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SEASONAL PREDICTION OF CLIMATE EXTREMES FOR THE PACIFIC: TROPICAL CYCLONES AND EXTREME OCEAN TEMPERATURES

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SEASONAL PREDICTION OF CLIMATE EXTREMES FOR THE PACIFIC: TROPICAL CYCLONES AND EXTREME OCEAN TEMPERATURES

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Key words: seasonal prediction, climate extremes, tropical cyclones, extreme ocean temperatures.

ABSTRACT

Climate change and climate extremes have a major impact on Australia and Pacific Island countries. Of particular concern are tropical cyclones and extreme ocean temperatures. As a practical response to climate change, through the Pacific Australia Climate Change Science and Adaptation planning Program (PACCSAP), enhanced web-based information tools to provide seasonal forecasts for climatic extremes in the Western Pacific have been developed. Using the dynamical seasonal prediction model POAMA (Predictive Ocean Atmosphere Model for Australia), we aim to improve accuracy of seasonal forecasts of tropical cyclone activity and extreme sea surface temperatures for the Western Pacific. Since the PACCSAP has commenced, encouraging scientific and technological results have been obtained, particularly in the development of web-based information tools to provide climatic extremes forecasts in the Pacific and the Australian regions. Improvements to a statistical model for seasonal tropical cyclone prediction in the Australian region have been made. Additional functionality was added to the Pacific Tropical Cyclone Data Portal, such as enhanced flexibility of spatial and temporal selection. New web-based information tool for sea surface temperature seasonal prediction is also currently under development. Improved knowledge of extreme climatic events, together with the assistance of tailored forecast tools, will help enhance the resilience and adaptive capacity of Australia and Pacific Island Countries under climate change.

I. INTRODUCTION

The Pacific Australia Climate Change Science and Adaptation planning Program (PACCSAP) is an integral part of the International Climate Change Adaptation Initiative (ICCAI) - an Australian Government initiative to address high priority climate adaptation needs in vulnerable countries in the Asia-Pacific region. The ICCAI recognizes that seasonal and inter-annual climate variability is a major factor in determining the vulnerability of countries to climate change. An important aspect of climate variability is that it interacts with the changing background climate to produce many of the first noticeable impacts of climate change and expose regions of greatest vulnerability. Droughts, floods, tropical cyclones, high oceanic and air temperatures all lead to social and economic stress within the Pacific region. Importantly, the character of such events varies with seasonal climate variability and will also change as a consequence of future climate change.

Climate change and climate extremes have a major impact on Australia and Pacific Island countries. The PACCSAP works with Western Pacific countries both north and south of the equator to deliver improved seasonal forecasting technologies and capacity. Subsequently referred to as the "Partner Countries", those involved are Timor Leste and 14 Pacific Island Countries: Papua New Guinea, Tuvalu, Kiribati, Fiji, Marshall Islands, Federated States of Micronesia, Palau, Nauru, Cook Islands, Samoa, Tonga, Niue, Solomon Islands, and Vanuatu.

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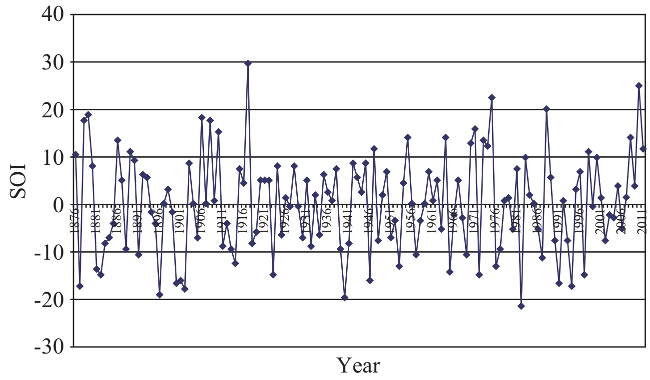

Fig. 1. Time series of the Southern Oscillation Index (SOI) for September.

