CORRESPONDENCE

Comments on "Estimation of Tropical Cyclone Wind Hazard for Darwin: Comparison with Two Other Locations and the Australian Wind-Loading Code"

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ABSTRACT

Cook and Nicholls recently argued in this journal that the city of Darwin (Northern Territory), Australia, should be located in wind region D rather than in the current region C in the Australian/New Zealand Standard AS/NZS 1170.2 wind actions standard, in which region D has significantly higher risk. These comments critically examine the methods used by Cook and Nicholls and find serious flaws in them, sufficient to invalidate their conclusions. Specific flaws include 1) invalid assumptions in their analysis method, including that cyclones are assumed to be at the maximum intensity along their entire path across the sampling circle even after they have crossed extensive land areas; 2) a lack of verification that the simulated cyclone tracks are consistent with the known climatological data and in particular that the annual rate of simulated cyclones at each station greatly exceeds the numbers recorded for the entire Australian region; and 3) the apparent omission of key cyclones when comparing the risk at Darwin with two other locations. It is shown here that the number of cyclones that have affected Port Hedland (Western Australia), a site in Australia's region D, greatly exceeds the number that have influenced Darwin over the same period for any chosen threshold of intensity. Analysis of the recorded gusts from anemometers at Port Hedland and Darwin that is presented here further supports this result. On the basis of this evidence, the authors conclude that Darwin's tropical cyclone wind risk is adequately described by its current location in region C.

1. Introduction

Tropical cyclone wind risk is incorporated into Australian building codes and standards by the Australian/New Zealand Standard AS/NZS 1170.2 wind actions standard (Standards Australia 2002), which divides the tropical cyclone–prone part of the coast into two regions.

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Region D defines the highest level of risk and covers that part of the west coast between latitudes 20° and 25°S, and region C defines a lower level of risk and covers the remainder of the coast from 27°S in the west to 25°S in the east, together with an additional region inland of region D. Cook and Nicholls (2009, henceforth CN09) recently argued that Darwin (Northern Territory), Australia, should not be included in region C as it is at present but rather should be in region D. Their arguments are based on a comparison of the risk at Darwin with that at two other centers in Australia, Port Hedland (Western Australia; in region D) and Townsville (Queensland; in region C), using three different techniques. Those techniques are

1) an analysis of a set of simulated synthetic tropical cyclone tracks from WindRiskTech LLC (WRT) that were prepared by the methods described in Emanuel et al. (2004, 2006a,b) and Emanuel (2006),
2) an analysis of the historical record of intense storms passing within 50 km of those locations dating from the earliest European settlement, and
3) an analysis of the historical record of intense storms passing within 350 km of those locations since 1985.

We have carefully examined their analyses and find that they are without merit. For item 1, CN09 did not show that the WRT-simulated tracks were consistent with the known track climatological record in the Australian region. On the scant information supplied, the simulated tracks have substantial differences from the climatological record, and therefore conclusions drawn from the simulated tracks are without foundation. The analysis technique used by CN09 for items 2 and 3 has serious flaws, and their application of it to Port Hedland and Townsville appears to omit significant storms from the record, such that the relative risk at Darwin relative to those centers is inflated. In addition, we present evidence from anemometer records and from the historical record that supports the conclusion in AS/NZS 1170.2 that Darwin has a lower risk from tropical cyclone winds than does Port Hedland.

2. Data used

We use the same version of the historical "best track" database that CN09 did, containing data up to the 2006/07 season, and apply the same gust factor of 1.41 to convert the estimated intensities (in terms of the maximum 10-min mean wind) to 3-s gusts. Although we have some reservations about the use of this gust factor for estimating wind risk over land, since the rougher surface will imply a lower mean wind speed but higher gustiness than over ocean (e.g., Harper et al. 2008a), for consistency we adopt the same gust factor as was used in CN09. There is limited information available as to the accuracy of or any biases in the best-track data because of the lack of independent verifying data—by definition, the best track uses all data available at the time of analysis. The estimated minimum central pressure and peak winds in the best track inevitably contain random errors and possibly systematic biases as well, although the latter are unknown. One possible source of systematic bias is the maximum wind–central pressure relationship used, including the fact that different relationships were until recently used in the western, northern, and eastern Australian regions (Courtney and Knaff 2009). Changes in observational technology and analysis technique over time are further known sources of bias (McBride et al. 2006; Kossin et al. 2007; Knutson et al. 2010), with Harper et al. (2008b) suggesting an underestimation of intensity was likely in northwestern regions prior to 1980. Hence we advise against an uncritical use of the best-track data and recommend that their use be supplemented by the analysis of other data, including anemometer records.

We also utilize anemometer data collected by the Bureau of Meteorology at Darwin, Port Hedland, and Townsville and available from the National Climate Centre within the Bureau. Up until about the late 1980s, the instrument in use was the Dines pressure-tube anemometer with a clockwork chart recorder. From this time, the Bureau progressively changed over to electronically logged cup anemometers. The instruments in question are all located at airports near the coast and so are well exposed. The measurement height is 10 m. Both daily maximum gusts and 10-min mean winds at synoptic times are reported, of which we use the gust data.

