Chapter 2
Tropical Cyclone Detection and Tracking Method

2.1 Introduction

As described in Chap. 1, detection of TCs in operational practice may be subjective and sometimes controversial. That is also the case for detection of simulated TCs from model outputs. Research groups around the world have adopted TC tracking schemes using various techniques and threshold criteria. However, they are often not well explained [15]. Generally speaking, numerical tracking of TCs starts by locating a localized minimum in sea level pressure (SLP) or maximum in vorticity field to define the center of a potential TC. Then tracks are filtered by maximum wind speed, magnitude of vorticity, a measure of warm-core, and duration for which these criteria are met. Hereafter, for convenience, tracking schemes using these four parameters shall be referred to as *base* tracking. In addition to the base tracking parameters, some studies, especially those with high-resolution models, have adopted some measure of vertical variation of tangentional maximum wind speeds and horizontal temperature anomalies (referred to as *structure* criteria), genesis location criteria, and SLP anomaly thresholds.

One of the first studies to evaluate the skill of numerical models in reproducing the global TC climatology is Bengtsson et al. [1] using European Centre for Medium range Weather Forecasting (ECMWF) operational global forecasting model at $\sim$200 km resolution. They used only wind speed (>25 m s^{-1} at 850 hPa) and 850 hPa vorticity (>7.0 $\times$ 10^{-5} s^{-1}) criteria for detection of simulated TCs. A little over a decade later, as model resolution increased and started to resolve the thermal structure of TCs better, Bengtsson et al. [2] introduced warm-core and structure criteria to provide a more accurate separation of simulated TCs from extratropical low pressure systems. Parameters and thresholds used for TC tracking have not been changed much since then, even though the resolution has markedly increased. At resolutions coarser than 100 km, numerical models can only produce TC-like vortices. But it is generally considered that models with 50 km horizontal resolution or less can resolve the major characteristics of TCs adequately; namely

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the eye, warm-core, axisymmetric wind circulation, and spiral bands, although not the maximum winds or other core details (e.g., [12, 13]. Thus the TC tracking scheme should vary to reflect the model resolution difference. However, when studies with T42 ($\sim$300 km) resolution and 20 km resolution use a comparable TC tracking criteria, as represented by Krishnamurti et al. [10] and Oouchi et al. [12] respectively, them both producing reasonable global TC climatologies raises questions of how this could occur.

Table 2.1 compares TC detection and threshold criteria from recent regional and global climate modeling studies using horizontal resolutions of 50 km or less. Even though model resolutions are similar, TC detection criteria exhibits a large variation between the different studies. All of them use maximum wind speed, relative vorticity, warm-core measure, and duration criteria. But the usage of structure criteria and SLP anomaly between the different studies is not universal. Variability in threshold values in each parameter is quite large, especially for maximum wind speed (ranging from 14 m s^{-1} at 850 hPa to 17 m s^{-1} at 10 m above the surface). Measures of warm-core are also quite diverse. Some use the vertical mean of horizontal temperature anomalies, while others take the sum of multiple levels. Interestingly, simulated frequencies of TCs from these studies are all comparable to each other. Some studies use a strict/strong threshold criterion in one parameter (limiting towards detecting more warm-core-like and/or intense storms, e.g., higher wind speed) although often compensated by relaxing other criteria. Consider the two studies of Chauvin et al. [3] and Stowasser et al. [13], for example. Their model resolutions are the same at $\sim$50 km (0.5°), but in Chauvin et al., wind speed criteria is much less strict, but all other base tracking parameters are stricter than Stowasser et al.. All of the studies listed in Table 2.1 are global warming experiments and the TC tracking criteria and thresholds are chosen so that the detected number of storms matches those observed in the current era. This may be a sensible procedure for global warming experiments, when the major concern is for the determination of future changes. But subjectively tuning the TC tracking method parameters does not allow for an objective assessment of the model's performance, leaves uncertainty in the simulated TC frequency, and potentially impacts the changes in future climate.

This chapter assesses the TC tracking scheme in attempt to answering the following two questions:

(1) What is the range of uncertainty associated with varying tracking parameters and their thresholds in TC tracking schemes?
(2) Are the commonly used criteria strict enough to distinguish TCs from other low-pressure systems?

The first point is examined through a series of sensitivity experiments. First, the base tracking parameters are varied within the range of commonly used values, and second, structure criteria are applied. To our best knowledge, the latter point has not been discussed in literature. It is clear that the significance of addressing these issues becomes more important as models are now able to simulate mesoscale systems with greater detail, potentially making it more difficult to

Table 2.1 TC tracking criteria and threshold used by past global/regional climate modeling studies with horizontal model resolutions of approximately 50 km or less

	Model resolution (km)	Wind speed (m/s)	Vorticity at 850 mb ($\times 10^{-5}$ s^{-1})	Temp. anomaly (K)	Structure, location	SLP anomaly (hPa)	Duration (days)
Walsh et al. [14]	30	17 at 10 m	1	$T'300 + T'500 + T'700 > 0$	$T'300 > T'850$ $V850 > V300$	–	1
Chauvin et al. [3]	~50	15 at 80 hPa	14	mean($T'300 \sim T'700$) > 3	$T'300 > T'850$ $V850 > V300$	–	1.5
Oouchi et al. [12]	20	15 at 850 hPa	3.5	$T'300 + T'500 + T'700 > 2.0$	$V300 < V850$ or $< 35°$ latitude	2	1.5
Knuston et al. [9]	18	17 at lowest model level	1.6	mean ($T'300 \sim T'500$) > 0.8	–	4	2
Stowasser et al. [13]	~50	17 at lowest model level	2.5	mean ($T'300 \sim T'850$) > 0	$V850 > V300$	–	2
Murakami and Wang [11]	20	14 at 850 hPa	3	$T'300 + T'500 + T'700 > 1.2$	V850–V300 > 2.5, and <45° latitude[a]	2	1.5

[a] V850 > V300 at genesis

T′xxx refers to horizontal temperature anomaly at xxxhPa, and Vxxx refers to maximum wind seed at xxxhPa distinguish TCs from other systems such as intense extratropical storms. To aid in this differentiation, the *cyclone phase* technique developed by Hart [7] is introduced into the tracking criteria.

