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# TempestExtremes: A Framework for Scale-Insensitive Pointwise Feature Tracking on Unstructured Grids

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**Abstract**

This paper describes the TempestExtremes package.

## 1 Introduction

The need for automated pointwise feature tracking has emerged as a major data processing challenge in climate science. These "trackers" have been employed throughout the literature to answer scientific questions on the expected changes in important atmospheric features under climate change. Exploration of the literature on trackers exposes a vast breadth of potential techniques (see Appendix A2) that have been applied to climate datasets with varied spatial resolution and temporal frequency. Nonetheless, the definition of an optimal objective criteria for atmospheric features has eluded development, suggesting that there may be no singular criteria capable of both perfect detection and zero false positive rate. Further, as observed by Walsh et al. (2007) for tropical cyclones and Neu et al. (2013) for extratropical cyclones, feature tracking schemes can produce wildly varying results depending on the specific choice of threshold variables and values. Consequently, we argue that conclusions drawn from these trackers should use an ensemble of detection thresholds and variables. To this end, it is the goal of this paper to develop and present a unified framework that enables a variety of tracking procedures applicable across effectively arbitrary spatial resolution and temporal frequency.

On reviewing the existing literature (Appendix A2), it quickly emerges that most algorithmic trackers share a common detection procedure:

1. Identify an initial set of candidate points by finding local extrema. Local extrema can be further isolated, for instance by requiring that the local extrema be sufficiently anomalous when contrasted with their neighbors. For most cyclonic structures, either minima in the sea level pressure field or maxima in the absolute value of the relative vorticity are used.



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2. Eliminate candidate points that do not satisfy a prescribed set of thresholds. For instance, tropical cyclones typically require the presence of an upper-level warm core that is sufficiently near the sea level pressure minima.

3. Connect candidate points together in time to generate feature paths, eliminating paths that are of insufficient length or do not meet additional criteria.

The procedure described above fits into a general framework known as MapReduce (**?**), which is a combination of a Map(), an embarrassingly parallel candidate identification procedure applied to individual time slices, and a Reduce(), which stitches candidates across time to build feature tracks.

The development of a tracking framework that is robust across essentially arbitrary datasets requires some additional considerations. In particular, we expect that our framework should:

> ...use great-circle arcs for all distance calculations. This avoids issues associated with latitude-longitude distance that emerges near the poles.
>
> ...support structured and unstructured grids. This eliminates the need for post-processing of large native-grid output files and enables detection and characterization simultaneous with the model execution.
>
> ...not contain hard-coded variable names, so as to ensure robust applicability across reanalysis datasets and applicability to a variety of problems.
>
> ...allow for easy intercomparison of detection schemes by enabling all detection criteria to be specified on the command line.

Well-known automated software trackers include Kevin Hodges' TRACK code (Hodges, 2015) and the Geophysical Fluid Dynamics Laboratory (GFDL) TSTORMS package (**?**) Others?. Both of these software packages have been used extensively throughout the literature for studies examining pointwise features in the atmosphere, but do not completely satisfy our four requirements above.

Although the precise parameters made throughout the tracking literature vary, there are clearly several core algorithms (kernels) must be exposed to the user. Kernels include:

- Identification of local extrema in a given 2D data field (for instance, sea level pressure minima).
- Determination of whether a closed contour exists in a data field around a particular point.
- Computation of anomalies in a data field from a spatially averaged mean.
- Determination of whether, in the neighborhood of a particular point, a data field satisfies a given threshold.
- Stitching of candidates from sequential time slices to build feature tracks.

Note that identification of local extrema is not a resolution-insensitive procedure, since the number of extrema will often scale with the number of spatial data points, and so initial identification is typically augmented with the more scale-insensitive closed contour criteria (see section 2.4).

The software described in this manuscript has been released as part of the TempestExtremes software package, and is available for use under the Lesser GNU Public License (LGPL). All software can be obtained from GitHub here:

`https://github.com/ClimateGlobalChange/tempestextremes`

The remainder of the paper is organized as follows: Section 2 describes the algorithms and kernels that have been implemented in the TempestExtremes software framework. Selected examples of tropical cyclone, extratropical cyclone and tropical easterly wave detection are then provided in section 3, followed by conclusions in section 4. The appendices provide a review of relevant literature on pointwise feature trackers of extratropical cyclones (appendix A1), tropical cyclones (appendix A2) and tropical easterly waves (appendix A3). A technical guide to the use of `DetectCyclonesUnstructured` and `StitchNodes` is provided in appendices A4 and A5.

## 2 TempestExtremes Algorithms and Kernels

This section describes the building blocks that have been utilized in constructing our detection and characterization framework. As mentioned earlier, in order to avoid sensitivity of the detection scheme to grid resolution, great circle distance has been employed throughout. In terms of regular latitude-longitude coordinates, great circle distance between points $(\lambda_1, \varphi_1)$ and $(\lambda_2, \varphi_2)$ is defined via the symmetric operation

$$r(\lambda_1, \varphi_1; \lambda_2, \varphi_2) = a \arccos\left(\sin\varphi_1 \sin\varphi_2 + \cos\varphi_1 \cos\varphi_2 \cos(\lambda_1 - \lambda_2)\right). \quad (1)$$

Algorithmically, this calculation is implemented as `gcdist(p,q)` for given graph nodes `p` and `q`.

Add _ANOMAVG and _MEAN operator

### 2.1 Efficient neighbor search using $k$-d Trees

Three-dimensional ($k = 3$) $k$-d trees (Bentley, 1975) are used throughout our detection code using the implementation of Tsiombikas (2015). Although $k$-d trees use straight-line instance instead of great circle distance, we utilize the observation that straight-line and great-circle distance maintain the same ordering for points confined to the surface of the sphere. In particular, we utilize three key functions made available by the $k$-d tree implementation:

`K = build_kd_tree(P)` constructs a $k$-d tree `K` from a point set `P`.

`q = kd_tree_nearest_neighbor(K, p)` locates the nearest neighbor `q` to point `p` using the $k$-d tree `K`.

`S = kd_tree_all_neighbors(K, p, dist)` locates all points that are within a distance `dist` of a point `p` within the $k$-d tree `K`.

A key advantage of KD trees is their relatively efficient $O(n \log n)$ construction time and $O(\log n)$ average time nearest neighbor search.

