NOTES AND CORRESPONDENCE

Improving the Accuracy of Mapping Cyclone Numbers and Frequencies

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ABSTRACT

The uncertainties associated with the mapping of cyclone numbers and frequencies are analyzed using the 42-yr winter climatology of cyclone tracks derived from 6-hourly NCEP–NCAR reanalysis. Tracking is performed using an automated procedure, based on computer animation of the sea level pressure field. Uncertainties in the mapping result from an incomplete catchment of cyclones by the grid cells: the coarse temporal resolution of data causes fast-moving storms to skip grid boxes. This introduces error into estimates of cyclone frequency, with cyclone counts systematically underestimated. To minimize these biases, it is possible to simulate higher temporal resolution of the storm tracks by linear interpolation applied to the original tracks. This simple procedure reduces bias in estimates of both cyclone frequencies and numbers and enables quantitative estimation of errors. Errors in cyclone counts are estimated over the Northern Hemisphere for different time resolutions and different grids. Standard errors in cyclone frequencies increase from 5%–15% to as much as 50% as the original temporal resolution of the storm tracks decreases from 6 to 24 h. Mapping the results on circular grids reduces these errors. Appropriate grid sizes for different temporal resolutions of the storm tracks are recommended to minimize the uncertainties in storm occurrence mapping.

1. Introduction

Cyclone activity is usually characterized by cyclone frequency maps derived from sea level pressure (SLP) data using automated storm tracking algorithms (e.g., Alpert et al. 1990; Le Treut and Kalnay 1990; Murray and Simmonds 1991; Koenig et al. 1993; Hodges 1994; Sinclair 1994, 1997; Serreze 1995; Serreze et al. 1997; Blender et al. 1997; Sinclair and Watterson 1999). Blender and Schubert (2000) recently studied the impact of different space–time resolutions on the results of cyclone tracking and found that a coarser temporal resolution may result in 10%–50% biases in cyclone counts (when the resolution decreases from 2-hourly to 24-hourly). Decreasing spatial resolution from T106 to T42 introduces approximately 30% bias in the number of cyclones. However, accuracy of storm tracking is not the only source of uncertainty in the analysis of cyclone activity. The procedures involved with mapping cyclone occurrences can also introduce error.

For latitude–longitude grids, there has been much debate on the choice between the so-called equal-area grids and scaling the results with latitude. Hayden (1981b) found that normalization by latitude results in biases in cyclone occurrence and recommended the mapping of raw frequencies or use of equal-area grids (e.g., Bellenzwieg 1959). However, Hayden (1981a,b) only considered the latitudes from 25° to 45°N, for which the area change of a latitude–longitude box is less than 25%. In the high latitudes, mapping becomes very sensitive to the cell size. In Arctic cyclone climatologies (Serreze and Barry 1988; Serreze et al. 1993, 1997; Serreze 1995), it is a common practice to use an equal-area grid based on the Lambert polar stereographic projection, when the grid cells are referenced to the Cartesian coordinate system (Thornrike and Colony 1980). However, in the midlatitudes and subtropics the actual configuration of cells of such grids becomes very different from that for the high latitudes and may not necessarily provide an effective catchment of cyclones. This is the second mapping problem, first quoted by Taylor (1986). To account for the varying density of the cyclone tracks of different directions, Taylor (1986) introduced the so-called effective cross sections, which require the use of gerrymander-type grids, which are impractical. An alternative approach is to use circular cells, first recommended by Kelsey (1925) and used for mapping cyclone frequencies in the Southern Hemisphere by Sinclair (1994). Circular networks are very effective for the consideration of regional climatologies. However, on a
Fig. 1. An idealized example of estimating storm frequencies \( n \) and \( ni \) and numbers \( nc \) and \( nci \) for the 10 idealized boxes from the storm tracks with original temporal resolution \( n, nc \) and simulated 1/6 temporal resolution \( ni, nci \).

global scale they may result in variable spatial smoothing at different latitudes. Some authors convert the raw frequencies into percent frequencies (Keegan 1958; Serrere et al. 1993). In this case, a given cell is associated with a percentage of the total number of lows over the hemisphere. However, the use of the percent frequencies creates difficulties in studying interannual variability in the cyclone activity.

The third problem of cyclone frequency mapping is the dependence of the catchment of cyclones on the temporal resolution of storm tracks. No grid (be it rectangular, circular, or other) can account fully for fast-moving cyclones that pass one or more grid cells during one time step. These biases tend to underestimate storm counts. Murray and Simmonds (1991), Sinclair (1994), and Chandler and Jonas (1999) interpolated 12-hourly track points to 6-hourly spacing to account for this problem. Nevertheless, a general approach to minimizing and understanding this bias has yet to be well developed.