2.2 Description of Cyclone Phase Technique

As shown in Table 2.1, structure criteria consist of either one or both of the conditions, V850 > V300 and/or T′300 > T′850, where V denotes maximum tangentional wind and T′ is the horizontal temperature anomaly. The first condition is based on the observed vertical variation of tangentional wind speeds, which maximizes near the top of boundary layer (e.g., [5, 6]). The second condition is also based on the observed vertical variation of horizontal temperature anomalies, which maximizes in the upper-troposphere in mature TCs. Both are physically sound conditions for TCs but they only take two different levels and do not represent the whole vertical variation of thermal structure of low-pressure systems.

The cyclone phase technique [4, 7, 8] provides a more comprehensive measure of the vertical thermal structure of low-pressure systems. It consists of the following three parameters:

(i) *B term*: a measure of axisymmetricity, defined as the difference of 600–900 hPa thickness, calculated within 500 km radius of the storm center, to the right and left of the storm center with respect to the direction of storm movement;

$$B = h\left(\overline{Z_{600\text{ hPa}} - Z_{900\text{ hPa}}}|_R - \overline{Z_{600\text{ hPa}} - Z_{900\text{ hPa}}}|_L\right),$$

where $h = +1$ for Northern hemisphere, and $h = -1$ for southern hemisphere and Z denotes geopotential height. Tropical systems are axisymmetric and typically have values of B close to zero, whereas mid-latitudinal systems are non-axisymmetric due to their baroclinic frontal nature and are typically associated with B > 10 [8].

(ii) $-VTL$ *term*: a measure of the vertical thermal structure in the lower-troposphere, defined as vertical derivative of horizontal height perturbation from 900 to 600 hPa;

$$-|VTL| = \left.\frac{\partial(\Delta Z)}{\partial \ln p}\right|_{900\text{ hPa}}^{600\text{ hPa}}$$

(iii) $-VTU$ *term*: similar to −VTL but for the upper-troposphere;

$$-|VTU| = \left.\frac{\partial(\Delta Z)}{\partial \ln p}\right|_{600\text{ hPa}}^{300\text{ hPa}}$$

−VTL and −VTU terms represent the vertical variation of thermal wind. For deep warm-cored TCs, both terms are positive as the height perturbation (and hence the tangential wind) is maximized near the top of the boundary layer. For mid-latitudinal systems the horizontal geopotential height perturbation is maximized in the upper troposphere. As a result, $-$VTL and $-$VTU terms are negative. Occasionally $-$VTL and $-$VTU terms may have different signs for a system that is transitioning from cold-core to warm-core (or vise versa), as represented by Hurricane Olga (2001) [8].

2.3 Sensitivity Experiment Design

Sensitivity to varying parameters and their thresholds in TC detection criteria is explored using January–December 2005 data from the Nested Regional Climate Model (NRCM) tropical channel simulation (described in Chap. 3). These data cover the global tropics at 36 km resolution with 51 vertical levels archived at six hourly intervals. We choose this dataset over reanalysis because of the horizontal resolution. The shortfall of using the channel simulation data is that there is no "correct TC frequency" with which to compare the number of TCs detected from TC tracking. Even though this simulation is driven by reanalysis, it is not appropriate to assume that the model produces TCs at the observed frequency. Hence, the results from the sensitivity tests are given in a relative sense; for parameters with variable thresholds (e.g., wind speed), variations of the number of detected TC tracks by varying the threshold values from a standard threshold will be given, and for parameters that are either binary (e.g., structure criteria) the difference of the number of detected TC tracks by turning the parameter on or off are presented.

Table 2.2 summarizes parameters and their threshold ranges for the sensitivity study. For base criteria, the maximum wind speed threshold is set to 17 m s^{-1} but the vertical level at which the wind speed is measured is allowed to vary between 850 hPa, 1,000 hPa, and 10 m above the surface. This approximately corresponds to varying the maximum wind speed from 13 to 17 m s^{-1} at 10 m [6]. The relative vorticity (RV, measured at 850 hPa) threshold is varied from 1.0×10^{-5} to 5.0×10^{-5} s^{-1}. A warm-core is defined by the sum of horizontal temperature anomalies at 300, 500, and 700 hPa and its threshold is varied from 0 to 3 K. Finally, the duration threshold is varied from 1 to 3 days.