## 2.2 Unstructured grid specification

For purposes of determining connectivity of the unstructured grid, we require the specification of a graph such as the one depicted in Figure 1. The connectivity information is stored textually as an adjacency list via a variable-length comma-separated variable file. The total number of nodes ($N$) is specified at the top of the file, followed by $N$ lines containing the longitude (lon), latitude (lat), number of adjacent nodes, and finally a 1-indexed list of all adjacent nodes, such as depicted below:

```
<total number of nodes>
<lon>,<lat>,<# adj. nodes>,<first adj. node>,...,<last adj. node>
...
```

## 2.3 Extrema detection

For purposes of computational efficiency, candidate points are initially located by identifying local extrema in a given field (for instance SLP) via `find_all_minima` (Algorithm 1). Candidates are then eliminated if they are "too close" to stronger extrema (Algorithm 2). The command line specification for the search procedure in TempestExtremes can be found in Appendix A4.

## 2.4 Closed contour criteria

Although a first pass at candidate points may be made by looking for local extrema (comparing against all neighboring nodes), this criteria is not robust across model resolution. That is, the distance between a node and its neighbors decreases proportional to the local grid spacing, and so does not definite "physical" criterion. Consequently, we instead advocate for a *closed contour criteria* to define candidate nodes. Closed contours were first employed by Bell and Bosart (1989), who used a 30m 500 mb geopotential height contour to identify closed circulation cen-

ters. Their approach used radial arms generated at 15° intervals over a great circle distance of 2° and required that geopotential heights rise by at least 30m along each arm. Unfortunately, the use of radial arms to define the closed contour is again sensitive to model resolution, since it has the potential to only sample as many neighbors as radial arms employed.

Here we propose an alternative closed contour criteria that is largely insensitive to model resolution that uses graph search to ensure that all paths along the unstructured grid from an initial location `p0` lead to a sufficiently large decrease (or increase) in a given field `G`. This criteria is illustrated in Figure 2, and is implemented in Algorithm 3 and 4 (for closed contours around local maxima). An analogous algorithm `no_closed_contour` is also provided, which has similar functionality but discards candidates that satisfy the closed contour criteria (this may be desirable, for instance, to identify cyclonic structures that do not have a warm core).

### 2.5 Thresholding

Additional threshold criteria may be applied at the Map() stage in order to further eliminate undesirable candidates. For example, a common threshold criteria requires that a field `G` satisfy some minimum value within a distance `dist` of the candidate, as implemented in Algorithm 5.

### 2.6 Stitching

The basic track stitching procedure (which represents the Reduce() stage in MapReduce) is implemented in Algorithm 6 using the output from the Map() procedure at each time level (stored in set array `P[1..T]`), a maximum great-circle-distance between nodes, `dist`, and a maximum gap size, `maxgap`. Here, gap size refers to the maximum number of sequential non-detections that can occur before a path is considered terminated. This argument is useful, for instance, for tracking tropical storms that temporarily weaken before strengthening into tropical cyclones.

For simplicity, $k$-d trees are constructed at each time level in order to maximize the efficiency of the search. Each candidate pair (time, node) can only be used in one path, and so construction simply requires exhausting the list of available candidates. Once paths have been constructed,

additional criteria can be applied – for instance, minimum path length or additional criteria based on minimum path length or minimum distance between the start and endpoints of the path (see Appendix A5). Thresholds based on field values may also be applied, *e.g.* sea level pressure must be below a particular value for at least 8 time steps of each track.

## 3 Selected examples

Several selected examples of the feature detection tool are now provided. The first three examples use data from the NCEP Climate Forecast System Reanalysis (CFSR), available at 0.5 degree global resolution with 6-hourly output from 1979-present (Saha et al., 2010).

### 3.1 Tropical cyclones in CFSR

Our first example is to employ the tracker for tropical cyclones. The command line we use to detect tropical cyclone-like features in CFSR is provided below. Three-dimensional (time + 2D space) hyperslabs of CFSR data have been extracted, with `TMP_L100` corresponding to 400hPa air temperature, and `U_GRD_L100` and `V_GRD_L100` corresponding to 850hPa zonal and meridional velocities. Candidates are initially identified by minima in the sea level pressure (`PRMSL_L101`), and then eliminated if a smaller minimum exists within a great circle distance of 2.0 degrees. The closed contour criteria is then applied, requiring an increase in SLP of at least 200Pa over a distance of 4 degrees away from the candidate node, and a decrease in 400hPa air temperature of 0.4K within 8 degrees of the node within 1.1 degrees of the candidate with maximum air temperature. Since CFSR is on a structured latitude-longitude grid, the output format is `i,j,lon,lat,psl,maxu,zs`, where `i,j` are the longitude and latitude coordinates within the dataset, `lon,lat` are the actual longitude and latitude of the candidate, `psl` is the SLP at the candidate point (equal to the maximum SLP within 0 degrees of the candidate), `maxu` is the vector magnitude of the maximum 850 hPa wind within 4 degrees of the candidate, and `zs` is the topographic height at the candidate point.

```
./DetectCyclonesUnstructured
```

```
  --in_data "$uvfile;$tpfile;$hfile" --out $outf
  --searchbymin PRMSL_L101 --mergedist 2.0
  --closedcontourcmd "PRMSL_L101,200.,4,0;
     TMP_L100,-0.4,8.0,1.1"
  --outputcmd "PRMSL_L101,max,0;
     _VECMAG(U_GRD_L100,V_GRD_L100),max,4;
     HGT_L1,max,0"
```

All outputs from DetectCyclonesUnstructured are then concatenated into a single file containing candidates at all times (`pgbhnl.dcu_tc_all.dat`). Candidates are then stitched in time to form paths, with a maximum distance between candidates of 8.0 degrees (great circle distance), consisting of at least 8 candidates per path, and with a maximum gap size of 2 (most consecutive timesteps with no associated candidate). Because localized low-pressure regions that are unrelated to tropical cyclones can form as a consequence of topographic forcing, we also require that for at least 8 time steps the underlying topographic height (`zs`) be at most 100 meters. The associated command line for StitchNodes is:

```
./StitchNodes
  --in pgbhnl.dcu_tc_all.dat
  --out pgbhnl.dcu_tc_stitch.dat
  --format "i,j,lon,lat,psl,maxu,zs"
  --range 8.0 --minlength 8 --maxgap 2
  --threshold "zs,<=,100.0,8"
```

Once the complete set of tropical cyclone paths has been computed, total tropical cyclone counts over each 0.5 degree grid cell is plotted in Figure 3. Overall the results show very good agreement with reference fields (Citation?).