3. Specific comments

a. *Historical evidence of the relative tropical cyclone activity at Darwin, Port Hedland, and Townsville*

Figure 1 shows the recorded peak gusts during each of the tropical cyclones that produced gusts of 15 m s^{-1} or more at Darwin and Port Hedland Airports, from the periods of 1960–2005 and 1958–2004, respectively. These values and the cyclone names for the Darwin data are listed in Table 1. The two anemometers have broadly similar exposure, anemometer types, and record duration. Although the anemometer type and recording method have changed with time, these changes have occurred at similar times and so it is reasonable to compare the two records. Even a casual inspection of these figures gives ample reason to doubt CN09's assertion that the risk is similar at these two locations.

Figure 2 presents an analysis of the data used in Fig. 1 in a simple ranked-frequency context. We estimate the return period R for any given intensity by

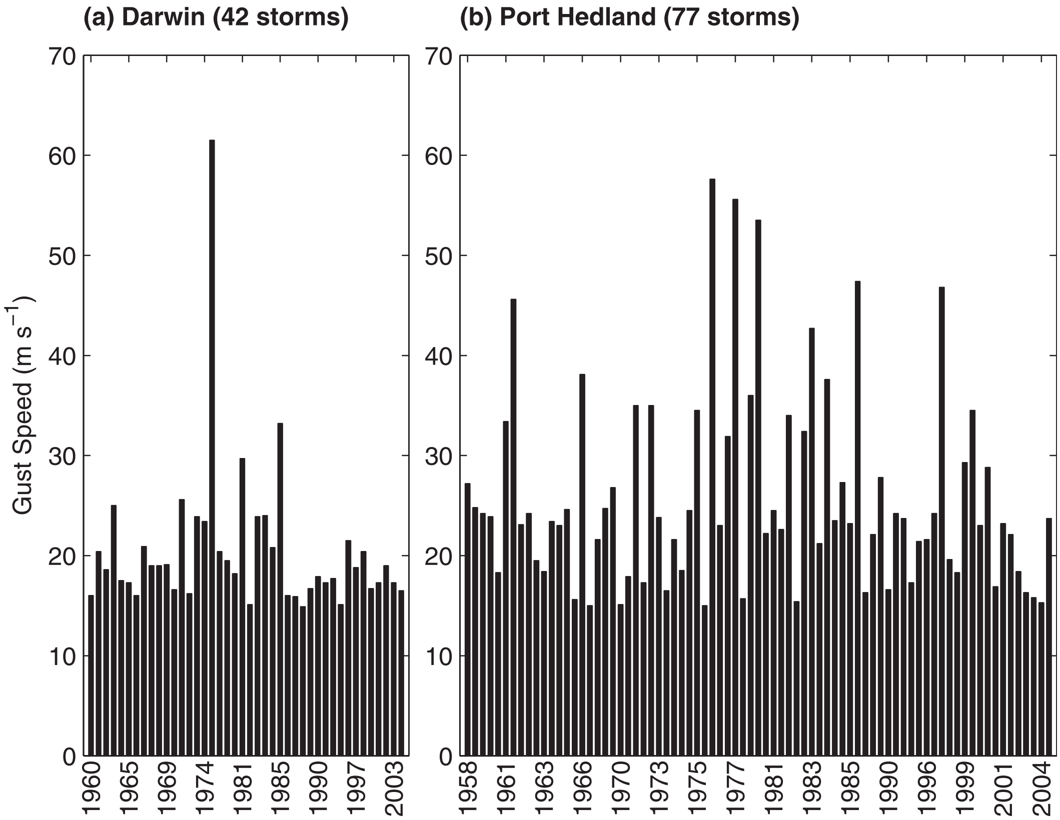

FIG. 1. Recorded maximum gusts exceeding 15 m s^{-1} from individual tropical cyclones at (a) Darwin Airport during 1960–2005 and (b) Port Hedland Airport during 1958–2004. The abscissa is the index number of each event but is labeled with the year of occurrence.

$$R = \frac{T}{m}\frac{n+1}{n}, \tag{1}$$

where T is the time period of the observations, m is the number of storms to exceed that intensity, and n is the total number of storms in the period. This formula follows, for example, from Makkonen's (2008) demonstration that the probability of exceeding the mth-ranked observation of n observations is $m/(n + 1)$, scaled by the annual occurrence frequency n/T. It is clear that Port Hedland experiences a significantly greater wind risk than does Darwin and that region-C wind criteria comfortably exceed Darwin's recorded winds. Tracy remains an outlier in this context at Darwin, but this does not preclude the possibility that it potentially represents a 1000-yr return period event.

A further indication of greater intense tropical cyclone activity at Port Hedland than at the other locations is provided by the central pressures in the historical record. Figure 3 displays the return period for cyclones exceeding a certain intensity (as measured by the estimated central pressure), within radii of 100 and 200 km of each location,[1] according to the historical record. The return period R for any given intensity is estimated using Eq. (1). Central pressures are used as the measure of intensity since the earlier part of the record does not include wind data. The beginning year was chosen to be either 1970 to cover the satellite era, during which it is generally accepted that no significant storms were missed, or 1985 to cover the period following the introduction of the modern infrared Dvorak technique (Dvorak 1984; Velden et al. 2006), prior to which intensity estimates are expected to have larger uncertainties. Note also that different maximum wind–central pressure relationships were used at the three centers (Courtney and Knaff 2009). Nevertheless, the figure shows that the return periods for Darwin and Townsville are very similar, with Darwin having the

[1] All distances are measured from the respective city centers, rounded to 1 min of latitude/longitude. The locations are Darwin: 12°26′S, 130°51′E; Port Hedland: 118°35′S, 20°19′E; and Townsville: 19°15′S, 146°49′E.

