An intercomparison of tropical cyclone best-track products for the Southwest Pacific

Andrew D. Magee[1], Danielle C. Verdon-Kidd[1], Anthony S. Kiem[2]

[1] Environmental and Climate Change Research Group (ECCRG), School of Environmental and Life Sciences, Faculty of
5 Science and Information Technology, The University of Newcastle, Callaghan, NSW, 2308, Australia
[2] Centre for Water, Climate and Land Use (CWCL), Faculty of Science and Information Technology, The University of
Newcastle, Callaghan, NSW, 2308, Australia

Correspondence to: A. D. Magee (andrew.magee@uon.edu.au)

Abstract. Recent efforts to understand tropical cyclone (TC) activity in the Southwest Pacific (SWP) have led to the

10 development of numerous TC databases. The methods used to compile each database vary and are based on data from different
meteorological centres, standalone TC databases and archived synoptic charts. Therefore the aims of this study are to (i)
examine spatial and temporal differences between the TC databases, and, (ii) investigate how changes in observational
technology influence the temporal quality of TC records over time. To achieve this, we compare three best-track TC databases
for the SWP region (0º-35ºS, 135ºE-120ºW) from 1945-2011: the Joint Typhoon Warning Center (JTWC), the International

15 Best Track Archive for Climate Stewardship (IBTrACS), and the Southwest Pacific Enhanced Archive of Tropical Cyclones
(SPEArTC). The results of this study suggest that SPEArTC is the most complete repository of TCs for the SWP region. In
particular, we show that the SPEArTC database includes a number of additional TCs, not included in either the JTWC or
IBTrACS database. These SPEArTC events do occur under environmental conditions conducive to tropical cyclogenesis (TC
genesis). Further, while changes in observational technologies from 1945 have undoubtedly improved our ability to detect and

20 monitor TCs, we show that the number of TCs detected prior to the satellite era (1945-1969) are not statistically different to
those in the post-satellite era (post-1970). Although studies on TC intensity should be limited to post-satellite/post-
geostationary satellite eras only, this study suggests that SPEArTC data (from 1945) may be used to investigate long-term
variability of TC counts and TC genesis locations.

25 **Keywords:** tropical cyclone, Southwest Pacific, TC databases, JTWC, IBTrACS, SPEArTC

1. Introduction

Recently, there has been a concerted effort towards understanding the relationships between climatic variability/change and
the spatio-temporal variability of tropical cyclone (TC) activity in the Southwest Pacific (SWP; 0º-35ºS, 135ºE-120ºW) and
smaller regions within the Pacific basin (Chand and Walsh, 2009, 2010; Chand et al., 2013; Diamond and Renwick, 2015a,

30 2015b; Diamond et al., 2013; Dowdy et al., 2012; Kuleshov et al., 2008, 2010). In order to achieve this, it has been necessary
to develop quality controlled TC databases that provide information about TC frequency, magnitude, onset location and
subsequent TC tracks (Chu et al., 2002; Diamond et al., 2012; Knapp and Kruk, 2010; Kuleshov et al., 2010). As a result,
several SWP TC databases exist including: the Joint Typhoon Warning Centre (JTWC) Best-Track Database, the International
Best Track Archive for Climate Stewardship (IBTrACS) and the Southwest Pacific Enhanced Archive of Tropical Cyclones

35 (SPEArTC), among others explored further in Section 2 (where best-track (BT) data refers to the estimates of position and
intensity at intervals of 6-hours for the duration of a TC event). Each dataset draws on data from meteorological centres,
standalone TC databases and archived synoptic charts to develop their collection of TC events (further detailed in Section 2).
Such quality controlled, homogenous databases are necessary for producing meaningful conclusions from TC modelling or
climate attribution studies (Dowdy et al., 2012). However, given that multiple databases exist, a study of the similarities and

differences between each dataset and an assessment of which one(s) is (are) the most complete and/or accurate is urgently needed.

In addition to the choice of TC dataset, questions have been raised over the accuracy and therefore usefulness of TC observations before 1969 (i.e. prior to the inclusion of satellite derived information on TCs) (Holland, 1981). In the SWP region, these concerns have primarily been based on the early work of Holland (1981) who used a collection of TC events from the Australasian region (105-165°E, 0-32°S) compiled by Lourensz (1977), to quantify possible errors and/or missing data from 1909 through to 1979. Holland (1981) studied a number of parameters, including TC occurrence, coastal crossings, location and intensity and found that TC data were more reliable closer to the coast (within 500 km) for all parameters studied. Importantly, Holland (1981) noted a change in the quality of TC observations over time. In particular, from 1909 to 1959, the study estimated that up to 50% of TCs were missing from the Lourensz (1977) database. An increase in reliability of the database was observed from 1959 (up to 30% missing), as a result of the introduction of radar observations. The most substantial improvement in the quality of TC observations (up to 15% missing) occurred with the introduction of routine enhanced observational technologies from 1969, termed the 'satellite-era' (Kuleshov, 2002; Webster et al., 2005). Importantly, the findings of Holland (1981) have been used as a basis for limiting TC climate analysis studies to the 'post-satellite' era from 1969 onwards (Chand and Walsh, 2010; Diamond and Renwick, 2015b; Kuleshov et al., 2010; Wijnands et al., 2014). Some studies have constrained this further, using TC data from 1982 only (Dowdy, 2014; Dowdy and Kuleshov, 2012; Kossin et al., 2014; Kuleshov et al., 2008), the period of continuous and routine geostationary satellite observations for the region, to allow for reliable intensity estimates (Dvorak, 1984; Klotzbach, 2006). However, this temporal constraint makes it difficult to rigorously assess any long-term trends in TCs and prevents the study of potential impacts of multi-decadal process such as the Interdecadal Pacific Oscillation (IPO) on TC activity. As such, a contemporary analysis revisiting the usefulness of pre-satellite TC data for the SWP is urgently needed.

The aims of this study are to: (i) provide a spatio-temporal comparison of three TC BT databases and explore any differences between them (and any associated implications); and (ii) investigate if there are any spatial, temporal or statistical differences between pre-satellite (1945-1969), post-satellite (1970-2011) and post geostationary satellite (1982-2011) era TC data.

2. Review of Best-Track Databases

Many records of TC tracks exist for the SWP (Table 1; Chu et al., 2002; Diamond et al., 2012; Giovannelli, 1952; Kerr, 1976; Knapp and Kruk, 2010; Lourensz, 1977, 1981; Revell, 1981; Visher, 1925), which have been collated from irregular ship reports, land observations, TC reconnaissance missions, geosynchronous satellite observations and best-track reanalyses (summarised in Table 2). In addition to many different data sources, inconsistencies between TC databases may be attributed to changes in observational technologies (Chu et al., 2002), changes in data analysis techniques over time and changes in the definition of TCs (Knapp and Kossin, 2007). Interagency differences may also exist, such as different wind speed averaging methods (Knapp and Kruk, 2010). Spatially, the accuracy of tropical cyclogenesis (TC genesis) points and TC tracks may be questionable, due again to changes in observational technologies and the subjective nature of defining best-tracks (see Guard et al., 1992 on difficulties of track forecasting). Each dataset also varies in spatial and temporal coverage.

Of the TC databases listed in Table 1, three were chosen for further analysis based on there: (i) comparable geographical extent; which for the purposes of this investigation has been defined as: 0°-35°S, 135°E-120°W (Figure 1), (ii) overlapping time-period; 1945-2011, and (iii) use in peer-reviewed literature. Where spatial and temporal values exceed these ranges, databases were trimmed to ensure homogeneity. The study domain of the SWP region spans numerous World Meteorological Organisation (WMO) TC Regional Specialised Meteorological Centres (RSMCs) and Tropical Cyclone Warning Centres (TCWCs). The following provides a review of the BT databases used in this investigation.

