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ORIGINAL PAPER

Tropical cyclone early warnings for the regions of the Southern Hemisphere: strengthening resilience to tropical cyclones in small island developing states and least developed countries

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Abstract

Tropical cyclones (TCs) affect countries in the Southern Hemisphere (SH) tropics every year causing significant humanitarian impacts and much damage to the natural environment. To reduce TC impacts on societies, early warning systems (EWS) are used to communicate the risk to the public. In 1999, the Climate Change and Southern Hemisphere Tropical Cyclones International Initiative (CCSHTCII) was established to enhance EWS for TCs in SH countries, with particular focus on support for small island developing states and least developed countries to provide effective public early warnings of TC risk. In this paper, recent activities of the CCSHTCII to strengthen TC EWS are presented. Using TC best track data from the SH TC historical data archive, the impact of the El Niño–Southern Oscillation (ENSO) on inter-annual and spatial variability of TC activity is examined. TC-ENSO relationships in the SH are analysed and used as a scientific basis for the production of TC season outlooks. Communication of TC early warnings through TC season outlooks is described, and recommendations for improving outlooks are provided.

Keywords Tropical cyclones · Small island developing states (SIDS) · Least developed countries (LDCs) · Early warning systems (EWS) · Risk communication to the public · Disaster risk reduction

1 Introduction

Tropical cyclones (TCs) affect countries in the Southern Hemisphere (SH) tropics every year causing significant loss of life, property and income from destructive winds, torrential rain, high ocean waves and storm surge. Typically, TC impacts on small island developing

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states (SIDS) and least developed countries (LDCs) are particularly devastating due to their high vulnerability, fragile economy and low resilience.

A recent example of severe TC impact on Pacific Island Countries was TC *Winston*, which devastated Fiji in February 2016. Severe TC *Winston* was the most intense tropical cyclone on record in the SH, and the strongest to make landfall in the SH. TC *Winston* was also the costliest TC on record in the South Pacific Ocean (SPO). In Fiji, 44 fatalities were related to impact of TC *Winston*, while damage and economic losses totalled about $1.4 Billion (2016 USD) (Cyclone Winston 2016). In the South Indian Ocean (SIO), TC *Idai* made landfall in Mozambique in March 2019 bringing heavy rainfall, strong winds and significant storm surge. TC *Idai* caused over 1300 fatalities and over $2.2 billion (2019 USD) in damages (Cyclone Idai 2019), making it the deadliest and costliest TC recorded in the South-West Indian Ocean.

To reduce the impact of TCs on society, early warning systems (EWS) are used to communicate the threat to the public. Strengthening EWS is vital for improving preparedness, and this goal is aligned with the seventh global target of the Sendai Framework for Disaster Risk Reduction. This framework calls for a substantial increase in multi-hazard EWS. The Sendai Framework further refers to EWS as a critical element for disaster risk reduction. National Meteorological and Hydrological Services (NMHSs) issue early warnings for TCs, and the government authorities, including Disaster Risk Management (DRM) offices, subsequently take appropriate action. It is recognised that TC EWS need to be further strengthened and threat communication to the public improved, particularly in LDCs and SIDS. However, NMHS and DRM offices in small countries often consist of only a few staff. The number of professional staff of these agencies is limited, and they need additional training to adapt new technologies and develop new services. As such, when new technologies become available, it is not always easy for these agencies to immediately benefit from them. Support from the international TC community is necessary to assist NMHS and DRM offices in SIDS and LDCs with strengthening TC EWS (Kuleshov 2016; Kuleshov et al. 2012a, 2014).

In this paper, recent activities of the Climate Change and Southern Hemisphere Tropical Cyclones International Initiative (CCSHTCII) on strengthening TC early warnings and risk communication are described. The framework for Resilient Development in the Pacific (2016) identifies "strengthened disaster preparedness, response and recovery" as one of its key goals. The framework prioritises strengthening effective multi-hazard EWS and the use of science and technology to inform DRM offices about upcoming potentially disastrous events. This includes ensuring early warning messages are communicated to managers and decision-makers, civil society and communities in an accessible language. A high priority is addressing the needs of Pacific Island Countries with improving EWS for TCs, and the CCSHTCII follows this strategic approach of the Framework. Activities of the CCSHTCII described in this paper include strengthening EWS in the Pacific through translation of scientific advancements in TC research to operational services of NMHSs by improving historical TC datasets, tools for analysis of TC activity and exploring new ways of communicating TC early warnings which are better understood by the general public.

The paper is organised as follows. An overview of the CCSHTCII including the description of the SH TC historical data archive used in this study is given in Sect. 2. The SH TC climatology—results of spatial and temporal analyses of historical TC data in the SH and its regions—is presented in Sect. 3. The results of a statistical analysis of TC occurrences in Pacific Island Countries are given in Sect. 4. The communication of TC early warnings for the regions of the SH based on the developed TC seasonal prediction statistical methodologies is outlined in Sect. 5; discussion and conclusions are presented in Sect. 6.

2 CCSHTCII: strengthening hydro-meteorological and early warning services

In 1999, the CCSHTCII was established to strengthen EWS for TCs in SH countries. The aim of the Initiative is to improve our knowledge of TC genesis and development in the SH and enhance EWS to assist countries at risk, particularly SIDS and LDCs, with decision-making around climate change adaptation and disaster risk reduction. Since its inception, the CCSHTCII has, via successful international cooperation of regional academic, research and operational organisations, developed the regional consolidated TC database, TC climatology and TC seasonal prediction for the SH (Kuleshov 2013, 2020). Improving TC early warnings and communication is one of the top priorities for the CCSHTCII. A brief summary of major results of the Initiative is presented in this paper.

A key task for the Initiative was to create a consolidated archive of TC best track data for the SH. The first version of the SH TC historical data archive was prepared at the National Climate Centre of the Australian Bureau of Meteorology (BoM), in collaboration with NMHSs of Fiji, France and New Zealand. Since its first release in 2003 (Kuleshov and de Hoedt 2003), the SH TC historical data archive has been revised and updated on a regular basis (Kuleshov et al. 2008, 2010; Dowdy and Kuleshov 2012; Kuleshov 2020). It currently consists of TC best track data from the 1969/70 season, when geostationary and polar-orbiting satellite images were first utilised operationally in NMHSs of WMO Regions I (Africa) and V (South-West Pacific) (Broomhall et al. 2014).

