Objectively Determined Resolution-Dependent Threshold Criteria for the Detection of Tropical Cyclones in Climate Models and Reanalyses

K. J. E. Walsh

School of Earth Sciences, University of Melbourne, Melbourne, Australia

M. Fiorino*

Lawrence Livermore National Laboratory, Livermore, California

C. W. Landsea

NOAA/OAR/AOML/Hurricane Research Division, Miami, Florida

K. L. McInnes

CSIRO Marine and Atmospheric Research, and ACE CRC, Hobart, Australia

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ABSTRACT

Objectively derived resolution-dependent criteria are defined for the detection of tropical cyclones in model simulations and observationally based analyses. These criteria are derived from the wind profiles of observed tropical cyclones, averaged at various resolutions. Both an analytical wind profile model and two-dimensional observed wind analyses are used. The results show that the threshold wind speed of an observed tropical cyclone varies roughly linearly with resolution. The criteria derived here are compared to the numerous different criteria previously employed in climate model simulations. The resulting method provides a simple means of comparing climate model simulations and reanalyses.

1. Introduction

Global climate models (GCMs) are able to generate low pressure systems that have many of the observed characteristics of tropical cyclones. The early studies of Manabe et al. (1970), Bengtsson et al. (1982), Krishnamurti et al. (1989), Broccoli and Manabe (1990), Wu and Lau (1992), and Haarsma et al. (1993) were succeeded by finer-resolution simulations such as those of Bengtsson et al. (1995, 1996). More recently, a number of studies have been performed with various models demonstrating their capability to generate tropical cyclones (e.g., Walsh and Watterson 1997; Krishnamurti et al. 1998; Royer et al. 1998; Yoshimura et al. 1999; Vitart et al. 1999; Vitart and Anderson 2001; Nguyen and Walsh 2001; Tsutsui 2002; Sugi et al. 2002; Walsh et al. 2004; Camargo et al. 2005; McDonald et al. 2005; Oouchi et al. 2006). While there is little dispute that climate models can and do generate tropical cyclones, these studies have used different threshold criteria for deciding the cutoff between systems of tropical storm and tropical depression strength, which for observed storms in the eastern hemisphere is a 10-min wind speed of 17.5 m s^{-1} (39 mph) measured at a height of 10 m (1-min winds in the Western Hemisphere).

Table 1 summarizes the various detection criteria that have been used. Most schemes employ a wind speed threshold, for obvious reasons, and some also employ a vorticity threshold. The structural requirement that the storm be warm-cored is used to exclude midlatitude cyclones, as is a condition that low-level

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* Current affiliation: National Hurricane Center, Miami, Florida.

Corresponding author address: Kevin J. E. Walsh, School of Earth Sciences, University of Melbourne, Melbourne, 3010 Victoria, Australia.
E-mail: kevin.walsh@unimelb.edu.au

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TABLE 1. Minimum threshold detection criteria for tropical cyclones employed by modeling studies. Here, "V" refers to wind speed and "T" to temperature anomaly vs the surrounding environment, at the pressure levels (hPa).