Specific steps of base tracking are as follows:

- First, the sea level pressure (SLP) field is scanned to locate all local minima, which are marked as potential centers of TCs. There is no requirement on the minimum SLP value, or the difference from the environmental SLP value;
- Next the maximum wind speed and the magnitude of 850 hPa RV are found within a box $\pm1°$ latitude/longitude from the SLP minimum location;
- Horizontal temperature anomalies are calculated as the difference between the average in the TC core area (within 1° from the center) and the surrounding environment (1–10° from the center);

Table 2.2 Summary of tracking parameters and their threshold ranges used for the sensitivity experiment

	Parameter	Threshold range
Base tracking	Maximum wind level	850 mb, 1,000 mb, or 10 m surface
	Relative vorticity (s^{-1}),	1.0 to 5.0 × 10^{-5}
	$T'300 + T'500 + T'700$(K),	0.0 to 2.0
	Duration (days)	1 to 3
Structure criteria	V850 > V300 and T′300 > T′850	Yes or no
Cyclone phase	B	−20 to 50
	−VTL	−100 to 200
	−VTU	−100 to 200

- Once the tracker finds a feature that satisfies the base criteria of 850 hPa wind speed >17 m s^{-1}, cyclonic RV > 1.0 × 10^{-5} s^{-1}, and T′ > 0, it searches for the location of the same feature at the next time step within 5° of the previous location. If there exists more than two systems within the search box, then the closest one to the last location is chosen.
- A successful track must retain the base parameter thresholds for at least 1 day.

After base tracking is completed, values of V850–V300, T′300–T′850 and cyclone phase parameters are calculated along each of the tracks at each time step. Tracks resulting from base tracking are then further filtered based on the satisfaction of all of the base parameters, structure and cyclone phase criteria. As defined in Sect. 2.2, the thresholds for the cyclone phase of pure tropical warm-core systems are $B < 10$, $-VTL > 0$ and $-VTU > 0$. The sensitivity of these criteria to varying these cyclone phase thresholds (as described in Table 2.2) is tested in the next section.

2.4 Results

Table 2.3 shows the changes in the number of detected tracks (per year) by adding structure and cyclone phase criteria for the strongest (maximum wind level at 10 m, RV = 5.0 × $10^{-5}s^{-1}$, T′ = 2 K, and duration = 3 days) and the weakest (maximum wind level at 850 hPa, RV = 1.0 × 10^{-5} s^{-1}, T′ = 0 K, and duration = 1 day) base parameter combinations. Only the results from the strongest and the weakest base combinations are presented here because the numbers of detected tracks from all other combination lie between the two. For simplicity, cyclone phase parameters are set to those recommended by Hart [8] for TCs. Without structure or cyclone phase filtering, the numbers of detected tracks vary by an order or magnitude, from 155 to 1,467 (Table 2.3, first row). With the weakest base combination, the TC tracker detects numerous small-scale systems such as mesoscale convective systems and orographically-induced systems in high terrain. The extremely high count of 1,476 per year using the weakest base criteria without structure or cyclone phase filtering is due to inclusion of such erroneous

Table 2.3 Number of detected tracks (per year) from base tracking only (*top*), from base tracking with structure criteria (*middle*), and from base tracking with both structure and cyclone phase criteria (*bottom*)

	Strongest base (win. lev. = 10 m, $T' = 2$, RV = 5.0, duration = 3)	Weakest base (win. lev. = 850 mb, $T' = 0$, RV = 1.0, duration = 1)
Base only	155	1,467
Base + structure	106	691
Base + structure + basic CP[a]	62	363

[a] Basic CP = recommended threshold by Hart [7] ($B < 10$, $-VTL$ and $-VTU > 0$)

Left column is the strongest base case where all of parameters within base tracking are set to be the most strict value. *Right column* is the weakest base case

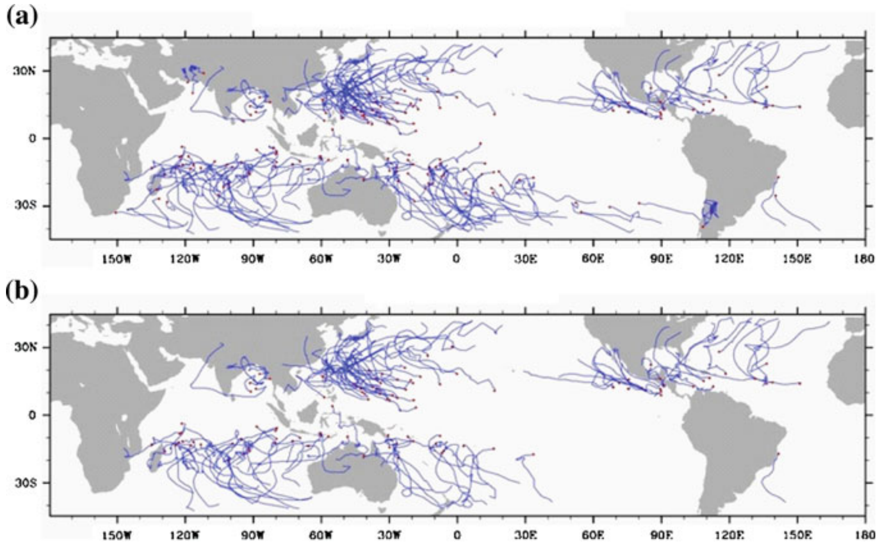

Fig. 2.1 Tracks from the strongest base case without structure criteria (*top*) and with structure criteria (*bottom*). *Red dots* are track start points, and *blue lines* are tracks. (**a**) No structure criteria. (**b**) With structure criteria

systems. If the maximum wind measurement level is at 10 m and duration is increased to 3 days, the inclusion of mesoscale convective systems is reduced significantly. But this is not sufficient to exclude some orographically induced systems and subtropical cyclones in the Southeast Pacific (Fig. 2.1a).

