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To cite this article: Sarvesh Kumar *et al* 2025 *Environ. Res. Lett.* **20** 014039

ENVIRONMENTAL RESEARCH
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RECEIVED
14 October 2024

REVISED
18 November 2024

ACCEPTED FOR PUBLICATION
11 December 2024

PUBLISHED
20 December 2024

LETTER

An inter-comparison of tropical cyclone datasets for the Australian region

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Keywords: tropical cyclone datasets, Australian tropical cyclones, area of responsibility boundary limits, data inconsistency

Abstract

Tropical cyclone (TC) best track datasets have temporal inhomogeneity, mostly associated with changes in monitoring practices and technological improvements. Temporal inconsistencies are often mitigated by using TC data from more homogeneous periods. For example, TC records since 1980 are preferred for frequency and track analysis, while records for intensity analysis have become more consistent since ∼2000. However, such measures reduce the sample size for trend analysis, potentially leading to conflicting conclusions due to natural climate-variability. Inter-agency best track data can also vary, due to differences in the way best track information—such as centre fix locations and associated intensity estimates—are defined and assessed. When comparing global datasets and regional datasets, additional inconsistencies can be introduced where TCs form or track just outside the official area of responsibility for each agency. We highlight discrepancies in Australian TC best track data from various sources by comparing it to a more rigorously scrutinized dataset compiled by the Australian Bureau of Meteorology. This dataset is found to have highly accurate TC records for the Australian region. We also highlight the implications of data differences on TC-related trend analysis, aiming to increase awareness of dataset inconsistencies while guiding credible climate-change detection and attribution messages.

1. Introduction

Tropical cyclone (TC) datasets are a key tool for climate risk analysis, with considerable socio-economic implications. There are long-standing questions around consistency, reliability, and accuracy of historical TC records (Harper *et al* 2008, Chand *et al* 2019, Courtney *et al* 2021, Bell *et al* 2022, Kim *et al* 2022), despite considerable technological and methodological advancement in monitoring and recording of TC events globally over the past several decades (Klotzbach *et al* 2022, Holbach *et al* 2023, Sheng and Hong 2023, Qian *et al* 2024). However, even with these technology improvements, inconsistencies between different datasets remain (e.g. Kim *et al* 2022 and Li *et al* 2024), largely due to the way best track data are compiled and analysed by independent agencies: these data are prepared at the end of each TC season using the best-available observations and analysis methods at the time. Therefore, careful consideration must be given to each dataset when comparing TC metrics, particularly when region-specific sources are evaluated against global databases. Our emphasis here is on the assessment and evaluation of Australian region TC datasets produced by different agencies.

The first summary record of TCs over Australia was created for the period 1779–1922 by Visher (1922). Subsequent studies led to the compilation and reappraisal of TC records for the period up to the 1970s (Lourensz 1981). Holland (1981) was the first to assess the quality and consistency of the

Australian TC database for the period 1909–1979 and found that TC data before the 1960s were largely inconsistent and incomplete due to lack of surface observations and monitoring. Satellite sensing commenced in the early 1960s, and became technologically more advanced thereafter, leading to vast improvements in the way TCs were imaged and tracked (Ramsay 2017). However, lack of objective methodologies for estimating TC intensities from satellite data constrained the quality of TC intensity data estimates prior to the 1970s. Consequently, studies that utilised updated region-specific databases for climate-related trend analysis focussed only on data from 1970 onwards (Harper *et al* 2008, Hassim and Walsh 2008, Ramsay *et al* 2008, Dowdy and Kuleshov 2012, Dowdy *et al* 2012) whereas those that utilised globally-homogenised databases typically considered data from 1980 onwards (Wu *et al* 2015, Bhatia *et al* 2019, Kossin *et al* 2020, Bell *et al* 2022).

The two most widely used TC datasets for the Australian region are the region-specific Australian Tropical Cyclone Database (hereafter, ATCD) and the globally used dataset, the Joint Typhoon Warning Center (JTWC) database. The ATCD best track dataset is comprehensively compiled by the Australian Bureau of Meteorology with records of TCs covering its area of responsibility south of the equator and between 90°E and 160°E (Australian Bureau of Meteorology 2011). Extra data for systems either moving into or out of the Australian region may be included in the ATCD. This data could be determined by the Australian Bureau of Meteorology or provided by other agencies such as Nadi (Fiji) or Wellington (New Zealand) Tropical Cyclone Warning Centres from the east of 160°E. From the west of 90°E, La Reunion (Meteo-France) may contribute the best track data and Jakarta (Indonesia) or Port Moresby (PNG) may contribute TC best track information from the north of the Australian region (see World Meteorological Organization (2020) for details on Regional Specialized Meteorological Centres (RSMC) and Tropical Cyclone Warning Centres). On the other hand, the JTWC database (Jan-Hwa Chu *et al* 2002) consists of best track data compiled independently by the United States Naval Meteorology and Oceanography Command covering the Western Pacific Ocean, Northern Indian Ocean, Southern Indian Ocean and South Pacific Ocean. Initially established in 1959 to provide reliable information about cyclones to U.S. military operations in its area of responsibility, the JTWC now also provides cyclone warnings to governments such as Guam, the Federated State of Micronesia, and the Marshall Islands. Other warning centres within their area of responsibility often consider JTWC warnings to prepare their advisories (Guard *et al* 1992).

