State of the Tropical Western Pacific Ocean around the Islands: A case study

Authors: Elisabeth Holland, Karina von Schuckmann, Maeva Monier, Jean-François Legeais, Silvia Prado, Shubha Sathyendranath, Cecile Dupouy

Products used

Ref. No.	Product name & type	Documentation
3.1.1	1.5.1 DUACS (Data Unification and Altimeter Combination System) delayed-time altimeter daily sea level products, Altimetry	http://climate.copernicus.eu/climate-data-store
3.1.2	GLOBAL_REANALYSIS_PHY_001_026 Reanalysis	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-GLO-PUM-001-026.pdf QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-GLO-QUID-001-026.pdf
3.1.3	INSITU_GLO_TS_OA_REP_OBSERVATIONS_013_002_b In situ for the year 2017: INSITU_GLO_NRT_OBSERVATIONS_013_030 In situ	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-INS-PUM-013-002-a.pdf ; QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-INS-QUID-013-002a.pdf) for the year 2016: PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-INS-PUM-013.pdf QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-INS-QUID-013-030-036.pdf
3.1.4	GLOBAL_REP_PHY_001_021 In situ, remote sensing	PUM : http://marine.copernicus.eu/documents/QUID/CMEMS-GLO-QUID-001-021.pdf QUID : http://marine.copernicus.eu/documents/PUM/CMEMS-GLO-PUM-001-021.pdf

3.1.5	OCEANCOLOUR_GLO_CHL_ L3_REP_OBSERVATIONS_009 _065 Remote sensing	PUM: http://marine.copernicus.eu/documents/PUM/C MEMSOC- PUM-009-ALL.pdf QUID: http://cmemsresources. cls.fr/documents/QUID/CMEMS-OC-QUID- 009-064-065-093.pdf

Fiji served as President of the UN General Assembly in 2017, linking climate (SDG13) and ocean (SDG14) as the foundation of blue economies for island and coastal states around the world. The resulting United Nations Oceans outcome statement stressed "the importance of enhancing understanding of the health and role of our ocean and the stressors on its ecosystems, including through assessments on the state of the ocean, based on science and on traditional knowledge systems. We also stress the need to further increase marine scientific research to inform and support decision-making, and to promote knowledge hubs and networks to enhance the sharing of scientific data, best practices and 'know-how.'" (UN, 2017).

The Southern Pacific Ocean remains one of the last frontiers for scientific research. Few in situ monitoring systems exist to document the state of the Pacific Ocean. Indeed, accessing available fisheries data is compromised because of the competitive nature of the fishing industry (Transform Agorau pers. comm.). The effective and growing Argo float network, with 3907 floats in February 2019 (http://www.argo.ucsd.edu/About_Argo.html), has truly revolutionized large-scale physical oceanography (Riser et al., 2016). The continuing limited capability of climate system models to adequately simulate ocean-climate coupling and dynamics, including the El Nino Southern Oscillation, underscores the importance of integrating the available data sets (Bellenger et. al. 2014).

The Copernicus Marine Service Atlas for the Pacific Ocean States goes beyond the unique compilation of CMIP3 climate model projections and data tools compiled by the Pacific Climate Change Science Program (PCCSP, 2011, 2014). A complete overview of tropical Pacific observing network is available in the WMO publication library (GCOS, 2014a, 2014b). Our study focuses on the application of the available CMEMS products to the Pacific domain defined by PCCSP.

The Pacific Islands Meteorological Services Directors have repeatedly emphasized the need to include ocean forecasting and services in the suite of the WMO Global Framework for Climate Services (SPREP, 2012), and the third Pacific Meteorological Council Meeting (SPREP, 2017). As president of COP23, Prime Minister Frank Bainimarama has emphasized the importance of the climate and ocean connection and the need to protect ocean health to protect the planet: 'We are all in the same canoe' (https://cop23.com.fj/fijian-prime-minister-cop23-president-remarks-assuming-presidency-cop23/). The Copernicus Marine Service Atlas for Pacific Ocean States compiled by the author team responds directly to Fiji's requests at the 2017 United

Nation Oceans for SDG 14, life below water and the 2017 COP23 for SDG13, climate action which goes beyond the Pacific.