Adding the structure filtering decreases the number of tracks for both the strongest and the weakest base cases (Table 2.3, second row). Structure filtering halves the number of detected tracks for the weakest base case and by ~30% for the strongest base case. Although the base parameters alone could not exclude orographically induced and subtropical cyclones, the addition of structure criteria appears to filter out these erroneous systems (Fig. 2.1b).

Adding cyclone phase filtering reduces the number of detected tracks further (Table 2.3, third row). This suggests that the cyclone phase filtering is excluding some of the systems that satisfy structure criteria and only more-TC-like systems are allowed to pass the filtering. This will be discussed in detail later in this chapter.

Table 2.4 summarizes the sensitivity to varying individual base parameters when structure filtering is also applied. These changes are shown both as absolute numbers and percentage changes from the standard case (note that % changes are not applicable for the maximum wind measurement level which provides the base). Here, the standard case is arbitrarily set to $T' = 2$, $RV = 5.0$ and duration =1. Considerable sensitivity to variations in all parameters is found when the other parameters are set at the weakest base criteria. However, the sensitivity is considerably reduced for the strongest base criteria, where changes to relative vorticity or temperature anomaly criteria make no difference. The highest sensitivity is to the maximum-wind measurement level (or wind speed at a particular vertical level) and duration, as these are the only terms for which there is any sensitivity for the strongest base case. Of course, this conclusion holds only within the range of parameter thresholds tested here. Outside this range the conclusion may well change.

As mentioned before, cyclone phase criteria are stricter than structure criteria in such a way that adding cyclone phase criteria on top of structure criteria further reduces the number of detected TC tracks (Table 2.3). This point is further investigated here. Figure 2.2 compares the composite plots of zonal vertical cross section of horizontal temperature anomaly for 50 cases chosen randomly where only structure criteria are satisfied (a) and instances where both structure criteria and cyclone phase criteria (using parameter threshold recommended by [8] are satisfied (b). The composite using only structure filtering shows a clear sign of warm-core structure, but is weaker when compared to the composite using both structure and cyclone phase criteria.

However, composite analysis can be contaminated by a small number of extreme cases, so it is instructive to examine some individual cases. Figure 2.3 shows the zonal vertical cross section of temperature anomaly for twelve randomly chosen instances that satisfy structure criteria but fail cyclone phase criteria. Most of the cases presented in Fig. 2.3 show a clear warm-core. However, many are not well vertically aligned, and a few (especially the case second to the left in the middle row) show very weak or no sign of warm-core at all. The addition of the cyclone phase criteria (Fig. 2.4), selects a warm core that is much more comparable with typical TC structures. All of the cases in Figs 2.3 and 2.4 use the strongest combination of base tracking, which includes $T' > 2$. Thus, the combination of traditional warm-core definition (as in the sum of horizontal temperature anomalies) and structure criteria may not be sufficient to differentiate tropical warm-core systems from other cyclonic systems. This conclusion is supported by the scatter plot of T' and $-VTL$ and $-VTU$ values in Fig. 2.5. $T' > 0$ does not necessarily mean $-VTL > 0$ and $-VTU > 0$ (Fig. 2.5a, b). This is also the case even when structure criteria are applied (Fig. 2.5c, d). $T' > 0$ only assures the

Table 2.4 Summary of detected number of tracks (per year) for base tracking sensitivity for (a) varying maximum wind measurement level, (b) varying temperature anomaly, (c) varying relative vorticity, and d) track duration

(a) Vary wind level

	strongest ($T' = 2$, $RV = 5.0$, duration = 3)	Weakest ($dt = 0$, $RV = 1.0$, duration = 1)
	# Tracks	# Tracks
850 hPa	133	691
1,000 hPa	115	272
10 m	106	223

(b)Vary temperature anomaly

		Strongest (win. lev. = 10 m, $RV = 5.0$, duration = 3)		Weakest (win. lev. = 850 mb, $RV = 1.0$, duration = 1)	
T'(K)	% change T' from $T' = 2$	# Tracks	% change from $T' = 2$ count	# Tracks	% change from $T' = 2$ count
0	−100	106	0	691	155.93
0.5	−75	106	0	569	110.74
1	−50	106	0	436	61.48
1.5	−25	106	0	337	24.81
2	–	106	–	270	–

(c)Vary relative velocity

		Strongest (win. lev. = 10 m, $T' = 2$, duration = 3)		Weakest (win. lev. = 850 mb, $T' = 0$, duration = 1)	
RV ($\times 10^{-5}$ s^{-1})	% change RV from RV = 5	# Tracks	% change from RV = 5.0	# Tracks	% change from RV = 5.0
1	−80	106	0	691	53.22
2	−60	106	0	634	40.58
3	−40	106	0	564	25.06
4	−20	106	0	503	11.53
5	–	106	–	451	–

(d)Vary duration

		Strongest (win. lev. = 10 m, $T' = 2$, $RV = 5.0$)		Weakest (win. lev. = 850 mb, $T' = 0$, $RV = 0.0$)	
Duration (days)	% change duration from duration = 1	# Tracks	% change from duration = 1	# Tracks	% change from duration = 1
1	−66.67	195	83.96	691	177.51
1.5	−50.00	160	50.94	573	130.12
2	−33.33	140	32.08	455	82.73
2.5	−16.67	117	10.38	323	29.72
3	–	106	–	249	–