The ATCD includes complete maximum sustained wind speeds since the adoption of the Dvorak Technique in 1972 with the earlier years being completed upon later reanalysis. Since its development in the 1970s after the advent of geostationary meteorological satellite monitoring, the Dvorak technique has become an important operational tool for forecasters. It primarily utilises satellite imageries to identify cloud patterns that act as proxies of TC intensities (Dvorak 1984). An important difference that exists between various agencies is the use of different wind averaging periods to define 'sustained wind speeds'. For example, ATCD employs a 10-minute wind averaging period to populate the windspeed field while JTWC uses a 1 min averaging period. Though 1 min winds are sufficiently reliable for capturing shorter variations such as turbulence in the natural winds, 10 min winds have a better representation of the background mean windspeed given the longer averaging periods (Harper *et al* 2010). Substantial discrepancies can arise in the estimates of the common denominators between the two datasets, particularly owing to the ways best track information is compiled and assessed by their respective agencies including, but not limited to, the use of different definitions of sustained wind speeds (Knapp and Kruk 2010, Levinson *et al* 2010, Mohapatra *et al* 2012). For example, Li *et al* (2024), using data from the China Meteorological Administration (a regional dataset) and JTWC, found that while there were good correlations between wind radii in the two datasets, there were still discrepancies related to TC sizes and locations. It is also well known that TC peak intensity estimates in the Japanese Meteorological Agency (JMA) best track dataset tend to be systematically lower than those in the JTWC dataset (Ramsay 2017), especially for major TCs (Knapp and Kruk 2010, Schreck *et al* 2014), even when adjusting for the different wind averaging periods. Shimada *et al* (2024) compared CyclObs data (a French TC database) with JTWC data and found a mean absolute difference of $\sim$6.7 m s^{-1} in maximum winds between the two datasets. Similarly, Kim *et al* (2022) found discrepancies in wind radii values of up to 38% when comparing regional datasets from the Korea Meteorological Administration, RSMC Tokyo and JTWC.

Recent ongoing efforts by the Australian Bureau of Meteorology have enhanced the quality of the ATCD dataset in the context of improved satellite monitoring technology, observational coverage, scientific developments, best track procedures, and subjective variations between analysts across time and agency (Courtney *et al* 2021). These efforts produced good results in terms of adding data and rectifying errors in the ATCD. Therefore, we assess the JTWC dataset (and other sources) against the ATCD to identify differences and potential inconsistencies. As an example of the inconsistency, we present the case of TC Madge (March 1973). The location of the lifetime maximum intensity (LMI) for TC Madge (March 1973) differs substantially between the ATCD and JTWC datasets (as indicated by the red asterisk for the ATCD and the black asterisk for JTWC in figure 1). A closer examination indicated that there were no wind data in the JTWC dataset for the second half of this system. However, the JTWC lowest surface pressure fields match ATCD peak intensity. The early JTWC pressure data do not match the corresponding winds suggesting a possible input error in the JTWC dataset. We also note that when comparing data from broader records (like JTWC) with those from region-specific sources (such as the ATCD), additional inconsistencies can be introduced by inadvertently including TCs from objectively-defined Australian region boundaries.

Our main objective here is to provide awareness of the limitations of various best track datasets and how these limitations can impact TC trend analysis for the Australian region. We anticipate that the information provided here can help consolidate conflicting climate-related studies that utilize different best track datasets, and hence help increase our confidence in climate change detection and attribution messages.

2. Data and definition

We analysed four different TC datasets:

- ATCD: The ATCD (Australian Bureau of Meteorology 2011) is a comprehensively compiled TC best track database specifically for the Australian region hosted by the Australian Bureau of Meteorology. This database has recently undergone a substantial update, as detailed in Courtney *et al* (2021), and is therefore used as a 'ground-truth' best track information for TCs in the Australian region. Therefore, it is highly recommended for all TC-related trend analyses for the Australian region.
- JTWC dataset: The JTWC best track dataset is independently compiled by the U.S. Naval Meteorology and Oceanography Command and is available for different TC basins worldwide. For our study, we sourced this dataset from the International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp *et al* 2010). Given some of the limitations mentioned in the introduction concerning JTWC regarding intensity and wind radii estimates, it is still the most highly used dataset for global TC analysis.
- Advanced Dvorak Technique—Hurricane Satellite dataset (hereafter, ADT-HURSAT): The ADT-HURSAT is a globally consistent, homogenized TC data record produced by Kossin *et al* (2020). The primary limitation of this dataset is that it is updated infrequently, unlike the more regularly updated ATCD and JTWC datasets. Nevertheless, the ADT-HURSAT dataset can increase confidence in projections of increased tropical cyclone intensity amid ongoing global warming (Kossin *et al* 2020).
- Objective Tropical Cyclone Reanalysis dataset (hereafter, OTCR): The OTCR dataset, archived by the Australian Bureau of Meteorology (2018), comprises of quality-controlled wind data from objective techniques including the ADT that have impacted Australia since 1981 and are used for the assessment of TC-related risks. While the primary limitation of OTCR is the absence of recent TC records, it nonetheless serves as a high-quality dataset for wind-related analysis in the Australian region.

