# Oceanographic and Atmospheric Risks in Wallis and Futuna

Clim.Systems.

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# The Latest CMIP6 IPCC Climate Models - Similarities and Points of Difference with CMIP5 for the Pacific Region

This is the first of six newsletters funded by the French Pacific Fund project, provided by ClimSystems and supported by the New Zealand Meteorological Service (MetService) and, of course, the French Embassy in Wellington. This initial document is a regional discussion piece on the similarities and differences between two sets of climate models released under the Intergovernmental Panel on Climate Change (IPCC) World Climate Research Programme (WCRP) Couple Model Intercomparison Project (CMIP). Subsequent newsletters will roll out every two months and cover five additional topics: ocean variables in CMIP6; sea level rise patterns and extreme still high-water levels with CMIP6 models; seasonal ocean temperatures profiles and fisheries; CMIP6 ocean current data and medium- and longer-term issues; and finally, CMIP6 atmospheric variables and FAO bioclimatic approaches for agricultural risk assessment and adaptation planning. These subsequent newsletters will have more of a focus on Wallis & Futuna.

ClimSystems is at the forefront in processing the considerable volume of CMIP6 raw General Circulation Model (GCM) data for the Pacific and the world. With a focus on atmosphere, land and ocean data over 60 variables have been processed for five key Shared Socioeconomic Pathways (SSPs). The latest CMIP6 data has also been applied in the French Pacific Funded physical climate risk assessment recently completed for Wallis and Futuna with the assistance of Météo-France and MetService in New Zealand. The assessment and newsletters support the World Meteorological Organisation's initiative of public and private institutional partnerships to meet the challenges posed by climate change.

### The History of CMIP Modelling

The latest Sixth Assessment Report (AR6) of the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) had its first planning meeting in 2013. This led to the publishing in 2016 of an overview of the design and organisational structure. This progressed in 2018 to the endorsement of 23 Model Intercomparison Projects (MIPs) involving 33 modelling groups in 16 countries. Four primary reports were scheduled for release:

- AR6 Climate Change 2021: The Physical Science Basis (released in August 2021)
- AR6 Climate Change 2022: Impacts, Adaptation and Vulnerability (released February 2022)
- AR6 Climate Change 2022: Mitigation of Climate Change (released April 2022)
- AR6 Synthesis Report: Climate Change 2022 (rescheduled for release in late 2022 or early 2023)

CMIP6 consists of the "runs" from around 100 distinct climate models being produced across 49 different modelling groups. These models are running several new and updated emission pathways that explore a much more comprehensive range of possible future outcomes than were included in CMIP5. In general, several models have notably higher climate sensitivity than models in CMIP5 (Zelinka et al. 2020). This higher sensitivity contributes to projections of greater warming this century – around 0.4C warmer than similar scenarios run in CMIP5 – though these warming projections may change as more models become available.

Several new scenarios are also being used for CMIP6 to give scientists a wider selection of futures to simulate. The new scenarios that can be applied for risk and vulnerability assessments are limited to the following five in SSPs: SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5.

As with CMIP5, there is a range of models available for application with CMIP6 depending on the variable being applied. This is important when applying methods for variables such as wind and for extreme analysis for rainfall that require sub-monthly data. Runs of 6 and 3 hourly rainfall permit higher temporal resolution analysis to support the short-term extreme rainfall event trend in some geographies where an increase in intensity is evident while monthly and annual rainfall could either vary little or decrease.

While there is always a level of uncertainty with any of the climate models, some trends are predicted with high certainty under the Intergovernmental Panel on Climate Change's (IPCC) latest CMIP6 models. For example, the frequency of heavy rainfall events is predicted to increase in the western tropical Pacific, while higher evapotranspiration may amplify or offset the effect of different rainfall patterns leading to an increase in drought events.

**Comparing CMIP6 to CMIP5**

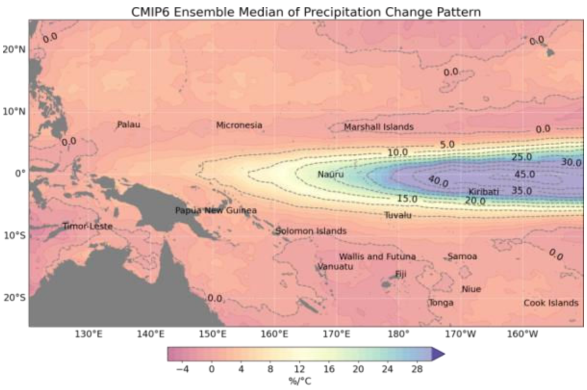
Interpreting CMIP6 versus CMIP5 outputs requires the consideration of baselines. CMIP6 baselines and models are based on two climatological windows that are different from the CMIP5 baselines and models. The IPCC Fifth Assessment Report (AR5), and IPCC CMIP5 datasets were the most important source for future climate projections and the baseline period generally ranges from 1986 to 2005 (centred on 1995). However, for CMIP6 the baseline generally ranges from 1991 to 2020 (centred on 2005).

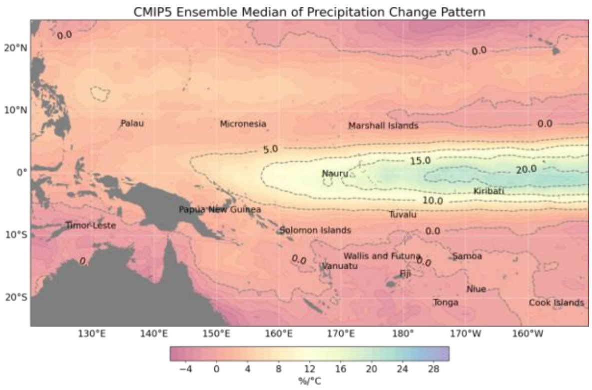
Although climate indices are calculated from daily or monthly time series data, they are presented as monthly or yearly statistics. All indices should be explained from the perspective of climatological statistics. Taking the index of Monthly Mean Temperature as an example, its value in a specific month for the baseline (i.e., 2005) is, in fact, the mean value of daily temperature in that month for the whole baseline period (i.e., 1991 – 2020), which is a typical 30-year climatological statistical value. For a future period (e.g., 2050), its value should be considered a statistical value for a specific ensemble percentile under a specific CMIP6 SSP.

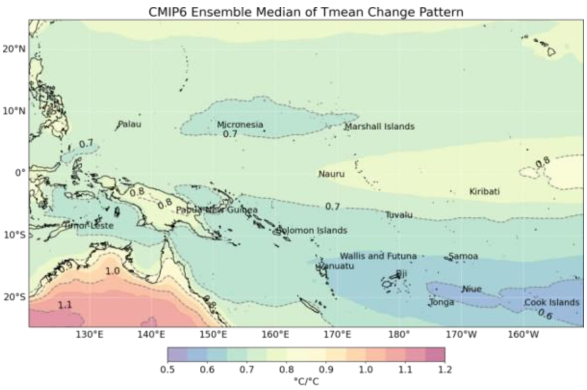
When interpreting the following comparison of AR5 versus AR6 outputs for the Pacific you will need to consider the shift in baseline (some climate change is baked into the results) and the heightened climate sensitivity of the CMIP6 models over the CMIP5 outputs. In general, the temperature outputs for the region against the global are similar with temperature increases slightly lower than the global trend per degree C at between 0.6 and 0.8 degrees per global 1.0 degree C increase. While as expected the continental interior of Australia is increasing slightly above 1.1 degrees C for each 1.0 degree C rise globally.

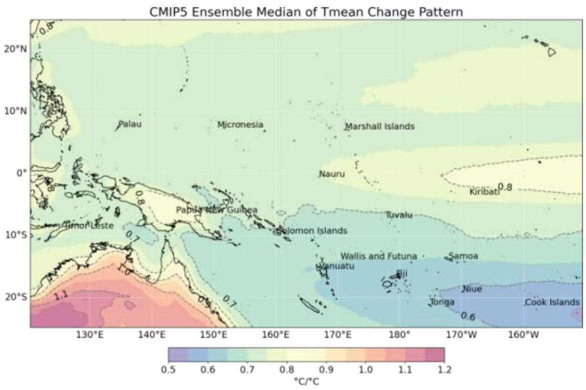
Precipitation is for most of the Pacific little changed in terms of percentage change versus global trends per degree C of global warming. However, for the northern part of the intertropical convergence zone, the central Pacific does show the potential for a considerable increase in rainfall with up to a 40 percent (versus 20 percent in CMIP5) increase in rainfall percentage of the global average change per degree C of warming.

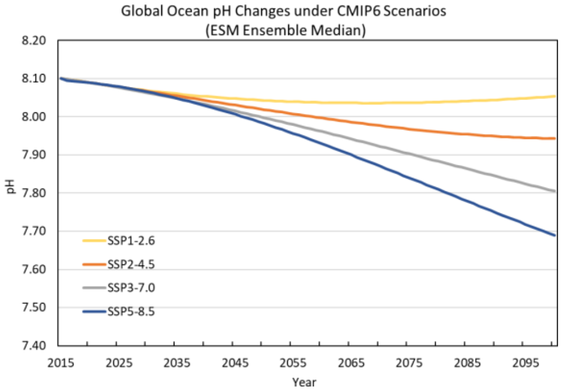
When considering the potential acidification of surface waters in the Pacific as shown in the pH map of the region it in important to consider global ocean changes. The graph of acidification represents the global changes in pH for all marine waters; while the map of the Pacific changes in pH are the changes regional in the context of global change. Therefore only in the equatorial zone is pH potentially going to be changed less than the global average, but only marginally so; the waters of the Pacific are still likely to become more acidic with all the implications this has already been shown to have on shellfish and coral reefs.