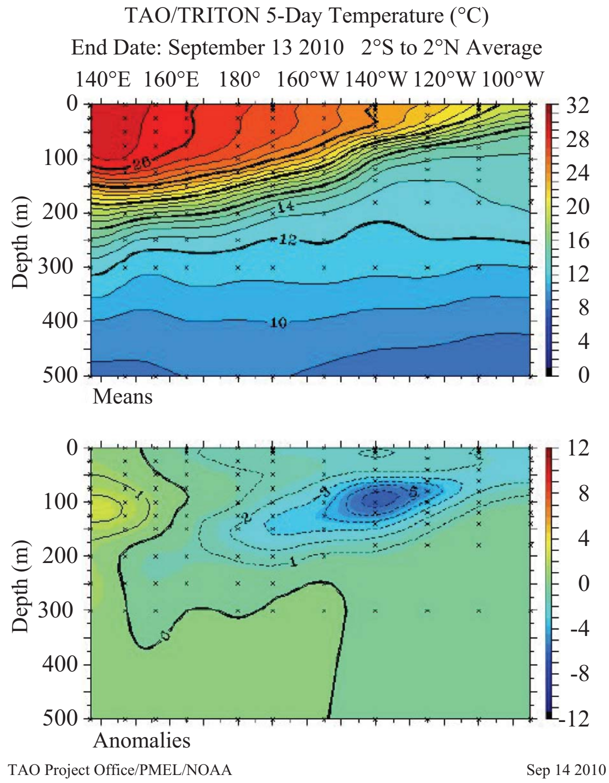

Fig. 2. September subsurface temperatures (5-day average) for the Pacific Ocean – mean values (top panel) and anomalies (bottom panel).

The Pacific Climate Change Science Program (PCCSP) has contributed substantially to our understanding of tropical cyclone variability over recent decades highlighting strong links to the El Niño-Southern Oscillation (ENSO), larger interannual variability and some trends. One issue that has emerged from the use of the PCCSP data is the problem in predicting tropical cyclone occurrence based on historical relationships. Under the Pacific Adaptation Strategy Assistance Program (PASAP) seasonal prediction project, we have developed dynamical model-based seasonal climate prediction which is presently implemented in the 15 Partner Countries [11]. As a continuation of our PCCSP and PASAP efforts and a practical response to adaptation to climate change, under the Theme 1 "Seasonal climate prediction and software tools" of the PACCSAP, we are developing enhanced web-based information tools for providing seasonal forecasts for climatic extremes in the Western Pacific. In this paper we describe the "Seasonal prediction of tropical cyclones" and "Seasonal prediction of extreme ocean temperatures/coral bleaching" projects.

At present, national meteorological services in Australia and the Partner Countries rely on statistical models for seasonal prediction, including prediction of tropical cyclones. However, statistical models cannot reliably account for aspects of climate variability and change that are not represented in the historical records. In a warming climate, environmental indicators used as predictors are now frequently observed outside of the range of historical records. Consequently, the prediction skill of statistical models is decreasing, and may lead to the provision of unrealistic forecasts. For example, prediction of seasonal tropical cyclone activity is usually based on statistical methods (see section 4 for details). In Fig. 1, long-term time series of observed values of the Southern Oscillation Index (SOI), which is commonly used as a predictor, are presented. Note that the SOI value for September 2010 was +25, the highest September value since 1917 (+29.7). Concurrently, temperatures below the surface of the Pacific Ocean were up to 5°C cooler than normal (Fig. 2) indicating that a strong La Niña was developing. A very active tropical cyclone season was expected in the Australian region based on statistical models which use historical tropical cyclone – ENSO relationship (20 to 22 cyclones were forecasted). Indeed, the 2010/2011 La Niña was a strong event, however, the 2010/2011 Australian region cyclone season was actually a near-average tropical cyclone season, with 11 tropical cyclones forming compared to an average of 12. This reinforced a message that in a changing climate, values of the environmental indicators frequently lie outside of the range of past variability which means that it is not possible to find historical analogues for seasonal conditions often faced by Pacific countries.

In contrast, dynamical physics-based models implicitly include the effects of a changing climate and can predict outcomes not seen previously. The transition from a statistical to a dynamical prediction system will provide more valuable and applicable climate information to a wide range of climate sensitive sectors throughout the countries of the Pacific region. This shift will reduce reliance on historical climatologies, whilst providing improved forecasts of extreme events, and is a key part of the projects we describe.

II. PREDICTIVE OCEAN ATMOSPHERE MODEL FOR AUSTRALIA

The Predictive Ocean Atmosphere Model for Australia (POAMA) is a state-of-the-art dynamical seasonal forecast