For the Australian region, the four databases (from three sources) under consideration have TC records commencing at different points in time, even in the post-satellite era (figures 2(a)–(d)). This is mainly due to scattered and incomplete records of some key TC parameters (such as winds and pressure fields required to create TC fixes) in the early phases of satellite reconnaissance, leading to subjective decisions by monitoring agencies—and independent studies that produced homogenised data—around what may constitute the 'best' starting period.

Three key parameters are extracted for each TC track from all data sources: fixes of TC track locations, the associated time, and maximum sustained wind speeds. We homogenised the wind speeds from the different datasets to 10 min sustained .values (in m s^{-1}), using a conversion factor of 0.88 (Harper et al 2008) for datasets that had records measured on a 1 min sustained baseline. We objectively defined a system as a TC when the 10 min sustained wind speed reached at least 17.5 m s^{-1} at some point in its lifetime and was identified as a 'tropical storm' or 'tropical cyclone' in the 'storm-type' field of the datasets. We define the Australian region as the region between 90° and 160° E longitude and south of the equator (figure 1). Extratropical systems are excluded by a latitude cutoff at 30°S for genesis and transition. Systems that formed inside the defined boundary and eventually exited, or those that formed outside and eventually moved into the defined region, have been included. A cyclone season is defined here as the period between July 1 of the first year to June 30 of the following year. For instance, the 2011 season would be the period between July 2010 to June 2011. We only consider data for the post-satellite era covering the period from 1970 to 2022. The ADT-HURSAT and OTCR data are available for the periods 1980–2016 and 1978–2017, respectively. All TCs are categorized according to the Australian Bureau of Meteorology classification scheme (Australian Bureau of Meteorology 2022).

3. Results and discussion

3.1. Wind and pressure data

Some common fields between the ATCD and the JTWC datasets are the TC name/identifier, location,

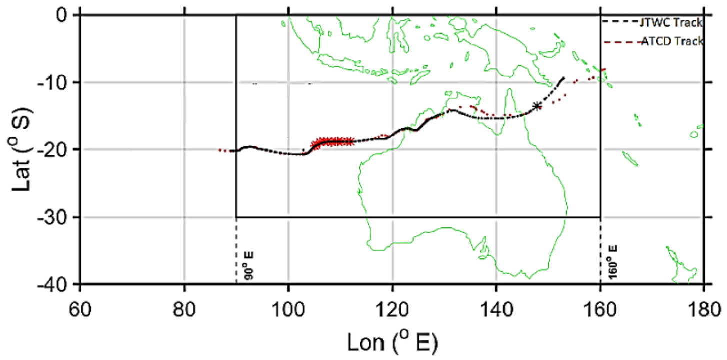

Figure 1. The Australian boundary considered for this study (90–160°E and 0–30°S) and TC Madge (March 1973). Asterisks (**) indicate the locations of maximum intensity.