To display and analyse historical TC data, a specialised web-based information tool—the SH TC data portal—has been developed. The portal's functionality allows users to perform spatial and temporal selection of TC data and display selected cyclone tracks over a specified geographical area and time period including displaying changes in TC intensity over the lifetime of a cyclone (Kuleshov et al. 2013). As an example, Fig. 1 shows the portal plotted tracks of 12 TCs which passed through the Australian Region in the 2017/2018

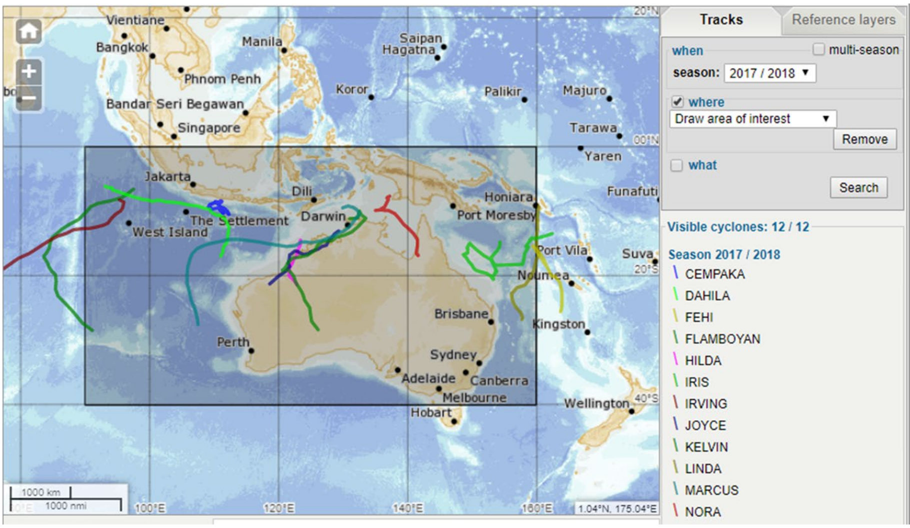

Fig. 1 Tracks of 12 TCs which passed through the Australian Region in the 2017/2018 TC seasons displayed in the SH TC data portal

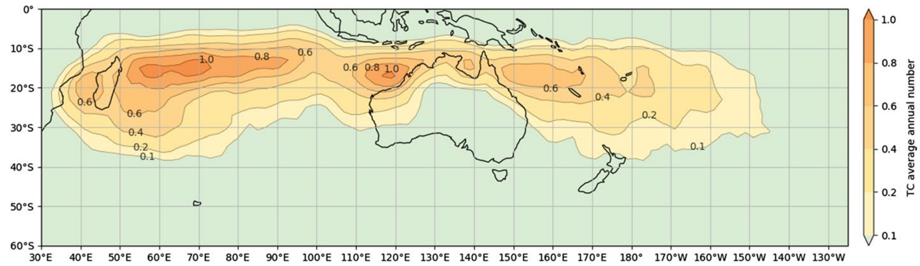

Fig. 2 Average annual number of TCs in the SH in all years

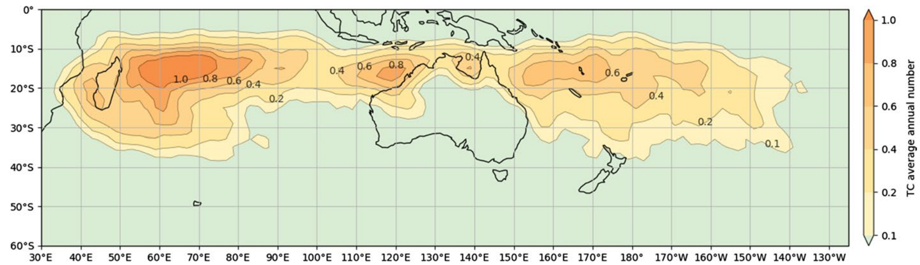

Fig. 3 Average annual number of TCs in the SH in El Niño years

TC season. A comprehensive description of the portal can be found in Kuleshov (2020); the publication also provides readers with a detailed users' guide. The SH TC data portal is used operationally by NMHSs of WMO Regions I and V.

3 SH TC climatology

Accurate long-term historical records are essential for deriving historical risk profiles for TC activity and variability. An analysis of TC best track data available from the SH TC archive demonstrates significant spatial and temporal variability in TC activity in the South Pacific and South Indian Oceans. Hence, it is essential to understand the influence of the main global climate forcings on TC variability. The El Niño–Southern Oscillation (ENSO) is one of the key global climate drivers which significantly influence inter-annual variability of TC activity in the SH. Using best track data from the SH TC archive, we examined ENSO impact on TC spatial and temporal variability in the SH and its regions.

Following the approach developed in our earlier studies (Kuleshov and de Hoedt 2003; Kuleshov et al. 2008), we produced a set of TC climatology maps which describe TC occurrence in the SH in terms of an average annual number using data for the 1969/70–2017/18 seasons. The maps were produced for all years (Fig. 2), El Niño years (Fig. 3), La Niña years (Fig. 4) and Neutral years (Fig. 5). The list of El Niño, La Niña and Neutral years developed by Kuleshov et al. (2009a) and subsequently extended to include the past decade is given in "Appendix1".