Study	Model horizontal resolution (km)	Wind speed ($m\ s^{-1}$)	Vorticity (s^{-1})	Warm core temperature anomaly (K)	Structure or location	Duration (days)
Bengtsson et al. (1982)	~200	25 at 850 hPa	7×10^{-5} at 850 hPa	—	<30° latitude	—
Broccoli and Manabe (1990)	~300 (R30)	17 at surface	—	—	<30° latitude	—
Haarsma et al. (1993)	~300	—	3.5×10^{-5} at 850 hPa	$T250 > 0.5$ $T500 > -0.5$ $T250 - T850 > -1$	—	3
Bengtsson et al. (1995)	~125 (T106)	15	3.5×10^{-5} at 850 hPa	$T700 + T500 + T300 > 3$	$T300 > T850$ $V850 > V300$	1.5
Tsutsui and Kasahara (1996)	~300 (T42)	$V900 > 17.2$	Cyclonic at 900 hPa	Thickness criterion	$V200 < 10$	2
Walsh and Watterson (1997)	125	6 and 10 at 10 m (area average)	2.0×10^{-5} at 850 hPa	$T700 + T500 + T300 > 0$	$T300 > T850$ $V850 > V300$	2
Krishnamurti et al. (1998)	~300 (T42)	15 at 850 hPa	3.5×10^{-5} at 850 hPa	$T700 + T500 + T300 > 3$	$V850 > V300$	1
Vitart et al. (1997)	~300 (T42)	17	3.5×10^{-5} at 850 hPa	$T_{200-500} > 0.5$ Thickness criterion	—	2
Vitart et al. (1999)	~300 (T42)	17	3.5×10^{-5} at 850 hPa	$T_{200-500} > 0.5$ Thickness criterion	—	2
Walsh and Katzfey (2000)	125	5 at 10 m (area average)	1×10^{-5} at 850 hPa	$T700 + T500 + T300 > 0$	$T300 > T850$ $V850 > V300$	1
Vitart and Anderson (2001)	~300 (T42)	17	3.5×10^{-5} at 850 hPa	$T_{200-500} > 0.5$ Thickness criterion	—	2
Nguyen and Walsh (2001)	125	5 at 10 m (area average)	1×10^{-5} at 850 hPa	$T700 + T500 + T300 > 0$	$T300 > T850$ $V850 > V300$	1
Sugi et al. (2002)	~125 (T106)	15 at 850 hPa	3.5×10^{-5} at 850 hPa	Mean of $(T850 + T700 + T500 + T300) > 3$	$V850 > V300$	2
Tsutsui (2002)	~300 (T42)	—	—	Thickness condition between 200 and 700 hPa	<40° latitude	—
Camargo and Zebiak (2002)	~300 (T42)	Basin dependent	Basin dependent			
Walsh et al. (2004)	30	17 at 10 m	1×10^{-5} at 850 hPa	$T700 + T500 + T300 > 0$	$T300 > T850$ $V850 > V300$	1
McDonald et al. (2005)	~300 and ~120	—	5×10^{-5} at 850 hPa	—	<30° latitude	—
Oouchi et al. (2006)	~20	17 at 850 hPa	3.5×10^{-5} at 850 hPa	$T700 + T500 + T300 > 1.5$	$V300 - V850 < 3\ ms^{-1}$ or <35° latitude	1.5

TABLE 2. Approximate conversion factors used to multiply winds at various pressure levels for conversion to 10-m height. After Franklin et al. (2003).

Central pressure of storm	Atmospheric height (hPa)			
	1000	950	900	850
1000	1.0	0.75	0.78	0.81
980	—	0.76	0.78	0.81
960	—	0.84	0.75	0.79
940	—	—	0.76	0.77
900	—	—	1.0	0.75

wind speeds be greater than upper-level wind speeds. Most schemes require that the specified conditions are satisfied for 24 h or longer. While all of the criteria used are physically reasonable, there are a few issues that arise when comparing them. The magnitude of the structural criteria imposed is often not well justified. Not all wind speed criteria account for the difference in wind speed that occurs between 850 hPa and the 10-m level that is used to define observed tropical cyclones. For instance, a 10-m wind speed of 17 m s^{-1} would correspond roughly to a 22 m s^{-1} wind speed at 850 hPa (Franklin et al. 2003; see Table 2). Thus, using a lower threshold than 22 m s^{-1} at 850 hPa would artificially increase the number of storms detected in a simulation. Often it is not clear from published work whether 10 m or the lowest model level wind is being used. Nor is there any systematic attempt to account for resolution differences, which must inevitably affect the intensity of the simulated storms, all other things being equal.