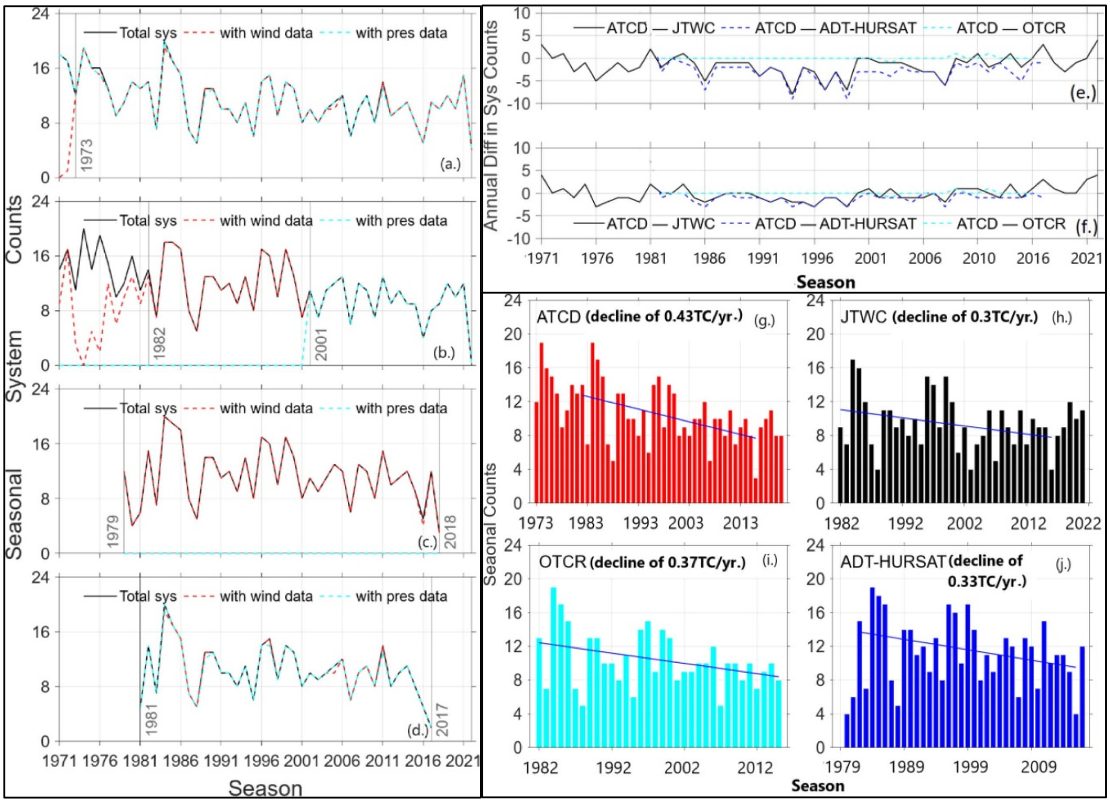

Figure 2. Comparisons of wind and pressure data post-1970 for (**a**) ATCD, (**b**) JTWC, (**c**) ADT-HURSAT, and (d) OTCR. The figure also depicts the total number of systems recorded in different datasets for each season (systems are where the definitions of a TC is not applied and include everything in the dataset such as depressions and other low pressure areas). There is increased consistency noted following the initial epochs indicated by vertical lines for wind and pressure data. Residual of annual counts across different datasets with respect to the ATCD data (e) without and (f) with the inclusion of systems with at least 50% of its lifetime in the Australian region. (g–j) Seasonal TC counts from different datasets based on the objective definition of TC discussed in the methods section; x-scales of the graph vary because the data from years of consistent wind speed recordings are used for each dataset.

maximum sustained wind speeds, minimum central pressure, system type and wind radii for different thresholds available on a 6 hourly basis. An important difference that we note in all four datasets is the year when the common parameters, especially windspeed and pressure fields, become available (figures 2(a)–(d)). As noted earlier, the ATCD includes complete maximum sustained wind speeds since the adoption of the Dvorak Technique in 1972 (figure 2(a)). Earlier records of wind fields can be found in the JTWC dataset but there are questions regarding its completeness. More consistent records can be seen to emerge from the early 1980s (figure 2(b)).

The ATCD includes records of pressure data since the early 1900s, and while the data is more complete since the 1940s (figure 2(a)), it is not considered homogeneous (Courtney *et al* 2021). In contrast, JTWC began recording pressure data more recently in the early 2000s (figure 2(b)). Sporadic records of the wind radii (not shown) can be found from the mid-1970s in the ATCD but became more comprehensive with quadrant values at gale, storm and hurricane force thresholds from the early 2000s (Courtney *et al* 2021). Similarly, JTWC has records of wind radii (not shown) from the early 2000s. Since OTCR and ADT-HURSAT are homogenised, the wind and pressure fields are consistently available for nearly all TC records in each dataset, except for ADT-HURSAT which does not have pressure data (figures 2(c) and (d)).

3.2. TC numbers

The use of different historical periods of TC records for climate-related trend analysis may contribute to conflicting conclusions between studies. However, our concern is around ways in which the best track information is compiled and analysed by different agencies, potentially leading to missing records or inconsistent estimation of TC intensities. Indeed, when comparing system counts in the ATCD with other databases for the Australian region, we note discrepancies in the seasonal counts (figures 2(e) and (f). As an example, we first compared raw counts of systems in ATCD with those in global databases where Australian region systems were extracted by explicitly defining the cut-off boundaries between 90° and 160°E. We note substantial departures in annual counts between databases (RMSE = 2.4 and 3.2 for JTWC and ADT-HURSAT, respectively), especially for the 1994 and 1999 seasons where differences of 8 TCs are noted between the ATCD and the ADT-HURSAT data and a difference of 7 TCs between the ATCD and the JTWC data. (Figures 2(e) and (f). The ATCD includes records of TCs that occurred well within the Australian region, but at times does not have records for some TCs that formed and tracked around the peripheral boundaries. Some TCs were not included in the ATCD if they spent less than 50% of their lifetime within the Australian region (other thresholds, not shown, were also considered which showed similar results). On the other hand, filtering Australian region TCs from global databases by explicitly defining longitudinal boundary conditions (i.e. 90° and 160°E) often leads to inclusions of TCs that were otherwise not present in the ATCD. Therefore, by excluding TCs that formed around the boundaries and spent less than 50% of their lifetime in the Australian region, we find that comparisons between ATCD and global databases improve substantially (RMSE = 1.6 and 2.3 for JTWC and ADT-HURSAT, respectively) (figure 2(f)). TC trends also become more consistent between databases (figures 2(g) and (j). This analysis provides insight into the methods used for monitoring the spatial movement of TCs by different agencies that often consider systems that are only within their area of responsibility. The monitoring then stops as the system moves out of its area of responsibility. This may have implications for the calculation of TC metrics used in climate-related trend analysis, especially when users prefer to utilise global datasets to analyse regional-scale trends. There are also instances of systems having multiple tracks identified as 'mains' and 'spurs' in the JTWC database as sourced from IBTrACS. Similarly, we note 'draft' tracks in the ATCD datasets for some intense systems (from 2019 onwards), which at the time of this analysis, were yet to be classified into storm types. This necessitates manual interventions from the users to minimize major discrepancies in TC-related metrics derived from different datasets.