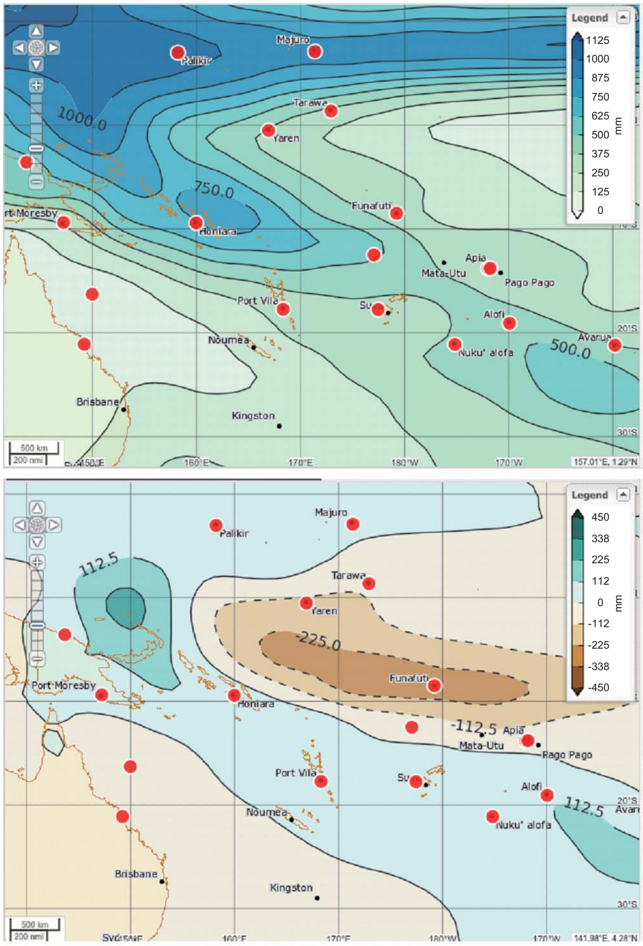

Fig. 3. Example ensemble mean forecast for accumulated rainfall for September – November 2011 (top panel) and accumulated rainfall anomalies (bottom panel).

system, developed by the Australian Bureau of Meteorology (BoM) and CSIRO. POAMA is a global seasonal ensemble prediction system, consisting of a coupled ocean–atmosphere model and initialisation systems for the ocean, land, and atmosphere [7,19]. The spatial resolution is about 2.5° by 2.5° and the temporal resolution is 720s for the atmospheric model. For the ocean model, the spatial and temporal resolutions are 0.5-1.5° by 2° and 900s, respectively. The system has internationally competitive skill in predicting ENSO up to 9 months in advance [5]. POAMA has been running operationally since 2002 and currently provides operational ENSO and Great Barrier Reef sea surface temperature (SST) forecasts [16].

Working on the PASAP project, we have developed and deployed prototype seasonal climate predictions based upon POAMA for the Western Pacific [3]. Outputs of the PASAP project provide national meteorological agencies in the Partner Countries with a new tool to analyse rainfall (e.g. Fig. 3), SSTs, air temperature and mean sea level pressure, as well as enabling preparation of more accurate seasonal climate predictions.

Presently, we are working on further extension of seasonal prediction under the PACCSAP with a focus on extreme climatic events. In particular, two projects which we describe in this paper are looking in detail at the seasonal prediction of both tropical cyclones and extreme ocean temperatures (and the associated coral bleaching risk).

III. PACCSAP PROJECTS

The infrastructure and knowledge built in the PASAP and PCCSP projects are now being used to explore the variability, predictability and ultimately the seasonal prediction of extreme climatic events. These are briefly described below.

1. Seasonal Prediction of Tropical Cyclones

Tropical cyclones are the most destructive weather systems impacting on Partner Countries. Interannual variability in the intensity and distribution of tropical cyclones is large, and presently greater than any trends that are ascribable to climate change. Historically tropical cyclones have had major impacts on life, agriculture, water supplies, safety, the economy, and in extreme cases threatened the sustainability of Partner Countries.

Better understanding the year to year variability in cyclone frequency and severity is a practical means for decreasing current and future vulnerability to tropical cyclones. In addition, understanding the drivers of variability provides greater confidence in future predictions and projections in tropical cyclones. This is particularly important as current predictions of tropical cyclones are primarily drawn from historical data and observed covariability with drivers such as the ENSO, which are less valid in a changing climate.

Tropical cyclones have significant local impacts in the region, are known to be predictable on seasonal timescales using statistical models and seasonal forecasts of tropical cyclone activity can inform and improve decision making and planning to improve Partner Country resilience and inform adaptation. Currently, a statistical technique is used to prepare tropical cyclone seasonal predictions for the Australian and the South Pacific regions. This statistical technique uses observed relationships between the ENSO and tropical cyclone activity. As the statistical model is based on historical data, it only accounts for the past relationship between the ENSO and tropical cyclone activity over recent decades. In a warming climate, it is likely that the ENSO will change [1] which in turn will affect tropical cyclone distribution over the Pacific and their intensity.

Early analysis has revealed that POAMA has skill in the prediction of climate drivers such as ENSO in the Pacific which are known to modulate tropical cyclone occurrence and intensity. Consequently, in addition to improving skill of a statistical model described in section 4, experimental operational dynamical model-based predictions for tropical cyclone activity in the South and North-West Pacific using outputs from POAMA as predictors is currently under development.