TABLE 1. Wind gust speeds of >15 m s^{-1} associated with tropical cyclones at Darwin Airport 1960–2006. Note that the value for Cyclone Tracy (1974) is based on the highest reading recorded before the anemometer failed. Boldface font highlights the outlier event Tracy and the three events that are depicted in Fig. 4.

Year	Name	Max gust (m s^{-1})
1960	Unnamed	16.1
1961	Unnamed	20.6
1964	Dora	18.1
1964	Carmen	25.3
1964	Flora	17.5
1965	Judy	17.5
1965	Marie	16.1
1965	Amanda or Giselle	21.1
1966	Unnamed	18.6
1968	Betty	18.6
1969	Audrey or Bonnie	18.9
1970	Beverley or Eva	16.1
1971	Kitty	25.8
1973	Bella	16.4
1973	Ines	24.2
1974	Selma	23.6
1974	**Tracy**	60.3
1978	Trudy	20.6
1980	Brian or Dean	19.7
1980	Felix	17.5
1981	Max	30.0
1981	Unnamed	15.3
1982	Bruno	24.2
1982	Esther	23.3
1985	Jacob	20.6
1985	Gretel	32.5
1986	Tiffany	16.1
1987	Kay	15.3
1988	Ilona	15.0
1989	Orson	16.4
1990	Marian	18.1
1992	Neville	17.5
1995	Bobby	17.5
1995	Chloe	15.3
1997	Rachel	21.7
1997	Sid	18.6
1998	**Thelma**	20.6
2000	Sam	16.4
2001	Alistair	17.5
2002	Bonnie	18.6
2003	Craig	17.5
2005	**Ingrid**	15.8
2006	**Monica**	16.5

slightly lower risk on this metric for storms within a radius of 100 km but not for storms within 200 km, for which the curves essentially coincide. Both panels show that Port Hedland has much shorter return periods at all intensities than do the other two locations and hence has higher risk of a storm occurrence within the given radius. These conclusions apply whether data from 1970 to 2007 (black curves) or from 1985 to 2007 (gray curves) are used, albeit with some quantitative differences that may reflect the small sample size. Note also that the return periods are approximately halved for the 200-km radius when compared with 100 km, as might be expected.[2] Similar calculations with other radii produced results that are consistent with this behavior.

b. *Comparison of anemometer data with CN09's simulation modeling*

Figure 3 in CN09 shows the predictions of gust wind speed versus return period from 1000 simulated tropical cyclones and comparison with those given for regions C and D in the wind actions standard (Standards Australia 2002). As noted by CN09 (p. 2333), the definition of ''return period'' in that standard is the reciprocal of the cumulative probability of exceedance of the expected maximum wind speed, accumulated *from all storms* in any one year. An alternative definition that gives nearly identical values is the average interval between upcrossings of the wind speed in question.

There is an extensive literature on methods of processing extreme wind speeds to make unbiased future estimates of wind speeds over long return periods. These may be applied directly to annual maximum wind speeds (e.g., Gumbel 1958; Whittingham 1964) or to data that are derived from independent storms (e.g., Cook 1982; Holmes and Moriarty 1999). These approaches are applicable to medium-to-large datasets, whether simulated or actual. CN09 did not consider any of these well-developed fitting approaches for the simulated data, however, instead opting in favor of a simple empirical upcrossing approach.

This decision has resulted in an unlikely discontinuous line for Darwin in CN09's Fig. 3 and the anomalous situation of two different wind speeds with the same return period (or probability of exceedance) for $R = 400$ yr. The discontinuities, for a single population, should not have occurred if a sufficient number of simulations had been used, and they may be characteristic of a mixed population.

The line for Port Hedland in CN09's Fig. 3 shows return periods of about 30 and 15 yr for gust speeds of 50 and 40 m s^{-1}, respectively. Our Fig. 2 indicates return periods of about one-half of these values for those wind speeds, however. Those values are consistent with our Fig. 1b, which indicates three crossings of 50 m s^{-1} in 46 years of record and seven crossings of 40 m s^{-1} in the same period. This result throws doubt on the consistency of the simulated data for Port Hedland with respect to

[2] This relationship is clearer at the lower return periods, for which the curves are less subject to sampling error.