Our study will quantify these biases for different mapping geometries and will suggest a simple procedure for their minimization. In section 2 we formulate the problem using an idealized example. Section 3 describes the data and the method used to perform storm tracking. Results of the quantitative estimation of the mapping uncertainties associated with the resolution of storm tracks for different grids are presented in section 4. Section 5 summarizes the results and discusses their possible applications.

2. Formulation of the problem

An idealized example, summarizing the problem, is shown in Fig. 1. Two cyclones (I and II) are tracked in the 10 neighboring boxes for the original temporal resolution \( t \), which varies in practice from 6 to 24 h for different analyses and models. We will term the number of the pressure minimum events, counted by an Eulerian observer within the box during the chosen time interval (e.g., month, season), the cyclone frequency \( n \). The number of cyclones that pass the box during the same time (multiple entries have to be ignored) will be defined as the number of cyclones \( nc \). These measures correspond to the cyclone density and track density, respectively, used by Sinclair (1994). The relationship between these two is not trivial. Cyclone frequency is influenced by both number of transients and their velocities, whereas number of cyclones is less affected by the propagation velocity. If we consider a single cyclone tracking, the derived cyclone frequency (the so-called partial frequency) is equal to the time of the cyclone’s passing through the box. It has an accuracy of \( \pm 2t \).

If the typical cyclone migration during one time step is comparable to the box size, both cyclone frequency and the number of cyclones will be biased. Biases will increase for fast cyclones (boxes 4 and 9 in Fig. 1) and for the cyclones “cutting” the box corners (box 7). Biases can be minimized if we simulate a higher temporal resolution by linear interpolation between the storm-track points. This procedure has to be applied to the results of the tracking and not to the initial SLP fields; that is, it does not imply any assumptions about the development of the SLP field during a \( t \)-hourly period and does not change the storm tracks. Linear interpolation results in the same tracks but with \( t/6 \) temporal resolution (Fig. 1). The estimates of cyclone frequencies and numbers from the interpolated data (\( ni \) and \( nci \), respectively) are less biased (their accuracy is \( \pm t/3 \)). To compare the frequencies derived from the original and interpolated data, partial frequencies have to be scaled with the cyclone lifetime. Table 1 shows the frequencies derived from the original and interpolated data. The coarse temporal resolution results in biases of both signs, which vary in magnitude from 50% to 100% of the mean values. If we enlarge the box size (holding the time step constant), the biases reasonably become
smaller. In the case of a very large box (say, the Atlantic Ocean, or the Northern Hemisphere), the biases are equal to zero. However, such large cells do not allow detailed mapping of regional cyclone numbers and frequencies and provide only large-scale estimates, which are, however, more accurate than the box averages. Thus, mapping cyclone frequencies and numbers requires either analysis of the relationship between the grid size and temporal resolution or interpolation between time steps for a given grid geometry.

3. Data and preprocessing

We used the results of storm tracking performed (Gulev et al. 2001) for the 42 winter seasons (January–March) from 1958 to 1999 from the 6-hourly National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) SLP fields using the software of Grigoriev et al. (2000). This software is based on a computer analysis of the SLP fields and simulates the manual procedure but makes it faster and less dependent on the subjective view and mistakes of a particular operator. The cyclone centers are defined automatically as a minimum pressure with respect to the eight neighboring points, and then the tracking is carried out by an interactive procedure. The output of the tracking is the coordinates, time, and corresponding SLP values. For use with the Grigoriev et al. (2000) software, we interpolated 2.5° SLP fields onto a 181 × 181 polar stereographic grid, using a modified version of a procedure of Akima (1970). Tracking errors, estimated from the outputs of different operators for the selected years, were less than 5% (Gulev et al. 2001). Although the NCEP–NCAR reanalysis provides 6-hourly SLP data, a coarser time resolution (12 and 24 h) is commonly used for cyclone analysis. Thus, the resolution of the NCAR SLP archive (Trenberth and Paolino 1980) is 12–24 h. Stein and Hense (1994) computed their storm counts using daily data. To estimate the uncertainties in mapping storm tracks of coarser temporal resolution, we derived datasets that correspond to 12-hourly (0000 and 1200 UTC) and 24-hourly (0000 UTC) resolution. This procedure has been applied to the storm tracks derived from the original resolution and not to the SLP data; that is, it did not affect the accuracy of the tracking itself.

