Chapter

Climate Risk and Early Warning Systems (CREWS) for Papua New Guinea

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Abstract

Developing and least developed countries are particularly vulnerable to the impact of climate change and climate extremes, including drought. In Papua New Guinea (PNG), severe drought caused by the strong El Niño in 2015–2016 affected about 40% of the population, with almost half a million people impacted by food shortages. Recognizing the urgency of enhancing early warning systems to assist vulnerable countries with climate change adaptation, the Climate Risk and Early Warning Systems (CREWS) international initiative has been established. In this chapter, the CREWS-PNG project is described. The CREWS-PNG project aims to develop an improved drought monitoring and early warning system, running operationally through a collaboration between PNG National Weather Services (NWS), the Australian Bureau of Meteorology and the World Meteorological Organization that will enable better strategic decision-making for agriculture, water management, health and other climate-sensitive sectors. It is shown that current dynamical climate models can provide skillful predictions of regional rainfall at least 3 months in advance. Dynamical climate model-based forecast products are disseminated through a range of Web-based information tools. It is demonstrated that seasonal climate prediction is an effective solution to assist governments and local communities with informed decision-making in adaptation to climate variability and change.

Keywords: drought, climate risk, early warning systems, seasonal climate prediction, Papua New Guinea

1. Introduction

Climate has been changing on a global scale since the beginning of the Industrial Revolution; particularly rapid climate change including changes in many extreme weather and climate events has been observed since about the 1950s [1]. The increase in the frequency and severity of extreme weather and climate events has resulted in an increased number of natural disasters impacting on the wellbeing of society. Asia-Pacific is one of the world's most disaster-prone regions, according to the “Asia-Pacific Disaster Report 2012” prepared by the United Nations (UN) Economic and Social Commission for Asia and the Pacific and the UN Office for Disaster Risk Reduction: “almost 2 million people were killed in disasters between 1970 and 2011, representing 75% of all disaster fatalities globally; the most frequent hazards in the region are hydro-meteorological, which affect the most people; since 2000, more than 1.2 billion people have been exposed to hydro-meteorological hazards alone, through 1215 disaster events” [2].

Economic losses in Asia and the Pacific in 1970–2016 attributed to disasters including droughts, floods, storms, earthquakes and tsunamis total to about $1.3 trillion [3]. Economic losses have been rising over the past decades, and it is projected that losses will continue to increase. UN assessment indicates that increase in frequency and magnitude of disasters combined with the increased vulnerability of society could cost the Asia-Pacific region $160 billion per year by 2030 [4].

Developing countries, least developed countries (LDCs) and Small Island Developing States (SIDS) are particularly vulnerable to impact of climate change and climate extremes, including drought, which could lead to water crisis or severe food shortage. For example, a prolonged drought episode related to the strong 2010–2011 La Niña event affected multiple SIDS in the Pacific, including Samoa, Tokelau, Tonga and Tuvalu. The impact of the drought was particularly severe in Tuvalu resulting in water crisis [5]. The Government of Tuvalu declared a state of emergency due to critically low water supplies, and households were rationed to about 40 L of freshwater per family per day [6]. In Papua New Guinea, severe drought caused by strong El Niño event in 2015–2016 affected about 40% of the population, with almost half a million people experiencing food shortages [7].

The Climate Risk and Early Warning Systems international initiative was established in 2015 [8] to enhance early warning systems (EWSs) for vulnerable countries dealing with climate change. CREWS presently operates in countries in Africa, the Pacific and the Caribbean, providing EWS to protect the most vulnerable populations against hydrometeorological hazards like tropical cyclones, droughts and floods [9]. In most of those countries, meteorological observation networks are currently barely adequate, and EWS are basic. The World Meteorological Organization (WMO), working in partnership with the national governments and hydrometeorological agencies of LDCs and SIDS through the projects of the CREWS initiative, strives to improve decision-making around climate change adaptation, disaster risk reduction and sustainable development.

In Africa—in the Democratic Republic of the Congo, Burkina Faso, Mali and Niger—CREWS supports the improvement of operational hydrometeorological forecasts and early warnings for agriculture and food security related to flood and drought risks. In the Caribbean, CREWS assists countries in the region to strengthen regional and national systems and capacity related to weather forecasting, hydrological services, multi-hazard impact-based warnings and service delivery, including tropical cyclones, for enhanced decision-making. In the Pacific—in Fiji, Cook Islands, Kiribati, Niue, Tuvalu, the Federated States of Micronesia, Samoa, Solomon Islands, Tonga, Palau, Nauru, the Marshall Islands, Tokelau and Vanuatu—CREWS projects strengthen the capacity of SIDS in hydrometeorological services and EWS. In Papua New Guinea, CREWS improves the existing drought monitoring network, as well as early warnings for the agriculture sector and emergency service managers.

In this chapter, the CREWS project for PNG and its implementation strategy are described; synergies with the International Climate Change Adaptation Initiative, the PNG Capacity Development Program and the Space-Based Weather and Climate Extremes Monitoring Demonstration Project (SEMDP) are outlined; and the project’s preliminary results are presented.

2. CREWS-PNG

The CREWS-PNG project develops improved drought monitoring and subseasonal-to-seasonal prediction that can foster better decision-making for agriculture, water management and other climate-sensitive sectors by creating an end-to-end EWS aimed at reducing the impacts of drought. In this section, a brief overview of climate impacts on PNG climate-sensitive sectors is presented, providing the rational for CREWS-PNG project and its implementation strategy.

2.1 Climate impacts on PNG climate-sensitive sectors

PNG is a country in the Southwest Pacific with a population of almost 7 million people, with agriculture providing a subsistence livelihood for 85% of the population. PNG, the largest of the Pacific Island Countries, faces multiple climate change-related challenges. Climate-related natural disasters, as well as gradual shifts in climatic and oceanic conditions, already pose significant risks to PNG, disrupting daily life, causing damage to assets and infrastructure, destroying livelihoods and killing or injuring people.

The El Niño-Southern Oscillation (ENSO) is one of the key drivers of interannual climate variability around the globe, with substantial impacts felt in PNG. During the warm phase of ENSO (El Niño), ocean surface waters in the central and western Pacific Ocean cool, causing a shift in weather patterns and associated rainfall towards the eastern Pacific. This often results in severe rainfall deficits in the western Pacific, leading to significant drought conditions across PNG. However during the cool phase of ENSO (La Niña), warmer than average ocean surface waters and enhanced convection and rainfall occur over the Maritime Continent, which can result in extreme precipitation, flooding and landslides in PNG. These climate extremes take a severe toll on both the population and economy of PNG people. For instance, the 2015–2016 El Niño, which was one of the three strongest El Niño events since the 1950s, had significant impacts on PNG agriculture and energy and mining sectors.

For agriculture, the 2015–2016 El Niño-induced drought and frost led to crop failures which affected almost 2.5 million people (approximately 40% of the population) with almost half a million people suffering severe food shortages [7]. Staple sweet potato crops in the highlands were severely damaged by frosts in August 2015—the result of reduced night-time cloud cover—which also destroyed wild plants that are usually eaten as a supplement source of food.

For energy, the hydropower plant at Yonki Dam, which supplies the entire highlands and the Momase regions with electricity, and the Sirinumu Dam, which supplies the nation's capital Port Moresby, were not able to adequately meet the expected energy demands due to low water levels. As a result, energy suppliers were forced to switch to diesel power generation which was both costly and environmentally unfriendly.

For mining, Ok Tedi, one of PNG's major mining operations, closed down its operations due to very low water levels in the Fly River which prevented cooper ore and other minerals from being shipped out.

It is expected that climate change will exacerbate those hazards already impacting on agricultural yields and the productivity of other economy sectors, further reducing the financial and social wellbeing of PNG population. Addressing these issues, the government of PNG through the Office of Climate Change and Development has put its emphasis on combating natural hazards in the country, including food insecurity caused by crop failures due to droughts and inland frosts.

The CREWS-PNG project aims to address this government priority through enhancing EWS and strengthening resilience to climate change by providing accurate and timely information about the current state of the climate and increasing the use of subseasonal-to-seasonal climate predictions. This will have a primary focus on drought- and food security-related impacts while providing benefits in other priority areas, e.g. climate change mitigation and adaptation, water and sanitation impacts of drought, etc.

2.2 CREWS-PNG key areas of activity

The main objective of the CREWS-PNG project is to build the capacity of the PNG National Weather Service and strengthen its cooperation with key business sectors, government departments and other stakeholders, in order to put in place complete systems that deliver warnings and relevant information to end-users. The following key components of the project—improvement of observations and databases, weather and climate monitoring and forecasts and support for EWS development—are designed in order to achieve this objective.

2.2.1 Improvement of observations and databases

Meteorological observations (i.e. collecting instrumental data about atmospheric pressure, temperature, moisture, precipitations, wind, solar radiation, ocean temperature and many other weather and climate essential variables which describe state of the environment) are one of the mandatory functions of National Meteorological and Hydrological Services (NMHSs) around the world. The PNG NWS currently has an observation network of 13 weather and climate stations, 7 rain gauge stations and 5 agrometeorological stations.