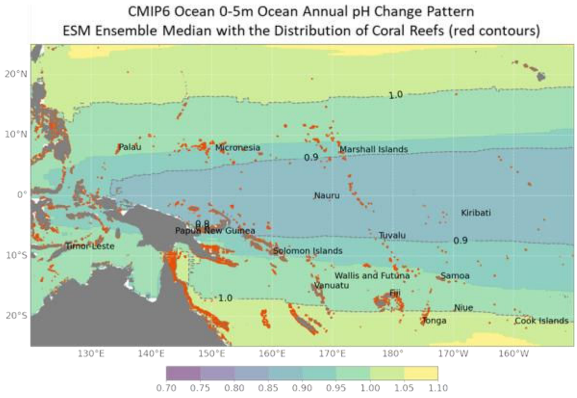

CMIP6 Ensemble Median of Precipitation Change Pattern


CMIP5 Ensemble Median of Precipitation Change Pattern


CMIP6 Ensemble Median of Tmean Change Pattern


CMIP5 Ensemble Median of Tmean Change Pattern

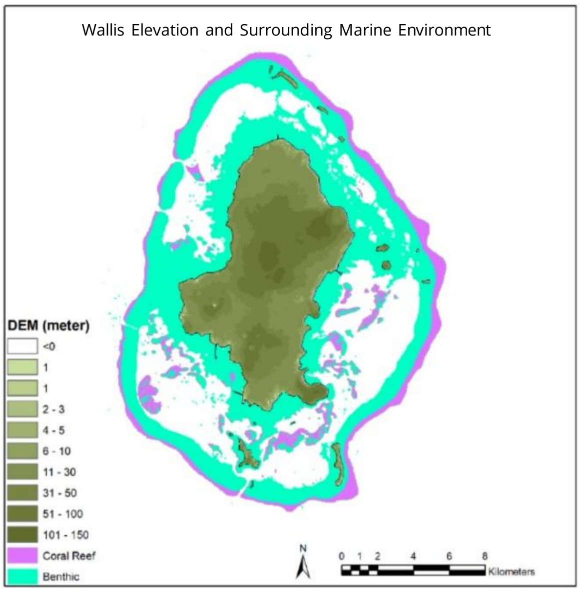

Global Ocean pH Changes under CMIP6 Scenarios
(ESM Ensemble Median)


CMIP6 Ocean 0-5m Ocean Annual pH Change Pattern
ESM Ensemble Median with the Distribution of Coral Reefs (red contours)

## CMIP6 Oceanic and Environmental Data

A key difference between CMIP6 and CMIP5 data can be found in the marine variables. monthly-mean 2-d ocean data (latitude, depth, region, time: month) over all oceans and also zonal mean for individual ocean basins are available. Data developed by modelling groups is provided on depth levels. The recommend levels match the 33 standard levels of Levitus observations: 0, 10, 20, 30, 50, 75, 100, 125, 150, 200, 250, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500, 1750, 2000, 2500, 3000, 3500, 4000, 4500, 5000, and 5500 meters.

The inclusion of such depth levels has led to an exponential increase in data available for marine environmental assessments. This has considerable implications in data holding and processing which is important when considering the application of these data sets in impact assessments. However, not all modelling groups have followed the data zonal recommendation. Much depends on the marine climate variable with for example more data outputs available for ocean temperature changes than for ocean currents and the key biogeochemical elements, such as salinity, dissolved nitrate, oxygen, phosphate, iron, silicate concentration, total alkalinity and salinity at the surface and net primary production of carbon by phytoplankton and pH.


Wallis Elevation and Surrounding Marine Environment

Most of the CMIP6 models generally outperform their CMIP5 predecessors in many regions and for most of the marine biogeochemical fields (Séférian et al. 2020). Most modelling groups have spun up their models over a longer period for CMIP6 than CMIP5. In the context of improving confidence in future climate projections, it is important to stress that the model mean state performance is not the only mean to understand multi-model uncertainty, comparisons against seasonal to multi-annual variations in observed quantities may ultimately prove most critical to building confidence in future climate projections in the marine space.

Importantly ocean GCM data can be supplemented by increasingly higher-resolution environmental data. For example, reef databases have improved dramatically in their categorisation and spatial resolution. Similarly, the burgeoning interest in blue carbon has led to more high-resolution data available for benthic environments, seagrass beds and mangroves, for example. The implications of changed oceanic environmental parameters can now be better modelled owing to the constantly improving quality of baseline marine biodiversity information, including fisheries data.

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# Seasonal ocean temperature profile forecasts for the Pacific - CFSv2 data and end-user availability and application, with a general focus on Wallis & Futuna

Climate change is having significant impacts on Pacific fisheries, both ecologically and economically. The Pacific Ocean is warming at a faster rate than other oceans, leading to changes in ocean currents, water temperature, and ocean chemistry. These changes affect the distribution and abundance of fish stocks and their habitats, which can have cascading effects throughout the food web.

Some of the impacts of climate change on Pacific fisheries include:

1. Changes in fish distribution and abundance: Warmer water temperatures are causing fish species to move to new areas, which can lead to changes in the abundance and availability of fish in different regions. For example, some fish species may move farther north or south, away from their traditional ranges (Palacios-Abrantes et al. 2022).

2. Changes in ocean productivity: Changes in ocean temperature and chemistry can affect the productivity of phytoplankton and other primary producers, which form the base of the marine food web. This can impact the abundance and distribution of fish and other marine species that rely on these resources for food (Goldfarb 2017).

3. Increased frequency and severity of extreme weather events: Climate change is causing more frequent and severe storms, floods, and droughts, which can disrupt fishing activities and damage infrastructure such as fishing boats and processing facilities. Landuse change and increased climate-induced erosive events can impact near shore turbidity and disrupt lifecycles for aquatic fauna. Potential shifts in sedimentation rates and dispersion of pollutants can also negatively impact coastal flora and blue carbon potential (Brown et al. 2019).

4. Economic impacts: Changes in fish distribution and abundance can have significant economic impacts on fishing communities that rely on these resources for their livelihoods. For example, a decline in certain fish species can result in lower catch volumes and reduced income for fishers. Climate change and seasonal shifts in water temperatures and fish distributions are therefore likely to alter food supplies and revenues of maritime countries like Wallis and Futuna. Understanding these potential changes is crucial when developing and implementing effective medium- and longer-term socio-economic policy and food sustainability strategies (Lam et al. 2016).

To address the impacts of climate change on Pacific fisheries, it is important to take steps to mitigate and adapt to these changes. This can include measures such as improving the sustainability of fishing practices, developing new technologies for monitoring and managing fish stocks, and supporting the development of alternative livelihoods for fishing communities.

In Wallis and Futuna and elsewhere in Oceania tuna fisheries are an important source of revenue and sustenance. Tuna are large, fast- swimming fish whose specific location and migratory patterns exploit various ocean depths and hence water temperatures, depending on the species of tuna. For example:

- Skipjack tuna: This species of tuna is found in tropical and subtropical waters worldwide, often in large schools near the surface. They can be found at depths ranging from the surface to about 260 meters.

- Yellowfin tuna: Yellowfin tuna are also found in tropical and subtropical waters worldwide, but they tend to be more solitary than skipjack tuna. They can be found at depths ranging from the surface to about 400 meters.

- Albacore tuna: Albacore tuna are found in temperate and tropical waters in the Atlantic and Pacific oceans. They can be found at depths ranging from the surface to about 300 meters.

- Bluefin tuna: Bluefin tuna are found in the Atlantic, Pacific, and Indian oceans, and are known to migrate long distances. They can be found at depths ranging from the surface to about 900 meters.

It is worth noting that these depths are approximate and can vary depending on the location, season, and other factors.

The South Pacific is home to several species of tuna. The most commonly caught tuna species in the region are:

1. Yellowfin Tuna (Thunnus albacares): This species of tuna is found throughout the world's oceans, including the South Pacific. It is popular among fishermen and is prized for its mild flavor and firm texture.

2. Bigeye Tuna (Thunnus obesus): This species of tuna is also found in the South Pacific and is similar in appearance to the yellowfin tuna. It has a higher fat content than yellowfin tuna, which gives it a richer flavor.

3. Skipjack Tuna (Katsuwonus pelamis): This is the most abundant tuna species in the world and is found in large numbers in the South Pacific. It is smaller than yellowfin and bigeye tuna and is commonly used for canned tuna.

4. Albacore Tuna (Thunnus alalunga): This species of tuna is found in the cooler waters of the South Pacific and is also known as "white tuna" due to its light-coloured flesh. It is typically sold canned or as a fresh steak.

5. Pacific Bluefin Tuna (Thunnus orientalis): This species of tuna is found in the North and South Pacific and is highly prized for its rich flavor and texture. It is often served as sushi or sashimi and is also used for canning. However, due to overfishing, Pacific Bluefin tuna populations are currently considered to be severely depleted.