3.3. TC intensity

We also note substantial discrepancies in TC intensity estimates between databases, and in particular, the classification of TCs into different intensity categories (figure 3). The most widely used approach for estimating TC intensities is the Dvorak technique (Dvorak 1984). Since its development in the 1970s, after the advent of geostationary meteorological satellite monitoring, the Dvorak technique has become an important operational tool for forecasters. It primarily uses satellite imagery to identify cloud patterns that act as proxies for TC intensity. However, this technique is highly subjective as it relies on expert analyses of cloud features and organisation under the assumption that storms with similar intensities have similar cloud patterns. The ATCD has 10 min sustained wind speed estimates derived from the Dvorak technique for the Australian region, whereas the JTWC and ADT-HURSAT databases have 1 min sustained wind speed estimates. As highlighted in the Methods section, we have converted all the 1 min wind speeds to corresponding 10 min wind speed values using a factor of 0.88 for ease-of-comparison. By objectively comparing maximum sustained wind speeds for each TC in the different databases, we identify several misclassification cases for different categories of TCs in global databases, particularly in the early period of the records (figures 3(a)–(d)). The maximum sustained TC wind speeds in the JTWC database are generally underestimated compared to the ATCD (figure 3(b)), though the absolute differences are mostly not statistically significant (at the 95% significance level, figure 3(e)). Nonetheless, differences in these intensity estimates can lead to substantial discrepancies in quantised counts for severe and non-severe TCs (i.e. severe TCs in the Australian region are those above Category 3 with intensities > 65knots; Chand *et al* 2019). Our results here are consistent with the findings

