
INNOVATIVE SOFTWARE FACILITATES CYCLONE TRACKING AND ANALYSIS

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Introduction

Statistics on atmospheric cyclones are of great interest to climate researchers because they characterize the intensity of atmospheric, synoptic-scale processes. Synoptic intensities are usually characterized by the variances of the synoptic resolution time series of sea level pressure (SLP) or the height of reasonably chosen geopotential level, say 500 hPa, which are band passed for the selected range [e.g., *Blackmon et al.*, 1984; *Ayrault et al.*, 1995, *Rogers*, 1997]. Analysis of cyclone statistics and tracks allows one to focus on the characteristics of individual cyclones and therefore to study their very complicated nature, which is beyond the scope of band-pass statistics.

Historically, the first approach to storm tracking was based on manual tracking using weather analysis maps. Later, when atmospheric analyses were assembled into climatological archives, a number of numerical schemes were developed [*Sinclair*, 1994; *Murray and Simmonds*, 1991; *Serreze and Barry*, 1998; *Blender et al.*, 1997]. These schemes locate the cyclone centers and then link them for sequential snapshots, sorting out propagating and newly generated cyclones. This step remains as the major source of uncertainty inherent in numerical schemes. Such uncertainty is most pronounced in the Northern Hemisphere and is primarily connected with the difficulties of identifying fast wave-type cyclones that overrun stationary lows, and have multicenter depressions and other complicated synoptic situations. Remarkably, the best schemes were developed for the Southern Hemisphere, where they demonstrate a reasonably higher level of accuracy in tracking [*Murray and Simmonds*, 1991]. Simplified versions of numerical tracking schemes are the so-called storm count algorithms, which define the cyclone centers and count cyclone frequencies in grid points or boxes [*Stein and Hense*, 1994; *Lambert*, 1996]. The uncertainties in these algorithms relate to the methods of determining cyclone centers. The output, i.e., what these algorithms term as cyclone frequencies, results from both the number of cyclones and the features of an individual cyclone's life cycle, and there is no way to separate these two sources.

Manual tracking, in comparison to numerical schemes, is considered to be more accurate because an experienced operator is involved in the procedure. Nevertheless, manual procedures are also influenced by random errors of manual cyclone identification, the subjective view of individual operators, and mistakes in digitizing the tracking results. Moreover, manual tracking requires considerable time and labor, which is the main reason why the less accurate numerical tracking method is preferred. Free software has been developed that is based on computer animation of pressure (or geopotential height) fields and that combines the advantages of both the numerical and manual tracking methods. We expect that the software will be helpful in addressing many practical, operational, and scientific needs concerning the analysis of atmospheric cyclones.

The Software Architecture and Operation

The software is free of charge and was developed as an application for Microsoft Windows 95/NT or higher versions and behaves as any Windows 95/98/NT application. It was coded in the Visual C++ environment. Operational requirements are the Pentium platform with at least 16 MB RAM. The software contains the animation system, the tracking engine, and visual applications for the analysis of results.

Interactive Animation System

Usually, standard animation systems deal with the digitized colors of image and not with physical values, which does not allow one to access the real value in a grid point of the domain. Our system, based on the approach of Grigoriev [1997], supports interactive access to the value beyond the color. It allows one to effectively animate any field represented by sequential fields of digital data in a rectangular domain. In order to speed up system access and achieve the highest degree of data compression, we designed a special data format. All physical values are converted into 2-byte binary integers. The problem of identifying physical floating point values is easily resolved through the

prescribed coefficient, which can be specified in the software options menu. For example, for the SLP data with one significant digit after the decimal point, the coefficient value is 10; that is, original SLP 1013.2 hPa will be presented as 10132. These binary files can be easily created from any source. In addition, we supply with the software (not as part of it) a simple program to convert net common data format (CDF) data to the format required. Similar programs can be written for other recognized formats (e.g., "gridded binary" (GRIB)). There are several ways to include the land data in the software. In general, the program assumes the minimum integer in the domain to be a landmark, and this information can be incorporated directly into the binary data file. In this case, land domains serve as masks, which is useful for the animation of parameters available only over either oceans or continents (e.g., sea surface temperature). This approach allows incorporation of any other mask that may not be stationary and that has its own dynamics (e.g., ice, cloudiness). In the case of storm tracking, there is no need to mask either continents or oceans; only an indication of the coastline is required. The latter is implied by a separate, simple "1 byte per value" coast file, performed for the same rectangular domain. The software performs storm tracking in polar projection, and one of the masks is used to display the hemispheric circle, which is cut from the rectangular domain.