Given PNG's total area is about 462,840 sq. km with rugged terrain and many remote microclimates, the existing meteorological observation network is not adequate to provide a comprehensive spatial coverage. Improvement of meteorological observations is an essential part of the project and is addressed through increased station network reliability and sustainability and improved control and maintenance procedures as well as through augmenting data from the existing surface-based observation stations with the data from additional automatic weather stations (AWSs) that will be established in partnership with the PNG Capacity Development Program (PNG-CDP) (see Section 2.3 for detail).

Collecting meteorological observations over a substantial period of time (e.g. the WMO standard for deriving climatology is 30 years of records) is vital for understanding the current climatic conditions as well as deriving trends in environmental variables. In some countries, NMHSs have long-term climate records going back to the nineteenth century. Historically, meteorological observations were kept as paper records. In modern times, these paper records have been digitized and stored electronically in computerized database management systems, and new data are archived in digital form.

In PNG, early historical records of rainfall for Port Moresby are available from the 1890s and are largely complete from 1905. Rainfall data from other meteorological stations located across the country are also available, typically from the 1950s to 1960s. Some historical climate records have been digitized as part of the International Climate Change Adaptation Initiative (ICCAI). However, substantial climate records are still stored in paper form and required digitization. One of the key areas of activities for CREWS-PNG is to continue the implementation of climate data rescue activities. Data digitizing is conducted at the climate section of the PNG NWS under supervision of experienced climatologists. Quality control procedures are in place to ensure that this invaluable historical climate record is preserved for future analysis. The improvement of historical databases, including data homogenization, is essential for deriving accurate climatology and trends. This important task is addressed by the CREWS-PNG project.

Once digitized, the records are archived in a modern climate database management system Climate Data for the Environment (CliDE) which has been used by the PNG NWS operationally for almost a decade. CliDE was developed as part of the ICCAI and implemented at 15 NMHSs across the Pacific, including PNG. CliDE is one of the WMO recommended climate database management systems and is included in the Climate Services Toolkit. CliDE is undergoing continuous development; further tailoring of the database to better suit requirements of the PNG NWS is undertaken as part of this project.

2.2.2 Weather and climate monitoring and forecasts

Currently, nationwide weather forecasts issued by the PNG NWS and provided to the media have lead times of 24 h, while seasonal climate predictions are produced at longer lead times of 3 months and limited to site-specific locations. While weather forecasts and seasonal climate predictions are currently recognized by users as useful products produced by PNG NWS, stakeholders from various economic sectors have noted that there is a need to enhance and expand these services.

To enhance the availability of numerical weather prediction (NWP) products, the CREWS-PNG project is increasing the availability of NWP limited area model guidance from the WMO Regional Specialised Meteorological Centre (RSMC) for use in short-range weather forecasts (up to 7 days).

Another valuable improvement of climate services is the transition to seamless forecasting, i.e. providing forecasts and early warnings on time scales from days right to weeks and months. For sub-seasonal to seasonal forecasts (i.e. at lead times of 1–4 weeks and 1–3 months), products from the WMO Global Producing Centres for Long-Range Forecasts (GPCLRFs) and Regional Climate Centres (RCCs) are used.

Development of an objective seasonal forecasting scheme for PNG, with skill measures that will be communicated to users accompanying the forecasts, is underway. This is partly based on the WMO Sub-Seasonal to Seasonal Project to provide daily forecasts for the next 60–90 days. National forecasts will add value to, and be based on, outputs from an objective regional forecasting scheme for the region. The regional seasonal forecasting model will similarly benefit other countries in the Asia-Pacific region.

2.2.3 Support for EWS development

While EWSs are currently in place, they have limited capacity for providing disaster- and food security-related warnings that can trigger effective action. To address this issue, this project will initiate the following activities focused on developing improved products for drought monitoring and prediction.

Currently, PNG NWS provides drought monitoring based on the analysis of rainfall observations from surface-based rain gauge stations, which currently consists of an observation network of 13 weather and climate stations and 7 rain gauge stations. This number of stations is considered inadequate to accurately capture the complex spatial distribution and variability of rainfall across the country.

A modern-day technology—satellite remote sensing—is an approach which will be used by CREWS-PNG to improve drought monitoring for PNG. Space-based observations not only provide global coverage but are now used by NMHSs around the world for weather monitoring and input to weather forecasting models. Space-based observations are a particularly valuable source of information for countries with a low density of surface-based meteorological stations like PNG. Recently, WMO established the SEMDP to assist NMHSs in the Asia-Pacific region with precipitation monitoring (for detail, see Section 2.3). SEMDP drought monitoring products available from NOAA and JAXA will be used by the PNG NWS to enhance its service.

In terms of drought forecasts, the PNG NWS currently produces outlooks based on a statistical model (Seasonal Climate Outlooks in Pacific Island Countries (SCOPIC)), which needs to be updated.

SCOPIC is a seasonal climate prediction tool used operationally by NMHS in 15 Pacific Island Countries for more than a decade [10]. In the past, statistical models demonstrated skill in predicting seasonal rainfall in Australia [11] and countries in the Pacific [10]. However, statistical models are based on long-term historical records and developed under the assumption that climate is stationary. A hindcast validation study which examined the forecast skill of SCOPIC in the Pacific revealed that the model demonstrated reasonable skill using a number of selected predictors, but the model's skill varied depending on the location and the season (e.g. the model's highest rainfall predictive skill was for the austral summer and lowest for the austral winter) [10].

In a warming climate, the underlying assumption about the stationarity of climate is no longer valid, and skill of statistical models deteriorates. Modern seasonal climate prediction models use dynamical climate modelling techniques, which are based on the laws of physics and account for natural climate variability and climate change not captured by historical data. Under the CREWS-PNG project, outputs of state-of-the-art dynamical climate model are used to strengthen the capability of the PNG NWS to perform skilful drought forecasts (see Section 3 for detail).

Based on improved drought monitoring and prediction capabilities at the PNG NWS, the national drought EWS will be enhanced. Drought EWS weather and climate information will be translated into drought early warning alerts and advisories for various sectors, with these trigger points set by a series of stakeholder consultations. Overall, the key project activities aim to provide impact-based forecasts and risk-informed warnings to assist decision-making by the users. To reach "the last mile" and ensure that no one is left behind, multichannel weather forecast and warning communication systems will be developed or enhanced, providing communities with actionable information and alerts.

2.3 Partnership with SEMDP and PNG-CDP

CREWS-PNG is implemented in partnership with the SEMDP and the PNG-CDP, to assist the PNG NWS with enhancing drought monitoring, observation network and weather forecasting. Synergies between the projects are briefly outlined in this section.

2.3.1 SEMDP

Recognizing a need to assist members to better utilize and improve their ability to monitor extreme weather and climate events from space, WMO established the SEMDP—a demonstration project for space-based weather and climate extremes monitoring, with focus on operational monitoring of extreme precipitation, notably drought and accumulated rainfall over 5–7 days [12]. In the first stage of the demonstration project (2018–2019), drought monitoring products will be available from satellite providers NOAA and JAXA for the Asia-Pacific region (SEMDP geographical domain is between 40°N–45°S and 50°E–160°W), with future expansion of the domain to other WMO regions and eventually globally, at subsequent stages of the project. The availability of SEMDP satellite-derived data and products over the Asia-Pacific domain allows them to be utilized by CREWS-PNG, through the PNG NWS, to provide an enhanced drought monitoring service for PNG.

NOAA satellite products for the SEMDP (gauge-based, satellite-estimated and gauge-satellite blended products of precipitation) are produced at the Climate Prediction Center (CPC). To construct a high-quality, high-resolution precipitation analysis over the globe through integrating information from satellite observations as well as in situ measurements and model simulations, the CPC morphing technique—CMORPH—is used (see [13] for detail). CMORPH products start from 1998 and are updated by CPC/NOAA on a quasi-real-time basis. JAXA products for the SEMDP are produced at the Earth Observation Research Centre (EORC). They are based on Global Satellite Mapping of Precipitation (GSMaP) data [14], with GSMaP version 6 (GSMaP_GNRT6) data reprocessed from March 2000.

The SEMDP products available from CPC/NOAA and EORC/JAXA include precipitation estimates at various time scales, e.g. hourly, daily, pentad (5 days), weekly, 10 days and monthly, as well as derived products, e.g. the standardized precipitation index (SPI), the normalized difference vegetation index (NDVI), the vegetation health index (VHI), etc. Here we present a few examples of these SEMDP products in the context of the CREWS-PNG project.

Prior to CREWS-PNG, the climate service team of the PNG NWS used only surface-based station rainfall data and statistics based on rain gauge observations. Utilizing SEMDP products, maps of precipitation on various time scales are now available to assist the PNG NWS with spatial analysis of precipitation. In **Figure 1**, a map of monthly average precipitation over the SEMDP domain for July 2018, derived from CPC/NOAA CMORPH data, is presented. Examining closely the PNG area, it can be seen that in some parts of PNG, only 2 mm/day or less of rain was received in that month compared to the long-term July climatological mean of 5–10 mm/day (**Figure 2**). Another valuable SEMDP product for operational rainfall monitoring is the weekly rainfall statistics, which includes both precipitation anomaly and percentage of normal rainfall (**Figure 3**).