The *Joint Typhoon Warning Centre (JTWC) Best-Track Database*, established in 1959, initially only included the Eastern North Pacific as its Area of Responsibility (AOR). With the goal of preventing loss of life and property (Guard et al., 1992), the JTWC AOR was then extended in October 1980 to include the Southern Hemisphere (west of 180° to the east coast of Africa). Since then, the BT archive for the SWP has been extended from 1945 to the present day and encompasses 135°E-

5 120°W of the South Pacific Basin. Three sources have been used to compile the JTWC database (Table 1). Its use in TC related studies are widespread (Chand and Walsh, 2009, 2010; Klotzbach, 2006).

The *International Best Track Archive for Climate Stewardship (IBTrACS)*, conceived and developed by National Oceanic and Atmospheric Administration's National Climatic Data Center is the most complete global repository of TC BT data (Knapp and Kruk, 2009). IBTrACS has been adopted by the World Meteorological Organization's Tropical Cyclone

10 Programme as its TC BT standard. Extending back to 1842, IBTrACS collates BTs from a number of forecast centres and meteorological agencies (Table 1). Where duplicate storms occur between two or more sources, the average location at each 6-hourly interval is taken (Kruk et al., 2010). A study comparing IBTrACS with JTWC, identified 109 more named storms in IBTrACS compared to JTWC (Knapp and Kruk, 2010), with the authors citing differences in intensity or operational procedures for the mismatch. Two versions of the IBTrACS database currently exists: (i) IBTrACS_ALL which contains all

15 RSMC and TCWC data aswell as other sources of data, e.g. JTWC, (ii) IBTrACS_WMO which only contains TC data collected from WMO-sanctioned forecast agencies, e.g. RSMCs and TCWCs, and is a subset of the more comprehensive database. See (https://www.ncdc.noaa.gov/ibtracs/index.php?name=ibtracs-data-access) for more detail on the differences between IBTrACS_WMO and IBTrACS_ALL. This analysis utilises the IBTrACS_ALL dataset. The use of IBTrACS_ALL database in TC studies is widespread (Liu and Chan, 2012; Ramsay et al., 2011).

20 The *Southwest Pacific Enhanced Archive of Tropical Cyclones (SPEArTC),* is the most recent reanalysis of available BTs for the SWP (Diamond et al., 2012). Building upon the IBTrACS database, SPEArTC incorporates a number of new sources of older scanned data coupled with a meticulous reanalysis of all of these sources from 1840-present. However, given the lack of observational data in the early part of the record, the developers note that some TC seasons are missing between 1840 and 1905. In the creation of SPEArTC, some unique quality control and duplicate track detection processes were

25 established, such as the Graphical Interpretation of Tracks (GrIT) method (Diamond et al., 2012), which applied objective and subjective guidelines to investigate duplicate events and to highlight possible errors. The dataset is utilised in the following studies, Diamond et al., (2013) and Diamond and Renwick, (2015a, 2015b).

3. Data

3.1. Tropical Cyclone Data

30 The three quality-controlled TC BT products discussed in Section 2 were obtained from:

- JTWC (dataset updated 8th July 2014: http://www.usno.navy.mil/NOOC/nmfcph/RSS/jtwc/best_tracks/shindex.php) (Chu et al., 2002),

- IBTrACS (v03r06: http://www.ncdc.noaa.gov/ibtracs/index.php?name=ibtracs-data) (Knapp et al., 2010),

- SPEArTC (dataset updated 28th January 2014: http://apdrc.soest.hawaii.edu/projects/speartc/) (Diamond et al., 2012).

35 The 'Lourensz TC database' (Lourensz, 1977, 1981) is also used in this analysis to compare with JTWC, IBTrACS and SPEArTC.

The SWP TC season is from 1st November – 30th April the following year (Terry, 2007). As the TC season straddles the Gregorian calendar year, events that occur during November and December are considered part of the following year's TC season (see Dowdy 2014). So for example, TCs that occur in November and December of 2010 are considered part of the 2011

TC season. The IBTrACS database was modified to the same reporting system – to ensure homogeneity across the three databases.

The lack of a unified method in collecting and recording TC data has resulted in numerous data formats (Schreck et al., 2014). During initial inspection of the IBTrACS database, these inconsistencies were identified, typically as duplications of parts of a TC track. As such, only 'main' TC tracks have been used in this analysis and the other categories, 'merge', 'split' and 'other' were not included.

3.2. Reanalysis Data

This study utilises 20th Century Reanalysis Version 2 (20CRv2) from the National Oceanic and Atmospheric Administration Earth System Research Laboratory (Compo et al., 2011). The 20CRv2 has four synoptic observations per day, ideal for this environmental reanalysis. To investigate if environmental conditions were suitable for TC genesis on selected dates, four geophysical parameters are investigated; (i) 700-hPa vorticity (VORT), or the vertical component of vertical velocity is calculated by Eq. (1), whereby u/v refers to zonal/meridional winds at 700hPa and x/y refer to coordinate axes (McBride and Zehr, 1981).

$$\zeta = \partial v/\partial x - \partial u/\partial y \qquad [1]$$

(ii) 700-hPa u/v winds, (iii) Environmental Wind Shear (EVWS), is calculated by the difference in 200hPa and 850hPa u/v winds (see Eq. (2)) (Gray, 1968):

$$EVWS = \sqrt{(u200 - u850)^2 + (v200 - v850)^2} \qquad [2]$$

and (vi) 700-hPa geopotential height (GPH).

This analysis uses anomaly values (except for EVWS) to represent deviations from the mean climatological state (1981-2010 climate normal). Anomaly values provide an indication on whether geophysical variables are suited, or not suited to TC genesis. The conditions most suited to TC genesis are discussed further in Section 4.2.

To validate the choice of environmental parameters, the above reanalysis fields were assessed during known TCs from the Australian landfalling TC database (Callaghan and Power, 2011). Five TCs were randomly selected from the eighteen TCs that made landfall within the study domain (between 1945-2011; see Table 3). Using the SPEArTC database, landfalling TCs were traced back to their point of TC genesis and the environmental conditions were assessed on the date of genesis. Plots of the environmental conditions have been included as supplementary material (Fig. S1-S5). A checklist of conditions for each event (Table 3) indicates that negative 700-hPa VORT, cyclonic 700-hPa winds and EVWS ($<= 10m\ s^{-1}$) were present in the immediate vicinity of TC genesis for four out of five TC events (see section 4.2 for more information). Negative 700-hPa GPH occurred for 3 out of 5 events, confirming our choice of parameters provides a reasonable indication of conditions conducive to TC development. It should be noted that this method is not used as a TC forecasting technique, rather to verify the choice of reanalysis fields for this analysis.

4. Methodology

4.1. Spatio-temporal comparison of tropical cyclone databases

In our analysis, annual (July-June) TC counts are considered along with two subsets of the TC season; the first half of the TC season – November to January (NDJ) and the second half of the TC season – February to April (FMA). Time series analysis compares annual and seasonal TC counts for JTWC, IBTrACS and SPEArTC. The average number of TCs per year and per

season was also compared between databases. For the purposes of this analysis, the point of TC genesis is defined as the first point of each unique TC track for each TC database.

Difference density plots are used to assess the spatial variability between JTWC, IBTrACS and SPEArTC. The frequency of annual TC events in 2.5º x 2.5º grid cells was calculated for each of the three databases and subtracted from one another. This resulted in three pairings: JTWC-IBTrACS, JTWC-SPEArTC and IBTrACS-SPEArTC. Positive/negative values indicate more/less TCs in that respective grid cell.

4.2. Cross comparison of tropical cyclone best-track databases and environmental reanalysis

By comparing TC counts between JTWC, SPEArTC and IBTrACS, we identified two TC seasons with the largest deviation in annual TC counts between JTWC, IBTrACS and SPEArTC, 1968 and 1981. TC events were subsequently categorised into one of three categories; (i) exact matches (TCs that match in all three BT databases), (ii) partial matches (conflicting date, latitude and longitude) and (iii) unique events (events that do not feature in any of the other databases). To identify if the TCs classified as unique events may have been legitimate TCs, we use 20CR data (see section 3.2) to establish if environmental conditions for the selected TC seasons were suitable for TC genesis. Anomaly values of key environmental conditions required for TC genesis are assessed (see Diamond and Renwick, 2015b). Using a climatological baseline of 1981-2010, anomaly values are compared with the location of TC genesis to determine whether environmental conditions are suited/not suited to TC genesis. Anomalous conditions suited to TC genesis include: negative 700-hPa VORT, cyclonic 700-hPa winds and negative 700-hPa GPH anomalies. Upon assessing the geophysical parameters, we classified the environmental conditions as suitable/less suitable for TC genesis.

