important component in the sustained analysis of nutrient concentrations and eutrophication.

Acknowledgements

The study utilised SYKE Alg@line FerryBox infrastructure as a part of the national FINMARI RI consortium. We thank two anonymous reviewers for their constructive comments and Danielle Bansfield for language editing.

Funding

The work has been supported by JERICO-S3 project, funded by the European Commission's H2020 Framework Programme under grant agreement No. 871153 and by the Academy of Finland (SEASINK: Evolving carbon sinks and sources in coastal seas - will ecosystem response temper or aggravate climate change?).

Section 3.3. Copernicus Marine Sea Surface Temperature and chlorophyll-a indicators for two Pacific Islands: a co-construction monitoring framework for an integrated, transdisciplinary, multi-scale approach

Authors: Alexandre Ganachaud, Karina von Schuckmann, Andra Whiteside, Cécile Dupouy, Pierre-Yves Le Meur, Maeva Monier, Simon Van Wynsberge, Antoine de Ramon N'Yeurt, Maria Mañez Costa, Jérôme Aucan, Annette Breckwoldt, Louis Celliers, Pascal Douillet, Sebastian Ferse, Elisabeth Holland, Heath Kelsey, Vandhna Kumar, Simon Nicol, Maraja Riechers, Awnesh Singh, David Varillon

Statement of main outcome: The ocean is an integral part for the three pillars of sustainable development: environment, society and economy. Pressures on the ocean from climate change, pollution, and over exploitation have increased over the past decades, posing unprecedented challenges, particularly for vulnerable communities such as the Large Ocean Island States, and these pressures need to be monitored. This study analyses the time series of Essential Ocean Variables sea surface temperature and chlorophyll-a in coastal reefs of two pilot regions in Fiji and New Caledonia. In situ measurements represent true local conditions, with a necessarily limited coverage in time and space. Remote sensing data have a broad coverage but are necessarily limited in terms of resolution and accuracy in the coastal zone. Our analysis points to the advantage in using these complementary data types for the same geographical areas at small spatial scales close to the coast, and in particular, for high frequencies and extreme events. We discuss the way forward for a co-constructed monitoring framework, drawing on ongoing initiatives in Oceania, and advocate a methodology for the use of ocean data to support society and economy. Co-construction with stakeholder involvement is paramount for this framework, including policy- and decision-makers, industry, scientists, local and indigenous, governmental and non-governmental organisations, all of whom need sound, multi-disciplinary science advice, targeted expertise, and reliable evidence-based information to make informed timely decisions for the right timescale. Such transdisciplinarity combines scientific, traditional, administrative, technical, and legal knowledge repertories.

Products used:

Ref. No	Product name and type	Documentation
3.3.1	Gridded chl-a (monthly, L4, ESA-CCI): OCEANCOLOUR_GLO_CHL_L4_REP_OBSERVATIONS_009_093	PUM: https://catalogue.marine.copernicus.eu/documents/PUM/CMEMS-OC-PUM-009-ALL.pdf QUID: https://catalogue.marine.copernicus.eu/documents/QUID/CMEMS-OC-QUID-009-030-032-033-037-081-082-083-085-086-098.pdf
3.3.2	Non-gridded chl-a (daily, L3, ESA-CCI): OCEANCOLOUR_GLO_CHL_L3_REP_OBSERVATIONS_009_065	PUM: https://catalogue.marine.copernicus.eu/documents/PUM/CMEMS-OC-PUM-009-ALL.pdf QUID: https://catalogue.marine.copernicus.eu/documents/QUID/CMEMS-OC-QUID-009-064-065-093.pdf
3.3.3	BULA IRD CAMELIA Alis Oceanographic Cruises	Fichez et al. (2006) Torréton et al. (2004) FICHEZ Renaud (2001) BULA 1 cruise, RV Alis, https://doi.org/10.17600/1100110 TORRETON Jean-Pascal (2002) BULA 2 cruise, RV Alis, https://doi.org/10.17600/2100040 DOUILLET Pascal (2003) BULA 3 cruise, RV Alis, https://doi.org/10.17600/3100050 PRINGAULT Olivier (2003) BULA 4 cruise, RV Alis, https://doi.org/10.17600/3100110 DOUILLET Pascal (2004) BULA 5 cruise, RV Alis, https://doi.org/10.17600/4100060 DOUILLET Pascal (2001) BULA, https://doi.org/10.18142/71
3.3.4	CMEMS Ocean Monitoring Indicator: Global map of chl-a trends GLOBAL_OMI_HEALTH_OceanColour_trend	PUM: https://catalogue.marine.copernicus.eu/documents/PUM/CMEMS-OMI-PUM-HEALTH-GLOBAL-OCEANCOLOUR.pdf

(*Continued*)

Continued.

Ref. No	Product name and type	Documentation
		QUID: https://catalogue.marine.copernicus.eu/documents/QUID/CMEMS-OMI-QUID-HEALTH-GLOBAL-OCEANCOLOUR.pdf
3.3.5	SST_GLO_SST_L4_REP_OBSERVATIONS_010_024	PUM: https://catalogue.marine.copernicus.eu/documents/PUM/CMEMS-SST-PUM-010-024.pdf QUID: https://catalogue.marine.copernicus.eu/documents/QUID/CMEMS-SST-QUID-010-024.pdf
3.3.6	ReefTEMPS network	http://www.reeftemps.science/en/home/ Cheype et al. (2015), Varillon et al. (2021), Cocquempot et al. (2019)
3.3.7	R/V Seamans cruise, station S288-019, October 2019	Whittaker (2020)

3.3.1. Introduction

Pressures on the ocean from climate change, pollution, and over-exploitation have increased with a growing world population and over time. With continued environmental stress on the ocean in response to ongoing global warming (e.g. IPCC 2019b, 2021), as well as with the prospective development of new ocean-related economic activities, these problems are only expected to further exacerbate (OECD 2020). The ocean is integral to Small Island Developing States' (SIDS) economies (Dornan et al. 2018; Keen et al. 2018) as their vast Exclusive Economic Zones are much larger than their actual land space (70-fold in Fiji, Gassner et al. 2019), and Pacific islanders have proposed to shift the terminology from SIDSs to Large Ocean Island States (LOIS) (Hau'ofa 2000; Morgan 2021). The SIDS/LOIS are particularly exposed to anthropogenic pressure on the ocean due to low elevation, small land area, narrow ecological zonation, climate sensitive ecosystems and natural resources; insufficient financial, scientific and technical capacities; unique social and political conditions, proportionally (compared to mainland countries) more limited human resources, and local and unique forms of bureaucracies (Magnan et al. 2019).