Examining TC spatial variability with ENSO phase shows the occurrence of TCs in the SPO substantially extends eastwards in El Niño years (up to 140°W; Fig. 3) compared

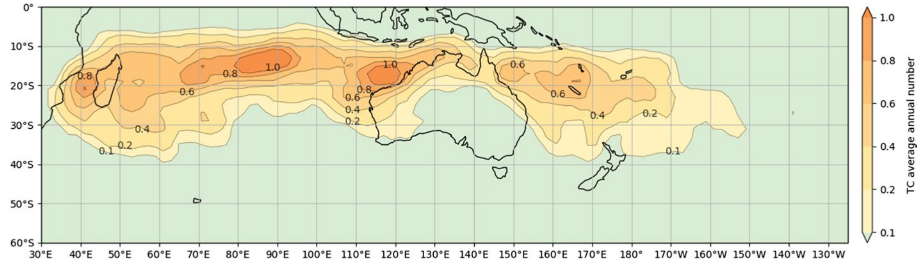

Fig. 4 Average annual number of TCs in the SH in La Niña years

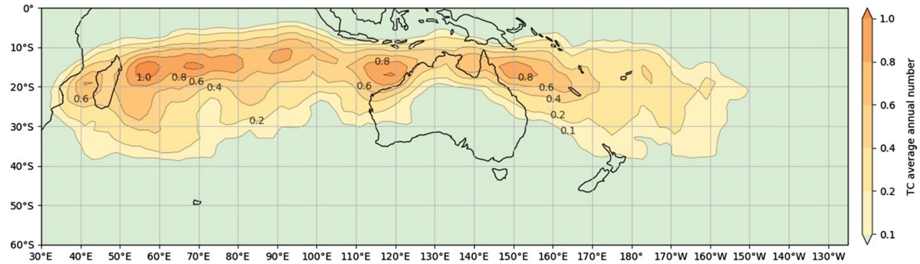

Fig. 5 Average annual number of TCs in the SH in Neutral years

Table 1 Average annual number of TCs with LMCP of 995 hPa or lower in the SH, the SIO and the SPO regions in all years, El Niño, La Niña and Neutral years

Region	Average annual number of TCs with LMCP of 995 hPa or lower			
	All years	El Niño	La Niña	Neutral
SH (30°E–120°W)	24	24	23	24
SIO (30°E–135°E)	15	13	16	16
SPO (135°E–120°W)	10	11	8	9

to La Niña years (up to 150°W; Fig. 4). This expansion of TC activity to the eastern SPO leads to higher exposure of Pacific Island Countries to TC risk.

We examined the impact of the ENSO on TC occurrence in the SH and two regions—the SIO (30°E–135°E) and the SPO (135°E–120°W). For this analysis, systems which attained a lifetime minimum central pressure (LMCP) of 995 hPa or lower were selected; records were examined for the 1969/70–2016/17 TC seasons, and results are summarised in Table 1.

On average, 24 TCs were recorded in the SH annually in the 1969/70–2016/17 TC seasons; little variability in total TC occurrence depending on phases of ENSO (El Niño, La Niña or Neutral years) was found. Regionally, TC activity in the SIO was higher than in the SPO, especially in La Niña years—on average, 16 TCs formed in the SIO region compared to 8 TCs in the SPO region. These findings—an increase in TC occurrence in the SIO region in La Niña years compared to El Niño years—are in line with results of earlier studies which examined the environment favourable for TC genesis and development in the regions of the SH (Gray 1988; Kuleshov et al. 2009b).

In this analysis, we have used a longitude of 135°E for subdividing the SH into two regions—the SIO and the SPO, as recommended in (Kuleshov et al. 2008) based on climatological considerations.

However, to provide TC advisories and warnings to the public, the SH is subdivided into three major regions: (1) Regional Specialised Meteorological Centre (RSMC) La Réunion, France, is responsible for the area south to the equator, 30°E to 90°E (the South-West Indian Ocean, or SWIO). (2) Tropical Cyclone Warning Centres (TCWCs) in Perth, Darwin and Brisbane, Australia; Jakarta, Indonesia; and Port Moresby, Papua New Guinea—for the area between 90°E and 160°E (the Australian Region, or AR). (3) RSMC Nadi, Fiji and TCWC Wellington, New Zealand—for the area between 160°E and 120°W (the South Pacific Ocean, or SPO). Such subdivision into three major regions—the SWIO, the AR and the SPO, with eight designated RSMCs and TCWCs—provides comprehensive coverage for TC activity in the SH. RSMCs as regional centres provide forecasting advisories, and NMHSs have responsibilities to communicate warnings about TC risk to the public in their respective countries. As such, it is pertinent to examine TC variability in these three regions.

Historical records indicate high inter-annual variability of TC activity in the SH and its regions. As an example, time series of TC occurrences in the AR are presented in Fig. 6a—for those systems which attained LMCP of 995 hPa or lower as well as those attained a LMCP of 970 hPa or lower [approximately corresponding to severe TCs according to the Australian TC scale (Australian Bureau of Meteorology 2019)]. TC season numbers ranged from a high of 19 in 1983/84 to a low of 3 in 2015/16. Downward trends in TC occurrences in the AR were detected. (Records were examined for the 1970/71–2019/20 TC seasons.) Similarly, high inter-annual TC variability was observed in the SWIO and the SPO (results are not shown) and in the SH (Fig. 6b), with downward trends in TC total annual numbers.

To analyse the impact of the ENSO on total annual number of TCs in the SWIO, the AR and the SPO, we used TC best track data from the 1981/82 season, which we identified as the beginning of reliable records for estimating intensity of severe TCs in the SH [for detail, see Kuleshov et al. (2010)]. In Table 2, the average annual numbers of TCs with LMCP of 995 hPa or lower in the SWIO, the AR and the SPO regions in all years, El Niño, La Niña and Neutral years are presented.

While ENSO significantly affected the spatial distribution of TCs in the SWIO region—the local maximum in TC occurrence shifted from between 55°E and 75°E in El Niño years (Fig. 3) to between 80°E and 95°E in La Niña years (Fig. 4)—the average annual number of TCs stayed around 9 for both warm and cold phases of ENSO. In the AR and the SPO regions, ENSO significantly affected both TC spatial distribution and total annual number of TCs. In La Niña years, on average 10.3 TCs affected the AR, while in El Niño years, its average annual number was reduced to 8.2. The highest TC activity in the AR was recorded in Neutral years—12.1 TCs on average annually. In contrast, in the SPO region an increase in TC activity was observed in El Niño years (9.1 TCs on average) and a decrease in La Niña and Neutral years (6.9 and 5.9 TCs on average, respectively).