Absolute values of wind shear are included in this analysis. Absolute EVWS values between 2-4 m s^{-1} are most favourable for TC genesis, whilst EVWS values exceeding 10 m s^{-1} does not favour intensification of a TC system (Paterson et al., 2005). As such, if TC genesis occurs in a region where shear exceeds 10m s^{-1}, conditions will be deemed less favourable (but still possible) for TC genesis. For the purposes of this study, we are investigating if environmental conditions were suitable for TC genesis. We are not suggesting that TC genesis occurred and that particular event intensified into a TC. The authors acknowledge the caveats of using reanalysis data as a method to verify historical TCs (Nicholls et al., 1998)

4.3. Assessing the impact of changing observational technologies on the quality of tropical cyclone databases

As an update and extension to previous work (Holland, 1981), herein the work of 'Holland', we investigate the potential impact of changing observational technologies on the quality of JTWC, IBTrACS and SPEArTC. We use the introduction of two 'significant' observational technologies, the satellite era (1969), and routine geostationary satellites (1982) as breakpoints in the time series (Holland, 1981; Nicholls et al., 1998). As such, our TC time series consists of three time periods: 1945-1969 (pre-satellite era), 1970-2011 (post-satellite era) and 1982-2011 (post-geostationary satellite era).

An assessment of significance of differences between the time periods was addressed in two ways: (i) non-parametric Mann-Whitney U Test and, (ii) a parametric Generalised Linear Mixed Model (GLMM). A Mann-Whitney U Test (Mann and Whitney, 1947) is used to compare the median values of the pre-satellite, post-satellite and post-geostationary satellite TC counts. Furthermore, a parametric generalised linear mixed model (GLMM) is applied to compare mean TC counts between each of the time periods and derive a statistical significance of the values (McCulloch and Neuhaus, 2001). The Poisson distribution has been used to model variability, as this is a suitable choice for counted data. A random effect was used to account for possible overdispersion due to differences in TC counts between years, for example, large outlier TC seasons such as 1962/1963. The significance of differences in TC counts was assessed from the mixed model main effect term of the two versions of the time period: (i) 1945-1969 versus 1970-2011, and, (ii) 1945-1981 versus 1982-2011. As we are using these

statistical tests to investigate whether changing observational technologies has a substantial influence on TC counts, a p-value <0.05 would indicate a statistically significant value.

In addition to assessing temporal variability caused by changing observational technologies, we also investigate the spatial variability of TC activity influenced by the introduction of each technology. This study makes use of mean genesis

5 locations (Chand and Walsh, 2010; Wu et al., 2015), calculated by averaging the latitude (x) and longitude (y) of a collection of TC events. The mean centre of cyclogenesis (MCC) technique provides an insight into how the introduction of various observational technologies has impacted TC genesis. The vast longitudinal and latitudinal expanse of the study area is acknowledged, however this technique provides an effective comparison of the spatio-temporal modulation of TC activity.

10 ## 5. Results and Discussion

5.1. Spatio-temporal comparison of JTWC, IBTrACS and SPEArTC tropical cyclone databases

Comparing the annual and seasonal TC counts (Table 4, Figure 2) highlights variability between the three BT products. The most conservative (i.e. lowest number of TCs listed in the database) is JTWC, which lists a total of 753 TC events between 1945-2011. In contrast, SPEArTC contains 844 events, a difference of 91 TCs (approximately 12% more than JTWC). This

15 same pattern is evident seasonally, e.g. NDJ with 47 more TCs (a difference of 15.5%) in SPEArTC compared with JTWC. A number of years show a higher degree of temporal variability between databases, which is investigated further in Section 5.2.

Difference density plots were created to assess spatial variability between the three TC databases (method detailed in Section 4.1). In Figure 3, the first two pairings for the difference density plot use JTWC as a base, therefore positive (negative) values indicate *more* (less) events in JTWC (IBTrACS/SPEArTC). The last pairing, IBTrACS-SPEArTC, indicate that positive

20 (negative) values indicate *more* (less) events in IBTrACS (SPEArTC). The JTWC-SPEArTC pairing highlights the greatest spatio-temporal difference in TC counts between our paired TC databases. In total, 42.6% of the area recorded more SPEArTC events than JTWC. TC counts for the IBTrACS-SPEArTC pairing are the most consistent with 40.4% of the total area containing the same number of TCs. The greatest inconsistency occurs around the Gulf of Carpentaria and the Coral Sea.

The results presented thus far confirm that spatial and temporal inconsistencies exist between JTWC, IBTrACS and

25 SPEArTC. Therefore, conclusions drawn from TC related analyses may be influenced by the choice of BT database depending on the application.

5.2. Cross-comparison of tropical cyclone best-track products

An analysis of JTWC, IBTrACS and SPEArTC revealed that the years with the largest discrepancy in TC frequency were the

30 1968 and 1981 TC season. For these two TC seasons, each TC event was categorised into one of three distinct TC categories: (i) exact matches, (ii) matched TCs with inconsistent temporal/spatial data (date, latitude, longitude), and (iii) unique events (Figure 4). Both the pre-satellite (1968) and post-satellite (1981) era are represented in this analysis, the significance of which is explored in Section 6.

For the 1968 TC season, seven exact TC matches were noted. A further six matching events had inconsistent spatio-

35 temporal data, however were identified as the same TC event (see Figure 4, panel A) and six unique TCs were identified in SPEArTC (Figure 4, panel B). The literature offers a number of explanations to account for conflicting date/locational information including, (i) difficultly and subjectivity in defining a BT (Holland, 1981), (ii) an acceptable margin of error of up to 110km when collating BT data (Chu et al., 2002) and (iii) inconsistencies in operational procedures (Diamond et al., 2012; Knapp and Kruk, 2010). TC Gisele is one such event which was recorded in all three BT products, however, IBTrACS and

40 SPEArTC place the point of TC genesis approximately 498km SW of JTWCs TC genesis point.

For the 1981 TC season, two exact matches were noted, while eight TC events are classified as matching with inconsistent temporal/spatial data (Figure 4, panel C). The spatial variability between each matching TC event is considerably more than the 1968 TC season, with spatial differences of up to 781km between BT product for TC Fran, 756km for TC Eddie and 480km for TC Betsy. There is one unique TC in 1981 identified in the SPEArTC database (Figure 4, panel D). The fewer
5 unique events in the 1981 TC season compared to the 1968 TC season may be an indication of the improved observational technologies in the post satellite era. Section 4.3 further explores the pre-satellite, post-satellite and post-geostationary satellite era, and provides a spatio-temporal comparison of each BT product.

To assess the environmental conditions associated with the unique TC events identified in SPEArTC, we perform an analysis based on four geophysical parameters required for TC genesis (see validation of the use of these variables in section
10 3.2). The purpose of this technique is twofold: (i) to ensure that conditions are suited to TC genesis and, (ii) to verify the inclusion of these events within the SPEArTC database. Table 5 summarises a checklist of the parameters required for TC genesis for each unique TC event. The cyclone ID # is used as an identifier which corresponds to Figure 4 (Panel B and D). An inspection of each geophysical variable confirms (for TC# 2-7) that many of the environmental conditions were suitable for TC genesis (for TC# 2-7), particularly for 700-hPa Vorticity, 700-hPa Winds and 700-hPa GPH. To highlight how this
15 conclusion was drawn, Figures 5-7 plot the anomaly values for the selected geophysical parameters for two selected events; TC #3 (1968) and TC #7 (1981).