CFSv2 (Couples Forecast Systems Version 2) data are applied at various ocean depths to exemplify the seasonal shifts in ocean temepratures are different sampled depths. In this newsletter example it is at 5, 25, 55 and 105 metres. See the images below for the historical monthly sea temperatures for the Wallis and Futuna region for a three month period. The second set of maps represents the anomalies to the long term normal at the sampled depths. This is a simplified example as various depths could be explored (list of depths can be found below) to forecast for different impacts on flora or fauna and tropical cyclogenisis.
The CFSv2 ocean forecasting is available at various depths: 10 metre steps from 5 metres to 225 metres, then somewhat irregular therafter: 5, 15, 25, 35, 45, 55, 65, 75, 85, 95, 105, 115, 125, 135, 145, 155, 165, 175, 185, 195,
205, 215, 225, 238, 262, 303, 366, 459, 584, 747, 949, 1193, 1479, 1807, 2174, 2579, 3016, 3483, 3972, 4478. The forecast is updated every ten days.

## Discussion

The issue of seasonal changes in ocean temperature at various depths is important. Some tuna exhibit distinct diurnal vertical movements, remaining in upper layers at night and in deeper layers during daytime. Seasonal temperature patterns indicated that the vertical thermal structure of the ocean might influence this ascent behaviour of juvenile tuna (Hino et al. 2019). Subtle changes in the thermocline of the range of a tuna species habitat may have a direct impact on their reproductive behaviour, survival rates of juveniles and species distributions. With this in mind, mapping of the various depths of the ocean thermoclines across the Wallis and Futuna EEC was conducted to explore how temperatures can change at depth and how the forecasted anomalies from longer term normal change over a monthly timestep. The maps below depict three CFSv2 (NCEP coupled forecast system model version 2) temperature anomaly forecast for samples layers of 5-, 25-, 55- and 105-meter depths and for three months into the future.

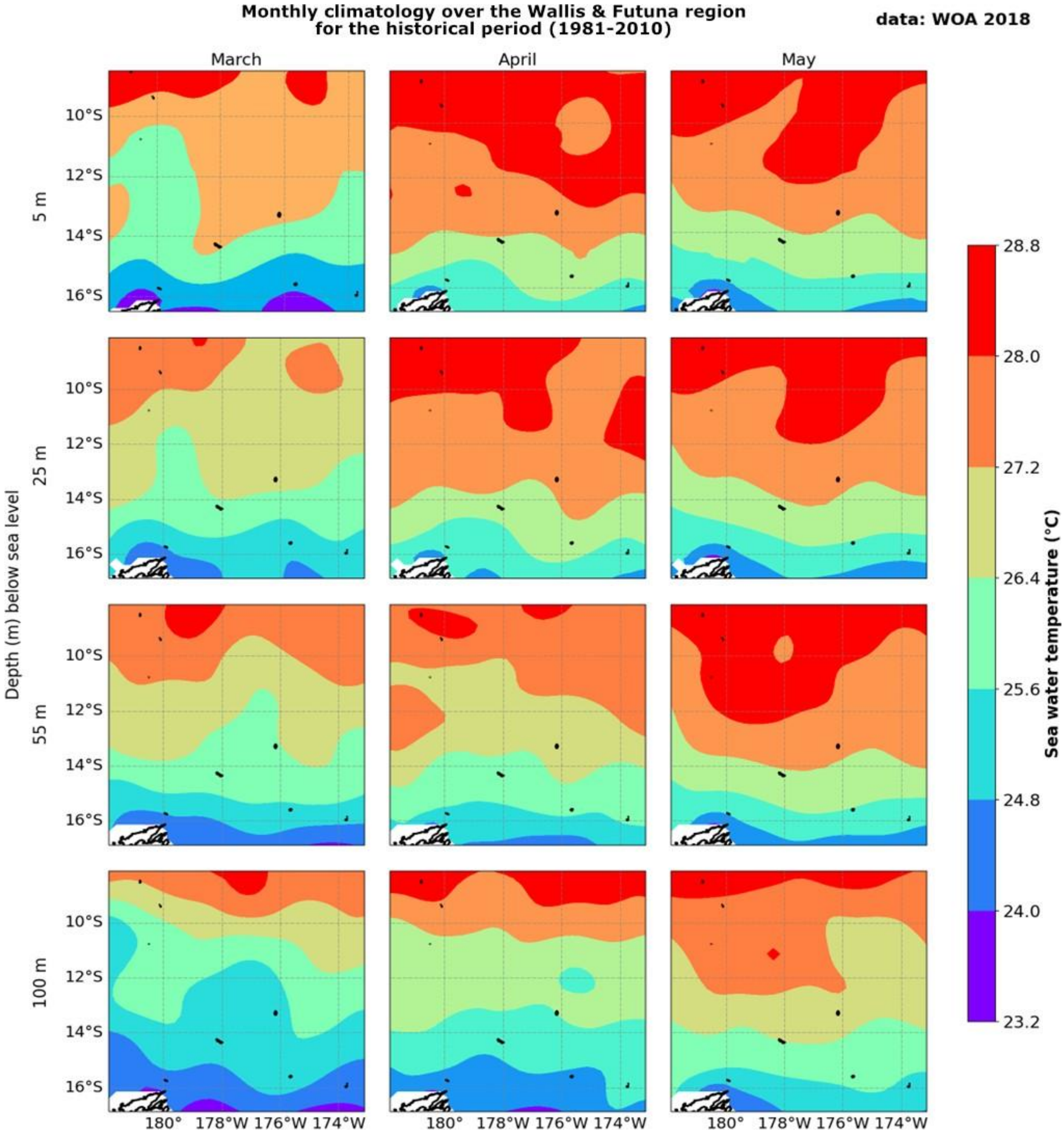
For the forecast period several aspects are apparent. For the historical period there is a distinctive north to south gradient in sea temperatures at each of the marker depths and the range is considerable as at 5 meters depth the range is between roughly 29 to 23 degrees C.

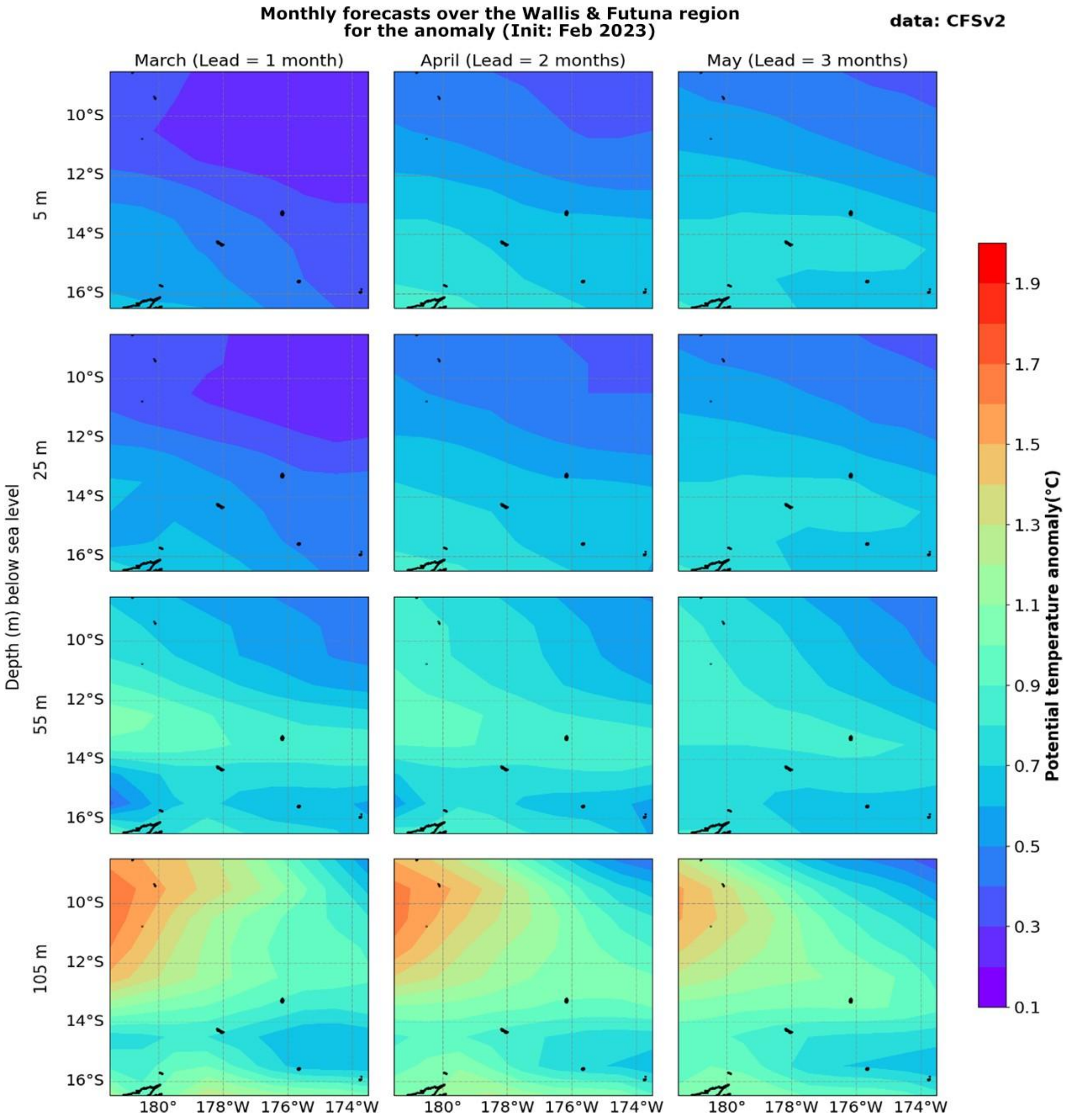
With the three-month forecast the current trend is for a warming of the waters at all depths but at very different pace in the anomaly over the three months at each depth. At a 5-meter depth the slow pace of anomalous warming increases over the three months. A similar trend appears at 25 meters.