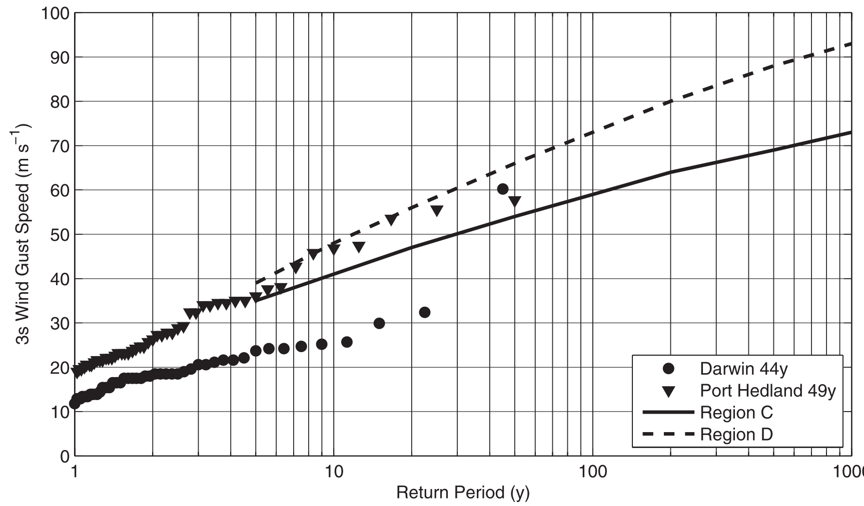

FIG. 2. Analysis of tropical cyclone maximum wind gusts observed at Port Hedland Airport and Darwin Airport in comparison with AS/NZ 1170.2 (2002) regional wind speeds.

the recorded history. The veracity of the simulated data is further considered in the next section.

c. *Lack of validation and inaccuracy of simulation modeling*

CN09 use the results of the WRT simulation (described in their section 3a) without first validating the model results. The accepted method for using tropical cyclone simulation models for risk assessment involves validation of all model components, including verifying that the statistical distributions of heading, distance of closest approach, central pressure, translation speed, and so on match the historic records. It is also critical that the wind field model used in the model is shown to be able to reproduce observed wind speeds—that is, given a track defined by central pressure, radius to maximum

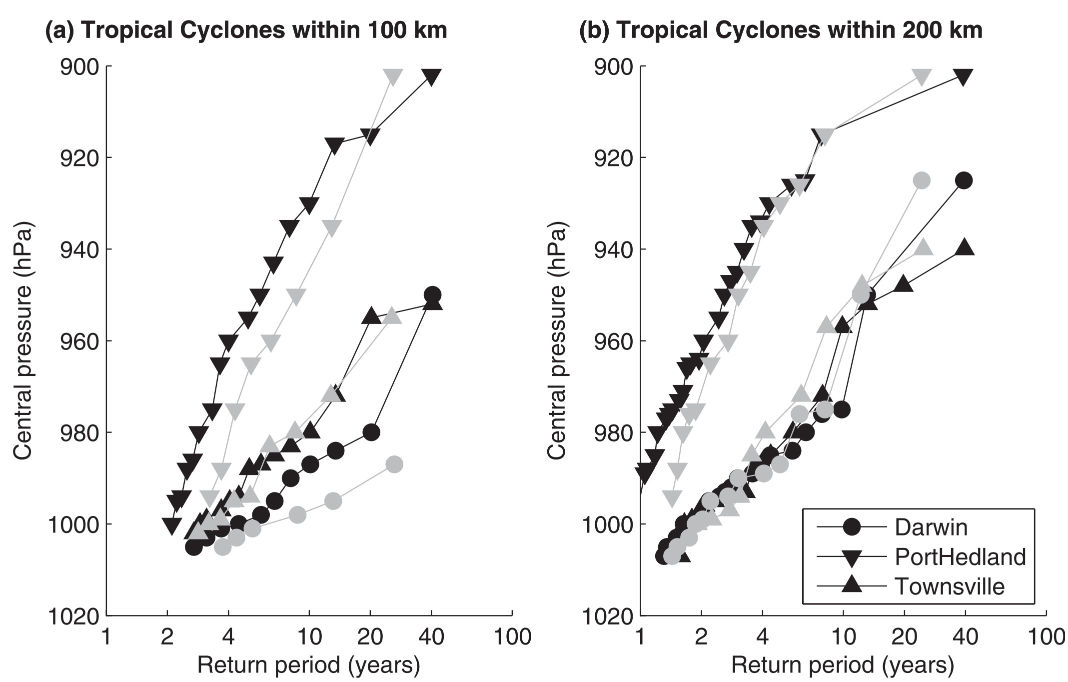

FIG. 3. Return period for cyclones within (a) 100 and (b) 200 km of Port Hedland (inverted triangles), Darwin (circles), and Townsville (triangles) that exceeded the given intensity, as measured by central pressure, during 1970–2007 (black) and 1985–2007 (gray), according to the historical record.

winds, and locations at given time intervals, the model should be able to reproduce observed wind speeds. Other key components that require validation include the decay of the tropical cyclone once it makes landfall and the relationships between storm size and intensity. The results of such validation must be presented, since they are important in enabling a scientifically sound interpretation of the simulation results. Examples of such validation exercises are described in Georgiou et al. (1983), Harper (1999), James and Mason (2005), and Vickery et al. (2009a,b,c), and Kepert (2006) points out that multivariate verification measures may be appropriate in some circumstances. A relatively limited set of verification statistics was presented for the WRT technique by Emanuel et al. (2004, 2006a,b) and Emanuel (2006). These statistics were all for the North Atlantic Ocean, however, and, while it might be hoped that the dynamically based components of this technique are more portable to other regions than a purely statistical scheme would be, the requirement for verification remains. The fact that CN09 do not demonstrate the validity of *any* portion of the cyclone simulation model in the Australian region therefore brings into doubt the usefulness of *all* of their results.