The Vorticity-Wind plots (Figure 5) demonstrate that conditions were suitable for TC genesis during the two unique events, given that negative vorticity and cyclonic like wind flow patterns are all conditions suitable for TC genesis. In fact, areas of substantial negative vorticity are evident for six of the seven events analysed in this study. EVWS <10 m s^{-1} is generally
20 more favourable for TC genesis (Nolan and McGauley, 2012), which occurred in the region of TC genesis for TC #3 and TC #7 (Figure 6) and for a total of five of the seven TC events analysed. Five of the seven TC events analysed (Table 5) occur in a region of anomalously negative GPH, most suited to TC genesis. TC genesis in Figure 7, Panel A occurs in a region of anomalously negative GPH, while TC #7 (Figure 7, Panel B) occurs in a region of neutral GPH.

Although it is difficult to determine if the conditions observed during the TC event matured into a TC and satisfy the
25 minimum wind speed requirements to be defined as a TC, the analysis of environmental parameters confirms that conditions were favourable for TC genesis for each of the seven events analysed. Therefore, given that the SPEArTC database is likely to be the most complete for the SWP region, we focus on this database for our temporal analysis in the following section.

5.3. Assessing the impact of changing observational technologies on the quality of tropical cyclone databases

30 Given the importance of a reliable, homogenous dataset, many studies have opted to use only post-satellite TC data based on previous work (Holland, 1981). However, with the development of more contemporary TC databases, this assumption needs to be reviewed. To achieve this, an intercomparison of annual TC counts was carried out between the same Lourensz TC database (Lourensz, 1977) used in the findings of Holland, and the SPEArTC database. To lengthen the Lourensz TC database (Lourensz, 1977) to 1980, we utilised data from an extended Lourensz TC dataset (Lourensz, 1981). In this comparative study
35 only TCs that occurred between 135°E-165°E, 5°S-32°S (i.e. a subset of the wider SWP study region) during 1945-1980 were considered in this analysis (the common spatial and temporal extents of all databases). Figure 8a shows that, although the same spatial and temporal boundaries have been applied for this comparison, annual TC counts for the Lourensz TC dataset (5.1 TCs per year) are considerably lower than the SPEArTC database (7.4 TCs per year). This result is somewhat expected given the improved technologies available to identify historical TCs and construct the contemporary TC databases. Interestingly, the
40 magnitude of the upward trend in Eastern region TCs (135°E-165°E, 5°S-32°S) for the Lourensz TC database (Figure 8a), is not as noteworthy as the wider Australian region (105°E-165°E, 5°S-32°S; Figure 8b) originally investigated by Holland (although both trend lines are statistically significant at a=0.01 based on a Mann-Kendall test of linear trend). This suggests

that the western and northern region (west of 135°E) of the Lourensz database was the dominant driver of the observed increasing trend in TC counts in the original study. Further, when SPEArTC TC counts for the same region (from 1945) are overlaid in Figure 8a, although a slight increase is observed with time, the increase in not as substantial as the original Lourensz TC database and importantly, the trend is not statistically significant (a=0.05) when the data is extended to 2011 (based on a

5 Mann-Kendall test). This not only suggests that the original TC database has been superseded by more contemporary TC databases, more importantly, any conclusions on pre-satellite era data require re-examination using these contemporary TC databases.

There is no doubt that the introduction of new observational technologies has improved our ability to detect, monitor and disseminate more accurate information on TCs. However, a comparison of pre and post-satellite era SPEArTC TC counts

10 over the full SWP study region (0º-35ºS, 135ºE-120ºW) suggests that pre-satellite era data is not as erroneous and missing as many TCs as previous studies suggest (based on temporal, statistical and spatial analysis; Table 6). A comparison of average annual TC counts highlighted a small difference between the pre-satellite era and post-satellite eras, 12.2 TCs and 12.8 TCs per year respectively. Had the introduction of the satellite era had a significant influence on the number of TCs (whereby 30-50% of TC observations were missing from the Lourensz TC database (Holland, 1981)), then it would be expected that the

15 average number of TCs in the post-satellite era would be significantly elevated compared to the pre-satellite era. Further, cross referencing pre-satellite era SPEArTC events with known TCs from the Australian landfalling TC database by Callaghan and Power (2011), highlights that all TCs that made landfall between Ballina and Cairns are accounted for in the SPEArTC database (Table 7).

To determine (statistically) if changing observational technologies had a significant influence on TC counts (and

20 therefore the temporal quality of the database) a Mann-Whitney U Test and Generalised Linear Mixed Model (GLMM) was applied to the SPEArTC database. TC counts for two scenarios were compared: 1945-1969 (pre-satellite era) with 1970-2011 (post-satellite) and 1945-1981 with 1982-2011 (post-geostationary satellite era). The null hypothesis adopted was that there is no difference between the median (Mann-Whitney U) and mean (GLMM) in SWP TC counts before and after the change in technology. Table 8 shows for all time periods assessed, each test for SPEArTC returned p-values >0.05, suggesting there is

25 no statistical evidence against the null hypothesis. These results confirm, that there is no statistically significant evidence to suggest that there is a significant change in SPEArTC counts before and after a change in observational technology.

Figure 9 presents a time series of TC-frequency for SPEArTC using a 5-year running mean (for the entire SWP study region). Unlike Holland who carried out a similar analysis on the early TC database (albeit on a subset of our study region) which resulted in an almost linear increase in TCs over time between 1915 and 1975 (as shown in Figure 8b), Figure 9 displays

30 decadal to multidecadal variability in TC frequency. This variability might explained by processes other than changes in observational technologies, given that regime shifts displayed do not correspond to known changes in observational technology. For example, El Niño Southern Oscillation (ENSO; Rasmusson and Wallace, 1983) is known to influence the frequency of TCs in the SWP, whereby La Nina conditions result in heightened TC activity in the (15.3 TCs per season), compared with El Nino (15.0 TCs per season) (Diamond et al., 2013).

35 Using the MCC method (described in Section 4.3), Figure 10 summarises the annual and seasonal MCC for SPEArTC according to three time periods of interest. It can be seen that pre-satellite era MCCs are situated (on average) further west than post-satellite and post-geostationary satellite era MCCs for all seasons. This apparent spatial modulation may be attributed to increased observational power toward the east of the study region (open water) in more recent years (i.e. a result of changing observational technology) or could be due to the influence of large-scale climate drivers (e.g. IPO or ENSO). To investigate

40 the significance of the observed spatial variability, a number of simulations (200 in total) were produced to determine if the observed differences could be reproduced by statistics alone. This was achieved by first randomising the SPEArTC TC time series and then splitting the randomised time series into two groups (the first the same length as the pre-satellite era observations, the second the length of the post-satellite era). Figure 11 plots these Simulated Mean Centres of Cyclogenesis

(SMCC) with the original Mean Centres of Cyclogenesis (MCC). The SMCC distribution lies within close proximity of the MCC, which indicates that the spatial modulation of SPEArTC MCCs may be statistical, or related to chance (not significant) as opposed to any change in observational technology/climate driver.

5 **6. Conclusion**

This study provides a spatio-temporal intercomparison of three TC databases: JTWC, IBTrACS and SPEArTC for the SWP. Further, the study re-examines the impact of changing observational technologies on the quality of pre-satellite era data and compares the findings with Holland (1981), using the SPEArTC database from 1945. Although there is no doubting the numerous benefits in consolidating sources and creating a contemporary quality-controlled TC database, this study shows that

10 considerable spatial and temporal variability exists between all TC databases studied here. As such, the choice of dataset should be carefully considered, as it may influence the outcomes of subsequent analyses. It is suggested that the SPEArTC database is the most complete repository for the SWP, based on an intercomparison of TC events with the other BT products and the cross comparison using reanalysis data. Importantly, this analysis showed that environmental conditions were suited for cyclogenesis for a number of events listed only in the SPEArTC database. Further validation could determine if this is the case

15 for all unique events listed in the SPEArTC database.