Further development of the Pacific Tropical Cyclone Data Portal which we designed under the PCCSP [9] is also undertaken. The portal was designed using OpenLayers mapping technology to provide a user-friendly means for accessing detailed information and data on historical tropical cyclones for the Southern Hemisphere and it is now available through the BoM web site (http://www.bom.gov.au/cyclone/history/tracks/). Improvements to this portal will include enhanced functionality and capability to display historical cyclone information for the South and North-West Pacific as well as seasonal forecasts of tropical cyclone activity in the coming season.

2. Sea Surface Temperatures and Coral Bleaching

Increasing ocean temperatures under climate change will have widespread impacts on the health and productivity of many marine ecosystems, including coral reefs. Elevated ocean temperature has been established as the primary cause of mass coral bleaching events, with severity and scale of events increasing in recent decades. During the worldwide mass bleaching event of 1997/1998, 16% of the coral reefs of the world were effectively destroyed [20]. Water temperature extremes also affect fish growth, prey abundance and suitable habitat locations, thus impacting fisheries.

Prediction of thermal stress events enables the support of a range of adaptive and management activities that could improve reef resilience to extreme conditions. In this project we are developing dynamical POAMA based predictions for extreme ocean temperature conditions in territorial waters of Partner Countries.

The primary focus of this project is the seasonal predicttion of extreme SSTs and the associated risk of mass coral bleaching in the Western Pacific. The interaction of seasonal variability and a warming ocean under climate change is expected to result in an increasing number of extreme temperature events in the future. Extreme ocean temperatures, particularly when sustained over time and across large regions, can have widespread impacts on marine life such as coral reefs and fisheries. Coral reefs are very important resources in coastal regions, providing income from and resources for tourism, fishing, building materials, and coastal protection. Extensive coral reefs exist across the Western Pacific (Fig. 4) and serve these functions in many of the Partner Countries.

However, these highly productive ecosystems are vulnerable to a range of stressors including increasing ocean temperatures, tropical cyclones, freshwater plumes, ocean acidification and anthropogenic pollution. Mass coral bleaching events are primarily triggered by anomalously warm ocean temperatures, where bleaching is a result of loss of symbiotic algae from coral tissues under stress. These events can lead to widespread reef damage and in severe cases of prolonged thermal stress, mortality due to bleaching and/or subsequent disease can occur, leading to loss of reef structure and habitats. Under global warming, these events are expected to increase in both severity and frequency [6]. This predicted increased occurrence of future events reinforces the urgency of increasing knowledge and awareness of bleaching processes, in addition to the development of effective management plans and tools to minimise the impact of such events [17].

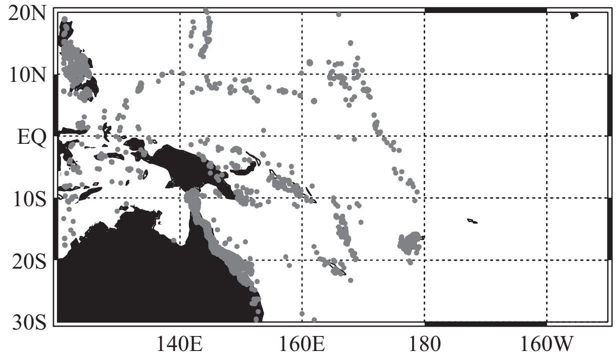

Fig. 4. Locations of the major stony coral reefs of the Western Pacific Ocean. Data provided by the United Nations Environment Programme's World Conservation Monitoring Centre (UNEP-WCMC) and ReefBase (information online at http://www.reefbase.org).

IV. PROJECT RESULTS

Since the PACCSAP has commenced, encouraging scientific and technological results have been obtained, particularly in the developing web-based information tools to provide climatic extremes forecasts in the Pacific and the Australian regions. Some of the achieved project outcomes are presented in this section.

1. Tropical Cyclone Seasonal Prediction

An improved statistical model for seasonal tropical cyclone prediction in the Australian region has been achieved through this project. Over recent decades, statistical model-based methods for prediction of tropical cyclone activity in the coming season have been developed for a number of regions in various ocean basins [2, 8, 13, 15]. Statistical models explore relationships between large-scale environmental drivers which modulate tropical cyclone activity, for example the ENSO phenomenon, and observed numbers of tropical cyclones. In our early studies we utilised historical data for the Australian region and the tropical cyclone-ENSO relationship to develop a statistical model to describe the variability and trends in tropical cyclone activity in the Australian and some other regions [10]. In the current project, we used this statistical model to predict seasonal tropical cyclone activity. We further improved accuracy of the statistical through enhancements to the model.