While at 55 metres the pace of change is muted and mixed in terms of the anomaly pace of change across the region. Finally, at 105 metres the pace slows rather than increases at a range of speeds above.

What these forecasts can expose is the trends in potential changes in sea water temperatures at various depths as part of the longer-term ENSO cycles. They can also be used to explore the analogous ocean heat and energy nexus for the generation of regional weather i.e., wetter and drier cycles.

There is increasing evidence of anomalous temperature changes at depth being important in tropical cyclone development, rapid intensification and intensity (Wu et al. 2018). The start and the future end of ocean heat waves can also be planned for through the application of seasonal water temperature at various depths forecasts. This can influence planning of economic activities and potential opportunities for mitigating ecosocial impacts through adaptive responses as has been seen in the forecasting of El Niño seasonal droughts in a Pacific island environment (Urich et al. 2009).


Monthly climatology over the Wallis & Futuna region
for the historical period (1981-2010)
data: WOA 2018
March
April
May
5 m
25 m
55 m
100 m
Depth (m) below sea level
10°S
12°S
14°S
16°S
180°
178°W
176°W
174°W
Sea water temperature (°C)
28.8
28.0
27.2
26.4
25.6
24.8
24.0
23.2


Monthly forecasts over the Wallis & Futuna region
for the anomaly (Init: Feb 2023)
data: CFSv2
March (Lead = 1 month)
April (Lead = 2 months)
May (Lead = 3 months)
Depth (m) below sea level
5 m
25 m
55 m
105 m
10°S
12°S
14°S
16°S
180°
178°W
176°W
174°W
Potential temperature anomaly(°C)
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9

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# Ocean Variables in CMIP6, Review, Parameters and Processing for End Users

The environment is changing on a global scale as a result of changes in the atmospheric concentrations of carbon dioxide (CO2) and other greenhouse gases caused directly by anthropogenic emissions and changes in land use and indirectly by processes such as the melting of the permafrost, which releases methane to the atmosphere. This increase in atmospheric concentrations causes an increase in air temperatures, commonly referred to as global warming or global climate change. No doubt exists that human activities are driving these accelerated changes.

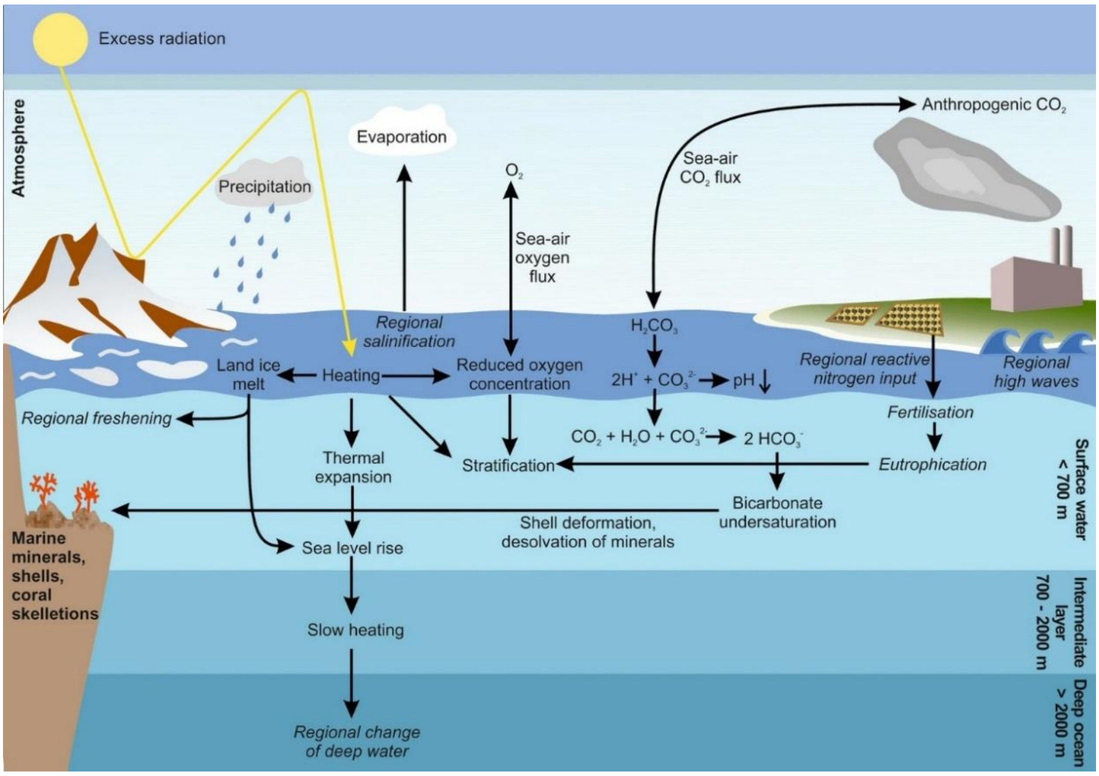


Figure 1: A simplified atmospheric, land, and ocean interactive model focused on ocean changes (Source: Käse and Geuer, 2018).

Climate change affects the atmosphere and terrestrial ecosystems and profoundly affects the oceans. Many of the ocean's biogeochemical cycles and ecosystems are becoming stressed by many factors driven by climate change: rising water temperatures through the near-surface ocean profile (<700 metres), ocean acidification, deoxygenation, regional salinification and secondary effects such as changes in extreme marine environment wind speeds and associated changes in significant wave heights. Marine heatwaves have entered the lexicon with new lessons being learned with each new event on the primary, secondary and tertiary ecosystems and economic impacts on livelihoods and community wellbeing. Of course, sea level change and extreme still high- water level events (to be covered in another newsletter) are also accelerating. Each of these variables can cause a substantial change in the physical, chemical, and biological environment, affecting the ocean's biogeochemical cycles and ecosystems in ways that we are only beginning to fathom (Figure 1).

This newsletter introduces some of the CMIP6 ocean parameters that have been processed for application in the Pacific and worldwide. Examples of several variables and their change over time for the EEZ of Wallis and Futuna are mapped.

Knowledge of marine variables, including sea temperature (SST), currents and sea level rise, is vital for small island States such as Wallis and Futuna. This newsletter provides an overview of the changes that Wallis and Futuna and its EEZ (Exclusive Economic Zone) may experience following different scenarios under the latest CMIP6 data for some of these variables. Key variables like ocean warming, acidification, deoxygenation, and upper-ocean nutrient and primary production are likely to decline under CMIP6 model projections.

Therefore, important climate change questions in fisheries and marine conservation research require projections of plausible climate forcing—and, therefore, scenarios—as input. Such questions include: Will species evolve to cope with climate change? Where and how far will species shift their geographic ranges as climates change? How will warming and species shifts associated with it impact trophic dynamics and food webs? How will climate change affect ocean currents and regional climates? How will ocean acidification progress, and what will its impacts be? Which coral reefs will survive this century? How might climate change interact with other human pressures on aquatic species and ecosystems? The answers to these questions have profound ramifications for ecosystems, coastal communities, and fisheries management.

In this newsletter, we provide slices of marine data. We have processed ten important biogeochemical impact indicators (Table 1).

Not all variables have data at all the following depths, but many are represented at up to 57 levels. From the surface to 100 metres, global ocean data is at five-metre intervals to 100 metres. From 100 metres to 500 metres, data is available at 25-metre intervals. From 500 metres to 1500 metres, data is at 50-metre intervals.

The CMIP6 archive provides future projections from many GCMs (Global Climate Models), which formed a large ensemble. Ensemble analysis is carried out, and the 50th ensemble percentile (i.e., Median) is displayed in the newsletter as the best estimation. At the same time, the range between the 5th and 95th can be applied as typical percentiles to describe the uncertainty of GCM projections.

Other processed marine data available from various marine datasets include marine heatwave days and frequency, mean sea level rise and extreme still high water levels that consider local vertical land movement trends.