The potential influence of changing observational technologies on the reliability (TC counts) of the SPEArTC database was investigated. Given the significant improvements in observational technologies, there is no doubt that our ability to detect and monitor TCs have improved with time. However, multiple lines of evidence (temporal, statistical and spatial analyses), revealed that the impact of the satellite (1969) and the geostationary satellite (1982) eras on the quality of the

20 SPEArTC database is not as significant as initially suggested (Holland, 1981). In particular, our spatio-temporal analysis of pre-satellite, post-satellite and post-geostationary satellite TC observations confirm that SPEArTC does not suffer from the same positive trend in TC counts after the satellite era as did the early database used by Holland (1981). Time series analyses also showed that observed temporal trends in the TC time series do not correlate with the introduction of observational technologies and there is no statistical evidence of a change in TC counts between the time periods associated with changes in

25 observational technology. The compilation of numerous sources in the construction of the more contemporary databases has no doubt improved the temporal consistency in TC counts. A study assessing the quality of a the HURDAT North Atlantic TC database (Chang and Guo, 2007), estimates that up to 1 non-landfalling TC per year may be missing from pre-satellite TC records (1920-1965). Similarly, this study does not suggest that all SWP pre-satellite era TCs (1945-1969) are accounted for, rather that the introduction of the satellite era has not caused a significant change in TC counts for the SPEArTC database. As

30 such, pre-satellite SPEArTC data (from 1945) may be used for certain applications, (e.g. climatological studies of TC counts and TC genesis). It is important to note that studies of trends in TC intensity should still be limited to the post/post geostationary satellite era, due to the lack of reliable intensity estimates prior to this time (Dvorak, 1984; Klotzbach, 2006).

Our analysis also highlighted a shift in the MCC of TCs, with pre-satellite era TCs situated further west in the SWP, and post-geostationary satellite TCs situated further east. Given the pre-satellite (1945-1969) and post-satellite eras (1970-

35 2011) overlap somewhat with IPO negative (1946-1977) and IPO positive (1978-1998) conditions, changes in environmental conditions consistent with these phases may be responsible for this observed spatial modulation (Grant and Walsh, 2001). Therefore, further work will look at the relationship between phases of the IPO and TC activity in the SWP region – which will be made possible through the use of the extended TC database.

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Tables

Table 1. Review of Tropical Cyclone Databases for the Southwest Pacific

Product	Basin	Latitude		Longitude		Temporal	Sources (Not Exhaustive)	Extent suitable for this study?	
		Min	Max	Min	Max			Spatial	Temporal
Joint Typhoon Warning Centre (JTWC) (Chu et al., 2002)	S. Hemisphere	-90	0	15	-110	1945-2013	- A Fleet Numerical Meteorology and Oceanography Center (FNMOC) database - Automated TC Forecasting System (ATCF) database (Sampson and Schrader, 2000)	✓	✓
	N. Indian Ocean	0	90	20	100				
	W. North Pacific	0	90	90	180				
International Best-Track Archive for Climate Stewardship (IBTrACS) (Knapp et al., 2010)	N. Indian	0	90	30	100	1842-2013	- National Climatic Data Center TD9636 dataset - Australian Bureau of Meteorology (BoM) (TCWC Perth, Darwin, Brisbane) - Fiji Met Service (RSMC Nadi) - India Meteorological Department (RSMS New Delhi) - Japan Meteorological Agency (RSMC Tokyo) - Meteo-France (RSMC La Reunion) - Met Service of NZ (TCWC Wellington) - NOAA's Central Pacific Hurricane Center (RSMC Honolulu) - NOAAs National Hurricane Centre (NHC) - China Met Administration's Shanghai Typhoon Institute (CMA/STI) - Hong Kong Observatory (HKO) - U.S. Department of Defense - Joint Typhoon Warning Centre (JTWC) - C. Neumann's Southern Hemisphere Data	✓	✓
	W. Pacific	0	90	100	180				
	E. Pacific	0	90	180	Variable				
	N. Atlantic	0	90	Variable	30				
	S. Indian	-90	0	10	135				
	S. Pacific	-90	0	135	-70				
	S. Atlantic	-90	0	-70	10				
Southwest Pacific Enhanced Archive of Tropical Cyclones (SPEArTC) (Diamond et al., 2012)	SW Pacific	-65	-5	135	-120	1840-2014	- Joint Typhoon Warning Centre (JTWC) - BoM - IBTrACS - RSMCs Nadi and TCWC Wellington - Visher (1925) - TC tracking maps from Fiji, New Caledonia, New Zealand, Tonga, Solomon Islands and Vanuatu	✓	✓
Australian Bureau of Meteorology National Climate Centre (BOM NCC) (Trewin, 2008)	Australian Region/SW Pacific	-30	-5	90	160	1907-2009	- Incorporates Lourensz (1981) and Coleman (1971) data	x	✓
BoM Database (Lourensz, 1981)	Australian Region/SW Pacific	-32	-5	105	165	1909-1980	- BoM	x	x
BoM Database (Coleman, 1971)	Australian Region/SW Pacific	-30	-5	105	165	1909-1969	- BoM	x	x
Woodside Energy, Ltd (WEL) (Harper et al., 2008)	Australian Region	-30	-5	90	160	1969-2001	- BoM and TCWC Wellington	x	x
New Zealand Meteorological Service (Kerr, 1976)	SW Pacific	-30	0	150	-150	1939-1969	- New Zealand Meteorological Service - BoM - Met services of: New Caledonia, Fiji, French Polynesia and Western Samoa	x	x

Table 2. Changes in TC observational technologies from 1940 (adapted from Chu et al. 2002)

1940	1950	1960	1970	1980	1990	2000	2010
Ship Logs and Land Observations							
Transmitted Ship and Land Observations							
Radiosonde Network							
Military Aircraft Reconnaissance							
	Research Aircraft Reconnaissance						
	Radar Network						
		Meteorological Satellites					
			Satellite Cloud-Tracked and Water Vapor-Tracked Wind				
					SSM/I & QuikSCAT Wind, MODIS		
			Omega and GPS Dropsondes				
			Databuoys				
				SST Analysis			
			Dvorak Technique				
DOD TC Documentation published (ARK, ATCR)							
			McIDAS and other interactive systems (AFOS, ATCF, AWIPS and MIDAS etc..)				

Table 3. Checklist of environmental parameters for five randomly selected TCs from the Callaghan and Power (2011) dataset. Suitable environmental conditions include, anomalously negative 700-hPa vorticity, cyclonic 700-hPa winds and negative 700-hPa geopotential height. Absolute value of <=10 m s^{-1} has been applied to Absolute Wind Shear variable as per (Nolan and McGauley 2012).

Event # (as per Callaghan and Power 2011)	Event # (for the purposes of Identification in this analysis)	Landfalling Event Date (as per Callaghan and Power 2011)	Event Name (as per Callaghan and Power 2011)	SPEArTC: Date and Location of Cyclogenesis	Negative 700hPa Vorticity	Cyclonic 700hPa Winds	Wind Shear (EVWS) <=10 m s^{-1}	Negative 700-hPa GPH	Number of variables suited to TC genesis
26	1	02/3/1949 or 03/3/1949	-	26/02/1949 14.0°S, 156.0°E	✓		✓		2
27	2	11/03/1950	-	05/03/1950 13.1°S, 146.2°E		✓			2
29	3	7/03/1955	-	01/03/1955 12.9 °S, 157.54°E	✓	✓	✓	✓	4
40	4	01/02/1986	TC Winifred	28/01/1986 12.5°S, 144.5°E	✓	✓	✓	✓	4
41	5	04/04/1989	TC Aivu	29/03/1989 11.4°S, 158.2°E	✓	✓	✓		3
% of Time Conditions were climatologically suitable					80%	80%	80%	60%	

Table 4. Average annual and seasonal TC frequency for JTWC, IBTrACS and SPEArTC database from 1945-2011.