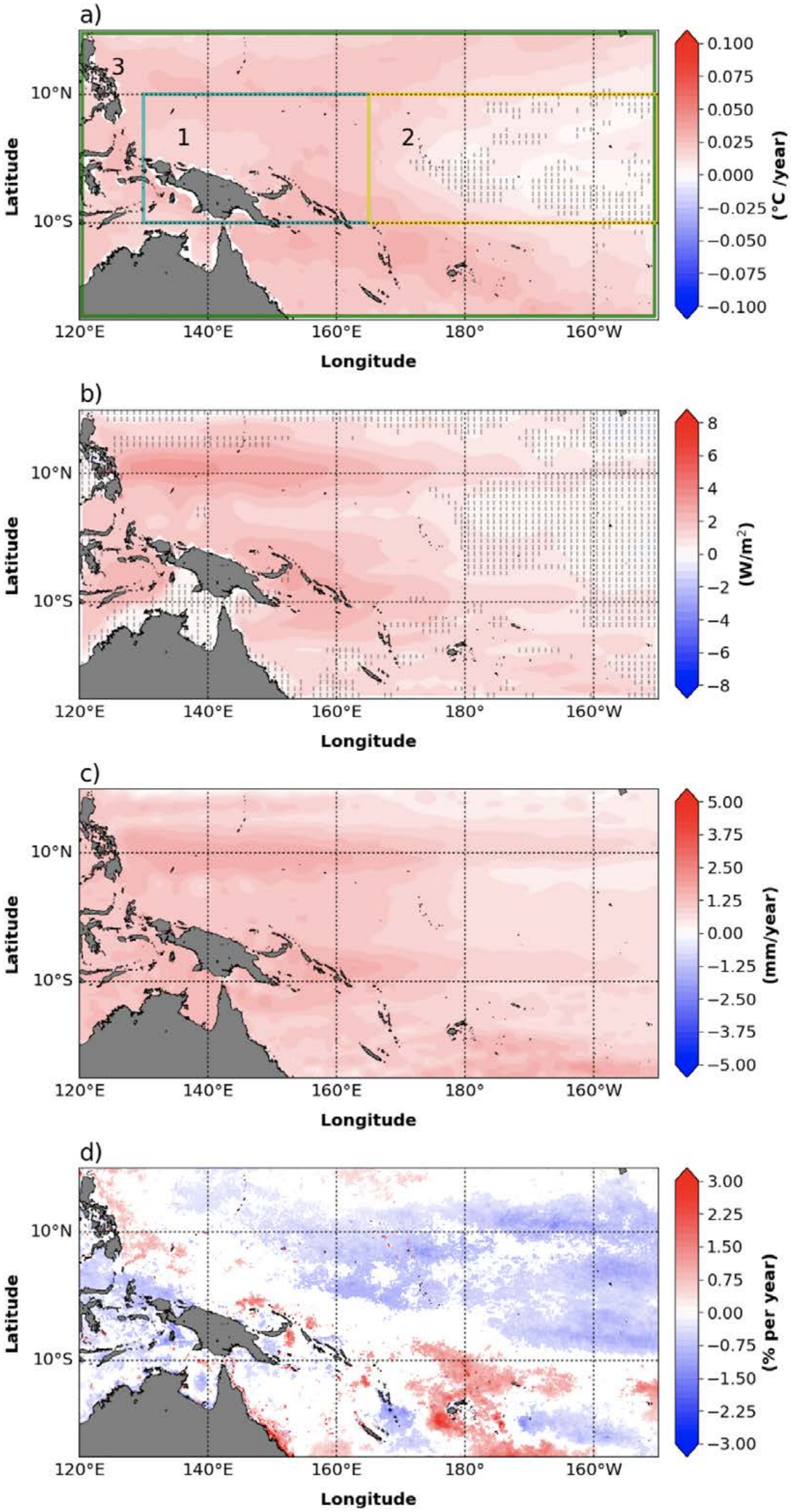
a)
b)
c)
d)
1
2
3
10°N
10°S
120°E
140°E
160°E
180°
160°W
Latitude
Longitude
(°C /year)
0.100
0.075
0.050
0.025
0.000
−0.025
−0.050
−0.075
−0.100
(W/m^2)
8
6
4
2
0
−2
−4
−6
−8
(mm/year)
5.00
3.75
2.50
1.25
0.00
−1.25
−2.50
−3.75
−5.00
(% per year)
3.00
2.25
1.50
0.75
0.00
−0.75
−1.50
−2.25
−3.00