We also examined the occurrence of severe TCs in the SH and its three regions—the SWIO, the AR and the SPO—for the 1981/82–2016/17 TC seasons. According to the Australian TC scale, severe TCs (Categories 3, 4 and 5) have strong winds with typical gusts over open flat land or water of more than 165 km/h (Australian Bureau of Meteorology 2019); these winds correspond to the highest category on the Beaufort scale, Beaufort 12 (Hurricane), and are very destructive. In this study, we examined occurrences of severe TCs which attained LMCP of 970 hPa or lower (Table 3); such systems approximately correspond to severe TCs of Categories 3–5.

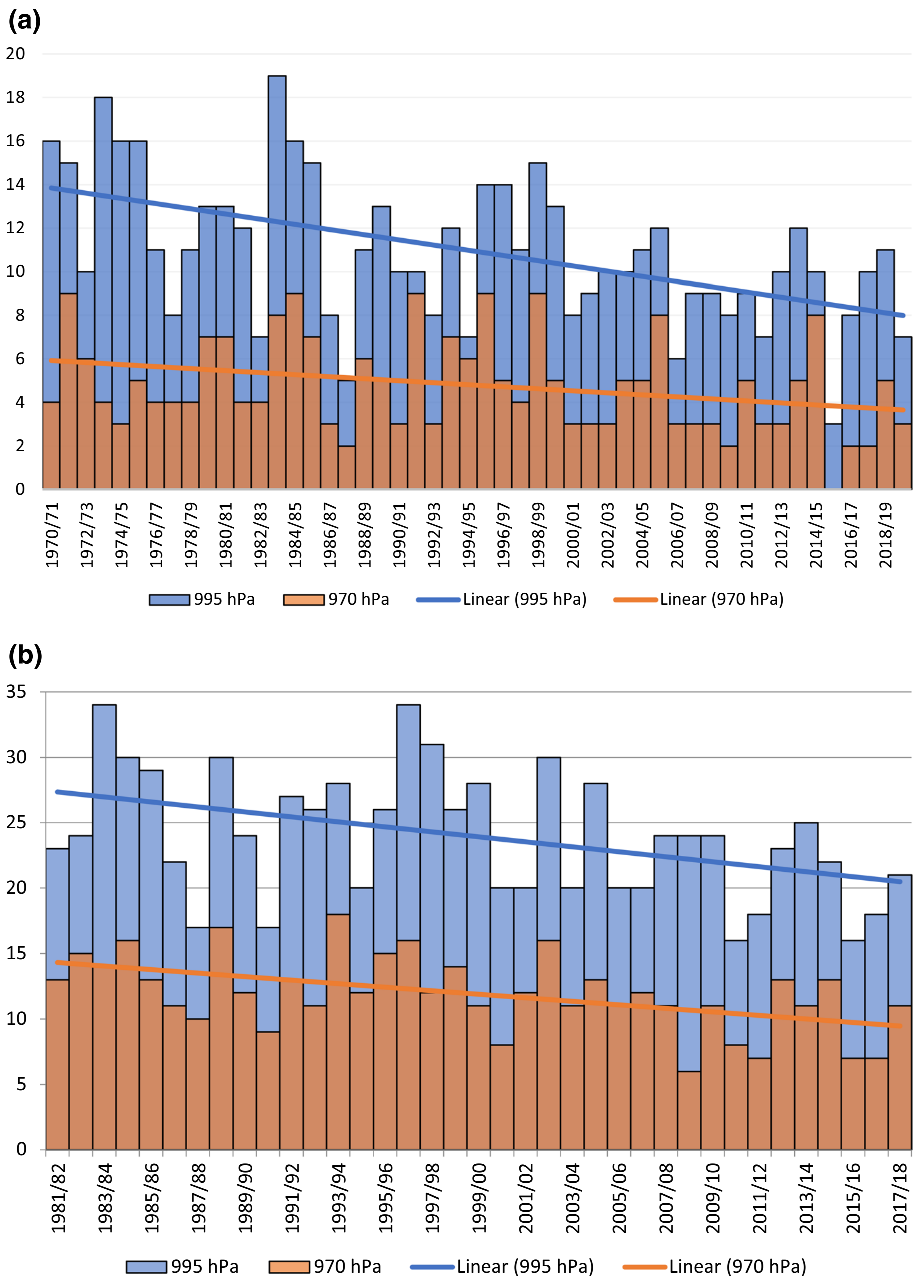

Fig. 6 TC time series for **a** the Australian Region and **b** the Southern Hemisphere

The results demonstrate that in each of the three regions, approximately 50% of TCs which attained LMCP of 995 hPa (Table 2) further developed into severe TCs with LMCP of 970 hPa or lower (Table 3). The ENSO impact on TC occurrence in all three regions is also evident, e.g. in the SPO on average 5.0 severe TCs developed in El Niño

Table 2 Average annual number of TCs with LMCP of 995 hPa or lower in the SWIO, the AR and the SPO regions in all years, El Niño, La Niña and Neutral years

Region	Average annual number of TCs with LMCP of 995 hPa or lower			
	All years	El Niño	La Niña	Neutral
SWIO (30°E–90°E)	9.5	9.4	9.0	9.9
AR (90°E–160°E)	10.3	8.2	10.3	12.1
SPO (160°E–120°W)	7.2	9.1	6.9	5.9

Table 3 Average annual number of severe TCs with LMCP of 970 hPa or lower in the SWIO, the AR and the SPO regions in all years, El Niño, La Niña and Neutral years

Region	Average annual number of severe TCs with LMCP of 970 hPa or lower			
	All years	El Niño	La Niña	Neutral
SWIO (30°E–90°E)	4.8	4.8	3.7	5.2
AR (90°E–160°E)	4.8	3.9	4.9	5.4
SPO (160°E–120°W)	3.6	5.0	3.1	2.6

Table 4 Total number (proportion, %) of the most severe TCs with LMCP of 920 hPa or lower in the SH, the SWIO, the AR and the SPO regions in all years, El Niño, La Niña and Neutral years

Region	Total number (proportion, %) of severe TCs with LMCP of 920 hPa or lower			
	All years	El Niño	La Niña	Neutral
SH (30°E–120°W)	61 (100%)	27 (44%)	10 (16%)	24 (39%)
SWIO (30°E–90°E)	24 (100%)	8 (33%)	2 (8%)	14 (58%)
AR (90°E–160°E)	21 (100%)	6 (29%)	8 (38%)	7 (33%)
SPO (160°E–120°W)	16 (100%)	13 (81%)	0 (0%)	3 (19%)

years, 3.1 in La Niña and 2.6 in Neutral years, compared to 3.6 TCs as an average for all years.