Globally, ocean knowledge is of great benefit to inform policy, decision making, governance and management and therefore to increase the likelihood of developing sustainability (Colglazier 2018; Hermes et al. 2019; Kaiser et al. 2019). The concept of Essential Ocean Variables (EOVs) as implemented by the Global Ocean Observing System (GOOS) is based on relevance for climate and ocean services, including ocean health (Le Cozannet et al. 2017; Le Traon et al. 2017), and considering feasibility, maturity of the science and measurement techniques, and cost effectiveness (Lindstrom et al. 2012). Similarly, the framework of Global Climate Indicators as introduced by the World Meteorological Organisation (WMO 2017) in the light of SDG 13 'Climate action' includes a subset of key indicators – many of them ocean-related – designed to be comprehensive and understood by non-scientific audiences, and form the basis of their annual Statement of the State of the Global Climate (e.g. WMO 2020) used amongst others by the UN Framework Convention for Climate Change. Within the large scale or global processes, the need to include local and indigenous knowledge in adaptation planning and adaptive management remains a challenge (Celliers et al. 2021).

Sea Surface Temperatures (SST) and Chlorophyll-a (Chl-a) are EOVs for the Earth's ocean system (O'Carroll et al. 2019; Sathyendranath et al. 2019). SST impacts marine ecosystems. Satellite derived SST anomalies, and derived indicators (e.g. degree heating weeks (DHW) coral bleaching alert) directly provide relevant information in near-real time that can be used by managers. Monitoring and forecasting local thermal regimes are important for understanding and protecting potential refugia for coral species (Foo and Asner 2020; Schoepf et al. 2020), or managing aquaculture activities (Van Wynsberge et al. 2020). For instance, a warning of abnormal conditions is useful to initiate more intensive *in situ* monitoring, or prepare for action in case of bleaching (Heron et al. 2016; Andréfouët et al. 2018; Sully et al. 2019; Skirving et al. 2020).

The EOV Chl-a is a proxy for the amount of photosynthetic plankton in the ocean, which is an indicator of carbon uptake, productivity and overall health of the ocean (e.g. Martinez et al. 2009; Mélin et al. 2017). Together with nutrients and suspended sediments, Chl-a is also an indicator of water quality, one of the pressures on vulnerable ecosystems such as the seagrass beds and coral reefs (Devlin et al. 2020; Vollbrecht et al. 2021). At the local scale, it is used to monitor changes in coastal lagoon water quality (Dupouy et al. 2018a; Vollbrecht et al. 2021); it also impacts larval recruitment (Wilson et al. 2018). For instance, Putra et al. (2021) showed that most of the potential fishing ground in Riau Islands (Indonesia) were linked to Chl-a increases associated with different monsoon types. Understanding the drivers of Chl-a variations is therefore important to marine spatial planning efforts and managing marine ecosystems, but the access and ability to make use of such data around Fiji are not yet available to stakeholders (Gassner et al. 2019; MACBIO project – Marine and Coastal Biodiversity in the Pacific Island Countries[2]).

Here we analyse SST and Chl-a, as measured at regional (remote sensing/CMEMS products) and local (in situ) scales in two Pacific Islands, Fiji and New Caledonia, to provide insights about CMEMS products' usefulness and limitations for local ecosystem management. These products are often developed for broader applications and not designed for specific local needs. In our discussion, we, therefore, advocate the importance of a local, specific and transdisciplinary approach to co-construct data products that best serve scientists, administrations, authorities, managers, business, and local communities to support ocean sustainability in the long term. We discuss future ways to tackle the missing elements (plural knowledge and norm repertoires of various actors) in the construction of relevant indicators and monitoring frameworks.

3.3.2. Two EOV indicators in Fiji and New Caledonia

3.3.2.1. Data used

For SST, we used large-scale satellite observations from the ESA CCI project (product ref. 3.3.5). This satellite-derived SST product provides a bulk SST, equivalent to water temperature at 20 cm below the sea surface (Product ref. 3.3.5). We will refer to it as *SSTSAT*. The inputs to the system are SSTs at 10:30 am and pm local time which means that the SST provided by this product roughly corresponds to the daily average. SSTSAT anomalies are relative to the daily SSTSAT climatology from January 1st to December 31st of the ESA CCI data period. SSTSAT extracted from the product were used directly, without any further processing. The SSTSAT values from this product were compared to local in-situ SST observations for Fiji and New Caledonia using sites from the ReefTEMPS observing network (product ref. 3.3.6), which is part of the French Research Infrastructure for Coastal Oceans and Seashores (ILICO), and also known as the Pacific Insular Coastal Waters Observation Network. ReefTEMPS consists of a number of monitoring platforms at 6–60 m depth scattered around 20 Pacific Island countries, with 30 monitoring stations in New Caledonia, and 11 in Fiji (Cheype et al. 2015; Cocquempot et al. 2019; Varillon et al. 2021). For the purpose of the current analysis, one station in Fiji and four in New Caledonia were selected to maximise the mutual temporal coverage of remote sensing and in-situ measurements.

For Chl-a, we jointly use four different data products, i.e. a monthly gridded (product ref 3.3.1) and daily non-gridded CMEMS (product ref 3.3.2) remote sensing, the CMEMS Ocean Monitoring indicator (product ref 3.3.4). These Chl-a satellite products are designed for open ocean use – what are called *Case 1 waters* whose optical signal is dominated mainly by phytoplankton present at low concentrations – and are not designed to be used in optically complex coastal waters – called *Case 2 waters* (IOCCG 2000). Lagoon waters would require adapted algorithms such as the one issued from the comparison of MODIS and in situ Chl-a concentration coincidences all around New Caledonia (Case 1 and 2 waters, Wattelez et al. 2016) and that are yet to be applied to other lagoons. Therefore, only CMEMS data offshore (Case 1 waters) were selected for this study, and only the evolution of offshore waters is discussed. These are compared with *in situ* data collected during five oceanographic cruises South of Fiji from 2001 to 2004 (Bula programme, by IRD / UR CAMELIA, ANSTO and U. South Pacific, product ref. 3.3.3). In-situ Chl-a data were measured after filtration on a 0.7 µm GF/F filter and extraction of the phytoplankton retained in methanol (Chifflet et al. 2004). In addition, a Chl a data point south of the region (178.79° E, 18.48° S) was used to represent the 'bluest water' (product ref. 3.3.7).