It can be argued that for models of limited horizontal resolution, a wind speed threshold that is lower than the observed is appropriate, as we know a priori that because of its limited horizontal resolution, the model will not be able to generate storms that are as strong as those seen in reality. Thus, the purpose of any such adjusted criterion would be to determine the native ability of the model to generate tropical lows. A truly objective criterion would enable effective comparisons between models of different resolutions and would help diagnose whether a particular model is really generating the correct number of such lows. This is crucial for such a model to be able to make inferences about changes in the numbers of such storms due to climate variability or climate change. Unless the model is believed to produce a good climatology of cyclone numbers, less confidence will be placed in its predictions. In addition, an objective criterion would be useful for weather forecasting models to assess how well they are able to predict tropical cyclone formation, as an objective criterion appropriate to their resolution would determine whether cyclogenesis has occurred (e.g., Cheung and Elsberry 2002).

Accordingly, we here suggest an objectively derived resolution-dependent wind speed threshold criterion that should be universally applicable to any climate model simulation. This is derived from Atlantic tropical cyclone observations but can be used in any region where tropical cyclones form. It can also be applied to reanalyses as a means of evaluating the ability of the reanalysis to represent tropical cyclones.

2. Methods and results

The data analyzed are the extended best track file of Pennington et al. (2000) from 1988 to 2003, recently analyzed by Kimball and Mulekar (2004). These data contain not only the cyclone position and central pressure, but also structural criteria such as the radius of maximum winds. For each cyclone analyzed, the central pressure and radius of maximum winds were used to create an idealized wind field profile, using the method of Holland (1980). In this method, the gradient wind field is given by

$$V_g = \left[AB(p_n - p_c)\exp\left(-A/r^B\right)/\rho r^B + r^2f^2/4\right]^{1/2} - rf/2, \tag{1}$$

where A and B are shape parameters, p_n is the surrounding environmental pressure, p_c is the central pressure of the storm, r is the distance from the center, and f is the Coriolis parameter. The shape parameters were diagnosed from the radius of maximum winds and the central pressure, using formulas given by Holland (1980). It was assumed that the environmental pressure was 2 hPa greater than the pressure of the last closed isobar given in the Pennington et al. (2000) dataset, as this is the contour interval in the dataset for this variable. An adjustment factor of 0.75 was used to reduce the gradient-level wind to the 10-m level (Franklin et al. 2003). Only storms with maximum winds of exactly 35 kt were analyzed, as these represent threshold tropical cyclones and are thus appropriate to establish a threshold detection criterion. Storms north of 30°N were excluded to avoid extratropical influences on storm structure.

The constructed profiles were then subsampled at various resolutions, and the average wind speed at these degraded resolutions was then calculated for all storms. Figure 1 shows a schematic diagram illustrating the effect of limited resolution on the maximum detected wind speed for an idealized wind profile, for a grid of resolution 30 km. The maximum wind speed for this grid is approximately 16.6 m s^{-1}, rather than 17.5 m s^{-1} at a resolution of 1 km. The grid was then moved

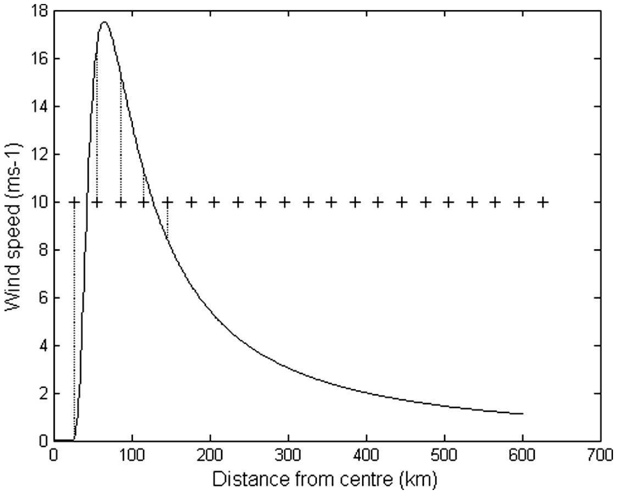

FIG. 1. Schematic diagram illustrating the effect of a limited resolution on the maximum detected 10-m wind speed for a 30-km grid.