		JTWC		IBTrACS		SPEArTC	
		Total number of TCs	Average number of TCs/year	Total number of TCs	Average number of TCs/year	Total number of TCs	Average number of TCs/year
1945-2011	Annual	753	11.2	815	12.2	844	12.6
	NDJ	303	4.5	337	5.0	350	5.2
	FMA	414	6.2	438	6.5	456	6.8

Table 5. Checklist of variables representing the environmental conditions conducive to tropical cyclogenesis for each cyclone ID #. See plots summarising geophysical parameters (Figures 5-7) for highlighted events. Suitable anomaly conditions are listed in the respective headers (calculated using 1981-2010 climatology from 20CR (Compo et al., 2011)). Ticks indicate if these conditions were present in the vicinity of TC genesis. X indicates conditions were not present in the vicinity of TC genesis and were therefore less favourable.

Cyclone TC #	Date	Latitude	Longitude	Anomalously Negative 700-hPa Vorticity	Anomalously Cyclonic 700-hPa Winds	Absolute Wind Shear (EVWS) <=10 m s^{-1}	Anomalously Negative 700-hPa GPH
1	1-Jan-1968	-15.4	162.99	X	X	✓	X
2	23-Jan-1968	-27.43	173.18	✓	✓	✓	✓
3	8-Feb-1968	-16.06	188.15	✓	✓	✓	✓
4	11-Feb-1968	-8.83	161.23	✓	✓	✓	✓
5	21-Feb-1968	-23.78	171.86	✓	✓	X	✓
6	20-Mar-1968	-20.3	177.8	✓	✓	X	✓
7	1-Dec-1980	-12.68	-174.01	✓	✓	✓	X

Table 6. Annual and seasonal mean SPEArTC TC counts according to pre-satellite (1945-1969), post-satellite (1970-2011) and post-geostationary satellite (1982-2011) era.

	Season	Mean SPEArTC Counts
1945-1969	Annual	12.2
	NDJ	5.1
	FMA	6.7
1970-2011	Annual	12.8
	NDJ	5.3
	FMA	6.9
1982-2011	Annual	12.0
	NDJ	4.8
	FMA	6.5

Table 7. List of Landfalling TCs used in the Callaghan and Power (2011) database from 1945.
Events have been crossed referenced with SPEArTC databases with the date and location of
TC genesis listed.

Event # (as per Callaghan and Power 2011)	Landfalling Event Date (as per Callaghan and Power 2011)	Event Name (as per Callaghan and Power 2011)	SPEArTC: Date and Location of TC Genesis
26	2/3 March 1949	-	26th February 1949 14.0°S, 156.0°E
27	11th March 1950	-	5th March 1950 13.1°S, 146.2°E
28	20th February 1954	-	12th February 1954 10.7°S, 177.7°E
29	7th March 1955	-	1st March 1955 12.9 °S, 157.54°E
30	6th March 1956	TC Agnes	24th February 1956 17.0 °S, 175.0°E
31	1st April 1958	-	31st March 1958 17.4 °S, 150.8°E
32	16th February 1959	TC Connie	11th February 1959 15.6°S, 152.56°E
33	28/30th January 1967	TC Dinah	22nd January 1967 11.9°S, 165.1°E

Table 8. p-values of Mann-Whitney U-Test and Generalised Linear Mixed Model (GLMM) on SPEArTC counts for pre-satellite, post-satellite and post-geostationary satellite eras (annual and seasonal).

	Mann-Whitney U-Test		Generalised Linear Mixed Model (GLMM)	
	1945-1969 versus 1970-2011	*1945-1981 versus 1982-2011*	*1945-1969 versus 1970-2011*	*1945-1981 versus 1982-2011*
Annual	0.34	0.34	0.62	0.23
NDJ	0.97	0.16	0.38	0.12
FMA	0.62	0.45	0.76	0.44