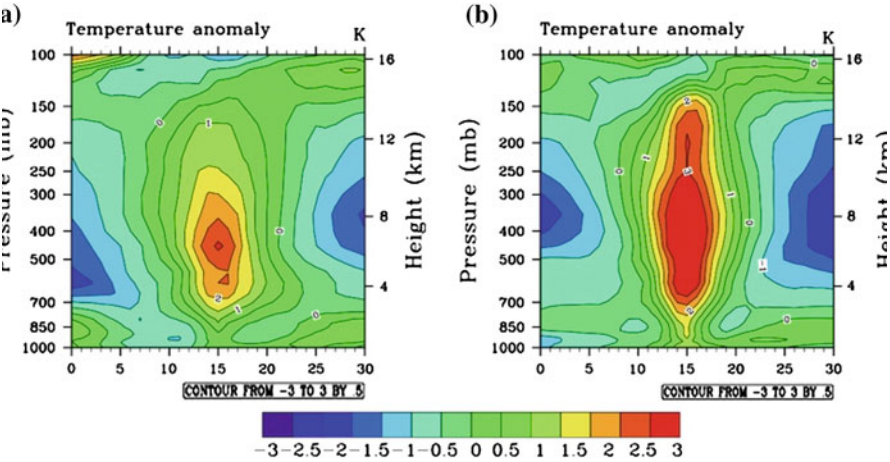

Fig. 2.2 Composite plots of vertical cross-section of horizontal temperature anomaly for 50 randomly chosen instances where only structure criteria is satisfied (*left*) and both structure and basic ($B < 10$, $-VTL > 0$, and $-VTU > 0$) cyclone phase criteria are satisfied (*right*). Both cases are using the strongest base parameter combination. (**a**) Satisfy structure but not CP. (**b**) Satisfy both structure and CP

existence of warm-core but not the vertical variation or the location of vertical maximum. It appears that simply taking a difference at 300 and 850 hPa is not sufficient to capture the vertical thermal profile throughout the troposphere.

The threshold of $-VTU$ and $-VTL$ at 0 is determined theoretically and is therefore set for an objective TC tracking. However, setting the threshold for B at 10 is debatable. Hart [7] and Evans and Hart [4] justify the $B < 10$ cut-off because no major hurricane has and associated value of B that exceeded 10 based on ECMWF reanalysis. However, weaker TCs (tropical storms and category 1–2 hurricanes) can have B values exceeding 10, often times greater than 20 [4]. As the aim of objective TC tracking is to detect hurricane strength systems and tropical cyclones (with maximum wind speeds >17 m s^{-1}), setting $B < 10$ may be too strict. As shown in Fig. 2.6, the sensitivity to parameter B disappears for $B > 20$, and there is no significant difference in the composite of vertical structure when $10 < B < 20$ or $20 \leq B$ (Fig. 2.7). From these results, the threshold for B term may be increased to (or beyond) 20 as long as the conditions $-VTL > 0$ and $-VTU > 0$ are satisfied for TC detection.

Next, the base tracking sensitivity experiments are repeated with cyclone phase filtering included, in order to assess its impact (Table 2.5). This time only maximum wind measurement level and durations are varied and tested. The sensitivity to maximum wind measurement level is about the same with and without cyclone phase filtering when the other three base parameters are set to be the strongest level (though the total number has changed: compare Tables 2.4a, 2.5a). For the weakest base case, the sensitivity to maximum winds increases from 50 to 68% with cyclone phase filtering. This implies that the addition of cyclone phase

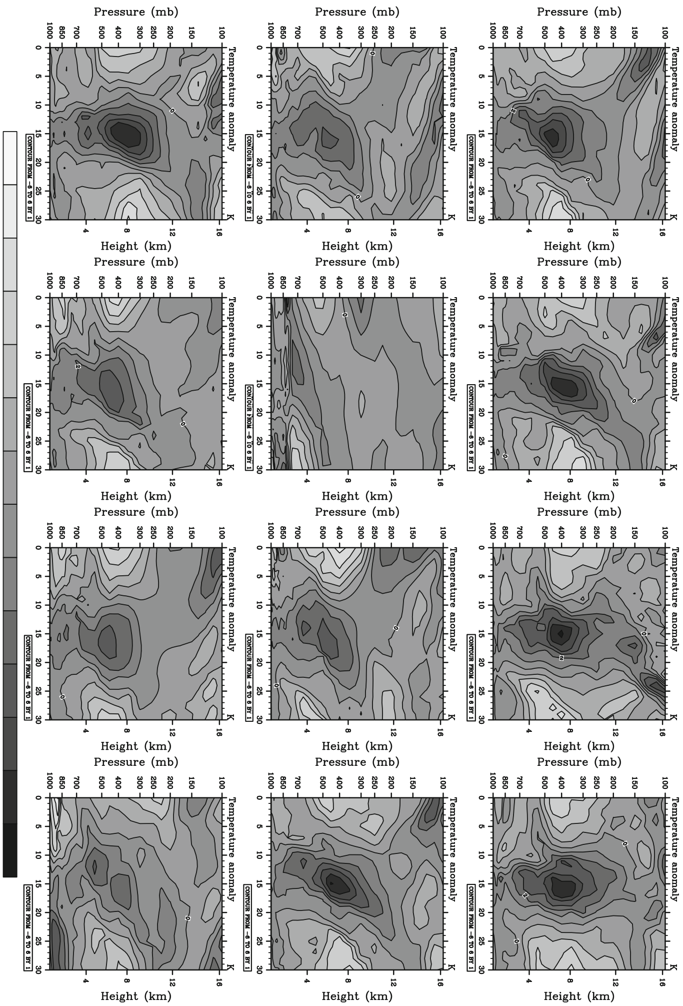

Fig. 2.3 Vertical cross-section of horizontal temperature anomaly for 12 randomly chosen instances where structure criteria is satisfied but not cyclone phase. Base parameters are set to be the strongest combination

filtering causes minimal alteration to sensitivity to varying the intensity threshold. However, sensitivity to duration threshold changes is magnified when cyclone phase filtering is applied. For the weakest base case, as an example, the maximum change increases from 177 to 274% (Tables 2.4d, 2.5b). Satisfaction of the cyclone phase criteria for TCs requires the presence of a robust and vertically aligned warm-core; such warm-cores can be short-lived. This is considered to be the primary reason why sensitivity of duration threshold increases when cyclone phase filtering is applied.