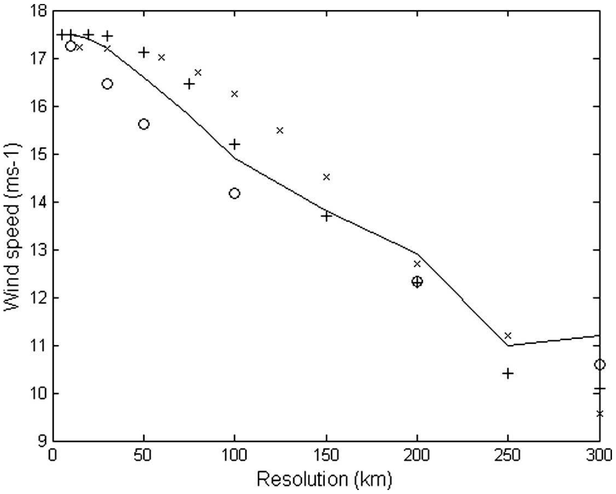

FIG. 2. Variation of threshold detection with resolution, as derived from analytical curve fitting using the method of Holland (1980) for (solid line) gridbox averages and (plus signs) gridpoint calculations. Also indicated (circles) are values derived from a selection of HRD wind analyses and values (x symbols) derived using the model of Hubbert et al. (1991).

by 5 km and the maximum detected wind speed was recalculated. The process was then repeated until all possible grids at this resolution were sampled. Figure 1 shows a one-dimensional version of a grid, but grids were constructed in two dimensions by moving them on both the *x* and *y* axes. The maximum wind speed was then calculated over each two-dimensional grid; this represents the maximum wind speed for that grid placement at the chosen resolution. The average of all these maximum wind speeds over all grid iterations then is taken as the typical maximum wind speed for this resolution of the selected storm. This process was repeated for all 35-kt storms selected from the database, and the average of these results was defined as the resolution-appropriate threshold detection criterion. A small multiplicative factor was used to convert 35 kt (18 m s^{-1}) to 17.5 m s^{-1}, consistent with the observed tropical cyclone threshold. For comparison purposes, another technique was employed whereby the grid was fixed, the center was moved randomly a number of times, and averages were calculated over grid boxes at this resolution rather than grid points. The process whereby an average maximum wind was calculated was then repeated for gridbox averages rather than gridpoint values.

It is recognized that the observed maximum wind speed in the Pennington et al. (2000) database may not be precisely accurate, but it is assumed that any observational errors cancel each other when the average is taken over all storms. In addition, it was found that for many 35-kt storms, the Holland wind profile was a poor fit to the actual storm wind profile, with the wind speeds decreasing too rapidly with radius outside of the radius of maximum winds (see also Willoughby and Rahn 2004; Willoughby et al. 2006). This can be shown by comparing the Holland profile to the observed radius of 34-kt winds. The analysis was therefore limited to storms whose wind speeds as given by the Holland profile at the observed tangential-average radius of gale-force (34 kt) winds were within 3 m s^{-1} of 17.5 m s^{-1} (i.e., 34 kt). The data were also preprocessed to remove missing or unphysical values. A total of 113 storm days were thereby selected, representing about 35% of all valid 35-kt storm days south of 30°N in the Pennington et al. (2000) dataset.

As an independent check, another implementation of the Holland (1980) model, that of Hubbert et al. (1991), was analyzed in a similar fashion. A set of grids was created at various resolutions, and for each selected storm event the wind fields were generated across each grid for 500 randomly selected locations of the storm center in a 20° latitude–longitude square. The maximum wind speed over each grid was calculated. These maxima were then averaged across all 500 grid locations and all 113 storms to yield a threshold wind speed for each resolution.