### 3.2 Extratropical cyclones in CFSR

For our second example, we are interested in tracking extratropical cyclone features. The command line we have used to detect cyclonic features without the characteristic warm-core of

tropical cyclones (here referred to as extratropical cyclones) is given below. The command is identical to the TC detection configuration specified in section 3.1, except requiring that the feature does not possess a closed contour in the 400hPa temperature field (no warm core).

```
./DetectCyclonesUnstructured
  --in_data "$uvfile;$tpfile;$hfile" --out $outf
  --searchbymin PRMSL_L101 --mergedist 2.0
  --closedcontourcmd "PRMSL_L101,200.,4,0?
  --noclosedcontourcmd "TMP_L100,-0.4,8.0,1.1?
  --outputcmd "PRMSL_L101,max,0;
     _VECMAG(U_GRD_L100,V_GRD_L100),max,4;
     HGT_L1,max,0"
```

Stitching is similarly analogous to section 3.1, except using a slightly more strict criteria on the underlying topographic height. The topographic filtering proved necessary in order to adequately filter out an abundance of topographically-driven low pressure systems, particularly in the Himalayas region. The command line used for stitching is given below:

```
./StitchNodes
  --in pgbhnl.dcu_tc_all.dat
  --out pgbhnl.dcu_tc_stitch.dat
  --format "i,j,lon,lat,psl,maxu,zs"
  --range 8.0 --minlength 8 --maxgap 2
  --threshold "zs,<=,70.0,8"
```

Once the complete set of extratropical cyclone paths has been computed, total extratropical cyclone density over each 0.5 degree grid cell is plotted in Figure 4. Although not extensively verified, the qualitative density of extratropical cyclones is well within the range of results from different trackers, as given by Neu et al. (2013).

### 3.3 Northern hemisphere tropical easterly waves in CFSR

Tropical easterly waves are our third example of a pointwise feature that has been assessed in the tracking literature. In this example, tracking is performed using maxima in the 850hPa

relative vorticity field. Since CFSR only provides absolute vorticity, relative vorticity must first be extracted by taking the difference between absolute vorticity and the planetary vorticity (the Coriolis parameter). This is done on the command line via `_DIFF(ABS_V_L100,_F())`, where `ABS_V_L100` is the CFSR absolute vorticity variable and `_F()` is a built-in function for computing the Coriolis parameter (equal to $f = 2\Omega \sin\phi$). Here, we have isolated tropical easterly wave features by requiring a drop of relative vorticity equal to $5 \times 10^{-5}$ s$^{-1}$, and have discarded detections outside of the latitudinal range $[30S, 30N]$. The command line used is as follows:

```
./DetectCyclonesUnstructured
  --in_data "$uvfile;$hfile" --out $outf
  --searchbymax "_DIFF(ABS_V_L100,_F())" --mergedist 2.0
  --closedcontourcmd "_DIFF(ABS_V_L100,_F()),-5.e-5,4,0"
  --outputcmd "_DIFF(ABS_V_L100,_F()),max,0;
      HGT_L1,max,0"
  --maxlat 30.0
```

Tropical easterly wave paths are constructed using a maximum distance of 4° great-circle-distance between subsequent detections, a minimum path length equal to 8 sequential detections and no allowed gaps. We further require that the easterly waves have a distance of at least 16° between start and endpoints and are present in the northern hemisphere ($\phi \geq 0°$) for at least 8 timesteps. The command line is as follows.

```
./StitchNodes
  --in pgbhnl.dcu_aew_all.dat --out pgbhnl.dcu_aew_stitch.dat
  --format "i,j,lon,lat,relv,zs"
  --range 4.0 --minlength 8 --maxgap 0
  --min_endpoint_dist 16.0
  --threshold "lat,>=,0,8"
```

Counts of tropical easterly waves within each CFSR grid volume are given in Figure 5, showing heavy wave activity throughout the Atlantic and Pacific basins. Examining the Figure 3, it is

clear that regions with a northward bulge in tropical Easterly wave activity are also key regions for tropical cyclone development.

### 3.4 Tropical cyclones in a simulation with CESM

For our final example, we assess the differences in tropical cyclone character obtained from native and regridded datasets. Using the variable-resolution option in the Community Earth System Model (VR-CESM) to refine the northern hemisphere to 0.25° resolution, a simulation of a complete hurricane season (September - January) has been performed. With the high-order spectral element dynamical core used to solve the fluid equations in the atmosphere, VR-CESM has been demonstrated to be effective in simulating tropical cyclone-like features (Zarzycki and Jablonowski, 2014; Zarzycki et al., 2014). However, even at the relatively fine global resolution of 0.25°, the eye of the tropical cyclone is only partially resolved. Since VR-CESM uses an unstructured mesh with degrees of freedom stored at spectral element Gauss-Lobatto (GL) nodes, data is typically analyzed only after being regridded to a regular latitude-longitude mesh of approximately equal resolution. The regridding procedure has the potential to smear out grid-scale features.

For this example, we use the high-order regridding package TempestRemap (Ullrich and Taylor, 2015; Ullrich et al., 2016) for remapping the native spectral element output to a regular latitude-longitude grid with 0.25° grid spacing. For purposes of determining connectivity on the variable-resolution spectral element mesh, we connect GL nodes along the coordinate axis of each quadrilateral element. DetectCyclonesUnstructured is then applied to both the native grid data and the regridded data on the regular latitude-longitude mesh (using the configuration specified in section 3.1) and tropical cyclones categorized by maximum wind speed (Colin: more here). The results of this analysis are depicted in Figure 6. As expected, the native grid output produces almost identical tracks, but more powerful tropical cyclones overall (with many tropical cyclones dropping down by a full category as a consequence of the remapping procedure).

## 4 Conclusions

Conclusions.

*Acknowledgements.*

## A1 A Review of Extratropical Cyclone Tracking Algorithms

Manual counts of cyclones were performed by Petterssen (1956) in the Northern hemisphere from 1899-1939, and latter binned by Klein (1957) to determine the spatial distribution of such storms. These techniques were later refined by Whittaker and Horn (1982) by accounting for cyclone trajectories. A similar survey in the Southern hemisphere was performed by Taljaard (1967) for July 1957 - December 1958. Manual tracking and characterization of cyclones was also performed by Akyildiz (1985) using ECMWF forecast data for the 1981/82 winter.