The standardized precipitation index is widely used to characterize and monitor meteorological drought, i.e. drought that occurs when below average precipitation occurs for a prolonged period of time [15]. Standardized precipitation is the

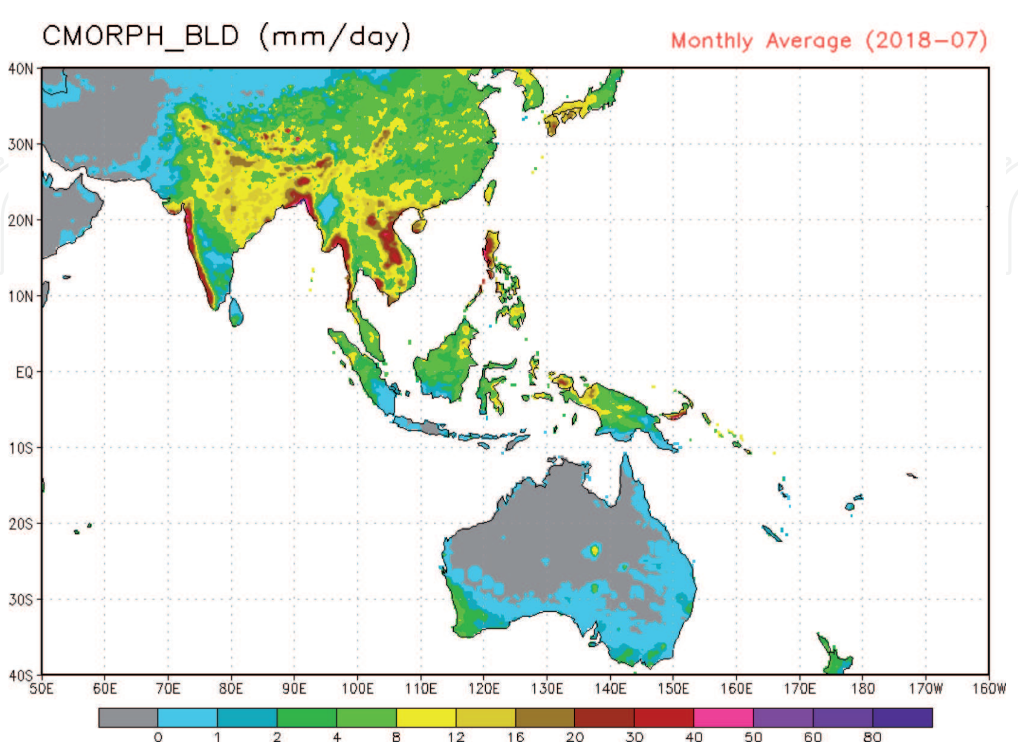


Figure 1.
CPC/NOAA CMORPH monthly average precipitation over the SEMDP domain for July 2018.

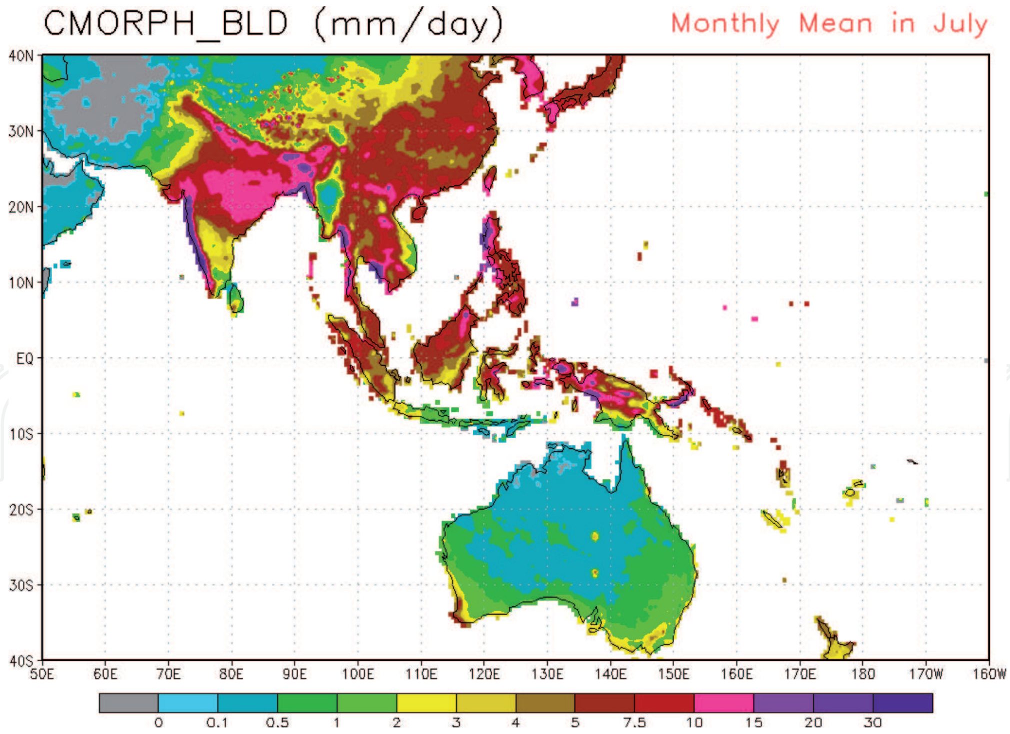


Figure 2.
CPC/NOAA CMORPH monthly mean precipitation (climatology) for July (1998–2017 base period).

difference of precipitation from the mean for a specified time (e.g. 30, 60 and 90 days or longer time period) divided by the standard deviation; the mean and the standard deviation are both determined from the climatological record. The SPI values are interpreted as follows: 2.0 < SPI, extremely wet; 1.5 < SPI < 2.0, very wet; 1.0 < SPI < 1.5, moderately wet; −1.0 < SPI <1.0, near normal; −1.5 < SPI < −1.0, moderately dry; −2.0 < SPI < −1.5, severely dry; and SPI < −2.0, extremely dry. The 60-day and 90-day SPI ending at 2 December 2018 is presented in **Figure 4**, top and bottom panels respectively, indicating severely dry (−1.5 and below) and extremely dry (−2.0 and below) conditions in most parts of the eastern and southern provinces of PNG during September, October and November 2018.

The impact of the 2015–2016 El Niño on the agricultural sector of PNG was discussed earlier. Here we demonstrate the value of space-based observations for drought monitoring utilizing the vegetation health index [16]. The VHI is computed using observations from Advanced Very High Resolution Radiometer (AVHRR), instrument onboard the NOAA polar orbiting satellites, in the visible, infrared and near-infrared bands, and used to identify stress on vegetation related to drought. Maps of the VHI for the first week of January 2015 and the first week of December 2015 are presented in **Figure 5**, top and bottom panels respectively. These maps clearly demonstrate the difference between relatively healthy vegetation over PNG in January and stressed vegetation in December when the impact of El Niño was very strong [the 3-month average of the Oceanic Niño Index (3-month running mean of sea surface temperature anomalies in Niño 3.4 region; for detail, see [17]) from November 2015 to January 2016 had peaked at +2.6°C. Overall, the 2015–2016 El Niño event was classified as one of the three strongest events since the 1950s].

In addition to the impact on vegetation due to drought caused in PNG by the El Niño event in 2015, frost also occurred in highlands. Frost was caused by the reduced night-time cloud coverage allowing increased loss of heat to space during the night, resulting in severe damage to the staple sweet potato crops leading to food shortages. Cloud coverage could be estimated using AVHRR space-based observations to measure the amount of outgoing longwave radiation (OLR). Negative OLR