The results are shown in Fig. 2. For horizontal resolutions finer than about 10 km, the results show that the observed threshold criterion of 17.5 m s^{-1} for the 10-m wind speed is appropriate. For a 30-km resolution model, a wind speed threshold of about 17.0 m s^{-1} should be applied. For a T106 climate model with an effective resolution of about 125 km, a 10-m wind speed of roughly 14.5 m s^{-1} is more appropriate. Finally, for a T42 simulation of approximately 300-km resolution, a 10-m wind speed of about 10.5 m s^{-1} is best. At these coarse resolutions, some scatter in the results was caused by the resolution not being an even divisor of the domain size in which the grids are placed. For conversion from 1- to 10-min winds, a factor of 0.89 can be applied (Powell et al. 1996).

It could be argued that the analytical results shown in Fig. 2 might not be representative of actual two-dimensional storm winds. Accordingly, a similar analysis was performed on Hurricane Research Division (HRD) wind analyses (Powell et al. 1998). Six storm times were selected from the publicly available data that had maximum intensities between 16.5 and 20 m s^{-1}. The resulting average grid maximum wind speeds were then scaled back to 17.5 m s^{-1}: for instance, if the storm had a maximum wind speed of 19 m s^{-1} in the analyses, the average grid maximum wind was multiplied by 17.5/19, for consistency with the defined tropical cyclone threshold. The average of the maxima for all six storms as a function of resolution is shown by the circles in Fig. 2. There is reasonable agreement with results from the analytical techniques, but for resolutions better than about 200 km all analytical techniques give larger values than the reanalyses. It would be useful to analyze many more reanalysis wind fields to obtain an average over more storm times, as this method would give a more realistic result than the analytical techniques.

Some tropical cyclones can be very intense, but small, known as "midget" cyclones (Arakawa 1952). An example was Hurricane Andrew (1992), which was an intense storm with a small eye and a small radius of gale force winds. This is clearly indicated in an analysis of the time evolution of the maximum wind speeds of Andrew, as estimated from the Holland profile model when degraded to various resolutions (Fig. 3). At a resolution of 300 km, Andrew only just reaches tropical storm strength. Hurricane strength is not exceeded until the resolution drops to 100 km. Thereafter, wind speed increases rapidly as resolution becomes finer. However, even at a resolution of 300 km, Andrew would be clearly detectable at the resolution-appropriate threshold indicated in Fig. 2 of about 10.5 m s^{-1}. Thus, these storms would not necessarily be missed in coarse-resolution analyses. Even so, small storms that are considerably weaker than Andrew may well be missed (Camargo and Zebiak 2002).

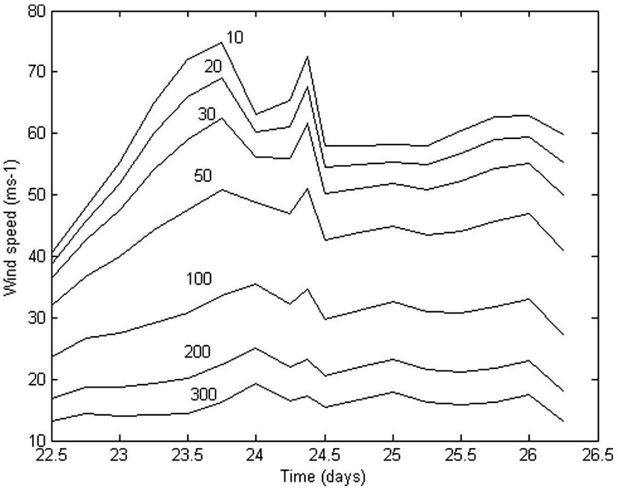

FIG. 3. Variation of typical maximum wind speed of Hurricane Andrew as a function of resolution (in km) for the period 22–26 Aug 1992.