One of the first automated detection and tracking for extratropical cyclones was developed by Williamson (1981) using nonlinear optimization to fit cyclonic profiles to anomalies in the 500-mb geopotential height field. Storms were then tracked over a short forecast period using the best fit to the cyclone's centerpoint.

Counts of cyclones neglecting the cyclone trajectory were automatically generated from climate model output for both hemispheres by Lambert (1988) using local minima in 1000-hPa geopotential height. This method had some shortcomings, including mischaracterization of local lows due to Gibbs' ringing and topographically-driven lows. To overcome these problems, Alpert et al. (1990) proposed an additional minimum threshold on the local pressure gradient. Similarly, Le Treut and Kalnay (1990) detected cyclones in ECMWF pressure data using a local minima in the sea-level pressure that must also be 4 mb below the average sea-level pressure of neighboring grid points, and must persist for three successive 6- or 12- hour intervals.

Murray and Simmonds (1991) extracted low pressure centers from interpolated GCM data using local optimization, based on earlier work in Rice (1982).

Feature tracking on the sphere was revisited by Hodges (1995), which extended tracking algorithms designed for Cartesian geometry Hodges et al. (1994) that were built from image processing techniques.

## A2 A Review of Tropical Cyclone Tracking Algorithms

Extratropical cyclone tracking techniques have been modified in order to support tropical cyclone tracking. To eliminate "false positives" associated with extratropical cyclones and weak

cyclonic depressions, many schemes require that the candidate be associated with a nearby warm core and be associated with a minimum threshold on surface winds for at least 1-3 days. The definition of a "warm core" varies between modeling centers, including such options as air temperature anomaly on pressure surfaces (Vitart et al., 1997; Zhao et al., 2009a; Murakami et al., 2012), geopotential thickness (Tsutsui and Kasahara, 1996) and decay of vorticity with height (Bengtsson et al., 2007a; Strachan et al., 2013). Additional filtering of candidate storms over topography or within a specified latitudinal range may be required. To better match observations, additional geographical, model or feature-dependent criteria may be applied (Camargo and Zebiak, 2002; Walsh et al., 2007; Murakami and Sugi, 2010; Murakami et al., 2012). It is widely acknowledged that weaker tropical storms are difficult to track, and the observational record of these less-intense, short-lived storms is questionable (Landsea et al., 2010).

A tabulated overview of the thresholds utilized by many of these schemes can be found in Walsh et al. (2007), along with several proposed guidelines on detection schemes. We extend this tabulation with the following short descriptions of many published schemes.

Define local = among points immediately neighboring each candidate

- Broccoli and Manabe (1990): Assessed a R15 ($\sim$ 600 km) and R30 ($\sim$ 300 km) dataset. Search on PSL with 1.5 mb local min (R15) or 0.75 mb local min (R30), with local surface wind velocity $>$ 17 m/s, latitude $<$ 30°. Cyclones are tracked over a range of 1200 km / day.

- Wu and Lau (1992): Assessed a 7.5° longitude $\times$ 4.5° latitude dataset. Search on minimum 1000mb geopotential height, requiring positive 950mb relative vorticity, negative 950mb divergence, positive 500mb vertical velocity, latitude $<$ 40.5°, 200mb minus 1000mb layer thickness must be locally maximal and exceed by 60 m the average layer thickness within 1500km west to east, and 950mb wind must be $>$ 17.2 m/s locally. Cyclones are tracked over a range of 7.5° longitude or 9° latitude per day.

- Haarsma et al. (1993): Assessed a $\sim$ 300 km dataset. Search on local minimum PSL and require 850mb relative vorticity $> 3.5 \times 10^{-5}\mathrm{s}^{-1}$, and temperature anomaly at 250mb $\Delta T250 > 0.5K$, at 500mb $\Delta T500 > -0.5K$, and $\Delta T250 - \Delta T850 > -1.0K$, where

the anomaly is computed against a $15^\circ \times 15^\circ$ spatial mean around the center of the storm. Cyclones are tracked for a minimum of 3 days.

– Bengtsson et al. (1995, 1996): Assessed a T106 ($\sim$ 125 km) dataset. Search on 850mb relative vorticity $> 3.5 \times 10^{-5}\text{s}^{-1}$. Require a 850mb wind maximum $> 15$ m/s, local SLP minimum, and mean 850mb wind $>$ mean 300mb wind within 7x7 grid points around candidate. Further require temperature anomaly sum $\Delta T700 + \Delta T500 + \Delta T300 > 3$ K and $\Delta T300 > \Delta T850$ where the anomaly is computed against a 7x7 gridpoint average centered on candidate. Cyclones are tracked for a minimum of 1.5 days.

– Krishnamurti et al. (1998): Assessed a T42 ($\sim$ 300 km) climate dataset. Similar to Bengtsson et al. (1995, 1996), except using a 4x4 grid point region for 850mb wind maximum, SLP minimum and temperature mean. Cyclones are tracked for at least 1 day.

– Sugi et al. (2002): Assessed a T106 ($\sim$ 125 km) climate dataset. Tracking criteria similar to Bengtsson et al. (1995). Search is conducted for local PSL minima that are at least $<$ 1020 hPa. Cyclones are tracked for a minimum of 2 days.

Oouchi et al. (2006): Assessed a 20 km dataset using a similar technique to Sugi et al. (2002). PSL at storm center must be 2 hPa lower than mean over 7x7 grid box and require that storm center latitude $< 45^\circ$ with an initial position $< 30^\circ$. Near the storm require relative vorticity at 850 hPa must be $> 3.5 \times 10^{-5}\text{s}^{-1}$, maximum wind speed at 850hPa must be $>$ 15 m/s, and the maximum wind speed at 850hPa is larger than at 300hPa. Further require temperature anomaly sum $\Delta T700 + \Delta T500 + \Delta T300 > 2$ K near storm. Cyclones are tracked for at least 1.5 days.