The basic data file is accompanied by a small header file, which contains information about the dimensions of the domain, number of sequential snapshots, scale factor, and temporal resolution of data used. This resolution varies in the current version from 6 hourly to annual and provides a running indication of real time of each snapshot during the animation. The header file also contains information about the coastline and masks used. Both coastline and mask data can be turned off without affecting the data files. The software provides friendly and simple interactive editing of the header file before animation. Visualization of the field is based on the user-defined color scale. Currently, the software provides a color bar of 16 colors, which are "red-green-blue" (RGB) outputs. Users can edit the scale, corresponding to the Red-Blue color palette, with respect to the data type and particular task. There is no requirement of equally spaced value ranges, which correspond to the 16-color bar. The value ranges are also stored in the header file and can be edited interactively at any moment of animation, resulting in an instantaneous change of the color palette. Note that this is a general approach used in animation and applied to other options. For instance, the software makes it possible to scale the size of the animation on the screen in order to enlarge the image. For this purpose, in the current version, zoom factors from 1 to 8 are available, and their changes are accepted at any moment and applied instantaneously to the image.

Animation goes in any direction, step by step, and can be controlled manually by arrow keys or the mouse. Alternatively, a user can choose a nonstop animation with speed controlled in the same manner as a zoom factor, i.e., instantaneously accepted speed up and slow down. The date and time of the current field are displayed in the status bar. The software controls the current position of the mouse at any time in the animation, displaying in the status bar the coordinates and the data value under the mouse pointer. For some tasks it is useful to animate simultaneously two or more data files. For instance, with respect to storm tracking, joint consideration of SLP and winds or pressure Laplacian is helpful. For this purpose the software allows one to synchronize all running animations of different parameters.

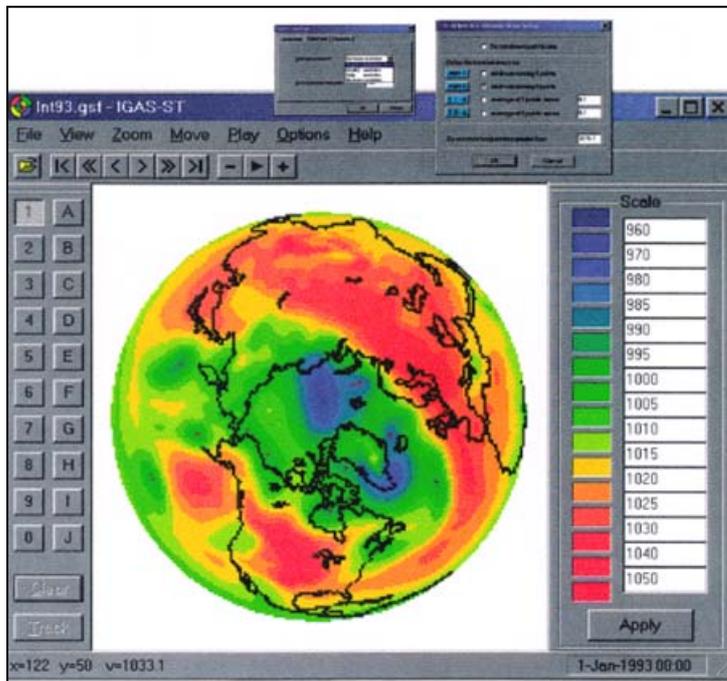


Fig. 1. Design of the main software window and local minima visualization menu.

Figure 1 shows the design of the animation window. Bottom status bars are for the current date, coordinates, and value of the mouse pointer. The "file" menu provides the selection of data files and interactive editing of the header fields. "Zoom" implies the scaling of animation, "recorder" buttons control the animation, and the color bar shows the color scale selected and the value ranges. Users can change the arrangement of bars, close and activate the color bar, among other options.