Various indices are employed to describe strength of the ENSO. The NIÑO3.4 index (SST anomalies in Niño3.4 region) and the SOI are two most commonly used indices in defining the ENSO phases. A multivariate ENSO index, based on the first principal component of monthly Darwin mean sea level pressure (MSLP), Tahiti MSLP, and the NIÑO3,

Table 1. Multiple linear regressions with both time trend and the September 5VAR (model 1), the August-September NIÑO3.4 (model 2) and the July-August-September SOI (model 3) respectively.

	Model 1		Model 2		Model 3	
	Coeff.	*p*-value	Coeff.	*p*-value	Coeff.	*p*-value
T	-0.054	0.13	-0.056	0.13	-0.067	0.058
5VAR	-2.240	4e-06	-	-	-	-
NINO3.4	-	-	-2.561	2e-05	-	-
SOI	-	-	-	-	+0.233	5e-06
Resid. s.e	2.592		2.711		2.605	
Adj R^2	0.452		0.401		0.446	

Table 2. Multiple linear regression models (as per Table 1) with influential points removed.

	Model 1.1		Model 2.1		Model 3.1	
Point removed	1		1		1	
	Coeff.	*p*-value	Coeff.	*p*-value	Coeff.	*p*-value
T	-0.079	0.026	-0.083	0.025	-0.094	0.007
5VAR	-2.055	8-06	-	-	-	-
NINO3.4	-	-	-2.350	4e-05	-	-
SOI	-	-	-	-	+0.218	4e-06
Resid. s.e	2.428		2.528		2.391	
Adj R^2	0.486		0.443		0.501	

NIÑO3.4 and NIÑO4 SST indices, has been developed at the National Climate Centre (see also [10] for details). Its base period is 1950-1999. Strength of a multivariate index is in integrating both atmospheric and oceanic responses to changes in the ENSO phases in one index. We denote this standardised monthly anomaly index as the 5VAR index. In this project, we developed statistical models using the NIÑO3.4, the SOI and the 5VAR indices. We modified the simple linear regression model developed earlier in [10] by adding a temporal trend variable (T) as one of the predictors. The candidate models were

Model 1

$$AR = \beta_0 + \beta_1 T + \beta_2 5VAR + \varepsilon \tag{1}$$

Model 2

$$AR = \beta_0 + \beta_1 T + \beta_2 NINO3.4 + \varepsilon \tag{2}$$

Model 3

$$AR = \beta_0 + \beta_1 T + \beta_2 SOI + \varepsilon \tag{3}$$

where ε denotes the noise variable, assumed to be normally distributed with mean 0 and variance σ^2, i.e., $\varepsilon \sim N(0, \sigma^2)$.

All the model fitting were carried out using R software (http://www.r-project.org/). The estimated regression model results are presented in Table 1.

All three models have significant coefficients for the three indicial predictors. It was found, as in our earlier study, that the regression model with 5VAR as the predictor surpasses the other two models with SOI or NIÑO3.4 as the predictors. In our analyses, we also take into account an influential point, which is an observation that greatly affects the slope of the regression line. Three influential points were detected for models 1 and 2, and two influential points for model 3. After adjusting the models to account for influential points, we obtained modified model fitting results (Table 2).

The first influential point (five tropical cyclones observed in the 1969/1970 season) was found to be the most influential point for all three models. All three indices along with the temporal trend explained 44% to 50% of the total variation in the annual number of tropical cyclones in the Australian region. After removing the influential point, one can see (Table 2) that all three modified regression models perform better in terms of improved adjusted R^2 values. The temporal trend effect also became significant (P-values < 0.05) after removing the first influential point, making the temporal trend an essential predictor for the annual number of tropical cyclones in Australian region.

By comparing with the simple linear regression counterparts in [10], all the developed models have improved performance. For example, the model using the SOI as a predictor was not the best model in our earlier study with the adjusted R^2 of about 40%, while in the current analyses the model demonstrates an improvement in modelling the annual number of tropical ccylones with the R^2 reaching 50%.

Using the developed models, we compared the modelled annual number of tropical cyclones in the Australian region with the observed and found that new models demonstrate improved skill compared to the earlier model. For example, in 2010/2011 tropical cyclone season 11 cyclones were recorded in the Australian region. Using the new models, predicted number was 14, which is higher than the observed number of 11 cyclones; however the models demonstrated improvement in prediction skill compared to the statistical model used operationally by BoM which predicted 20 to 22 cyclones.