3.3.2.2. Regional results from satellite products

3.3.2.2.1. Ocean temperatures. Over the periods that span available in situ data, SSTSAT changes are characterised by surface warming around Fiji and New Caledonia between 2013 and 2019 (Figure 3.3.1(a)), and in the north-eastern part including Fiji between 1997 and 2019 with more than 0.02°C per year (Figure 3.3.1(b)). For comparison, global mean SST increased at a rate of 0.015 ± 0.001°C per year over the period 1982–2019 (CMEMS 2021b). In contrast, the area north-east of New Caledonia (Figure 3.3.1(b)) showed cooling conditions over the period 1997–2019 at rates of around −0.01°C per year, while the area south-west of New Caledonia showed surface warming conditions over this period, at rates between 0 and 0.02°C per year. Cravatte et al. (2009) and Quinn et al. (1998) found such strong spatial variability in ocean surface warming over many time scales (see also Sun et al. 2017). In the western tropical Pacific, SST vary strongly with the modes of the El Niño Southern Oscillation at interannual time scales, thereby influencing trend calculations over these short periods (e.g. Gouriou and Delcroix 2002).

3.3.2.2.2. Chl-a. The Chl-a trend over the period 1997–2019 is characterised by a decrease between the New Caledonia and Vanuatu archipelagos of more than 1%, and an increase south of Fiji at rates of more than 1% per year (Figure 3.3.1(c)). These trends in biomass of phytoplankton are weak relative to global ocean changes

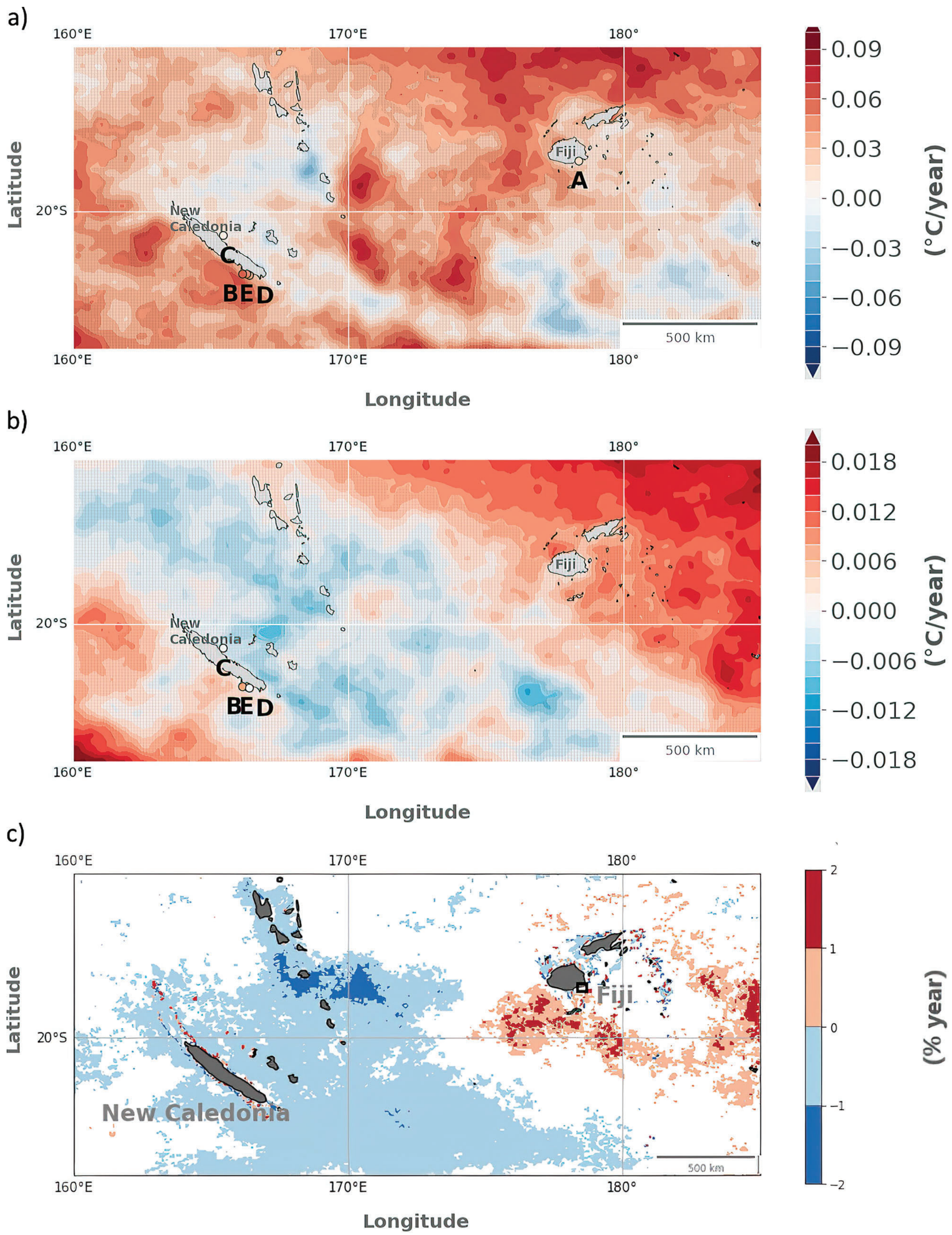


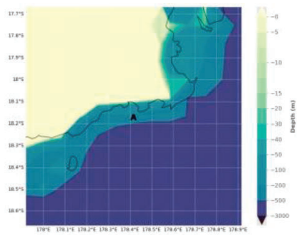
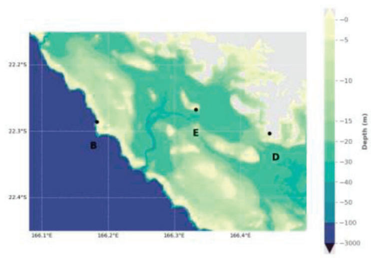
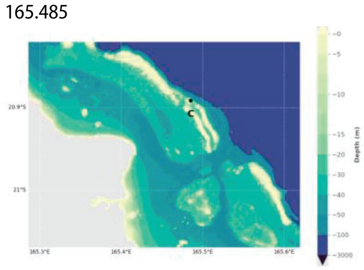
Figure 3.3.1. SST & Chl-a: Trend of Sea Surface Temperature (average yearly anomalies) as derived from product ref. 3.3.5 over the period (a) 2013–2019 and (b) 1997–2019 (units: °C per year). The two periods have been chosen to overlap with the availability of in-situ records. Coloured circles indicate corresponding trend estimates as derived from in-situ observations (product ref. 3.3.6, see Figure 3.3.4). Note the difference in colour scales in the two plots (c) Chl-a trend (units: % per year) over the period 1997–2019 from product ref. 3.3.3. White pixels are not statistically significant.