Heatwaves like on land can occur in the ocean, and are known as marine heatwaves (i.e., MHWs). Marine heatwaves are defined as when ocean temperatures are extremely

| | |
|---|---|
| Net primary production of carbon by phytoplankton (gC/m3/day) | Dissolved nitrate concentration (mmol/m3) |
| Dissolved oxygen concentration (mol/m3) | Dissolved phosphate concentration (mmol/m3) |
| Dissolved iron concentration (umol/m3) | Dissolved silicate concentration (mmol/m3) |
| pH | Total alkalinity (mol/m3) |
| Sea temperature (˚C) | Surface salinity (PCU) |

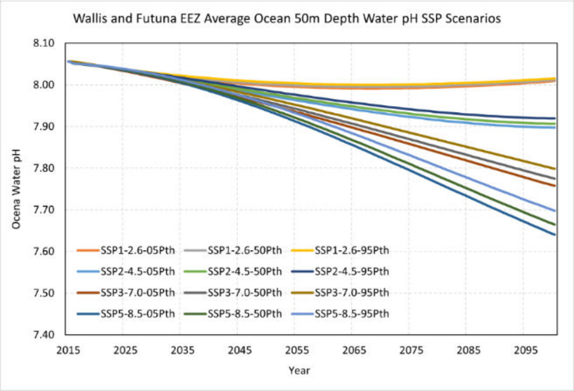
Table 1: Processed biogeochemical impact indicators

warm for an extended period. The key baseline data set is derived from the NOAA Optimum Interpolation (OI) Sea Surface Temperature (SST) V2. To be defined as a heatwave daily SST must exceed the calendar-day 90th percentile (SST90) for at least five consecutive days. The SST90 is a daily percentile climatology with a length of 366 days.

Despite a growing appreciation of their importance, scientific understanding of marine heatwaves (MHWs) is in its infancy compared to atmospheric heatwaves. Marine heatwaves affect ecosystem structure by supporting certain species and suppressing others thus changing the habitat ranges of certain species. Biodiversity can be drastically affected. Moreover, marine heatwaves can cause economic losses through impacts on fisheries and aquaculture.

Sea water salinity is expressed as a ratio of salt (in grams) to a litre of water. Seawater typically has close to 35 grams of dissolved salts per litre. It is written as 35‰ (or 35 PCU). The normal range of ocean salinity ranges between 33-37 grams per litre (33‰ - 37‰) or (33PCU - 37PCU), but some places tend to be higher or lower.

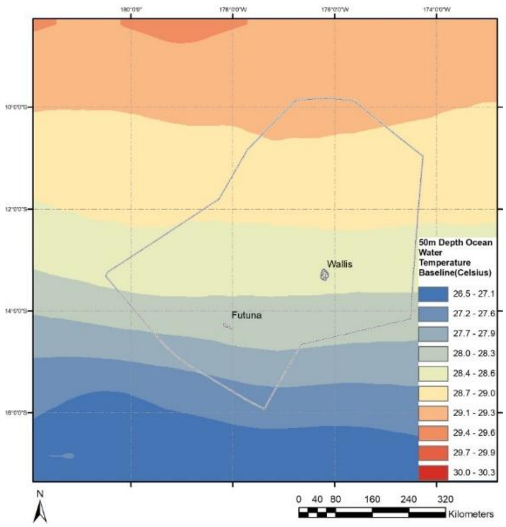
The pH scale runs from 0 to 14, with 7 being a neutral pH. Anything above 7 is basic (or alkaline), and anything lower than 7 is acidic. Seawater is naturally alkaline. The pH of seawater is >7 and is slightly alkaline due to dissolved basic minerals and the natural buffering from carbonates and bicarbonates in the water.



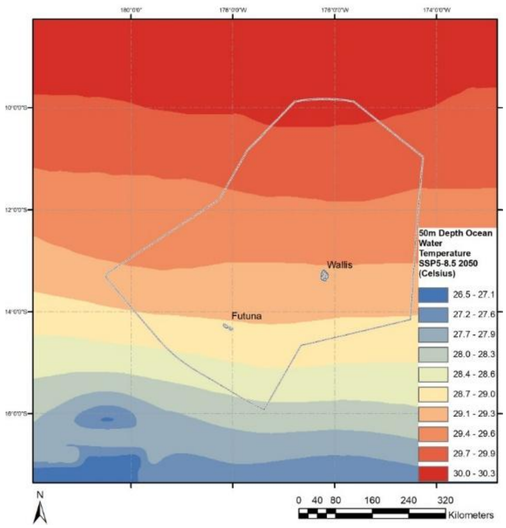
The temperature of ocean water varies by location – both in terms of latitude and depth, due to variations in solar radiation and the physical properties of water. This, for example, can be impactful on tuna movement through the region. Thermal stratification and other environmental characteristics such as dissolved oxygen (DO) concentration, pressure, light intensity and quality, and prey abundance can vary considerably with depth, latitude, and seasonally. In a climate-changed future, it will be essential to understand tunas' spatial and temporal movement patterns and to measure the correspondingly altered environmental conditions that influence them.

Understanding wave characteristics is crucial for marine activities, coastal environments, weather forecasts, and climate change. There are several aspects to wave characterisation: significant wave height (H s), mean wave direction (θ), and mean wave period (Tmn) are often used for fishing, shipping, tourism, and other leisure activities. Efficient marine transportation and navigation depend on wind wave estimation and simulation. Sedimentation and erosion processes due to incoming waves can impact reef and shore environments and beach morphologies. Shoreline orientation can be sensitive to directional changes in waves. Storm surges have an additional impact when accompanied by high waves and low atmospheric pressures and can have profound economic impacts on coastal communities, their economy, and recovery.

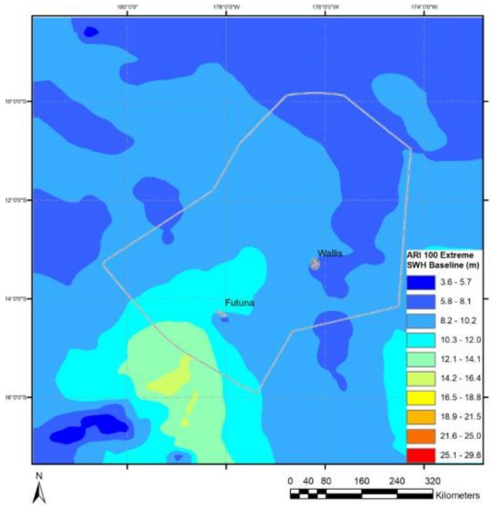
Wallis and Futuna EEZ 50m Depth Ocean Water Temperature
Baseline



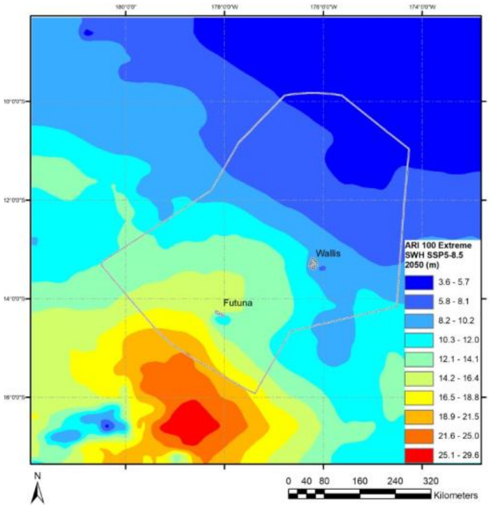
Wallis and Futuna EEZ 50m Depth Ocean Water Temperature
SSP5-8.5 2050 GCM Ensemble Median

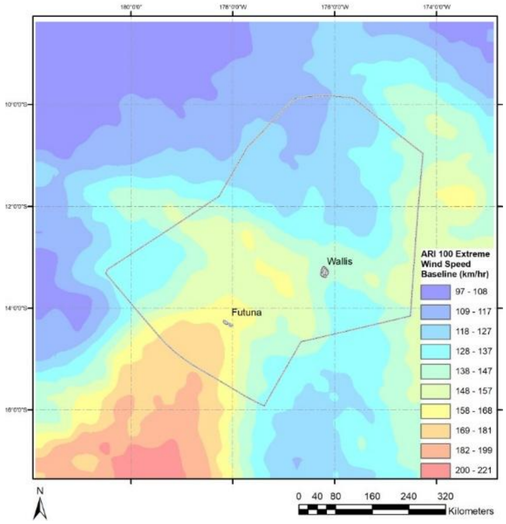


Wallis and Futuna EEZ ARI 100 Extreme Significant Wave Height
Baseline

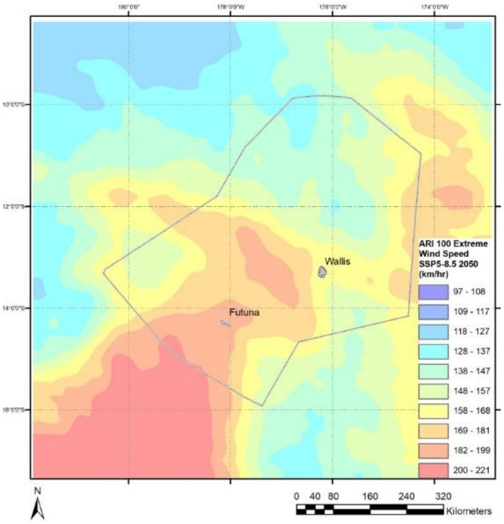


Wallis and Futuna EEZ ARI 100 Extreme Significant Wave Height
SSP5-8.5 2050 GCM Ensemble Median