We further note that the simulation used by CN09 required 74 000–82 000 tropical cyclones to be simulated over 2700–3000 yr for each of Darwin, Port Hedland, and Townsville. Thus, more than 25 cyclones per annum were generated for each location. The historical record shows that the annual frequency of occurrences of tropical cyclones in the *entire Australian region* is about 12. We conclude, on the basis of the evidence supplied by CN09, that the simulation modeling cannot be correctly describing the climatological data record *anywhere* within the Australian region, including at Darwin, Port Hedland, and Townsville. Moreover, we see in our Figs. 1 and 2 that Port Hedland is affected by about two cyclones every year, in contrast to about one per year at Darwin. The simulation period required by CN09 to generate 1000 cyclones within 100 km of Port Hedland (3000 yr) was *greater* than that for Darwin (2700 yr), the opposite of what is observed in the instrumental record presented in our Figs. 2 and 3. In summary, the WRT simulation fails to reproduce the actual climatological data record on two simple tests. CN09 give such scant details of the WRT simulation that more comprehensive testing is not possible.

d. Return-period calculations from the historical record

CN09 estimate return periods for defined gust wind speeds from the recent historical record using their Eqs. (1)–(5). In this section we will, first, argue that their method has serious flaws that cause it to significantly overestimate the risk and, second, show that there is an error in their application of their method to the historical data at Port Hedland and Townsville. This error has the result that their Fig. 4b would severely misrepresent the relative risks at the three locations, even if their method were correct.

Equation (4) of CN09 was cited as obtained from the unrefereed Nicholls (2007) report, in which the worked examples show that it is apparently based on simple geometric probability principles. Note that, whereas that report describes the estimates as ''ballpark'' and the technique as ''grossly simplified,'' these appropriate cautions were not repeated by CN09. CN09 cite also Murnane (2000) in support of their Eq. (4), but we note that, although a similar equation appears in Murnane's (2000) model, CN09 omit much of that model. Their approach has some similarity to the methods used to predict tornado wind probabilities [such as by Twisdale and Dunn (1983)] but is seldom used for hurricanes and tropical cyclones for which more-sophisticated techniques have been proven to be necessary (e.g., Georgiou et al. 1983; Harper 1999; Vickery et al. 2000, 2009b). We note also that their Eq. (4) contains a constant 1, the units of which are not given, that appears in neither of their cited references and that will have the effect of increasing the estimated risk. We will assume that the units of this constant are kilometers, with the calculation not being highly sensitive to other reasonable choices.

CN09's Eq. (2) is better written in the form $R = (\lambda P_c P_s)^{-1}$, where λ is the annual frequency of cyclones entering the sampling radius, P_c is the probability of a given wind speed being exceeded anywhere in the event given the occurrence of a cyclone, and P_s is the probability of intersection of the band of maximum winds intersecting with a particular location within the circle. In either form, Eq. (2) assumes independence between the temporal and spatial probabilities, which may not be the case. Consequently, for all but the most intense storm, the form of CN09's Eqs. (1)–(5) effectively assumes that the radius to maximum winds R_{MW}, and hence the spatial probability P_s, for the more intense storms are the same as those of the storm being processed (i.e., the annual probability of exceedance is not correctly accumulated for the weaker storms).

The following assumptions are inherent in the geometrical arguments of Nicholls (2007) that were adopted by CN09, although they list only the latter two:

1) cyclones are at the maximum intensity experienced within the sampling circle along their entire path across the circle, including after they have crossed extensive land areas,