We also analysed the occurrence of the most severe TCs in the SH and its three regions—the SWIO, the AR and the SPO. For this analysis, we selected only those cyclones which attained LMCP of 920 hPa or lower. The list of the most severe TCs with corresponding LMCP recorded in the SWIO, the AR and the SPO regions since the 1981/82 season is presented in "Appendix 2", Tables 6, 7, 8, respectively. A summary is provided in Table 4, presenting a total number (and proportion, %) of the most severe TCs which were recorded in the SH and its three regions during the examined period. The data were also stratified between El Niño, La Niña and Neutral years.

The summary table shows the ENSO has a noticeable impact on the occurrence of the most severe TCs in the SH and the regions. In the SH, the most severe TCs occurred more than twice as often in El Niño (44%) and Neutral (39%) years compared to La Niña years (16%). The pronounced impact of the ENSO on TC activity is also evident in all three regions. In La Niña years, 80% of the most severe TCs that occurred in the SH were recorded in the AR. In the SWIO, 58% of the most severe cyclones were recorded in Neutral years, 33% in El Niño years and only 8% in La Niña years. In the SPO region, no occurrence of TCs with LMCP of 920 hPa or lower was recorded in La Niña years; the most severe TCs occurred in El Niño (81%) and Neutral (19%) years. This dramatic increase (decrease) in the number of the most severe TCs in the SPO region in El Niño (La Niña) years is attributed to warming (cooling) of sea surface temperatures (SSTs) and enhanced (suppressed) atmospheric convection in the eastern equatorial Pacific (Gray 1988; Kuleshov et al. 2009b).

This analysis of the ENSO impact on TC activity in the SH and its three main regions provides important scientific insights as well as excellent background information for communicating early warnings to the public about potential increases or decreases in TC activity in a coming season. We further discuss implications of these scientific findings in relation to communicating TC early warnings in Sect. 5.

4 TC occurrences in Pacific Island Countries

Several Pacific Island Countries experience on average one to two tropical cyclones per year (Kuleshov et al. 2009b, 2012c; Dowdy et al. 2012). Here, we present an analysis of TC occurrence in the Exclusive Economic Zones (EEZs) of ten Pacific Islands Countries in the SH: Australia, Cook Islands, Fiji, Niue, PNG, Samoa, Solomon Islands, Tonga, Tuvalu and Vanuatu (Fig. 7).

In Table 5, occurrences of TCs that attained a LMCP of 995 hPa or lower in the EEZ of ten Pacific Island Countries in El Niño, Neutral, La Niña and all years are presented. This table shows that TC occurrences in the EEZ of these countries are highly dependent on phases of ENSO. Three clusters of countries are identified based

Fig. 7 The EEZ of Australia, Cook Islands, Fiji, Niue, PNG, Samoa, Solomon Islands, Tonga, Tuvalu and Vanuatu displayed in the SH TC data portal

Table 5 TC occurrences in the EEZ of ten Pacific Island Countries in El Niño, Neutral, La Niña and all years presented as an annual average number (TC, avg) and percentage (TC, %)

Country	El Niño years		Neutral years		La Niña years		All years	
	TC, avg	TC, %	TC, avg	TC, %	TC, avg	TC, %	TC, avg	TC, %
Australia	6.6	30.0	8.8	42.7	8.9	27.2	8.0	100
Cook Isl	2.7	62.0	1.3	30.4	0.5	7.6	1.6	100
Fiji	3.1	41.2	2.6	36.0	2.6	22.8	2.8	100
Niue	1.6	54.9	0.8	31.4	0.6	13.7	1.0	100
PNG	1.3	30.0	2.2	52.5	1.2	17.5	1.6	100
Samoa	1.1	52.6	0.6	31.6	0.5	15.8	0.8	100
Solomon Isl	3.9	50.4	2.4	33.1	1.9	16.5	2.8	100
Tonga	2.3	41.6	2.1	38.6	1.7	19.8	2.1	100
Tuvalu	1.5	62.8	0.6	27.9	0.3	9.3	0.9	100
Vanuatu	2.7	40.8	1.9	30.0	2.9	29.2	2.4	100

upon the ENSO impact on TC activity. In the EEZ of five countries (Cook Islands, Niue, Samoa, Tuvalu and Solomon Islands), more than 50% of TC occurrences were recorded in El Niño years, but the proportion of TCs recorded in La Niña years was relatively small (7.6% to 16.5%). In the EEZ of Fiji, Tonga and Vanuatu, over 40% of TCs were recorded in El Niño years, but the proportion of TC occurrences in La Niña years was moderate (22.8%, 19.8% and 29.2%, respectively). Finally, in the EEZ of PNG and Australia, 52% and 43%, respectively, of TCs occurred in Neutral years, while both countries observed 30% of their TCs in El Niño years.

The different impacts of the ENSO on TC inter-annual variability in these three clusters are explained by the countries' position in relation to the South Pacific Convergence Zone (SPCZ). The SPCZ is a large-scale band of low-level convergence, cloudiness and precipitation which extends from the Western Pacific Warm Pool at the maritime continent south-eastwards towards French Polynesia. Its climatological (average over 30 years) position is presented as a line with coordinates 5°S 150°E–30°S 120°W (Folland et al. 2002). Examining TC genesis in the area between the equator and the SPCZ in El Niño, Neutral and La Niña years for the 1969/1970 to 2017/2018 TC seasons shows significant differences in cyclogenesis. In this period, 97 TCs were formed during the ENSO warm phase (58%), 51—when the ENSO was in the Neutral phase (30%) and 20—during the ENSO cold phase (12%).

This strong dependence of TC occurrences on phases of ENSO for countries near the SPCZ has implications for forecasting TC activity in a coming season using dynamical models. Current coupled ocean atmospheric models have poor skill in forecasting the SPCZ location at long timescales. Results from CMIP5 models suggest that this may be due to a 'cold tongue' bias of the models' SST fields (Brown et al. 2013). Studies at the BoM for two operational seasonal forecasting models showed similar behaviour, with both systems [Predictive Ocean Atmosphere Model for Australia (POAMA) and the Australian Community Climate and Earth-System Simulator—Seasonal (ACCESS-S)] forecasting SPCZ locations that are too 'zonal' (Charles et al. 2010; Beischer et al. 2020).