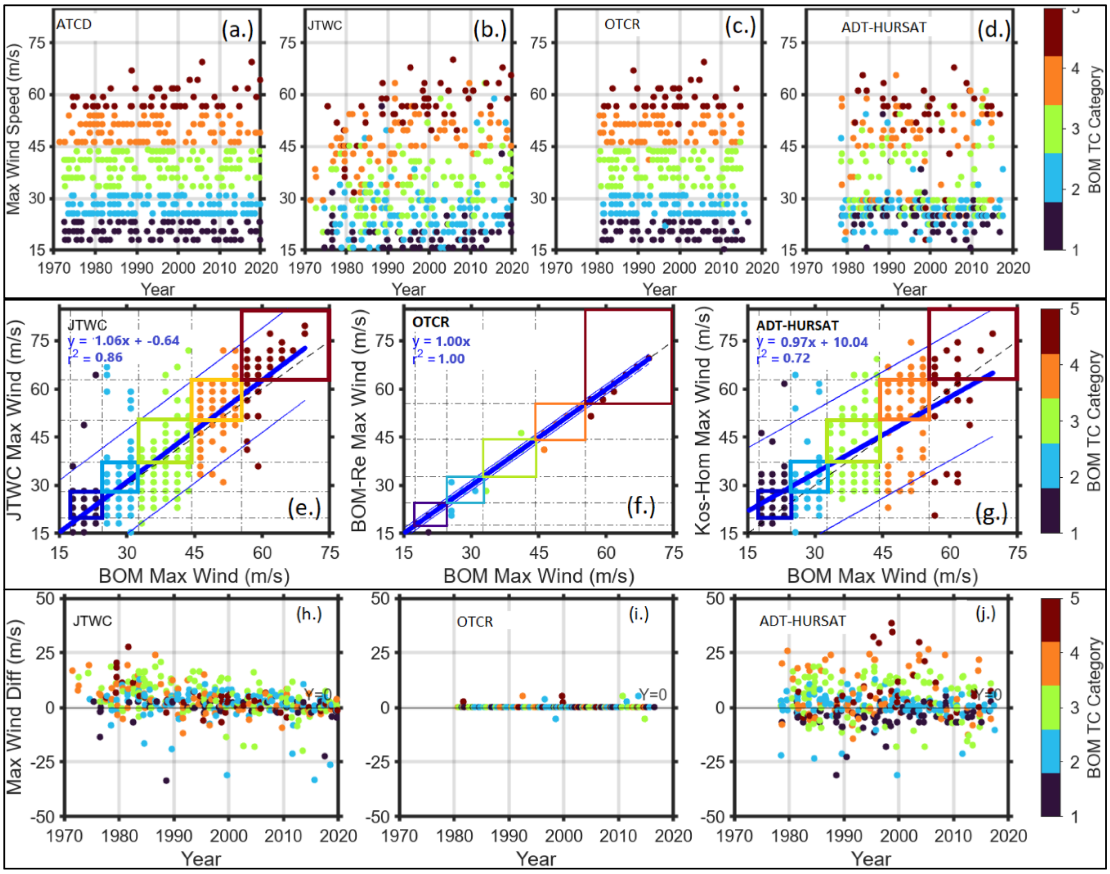

Figure 3. (a)–(d) Scatter plots of TC lifetime maximum intensity (LMI) vs. Year of different datasets, binned into Australian Bureau of Meteorology TC intensity categories (colours). (e)–(g) Scatter plots illustrating the relationship between raw LMI (in native sustained wind speed values converted to m s^{-1}) of: (e) JTWC, (f) OTCR, and (g) ADT-HURSAT, vs. ATCD. The thick blue line indicates the linear best-fit line while the thin blue lines indicate the 95% confidence bound. (h)–(j) Scatter plots showing differences in the LMI relative to the ATCD LMI (ATCD—Others) vs. Year for: (h) JTWC, (i) OTCR, and (j) ADT-HURSAT. All analyses are in 10 min sustained wind values unless specified otherwise.

of Schreck *et al* (2014) for the Australian region who showed similar inconsistencies, especially for Category 3 and 4 TCs. Similar discrepancies are noted between the ATCD and the ADT-HURSAT dataset (figure 3(g)). We do not find any discrepancy between ATCD and OTCR (figure 3(f)). The OTCR dataset is based on the Advanced Devorak Technique from Cooperative Institute for Meteorological Satellite Studies (Australian Bureau of Meteorology 2018) which underwent rigorous quality control. Therefore, the correlation between OTCR and ATCD further verify the homogeneity of ATCD over time. Noting the rigorous review the ATCD has gone through, we emphasize that users of JTWC and ADT-HURSAT datasets must take caution when using such datasets for regional-scale TC trend analysis.

3.4. Latitude of LMI and TC days

While there are a few cases of mismatch in the latitude of LMI between datasets, there is generally a good agreement between datasets for this metric (figures 4(a)–(c)). However, this correlation does not translate to similar trends in seasonal LMI latitude. Figure 4(d) highlights that there is a mismatch in the seasonal average trend of LMI latitude. While global datasets indicate a poleward trend in LMI latitude (e.g. Kossin *et al* 2014), regional data indicates a very slight, though statistically insignificant, movement equatorward. The total TC days of individual systems (figures 5(a)–(c)) derived from the four datasets appear to be well-correlated. However, there are instances where certain long-lived systems in the JTWC and the ADT-HURSAT databases are recorded as short-lived systems in ATCD (figures 5(a) and (c)). We identified that this was due to the peripheral boundary conditions where the Australian Bureau of Meteorology only monitors TCs within its area of responsibility. The complete tracks of TCs that extend from the Australian region to neighbouring regions are occasionally not recorded. As suggested earlier, the onus is then on users to gather other RSMC data for beyond Australian borders to make calculations consistent. Additionally, noticeable discrepancies are identified on seasonal timescales, even when the inclusion of TCs that spent at least 50% of their time in the Australian region for global datasets is considered. While the rate of decay in the TC lifetime (figures 5(d) and (e)) across all datasets is similar,