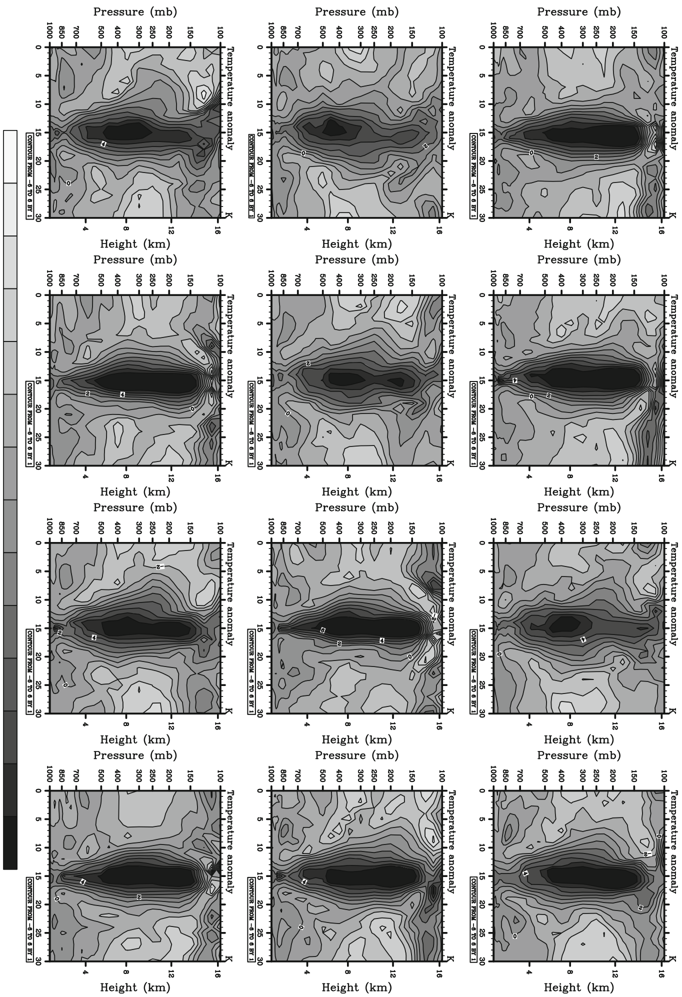

Fig. 2.4 Similar to Fig. 2.3, but for cases where both structure and cyclone phase criteria are satisfied

Finally, the sensitivity of intensity distributions to the tracking criteria is examined. Here we compare the distributions of lifetime maximum intensity (measured as wind speed at 10 m above surface) from the weakest and the strongest base cases. Here both cases satisfy structure and cyclone phase filtering. Observed intensity probability is maximized at tropical cyclone (17–33 m s^{-1}) strength and quickly decays towards higher intensity (Fig. 2.8). Distribution from the weakest base case shows a similar distribution shape, but the distribution from the strongest base case is more normal-shaped with maximum probability in Category 1 (33–42 m s^{-1}) strength. Note the truncation of the NRCM intensity

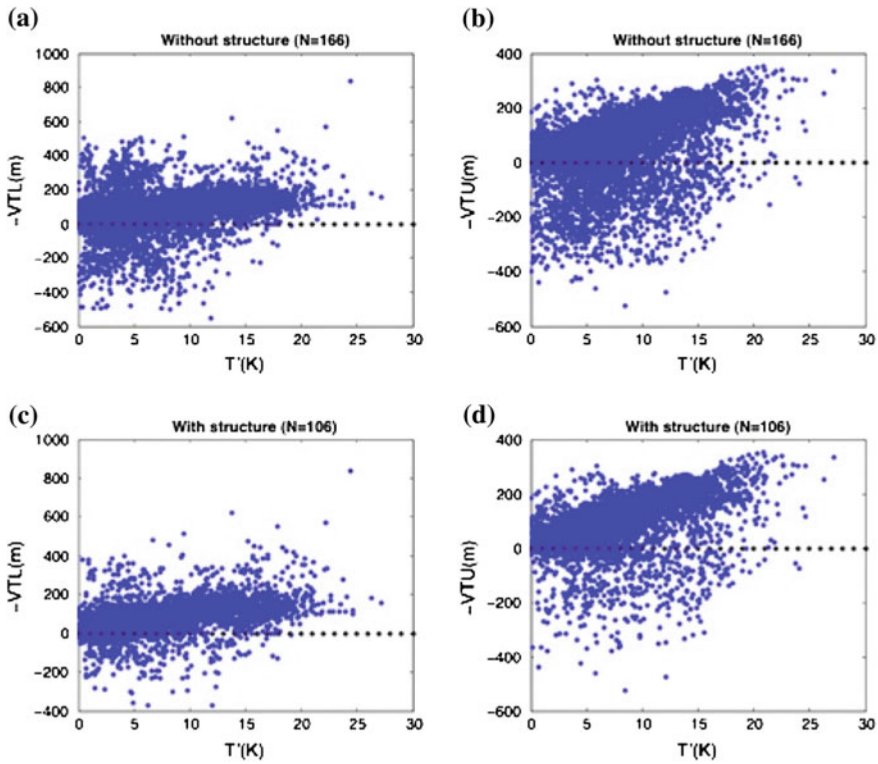

Fig. 2.5 Scatter plots of traditional warm-core definition value (sum of horizontal temperature anomalies at 300, 500, and 700 hPa) versus −VTL (*left column*) and −VTU (*right column*) terms without *(top)* and with structure criteria (*bottom*). N is sample population