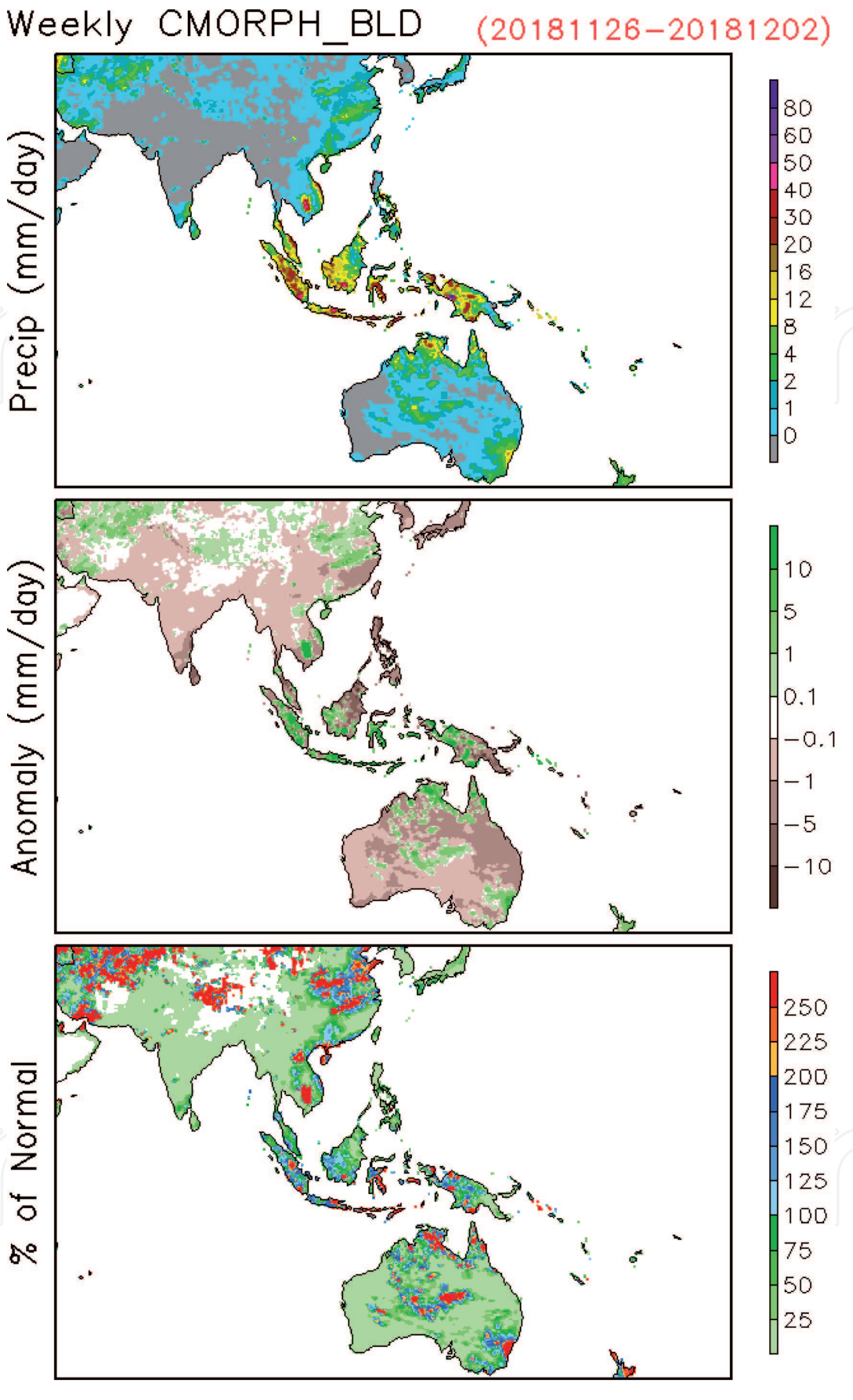
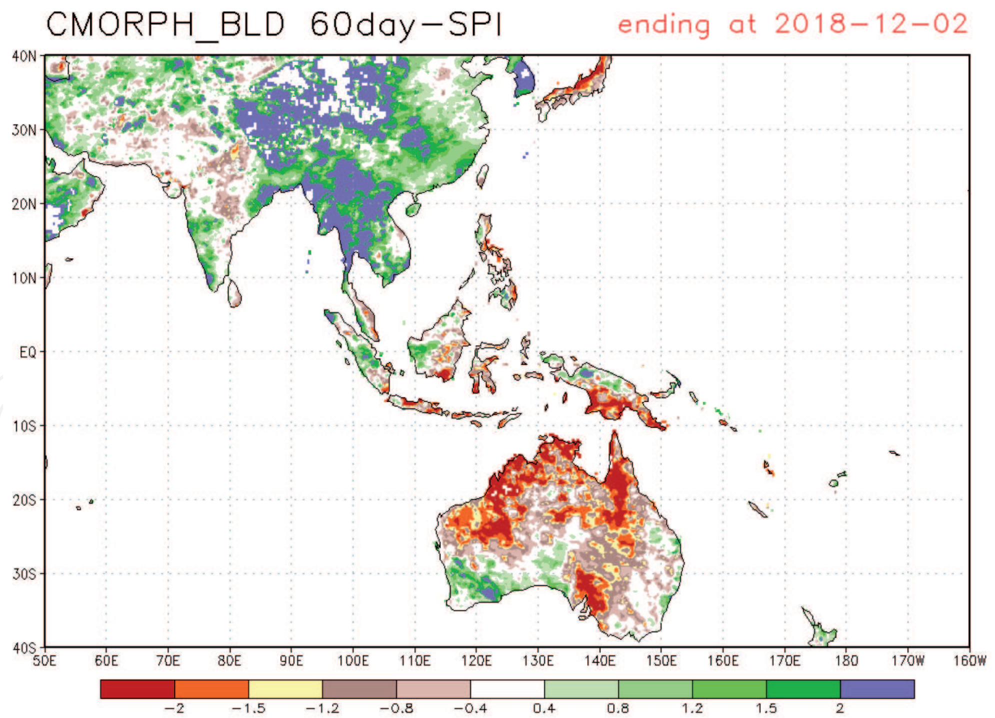


Figure 3.
CPC/NOAA CMORPH weekly summary: mean precipitation, mm/day (top panel); precipitation anomaly, mm/day (middle panel); and precipitation percentage of normal, % (bottom panel) for a week from November 26, 2018 to December 2, 2018.

anomalies indicate enhanced convection and hence increased cloudiness, while positive OLR anomalies indicate suppressed convection and decreased cloudiness. In **Figures 6** and 7, maps of AVHRR OLR and OLR anomalies for 6–10 January 2015 (pentad 2) and 15–19 August 2015 (pentad 45), respectively, are presented. Large



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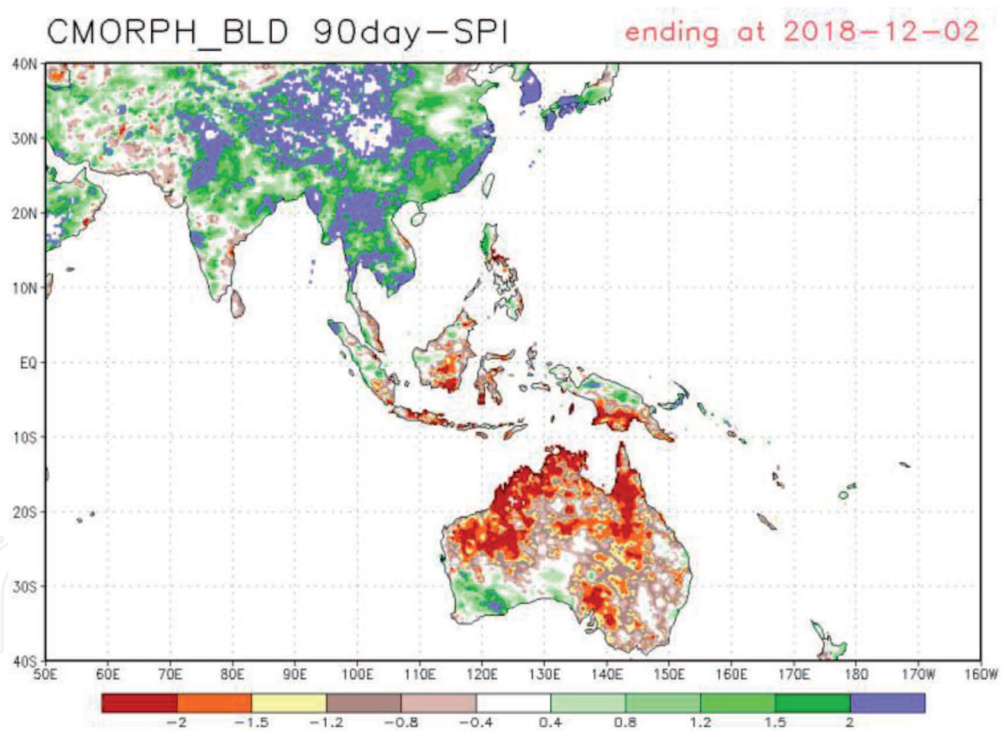

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Figure 4.
CPC/NOAA CMORPH 60-day (top panel) and 90-day (bottom panel) SPI ending at December 2, 2018.

negative OLR anomaly is evident over PNG in January 2015 indicating more cloud coverage (**Figure 6**, bottom panel), while in August 2015 it is the opposite—OLR anomaly is strongly positive indicating reduced cloud coverage over the country (**Figure 7**, bottom panel).

In summary, the introduction of SEMDP drought monitoring products is significantly strengthening the capacity of the PNG NWS to provide users in agriculture and other sectors with valuable information for decision-making which was not available prior to implementing CREWS-PNG project.