(− 6–10% per year, CMEMS 2021a) and regional Western Pacific changes (−3% to 3% for the same period, Holland et al. 2019). Observations of either a decrease or an increase of Chl-a towards an island in different archipelagoes of the Western tropical Pacific have been attributed to island mass effects (Dandonneau and Charpy 1985). Such variations in Chl-a may originate from a large range of triggering factors including physical environment changes altering the supply of essential nutrients, already found at a large scale in the Pacific Ocean (Dupouy et al. 2004; Martinez et al. 2009). Chl-a trends might also result from changes in phytoplankton species which have different optical properties (e.g. an increase in the proportion of diazotrophs vs picoplankton, a major component of phytoplankton in the region; Dupouy et al. 2018b). Evaluating phytoplankton composition change over this long period of time would require algorithms for discriminating phytoplankton groups based on CMEMS reflectance observations (IOCCG 2021).

3.3.2.3. Regional to local results: Comparison with in situ data

3.3.2.3.1. Ocean temperatures. SSTSAT *trends* compared well with in-situ observations during both overlapping study periods (Figure 3.3.1 and Table 3.3.1). However, pointwise examination of the time series reveals a small, systematic underestimation in satellite data. For example, the Suva Reef (Viti Levu Island, Fiji) recorded an in-situ warming rate of 0.024 ± 0.01° C per year (December 2012 to December 2019), whereas the satellite-derived estimate is barely significant at

Table 3.3.1. In situ temperature meta data and correlation coefficients for the comparison with SSTSAT. Station positions on regional scales, and overlapping time series lengths are provided in Figures 3.3.1 and 3.3.2, respectively. The significance level at 95% would be 0.55 if we had only 10 independent samples and 0.38 for 20 samples. Maps are based on Etopo5 in Fiji, and a high resolution SHOM DEM in New Caledonia.

Platform	Date begin Date end	Depth (m)	Situation Map	Correlation from daily (monthly) values
A-Fiji Suva Reef, Viti Levu 02	21/12/2012 04/03/2020	12	−18.15975 178.3999 	0.78 (0.9)
B-NCL Fausse Passe de Uitoe 01	22/05/1992 02/12/2019	11	−22.28586 166.1832	0.77 (0.86)
				0.87 (0.93)
C-NCL Poindimié 01	09/12/1996 08/06/2021	12.5	−20.89183 165.485 	
D-NCL Anse Vata 01	16/04/1997 19/10/2021	2	−22.30376 166.44331	0.75 (0.88)
E-NCL Récif du Prony 01	12/01/1996 28/10/2021	10.5	−22.26733 166.3325	0.84 (0.89)

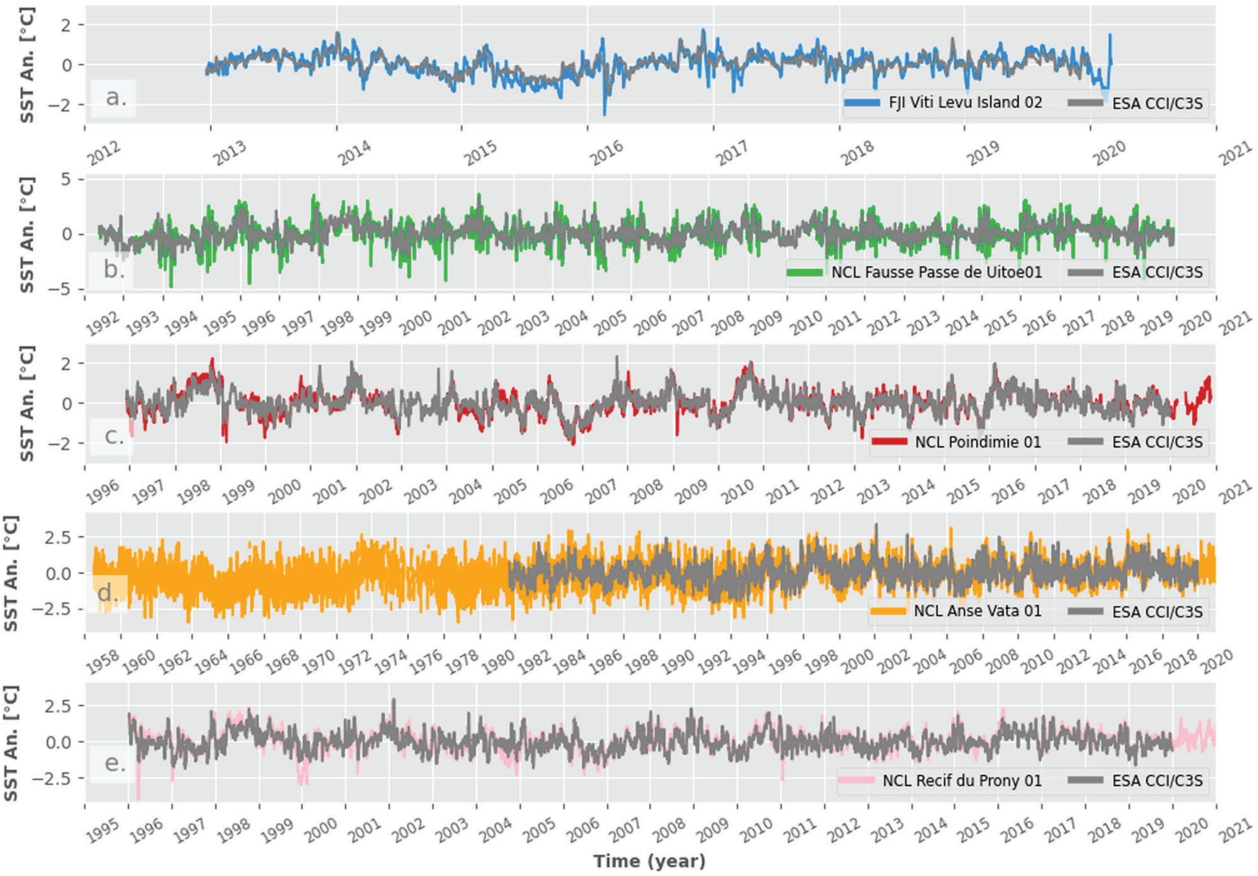


Figure 3.3.2. Time series of daily in-situ SST anomalies at some measurement platforms (coloured lines) in Fiji and New Caledonia of the ReefTEMPS observing network (product ref. 3.3.6). Station locations (a) Suva Reef, Viti Levu, Fiji; (b) Uitoe01, New Caledonia; (c) Poindimié, New Caledonia; (d) Anse Vata, New Caledonia; (e) Prony, New Caledonia] are indicated in the maps of Figure 3.3.1. Satellite derived daily SSTSAT (product ref. 3.3.5) anomalies closest to each measurement platform have been added, respectively (grey line). Anomalies were calculated with respect to the annual climatology over the overlap periods.