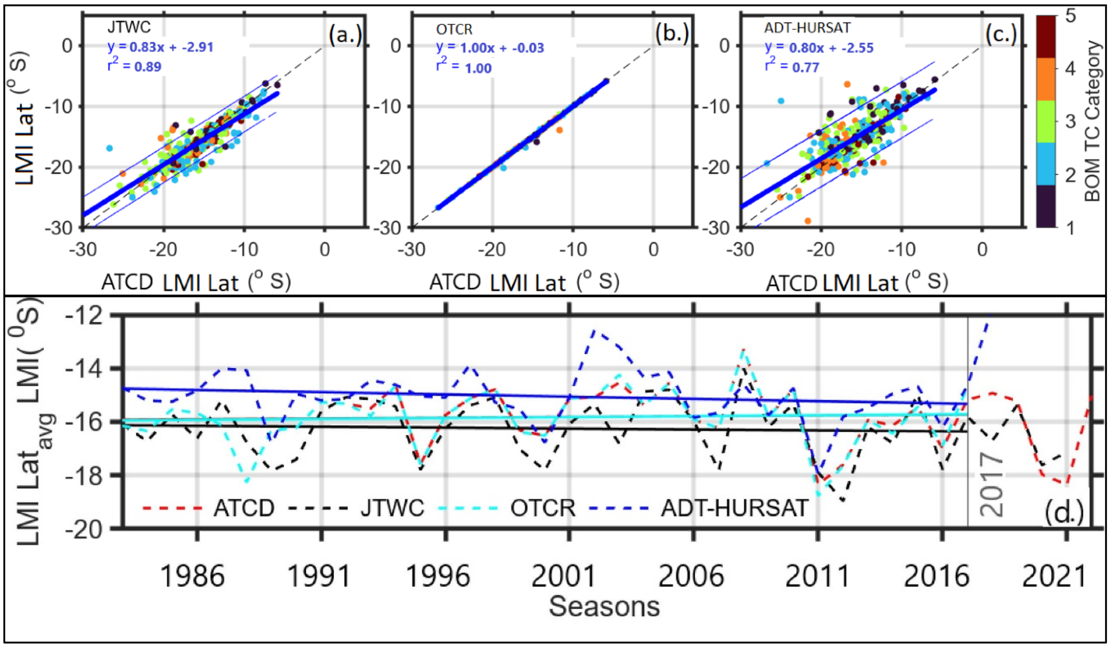

Figure 4. (a)–(d) Scatter plots of lifetime maximum intensity (LMI) latitude of individual TCs for (a) JTWC, (b) OTCR and (c) ADT-HURSAT vs the corresponding ATCD LMI latitude. (d) Time series of lifetime maximum intensity latitude from the four datasets. The linear trends in each data set are represented by solid lines of their respective colours.

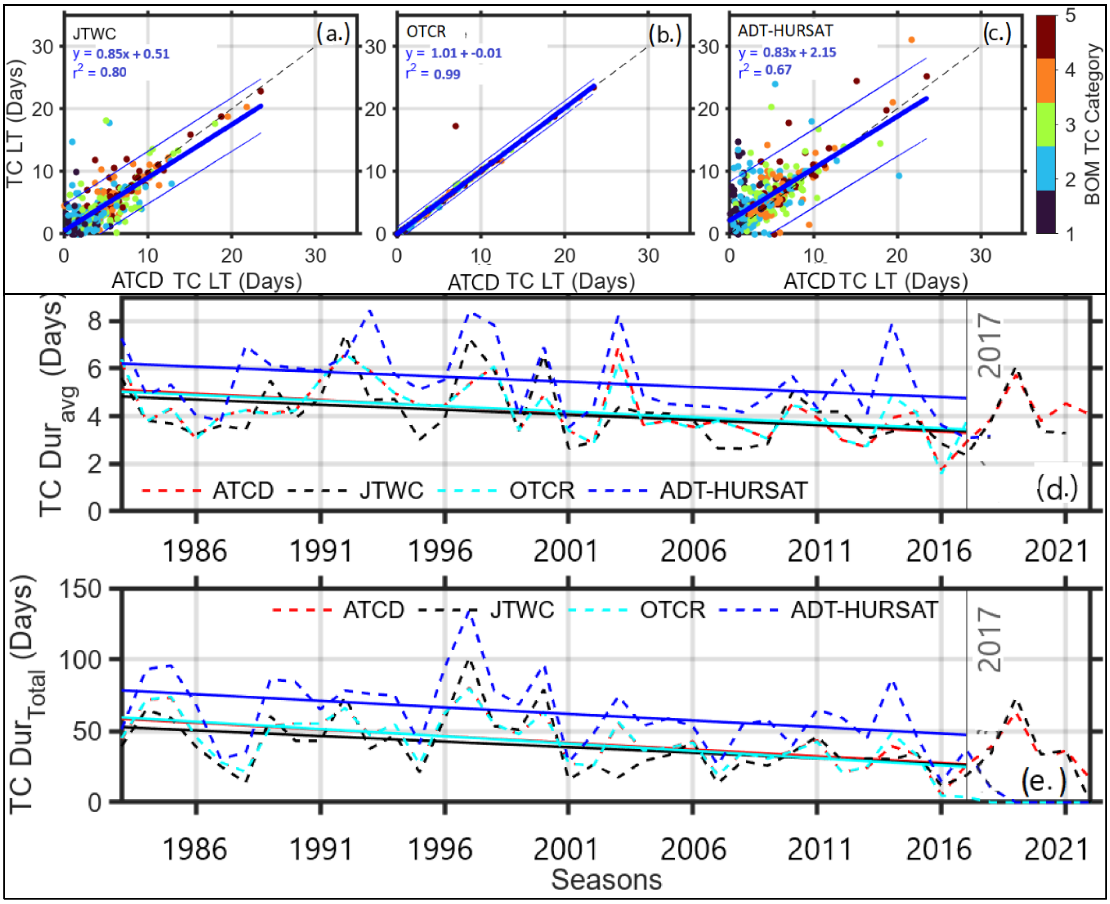

Figure 5. (a)–(c) Scatter plot of individual TC lifetime of (a) JTWC, (b) OTCR and (c) ADT-HURSAT vs corresponding ATCD TC lifetime. The thick blue line indicates the linear best-fit line while the thin blue line indicates a 95% confidence bound. (d), (e)Time series of (d) average TC lifetime/duration, (e) total TC lifetime/duration. The linear trends in each data set are represented by solid lines of their respective colours.