– **??**Vitart and Anderson (2001): Assessed a T42 (2.8°, $\sim$ 300 km) dataset. Search on 850mb relative vorticity maxima $> 3.5 \times 10^{-5}\text{s}^{-1}$ with a nearby PSL minimum. Must possess a warm core within $2^\circ$ latitude defined as a local average 500mb to 200mb temperature maximum with a decrease of 0.5 K in all directions within $8^\circ$. Must possess a local maximum in 200mb - 1000mb thickness with a decrease of 50m in all directions within $8^\circ$. When tracking, the minimum distance between storms is 800 km / day, tracks must last at

least 2 days and the maximum wind velocity within 8° of the storm center must be 17 m/s for at least 2 (not necessarily consecutive) days.

– Tsutsui and Kasahara (1996): Assessed a T42 (2.8°, $\sim$ 300 km) dataset. Search on minima in 1000mb geopotential height field, with at least an average drop of 20 m among neighboring points, and a further 20 m drop of average among neighboring points from periphery. Require average local 900mb vorticity to be cyclonic, average local 900mb divergence to be negative, average local 500mb vertical velocity to be upward, 200mb minus 1000mb layer thickness maximum among neighbors is greater than any value in periphery, and average local 200mb zonal wind velocity is less than 10 m/s or local points contain at least one point with easterly velocity. Require the latitude $< 40°$, topographic height underlying candidates should be $< 400$ m, one local point must have a 900mb wind speed of at least 17.2 m/s, and one local point must exceed 100 mm/d over at least one day. Cyclones are tracked for a minimum of 2 days.

  Tsutsui (2002): Assessed a T42 (2.8°, $\sim$ 300 km) dataset. Search is performed similar to Tsutsui and Kasahara (1996), but with a simplified criteria. PSL is required to be less than the local average minus 2 hPa, and local average must be less than periphery average minus 2hPa. Layer thickness between 200hPa and 700hPa, denoted by $Z$, must satisfy $Z_0 + \max(Z_{\pm 1\Delta}) > 2\max(Z_{\pm 2\Delta})$, where $Z_{\pm 1\Delta}$ denotes immediate neighbors and $Z_{\pm 2\Delta}$ denotes the periphery.

– Walsh (1997); Walsh and Watterson (1997); **?**: Assessed a 125 km regional climate dataset over Australia. Required 850 hPa relative vorticity $> 2.0 \times 10^{-5}\mathrm{s}^{-1}$, temperature anomaly sum $\Delta T700 + \Delta T500 + \Delta T300 > 0$ K and $\Delta T300 > \Delta T850$, with anomaly computed against the mean over a region 2 grid points north/south and 13 grid points east/west. Further require 10m surface wind $> 10$ m/s and 850 hPa tangental wind speed $> 300$ hPa tangental wind speed. Cyclones are tracked for a minimum of 2 days.

– Nguyen and Walsh (2001): Similar to Walsh and Watterson (1997), assessed a 125 km regional dataset over Australia. Vorticity requirement was changed to 850 hPa relative vorticity $> 1.0 \times 10^{-5}\mathrm{s}^{-1}$ with PSL minimum within 250km. Also required mean wind

speed in 500km $\times$ 500km region at 850 hPa was larger than at 300 hPa and a mean tangental wind speed within a radius of $1^\circ$ and $2.5^\circ$ greater than 5 m/s. Cyclones were tracked for a minimum of 1 day, with relaxed criteria after this time.

Walsh et al. (2004): Assessed a 30 km dataset using a similar tracking strategy to Nguyen and Walsh (2001). The temperature anomaly was computed against a 1200km longitude $\times$ 400km latitude region, and the mean wind speed was computed over a 800km $\times$ 800km region around the storm. Further required that V10 $\geq$ 17 m/s near storm.

McDonald et al. (2005): Assessed a $2.5^\circ$ latitude by $3.75^\circ$ longitude dataset. Search on local maxima of 850hPa relative vorticity with magnitude greater than $5 \times 10^{-5}\mathrm{s}^{-1}$ with initial latitude $< 30^\circ$. Temperature anomalies must satisfy $\Delta T300 > 0$ along the track, $\Delta T300 > 0.5$ K for any two points along the track and $\Delta T300 > \Delta T850$ for any two points along the track, where the anomaly was computed against a $15^\circ \times 15^\circ$ mean. Cyclones are tracked for a minimum of 2 days.

McDonald et al. (2005): $2.5^\circ$ latitude by $3.75^\circ$ longitude
ZETA850: $> 5 \times 10^{-5}$
Latitude: $< 30^\circ$
Temp: $\Delta$T300 $> 0$ at all points along track, $\Delta$T300 $> 0.5$K at two points, $\Delta$T300 ¿ $\Delta$T850 at two points (against mean $15^\circ \times 15^\circ$)

Bengtsson et al. (2007b): T63, T213 and T319
ZETA: ZETA850 - ZETA250 $> 6 \times 10^{-5}$, ZETA850 $> 6 \times 10^{-5}$, ZETA positive at all levels between 850hPa and 250hPa (all for 4 consecutive timesteps) Latitude: Northern hemisphere [0,60N]

Zhao et al. (2009b): $\sim$ 50 km
ZETA: ZETA850 $> 1.6 \times 10^{-4}$ within $6^\circ \times 6^\circ$ areas
SLP: minimum within $2^\circ$ of vorticity maximum
Temp: $(T300 + T500)/2$ maximum within 2 deg, 1K warmer than local mean
Wind: $> 17$ m/s for at least 3 days

Tracking range: 400km
Duration: 3 days
Add Thorncroft and Hodges (2001)

### A3 A Review of Tropical Easterly Wave Tracking Algorithms

A similar manual study to Akyildiz (1985) was performed by Reed et al. (1988) to detect and track African easterly waves.

Storm tracks and African easterly waves were tracked by Hodges et al. (2003).

König et al. (1993) uses minima in the 1000 hPa geopotential height to identify cyclones with associated maxima in the 850 hPa vorticity.

### A4 Software Documentation: DetectCyclonesUnstructured

```
Usage: DetectCyclonesUnstructured <parameter list>
Parameters:
  --in_data <string> [""]
  --in_connect <string> [""]
  --out <string> [""]
  --searchbymin <string> [""] (default PSL)
  --searchbymax <string> [""]
  --maxlat <double> [0.000000] (degrees)
  --minlat <double> [0.000000] (degrees)
  --topofile <string> [""]
  --maxtopoht <double> [0.000000] (m)
  --mergedist <double> [0.000000] (degrees)
  --closedcontourcmd <string> [""] [var,dist,delta,minmaxdist;...]
  --noclosedcontourcmd <string> [""] [var,dist,delta,minmaxdist;...]
  --thresholdcmd <string> [""] [var,op,value,dist;...]
  --outputcmd <string> [""] [var,op,dist;...]
```

```
--timestride <integer> [1]
--regional <bool> [false]
--out_header <bool> [false]
--verbosity <integer> [0]
```

`--in_data <string>`
A list of input datafiles in NetCDF format, separated by semi-colons.