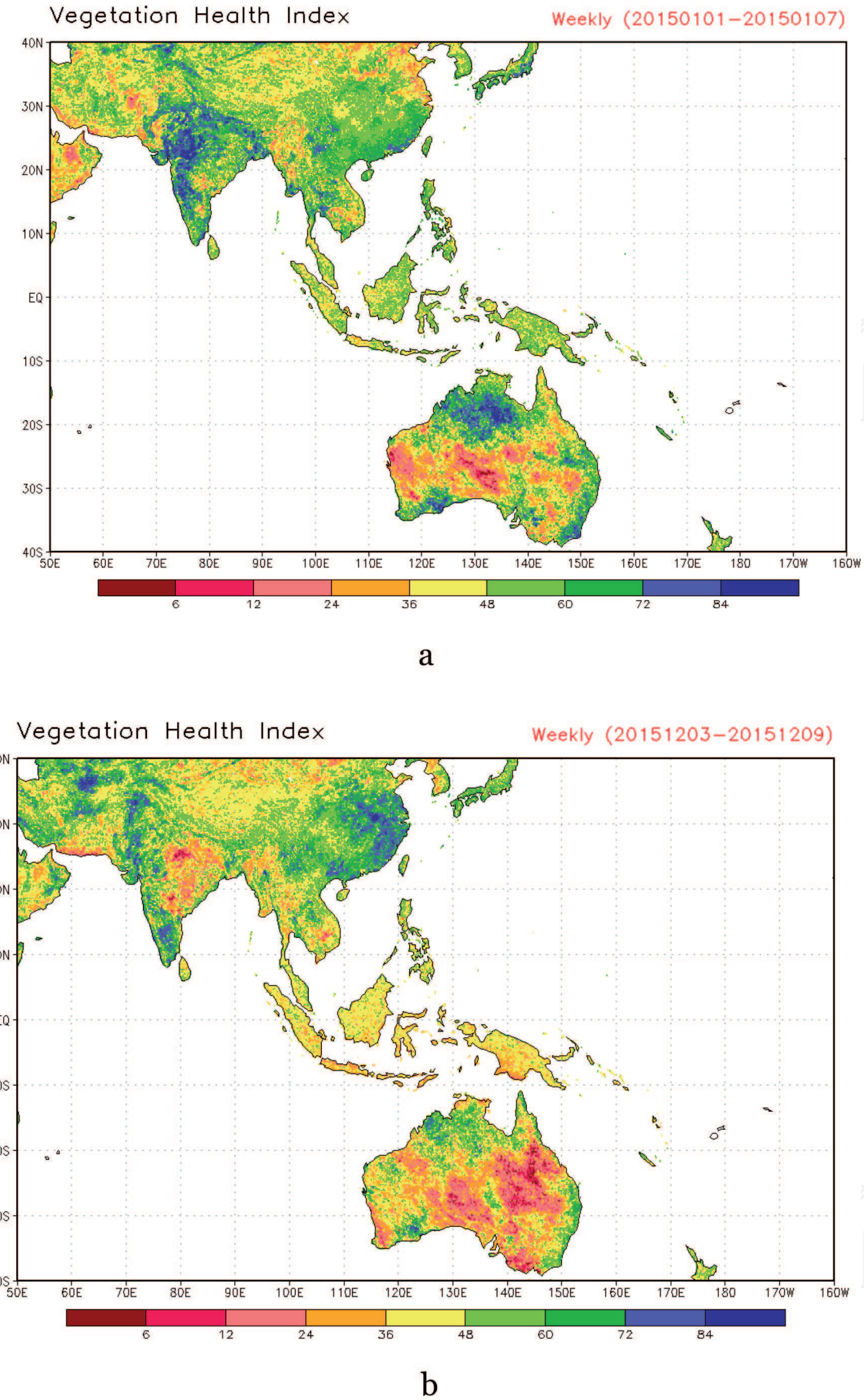

Figure 5.
CPC/NOAA CMORPH VHI for January 1–7, 2015 (top panel) and December 3–9, 2015 (bottom panel).

2.3.2 PNG-CDP

The CREWS-PNG project partners with the PNG-CDP—a project which is focused on enhancing the meteorological observation network in the country. Meteorological observations are critical for the operations of national meteorological services of all 192 WMO Members. The quality of meteorological observations from each country directly affects the accuracy of national as well as global weather forecasts, and the free exchange of these observations and other relevant data is

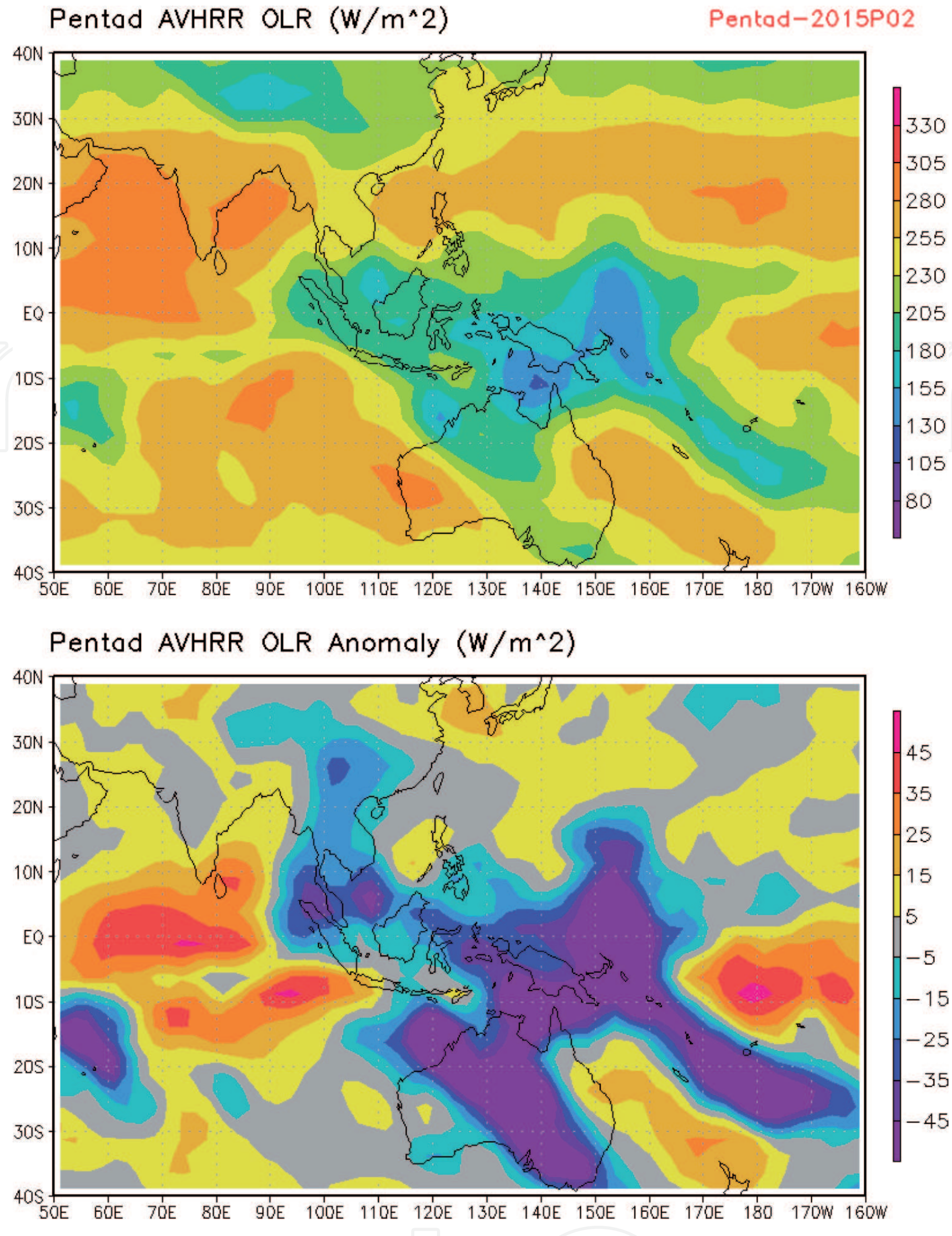

Figure 6.
AVHRR OLR for January 6–10, 2015, i.e. pentad 2 (top panel) and pentad OLR anomaly (bottom panel), W/m^2.

critical to each forecasting service. The international nature of many sectors, e.g. transport sector (aviation, shipping, road transport, etc.) and tourism, means that forecasts and warnings issued by any country can directly affect the lives of citizens of other countries and the security environment of each region is also influenced by how well weather-related natural disasters are warned for and managed. It is therefore in the global interest that all NMHSs are able to participate fully in the international effort to provide high-quality meteorological observations, weather and climate monitoring and prediction services.

A high functioning weather service is imperative to the transport sector in any country, to allow transport agencies such as air traffic management, maritime regulatory agencies and search and rescue agencies to provide a reliable service to the public. PNG is a nation with intense transport challenges. The topography, multi-island nature, population make-up and tropical climate pose issues for aviation, land and maritime transport. All transport sectors are vulnerable to weather. PNG has a monsoonal climate with intense summer rainfall and a large variation in climate across the country.