distributions at approximately 60 m s^{-1} is due to the model resolution. Once again, intensity distribution is the most sensitive to maximum wind speed and duration thresholds. The other two base parameters (RV and warm-core) do not have a significant impact. This shows that relaxing tracking criteria can capture a broader range of intensity, but at the cost of capturing spurious systems. The number of tracks for the strongest base case is 62 (per year) but the weakest base case is 363 as it picks up more orographically induced tracks.

2.5 Summary and Concluding Remarks

A survey of recent global/regional modeling studies of TC climatology reveals a large variability among TC detection and tracking criteria and thresholds, even when model horizontal resolutions are similar. Further, many of these studies do not examine the TC detection sensitivity of their underlying parameters. Despite such

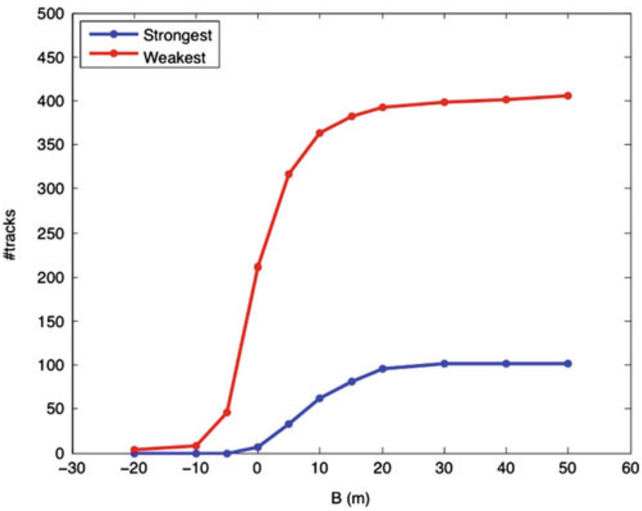

Fig. 2.6 Number of detected tracks (per year) as a function of B term for the strongest (*red*) and the weakest (*blue*) base parameter combinations, when structure criteria, as well as conditions −VTL > 0 and −VTU > 0 are satisfied

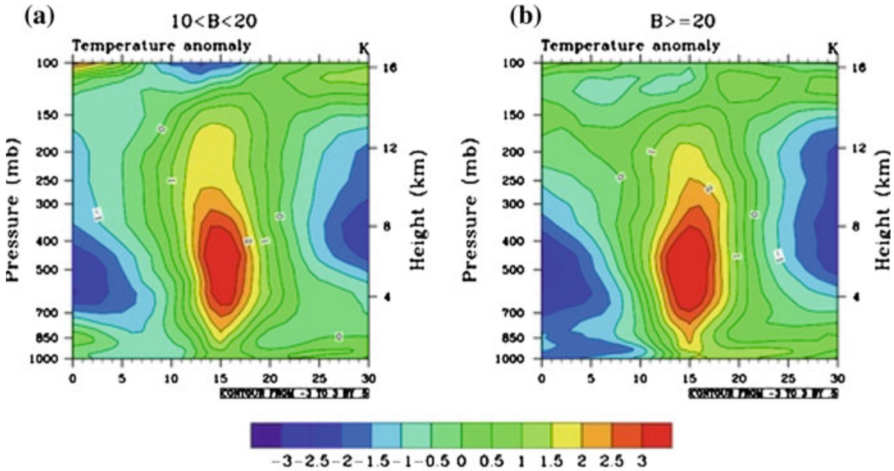

Fig. 2.7 Composite plots of vertical cross section of horizontal temperature anomaly of 50 randomly chosen instances satisfying the strongest combination of base criteria, structure criteria, and −VTU > 0 and −VTL > 0, with (**a**) 10 < B < 20, and (**b**) B ≥ 20

diversity in TC detection scheme, the resulting TC frequencies among the different studies closely follow observations as the criteria are tuned to ensure that this occurs. Potential risks of deliberate tuning of the TC tracking criteria include (1) lack of proper assessment of model biases; and, (2) biasing future TC changes due to changes in TC characteristics that are incorrectly represented in the TC trackers.

Table 2.5 Similar to Table 2.4 but with basic cyclone phase criteria, and only for (a) varying maximum wind speed measurement level and (b) varying duration

(a) Vary wind level

	Strongest (T′ = 2, RV = 5.0, duration = 3	Weakest (dt = 0, RV = 1.0, duration = 1)
	# Tracks	# Tracks
850 hPa	78	363
1,000 hPa	69	213
10 m	62	179

(b)Vary duration

		Strongest (win. lev. = 10 m, T′ = 2, RV = 5.0)			Weakest (win. lev. = 850 mb, T′ = 0, RV = 0.0)		
Duration (days)	% change duration from duration = 1	# Tracks	% change from duration = 1	% change ratio	# Tracks	% change from duration = 1	% change ratio
1	−66.67	160	158.06	−2.37	363	274.23	−4.11
1.5	−50.00	124	100.00	−2.00	267	175.26	−3.51
2	−33.33	94	51.61	−1.55	182	87.63	−2.63
2.5	−16.67	80	29.03	−1.74	128	31.96	−1.92
3	–	62	–	–	97	–	