`--in_connect <string>`
A connectivity file, which uses a vertex list to describe the graph structure of the input grid. This parameter is not required if the data is on a latitude-longitude grid.

`--out <string>`
The output file containing the filtered list of candidates in plain text format.

`--searchbymin <string>`
The input variable to use for initially selecting candidate points (defined as local minima). By default this is "PSL", representing detection of surface pressure minima. Only one of `searchbymin` and `searchbymax` may be set.

`--searchbymax <string>`
The input variable to use for initially selecting candidate points (defined as local maxima). Only one of `searchbymin` and `searchbymax` may be set.

`--maxlat <double>`
The maximum absolute latitude for candidate points. Candidates at higher latitudes are discarded.

`--minlat <double>`
The minimum absolute latitude for candidate points. Candidates at lower latitudes are discarded.

`--mergedist <double>`
Merge candidate points with distance (in degrees) shorter than the specified value. Among two candidates within the merge distance, only the candidate with lowest `searchbymin` or highest `searchbymax` value will be retained.

`--closedcontourcmd <cmd1>;<cmd2>;...` Eliminate candidates if they do not have a closed contour. Closed contour commands are separated by a semi-colon. Each closed contour command takes the form `var,dist,delta,pivotdist`. These arguments are as follows.

`var <variable>` The variable used for the contour search.

`dist <double>` The great-circle distance (in degrees) from the pivot within which the closed contour criteria must be satisfied.

`delta <double>` The amount by which the field must change from the pivot value. If positive (negative) the field must increase (decrease) by this value along the contour.

`pivotdist <double>` The distance away from the candidate to search for the pivot. If `delta` is positive (negative), the pivot is a local minimum (maximum).

`--noclosedcontourcmd <cmd1>;<cmd2>;...`
As `closedcontourcmd`, except eliminates candidates if a closed contour is present.

`--thresholdcmd <cmd1>;<cmd2>;...` Eliminate candidates that do not satisfy a threshold criteria (there must exist a point within a given distance of the candidate that satisfies a given equality or inequality). Threshold commands are separated by a semi-colon. Each threshold command takes the form `var,op,value,dist`. These arguments are as follows.

`var <variable>` The variable used for the contour search.

`op <string>` Operator that must be satisfied for threshold (options include >, >=, <, <=, =, !=).

`value <double>` The value on the RHS of the comparison.

`dist <double>` The great circle distance away from the candidate to search for a point that satisfies the threshold (in degrees).

`--outputcmd <cmd1>;<cmd2>;...` Include additional columns in the output file. Output commands take the form `var,op,dist`. These arguments are as follows.

`var <variable>` The variable used for the contour search.

`op <string>` Operator that is applied over all points within the specified distance of the candidate (options include `max`, `min`, `avg`, `maxdist`, `mindist`).

`dist <double>` The great circle distance away from the candidate wherein the operator is applied (in degrees).

`--timestride <integer>`
Only examine discrete times at the given stride (by default 1).

`--regional`
When a latitude-longitude grid is employed, do not assume longitudinal boundaries to be periodic.

`--out_header`
Output a header describing the columns of the data file.

`--verbosity <integer>`
Set the verbosity level (default 0).

### A4.1 Variable Specification

Quantities of type `<variable>` include both NetCDF variables in the input file (for example, "Z850") and simple operations performed on those variables. By default it is assumed that NetCDF variables are specified in the `.nc` file as

`float Z850(time, lat, lon)` or `float Z850(time, ncol)`

for structured latitude-longitude grids and unstructured grids, respectively. If variables have no time variable, they have the related specification

`float Z850(lat, lon)` or `float Z850(ncol)`

If variables include an additional dimension, for instance,

`float Z(time, lev, lat, lon)` or `float Z(time, lev, ncol)`

they may be specified on the command-line as `Z(<lev>)`, where the integer index `<lev>` corresponds to the first dimension (or the dimension after `time`, if present).

Simple operations on variables are also supported, including

`_VECMAG(<variable>, <variable>)` 2-component vector magnitude,

`_PLUS(<variable>, <variable>)` Pointwise sum of variables,

`_DIFF(<variable>, <variable>)` Pointwise difference of variables.

The following are valid examples of `<variable>` type,

`_VECMAG(U850, V850)` and `_DIFF(U(3),U(5))`.

## A5 Software Documentation: StitchNodes

```
Usage: StitchNodes <parameter list>
Parameters:
  --in <string> [""]
  --out <string> [""]
  --format <string> ["no,i,j,lon,lat"]
  --range <double> [5.000000] (degrees)
  --minlength <integer> [3]
```

```
--min_endpoint_dist <double> [0.000000] (degrees)
--min_path_dist <double> [0.000000] (degrees)
--maxgap <integer> [0]
--threshold <string> [""] [col,op,value,count;...]
--timestride <integer> [1]
--out_format <string> ["std"] (std|visit)
```

`--in <string>`
The input file (a list of candidates from DetectCyclonesUnstructured).

`--out <string>`
The output file containing the filtered list of candidates in plain text format.

`--format <string>`
The structure of the columns of the input file.

`--range <double>`
The maximum distance between candidates along a path.

`--minlength <integer>`
The minimum length of a path (in terms of number of discrete times).

`--min_endpoint_dist <double>`
The minimum great-circle distance between the first candidate on a path and the last candidate (in degrees).

`--min_path_dist <double>`
The minimum path length, defined as the sum of all great-circle distances between candidate nodes (in degrees).

`--maxgap <integer>`
The largest gap (missing candidate nodes) along the path (in discrete time points).

`--threshold <cmd1>;<cmd2>;...`
Eliminate paths that do not satisfy a threshold criteria (a specified number of candidates along path must satisfy an equality or inequality). Threshold commands are separated by a semi-colon. Each threshold command takes the form `col,op,value,count`. These arguments are as follows.