2. The Pacific Tropical Cyclone Data Portal

The Pacific Tropical Cyclone Data Portal developed under the PCCSP project (Fig. 5) allows users to examine historical information about tropical cyclones in the Pacific and Indian Oceans of the Southern Hemisphere. The tropical cyclone portal was developed using the OpenLayers web mapping library. This allows dynamic map navigation, presenting detailed information for a selected region and the display of changes in tropical cyclone intensity over the lifetime of a cyclone. Further development of this useful web-based

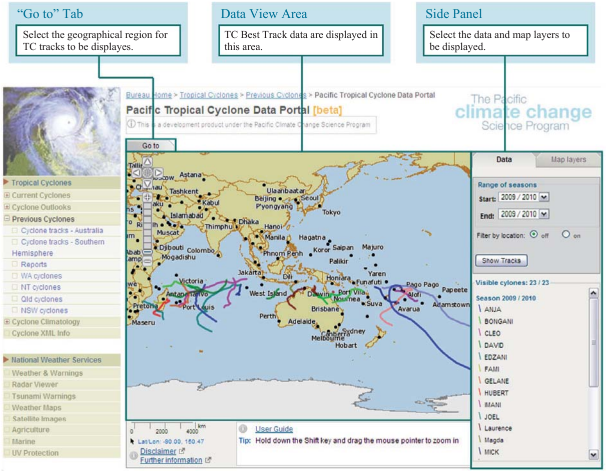

Fig. 5. Initial view of the Pacific Tropical Cyclone Data Portal.

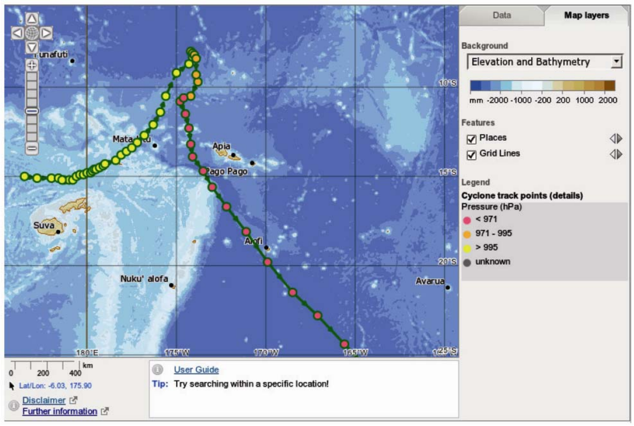

Fig. 6. An example of tropical cyclone tracks in the Pacific displayed over "Elevation and Bathymetry" background.

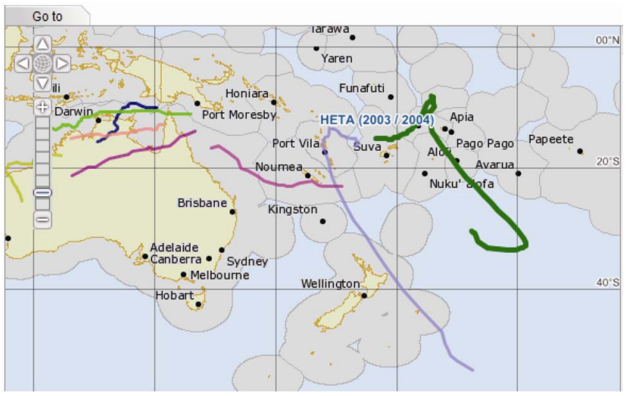

Fig. 7. An example of tropical cyclone tracks in the South Pacific in 2003-2004 season displayed over "Economic Exclusion Zones" background.

information tool has been undertaken in the PACCSAP project.

The first tropical cyclone archive for the Southern Hemisphere has been prepared at the National Climate Centre, Australian Bureau of Meteorology in 2003 and subsequently updated over the past years [12]. The archive is a result of multinational efforts of the National Meteorological Services from the Southern Hemisphere nations and has been derived from several data sources. The data for the western South Indian Ocean (30°E to 90°E) have been provided by Météo-France (La Réunion), for the Australian region (90°E to 160°E) by the Australian Tropical Cyclone Warning Centres (Brisbane, Darwin and Perth), and for the eastern South Pacific Ocean (east of 160°E) by the Meteorological Services of Fiji and New Zealand. Tropical cyclone tracks from these archives were merged into one archive, ensuring consistency of track data when tropical cyclones cross regional borders. Significant extension of historical tropical cyclone data archive was achieved through collaboration with the Regional Specialised Meteorological Centre (RSMC) Tokyo. Under the PACCSAP project, we extended geographical coverage to the North-West Pacific using best track data prepared by the RSMC Tokyo. This extension enables our partners from the countries in the Pacific to analyse tropical cyclone activity in their regions using the Pacific Tropical Cyclone Data Portal and display the tracks over different map layers (Fig. 6).

Additional features of the portal's functionality were developed, such as enhanced flexibility of spatial and temporal selection of the area of interest (e.g. selection of a country's Economic Exclusion Zone to examine tropical cyclone occurrences in its territorial waters, or selection of El Niño / La Niña years to examine how changes in the ENSO phases modulate tropical cyclone activity in the region). Enhancement of the spatial selection function within the portal allows cyclone tracks which pass through an area of any regular or irregular shape such as for example Economic Exclusion Zones to be displayed (Fig. 7).