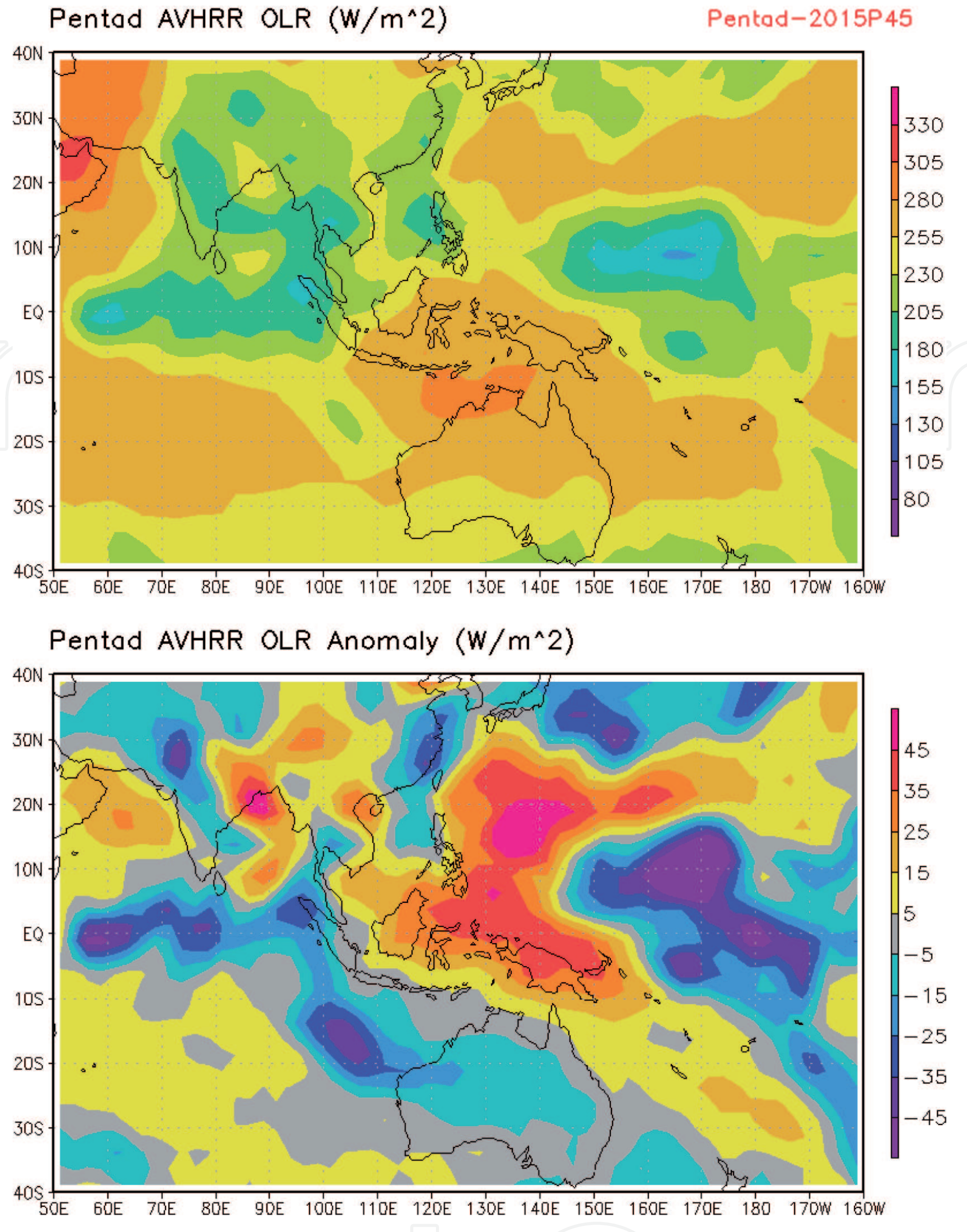

Figure 7.
AVHRR OLR for August 15–19, 2015, i.e. pentad 45 (top panel) and pentad OLR anomaly (bottom panel), W/m^2.

The PNG NWS is positioned within the Technical Services Division of the PNG Department of Transport (DoT) and operates within a highly challenging physical and social environment, providing critical warning, weather and climate services to a diverse community of marine, aviation and road transport users, emergency service organizations, agricultural users and the general public.

In 2014 the PNG DoT, supported by the Australian Government Transport Sector Support Program (TSSP) and the Australian Department of Infrastructure, Regional Development and Cities (DIRDC), commissioned a “mini-diagnostic” of the PNG NWS. The Australian Bureau of Meteorology and the International Civil Aviation Organization contributed subject matter experts to conduct this assessment. The mini-diagnostic concluded that the current capacity of the PNG NWS is not sufficient to provide high-quality observations and forecasts and there is a need to enhance capacity of PNG weather and climate services.

In response to the findings and recommendations of the mini-diagnostic, PNG and Australia agreed to add meteorology as a field of cooperation under an annex to the memorandum of understanding (MOU) between the Government of PNG and the Government of Australia on Cooperation in the Transport Sector. The PNG-CDP was established under this MOU in 2017, and initial activities were focused on two key areas: (i) the establishment of a strategic planning process for the PNG NWS and (ii) the provision of training to support the delivery of improved weather services and forecasting support for APEC 2018.

As part of the initial strategic evaluation, the WMO provided a meteorological observations expert to work with Bureau staff in examining the state of the observation network in more detail. The resultant report again underlined the very real challenges facing the PNG NWS but also outlined practical and useful steps forward to enhance the meteorological observation network in the country. Based on the WMO recommendations, the scope of the PNG-CDP has broadened to include provision and ongoing management of a third-party AWS observation network.

CREWS-PNG and the PNG-CDP collaborate on enhancing the meteorological observation network. Working in partnership with the PNG Remote Sensing Center (RSC), the PNG-CDP supports the PNG NWS to supplement their government-owned observation network with an existing third-party AWS network. The intention is to address the immediate need for the provision of observational data across PNG, while in parallel efforts are made to restore the existing surface-based station network to its full capacity. Over the past 10 years, the PNG RSC has created and maintained a climate monitoring network across PNG through the installation of AWSs on mobile phone towers. The network density has incrementally increased to include 37 AWSs distributed across all the climatic zones of PNG, including the majority of towns and airports. These stations have been inspected by a WMO representative to ensure that they record meteorological observations which meet the minimum threshold requirements for predictive weather and aviation purposes. A number of AWSs also support web camera technology. **Figure 8** depicts the AWS

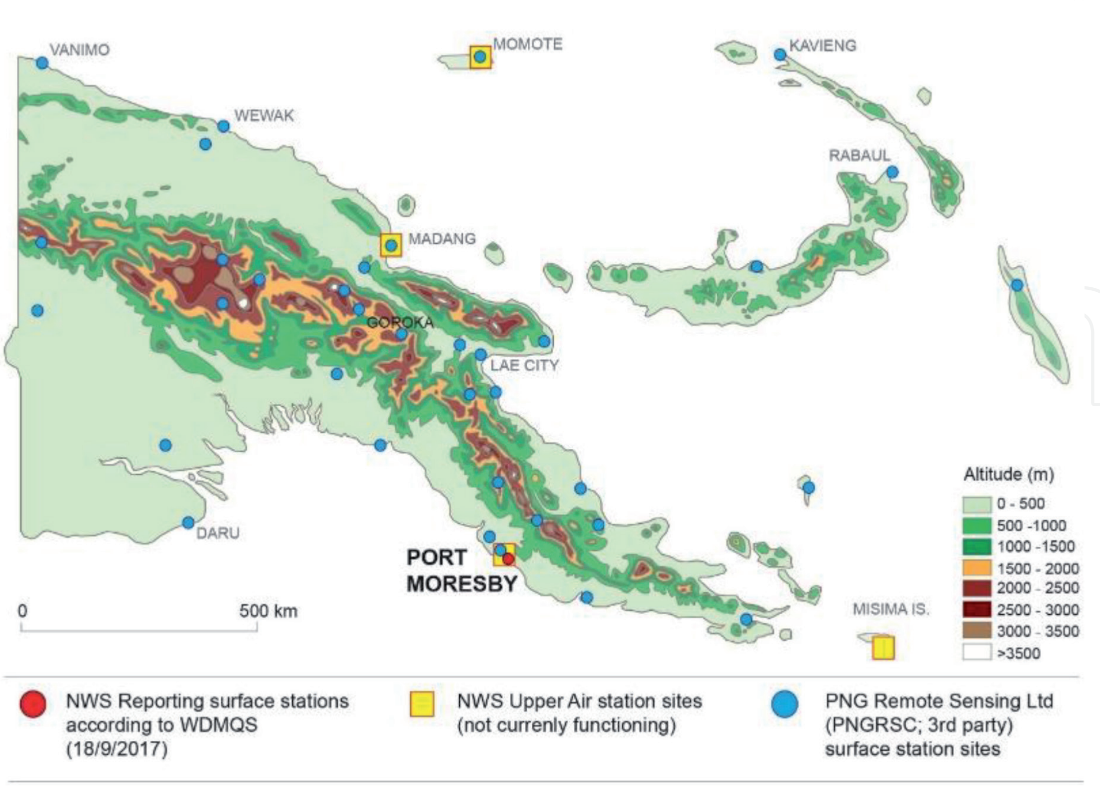

Figure 8.
Schematic map of Papua New Guinea depicting topographic extremes and the observations received from the NWS surface network on the morning of September 18, 2017, the NWS historically active upper air station sites (not currently functioning) and the location of 37 PNG Remote Sensing Centre Ltd. automated weather station sites (third party privately owned).

locations of the third-party AWS network (PNG RSC) together with the location of an existing PNG NWS surface-based stations (currently reporting) and PNG NWS upper air stations (not currently reporting).

The PNG RSC AWS data are delivered using the mobile network and a variety of web-based platforms. The PNG-CDP works with the PNG RSC to quality control the data and formats, utilize new and innovative approaches for addressing communication and Internet connectivity issues for data extraction (i.e. Amazon Web Services) and integrate the data with the PNG NWS systems to ensure it is useful, usable and used by PNG meteorologists.