`col <integer>` The column in the input file to use in the threshold criteria.

`op <string>` Operator used for comparison of column value (options include >, >=, <, <=, =, !=).

`value <double>` The value on the right-hand-side of the operator.

`count <integer>` The minimum number of candidates along the path that must satisfy this criteria.

`--timestride <integer>`
Only examine discrete times at the given stride (by default 1).

**Algorithm 1.** Locate the set of all nodes `P` that are local minima for a field `G` (for instance, SLP) defined on an unstructured grid. The procedure for locating maxima is analogous.

```
set P = find_all_minima(field G)
  for each node f
    is_minima[f] = true
    for each neighbor node v of f
      if G[v] < G[f] then
        is_minima[f] = false
    if is_minima[f] then
      insert f into P
```

**Algorithm 2.** Given a field `G` defined on an unstructured grid and a set of candidate points `P`, remove candidate minima that are within a distance `dist` of a more extreme minimum, and return the new candidate set `Q`.

```
set Q = merge_candidates_minima(field G, set P, dist)
  K = build_kd_tree(P)
  for each candidate p in P
    retain_p = true
    N = kd_tree_all_neighbors(K, p, dist)
    for all q in N
      if (G[q] < G[p]) then retain_p = false
    if retain_p then insert p into Q
```



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**Algorithm 3.** Find the node `pmax` containing the maximal value of the field `G` within a distance `maxdist` of the node `p`. An analogous procedure `find_min_near` is provided for locating nodes containing minimal values of the field.

```
node pmax = find_max_near(node p, field G, maxdist)
  set visited = {}
  set tovisit = {p}
  pmax = p
  while tovisit is not empty
    q = remove node from tovisit
    if (q in visited) then continue
    add q to visited
    if (gcdist(p,q) > maxdist) then continue
    if (G[q] > G[pmax]) then pmax = q
```



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**Algorithm 4.** Determine if there is a closed contour in field `G` of magnitude `thresh` around the point `p0`, defined by `p0 = find_max_near(p, G, maxdist)`, within distance `dist`. That is, along all paths away from `p0`, the field `G` must drop by at least `thresh` within distance `dist`. The closed contour criteria is depicted in Figure 2. An analogous procedure is defined for closed contours around minima.

```
closed_contour_max(point p, field G, dist, maxdist, thresh)
  p0 = find_max_near(p, G, maxdist)
  set visited = {}
  set tovisit = {p0}
  while tovisit is not empty
    q = remove point from tovisit
    if (q in visited) then continue
    add q to visited
    if (gcdist(p0,q) > dist) then return false
    if (G[p0] - G[q] < thresh) then
      add all neighbors of q to tovisit
  return true
```

**Algorithm 5.** Determine if a candidate node `p` satisfies the requirement that there exists another node `p0` within distance `dist` of `p` with `G[p] > thresh`.

```
threshold_max(node p, field G, dist, thresh)
  p0 = find_max_near(p, G, dist)
  if (G[p0] < thresh) then
    return false
  else
    return true
```



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**Algorithm 6.** Determine all feature paths `S`, given array of candidate nodes `P[1..T]` and maximum great-circle distance between nodes at subsequent time levels `dist`.

```
path set S = stitch_nodes(set array P[1..T], dist, maxgap)
  for each time level t = 1..T
    K[t] = build_kd_tree(P[t])
  for each time level t = 1..T
    while P[t] is not empty
      initialize empty path s
      p = remove next candidate from P[t]
      add p into s
      gap = 0
      for time level u = t+1..T
        q = kd_tree_nearest_neighbor(K[u], p)
        if (q in P[u]) and (gcdist(p,q) < dist) then
          add q into s
          remove q from P[u]
          p = q
        else if (gap < maxgap) then
          gap = gap + 1
        else
          break
      add s into S
```

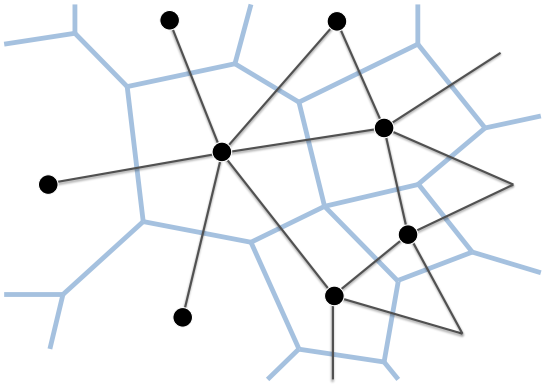

**Fig. 1.** An example adjacency graph describing an unstructured grid (blue lines), where nodes are co-located with volume centerpoint locations (solid circles) and edges connect adjacent volumes.

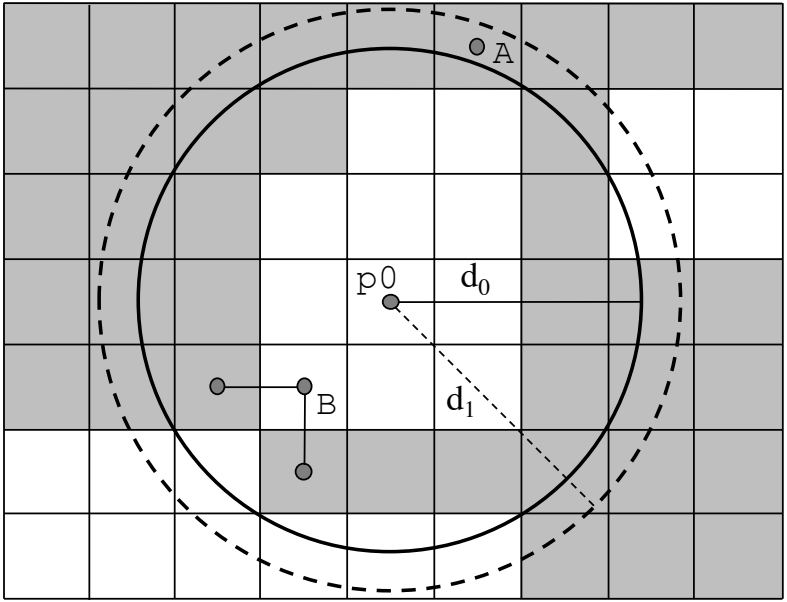


**Fig. 2.** An illustration of the closed contour criteria. Nodes shaded in white (gray) satisfy (do not satisfy) the threshold of the field value at `p0`. Since only edge-neighbors are included, `B` constitutes a boundary to the interior of the closed contour. Because `A` lays outside the solid circle, the contour with distance $d_0$ is not a closed contour, whereas the dashed contour with distance $d_1$ does satisfy the closed contour criteria.