0.009 ± 0.007 (Table 3.3.2). For New Caledonia at Poindimié, which is located in the north-eastern part of the country, the surface ocean warming trend is non-significant over the 25 years from both in situ and SSTSAT (Table 3.3.2). These in situ variations in local trends are related to the large spatial variability in trends (Figure 3.3.1) and to numerous local effects, combined with a high variability at interannual timescales (Quinn et al. 1998). At the southwestern part of New Caledonia, both stations Uitoe01 (Figure 3.3.4(b)) and Anse Vata (Figure 3.3.4(b)) show surface warming rates close to the global mean average, with Anse Vata covering the period February 1958 to early 2020. Rates of temperature change as derived from the satellite data underestimate the warming at these locations, in particular at Anse Vata (−36%) and Viti Levu (−62%).

Daily satellite and in situ time series correlations are all above 0.75, well above the significance level (Table 3.3.1). The maximum correlation was found for the logger deployed on the reef slope at Poindimié (0.87), which is of the same order of magnitude as correlations found between SSTSAT and coastal temperature reported by other coral reef studies (Smale and Wernberg 2009; Van Wynsberge et al. 2017; Gomez et al. 2020). With respect to extreme amplitudes, the coloured, regular peaks in Figure 3.3.3 with the overlain satellite series in grey shows a prominent underestimation by satellite products. For a 'hot extreme' definition at two standard deviation, SSTSAT is on average lower by 0.9°C (Uitoé); 0.7° (Vata); 0.4° (Prony); 0.4° (Viti Levu) and 0.3°C (Poindimié), with common excursions at 2°. Equivalently, SSTSAT can overestimate cold temperature by up to 4°C. Previous studies concluded that differences between SSTSAT and temperature recorded by *in situ* sensors deployed on outer reef slopes or in open and exposed lagoons were mostly due to vertical stratification (including a skin effect) of water and localised upwelling along the reef slope that generates lower *in situ* temperature than SSTSAT (Sheppard 2009; Castillo and Lima 2010; Claar et al. 2020). These

Table 3.3.2. Trend calculations during overlapping periods for SST time series from in situ reef loggers (ref 3.3.6) and the remote sensing product (ref 3.3.2).

Station	Station trend (°C/year)	ESA trend (°C/year)	Period
A- FJI Viti Levu Island 02	0.024 ± 0.01	0.009 ± 0.007	21/12/2012 to 31/12/2019
B- NCL Fausse Passe de Uitoe01	0.016 ± 0.002	0.013 ± 0.002	22/05/1992 to 02/12/2019
C- NCL Poindimié01	−0.0001 ± 0.002	−0.003 ± 0.002	09/12/1996 to 31/12/2019
D- NCL Anse Vata 01	0.011 ± 0.001	0.007 ± 0.001	01/09/1981 to 31/12/2019
E- NCL Récif du Prony 01	0.0048 ± 0.002	0.0001 ± 0.002	12/01/1996 to 31/12/2019

processes are unlikely to generate an underestimation of satellite-derived products which, particularly during summer months, are likely to result from higher variability in shallow coastal waters (see, e.g. the shallower sensor D-NCL Anse Vata located near the coast). This higher variability of temperature at local scale could not be captured by the spatial resolution of SSTSAT products (Stobart et al. 2008; Van Wynsberge et al. 2017; Gomez et al. 2020; Van Wynsberge et al. 2020). The underestimation of extremes that we find here requires further analysis and needs to be adapted to relevant extreme indicators, e.g. DHW versus anomalies (see subsection 3.1 below) (Figure 3.3.2).

3.3.2.3.2. Chl-a. Just south of Fiji (Figure 3.3.3(A)), daily (Figure 3.3.3(B)) and monthly (Figure 3.3.3(B)) images depict differences during the months of April and September within the same year. These two dates were chosen to illustrate a case of high Chl-a (> 0.6 mg.m-3) south of Fiji, extending as a large plume off the coast towards the South (April), and a case of low Chl-a (< 0.4 mg.m-3) and no plume (September). For comparison, tropical oligotrophic open ocean Chl-a ranges from 0 to 0.35 mg.m-3 (Dupouy et al. 2018b). For the dates of the Bula cruises, CMEMS daily data were available only on September 2, 2003. Very few daily non-gridded data (product ref 3.3.2, Figure 3.3.3(B)) are available due to heavy cloud cover over this highly convective region, in particular over land and near coasts (Vincent et al. 2011). As a result, we had to rely on the monthly gridded composites (product ref 3.3.4) for our comparison with in-situ Chl-a observations.