Figure 3.1.1: *Regional trends of a) sea surface temperature and b) upper ocean (0-700m) ocean heat content over the period 1993-2017 for the western tropical Pacific. The results are derived from a multi-product approach (ensemble mean of product 3.1.2-3.1.4). Black dots indicate areas where the noise exceeds two times the signal. c) Regional sea level trend (in mm/yr) for the western tropical Pacific over the period Jan 1993-May 2017 (note to reviewer: will be up-dated until DEC-2017) as derived from re-processed satellite altimetry data (product reference 3.1.1). No Glacial Isostatic Adjustment correction is applied on the altimeter data. D) Map of regional chlorophyll trend (September 1997- December 2017) in the western tropical Pacific as observed by remote sensing. Only statistically significant (p<0.05) trends are shown, and are based on the CMEMS product 3.1.5. See Table 3.1.1 for the definition of the dataset, and access to related documentation. Regions for analysis are indicated in a), i.e. Western Pacific Islands (blue, Box 1; 130°E-165°E; 10°S to 10°N to encompass the Western Pacific Warm Pool); Central Pacific Islands (yellow, Box 2: 165°E-150°W; 10°S to 10°N); and Entire Pacific Islands domain (green, Box 3 is consistent with domain used for the Pacific Climate Change Science Program).*

The data sets available through the Copernicus Marine Service provide a valuable window on the under-observed Pacific Ocean and help build a foundation for providing ocean services, including food security, essential biological variables and indicators of ocean health, data to inform early warning systems and climate adaptation. To begin, we address the following key ocean variables:

- sea surface temperature, a much-needed variable for assessing coral reef health and bleaching and tropical cyclone forecasting
- ocean heat content trends for the upper 700m depth, to monitor ocean warming and thermal volume changes contributing to sea level rise; to track changes in stratification, ocean currents, as well as marine ecosystems and human livelihoods. Moreover, this indicator is linked to the ocean's role as a major heat source for the global atmospheric circulation and has important implications for regional and global climates, including severe events.
- sea level trends from 1993 to 2017 to better inform climate adaptation and coastal planning. Sea level trend values in the entire Pacific Islands domain (Box 3) range between -0.5 mm/yr and +7.2 mm/yr, illustrating the non uniformity of the sea level rise in this region.
- near surface chlorophyll concentrations - as linked to phytoplankton populations - to assess ocean productivity and health as their changes can imply major impacts on ecosystem processes and biogeochemical cycling, which in turn can have significant implications for economy productivity and food availability.

To develop the Pacific case study, the domain was defined to encompass the 15 P-ACP (African, Caribbean and Pacific) countries defined by the EU Cotonou agreement and served by the EU's ACP secretariat (http://www.acp.int/) including: Cook Islands, Federated States of Micronesia, Fiji, Kiribati, Nauru, Niue, Palau, PNG, RMI, Samoa, Solomon Islands, Timor-Leste, Tonga, Tuvalu, and Vanuatu. The domain corresponded to that used for the Pacific

Islands in the Pacific Climate Changes Science Program (Australia Bureau of Meteorology and CSIRO 2011). To explore the dynamics inside and outside the Western Pacific Warm Pool, the domain was further subdivided.