For guidance on the values that should be used for the other detection criteria shown in Table 1, the sensitivity of cyclone detection in a model to variations in values of these parameters was investigated. Table 3 shows the results of running a version of the Walsh et al. (2004) cyclone detection scheme for various values of the imposed parameters and for various model resolutions. The models analyzed are the regional climate models used in the Walsh et al. (2004) study, at 30- and 125-km horizontal resolution. At 30-km resolution, Fig. 1 suggests a detection threshold wind speed of 17 m s^{-1}. This gives a number of detected cyclones quite similar to observed in this region. Decreasing this threshold gives an increasingly larger numbers of storms: at 11 m s^{-1}, there are 108 detected storms. Adjusting the strength of the warm-core temperature anomaly threshold leads to some variation in detection. For storms stronger than 17 m s^{-1}, sensitivity to changing the warm-core detection threshold is low, as these strong storms mostly have strong warm cores that easily exceed the basic threshold, even if it is increased from 0° to 2°. For weak storms (11 m s^{-1} or greater), sensitivity is much greater to the warm-core criterion value, as increasing it to 2° decreases numbers greatly, while decreasing it to $-2°$ only increases numbers a little. Thus, simply assuming that the sum of the temperature anomalies at the three chosen atmospheric levels (700, 500, and 300 hPa) must add up to at least zero seems appropriate, in that it specifies that the system must have a warm core without artificially reducing the number of systems that would otherwise be detected based upon their wind speed criterion alone. Decreasing the resolution to 125 km causes the numbers of simulated storms to decrease. At this resolution, Fig. 2 shows that an appropriate wind speed threshold might be about 14.5 m s^{-1}; the results of Table 3 show that the model is undersimulating observed storm numbers considerably

TABLE 3. Sensitivity of detection of tropical cyclones in climate model simulations to changes in the parameters listed in Table 1 and to horizontal resolution. Detection is for January formation between 145° and 175°E in the Southern Hemisphere. Simulations analyzed are those of Walsh et al. (2004).

Model horizontal resolution (km)	10-m wind speed (m s^{-1})	Lowest level vorticity (s^{-1})	Warm core temperature anomaly (K)	Structure or location	Duration (days)	No. of storms formed
Observed	—	—	—	—	—	60
30	17	1×10^{-5}	T700 + T500 + T300 > 0	T300 > T850 V850 > V300	1	62
30	14.5	″	″	″	″	81
30	14	″	″	″	″	88
30	11	″	″	″	″	108
30	17	″	T700 + T500 + T300 > 2	″	″	60
30	″	″	T700 + T500 + T300 > −2	″	″	62
30	11	″	T700 + T500 + T300 > 2	″	″	68
30	11	″	T700 + T500 + T300 > −2	″	″	114
125	17	″	T700 + T500 + T300 > 0	″	″	14
125	14.5	″	″	″	″	28
125	11	″	″	″	″	43
30	17	3×10^{-5}	″	″	″	58
125	14.5	1×10^{-5}	Any value	Any value	″	43
30	17	″	T700 + T500 + T300 > 0	T300 > T850 V850 > V300	2	53

at this resolution. Increasing the vorticity to 3×10^{-5} has little effect for storms with minimum speeds of 17 m s^{-1}, as these almost invariably have higher maximum vorticities than this. In the Walsh et al. (2004) detection scheme, though, the vorticity threshold is specified only to speed up the routine and was chosen to be quite low for this purpose. Indeed, there is little justification for specifying a vorticity criterion that is so high that it eliminates warm-core tropical systems of sufficient maximum wind speed that would otherwise be declared as tropical cyclones. Removing the structural criteria and permitting any storm to be detected greatly increases the number of storms and also enables storms to be detected in the midlatitudes that are clearly not tropical cyclones (not shown). Whether the difference between the 850- and 300-hPa wind speeds or temperatures should be set to a value different from zero is debatable, but here we have made the simplest assumption consistent with the warm-core structure of a tropical cyclone. Finally, there is some sensitivity to changing the minimum storm duration, as increasing this to 2 days decreases storm numbers by about 15%. For lack of any independent guidance on this choice, however, we suggest 24 h as a minimum duration.