Figures
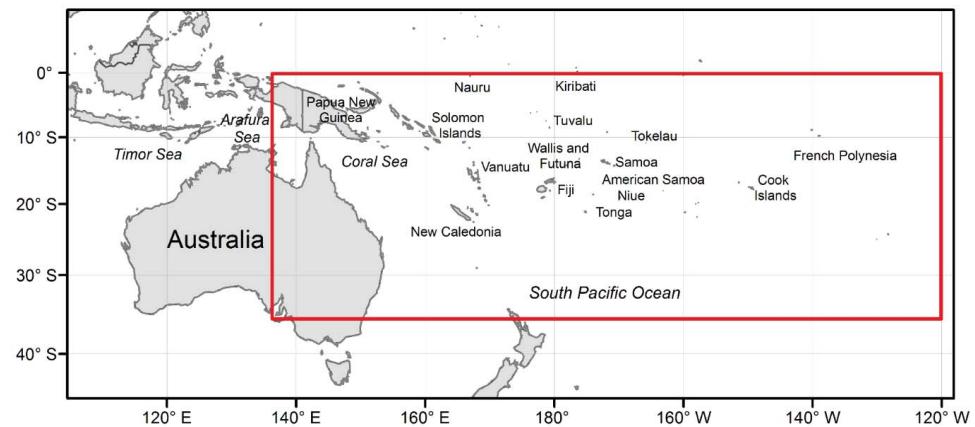
Figure 1. Study area of Southwest Pacific (SWP) (0°-35°S, 135°E-120°W).
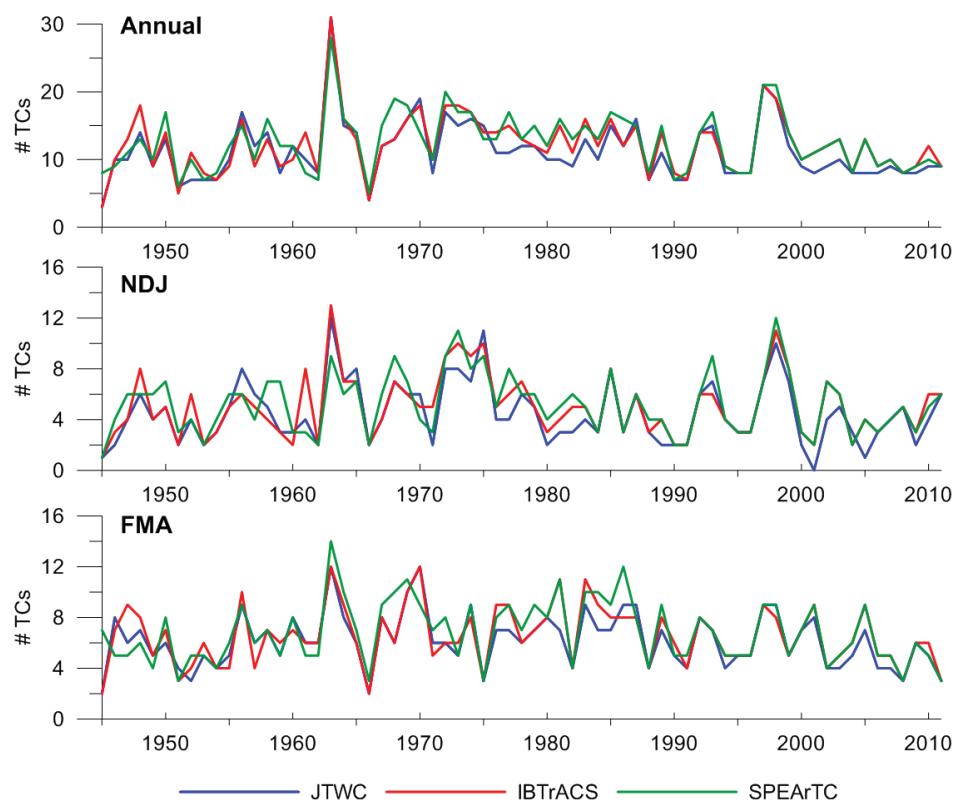
Figure 2. Time series of annual and seasonal TC counts (1945-2011) for JTWC, IBTrACS and SPEArTC database.
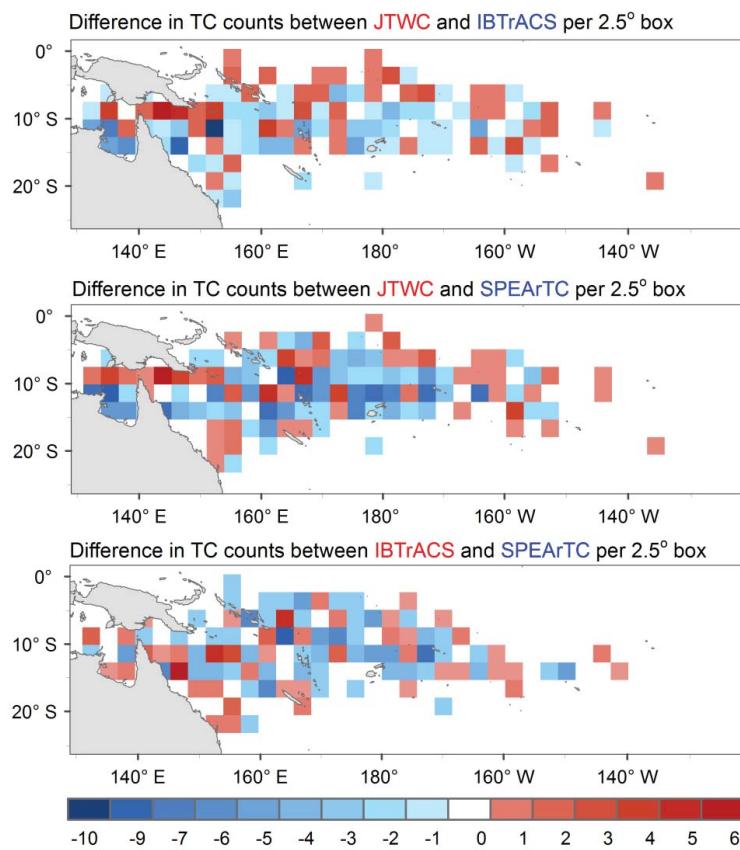
Figure 3. Difference (Total Annual TC counts) between various pairings of TC databases from 1945-2011.
Red (blue) values correspond to more TC counts in TC database named in red (blue).
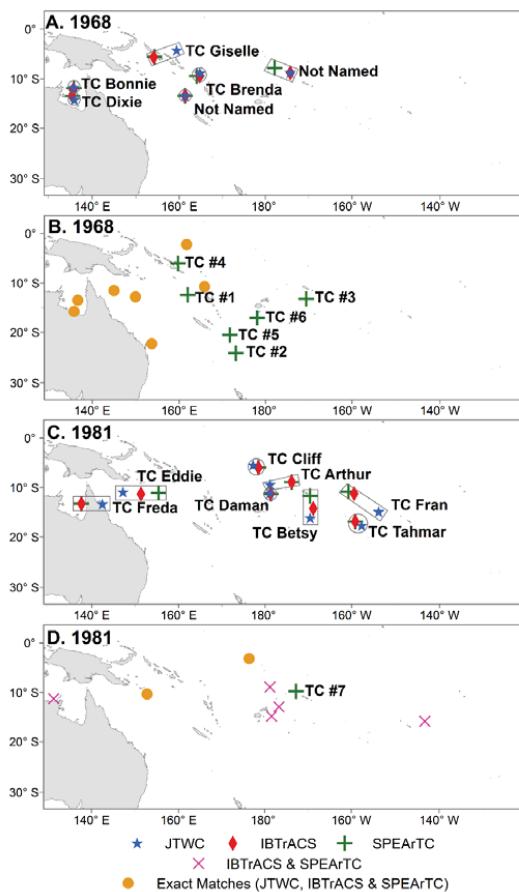
Figure 4. Cross-comparison of JTWC, IBTrACS and SPEArTC TC events for
two seasons; 1968 (Panel A and B) and 1981 (Panel C and D). Panel A and C plot
TCs that partially match across each database (conflicting date, latitude and longitude).
Panel B and D plot TCs that are exact matches across all three BT products and unique
TC events that do not feature in any of the other databases.
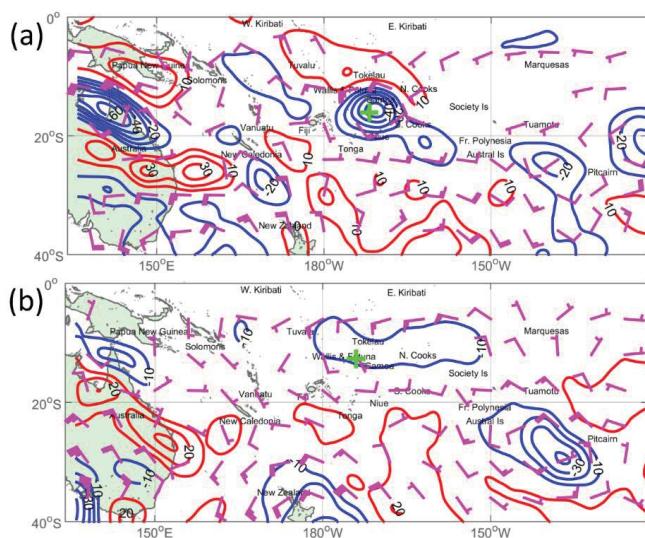
Figure 5. Vorticity -Wind Plots for TC #3, 1968 (panel A) and TC#7, 1981 (panel B).

Anomalies of vorticity (10 sec $^{-1}$ 10^{-6} contours) - blue - negative; red - positive; zero contour

omitted; 700-hPa U- and V-winds (5-kt contour barbs). Based on 1981-2010 climatology

from 20th Century Reanalysis (Compo et al., 2011). Green marker indicates point of cyclogenesis.
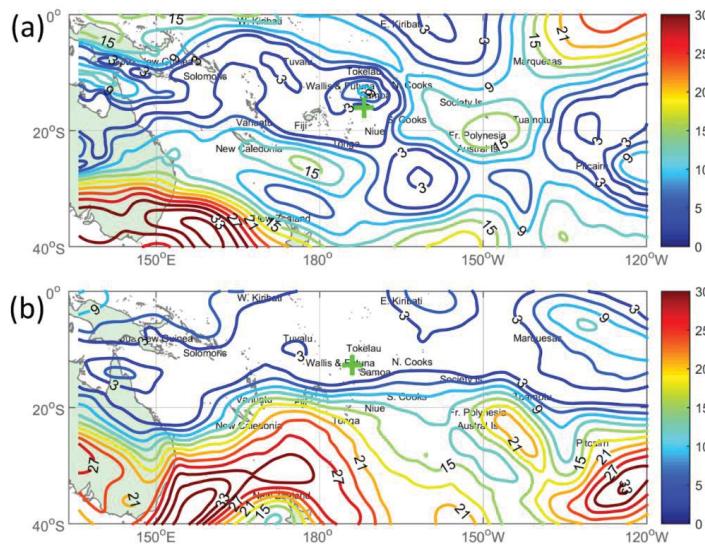
Figure 6. Absolute wind shear values (3 m/s^{-1} contours) for TC #3, 1968 (panel A)
and TC#7 (panel B) using 20th Century Reanalysis (Compo et al., 2011). Green
marker indicates points of cyclogenesis.
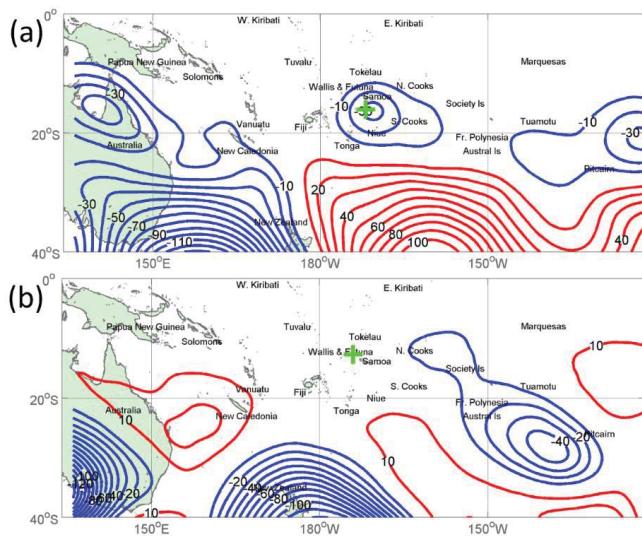
Figure 7. GPH for TC #3, 1968 (panel A) and TC #7, 1981 (panel B). Anomalies of

Geopotential Height (10 gpm contours) - blue - negative; red - positive; zero contour

omitted. Based on 1981-2010 climatology from 20th Century Reanalysis (Compo et al., 2011).