5 Communicating TC early warnings

Multi-hazards associated with TCs often lead to human suffering and significant damage to infrastructure and economy. Effective communication of TC risks to the public and government authorities can reduce impacts. Thanks to improvements in TC modelling, NMHSs now produce accurate TC public warnings of TC tracks, expected strength and intensity several days in advance, while sub-seasonal forecasts can skilfully assess potential TC hot spots at up to 3 to 4 weeks lead time (Gregory et al. 2019, 2020).

However, despite accurate TC forecasts, impacts on communities at risk can still be significant. For example, typhoon *Haiyan* (*Yolanda*) was the deadliest TC in the Philippines in recent times killing at least 6,300 people and leaving thousands injured and missing, with many casualties as the result of storm surge, rather than winds (WMO 2015). Before landfall, the NMHS of the Philippines issued accurate advance warnings for destructive winds and heavy rainfall, and the government authorities deployed planes and helicopters to the vulnerable regions. However, if better knowledge about the expected storm surge was available, a more extensive evacuation from exposed areas could have saved more lives. This example demonstrates the importance of producing impact-based forecasts rather than pure weather forecasts. It also demonstrates that successful impact-based forecasting requires collaboration between NMHSs and other agencies which have the additional necessary expertise, resources and knowledge (such as demographic data and geographic information systems) to deliver impact services that NMHSs may not be able to do on their own.

TC warnings are issued by NMHSs as TC short-term forecasts (up to 7 days ahead) and TC season outlooks which describe expected TC activity in a coming season (e.g. 6 months in the SH). Recently, TC warnings on sub-seasonal timescales (2 to 4 weeks) have been introduced by the European Centre for Medium-Range Weather Forecasts (ECMWF) and the BoM (experimental products), to bridge the gap between the conventional TC short-term forecasts and TC season outlooks (Vitart et al. 2012; Camp et al. 2018; Gregory et al. 2019, 2020). WMO guidelines on multi-hazard impact-based forecast and warning services related to TC short-term forecasts can be found in WMO 277 (2015). In this paper, we discuss the communication of TC early warnings to the public through TC season outlooks, focusing on SH regions.

The SH TC season typically lasts from November to April, when both the atmospheric and oceanic conditions are favourable for TC genesis and development (Gray 1988; Kuleshov et al. 2009b). As shown earlier, ENSO has significant impact upon inter-annual variability in TC activity in the SH, changing the spatial distribution of the SSTs in the central Pacific Ocean and modulating the atmospheric environment (Walker circulation). Based on TC-ENSO relationships, statistical models were developed by Kuleshov et al. (2009a, 2012b) for the BoM to produce operational TC season outlooks. From 2009, the BoM has produced a public TC season outlook for the Australian region (https://www.bom.gov.au/climate/cyclones/australia/), while a TC season outlook for the South Pacific Island Nations has also been produced from 2010 (https://www.bom.gov.au/climate/cyclones/southpacific/). The outlooks are issued in October, to provide early warnings to communities at risk of TCs and assist governments, non-government organisations (e.g. the International Federation of Red Cross and Red Crescent Societies) and industry sectors with their preparedness.

The Fiji Meteorological Service (FMS) also produces TC season outlooks for the SPO using relationships between TC activity and the ENSO. (The outlook is based upon the status of the ENSO over the preceding July to September period and international guidance forecast of ENSO state during the coming TC season.) To predict TC activity in a coming season, Fijian climatologists use an analogue method, i.e. they first identify several analogues of past seasons with similar atmospheric and oceanic conditions and then, based on historical records of TC activity during the analogue seasons, predict the amount of TC activity which may be expected in the coming season. TC season outlooks issued by the FMS also provide expert advice to the public, describing in which parts of the SPO TC activity are expected to be normal, and in which parts reduced or increased risk of TC activity are expected. They also include TC early warnings for seven South Pacific Island Countries and territories.

As both the FMS and the BoM use methodologies which relate TC activity to the state of the ENSO, there is often a general agreement between outlooks. Moreover, in recent years, further improvement in consistency of TC season outlooks issued by different agencies in the region was achieved through inter-agency consultation prior to the beginning of a TC season, which aims to achieve an understanding of differences and similarities between the outlooks, and hence enables agencies to avoid sending conflicting messages to the public. In this paper, communication of TC early warnings to the public is described using examples from TC season outlooks issued by the BoM.

Communicating scientific information to the public in general terms is crucial to ensure that TC early warnings are clear and understood. Firstly, the key message about expected TC activity in the regions is presented using simple statistical terminology, i.e. above average, near average or below average. Examples of key messages include: "*More cyclones than average likely for Australia*", "*Near average cyclone season most likely for Australia*", ''*El Niño likely to decrease Australian cyclone numbers*", "*Tropical cyclone activity for the South Pacific is expected to be higher than average in the western region and lower than average in the eastern region*", "*Average number of cyclones is likely in the western Pacific Ocean*", etc.

Following the key message, the outlooks provide important statistics about TC activity in the regions based on historical data, e.g. "*On average, there are 10 to 13 tropical cyclones each season in the Australian region, four of which typically cross the coast*", "*The average numbers of tropical cyclones during the season in the western and eastern regions of the South Pacific are four and seven, respectively*", etc.

Background information referring to the current state of the ENSO and its expected development over the coming months is also presented to assist the public with understanding the climate science behind the outlook. However, it is widely recognised that communicating science to the general public is not an easy task. Hence, the outlooks provide a simple description of typical ENSO impacts supported by easily understood statistical information, e.g. "*El Niño typically reduces the number of coastal crossings in Australia, but at least one tropical cyclone has crossed the Australian coast each season since reliable records began in the 1970s*", "*During El Niño years, the first tropical cyclone to cross the coast is typically during the second week of January*", "*During ENSO-neutral years, the first tropical cyclone to make landfall over Australia typically occurs in late December*", "*In La Niña years, the first cyclone landfall typically occurs around the first week of December*", etc. The timing of the first potential TC coastal impact is emphasised in these early warning messages alerting the communities at risk, giving them guidance and assisting with early and timely preparedness.

