Stride Search: A general algorithm for storm detection in high resolution climate data

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Dear Editorial Staff, Referees, and Readers,

We thank the three referees for their time and valuable comments regarding our discussion paper [1]. In particular, the additional references provided by Referees #1 and #3 were very helpful. We begin our response with a general remark based on all referees' responses. In the following sections we address the comments of each referee individually. We are grateful for the discussion provided by the review process.

Sincerely,

Peter A. Bosler

1 General remark

In most studies that require some sort of storm tracking algorithm (e.g., [3]), the focus is on the particular definition of a storm – what we refer to as *identification criteria* – and several studies investigate the consequences of choosing one set of criteria over another.

In developing Stride Search we also found a significant effect introduced at a lower level in each algorithm: the implementation of the spatial search. The same identification criteria can produce different results depending upon the specific definition of a neighborhood, or search sector. Moreover, we found that these effects change with latitude because the length scales associated with grid point distance also change with latitude. In other words, we found that the results of a storm search code are influenced by and coupled to the algorithm's search sector definition and how that sector is defined in the given data, regardless of the identification criteria used for a particular application. As discussed by many authors, different criteria have differing degrees of sensitivity to the spatial scales introduced by a code's sector definition; however, it is our opinion that the definition of a meteorological event should depend only on meteorological concerns, not algorithmic details.

Our goal was therefore to produce a general algorithm that would decouple the definition of a storm from both the underlying spatial search algorithm and the layout of a particular data set. In Stride Search, we achieve this by separating the choice of identification criteria from the search sector definition. In addition to the polar search capability that such an algorithm provides, the basic Stride Search algorithm remains unchanged when applied to different data layouts (e.g., unstructured grids, variable resolution meshes, etc.), and it accesses the data more efficiently than the basic grid point search which improves performance for today's increasingly high resolution data.

It is clear from all the reviewers' responses that the original manuscript did not emphasize these points clearly enough, and we will revise the paper to better convey them.

2 Response to referee #1

2.1 Major comments

1. Whether or not the angular distance formula (equation (3) from [1]) is used explicitly, it is implicitly used whenever a grid point distance is used. For example, ensuring that the 8 neighboring grid points have a higher SLP than the central point (e.g. [2, 3]), implicitly links the spatial scale of the data to the search algorithm. Some authors employ a smoothing algorithm or change the identification criteria to mitigate the effect of changing data resolution with latitude, others, e.g., [2] perform a remapping transformation as a preprocessing step. Stride search, via equations (5), (6), and (7), performs these modifications automatically.

   We agree with the referee that most grid point search methods do include physical distance on the sphere at some point into their algorithm. TSTORMS itself uses the geodesic distance formula (equation (4) from [1]) when it constructs storm tracks. As the referee notes, however, this inclusion is done in a way that may vary depending on the specific application and the specific identification criteria used, whereas in Stride Search spatial scales and meteorological variables are treated independently of each other.

   While the use of equation (4) to measure distance is not a new advance, its role in defining the search sectors in equation (7) is, and this has the consequence of decoupling the user's application from the data set which cannot be done when sectors are defined in grid point space. As the referee suggests, we will revise the article to highlight this point more clearly.

2. We stress that the main point of our work is in the division of the search region into sectors independently from the data – how storms are defined within each sector is up to the user. If a user is interested in the multi-centered cyclones studied by [2], he or she can use Stride Search in a variety of ways:

   (a) To locate a cyclone with multiple centers, the users could define their identification criteria to require multiple sea level pressure minima within one sector radius.

   (b) To locate individual circulation centers, a smaller sector radius can be chosen.

   (c) The tracking procedure of [2] could be used without alteration in conjunction with Stride Search to allow for the mergers, splitting, and reconnection of multicentered cyclone tracks.

2.2 Minor comments

1. Consider an application where a user requires a search of a global data set (all latitudes). We claim a grid point search can fail in such a scenario. Grid point search sectors are $(2n + 1) \times (2n + 1)$ neighborhoods with n fixed. If n is defined near the equator, those sectors will shrink in their zonal extent at polar latitudes and will no longer be capable of resolving zonal features. If n is chosen for a spatial scale at the pole, it may require accessing every longitudinal grid point. This obviously doesn't make physical sense at the equator, but more importantly it may cause memory overload or at least a considerable slowdown at lower latitudes.

   Of course users could run separate searches for different bands of latitudes, each with its own n, but this places an additional burden on the user. Some users may treat tracking software as a "black box," and may not be aware of the necessity to choose a different n for different sets of latitudes. Such users risk producing incorrect results when using a grid point search globally.

2. We will change this sentence in the revised article.

3. We will change this sentence in the revised article.

4. We will change this sentence in the revised article.

5. The cost of duplicate removal is negligible compared to the search of the original data set. We will quantify this statement in more detail in the revised article.

6. The two resolutions were chosen arbitrarily by two different researchers. One happened to choose unmodified powers of 2: the $\Delta\lambda = 0.35°$ data correspond to a $(513 \times 1024) = (2^9 + 1 \times 2^{10})$ latitude-longitude grid. The other chose to divide the spacing of a one-degree mesh by 4: the $\Delta\lambda = 0.25°$ data correspond to a $(721 \times 1440) = (180 \cdot 4 + 1 \times 360 \cdot 4)$ latitude-longitude grid.