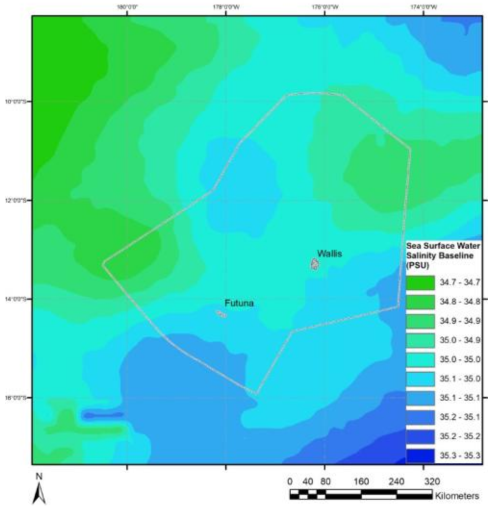




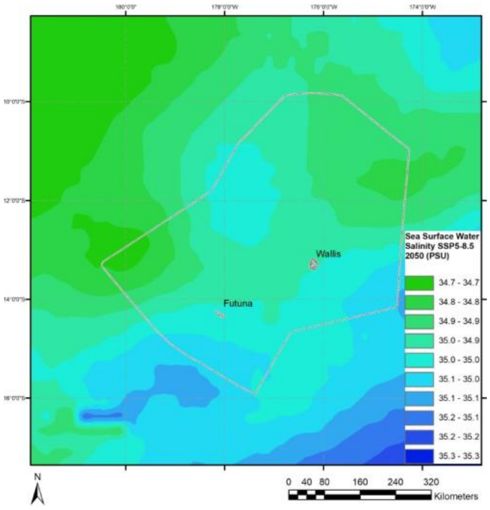
Wallis and Futuna EEZ ARI 100 Extreme Wind Speed
Baseline



Wallis and Futuna EEZ ARI 100 Extreme Wind Speed
SSP5-8.5 2050 GCM Ensemble 95 Percentile



Wallis and Futuna EEZ Sea Surface Water Salinity
Baseline



Wallis and Futuna EEZ Sea Surface Water Salinity
SSP5-8.5 2050 GCM Ensemble Median

## Data Sources

Historical ocean biogeochemical data

World Ocean Atlas (WOA) is the primary data source for biogeochemical variables; WOA 2018 data include the: Temperature, Salinity, Density, Conductivity, Mixed Layer Depth, Dissolved Oxygen, Percent Oxygen Saturation, Apparent Oxygen Utilization, Silicate, Phosphate, and Nitrate. (https://www.ncei.noaa.gov/products/world-ocean-atlas)

Ocean pH data could be obtained from multiple sources. OceanSODA-ETHZ data( https:// catalog. data. gov/ dataset/ oceansoda-ethz-a-global-gridded-data-set-of- the-surface-ocean-carbonate-system-for- seasonal-to-1)

The global ocean reanalysis wave system of Météo-France (WAVERYS) with a resolution of 1/5° degree provides analysis for the global ocean sea surface waves. The initial time series starts on January 15th, 1993 and is aggregated. This product includes 3-hourly instantaneous fields of integrated wave parameters from the total spectrum (significant height, period, direction, Stokes drift, etc), as well as the following partitions: the wind wave, the primary and secondary swell waves.

ERA5 provides hourly estimates for many atmospheric, ocean-wave and land-surface quantities. Hourly instantaneous 10m wind gust is an excellent data source for extreme speed.

Cross-validation of the data sources is applied to ensure the best is applied.

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# Climate Change and Risks to Infrastructure in Wallis and Futuna

Climate change significantly impacts the Pacific region, including its infrastructure. Rising sea levels, more frequent and intense storms, and ocean acidification are some of the consequences of climate change affecting Pacific island nations (Taylor and Barbara 2021).

One of the most significant infrastructure impacts is coastal erosion and inundation. As sea levels rise, waves become more powerful, and coastal erosion accelerates (Maharaj 2021). This can lead to the loss of beaches and land and damage to near-coastal buildings and infrastructure. In some cases, entire communities and food production areas may need to be relocated to avoid the risks of coastal erosion, flooding and saltwater intrusion.

Another significant impact is damage to infrastructure from extreme weather events. The Pacific region is already experiencing more frequent and severe storms, which can damage roads, bridges, buildings, and other critical infrastructure (ADB 2022). This can disrupt transportation, energy systems, and water supplies, leading to significant economic and social consequences.

Additionally, ocean acidification is affecting the infrastructure that relies on marine resources, such as fisheries and tourism. As ocean acidity increases, it can harm coral reefs and other marine ecosystems (Pacific Community 2022), leading to declines in fish populations and other aquatic resources. This can have serious economic consequences for Pacific island nations that rely on these resources.

Overall, the infrastructure impacts of climate change in the Pacific region are considerable and pose significant challenges to the development and sustainability of the region. Addressing these impacts will require considerable investment in infrastructure adaptation and resilience, as well as efforts to reduce greenhouse gas emissions and mitigate the effects of climate change.

## Wallis and Futuna

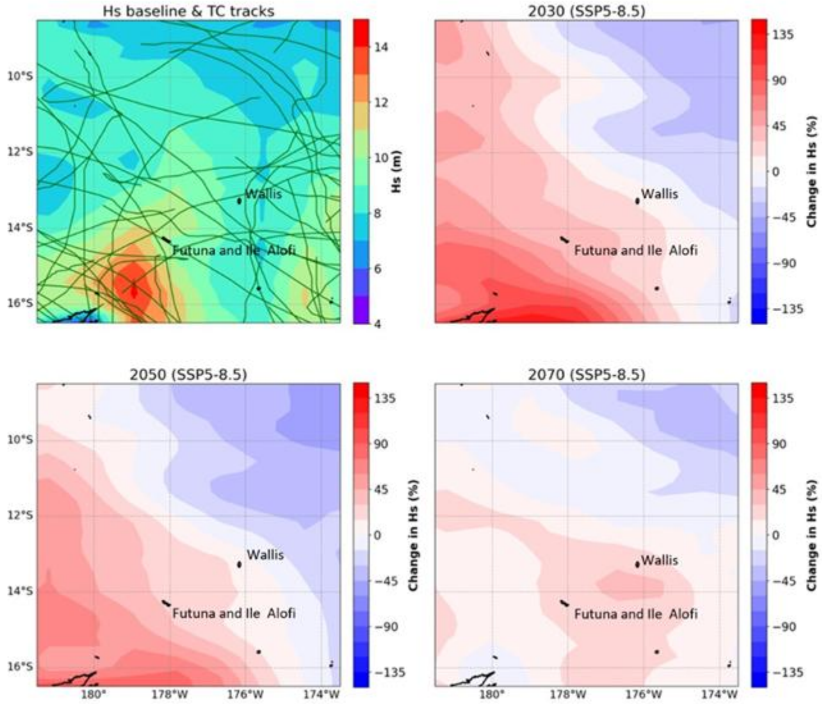
Coastal infrastructure is critical to the economy of Wallis and Futuna. Harbours, roads, airports and public and private buildings are concentrated around the coastlines of the two main islands of Wallis and Futuna. Changes in wave climate, tropical cyclone intensity and the constant but difficult-to-predict tsunami risks are ever-present.

Tropical cyclones are expected to increase in intensity over time; hence significant wave heights could increase. Futuna will likely experience a greater percentage increase in significant wave heights over time than Wallis. Under a shared socioeconomic pathway of 5- 8.5, this increase could be in the 30 to 45 per cent range, with the change first experienced by Futuna and impacting Wallis later this century (Figure 1).

Potential inundation for Wallis from such events is likely to be only slightly less than for Futuna (Figures 2 and 3). Levels of about 2.0 metres for a 1 in 100-year event and over 2.5 metres for a 1 in 1000-year event are possible.

Cyclone risk is one every two years at a category three intensity with winds between 178 and 209 kph. Tsunamis risk is more significant in terms of heights for Futuna, particularly the eastern end of the south coast where the 1 in 500 year return period tsunami high water level could be between 4.69 and 8.76 metres. Wallis' tsunami risk levels are considerably lower at 1.59 to 4.68 metres.

Cyclone historical tracks and change (%) in future significant wave heights SSP 5-8.5, 50th percentile



**Data:** Hs baseline - CMEMS
Hs projection - FIO-ESM
TC tracks - IBTrACS

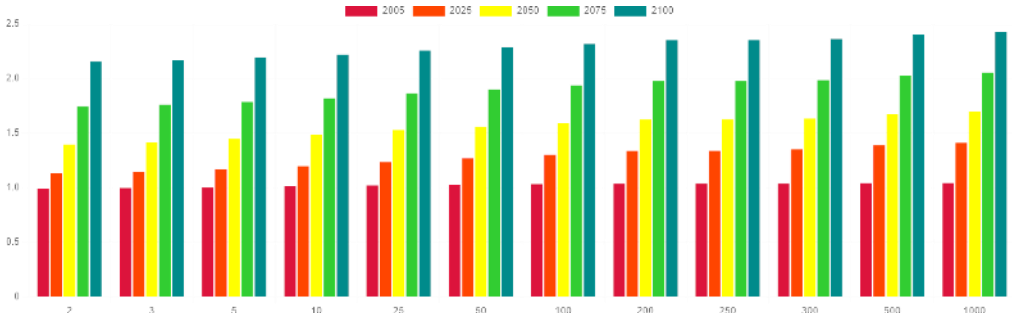


Figure 3: Extreme still high water level, Wallis, by return period under an SSP 5-8.5 95th percentile scenario (Source: Climate Insights)