TC season outlooks issued by the BoM also communicate the temporal variability to alert the public that even if there were no TCs during one or two months, TCs can occur any time during the season, e.g. "*Cyclone formation is rarely spread evenly throughout the season; often quiet periods are followed by bursts of activity*".

Ensuring communities remain vigilant is an integral part of early warning messages of the TC outlooks, e.g. "*Tropical cyclones affect Pacific island countries in most years and can impact coastal regions even when they remain well offshore*".

TC season outlooks also alert the public about tropical storms which do not reach TC intensity yet can still have significant impacts on communities, e.g. "*Tropical lows that do not intensify into cyclones, or lows that are the remnants of older cyclones, can still cause widespread rainfall and dangerous flooding*". As mentioned earlier, many hazards are associated with TCs (winds, rain, waves and storm surge). Winds associated with tropical low systems are less damaging than winds from TCs, and in these early warning messages, the significance of tropical low impacts related to torrential rain and potential flooding is emphasised. Messages also make clear that communities can be affected by hazards associated with TCs that do not directly pass over their location, e.g. "*Even tropical cyclones well offshore can produce extreme tides and dangerous waves*".

Communicating probabilistic forecast uncertainty to the general public is another important task. BoM TC season outlooks provide further explanations about prediction accuracy, e.g. "*Over the entire Australian region, this statistical relationship has proven to be highly accurate, or a skilful way to forecast tropical cyclone activity. However, across the sub-regions this relationship, and thus forecast skill, can vary. Some regions have much higher forecast skill than others. The North-western sub-region has good skill, while the Western and Eastern regions both have low skill and the Northern region has very low skill*", and "*The statistical model used for this outlook has a high level of accuracy predicting cyclone numbers in the western region of the South Pacific, but a very low level of accuracy for the eastern region*". Terms such as low, moderate and high have explicitly defined thresholds according to their Linear Error in Probability Space (LEPS) scores. Such information is useful for decision-makers when they evaluate potential TC risk taking into consideration accuracy of the models in particular regions.

6 Discussion and conclusions

For twenty years, the CCSHTCII has supported SIDS and LDCs in building their capacity to generate and communicate effective early warnings of TC risk to protect lives, livelihoods and assets.

Creating and maintaining the SH TC historical data archive for the satellite era that consists of consolidated TC best track data from RSMCs and TCWCs in WMO Regions I and V is an important contribution to strengthening TC EWS. This long (almost 50 years), accurate and carefully curated climatology for the SH allows analysis of TC spatial and inter-annual variability. Areas of high TC activity in the SH were identified: an area centred on approximately 42°E between east coast of Africa and Madagascar; an area between 50°E and 90°E in the SWIO; an area centred on approximately 120°E near west coast of Australia; an area between 150°E and 165°E in the SPO (Fig. 2). This TC climatology is a valuable means of communicating the long-term TC threat to communities in high risk areas.

Historical records also show high inter-annual variability in TC activity. Numerous studies have demonstrated a significant impact of the ENSO on TC variability. The specific task of the CCSHTCII was to examine TC-ENSO relationships in three regions of the SH—the SWIO, the AR and the SPO. Significant impact of the ENSO on TC activity is evident in all three regions. For example, in the SPO, an increase in TC occurrences in El Niño years compared to La Niña years is observed (Tables 2, 3, 4). Typically, this influence translates into increased TC occurrence in the EEZ of some Pacific Island Countries (Table 5). If El Niño is likely in a coming TC season, it is also likely that TC activity in the SPO will be above average; this information needs to be communicated to communities at risk through EWS.

The BoM closely monitors and forecasts the ENSO via fortnightly outlooks using real-time observations and dynamical climate models. State-of-the-art models from eight world-leading climate centres are examined, and the ENSO outlook for the next five months is issued (https://www.bom.gov.au/climate/model-summary/#region=NINO34&tabs=Pacific-Ocean). The ENSO outlook is a vital component of EWS for TCs.

Results of research on TC-ENSO relationships in the SH are used by the BoM for producing TC season outlooks. The BoM issues early warnings about expected TC activity in the AR and the SPO in October, ahead of a TC season. The outlooks are disseminated through the BoM's web site and the media, presented at high-level briefings and meetings, as well as at training events for Pacific personnel, etc.

Communication of TC early warnings through TC season outlooks has a high potential to assist communities with preparedness. Pre-season planning and preparation can help avoid dangerous situations, loss of life and excessive damage to property if a cyclone does strike a region. Over the years, improvements in skill of numerical weather predictive models have resulted in more accurate forecasts, and hence, using TC early warnings, planning and preparations for expected cyclone activity can begin well before TCs appear on the weather forecasts. This means when a TC is forecast, more effective protective actions can be taken by those at risk, as preliminary actions have already taken place. However, in some cases, loss of life and damage to property still remains high. For example, in 2016, TC *Winston* had a devastating impact on Fiji. Reasons for the continuing disasters caused by TCs in spite of better forecasts are complex, including more population and property at risk, lack of mitigation and/or lack of resources to respond effectively.

ENSO is one of the key global climate drivers that modulates TC inter-annual variability; however, other factors are also important. Ongoing research at the BoM for improving TC seasonal forecasting skill is focused on the impact of the Indian Ocean Dipole on TC activity, as Dowdy (2014) noted that most of the TC inter-annual variability in the AR over the past two decades is not as strongly correlated with the ENSO as it was in the past (Nicholls 1984). To select the optimal combination of climate indices for TC seasonal prediction, the use of machine learning methods such as support vector regression was explored. It has been demonstrated that the Dipole Mode Index, 5VAR index (Kuleshov et al. 2009a) and the SOI were the most frequently selected as explanatory variables for TC seasonal forecasting in the regions of the SH (Wijnands et al. 2014, 2015).