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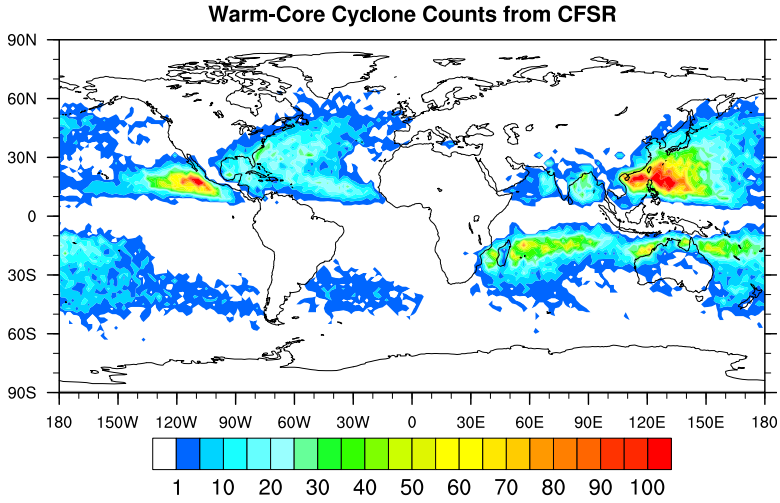


**Fig. 3.** Tropical cyclone counts over the period 1979-2010 obtained using the procedure described in section 3.1.



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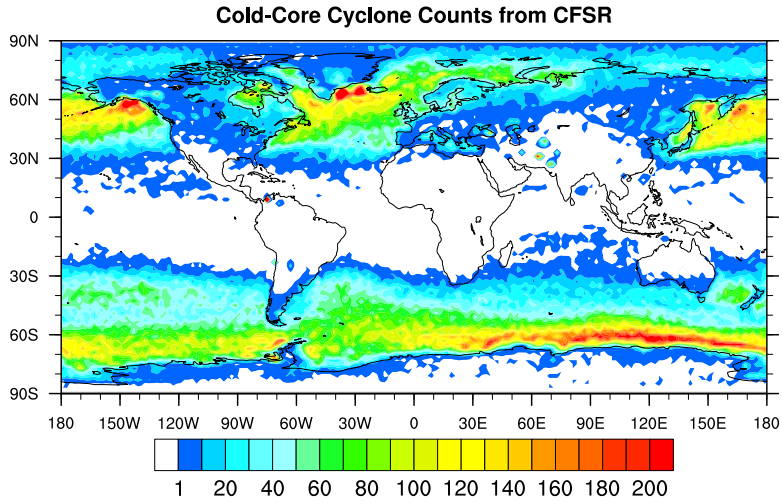


**Fig. 4.** Extratropical cyclone counts over the period 1979-2010 obtained using the procedure described in section 3.2.



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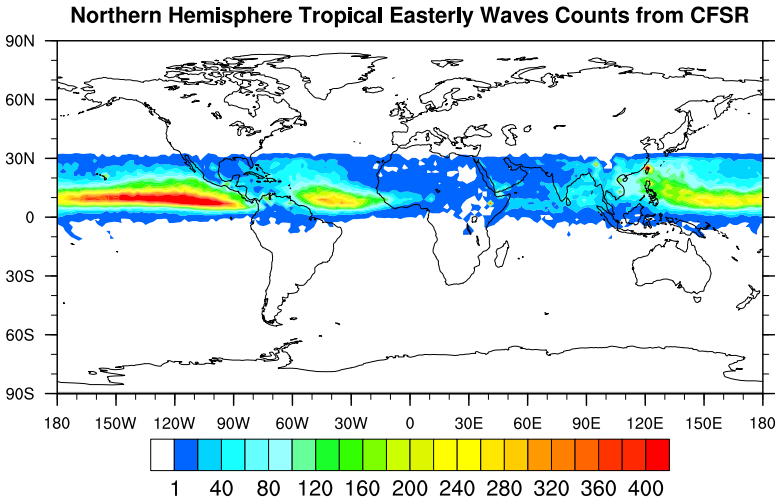


**Fig. 5.** Tropical easterly wave counts over the period 1979-2010 obtained using the procedure described in section 3.3.



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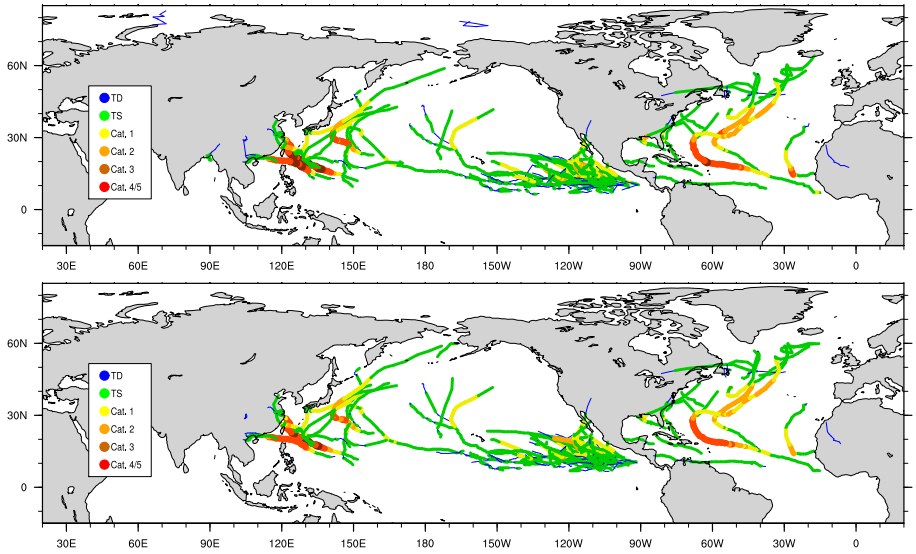


**Fig. 6.** Tropical cyclone trajectories and associated intensities as obtained from the simulation of a single hurricane season in CESM 3.4 using (top) native spectral-element grid data and (bottom) data regridded to a regular latitude-longitude grid with 0.25° grid spacing.

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