7. We will change this sentence in the revised article.

8. The search area for the tropical storms section never changes – it is 40S to 40N for all data resolutions. We did adjust the TSTORMS n parameter for each resolution. The number of sectors that TSTORMS has to search increases by a factor of 4 because TSTORMS visits every grid point, and there are 4 times as many grid points between 40S and 40N each time the grid resolution is halved.

9. We will change this sentence in the revised article.

10. The original statement is too broad and we will remove it from the revised article. See Minor Comment 1.

11. TSTORMS was not designed for polar applications. We felt it would be an unfair comparison to directly apply TSTORMS to polar search applications.

12. This paragraph and Figure 8 show a storm has small spatial scales (and thus requires high resolution data to resolve) and that is near the pole. Both issues (polar latitudes, high resolution data) were key design motivations for Stride Search and this figure is intended to show the algorithm's success. Rather than excluding the figure, we will revise the article to better convey its relevance.

13. We demonstrated Stride Search for two very different meteorological events, tropical cyclones and polar lows. The forcing for the two types of cyclones are very different, and their identification criteria are different as a result. For example, the identification criteria for tropical cyclones required only atmospheric data, while the identification criteria for polar lows includes both sea surface temperature and ice fraction.

    We will look into developing a third application to provide an additional demonstration of the algorithm's generality, however this may not be possible due to constraints of personnel time and funding. At a minimum, we will revise the article to better highlight the differences in the two applications and to stress the fact that the majority of the Stride Search code is used by them both.

14. We also had hoped that the two algorithms would produce the same results when using the same set of identification criteria and the same threshold values for those criteria. We considered adding a small discussion to document the adjustment of the criteria of one algorithm so that the two codes produce the same results, but it is not clear which of the 4 criteria used should be adjusted or how to adjust them.

    We chose to report the numbers as they are to emphasize the influence of the algorithm on the results – the only difference between the two codes is the spatial search sectors. Ultimately we felt that it was more illuminating to expose this difference between the algorithms for low-intensity storms, which was also noted in [3].

15. We address the additional artifacts produced by Stride Search (shown in Figure 3) on page 7742, lines 7–15.

3 Response to referee #2

3.1 Major comments

1. Regarding the use of the geodesic distance formula, please see our response to Referee #1 (section 2.1, item 1), for a discussion of this issue. Regarding computational performance, we agree that rerunning the timing experiments without the output subroutines will produce a valuable comparison. This will be including in the revised article. Unfortunately, the TSTORMS code crashes when run on $\Delta\lambda = 0.125°$ data sets, and we therefore have not been able to run a comparison of the two codes at such high resolution.

4 Response to referee #3

4.1 General comments

1. We chose to use only 3 months of data to produce a small enough number of storm tracks so that individual storms could be easily compared between both algorithms.

   We agree that performing an additional comparison on the entire 5-year data set could provide more insight. We will revise the article to also include the whole data set.

2. We will review the reference and add it to our revised paper.

4.2 Specific comments

1. We will change this sentence in the revised article.
2. We will change this sentence in the revised article.
3. We chose to define the temporal correlation steps and the distance traveled between timesteps as simply as possible. It would be only a small change to the algorithm to use more information for applications where more information is known, for example, in a tropical cyclone search where a westward-poleward drift is more probable.
4. We will change this sentence in the revised article. The location of a particular event is dependent upon the specific application, but we can provide a more elaborate discussion.
5. See previous comment.
6. We will change this sentence in the revised article.
7. We will find a reference and/or provide a more detailed discussion.
8. We will fix the typo in the revised article.
9. We will change this sentence in the revised article.
10. See above response to General Comment 1 (Section 4.1 item 1).
11. $U_{\max}$ and $t_{\min}$ were indeed chosen to match TSTORMS. Additionally, to match TSTORMS, times cannot be skipped – storms with a "missing time step" would be counted separately by both algorithms.
12. The only difference between the two algorithms is the definition of the search sector – the same criteria were used by both, and the track construction algorithm is identical between both codes. We suspect that the Stride Search results show more low intensity storms due to the effects discussed on page 7742, lines 7–15.

13. We will add definitions for P_{sl} and τ_P to the text.
14. We will fix the typo in the revised article.
15. We will change this sentence in the revised article.
16. We excluded the first year of data by habit; including it would have no consequence for this work. The data set was chosen because it was the highest resolution data to which the authors had easy access. It was produced from a study [4] whose objective was to demonstrate the capability of the Community Earth System Model to run at such high resolutions in high performance computing environments. Issues such as model spin up and physical parameterization tunings were not a focus of [4] and were not part of our investigation.
17. We can remove the grid lines from the plots of Figures 3 and 4.
18. We will add suitable labels to Figure 7.

References

[1] P. A. Bosler, E. L. Roesler, M. A. Taylor, and M. Mundt, Stride Search: A general algorithm for storm detection in high resolution climate data, *Geosci. Model Dev. Disc.*, 2015.

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[4] P. H. Worley, A. P. Craig, J. M. Dennis, A. A. Mirin, M. A. Taylor, and M. Vertenstein, Performance of the Community Earth System Model, in *International Conference for High Performance Computing, Networking, Storage, and Analysis (SC11)*, November 2011, Seattle, WA.