To get the reference estimates of cyclone frequencies and numbers, the original 6-hourly and simulated 12- and 24-hourly storm tracks were linearly interpolated on time steps of 10 min (36 points per one 6-hourly step). This guarantees nearly negligible biases. A typical cyclone migration during 10 min varies from 3 to 15 km, which is much smaller than the dimensions of the grid used to map the results. We examined three quasi-rectangular grids with the basic dimensions south of 88°N, and then uses

<table>
<thead>
<tr>
<th>Box No.</th>
<th>Original temporal resolution</th>
<th>Simulated 1/6 temporal resolution</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1/6 = 0.16</td>
<td>3/31 = 0.09</td>
<td>0.07</td>
</tr>
<tr>
<td>2</td>
<td>1/6 + 1/5 = 0.37</td>
<td>6/31 + 1/25 = 0.23</td>
<td>0.14</td>
</tr>
<tr>
<td>3</td>
<td>2/6 = 0.33</td>
<td>10/31 = 0.32</td>
<td>0.01</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>4/31 + 1/25 = 0.18</td>
<td>-0.18</td>
</tr>
<tr>
<td>5</td>
<td>2/6 + 1/5 = 0.54</td>
<td>8/31 + 2/25 = 0.34</td>
<td>0.2</td>
</tr>
<tr>
<td>6</td>
<td>1/5 = 0.20</td>
<td>3/25 = 0.12</td>
<td>0.08</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>6/25 = 0.24</td>
<td>-0.24</td>
</tr>
<tr>
<td>8</td>
<td>1/5 = 0.20</td>
<td>5/25 = 0.20</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>2/25 = 0.08</td>
<td>-0.08</td>
</tr>
<tr>
<td>10</td>
<td>1/5 = 0.20</td>
<td>5/25 = 0.20</td>
<td>0</td>
</tr>
<tr>
<td>1 + 2 + 6 + 7</td>
<td>2/6 + 2/5 = 0.73</td>
<td>9/31 + 10/25 = 0.69</td>
<td>0.04</td>
</tr>
<tr>
<td>4 + 5 + 9 + 10</td>
<td>2/6 + 2/5 = 0.73</td>
<td>12/31 + 10/25 = 0.78</td>
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<tr>
<td>Total</td>
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<td>2.00</td>
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</tr>
</tbody>
</table>

4. Results

To assess the problem, we first examined characteristics of cyclone propagation that are important for the estimation of mapping biases. Figures 3a and 3b show climatological winter maps of the mean and maximum cyclone propagation velocities, computed from the 6-hourly tracks. Mean cyclone propagation velocity (Fig. 3a) varies from a minimum of 25 to a maximum of 75 km h⁻¹. The largest mean velocities are observed in the central Pacific and over the eastern American coast. The regions of the slowest mean cyclone velocities are associated with the subpolar Pacific and Arctic basins. The highest maximum velocities are ranged from 100 to 120 km h⁻¹ and are associated with the subtropical Pacific,
American continent, and the North Atlantic midlatitudes (Fig. 3b). Figures 3c and 3d demonstrate the mean cyclone propagation vectors and the characteristics of their directional steadiness, which was estimated in percent for 45° directional classes. Average cyclone propagation directions are similar to climatological geostrophic winds. They are primarily eastward over the Gulf Stream and Kuroshio Current and turn to the northeast over the open midlatitudinal and subpolar Atlantic and Pacific. In the Arctic the preferential propagation of cyclones is to the northeast. Figure 3d shows the dominating eastward and northeastward cyclone propagation over the North Atlantic and North Pacific. However, some cyclones propagate in other directions. Over other regions, the scatter in the cyclone propagation directions is higher. Thus, it is difficult to select a single direction, determining the so-called effective cross section (Taylor 1986), that guarantees the effective catchment of lows.

It is important to introduce the relationship between a length scale $L$, a timescale $T$, and a speed $U$. From the cyclone propagation velocity we derived for every grid cell an estimate of the length of cyclone migration during 6-hourly time step ($r_{m6}$). It can be compared with the actual length of the cyclone trajectory captured by the same cell ($r_t$). Figure 3e shows the spatial distribution of the climatological ratio,

$$R = \frac{r_{m6}}{r_t} \sim \frac{UT}{L},$$

for grid 1. If the ratio $R$ is less than 1, the biases in cyclone frequencies and numbers are negligible. For the areas where $R$ is greater than 1, the biases associated with the poor catchment of transients by the grid cells will increase. Figure 3e shows that grid 1 is not effective, even for the 6-hourly storm tracks in most of the locations. The highest expected errors are observed in midlatitudes and in the Arctic basin. North of 30°N, $R$ varies from 1 to 4, indicating that the size of the grid cells in high latitudes was more or less properly selected. For instance, the use of the 5° grid north of 70°N results already in $R$ values of about 20–30.