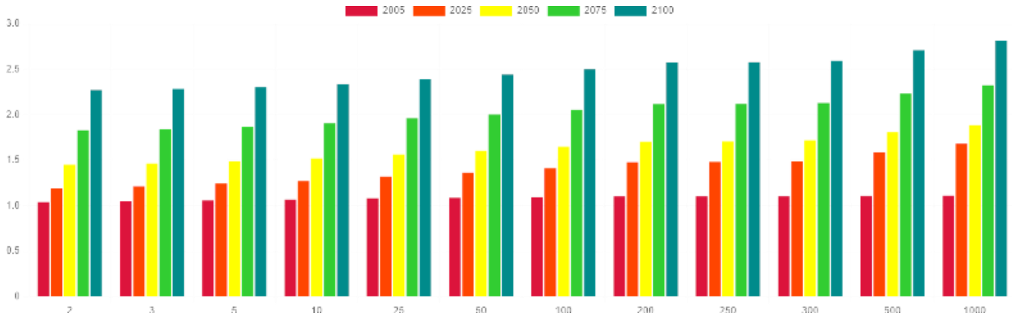
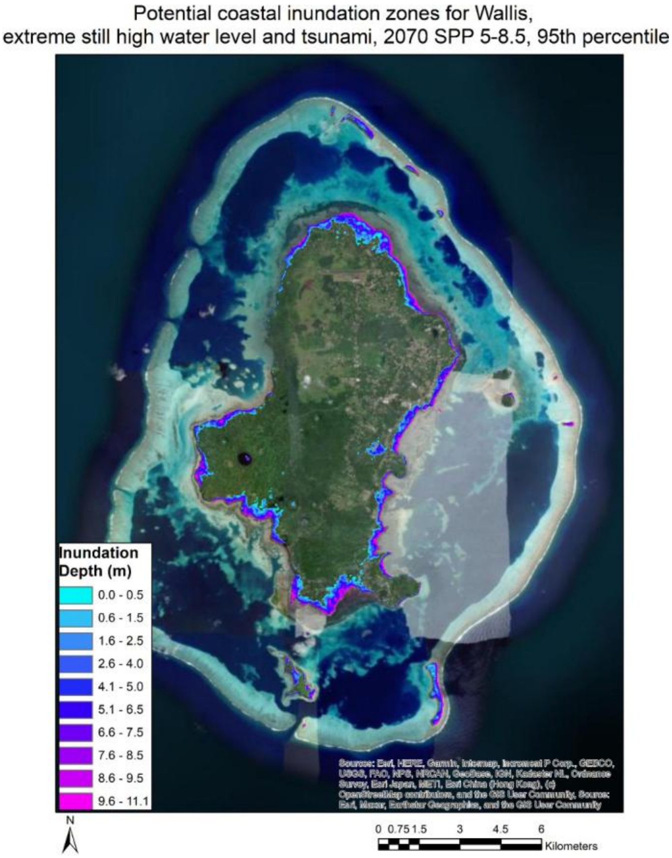


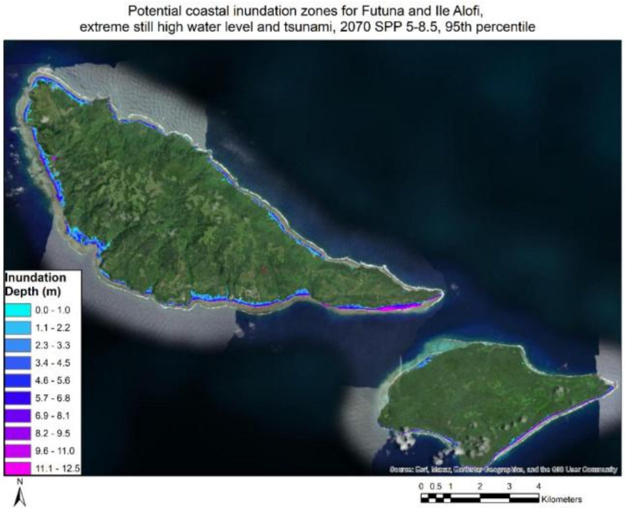
Figure 2: Extreme still high water level, Futuna, by return period under an SSP 5-8.5 95th percentile scenario (Source: Climate Insights)



Potential coastal inundation zones for Wallis,
extreme still high water level and tsunami, 2070 SPP 5-8.5, 95th percentile

Sources: Esri, HERE, Garmin, Intermap, Increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community, Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community

Figure 4: Various potential inundation levels depicted for the coastline of Wallis and select Islets



Potential coastal inundation zones for Futuna and Ile Alofi,
extreme still high water level and tsunami, 2070 SPP 5-8.5, 95th percentile

Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community

Figure 5: Various potential inundation levels depicted for the coastline of Futuna and Ile Alofi

## Airports and Ports

As the sea level rises, coastal airports can become more vulnerable to flooding and storm-related powerful waves and surges. This can lead to airport operations disruptions, infrastructure damage, and potential safety hazards for passengers, cargo, and aircraft. Specifically, sea level rise, storm events and tsunamis can significantly impact the coastal airport of Futuna and the ingress and egress roading infrastructure of both Futuna and Wallis.

Coastal airports may also be affected by changes in coastal erosion, which can lead to the loss of runways, taxiways, and other airport facilities. Rising sea levels can also increase the risk of saltwater intrusion, damaging airport infrastructure and affecting water quality.

To address these challenges, coastal airports may need to take steps to adapt to the impacts of sea level rise. This could include raising airport infrastructure and building protective barriers to reduce the risk of chronic sea level- related flooding and acute extreme events. Airport operators may also need to consider long-term planning and investment to ensure the resilience of coastal airports in the face of climate change.

The port of Mata-Utu is the main port of Wallis and Futuna and is located on the island of Wallis. It is a small port mainly serving inter- island traffic and small cargo vessels. The port has limited infrastructure, with one wharf and a small container yard. In addition to the port of Mata-Utu, several smaller ports and harbours are located around the islands. These include the ports of Leava and Vailala on the island of Futuna, which serve inter-island traffic and fishing vessels.

The coastal infrastructure of Wallis and Futuna is mainly focused on supporting the fishing industry, a significant source of income for the islands. Several fish processing plants are located around the islands, along with small boat harbours and landing sites for fishing boats.

The impact of chronic and acute sea level events could be mitigated by planning well in advance for future changes in sea level risks.

## Water Supply

Wallis and Futuna face significant challenges in accessing clean and safe drinking water. The primary source of drinking water on the islands is groundwater, which is often contaminated by saltwater intrusion, pesticides, and other pollutants.

The French government administers the territory and has implemented several water treatment initiatives on the islands to address these issues. These initiatives include constructing desalination plants, which convert seawater into freshwater, and installing water treatment systems that remove contaminants from groundwater.

One of the most significant water treatment projects in Wallis and Futuna is constructing a new water treatment plant on the island of Wallis. The plant, funded by the French government, is expected to provide clean drinking water to over 3,500 people on the island. The plant will use physical, chemical, and biological treatment methods to remove contaminants from the island's groundwater supply.

Another important initiative is installing rainwater harvesting systems in schools and public buildings. These systems collect rainwater, which is then treated and used for drinking and other purposes.

Water supply-related infrastructure tends to have medium to long-term service lives. Therefore, consideration in coastal environment changes from sea-related changes should be considered.

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# Wallis and Futuna – Blue Carbon

## Overview

‘Blue carbon’ refers to mangrove forests, seagrass meadows, and tidal salt marshes — vegetated coastal ecosystems that represent significant carbon stocks (Pendelton et al., 2012). Atwood, et al. (2015) depict below that, despite their small global extent, vegetated coastal habitats (seagrass meadows, mangroves and salt marshes) play a disproportionately large role in the global capture and storage of nature’s carbon.

Coastal ecosystems, such as mangroves, salt marshes and seagrass, also provide essential benefits and services, contributing to climate change mitigation and adaptation. These habitats support diverse ecological communities, offer food and coastal protection, and have significant carbon storage capacity. However, conservation efforts are hindered by limited understanding and awareness. Biosequestration in coastal habitats is a highly effective long-term carbon storage method. Understanding carbon stocks and emissions in blue carbon ecosystems is crucial for effective management. Various data sources, including satellite data, can be utilised for assessing these ecosystems.

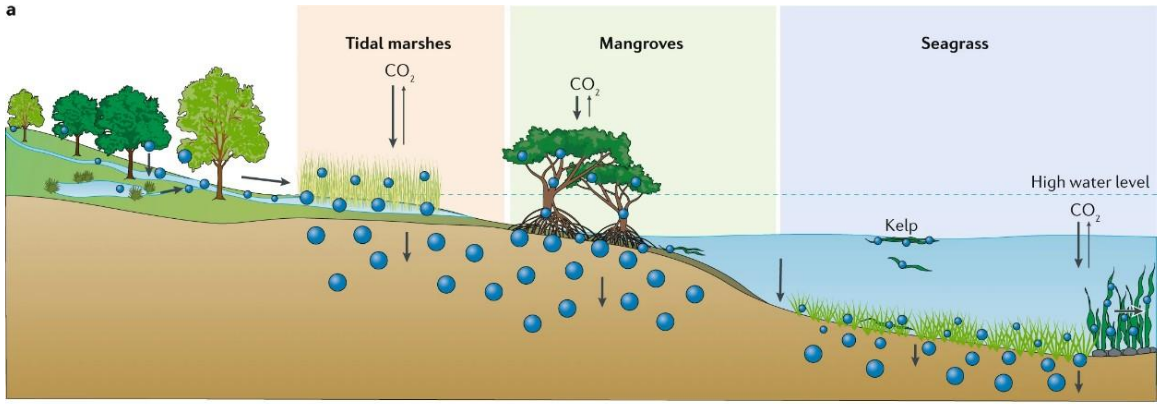

Figure 6: Key elements and processes in blue carbon cycling. Blue carbon ecosystems (BCEs) draw down CO2 from the atmosphere through photosynthesis, contributing to net accumulation of organic carbon within plant biomass and sediments

Blue carbon ecosystems (BCEs) occupy approximately 0.5% of the sea floor, from the upper intertidal zone down to about 50 m deep (depending on underwater light penetration), but contribute >50% of global carbon burial in the oceans (Macreadie, et al., 2021). Large amounts of autochthonous carbon are fixed in BCEs, and their position at the land-sea interface and high trapping capacity allows them to accumulate sediment and allochthonous carbon produced in other ecosystems (Duarte, 2013).