Variable	**Western Pacific Islands Box 1** 1993-2017 trend	**Central Pacific Islands Box 2** 1993-2017 trend	**Entire Pacific Islands domain, Box 3** 1993-2017 trend
SST °C • y-1	+0.02± 0.01	+0.01 ± 0.02	+0.02 ± 0.01
OHC (0-700 m) W • m-2	+1.9 ± 1.5	+0.8 ±0.7	+1.2 ± 0.7
Sea level mm • y-1	+4.8 ± 2.5	+2.8± 2.5	+3.5 ± 2.5
Chlorophyll % • y-1	-0.4 ± 0.02	-0.7 ± 0.001	-0.4 ± 0.001

Table 3.1.1: *Trend values and their uncertainties (90% confidence interval) of area mean Sea Surface Temperature (SST) and Ocean Heat Content (OHC) over the period 1993-2017 (ensemble approach from products 3.1.2-3.1.4), Sea Level over the period January 1993 to Dec 2017 (product ref. 3.5.1) and Chlorophyll concentration over the period September 1997- December 2017 (product ref. 3.5.5). Areas for box 1 & 2 are given in Fig. 3.1.1a, and full domain covers the western tropical Pacific as shown in the maps of Fig. 3.1.1. Note that the uncertainties related to the sea level internal variability are not included in the sea level trend uncertainties.*

Global mean sea surface temperature, upper ocean heat content and mean sea level all show pronounced increasing trends over the last decades and with strong evidence that the positive trend is related to the increase in greenhouse gas concentration (Rhein et al., 2013). Nevertheless, the global surface and subsurface warming and global mean sea level rise is not spatially uniform (Meyssignac et al., 2016). Long-term warming of the western Pacific is a well-documented consensus in literature (Deser et al., 2010; Cane et al.,1997; Cravatte 2009). Accordingly, the Copernicus Marine Service Atlas for the Pacific Islands area shows a significant surface and subsurface warming trend and sea level rise (Fig. 3.1.1 and 3.1.2) at values close to and even exceeding the global mean warming and sea level rise rates (see table 3.1.1, see also Chapter 1). The Western Pacific Islands area shows strong variability over various time scales (Sun et al., 2017, Merrifield et al., 2012, Han et al., 2014). At interannual time scales, western tropical Pacific surface and subsurface temperatures, and sea level vary in synchrony with the modes of the El Niño Southern Oscillation (Fig. 3.1.2, e.g. Ablain et al., 2017; Wang et al., 1999). The near surface layers warm in the easternmost box 2 during the 1997/1998 and 2015/2017 El Niño phase (shown in red) and cool during the 1998-2000, 2007/2008 and 2010/2011 La Niña phase (shown in blue, Fig. 3.1.2a). Moreover, year-to-year changes for western tropical Pacific sea level are thermosteric driven: sea level rises as ocean temperatures rise (Fig. 3.1.2 b, c).

We introduce chlorophyll concentration (Fig. 3.1.1d and Fig. 3.1.2d) to provide a measure of the amount of phytoplankton present with its corresponding marine productivity on which the entire marine ecosystem depends, directly or indirectly. Ocean chlorophyll could be used by decision makers to assess the health and productivity of natural resources and marine life that depend on phytoplankton. Reduced chlorophyll concentration and associated decrease in primary production may negatively impact fish and marine life, important for food security and economic health of the Pacific Islands countries that dependent on fisheries.