As a basis for further analysis we show first the winter cyclone frequencies and numbers (Figs. 4a,b) computed for grid 1 using results of cyclone tracking interpolated onto 10-min steps. They exhibit the number of pressure minima and the number of cyclones per winter per 218 000 km² (square of the 5° × 5° box at 45°N). General features of these charts were discussed in Gulev et al. (2001). The highest frequencies are associated with
Fig. 3. Winter climatological (a) mean and (b) maximum cyclone propagation velocities (km h⁻¹), (c) climatological cyclone propagation vectors (km h⁻¹), (d) directional steadiness of the cyclone propagation for the selected regions (%), and (e) ratio R for grid 1. Contour intervals are (a) 10 km h⁻¹, (b) 20 km h⁻¹, and (c) 1.
the Aleutian low and Icelandic low. The maxima of the number of cyclones are located over the Gulf Stream and Kuroshio Current, where they are higher than in the Aleutian and Icelandic low regions. Cyclone frequencies in Fig. 4a are referenced to 6-hourly time steps. To compare cyclone frequencies derived from the data with different temporal resolutions, we show in Fig. 4c the normalized (with respect to the cyclone lifetime) winter cyclone frequency, which will be used as a reference for future comparisons.

Figure 4d shows the absolute difference between the normalized cyclone frequencies, derived from the interpolated and the original 6-hourly storm tracks for grid 1. The spatial distribution of the differences shows that coarse temporal resolution results in both positive and negative biases in the storm frequencies, which lie within 15% of the mean normalized cyclone frequency (Fig. 4c). They do not exhibit any regular pattern. If the points of a coarse-resolution track are not captured by a grid cell, the frequency is underestimated. However, when

**Fig. 4.** Winter climatological cyclone frequency (events per winter), referenced to (a) 6-hourly time steps and (b) the number of cyclones (cyclones per winter), (c) cyclone frequency normalized with the cyclone lifetime, and (d) the spatial distribution of the absolute errors in the cyclone frequencies for 6-hourly resolution and grid 1.
the coarse-resolution track points are marked in the grid cell, the actual frequency, normalized with the cyclone lifetime, may be higher than for that derived from the high-resolution tracks. This is easily visible from an idealized example in Fig. 1. Thus, the uncertainty in cyclone frequencies appears random.

Figure 5 shows the standard errors in the normalized cyclone frequencies for 6-hourly (panel a) and 12-hourly (panel b) storm tracks for grid 1, estimated in percent of the frequencies derived from the interpolated (on 10-min resolution) storm tracks. Figures 5c and 5d compare the estimates of the number of cyclones derived from 10-min tracks with the raw cyclone numbers for 6-hourly and 12-hourly tracks. Corresponding estimates for 12- and 24-hourly temporal resolution but for grid 2, are shown in Figs. 6a–d. Cyclone frequencies demonstrate the highest standard errors over continental North America (in the Great Lakes and Rocky Mountains regions), the Mediterranean, and in the Arctic basin, where they are larger than 15% for 6-hourly temporal resolution and grid 1. Over the other regions, standard errors vary from 3% to 10%. For 12-hourly resolution and grid
Fig. 6. Same as Fig. 5 but for the (a), (b) 12-hourly and (c), (d) 24-hourly temporal resolution for grid 2.

1, standard error increases up to 25% over continental North America and the storm formation regions and up to 15% in the areas of Aleutian and Icelandic lows. For 12-hourly temporal resolution and grid 2 (Fig. 6a), the uncertainties grow up to 20%–30% over the main North Atlantic and North Pacific storm tracks and in the Arctic basin. Relative standard errors in the cyclone frequencies derived from 24-hourly data (Fig. 6c) may be higher than 50% for the midlatitudinal areas and in the Arctic.