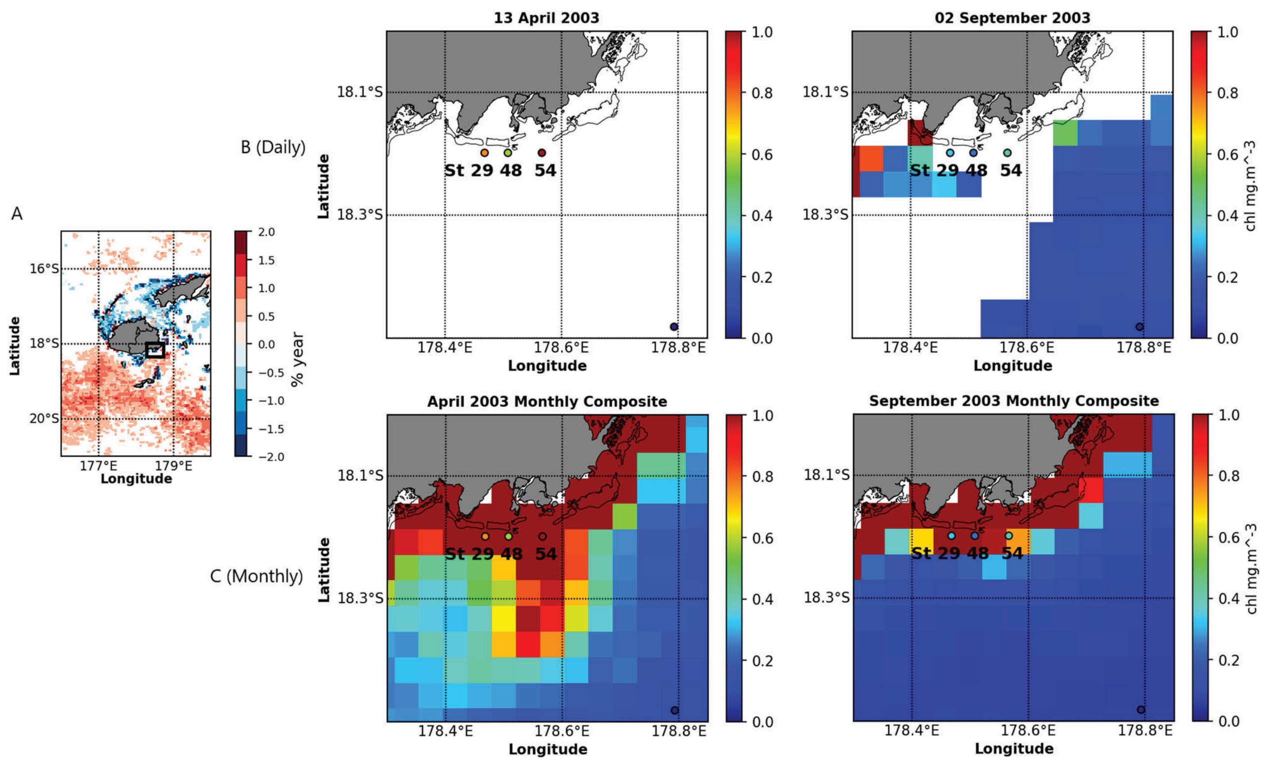


Figure 3.3.3. Chl-a observations: (A) Study area (black outlined box) in proximity to the wider Fiji zone, with Chl-a change (from product ref 3.3.1) (B) Chl-a in the proximity of Fiji in April and September 2003 for the day of the Bula cruise (product ref 3.3.2). In situ data are represented by the coloured circles, on the same colour scale (product ref 3.3.3) (C) Same as (A) based on the monthly Chl-a product (product ref 3.3.1), for April 2003 and September 2003. The two off-shore stations discussed are station 29 and station 48. Station 54 was discarded because of the Rewa river influence. The black dot to the south (178.79°E, 18.48°S) in 'bluest water' corresponds to a station sampled on October 2009 (product 3.3.7).

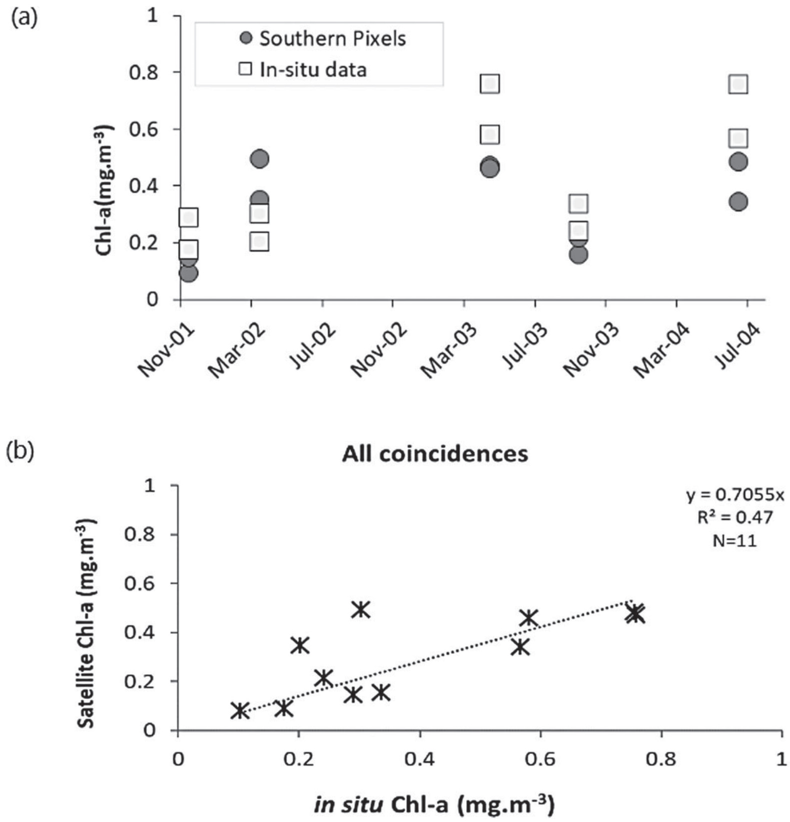


Figure 3.3.4. (a) Chl-a time series of monthly satellite-derived CMEMS Chl-a (product ref. 3.3.1) south of the position of the Bula stations 29 and 48 (grey bullets 'Southern Pixels'), and in situ Chl-a (product ref. 3.3.3) measured by fluorimetry (open squares) for the 5 Bula cruises (Bula 1: 6–11 Nov 2001, Bula 2: 12–19 March 2002, Bula 3: 12–22 May 2003 Bula 4: August 30–September 9, 2003; Bula 5: 5–15 June 2004) and for the S288 Seamans October 2019 cruise (b) Linear regression graph for Bula + Seamans data.

Among the Bula cruise data, two stations (St 29 and St 48) were sampled in open waters (Case 1 waters, behind the reef passages in Figure 3.3.3(B,C)). April and September monthly CMEMS products show Case 2 waters (in brown) near the coast. To avoid contamination by land in the CMEMS Case 2 waters, we selected pixels directly to the south of those stations for our comparisons. Station 54 is at the same distance from the coast, but was discarded because it is under the influence of the Rewa river output (Singh and Aung 2008) with high variability in Chl-a values linked to heavy and episodic sediment loads (Fichez et al. 2006).

Monthly satellite and instantaneous in-situ Chl-a for stations 29 and 48 are correlated despite the high temporal and spatial interpolations or smoothing (Figure 3.3.4(a)). The correlation is significant at 99% ($r^2 = 0.47$, $N = 11$) (Figure 3.3.4(b)).

Temporal evolution of monthly satellite Chl-a at these stations during the 1997–2021 period shows. An increase in variability of Chl-a in 2007 and 2011 at all stations (Figure 3.3.5). The generally higher mean Chl-a value at station 54 (mean Chl-a = 0.53 $mg.m^{-3}$) confirms the impact of the Rewa river episodic runoffs. It superimposes with seasonal and interannual cycles observed at stations 29 (mean Chl-a = 0.37 $mg.m^{-3}$) and 48 (mean Chl-a = 0.47 $mg.m^{-3}$). The Rewa River also increases the number exceedances of a 0.53 $mg.m^{-3}$ threshold: 33% of the time for station 54, 24% for station 48 and 5% for station 29. In contrast, the reference point far south of the 3 stations experiences low Chl-a and a more regular seasonal cycle.