3. Discussion and conclusions

Unless an objective, resolution-dependent criterion for tropical cyclone detection is employed, comparisons of simulated versus observed climatological cyclogenesis must be viewed with caution. For instance, the otherwise impressive simulations of Oouchi et al. (2006), which employed a global model at a resolution of about 20 km, appear to reproduce very well the observed climatological global cyclogenesis. Nevertheless, since they use a threshold of 17 m s^{-1} at 850 hPa, they may be oversimulating cyclone numbers by an undetermined amount, unless their higher vorticity and duration thresholds are compensating by excluding storms also. Walsh and Katzfey (2000) used an area-average wind speed criterion that may well have been unsuitable for their resolution of 125 km, even though their criterion was diagnosed from finer-resolution simulations. The results of Walsh et al. (2004) demonstrate good agreement between simulated and observed numbers and also used a resolution-appropriate threshold, but only by chance. The method of Vitart et al. (1997, 1999) and Vitart and Anderson (2001) may be justifiable, but it is not clear from their work whether 10-m wind speed was used; if it was, then Fig. 2 shows that their threshold is too high for a 300-km grid. In addition, Walsh and Watterson (1997) found that employing a rather lower vorticity threshold than usual in such studies was adequate to eliminate random, isolated points of cyclonic vorticity in order to speed up the detection routine. This should be the purpose of any vorticity threshold, as it is the 10-m wind speed that defines a tropical cyclone.

The relationship shown in Fig. 2 is approximately linear. Nevertheless, there are many nonlinear feedback processes that operate in tropical cyclones, including those involving air–sea interaction and its effects on intensity (e.g., Emanuel 1986). In a model, it is likely that an increase in resolution would cause a change in the magnitude of these feedback processes that would alter the intensity at a rate different from the roughly linear effect of resolution alone. This process is difficult to quantify, as it would be model dependent and related to the parameterizations employed in the model. We do not address this issue in this paper, but this involves model error rather than an observationally based detection criterion, so we still propose that Fig. 2 be used.

At times, model simulations may be analyzed that do not have information on the 10-m wind saved in the model output files. It is preferable to diagnose 10-m winds using Monin–Obukhov relations (Louis 1979) if the appropriate stability-related input variables are available. If not, Table 2 gives some approximate conversion factors between 10-m winds and various pressure levels, using the results of Franklin et al. (2003). These factors would vary depending upon the central pressure of the storm, but it can be seen that for winds at 850 hPa, an approximate conversion factor of 0.78 would give an error of only a few percent if applied at all storm intensities.

Another relevant issue is the relationship between the time step of the climate model and the time averaging of tropical cyclone winds. For instance, if the climate model had a time step of 20 min, then a further small correction would need to be made to account for this difference from 10-min average winds. This issue is also not addressed in this paper. In addition, most of the detection criteria listed in Table 1 impose a requirement that the storm satisfy the criteria for at least 24 h. We also suggest that this be employed, as climate model output is often only archived once per model day.

There are some observed situations in the Tropics near monsoon troughs where surface winds are greater than 35 kt, but there is no tropical cyclone present (Lander 1994). Climate models may be able to mimic these situations, so they would need to be excluded in any criterion that was trying to detect tropical cyclones only. We have not examined this issue here. Similarly, tropical cyclones with low maximum wind speeds tend to be asymmetrical, but the Holland wind profile model assumes a symmetric vortex. This is another reason why a similar study using a larger number of real wind analyses would be preferable. Alternatively, the improved wind profile of Willoughby et al. (2006) could be employed with a grid-averaging technique similar to that described in this paper.

Thus, we recommend the following:

1) all detection schemes should use wind speeds corrected to 10 m, rather than any other level;
2) 10-m wind speed thresholds should be determined by Fig. 2;
3) this criterion should be satisfied for at least 24 h; and
4) for correct diagnosis of cyclone numbers, any additional criteria must not further reduce storm numbers that have already been established by the above wind speed criterion. Thus, other criteria should be eliminated if they may potentially exclude tropical cyclones that satisfy the wind speed criterion unless they are structural criteria designed to exclude either midlatitude cyclones or tropical systems with high wind speeds that are not tropical cyclones.

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