If we consider the number of cyclones, coarse-resolution tracking results in systematic underestimation of the cyclone counts. For a 6-hourly resolution and grid 1 (Fig. 5b), the number of cyclones in the storm formation regions can be underestimated by 10%–20%. Relative errors grow considerably over the central Atlantic and central Pacific as well as in the Icelandic and Aleutian lows, reaching 50%. The use of 12-hourly resolution for grid 1 (Fig. 5d) results in a 20%–40% underestimation of the number of cyclones in storm formation regions and in 30%–80% biases in open-ocean regions and in the Arctic. Errors for grid 2 and a 12-hourly resolution (Fig. 6b) are slightly higher than those obtained for grid 1 and a 6-hourly resolution. The use of a 24-hourly resolution in combination with grid 2 (Fig. 6d) results in biases that are 5%–15% higher than for the 12-hourly tracking in grid 1.
Ratio $R$ determined by (1) shows how effective the chosen relationship between the grid size and temporal resolution of tracks is. Figure 7 demonstrates the scatter between this ratio and the error in the number of cyclones for 6-hourly resolution and grid 1. The underestimation of the number of cyclones grows exponentially with $R$, and the relationship can be approximated as

$$\delta(nc) = 0.049 \exp(1.238R),$$

(2)

where $\delta(nc)$ is the absolute error in the number of cyclones. A typical number of cyclones in the main storm track areas is from 5 to 18 per winter per box for grid 1. Thus, $R$ greater than 2.5 results in higher than 20% underestimation of cyclone counts. For coarser resolutions, the exponential dependence stands but the biases in the number of cyclones become 60% higher for 12-hourly resolution and nearly 100% higher for daily resolution. Use of grid 2 decreases the error in the number of cyclones by 1.4–2.6 times but again holds the exponential dependence valid.

It is interesting to estimate whether the use of circular networks (Sinclair 1994; Sinclair and Watterson 1999) can decrease the biases in mapping cyclone numbers. We derived the estimates of the number of cyclones for a circular network with a radius of 555 km (5° at the equator). This grid was used by Sinclair (1994) for a cyclone climatology in the Southern Hemisphere. In terms of the catchment area, such a grid corresponds to approximately $10^5 \times 10^5$ boxes in low latitudes. As for the latitude–longitude grids, for circular cells we estimated the number of cyclones from 6-hourly tracks and from the tracks interpolated onto a 10-min resolution. Spatial patterns of cyclone counts for this grid become much smoother. Multiple counts of cyclones in the overlapping neighboring circular cells have the effect of a smoothing operator. Figure 8a shows the absolute errors in the number of cyclones derived for a given circular grid from 6-hourly storm tracks. Underestimation of the cyclone numbers is within 5%–7% of mean values for most regions. For the 12-hourly resolution (Fig. 8b), biases increase up to 10%–15% of the mean values. The largest biases are observed in the midlatitudes. These
estimates can be compared very roughly with our results for grid 3 (10° × 10° boxes). Biases estimated for 6-hourly tracks and grid 3 are 1.5–3 times higher than those for a circular network. For the 12-hourly resolution, this ratio is from 1 to 2. Thus, a circular averaging geometry provides in general more effective cyclone catchment than do the rectangular boxes. However, the results derived for this geometry are influenced by inadequate spatial smoothing, especially in high latitudes.

### 5. Summary and discussion

Uncertainties inherent in cyclone frequencies and numbers for different grid cells have been analyzed using storm tracks of different temporal resolution. The relationship between the temporal resolution of storm tracks and the grid size determines the level of the random errors in cyclone frequencies and a systematic underestimation of the number of cyclones. To minimize these biases, we simulated a higher temporal resolution of the storm tracks by a temporal interpolation of storm tracks, which gives the least biased estimates of both cyclone frequencies and numbers. For the rectangular grid with the basic grid size of 5° and a 6-hourly temporal resolution, random errors in cyclone frequencies may be higher than 15% and an underestimation of the number of cyclones can range from 10% to 20%. The uncertainties grow considerably for coarser temporal resolutions. The use of a circular averaging geometry decreases the uncertainties but does not allow us to avoid them fully.