Significant trends, both positive and negative, have been reported on a regional basis, for both chlorophyll concentration and primary production (Mélin et al. 2017, Racault et al. 2017), and some of the most pronounced trends have been reported for the eastern and western Pacific region. In the western Pacific area (Box 1 of Fig. 3.1.2d, blue line), large variations from year-to-year characterize the chlorophyll concentrations, highlighting the need for regular monitoring services. River run off coincident with ITCZ and SPCZ dynamics in the equatorial coastal areas like that of northern Papua New Guinea explains the greater high-frequency variability than open ocean regions. In the central Pacific (Box 2 of Fig. 3.1.2d, yellow line), a reduction of chlorophyll concentration since the year 1997 is recorded at a rate of ~- 0.7 %/year which is either linked to decadal or longer variability (as observed in the northern Pacific e.g. Sun et al., 2017) or the impact of climate change. Chla is strikingly well correlated with the CP El Niño signal with high Chla associated with the negative (La Niña) phase of ENSO as seen in 1998, 1999, 2007 and 2010, and a lower Chla associated with the positive (El Niño) phase of ENSO as seen in 2015. For the entire Pacific Islands (green line, Box 3, Fig. 3.1.2d), Chla mimics that of the western Pacific (blue line, Box 1) with a lower amplitude due to the weaker correlation with CP ENSO events (yellow line, Box 2). In the Fijian Archipelago, at the inverse, Chla concentration is increasing between 0 and 2% per year (Fig. 3.1.1c), indicating a high positive response of phytoplankton, or/and a shift in phytoplankton composition (Dupouy et al., 2018).

Given that time series from remote sensing used here is only 18 years long, and the dominant signature is decadal scale variability (Gregg et al., 2017), this time series is admittedly too short to disentangle the effect of interannual variability and longer-term climate change. Nevertheless, this series demonstrates 1) the correlation between Chla and ITCZ in the western Pacific due to coastal areas in large Pacific Islands in the Western Pacific (Box 1), 2) the strong correlation between Chla and La Niña phase due to the equatorial upwelling enrichment in the Central Pacific (Box 2) and 3) less correlation for the entire region due to smoothing of the ENSO or ITCZ effects as demonstrated by the reduced variability (Box 3). The variability around the long-term trend appears visually to be inversely related to the MEI (Fig. 3.1.2d, yellow line).