A strategy for collaboration between the CREWS-PNG, the SEMDP and the PNG-CDP was discussed in detail during a workshop held in Port Moresby in February 2019. Extensive consultations with key PNG stakeholders were undertaken. Users of weather and climate information from the Department of Agriculture and Livestock, National Agriculture Research Institute, National Disaster Centre, Climate Change Development Authority, Fresh Produce Development Authority, Conservation and Environment Protection Agency, Cocoa and Coconut Research Institute, Coffee Research Institute, members of the PNG Disaster Management team and other stakeholders contributed to the development of the workshop's recommendations focusing on strengthening the capacity of the PNG NWS to provide high-quality meteorological observations, drought monitoring and prediction services addressing directly the users' needs.

Together, the CREWS-PNG, the SEMDP and the PNG-CDP, working in conjunction with the PNG NWS, will significantly strengthen capacity of the PNG NWS to provide users with valuable drought monitoring information, high-accuracy weather forecasts and subseasonal-to-seasonal climate prediction.

3. ICCAI: seasonal climate prediction for the Pacific Island nations

CREWS-PNG is building on the success of earlier Pacific projects such as the Pacific Adaptation Strategy Assistance Program (PASAP) and the Pacific-Australia Climate Change Science Adaptation Planning (PACCSAP) program undertaken under the Australian's Government International Climate Change Adaptation Initiative. Under those Pacific projects, a number of regional consolidated databases and web-based information tools were developed, to assist 15 partner countries in the Pacific with decision-making in climate change adaptation and disaster risk reduction.

It has been demonstrated that seasonal climate prediction tools are a valuable means to assist with climate change adaptation and disaster risk reduction [18]. For decades, seasonal climate prediction in Australia and the Pacific Island Countries was based on statistical models [10]. However, in a rapidly changing environment, the skill of statistical models which are solely based on past records is expected to deteriorate. Hence dynamical climate models, which are based on laws of physics rather than past relationships, are preferable for forecasting climate on time scales from weeks to months and beyond.

It has been shown that using the outputs of the dynamical climate model Predictive Ocean and Atmosphere Model for Australia (POAMA), skilful predictions of regional rainfall could be provided 2–3 months in advance [19, 20]. POAMA was developed [21] and used by the Bureau of Meteorology operationally to produce its seasonal climate outlooks from 2013. It is a state-of-the-art dynamical (physics-based) forecast model which used ocean, atmosphere, ice and land observations to initiate the model and produce outlooks for the season ahead.

Recently, a new higher resolution model—the Australian Community Climate and Earth-System Simulator (ACCESS)—has succeeded POAMA to further enhance the Bureau's capability in weather and climate prediction. Since August 2018 the Bureau's operational climate forecast system for multi-week, monthly, seasonal and longer-range climate outlooks is ACCESS-Seasonal (ACCESS-S). The atmosphere and land model components of ACCESS-S operate at an approximate global resolution of 60 km, providing far greater detail than POAMA which had an approximate resolution of 250 km. The multi-week and seasonal performance of ACCESS-S has been evaluated for Australia based on a 23-year hindcast set and compared to the previous operational system, POAMA [22]. However, hindcast skill and calibration have not been assessed for other countries in the region including PNG. One of the key tasks for CREWS-PNG is to assess and utilize outputs of ACCESS-S in order to produce accurate multi-week and seasonal climate outlooks that will improve drought prediction for the country.

4. Web-based information tools to disseminate climate monitoring and seasonal prediction products

CREWS-PNG is a successor of the Pacific projects of the ICCAI, and its implementation strategy is based on similar approaches to develop climate monitoring and seasonal prediction products as well as means of disseminating information. It is important to ensure that climate monitoring and subseasonal-to-seasonal prediction products are not only of high accuracy but also are delivered to users in a timely manner and in a way that can be utilized in their decision-making. As part of the PASAP and PACCSAP activities, the Pacific Seasonal Prediction Portal was developed to disseminate climate data and dynamical climate model-based forecast products through a range of web-based information tools (**Figure 9**). This portal could be accessed through the Australian Bureau of Meteorology's website: http://www.bom.gov.au/climate/pacific/projects.shtml.

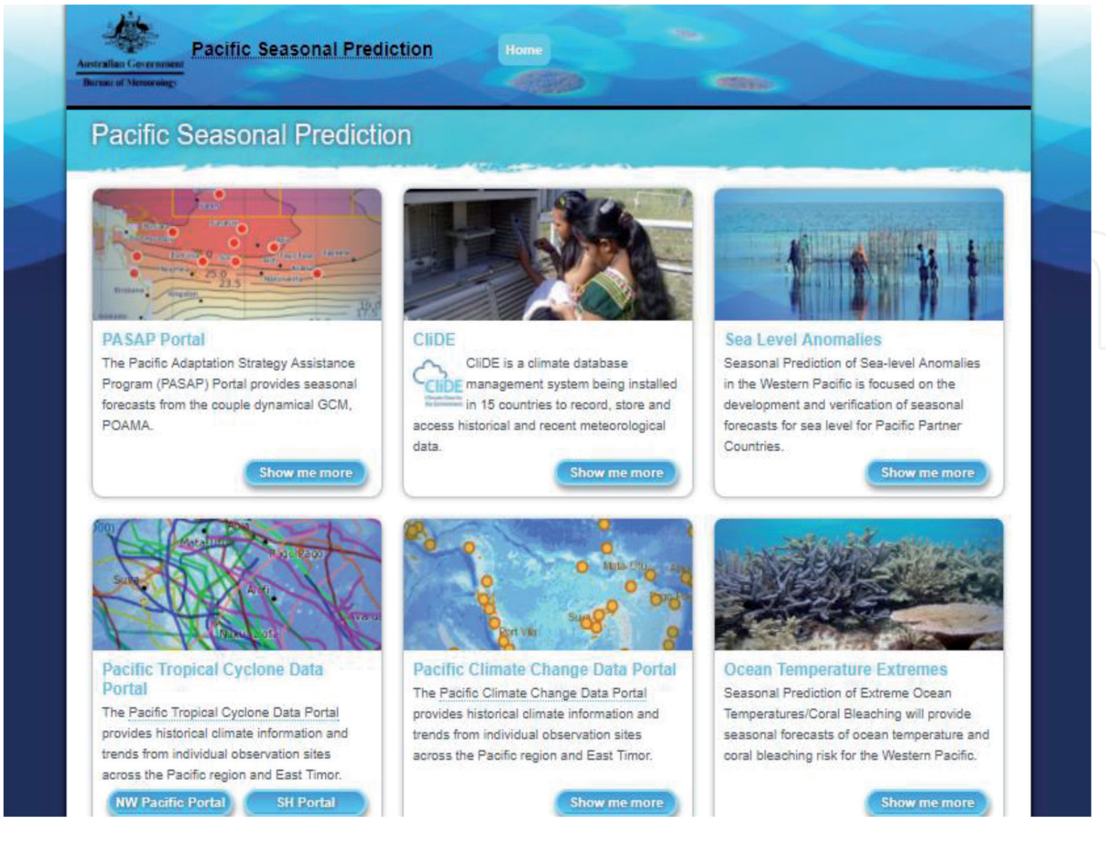

Figure 9.
Home page of the Pacific Seasonal Prediction Portal.

The Pacific Seasonal Prediction Portal provides users with access to a range of products for monitoring and prediction of weather and climate extremes. Here we briefly introduce some of these products, including key features of the tropical cyclone (TC) and seasonal prediction portals, including extreme ocean temperatures and potential coral bleaching.

TCs are severe weather events which affects Pacific Island Countries every year, causing loss of life land property. Damage caused by TCs is not only caused by destructive winds but also torrential rain, high ocean waves and storm surge. To be prepared for the multi-hazards associated with TCs, knowledge about regional historical cyclone tracks are important. Meteorological agencies of the Pacific Island Countries as well as numerous other users utilize the portal to access such information for areas of interest. As an example, tracks of 80 tropical cyclones which passed through exclusive economic zone of PNG between the 1969–1970 and 2016–2017 tropical cyclone seasons retrieved through the Southern Hemisphere Tropical Cyclone Data Portal are presented in **Figure 10**. A comprehensive description of the Southern Hemisphere Tropical Cyclone Data Portal could be found in [23], which also provides readers with the users' guide to the web-based information tool to select, retrieve, display and analyse TC data.

The importance of seasonal climate prediction to assist with decision-making is recognized by users from climate-sensitive sectors around the world. Seasonal climate outlooks at various levels—national, regional and global—are operationally produced by NMHSs, Regional Climate Centres (RCCs) and the WMO providing users with vital information about state of the El Niño-Southern Oscillation and its expected development, plus seasonal climate outlooks for temperatures, rainfall and a variety of other variables. Climate outlooks at the global scale are disseminated by the WMO, while at a regional level, WMO GPC LRFs and RCCs play a leading role in this task. In the Pacific, WMO GPC LRF Melbourne is tasked with disseminating outputs from the dynamical climate model POAMA to RCCs and NMHSs in the region. As an example, the seasonal prediction of sea surface temperature in the Pacific for January to March 2019 is presented in **Figure 11**, demonstrating a significant oceanic warming in equatorial central Pacific—a possible precursor to El Niño.