3.3.3. Discussion

3.3.3.1. Strengths and weaknesses of the EOV SST and chl-a products as indicators

We used five pilot sites in New Caledonia and Viti Levu in Fiji to provide insights about CMEMS SSTSAT and Chl-a products strengths and limitations (subsection 3.3.2.2.3 above) for potential application in an ecosystem monitoring and management framework. We found that the bias in SSTSAT products is important when considering extreme events, but acceptable when characterising long-term local changes, with respect to previous studies that find stronger biases (e.g. Sheppard 2009; Castillo and Lima 2010). This may be explained by

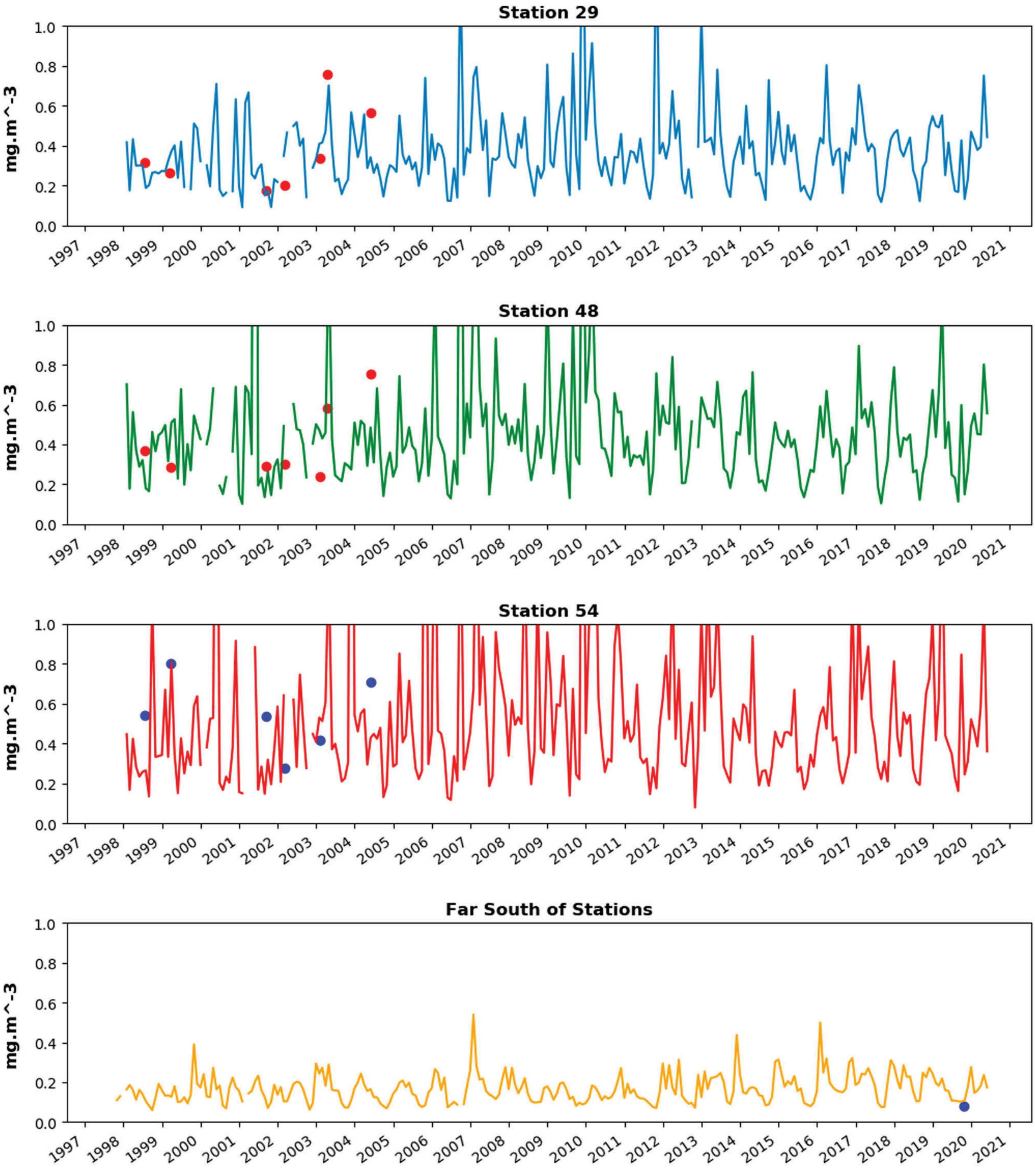


Figure 3.3.5. Satellite-derived monthly Chl-a (ref. 3.3.1) at a pixel just south of the in-situ stations st 29, st 48, st 54 and our reference point to the south (see Figure 3.3.3(B)). St 54 is heavily impacted by the Rewa river and therefore not included in the correlation analysis. Variability is much lower at the reference point to the south. The red and blue dots indicate in the Bula situ data (ref. 3.3.3).

the fact that these sites are either well-flushed with open-ocean waters (sites B-NCL, C-NCL, and A-Fiji), or face a lagoon that includes SSTSAT product pixels (sites D-NCL & E-NCL). Trend biases found here may therefore be unrepresentative of other reef and lagoon configurations that can be encountered in the Pacific region. Extreme warm ocean temperature, or 'Marine Heat Waves' (Holbrook et al. 2019; Oliver et al. 2021; Dayan et al. 2022; de Boisseson et al. 2022), which have major influences on ecosystems, are underestimated although their observation and predictions are essential for marine managers for adaptation and mitigation efforts. Specific analyses are necessary to assess precisely the relation between in situ and satellite-derived time series extremes (Holbrook et al. 2019).

SSTSAT products can provide gridded data on a quasi-real time basis, offering both adequate spatial and temporal resolution. The highest spatial resolution gridded product (L4) is 1 km (Merchant et al. 2019, product ref. 3.3.5), but its effective resolution is coarser. It is relevant for sufficiently wide water bodies (Van Wynsberge et al. 2020) but not for many coastal areas, in particular the complex lagoons and coral reefs relevant to the monitoring aspirations of this study. In contrast, in situ temperature loggers provide high accuracy on a small-scale local level. For coral bleaching applications, *in-situ* loggers can detect very localised temperature peaks caused by poor water circulation, local weather conditions, and water column stratification, or mass exchanges between inner lagoons and outer reef areas. Loggers, however, often provide short time series or series affected by gaps which limit their use for monitoring climate change. To properly describe a given coastal area for monitoring purposes, sensors must be deployed to capture a diversity of depth and reef locations, though very few have real-time transmission possibilities, which limits their practical use in many remote coral reefs. Modelling *in situ* temperature from SSTSAT on the basis of (shorter) temperature time series from loggers (Van Wynsberge et al. 2017) provides a promising downscaling approach to reconstruct long time series at the very local scale, but must be performed case-by-case to account for local specificities in hydrodynamics, reef configuration as well as lagoon size and depth (Van Wynsberge et al. 2017; Reid et al. 2020).

Our results have also explored the relevance of Chl-a products to environmental management. Ocean colour offshore the barrier reefs and south of the Fiji in-situ stations provides the decadal trends and responses of phytoplankton biomass through its Chl-a concentration. The observed increases in Chl-a may originate from the influence of terrestrial inputs such as sediment and dissolved organic matter transports, and ultimately can trace the dissemination of contaminants and responses of pelagic communities to increased nutrient inputs around Fiji (Fichez et al. 2006; Gassner et al. 2019), with potential effects on fish species and fish recruitments in offshore waters around the Fijian reefs. Chl-a increases can also indicate a change in phytoplankton composition (Dupouy et al. 2018a). As for temperatures, the biological activity and associated coastal water colour are influenced by many factors including small scale oceanic processes, human activities and sediment input, and it remains critical to relate satellite data to in situ data before any usage in a monitoring framework.