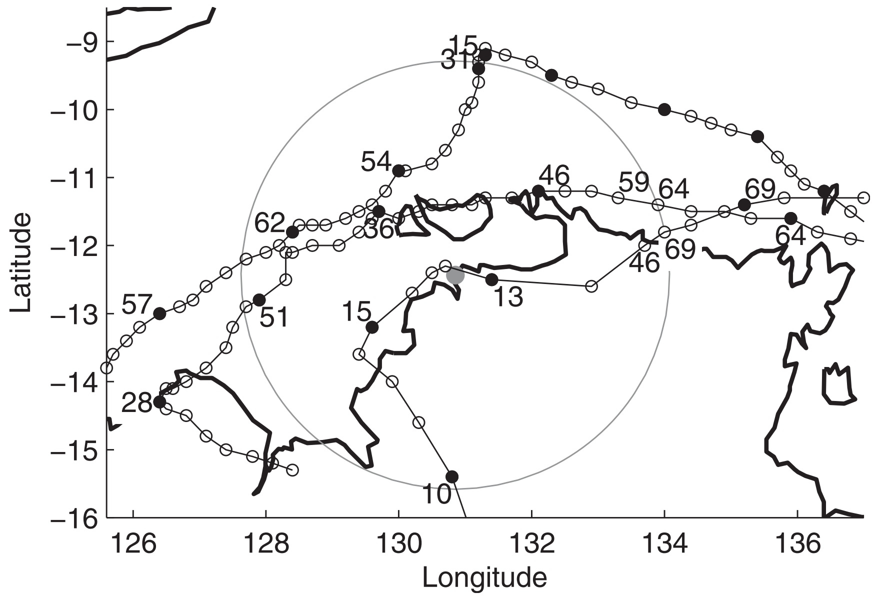

FIG. 4. Tracks of (from north to south) severe TCs Thelma, Ingrid, and Monica. The filled circles show the position at 0000 UTC, and the open circles are at 3- or 6-h intervals, depending on the data in the best-track database. The estimated intensity [maximum 10-min mean wind speeds (m s^{-1}) at 10-m height] are shown at 0000 UTC and at other times of particular interest. In each case the predominant cyclone movement is from east to west. Darwin is shown by the gray dot at the center of the circle, and that circle has a radius of 350 km. Data are from the Australian Bureau of Meteorology.

2) cyclone tracks are straight lines and may occur at any location within the sampling radius with equal probability,
3) the maximum gust wind speed is uniform anywhere within the radius of maximum winds but is zero elsewhere so that the horizontal wind field is effectively a step function, and
4) no account is taken of the forward motion of the cyclone on the predicted wind speeds.

Assumptions 1 and 2 are demonstrably false and have the effect of greatly increasing the estimated risk. For example, Fig. 4 shows the best-track estimated tracks and intensities (maximum 10-min mean wind at 10-m height) of Tropical Cyclones Thelma, Ingrid, and Monica. It is clear from Fig. 4 that the cyclone intensity varies significantly along the tracks. A major cause of such variation is landfall, leading to an immediate drop in the surface winds that is due to increased friction and a longer-term decay that is due to the loss of the oceanic heat source. The intensities ranged from 31 to 62, from 31 to 59, and from 10 to 69 m s^{-1} for the three cyclones while within the 350-km circle centered on Darwin used by CN09. Hence their first assumption, that of constant intensity, is invalid but will clearly inflate the estimated risk. The second assumption fails because it does not take into account the effect of land. Tracks over land will inevitably be less intense than those over sea—indeed, this is the main reason that Tropical Cyclone (TC) Monica rapidly weakened as it approached Darwin. CN09's method not only neglects the weakening of Monica but also assumes that storms identical to Thelma and Ingrid but displaced southward over land are as likely as the real Thelma and Ingrid. In reality, such a displacement would result in a substantially reduced intensity. The third assumption means that the winds from ''near misses,'' in which the location is close to the storm but is not within the radius to maximum winds, are not considered in determining the return period for these winds, which will have the effect of making the return-period curve too steep at lower wind speeds.

We now present our recalculation of CN09's Fig. 4b. We strongly emphasize that our presentation of this calculation should not in any way be regarded as an endorsement of their method. As discussed above, we consider their method to be fundamentally flawed. CN09's Fig. 4b could possibly mislead readers into thinking that their method has some validity, however, since it produces results that are in agreement with the wind-loading code for Port Hedland and Townsville. We will show that the return-period curves for Port Hedland and Townsville do not agree with those for regions D and C, respectively, contrary to CN09's computation. CN09's computation produces agreement only because they

TABLE 2. Data selected for the Darwin risk curve with $S = 350$ km, plus return period calculated using CN09 Eqs. (1)–(5).

Name	Season	V_{max} (m s^{-1})	V_{gust} (m s^{-1})	n	R (yr)
Monica	2005/06	69	98	1	746
Thelma	1998/99	62	87	2	303
Ingrid	2004/05	59	83	3	188
Neville	1991/92	44	62	4	92
Debbie	2003/04	33	47	5	55

apparently omitted some significant storms from their analysis, and therefore that apparent agreement should not be taken to support their approach. In fact, the disagreement that arises when all storms are included is further evidence that their method is flawed.

CN09 claim (section 3b, second paragraph, p. 2334) to use all storms after January 1985 with maximum gusts of >69 m s^{-1} for Darwin and Port Hedland and >36 m s^{-1} for Townsville—a statement that is clearly not correct, since their Fig. 4b curve for Darwin extends to V_{gust} well below 69 m s^{-1}. The calculations leading to their Fig. 4b are not much changed at the high-wind end by adding additional storms at the low-wind end, however, and therefore the precise cutoff used is not important. Because the aim is to compare the risk at the three centers, it is essential that the same cutoff be used for each. In the analysis here, the data selection is to use all storms from the 1985/86 to 2006/07 seasons with V_{max} of >30 m s^{-1} (10-min mean) at some time while they were within distance $S = 350$ km of the town in question. The storms selected for Darwin, Port Hedland, and Townsville are listed in Tables 2–4, respectively, in order of decreasing peak intensity, together with the associated return period calculated from CN09's Eqs. (1)–(5).