Climate change is another important factor which affects TC activity globally. Modelling indicates that it is likely that the global mean TC maximum wind speed will increase by 2100. However, the response in regional TC activity to climate change is still not well understood (IPCC 2014). It is expected that in the near future, the skill of statistical models used for climate prediction will deteriorate because the basic assumption of a stationary climate (atmosphere and ocean) is no longer valid. Being aware of the limitations of using statistical models for TC seasonal prediction in a rapidly warming climate means, we are planning to explore alternative forecasting approaches, including dynamical climate modelling.

Additional research at the BoM involves multi-week outlooks based on the ACCESS-S dynamical climate model to provide early warnings to emergency services and the general public of severe tropical weather impacts. These products involve forecasting sources of intra-week variability such as the Madden–Julian Oscillation (MJO) rather than just ENSO.

In future, it may be possible that an optimal combination of dynamical climate models and statistical relationships can be used to provide a forecast for TC numbers across regions of the SH at both monthly and whole-of-season timescales. For instance, on longer timescales, forecast Indian Ocean and Pacific Ocean indices may be combined with known concurrent relationships to give an estimate of the season as a whole, while dynamical models, which incorporate climate drivers at all timescales, are used for TC sub-seasonal outlooks.

Historically, TC season outlooks in the AR have been made for the nation as a whole, and for three sub-domains. As noted earlier, TC activity and its response to ENSO forcing differ in the three regions of the SH, with the AR being in the middle of the three. This may in part explain why statistical models have lower skill across the three Australian TCWC regions, with the northern region having the lowest skill. It is increasingly clear that splitting the AR region into three sub-regions reduces the number of TCs in each of them to a sub-optimal level for developing skilful models.

As a result, one solution for better AR region TC seasonal forecasts would be simply to divide the region into an Indian Ocean dominated sector and a corresponding Pacific Ocean one. Results shown above suggest that separation into east and west TC sub-regions may be sensibly performed at the 135°E meridian. Testing of this hypothesis will be examined in a future study.

In this paper, we mainly discussed the preparing and communicating TC early warnings through TC season outlooks for the sub-regions in WMO Region V (South–West Pacific). However, scientific results and web-based information tools developed under the CCSHTCII are used for preparing TC season outlooks by NMHSs in WMO Region I (Africa) as well. Since 2017, the SH TC historical data portal has been used at the SWIO Regional Climate Outlook Forum to develop the TC outlook in this region for a coming season. The SWIO region includes five Indian Ocean Commission members (Comoros, La Réunion (France), Madagascar, Mauritius and Seychelles) and coastal countries of the SWIO (Tanzania, Mozambique and South Africa). The BoM's experience in developing the SH TC historical data portal, issuing TC season outlooks and communicating TC early warnings to the public is shared at SWIO regional forums with RSMC La Réunion and NMHSs of WMO Region I, assisting these countries with TC risk preparedness.

For the past twenty years, the Climate Change and Southern Hemisphere Tropical Cyclones International Initiative (CCSHTCII) has enhanced EWS for TCs in SH countries. To further assist SIDS and LDCs in the Pacific and Indian Oceans with improving their preparedness for TCs, future activities of the CCSHTCII will be focused on continuing to improve regional TC databases, designing tools with enhanced functionality for analysis of TC activity, developing more skilful statistical and dynamical climate model-based sub-seasonal and seasonal TC prediction methodologies and communicating impact-based TC warnings.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix 1: List of ENSO years

El Niño 1969, 1972, 1976, 1977, 1979, 1982, 1986, 1987, 1991, 1992, 1993, 1994, 1997, 2002, 2004, 2006, 2009, 2015.

Neutral 1971, 1978, 1980, 1981, 1983, 1984, 1985, 1989, 1990, 1995, 1996, 2001, 2003, 2005, 2008, 2012, 2013, 2014, 2016, 2018. 2019.

La Niña 1970, 1973, 1974, 1975, 1988, 1998, 1999, 2000, 2007, 2010, 2011, 2017.

Appendix 2: Tables

See Tables 6, 7, 8.

Table 6 List of severe TCs recorded in the SWIO (30E–90E) with LMCP 920 hPa or lower since 1981/82 season

TC season	TC name	LMCP, hPa
1981/82	Chris-Damia	898
1984/85	Kirsty	920
1993/94	Geralda	905
1993/94	Litanne	910
1994/95	Marlene	920
1995/96	Bonita	920
1996/97	Danielle	915
1999/00	Hudah	905
2001/02	Dina	910
2001/02	Guillaume	920
2001/02	Hary	905
2002/03	Kalunde	905
2003/04	Gafilo	895
2004/05	Adeline-Juliet	905
2004/05	Bento	915
2005/06	Carina	915
2007/08	Hondo	906
2009/10	Edzani	910
2013/14	Bruce	920
2013/14	Colin	915
2013/14	Hellen	915
2014/15	Bansi	910
2014/15	Eunice	915
2015/16	Fantala	910

Table 7 List of severe TCs recorded in the AR (90E–160E) with LMCP 920 hPa or lower since 1981/82 season

TC Season	TC Name	LMCP, hPa
1983/84	Kathy	920
1988/89	Orson	905
1991/92	Graham	915
1993/94	Reva	920
1993/94	Theodore	910
1994/95	Chloe	920
1996/97	Pancho–Helinda	915
1998/99	Thelma	920
1998/99	Vance	910
1998/99	Frederic–Evrina	920
1998/99	Gwenda	900
1999/00	John	915
1999/00	Paul	915
2001/02	Chris	915
2002/03	Inigo	900
2003/04	Fay	910
2005/06	Floyd	916
2005/06	Glenda	910
2005/06	Monica	916
2006/07	George	902
2017/18	Marcus	912

Table 8 List of severe TCs recorded in the SPO (west of 160E) with LMCP 920 hPa or lower since 1981/82 season

TC Season	TC Name	LMCP, hPa
1982/83	Oscar	920
1984/85	Hina	910
1991/92	Fran	920
1997/98	Ron	900
1997/98	Susan	900
2002/03	Beni	920
2002/03	Dovi	920
2002/03	Erica	915
2002/03	Zoe	890
2003/04	Heta	915
2004/05	Meena	915
2004/05	Olaf	915
2004/05	Percy	900
2009/10	Ului	915
2014/15	Pam	896
2015/16	Winston	884

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