Coastal ecosystems are critical to maintaining human well-being and global biodiversity. In particular, mangroves, tidal salt marshes and seagrasses provide numerous benefits and services that contribute to people’s ability to mitigate and adapt to the impacts of climate change (The Blue Carbon Initiative, 2018).

Coastal and marine ecosystems can deliver a wide range of ecosystem services (defined as natural process attributes which directly or indirectly benefit humans) beyond just carbon sequestration (Groot, Wilson and Boumans, 2022). Groot et al. (2002) explain that there has been increased appreciation of blue carbon ecosystems (BCEs), including seagrass meadows, mangrove forests, tidal marshes and, potentially, seaweed beds, since 2009. BCEs are widespread, highly productive coastal habitats that host diverse ecological communities and support human well-being, providing food and coastal protection against erosion and sea-level rise, influencing the livelihoods of millions (Himes-Cornell, Grose and Pendleton, 2018).

The vast tropical Indo-Pacific has the highest seagrass diversity in the world, with as many as 14 species growing together on reef flats, although seagrasses also occur in very deep waters. In addition, seagrasses and seagrass habitats provide at least 24 different service benefits in the Indo-Pacific region. These include coastal protection, provision of food, cultural value and exceptional carbon storage ability beyond terrestrial forests. If properly managed, seagrass habitats could provide a highly significant carbon mitigation service in a high-CO2 world through a net influx of organic carbon both above- and below-ground (Brodie and N'Yeurt, 2018).

Coastal tidal wetlands are important for carbon accumulation and climate change mitigation. A study reveals global tidal wetland carbon accumulation rates and predicts future changes under climate change. Tidal wetlands globally accumulate a significant amount of carbon, with projections showing a net increase by 2100.

## Wallis and Futuna

Seagrass ecosystems are vital for coastal biodiversity and play important ecological roles. They are found in temperate and tropical coastlines and are distributed across six bioregions globally. Three seagrass species have been found in Wallis and Futuna (N'Yeurt and Payri, 2004). Seagrasses face climate change impacts, but the Pacific Islands exhibit relatively low pressures and higher resilience. Seagrass conservation efforts should be prioritised, and traditional knowledge plays a crucial role in managing these valuable resources.

Brodie and N'Yeurt (2018) discussed seagrass and seagrass habitats in 22 Pacific Island Countries and Territories (PICTs), including Wallis and Futuna, in the context of current and expected future climate change impacts across local, regional and global levels as dictated by available data. Although most seagrasses in the tropical Pacific are found in waters shallower than 10 m in the PICTs, seagrass habitats can be identified and divided into five broad types: "estuary", "bays and lagoons", "barrier and patch reefs", "island fringing reefs", and "deep water", all potential habitat zones in Wallis and Futuna (Waycott, McKenzie, Mellors and Ellison, 2011). The dominant processes in each of these locational seagrass habitat types influence the seagrass assemblage present, its growth, survival and exposure to potential disturbance. Each of these habitat types may be influenced in different ways by both climate change impacts and other human-related disturbances such as land run-off (Brodie and N'Yeurt, 2018).

Different tropical seagrass species show different tolerances to increased seawater temperatures, but thermal tolerance has not been well-studied in seagrass in the PICTs. Increases in seawater temperature also translate into stronger extreme weather events such as heavy rainfall, tropical cyclones and storms, which put additional stress on seagrass habitats through direct physical damage, increase in turbidity causing reductions in photosynthesis rates and growth, and a general loss of ecosystem resilience and productivity. Both gains and losses to seagrass resources will result from climate change, with increases in productivity due to higher CO2 levels being buffered by the negative consequences of higher seawater temperatures and, most importantly, additional anthropogenic factors such as "polluted" land runoff, which is an issue in Wallis and Futuna. These factors, when not managed, are very likely to result in increasing losses of vital ecosystem

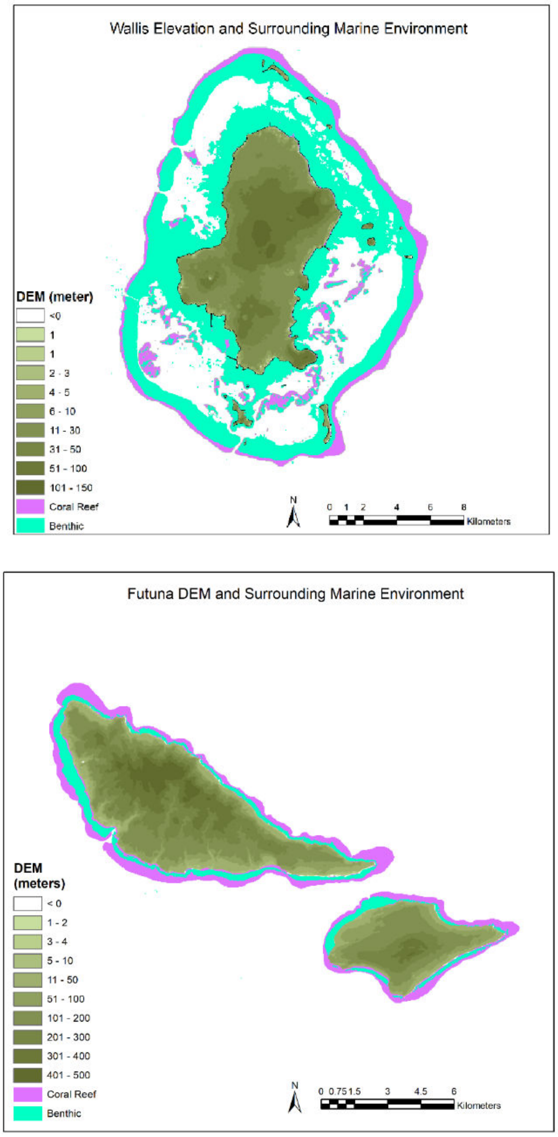

Figure 7: Distribution of benthic regions of Wallis, Futuna, and Alofi. Benthic refers to the bottom of the sea and the organisms that live there. These areas represent potential areas for sustaining either current blue carbon resources of potential areas for rehabilitation or expansion of blue carbon ecosystems.

services in Wallis and Futuna.

## Summary

For blue carbon to be included in major regulated schemes, additional work is needed, including scientific research, policy design, economic analysis, and policy advocacy. In particular, three activities should be given priority: reorienting scientific research from the natural sequestration to the emissions that occur upon destruction, estimating global and national aggregate figures for these emissions, and promoting blue carbon in key policy fora. It should be recognised that the development of major regulated cap-and-trade schemes with blue carbon offsets may take several years. In the meantime, efforts should also be made to develop national blue carbon policies in the countries with the most relevant habitats.

In Wallis and Futuna, benthic zones face threats from human activities and climate change, highlighting the need for sustainable management and community engagement. Blue carbon offers a cost-effective strategy for reducing greenhouse gas emissions while providing multiple co-benefits, such as habitat protection, pollution filtration, and storm defence. The financial and economic aspects of blue carbon project development

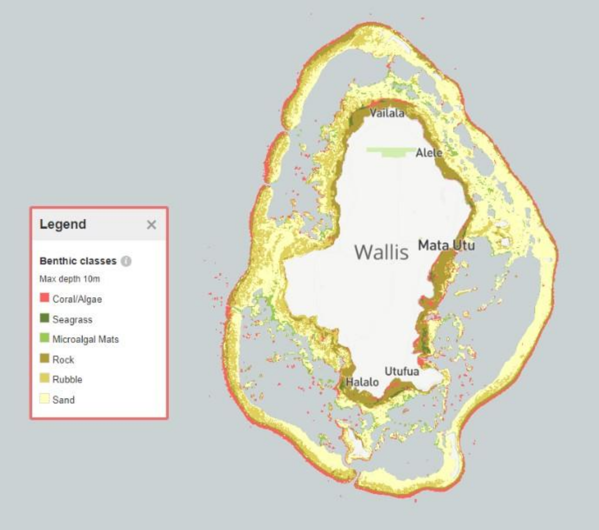

Figure 8: Benthic classes identified in Wallis

warrant investigation. Establishing a global blue carbon fund and integrating blue carbon activities into development policy and financing mechanisms are key. The Blue Carbon Initiative aims to promote climate change mitigation through the restoration and sustainable use of coastal and marine ecosystems.

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