If the tracking is performed on the basis of 6- to 24-hourly data, one has to be careful with the selection of the optimal grid for mapping cyclone frequencies and numbers. Table 2 summarizes the results for the three most frequently used temporal resolutions and the three rectangular grids on a hemispheric scale. Already for a 6-hourly resolution the uncertainties are not negligible. The average random error in the cyclone frequencies is 7.4% for grid 1. For the grids with larger boxes (grids 2 and 3) the uncertainties decrease but still remain at the 5% level. Temporal resolution of 12 h implies for grid 1 a relative standard error of 10%. It decreases by 10%–30% for the grids with larger boxes. The use of daily data results in uncertainties of 14% for grid 1 and about 10% for grid 3. Variations between different basins are not large, although there is a general tendency for decreasing uncertainties in the Arctic. The underestimation of the number of cyclones derived from the 6-hourly data is about 20%, 11% and 6% for grids 1, 2, and 3, respectively. For a coarser temporal resolution, this uncertainty grows and reaches a level of 50% for the daily data. The use of a circular averaging geometry results in the mean underestimation of the number of cyclones of 3.9% for 6-hourly tracks and 9.8% for 12-hourly tracks. These are 1.2–1.5 times smaller than for grid 3, which roughly can be taken as a reference for comparison with averaging within the radius of 555 km.

Different authors use different latitude–longitudinal grids for mapping the results of cyclone tracking. Taylor (1986) reviewed the gridbox sizes used in different studies. The typical grid size used is approximately 2° × 5° (e.g., Hayden and Smith 1982), although some climatologies are derived for 2° × 2° (e.g., Zishka and Smith 1980; Trigo et al. 1999) and even 1° × 1° (e.g., Colucci 1976). Approximately one-half of the climatologies were performed for the 5° × 5° grid (e.g., Dickson and Namias 1976; Whittaker and Horn 1981). Taking into account that most results were derived from 12-hourly or coarser resolution, we can conclude that the characteristics of cyclone activity reported by many authors were influenced by the uncertainties in cyclone frequencies and numbers. Sickmoeller et al. (2000) recently used very large boxes (of about 5° latitude) for the 6-hourly data. Chandler and Jonas (1999) used 8° × 4° grid over the Northern Hemisphere and partly accounted for the cyclones that pass the boxes faster than during 12 h. However, even their results at high latitudes are influenced by the uncertainties. Thus, if the original resolution of tracking is 6 or 12 h and no post-processing is applied, one should use at least a 5° × 10° grid to minimize the uncertainties to the level of 10%. The use of finer than 5° × 5° grids (say, 2.5° × 2.5°) may result in very high uncertainties in both cyclone frequencies and numbers. The use of circular averaging geometry is an advantage, because it gives 1.5-times smaller uncertainties with respect to the rectangular networks. However, even for these networks, biases are not negligible and an interpolation of the storm tracks is required, especially for the averaging radius smaller than 555 km. Moreover, multiple cyclone counts may result in the spatial smoothing of patterns, especially in high latitudes.

Interpolation, applied to the storm tracks, minimizes the level of uncertainties inherent in the gridded cyclone frequency datasets.
numbers and frequencies. It makes the mapping procedure practically independent of the original temporal resolution of the data used. It does not mean, of course, that this procedure can improve the accuracy results of the original analysis. Clearly, numerical storm tracking algorithms demonstrate higher skill for high-resolution data. The procedure recommended here also helps to account partly for the problem of the gridcell orientation (Taylor 1986). Simulation of very high temporal resolution of the storm tracks provides an effective catchment of cyclones even for cells that are not properly oriented with respect to the preferential directions of the cyclone propagation. Note that circular geometry also avoids this problem. Figure 9 shows the effective time step that can be used for interpolation to provide estimates of cyclone numbers with an accuracy of about 5% for grid 1, which guarantees that 95% of all cyclones passing the boxes will be marked at least once within the box. This map has been derived from the actual estimates of rm and rt for 42 winters from 1958 to 1999. For most regions, a 2–3-hourly resolution is appropriate. The main Atlantic storm-track area requires a somewhat finer resolution in comparison with the Pacific.

The development of this study can go in several directions. It is important to determine the optimal grids for the most effective catchment of cyclones. For limited areas (e.g., the North American east coast), a circular averaging geometry can be used. The procedures justified in our study will improve the accuracy of mapping of cyclone numbers and frequencies for such a grid, and will help to quantify uncertainty. Our study may also have implications for analysis of climate variability of cyclone characteristics. The cyclone life cycle may have pronounced interannual-to decadal-scale variability, associated with the changes in the intensity of synoptic processes on different scales (Gulev et al. 2000). Gulev et al. (2001) found that during the period from 1958 to 1999 there was a general tendency of increasing deepening rate, decreasing cyclone lifetime, and increasing number of relatively slow cyclones over the Northern Hemisphere. Changes in the cyclone velocities may produce time-dependent biases, if the time resolution used is inappropriate with respect to the grid size chosen for the averaging of results.

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