In calculating the return period, CN09 state that "maximum gust speeds were binned into three or more appropriate speed values and then Eqs. (1) and (5) were applied to produce the data points for comparison with the wind code's $V_{[gust]}$–R curves." Hence for a given gust speed, n in their Eq. (5) will be the number of storms in the selected set that equal or exceed that gust speed. Since these gust speed bins are arbitrary, we prefer instead to utilize the best-track V_{gust} as our thresholds or, equivalently, our Eq. (1) to calculate the return period. Because CN09's Fig. 4b is essentially a cumulative probability density function, this choice is appropriate. We have corrected also a further small error in their calculations, specifically that there are 22 cyclone seasons in the 1985/86–2006/07 period considered (or possibly 22.5 if you begin from 1 January 1985, as they do), but their example calculation for TC Monica (p. 2336) takes $T = 24$ yr.

The derived V_{gust}–R data in Tables 2–4 are plotted in Fig. 5a, together with the region-C and -D curves from the wind code. CN09's Fig. 4b is reproduced here as Fig. 5b to facilitate comparison. We note the following four features:

1) The curve for Darwin (circles) is similar to that in CN09, but those for Port Hedland (inverted triangles) and Townsville (triangles) are substantially above the corresponding curves in CN09.
2) The curve for Darwin is below that for Port Hedland at all return periods and below that for Townsville at short return periods.
3) The highest point on the curve for Port Hedland corresponds to TC Orson (Table 3), whereas that for

TABLE 3. As in Table 2, but for Port Hedland.

Name	Season	V_{max} (m s^{-1})	V_{gust} (m s^{-1})	n	R (yr)
Orson	1988/89	69	97	1	601
John	1999/2000	57	80		
Chris	2001/02	57	80		
George	2006/07	57	80	4	107
Annette	1994/95	54	76		
Bobby	1994/95	54	76		
Olivia	1995/96	54	76		
Glenda	2005/06	54	76		
Kara	2006/07	54	76	9	44
Fay	2003/04	51	72		
Monty	2003/04	51	72	11	33
Kirsty	1995/96	50	70		
Gwenda	1998/99	50	70	13	27
Elsie	1986/87	48	68		
Tiffany	1997/98	48	68		
Sam	2000/01	48	68	16	21
Ian	1991/92	46	65	17	19
Connie	1986/87	43	61	18	16
Jacob	1995/96	39	55		
Clare	2005/06	39	55	20	13
Ilona	1988/89	37	52	21	12
Naomi	1993/94	36	51		
Gertie	1995/96	36	51		
Rachel	1996/97	36	51		
Billy	1998/99	36	51	25	10
Daphne	1990/91	34	48	26	9
Norman	1999/00	31	44		
Steve	1999/2000	31	44		
Terri	2000/01	31	44	29	7

TABLE 4. As in Table 2, but for Townsville.

Name	Season	V_{max} (m s^{-1})	V_{gust} (m s^{-1})	n	R (yr)
Larry	2005/06	57	80	1	440
Aivu	1988/89	46	65		
Joy	1990/91	46	65	3	109
Steve	1999/00	42	59	4	73
Tessi	1999/00	39	55	5	54
Celeste	1995/96	36	51	6	41
Winifred	1985/86	35	49	7	34
Rona	1998/99	31	44	8	27

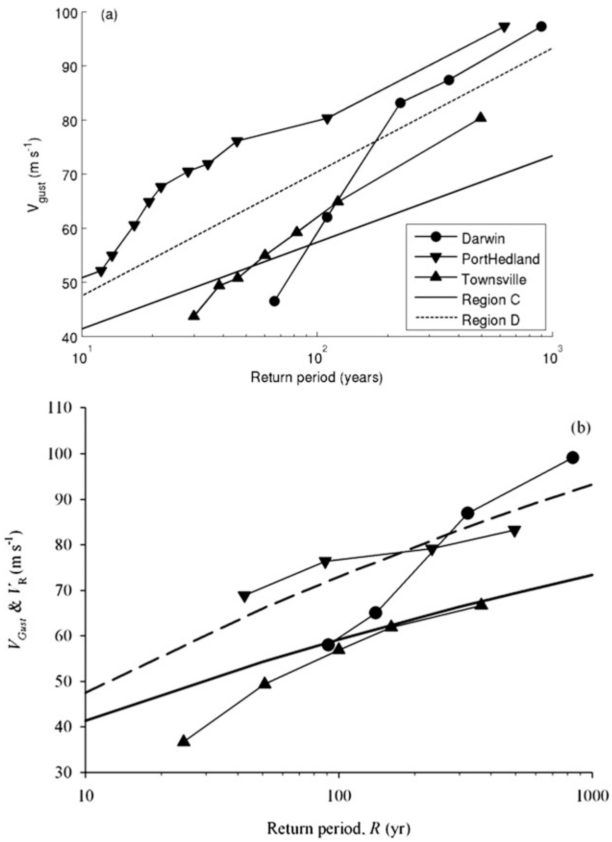

FIG. 5. (a) Curves of V_{gust} vs return period, calculated as described in the text, for Darwin (circles), Port Hedland (inverted triangles), and Townsville (triangles). The lines without symbols show the return periods according to the Australian wind actions standard for regions C (solid) and D (dotted or dashed). Note that our replotting of this graph does not constitute an endorsement of the technique used by CN09 to generate it, as discussed in the main text. (b) CN09's Fig. 4b, included for purposes of comparison. The curve for Darwin is similar to that in (a), but those for Port Hedland and Townsville indicate markedly lower risk.