Storm Tracking Engine

The tracking algorithm is realized through simulation of the manual tracking procedure. First, the cyclone centers are defined. There are several options to defining these centers in different numerical tracking schemes. The easiest way is to search for the SLP minima

with respect to either four or eight closest neighborhood grid points [e.g., Lambert, 1996]. A more advanced approach [Le Treut and Kalnay, 1990; Murray and Simmonds, 1991] assumes the local SLP minimum to be a cyclone center when it is also less than the average SLP in the five or nine closest grid points by a prescribed value that varies from several tens of hectopascals to several first hectopascals. We have realized all of these approaches in our software so

that users can choose the method for defining the cyclone centers. The menu for cyclone center definition is shown in Figure 1. Tropical areas may be characterized by the appearance of numerous local depressions (especially for the simplest "four-point minimum" definition), which cannot be identified with the cyclones. To avoid this effect, we introduced an additional parameter in the "local minima visualization settings," which allows one to drop local minima greater than a prescribed value. When the desired method is specified at the beginning of tracking, the calculated centers are marked on the map. As expected, different approaches demonstrate slightly different results in locating centers in the SLP field. As the animation goes on, the user can see whether the selected approach is effective enough, i.e., whether most of the marked centers belong to the real cyclones. In numerical schemes this problem is resolved by excluding from the analysis all cyclones with a lifetime of 24 hours, which seriously affect the reliability of the results.

Once the method for defining the centers is chosen, tracking can begin. The current cyclone position on the map (marked as cyclone center) should be clicked on with the left mouse button. This automatically applies the numbering, with the current pointer unique number appearing on the screen in the clicked point. There are 20 different pointers (see the pointer bar in Figure 1), and it is possible to switch to any one of these at any time. Thus up to 20 different cyclones can be tracked simultaneously. When the sequential snapshots change during the step-by-step animation, the numbers from the previous snapshots are recalled on the current screen during the cyclone life cycle until the user detects the end of the current cyclone track. Then the information for the current track (coordinates, date/time, and the corresponding SLP values) is saved as an ASCII file in the background of the animation, current track marks are removed from the screen, and this pointer number can be used for a new track. The software allows corrections of the tracking (such as moving, erasing, or adding some centers or whole tracks) at any time during the animation. The resulting ASCII file is automatically updated. By default, the output file has the same name as the data file and has the specific extension, but it is possible to redefine the output as any other file. To separate individual cyclones in the output file, we use the "time stamp" written at the beginning of every track. This "time stamp" consists of two lines, indicating the cyclone starting time and the number of time steps for a particular cyclone.

Applications for the Analysis of Results

The resulting ASCII file for the selected period (month, season, year) is used for a posterior analysis of cyclogenesis. This analysis can include the computation and mapping of cyclone frequency, the number of cyclones, and cyclone characteristics such as deepening rates, lifetimes, etc. In general, codes for the analysis can be written in any recognized language, and different graphic systems can be used to produce the output. These scientific applications are not included in the software and can be easily performed by users. Nevertheless, we found it reasonable to incorporate into the software some simple visual applications for preliminary analysis of the results. In particular, we provide the animation of the cyclone tracks using the output ASCII file. This application is performed in the same manner as the described SLP animation (Figure 2).

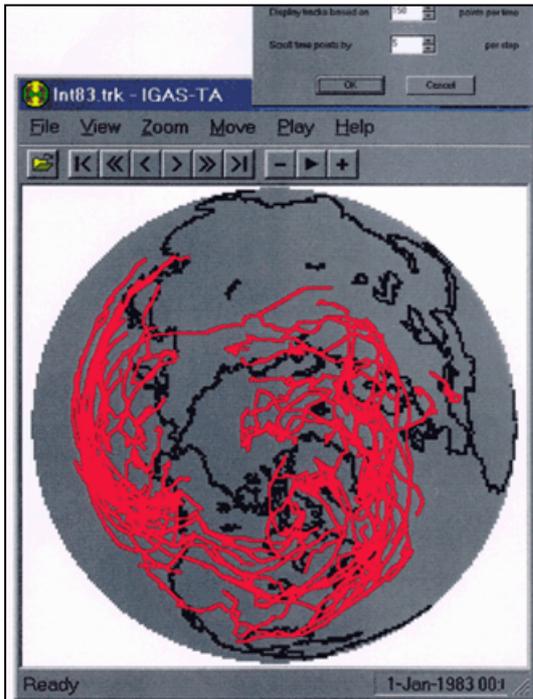


Fig. 2. Design of the storm track visualization window.