Green marker indicates point of cyclogenesis.
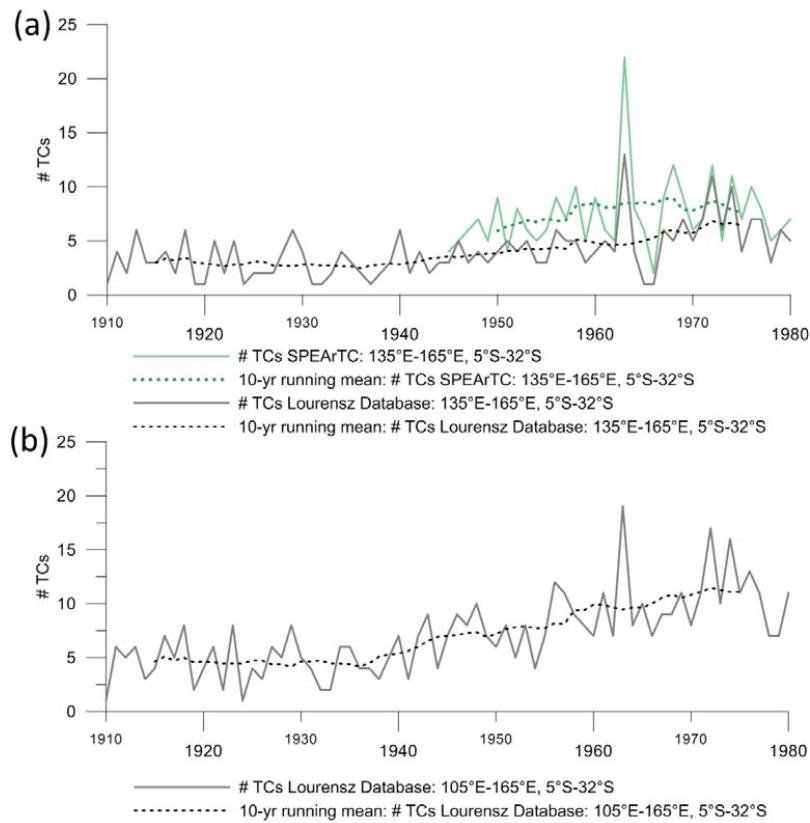
Figure 8. Panel A: SPEArTC and Lourensz (Lourensz, 1977, 1981) Time series of annual TC counts
for SPEArTC (1945-1980) and Lourensz (Lourensz, 1977, 1981) (1910-1980) TC database between
135°E-165°E, 5°s-32°s. Panel B: Time series of annual TC counts for Lourensz database between
105°W-165°W, 5°S-32°S (1910-1980). Solid lines indicate observed TC counts. Dashed lines
represents 10-year running mean.
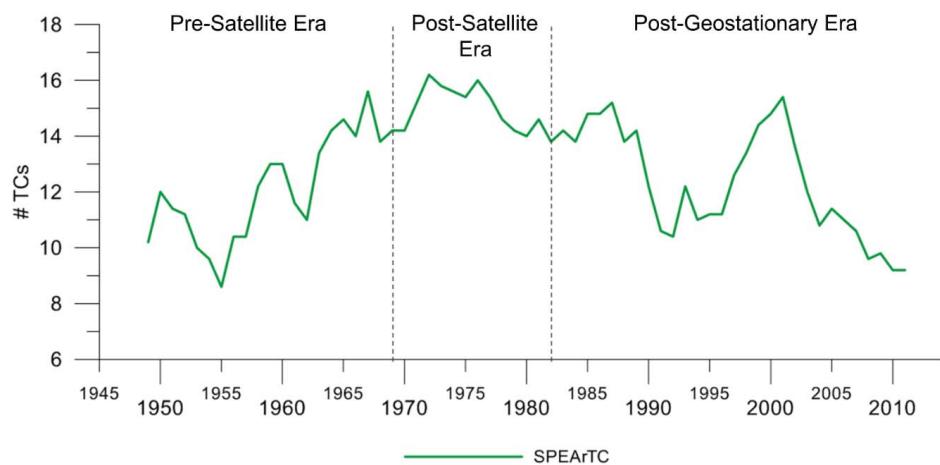
Figure 9. 5-year running mean time series of TC frequency for SPEArTC between 1945-2011.
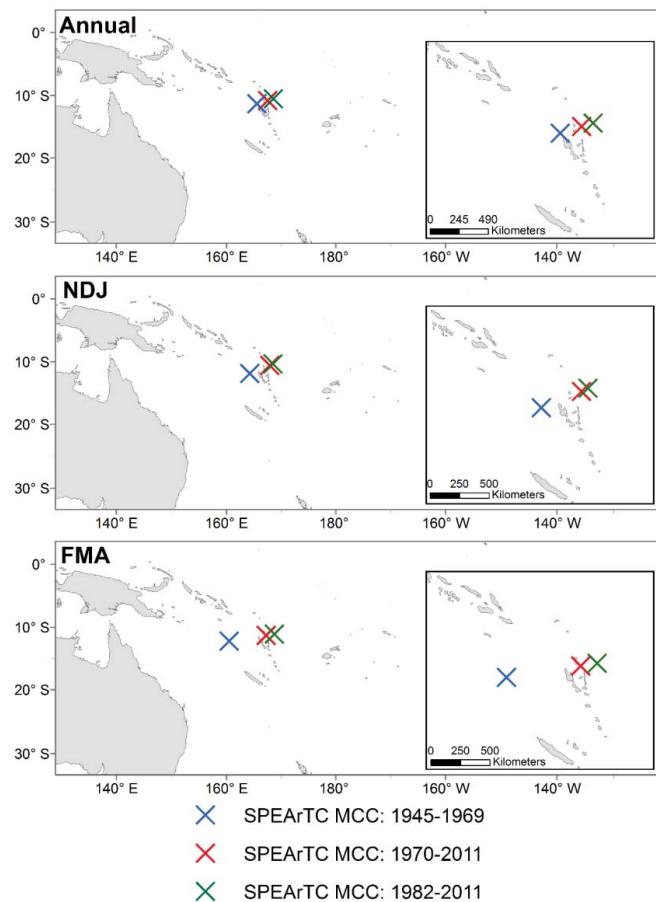
Figure 10. Annual and seasonal summary of the mean centre of cyclogenesis (MCC) for SPEArTC
during pre-satellite era (1945-1969), post-satellite era (1970-2011) and post-geostationary satellite
era (1982-2011).
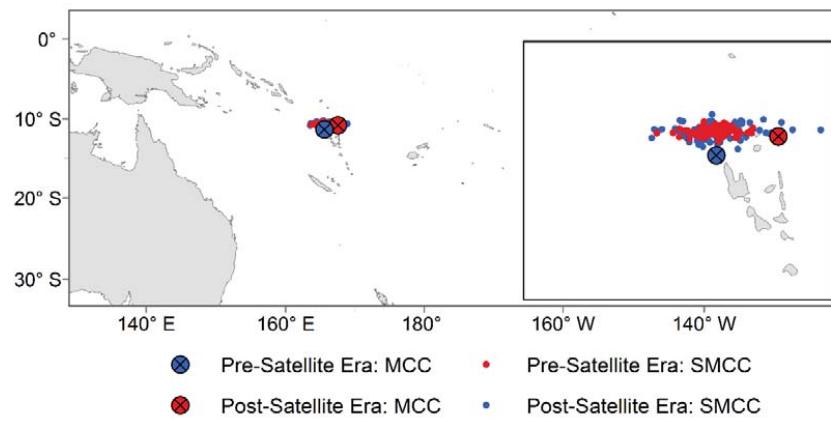
Figure 11. Comparison of pre-satellite (blue) and post-satellite (red) MCC for SPEArTC. Blue (red) points indicate the MCC for 200 random simulations of pre (post) satellite era TCs.