In addition to functions of displaying and analysing historical cyclone data, new functionally to present a seasonal outlook was developed. An example of tropical cyclone seasonal outlook for the South Pacific and the Australian regions is presented in Fig. 8.

3. Analysis of Historical Tropical Cyclone Records Using the Portal

The Pacific Tropical Cyclone Data Portal is an excellent web-based tool to display and analyse historical information about tropical cyclones. This portal allows users to examine tropical cyclone occurrences and their interannual variability in detail. For example, during the PCCSP training workshops, which were attended by representatives from 14 Pacific Island countries and Timor Leste, participants examined the influence of the ENSO on frequency of tropical cyclone occurrences in their countries.

Using the portal, the participants found significant changes in tropical cyclone occurrences (in terms of geographical distribution and intensity of occurrence maxima) depending on warm (El Niño) and cold (La Niña) phases of ENSO.

Table 3. Median dates of the first and last tropical cyclone landfall for the Australian region: climatology and stratified for El Niño, La Niña and neutral years.

	First date	Last date
Climatology	25 Dec	17 Mar
La Niña	10 Dec	27 Mar
El Niño	10 Jan	11 Mar
Neutral	29 Dec	20 Mar

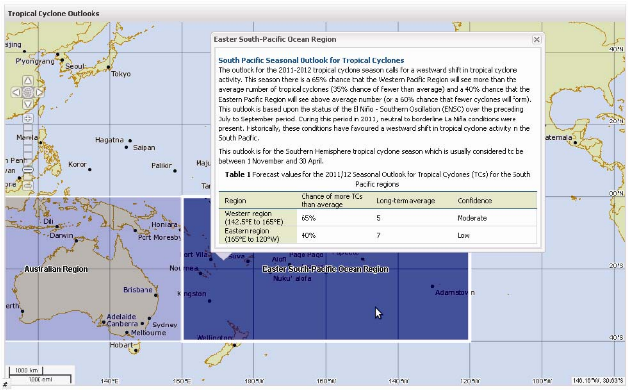

Fig. 8. An example of tropical cyclone seasonal outlook for the South Pacific and the Australian regions.

In particular, it was found that in the South Pacific Ocean, tropical cyclone occurrences in El Niño years in the area east of around 170°E are higher than in La Niña years. On the other hand, tropical cyclone occurrences in La Niña years in the area between around 140°E and 170°E are higher than in El Niño years. These findings could be subsequently used for early warning of an active cyclone season based on prediction of the ENSO state. Analysis of tropical cyclone time series is also possible using the portal. Users can examine a region of interest such as Australia, South Indian Ocean, South and North-West Pacific Oceans or Southern Hemisphere.

Another important application of the portal which we demonstrate here is examining dates of land fall of tropical cyclones. The median timing of a cyclone land-crossing for the Australian continent is summarised in Table 3 (first and last day, respectively). The genesis of a tropical cyclone is defined for this analysis as the time when a cyclonic system first achieved a central pressure less than or equal to 995 hPa.

On average, Australia has its first cyclone land crossing on the 25th of December (Table 3). Stratifying the data between El Niño and La Niña years, we found that the first cyclone land crossing in La Niña is earlier than climatology, with a median cross date of the 10th of December. On the other hand, first cyclone land-crossing in El Niño years occurs a month later, on the 10th of January. The last cyclone land-crossing date for the Australian continent is 17th of March (median), with dates for El Niño years earlier than climatology,