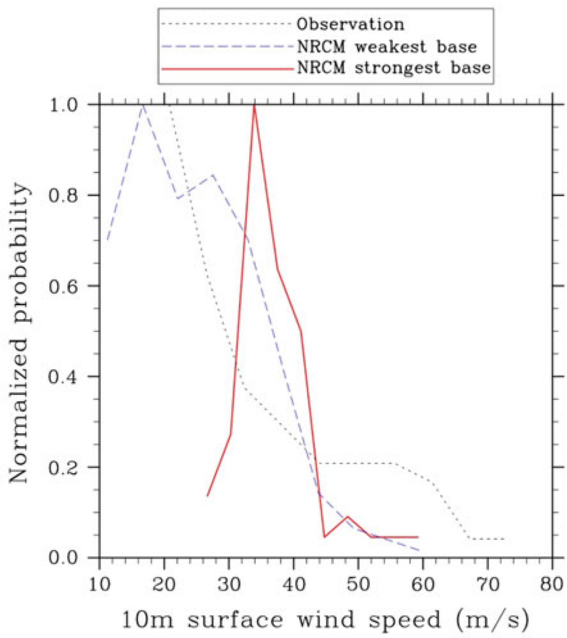

Fig. 2.8 Normalized probability (normalized by the maximum population) of lifetime maximum intensity of TCs satisfying the weakest (*blue*) and strongest (*red*) base criteria combinations, and of the observed TCs (*black*)

This study has examined the inherent sensitivity of TC detection to each TC tracking parameter. Parameter thresholds are varied across a reasonable range and tested for their relative impacts on the number of detected tracks. For an improved distinction of TCs from other low-pressure systems, the cyclone phase technique [7] is introduced to the TC tracking. The base data are the NRCM tropical channel simulation (Chap. 3).

The number of detected TCs can vary from none to more than 1,000 per year depending on the parameter configuration. Within the base tracking component, wind measurement level (equivalent to intensity) and duration provide the highest TC detection sensitivity. It is further shown that base tracking alone may not be enough to exclude orographically induced tracks and subtropical cyclones in South Pacific within the range of commonly used parameter values. Addition of structure criteria helps reduce detection of these erroneous TC. Further, vertical cross sections of horizontal temperature anomaly indicated that structure criteria can be satisfied even though there is no clear warm-core. Including cyclone phase parameters provides a more robust approach to detecting valid TCs with vertically aligned warm-cores. However, this also increases the detection sensitivity to cyclone maximum winds and duration parameters. It is also shown that the intensity distribution is sensitive to the TC tracking criteria. The stricter the intensity criteria, the more normal-shaped the distribution becomes.

In the subsequent analysis for the NRCM channel simulation (Chap. 3) and North Atlantic climate change experiment (Chap. 4), the following thresholds and criteria are used;

Table 2.6 Number of detected tracks and % changes by varying both intensity (10 m surface wind by 2.5 m s^{-1}) and duration (by 6-hours) thresholds from the standard set (intensity: 17 m s^{-1} at 10 m surface, duration: 48-h

	19.5 m/s, 54 h		17 m/s, 48 h	14.5 m/s, 42 h	
	# of tracks	% change	# of tracks	# of tracks	% change
North Atlantic	10	−16.7	12	14	16.7
East Pacific	8	−11.1	9	14	55.6
West Pacific	23	−11.5	26	33	26.9
Southeast Pacific	3	−40.0	5	7	40.0
Southwest Pacific	5	−44.4	9	15	66.7
Western Australia	5	0.0	5	10	100.0
North Indian	2	−60.0	5	6	20.0
South Indian	18	−18.2	22	26	18.2
Global	73	−21.5	93	125	34.4

- Maximum wind speed measured at 10 m surface >17 m s^{-1}
- RV > 1.0×10^{-5} s^{-1}
- Sum of horizontal temperature anomaly at 300, 500, and 700 mb > 2.0 K
- Structure criteria satisfied
- B < 10, −VTL > 0 and −VTU > 0
- Duration >2 days

Maximum wind speed threshold is based on the recommendation by Walsh et al. [15], who developed an objective framework for resolution-dependent intensity cut-off for numerical detection of simulated TCs. Structure criteria is kept to reduce erroneous tracks associated with orographically induced phenomena and to accelerate the track filtering process. The cyclone phase technique, even though treatment of B term may still be an issue, is adopted in order to detect only tropical warm-core systems. Other parameters are chosen to match the visual examinations of cyclone development using movie loops of 850 mb wind speed, OLR, and precipitable water.

The level of uncertainty in the number of detected tracks associated with TC tracking is infinite in the sense that one may tune the tracking parameters to detect no TCs or as many as thousands per year. While quantifying the level of uncertainty associated with TC tracking criteria is not possible, it is still helpful to set a sensible level of uncertainty. To do this, we arbitrarily choose to apply the level of uncertainty in the observed TC track data to the TC tracking. Unfortunately there is no established level of uncertainty in observed TC track data. A reasonable assumption is that the level of uncertainty in the observed data is proportional to the data resolution. Intensity is usually recorded in five knot (~2.5 m s^{-1}) increments, and the temporal resolution is 6-hourly. These increments are applied to TC tracking intensity and duration thresholds to test the inherent uncertainty, as summarized in Table 2.6. These provide a first order estimate of the level of uncertainty associated with TC tracking criteria.

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