The livelihood of many people in Pacific Island Countries is highly dependent on the productivity of the oceans including coral reefs which surrounds the islands. A

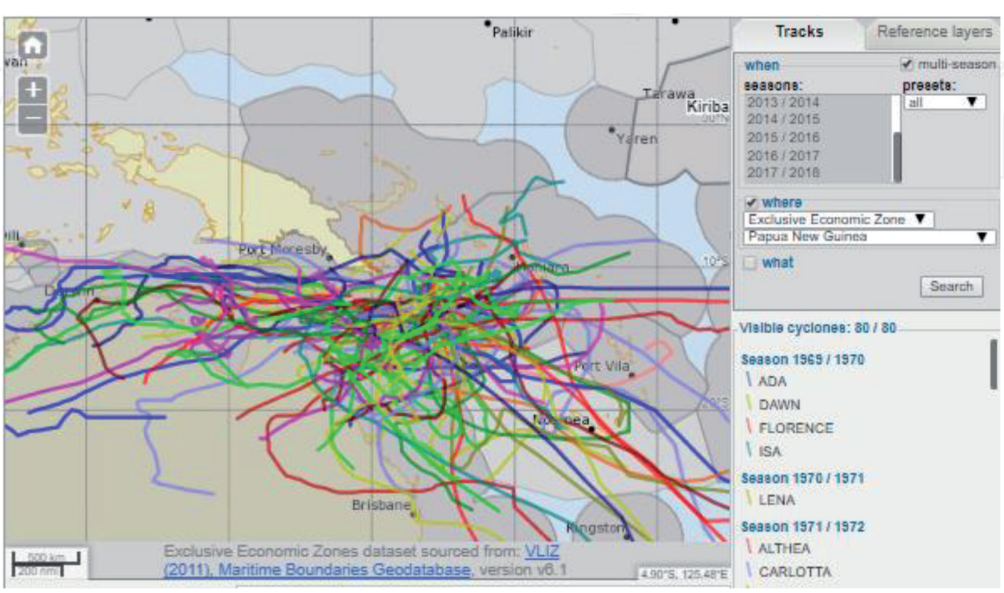

Figure 10.
Tracks of 80 tropical cyclones from the Southern Hemisphere Tropical Cyclone Data Portal which passed through the exclusive economic zone (EEZ) of PNG between the 1969–1970 and 2016–2017 tropical cyclone seasons.

dramatic impact of climate change on the health of coral reefs has been observed in recent decades due to the increase in ocean acidification and especially due to increase in frequency and intensity of extreme ocean temperatures which led to severe coral bleaching events and impacts on marine life [24]. Disseminating early warnings

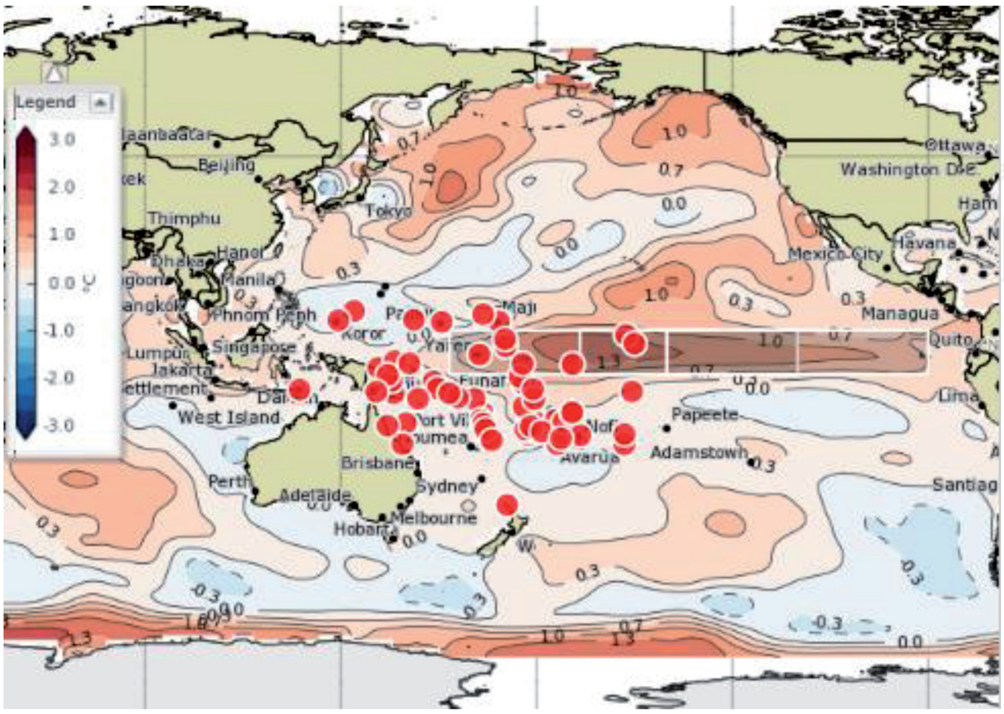

Figure 11.
Seasonal prediction of sea surface temperature in the Pacific for January–March 2019 based on outputs of POAMA retrieved through the Pacific Seasonal Prediction Portal—WMO GPC LRF Pacific Seasonal Prediction.

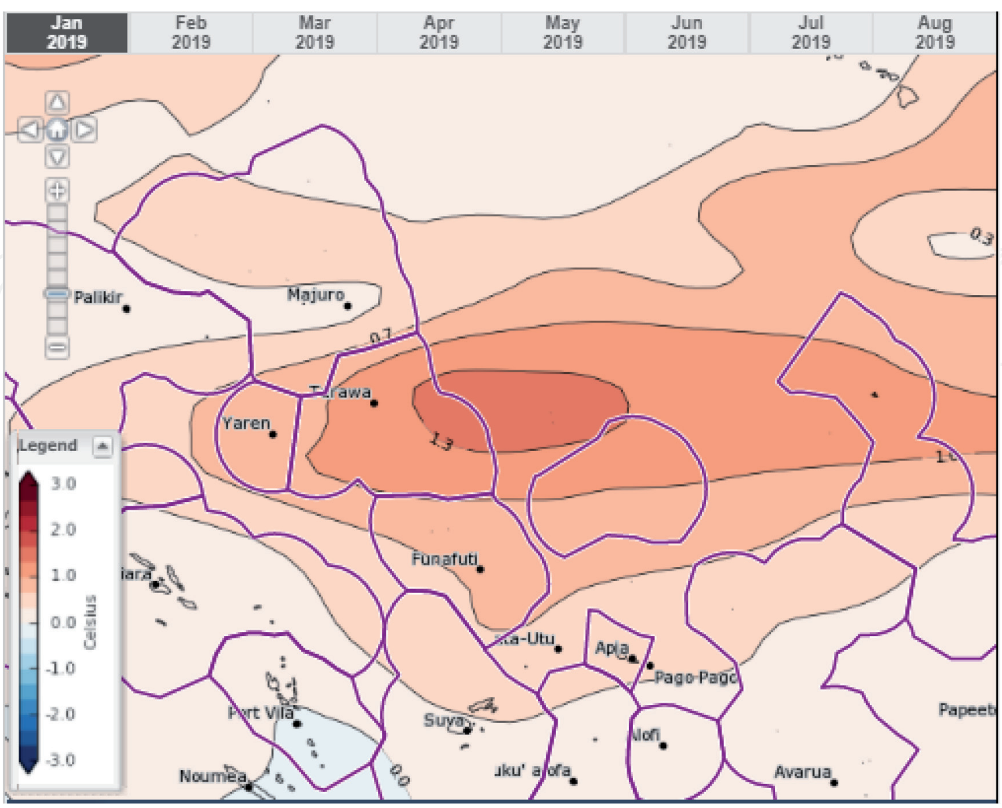

Figure 12.
Seasonal prediction of sea surface temperatures around Kiribati based on outputs of POAMA retrieved through the Pacific Seasonal Prediction Portal—extreme ocean temperatures and coral bleaching.

about possible extreme ocean temperatures, e.g. because of a coming El Niño event, is essential—it provides local government authorities with vital information 2–3 months in advance allowing them to implement protective measures. For example, the spatial distribution of predicted sea surface temperatures around Kiribati is presented in **Figure 12** (the forecast for January 2019 is based on outputs of POAMA; model was initialized on December 02, 2018). Extreme ocean temperatures in some areas of exclusive economic zone of Kiribati are expected to exceed 1.3°C compared to climatology (1982–2010), potentially leading to coral bleaching in those areas.

CREWS-PNG is taking the outlined above approach to disseminate climate information based on outputs of the new ACCESS-S dynamical climate model as part of its implementation strategy. The introduction of impact-based drought forecasts and associated risk-based warnings for improved decision-making is planned to be delivered through a specialized web-based information tool which will be an integral part of the Pacific Seasonal Prediction Portal. Products and climate services will be developed and implemented based on close consultation with stakeholders to understand their decision-making requirements.

5. Conclusions

Climate monitoring combined with skilful subseasonal-to-seasonal climate prediction enables NMHS to provide their governments, industry sectors and local communities with accurate information to assist in their decisions around how to adapt to climate variability and change. CREWS-PNG will contribute significantly to enhance EWS in PNG, and it is envisaged that cutting edge weather and climate monitoring and prediction products developed for PNG under this project could be expanded to include NMHS across the Asia-Pacific region. The result would be a significant advance for climate services provided by meteorological agencies of LDCs and SIDS in the region.

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Conflict of interest

Declaration: there is no conflict of interest.

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