In situ Chl-a data are much harder to acquire than temperature data, and therefore rare. Our Fijian case study illustrates that a monthly CMEMS Case 1 product partially reproduces the in-situ, instantaneous data for the 5 dates considered here. Case 2 Chl-a pixels were not used as they require different and adapted algorithms. Despite its design for large scale applications, the monthly CMEMS product shows a significant relationship with the limited coastal in situ data set that is available (Figure 3.3.4(b)), with some biases. It may therefore contain temporal and spatial information on oceanic variability around the islands, but its further use for monitoring is subject to validation with in situ Chl-a.

Our analyses of temperature and Chl-a time series therefore point to the advantage in having both in situ and remote sensing data for the same geographical areas. In-situ data are essential for accuracy monitoring at small spatial scales (e.g. local reef temperature, coastal ocean water quality), and in particular for extreme events. In situ measurements represent true local conditions, but with a necessarily limited coverage in time and space; whereas remote sensing data have broader coverage but are necessarily limited in terms of resolution and local accuracy. The corresponding data products and interfaces need therefore to be design according to local needs, as we discuss below.

3.3.3.2. A potential way forward: A co-construction monitoring framework using an integrated, transdisciplinary, multi-scale approach

Unprecedented and amplified impacts of ocean climate change occur at local scales, and adaptation measures (including socio-technical, political, cultural and or institutional innovations) and strategies need to be informed and designed at the regional and local levels. Actions need to be implemented in an integrated, transdisciplinary and multi-scale framework (Máñez Costa et al. 2017; Rölfer et al. 2020; Celliers et al. 2021). The UN Decade of Ocean Science for Sustainable Development provides a foundation to help achieve this objective and to ensure science responds to the needs of society 'to reverse the decline in Ocean health' by promoting codesign approaches (Ryabinin et al. 2019; GOOS 2022). Ocean products that are designed under global frameworks offer critical insights on general ocean change, variability and their drivers, but it may either be under-utilised or mis-utilised at local scales for various reasons: (1) other factors may need to be considered when working on mitigation or adaptation of an ecosystem (ecosystem/nexus approach); (2) the understanding by local actors about ocean climate change consequences may differ substantially from the scientific understanding underpinning the global monitoring frameworks; (3) local specificities challenge the downscaling or upscaling techniques; and (4) potential consequences can generate unanticipated and negative local effects.

To address these issues in Oceania and following Belmont Forum and Ocean Decade initiatives, we promote here the following considerations for stakeholders, including scientists, public officers and citizens of the Pacific Islands to share common objectives and actions in order to achieve environmental sustainability when designing monitoring systems:[3]

(1) *Ecosystem approach* (Skern-Mauritzen et al. 2016; Liu et al. 2018): Consideration of an ensemble of stressors, including environmental, socio-economic, cultural and political aspects (Zhang et al. 2021).
(2) *Shared understanding:* Local understanding and representation climate change impacts depends on knowledge, values, drivers, barriers and opportunities. The accessibility and utility of products for stakeholders needs to come with a shared understanding of climate change impacts and indicators (Kaiser et al. 2019; Mackenzie et al. 2019; Vargas-Nguyen et al. 2020).
(3) *Scalability in coastal areas*: Globally based indicators may miss important issues as revealed by local experience and combining and matching needs and knowledges produced at different scales and from different ontological viewpoints entails combining heterogeneous elements that cannot be 'added' to one another in many cases ('non-scalability') (Tsing 2012, 2015), nor generalised to other places (see Bergthaller et al. 2014 on 'the practice of environing').[4]
(4) *Forecast ethics:* Delivery of forecast products can have heavy consequences, given uncertainties, or generation of inequalities from unbalanced capacities to use it, and therefore needs to come with ethical considerations that include engagement and equity for end users (Hobday et al. 2019).

To produce those relevant indicators, extend existing EOVs (or implement new EOVs), and build interest and ability to use them, bottom-up driven consultations and developments are essential steps (e.g. Claudet et al. 2020). Such participative framework can foster an enriching dialogue, provide new insights about socio-ecological processes, and contribute to augment the perception of unprecedented ocean changes (Johannes 1981; Hviding 2005; Singh et al. 2021). Indigenous peoples and local communities (IPLC) can actively contribute to the process.[5] For instance, IPLC knowledge in combination with remote sensing allowed efficient mapping of the tropical marine habitat of the Solomon Islands (Lauer and Aswani 2008). Combined analysis of fishermen's local knowledge with remote sensing data for SSTSAT and Chl-a can lead to participatory mapping of fishing grounds (Rahimi bin Rosli 2017; Mason et al. 2019) and support marine conservation and management (Aswani and Hamilton 2004; Aswani and Lauer 2006). (See McNamara et al. (2020) and Chambers et al. (2021) for a review of such co-constructed projects for sustainability.) The identification and synthesis of data and knowledge sources by structured consultation with project partners, scientists, and stakeholders is therefore needed to take the next steps toward a co-designed monitoring framework (Vargas-Nguyen et al. 2020), including locally based and globally produced knowledge (Hviding 2003; Strang 2009; Sterling et al. 2017).

In Oceania, these efforts will come in support of ongoing projects, in particular, the SPC-lead Pacific Community Centre for Ocean Science (PCCOS) programme[6] for delivering integrated scientific services supporting ocean management, governance and observations; the Pacific Data Hub[7] as well as the Digital Earth Pacific[8] that aim at gathering available data and make it available for Pacific Member States to make more informed decisions and report their progress toward the United Nations SDGs,[9] and the recent USP/UNC Master in sustainability.

Section 3.4. Consistent data set of coastal sea level: The synergy between tidal gauge data and numerical modelling

Authors: Sebastian Grayek, Emil Stanev, Nam Pham, Antonio Bonaduce, Joanna Staneva

Statement of main outcome: The multiannual (1993–2020) variability of sea level in the Baltic Sea is reconstructed by applying a Kalman filter approach. This technique learns how to generate data sets with the same statistics as the training data set, which in the studied case was taken from the CMEMS Baltic MFC operational model. It is demonstrated that using tide gauge data and statistical characteristics of the Baltic Sea from the model enables the generation of a high-resolution reconstruction of the sea surface height. Results obtained in this study demonstrated that the reconstruction method offers comprehensive high-resolution estimates (space and time) of sea level variability in the