Darwin corresponds to TC Monica (Table 2). In the historical database, these storms have the same peak intensity of 69 m s^{-1}. They correspond here to slightly different return periods because of the different R_{MW}s from CN09's Eq. (1).

4) The highest point on the Townsville curve corresponds to TC Larry (Table 4).

In comparing our Fig. 5a with CN09's Fig. 4b, it is apparent that their curves for Port Hedland and Townsville are missing (at least) the contribution of severe TCs Orson and Larry, respectively. Note that we use the same version of the best-track database as CN09 specified. They do not list the storms used for their calculations, and therefore it is unclear why these differences arise. On their page 2335, they note that "[a]llowance was made for the weakening from the maximum wind speed values to landfall values," although without giving further details. Possibly this adjustment could account for the discrepancy between our Fig. 5a and their Fig. 4b with the Port Hedland and Townsville curves, but, if so, it is then unclear why they did not make a similar adjustment to the Darwin data.

The presentation of these calculations should not be regarded as being in any way an endorsement of CN09's calculations of return periods. As noted above, their technique includes assumptions that inflate the risk and overestimate the slope of the return-period curve, consistent with the fact that the curves in our Fig. 5a lie well above the lines from the wind code at the higher wind speeds but have a steeper slope at lower wind speeds. Rather, the purpose is to demonstrate that CN09 have incorrectly applied their technique by apparently omitting the most severe storm(s) to have affected Port Hedland and Townsville, but not Darwin. The good match between the return periods for Port Hedland and region D, and Townsville and region C, in CN09's Fig. 4b should not be interpreted as implying that their method is valid for those locations. Rather, that agreement arose because of CN09's apparent neglect of some very significant storms in those regions. When those storms are included, the mismatch with the wind code provides further cause to doubt the validity of their method.

These calculations should also not be used to infer that the risk at the high-wind end of the scale is similar in Darwin and Port Hedland, although the uppermost points for these locations in Fig. 5a nearly coincide. This near coincidence is meaningless because of the flaws in CN09's method.

We would have liked to have presented similar checks of CN09's Fig. 4a, but their description of how the necessary wind speeds were obtained is too imprecise to enable us to do so. We note, however, that it uses the same method as CN09's Fig. 4b but applied to a different portion of the best-track database. The flaws we have identified in CN09's method therefore apply to their Fig. 4a also.

e. *Choice of sampling radius*

For the approach that is based on recorded cyclones from after 1984, CN09 chose a sampling radius S of 350 km. No justification for this choice is given, but it is clear that the return period R assigned from their Eq. (5) for each event will depend on this choice. We have repeated these calculations for other choices of S and found the sensitivity to be large. For example, reducing S from 350 to 340 km is sufficient to remove the intense prelandfall stage of TC Monica (see Fig. 4) from the calculation for Darwin, demoting that storm from the most intense to the third most intense, with the resulting return-period curve barely exceeding that for region D (not shown). We tested values of S ranging from 150 to 500 km for Darwin and found that none resulted in a markedly higher risk than $S = 350$ km.

4. Summary

Cook and Nicholls (2009) have argued that the wind risk from tropical cyclones at Darwin is similar to that at Port Hedland and is much greater than that at Townsville on the basis of their analyses of a set of simulated tracks and of the historical best-track data. We have closely examined each of their analyses and found substantial flaws in their approach, sufficient to invalidate their conclusions. We also present analyses of anemometer data and of the historical record that suggest that the risk at Darwin is substantially lower than that at Port Hedland.

The accepted method for using tropical cyclone simulation models for risk assessment involves validation of all model components. CN09 made no attempt to demonstrate the validity of *any* portion of the cyclone simulation model data that they used, which brings into doubt the validity of *all* of the wind speed results generated in this way. The very scant data they provide of the climatological characteristics of the simulations were shown to be substantially inconsistent with the recorded climatological data record. In particular, the simulation produces far too many storms in the Australian region and the frequency is slightly higher at Darwin than at Port Hedland whereas the historical record suggests that it should be about one-half that of Port Hedland.

CN09's analysis of the historical best-track data relies on several assumptions that are demonstrably incorrect, some of which were omitted from their paper. These assumptions generally have the effect of markedly overestimating the risk. In addition, their calculations of return-period curves for Port Hedland and Townsville apparently omitted some severe storms, such that their results incorrectly imply that their method is consistent with the wind-loading code for these locations. We have shown that consistent application of their method leads to results that are inconsistent with the wind-loading standard (Standards Australia 2002) at all three locations, providing further reason to doubt the validity of their method.

We presented anemometer data at Darwin and Port Hedland from since 1960 and 1958, respectively, that clearly show a much greater frequency of intense gusts at the latter site, and we analyzed these data to confirm that the risk is markedly lower at Darwin than at Port Hedland. We also presented an analysis of the estimated central pressure of cyclones passing close to Darwin, Townsville, and Port Hedland since 1970 that showed that the risk at Darwin and Townsville is very similar and is markedly less than that at Port Hedland. The relative risk according to these analyses is thus consistent with the provisions of the current Australian building codes and standards.

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