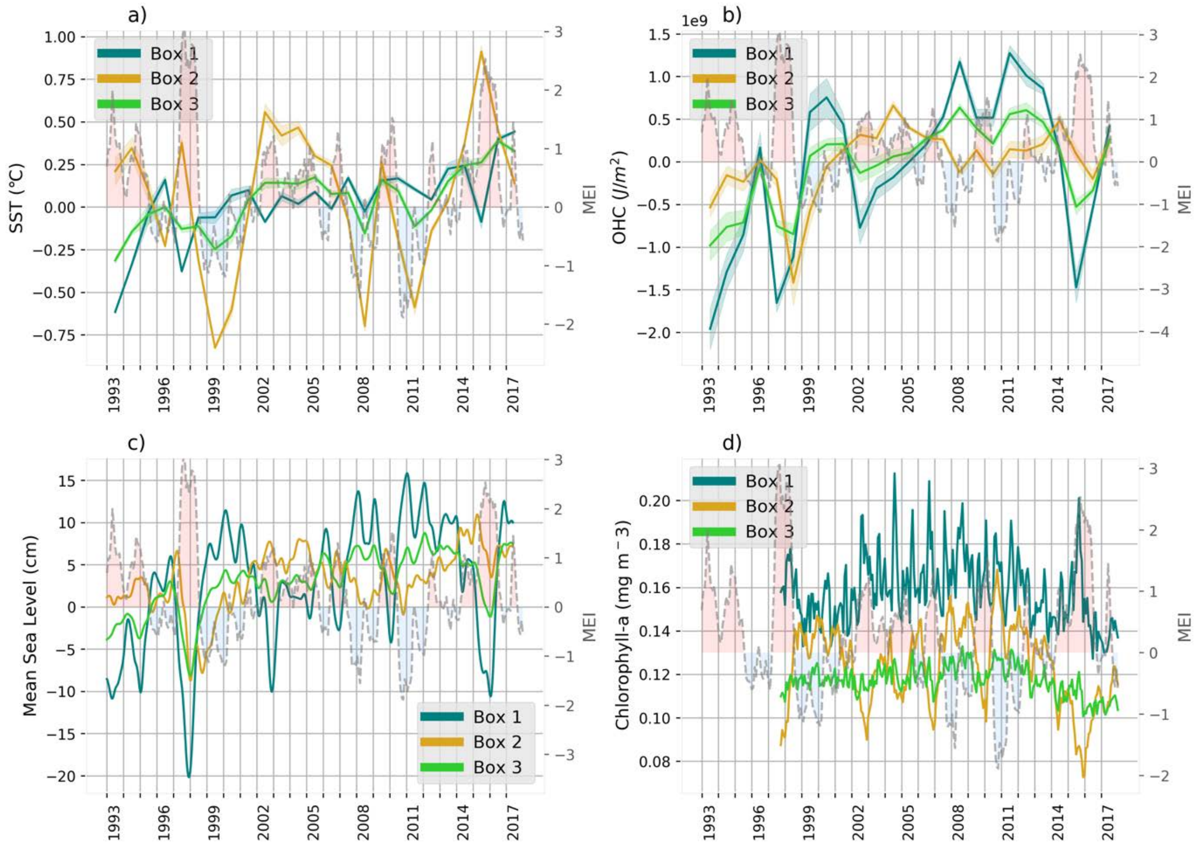

Fig. 3.1.2: *Averaged time series over the full area (green line, Box 3, full map area of Fig. 3.1.1a), and the western (dark blue line, Box 1) and eastern (yellow line, Box 2) tropical Pacific Ocean for a) sea surface temperature, b) ocean heat content, c) sea level and d) Chlorophyll-a. The seasonal cycle had been removed from all time series (1993-2014 for a)-c), 1997-2014 for d)). Details on box areas and data use is given in the caption of Fig. 3.1.1. The Multivariate El Niño Southern Oscillation Index is used to describe the ENSO phase with the El Niño phase shown as red (positive) shaded areas and La Niña shown as blue (negative) shaded areas (Wolter and Timmlin, 2011, downloaded: https://www.esrl.noaa.gov/psd/enso/mei/).*

The State of the Pacific Ocean case study is a first step as a demonstration of how Copernicus Marine Service products might be used to inform decision making in a region that regards itself as data poor, especially for ongoing monitoring of biological variables. The perception of data poverty results from limited capacity to access, display and analyze data (Holland 2018). The Copernicus Marine Services State of Pacific Ocean challenges those perceptions of data poverty by demonstrating the richness of the data available to inform decision making in the Pacific Islands.

Our hope is that the State of the Pacific Ocean atlas serves as a springboard to begin stakeholder engagement and dialogue on how to use the available data to inform decision making. In the

2018 Pacific Island Forum Leaders meeting, the Pacific leaders of the 16 forum member countries prioritized climate change and blue economies. Optimizing utilisation of the available data requires further dialogue at the science policy interface to generate the robust products required to inform decision making.

The Pacific Islands Forum Marine Sector Working Group (MSWG) has prioritized the need to document data available for the Pacific Islands domain. A first step will be to show the products to the MSWG and other stakeholders to engage them in collaborative discussions about how the data might be used. The long-term goal is to produce data products that would be to inform decision making for the blue economies of the Pacific. The data is available to inform decision making on an annual basis through the World Ocean Atlas, and could become useful on more refined time scales, quarterly to weekly to inform climate and ocean outlooks. One step might be to transform the data products provided here into real time data available to the Forum Fisheries agency, Honiara, Solomon Islands for display in their fisheries monitoring facility. Another step for the MSWG would be developing real time data displays that provide the more than 20 years of context for physical ocean monitoring (GCOS 184)

Future needs for the Copernicus data include refining the approach to finer time scales with the eventual goal of providing real time data and information services and short term 2 week forecasts. The data products are available through CMEMS, but i) regionalization (e.g. downscaling) and ii) cross-validation between products (e.g. link the consolidated products with the non-consolidated ones) are required. The data products shown are subset of the data available for the Pacific Islands to launch the much-needed dialogue with the key stakeholders and champions. With the successful launch of this Pacific Ocean Atlas, other ideas and innovations will emerge for research products and applications.

The Copernicus Marine Services State of Pacific Ocean analysis of available data demonstrates that the ocean surrounding the Pacific Islands is warmer, has higher heat content, with sea level rising at rates higher than the global mean and a decline in chlorophyll content.