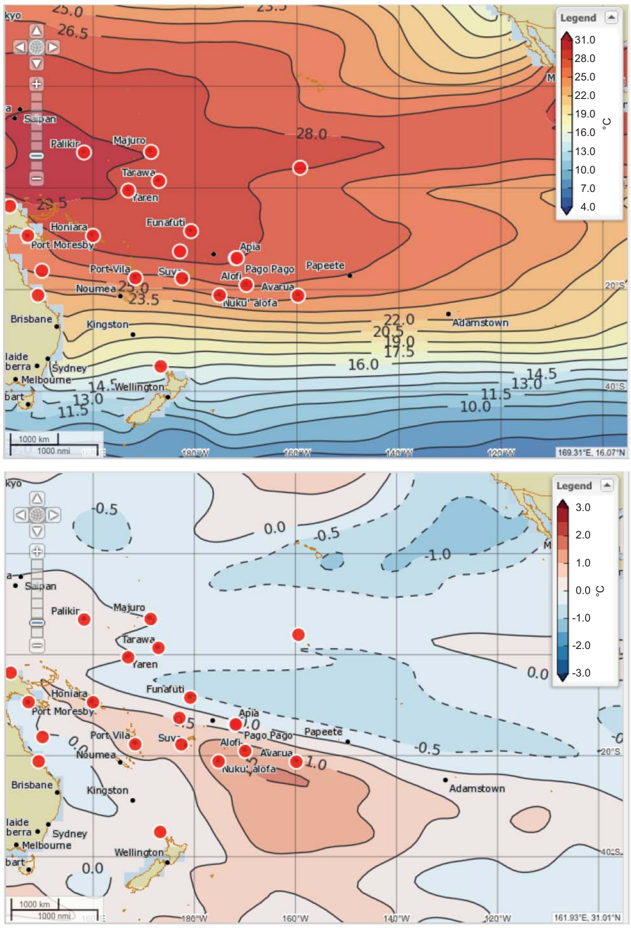

Fig. 9. Example ensemble mean forecast for SSTs for September – November 2011 (top panel) and SST anomalies (bottom panel).

on the 11th of March, and for La Niña years ten days later than climatology, on the 27th of March (Table 3). During neutral years, first and last cyclone land-crossing date are close to climatology.

4. SST Seasonal Prediction

Seasonal forecasts for coral bleaching risk have been developed for the Great Barrier Reef (GBR), Australia [18]. These forecasts are the first operational dynamical seasonal forecasts in the world for coral bleaching risk. Forecasts are issued fortnightly and delivered operationally online by the Australian BoM's Ocean Services at http://www.bom.gov.au/oceanography/oceantemp/GBR_SST.shtml. These products form an important component of the GBR Marine Park Authority (GBRMPA) Early Warning System [14]. The current project is building on this capacity to develop a tailored dynamical seasonal forecast service for coral bleaching risk in the South- and North-West Pacific.

This project utilises the latest version of POAMA which incorporates improved ensemble generation techniques and a state-of-the-art ocean data assimilation scheme. There are several advantages to using POAMA to produce seasonal

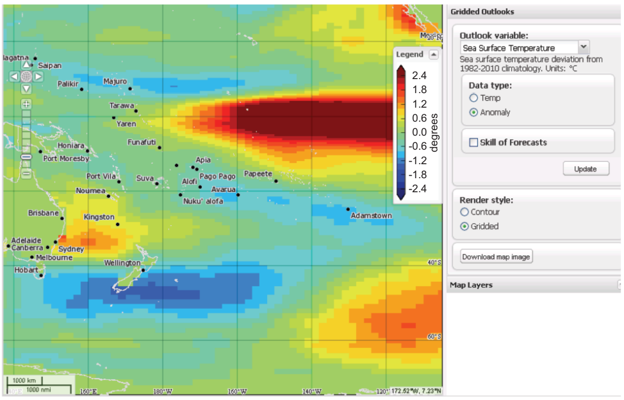

Fig. 10. New web-based information tool for sea surface temperature seasonal prediction.

forecast products for ocean temperature and coral bleaching risk. Firstly, POAMA is a fully coupled dynamical system that assimilates the most recent ocean and atmosphere observations. Under climate change it is likely that the relationships between large climate drivers such as ENSO and ocean temperatures in regions of the Western Pacific will change. By using a dynamical, physics-based model, the issues of these changing baselines can be avoided, unlike in a historically-based statistical model [17]. Secondly, the model is run operationally, forecasts are produced in real time and products will be available online so that Partner Countries can readily access the most up-to-date information. Thirdly probabilistic forecasts can provide the likelihood of warm conditions occurring and an estimate of forecast confidence, assisting management in any risk assessments. Finally, the skill of the system has been demonstrated as useful for both the GBR [18] and across the tropical oceans [4], indicating a high level of confidence that forecast products developed for the Western Pacific will be skilful. Examples of potential Pacific products include maps of SSTs and SST anomalies (Fig. 9), accumulated thermal stress and probabilistic forecasts of exceeding certain SST thresholds.

New web-based information tool for sea surface temperature seasonal prediction is also currently under development (Fig. 10). Seasonal forecasts of ocean temperature and coral bleaching risk is critical to Partner Countries in planning coastal development and safeguarding agricultural, marine and water resources.

V. CONCLUSIONS

Improved knowledge of extreme climatic events, with the assistance of tailored forecast tools, will enhance the resilience and adaptive capacity of Pacific Island Countries under climate change. Outcomes of projects such as PACCSAP provide National Meteorological Services of Partner Countries with valuable information and tools which contribute significantly to capacity building to support adaptive responses to climate variability and change. This approach of providing quality scientific tools, coupled with training and ongoing support, appears a highly effective capacity building model.

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