Using the menu, the user can define the time step of the animation and the running time window for which the tracks will be displayed. For instance, if both step and window are set to 10 days, each animation step will show all tracks observed during the past decade. Alternatively, if the window remains at 10 days but the time step is set to 1 day, the animation will display daily changes in storm tracks during the 10-day periods centered around the current date. By tuning these two parameters, one can easily produce, say, all tracks for the selected month or season, as well as animate the tracks on a daily basis. This application can be used for a definition of the most frequent storm track positions for a selected month (season) and for the rough monitoring of the weather regime changes. In addition, this application is quite useful for quick quality control of the tracking performed. It easily displays all operator mistakes (showing unreasonable track configurations), which can be corrected repeating the tracking procedure for the selected time moments in the neighboring window on the screen. Future versions of the software will contain more visual applications for analysis of results.

Pilot Study of Winter Cyclogenesis from the NCEP/NCAR Reanalysis Data

To test the software, we performed the winter cyclone climatology on the basis of 6-hourly SLP data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis

for the period 1958-1998. Data with a spatial resolution of 2.5 degrees were interpolated onto the polar 181 x 181 grid, and the output was converted to the software format. Physical aspects of the 40-year climatology and interannual changes in cyclogenesis will be discussed in a separate paper [S. K. Gulev *et al*, "Climate changes in the cyclogenesis over the Northern Hemisphere from the NCEP/NCAR Reanalysis data," submitted to *Climate Dynamics*, 2000]. Figure 3a is an example of the 30-year climatology of cyclone frequency for the period 1969-1998 and interannual changes in the number of cyclones over the Northern Hemisphere. The climatology performed demonstrates quite reasonable positions of storm tracks and shows somewhat more detailed regional features in comparison to those derived from the numerical algorithms. Particularly, we found many more cyclones that pass the Rocky Mountains and propagate over the eastern American continent. Many numerical schemes are not able to detect these cyclones and indicate their decay over the western American coast. Figure 3b shows interannual changes in the number of cyclones over the Northern Hemisphere. There were no significant trends found during a 30-year period. Nevertheless, pronounced decadal-scale variations in the number of cyclones are quite evident in Figure 3.

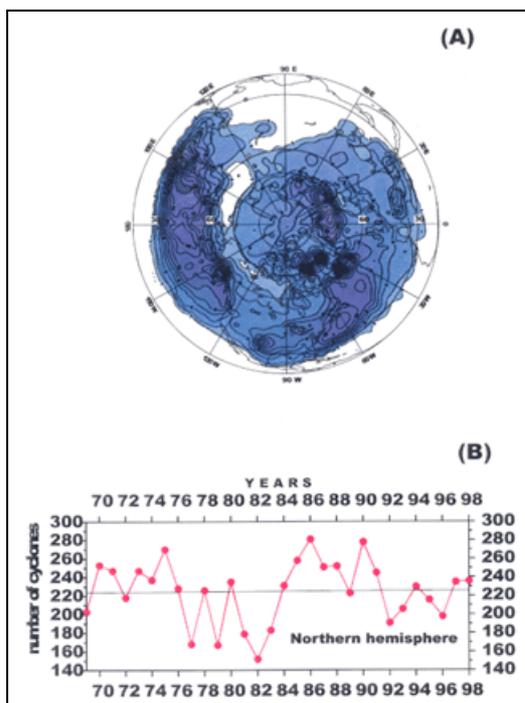


Fig. 3. a) Climatological winter cyclone frequency for 1969-1998 and b) interannual variability of the number of cyclones over the Northern Hemisphere for a 30-year period (1969-1998).

Concluding Remarks and Software Availability

The described software can effectively serve many purposes. Besides its scientific use, it can be applied for many operational needs. For example, it could be very useful for undergraduate and graduate meteorological education, presenting realistic pictures of highly variable atmospheric processes. We will continue to develop the software's applications. Focus will be on both analysis applications and the tracking engine itself. Currently, the latest version of this software and the demonstration data files are available by ftp from our server, <ftp://gulev.sio.rssi.ru/igas>, through an "anonymous" login. Please refer to included "readme" file for the technical details or e-mail Sergey Grigoriev (gri@gulev.sio.rssi.ru) with any questions.

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