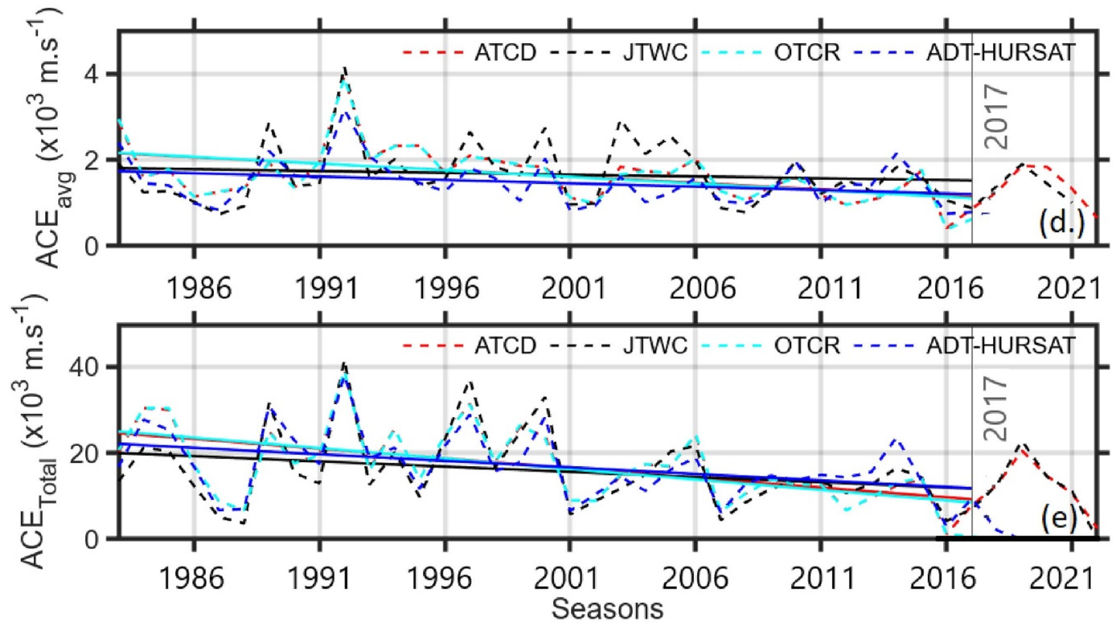

Figure 6. (a), (b) Time series of (a) seasonal average accumulated cyclone energy (ACE), i.e. ACE per storm and (b) total ACE. The solid lines show the linear trends of the data sets calculated for the overlapping years.

the ADT-HURSAT dataset shows significantly longer-lasting TCs (e.g. Kossin 2018) compared to other records. There are also instances where total TC days in JTWC relative to ATDC and OTCR data are notably different, especially during the earlier period (i.e. before 2000). Total TC days have become more consistent between datasets since 2004.

3.5. Accumulated cyclone energy

Finally, we derived Accumulated Cyclone Energy (ACE, figures 6(a) and (b)) to examine its temporal consistency across datasets produced by different agencies. The trends in the time series are in good agreement for both the seasonal average and the seasonal total ACE index. However, there are noticeable discrepancies for individual years between the Australian Bureau of Meteorology and the global datasets, particularly for the seasonally-averaged ACE index. This is due to the discrepancies noted earlier in individual TC components that comprise ACE such as mismatches in TC frequencies, under/overestimation of wind intensity, differences in TC days and peripheral boundary conditions around which regional monitoring agencies operate.

4. Conclusion

Our study has highlighted that while Australian regional data (ATCD and OTCR) sets appear to be more consistent, care must be exercised when using other datasets (such as the JTWC) for the Australian region TC studies. The results of this study indicate that although substantial agreements exist in key TC metrics compiled by different agencies, particularly in recent years, there are still data inconsistencies that create differences in trend analysis between regional (e.g. ATCD and OTCR) and global datasets (e.g. JTWC and ADT-HURSAT). In particular, regional monitoring area restrictions by local agencies, the use of native wind speed values, and objective definitions around both geographical boundaries and TC categorizations can potentially contribute to these disagreements. When comparing regional datasets with global datasets, careful consideration must be given to these factors and if needed, extra data from neighbouring agencies must be considered for complete TC tracks in regional datasets. We recommend that future studies carry out similar verifications for other regions and ultimately adopt a global verification task. Integrating other TC datasets that were not considered in this study for more comprehensive analysis is also suggested. To the users of TC datasets, these findings highlight the need for careful manual intervention. Although global datasets are considerably more consistent since ∼2000, addressing inconsistencies for the earlier period is crucial for enhancing the reliability and comparability of TC datasets across agencies and regions to build confidence in climate-related trend analysis.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: www.bom.gov.au/cyclone/tropical-cyclone-knowledge-centre/databases/; www.ncei.noaa.gov/products/international-best-track-archive; www.pnas.org/doi/abs/10.1073/pnas.1920849117#supplementary-materials.

Acknowledgments

We want to thank the reviewers for their helpful comments and suggestions. We would also like to acknowledge the support of Gallagher Re through the Gallagher Research Centre Global Tropical Cyclone Consortium. HR acknowledges funding support from the Climate Systems Hub of the Australian Government's National Environmental Science Program (NESP). We also acknowledge the contribution of Dr Samuel S. Bell for conducting a thorough recheck of the paper before final submission.

Conflict of interest

The authors declare no conflict of interest.

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