A Climatological Investigation of the Activity of Summer Subtropical Vortices*

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ABSTRACT

By applying a new vortex detection method to the ECMWF 40-yr reanalysis (ERA40) data from 1985 to 2002, the climatology of summer vortices has been investigated in five subtropical regions, i.e., the northwestern Pacific, northeastern Pacific, northwestern Atlantic, northeastern Atlantic, and Australia-South Pacific, followed by validation with NCEP/NCAR reanalysis data. Results are as follows: (1) The spatial distributions of ERA40 vortex activities (VAC) were well consistent with those of NCEP/NCAR reanalysis (NRA) results in all regions, especially in northwestern Pacific. (2) Because of different model resolutions, both the number and intensity of vortices obtained from NRA were significantly weaker than ERA40's. (3) Vortices mainly cruised in coasts and the adjacent seas, from where to the land or the open sea vortex activities were gradually decreased. (4) There were two active centers in the northwestern Pacific: one was located in South China Sea and the other, as the largest center of the five regions, spread from the east side of the Philippines to Japan. (5) Over the northwestern Atlantic, most vortices occurred in Panama and its west-side offshore. (6) The spatial distributions of vortices were alike between the northeastern Pacific and northeastern Atlantic, both spreading from coasts to the west-side sea at 5°–20°N. (7) In the Australia-South Pacific, vortices were not as active as those in the other four regions, and mostly took place in the equator-side of near ocean areas. (8) Except the northwestern Pacific and northwestern Atlantic, the VAC interannual variations in the other three regions were different between ERA40 and NRA data. (9) In the northwestern Pacific and northwestern Atlantic, the VAC interannual variation could be separated to several distinct stages. (10) Since the mid 1980s, mean vortex intensity was getting increased in the northwestern Pacific, which was most significant in the subtropical areas on a global basis. In the western North Atlantic, there was a decreasing (increasing) trend of the mean vortex intensity before (after) the mid 1990s.

Key words: subtropics, vortex climatology, vortex intensity, vortex detection

1. Introduction

Vortex structures play a significant role in the atmospheric circulation. Barry and Carleton (2001) provided a comprehensive review about the vortex climatology research in the 20th century. In their work, the vortices in extratropical and tropical regions were primarily discussed, but not for subtropical area.

Since the 21st century, the activity of subtropical vortices has been paid more and more attentions. Qin et al. (2002) gave some new facts about the cyclone climatology over the East China Sea and northeastern Pacific. Wu et al. (2000) elaborated dynamics of the formation and variation of subtropical anticyclones. Hirsch et al. (2001) investigated the winter storm climatology of America East Coast, involving frequency and intensity characteristics of subtropical vortices. Above-mentioned studies enriched the research of subtropical vortex climatology, and lay the foundation for this article.

With respect to the subtropical vortex climatology, we noticed that researchers mainly focused on vortices of particular intensity in a given area, such as subtropical cyclone (tropical cyclone or subtropical high) in the East China Sea (northwestern Pacific), with a single dataset, e.g., NCEP/NCAR reanalysis data. In order to obtain a more comprehensive understanding of global subtropical vortex behavior, five representative regions were selected in this article. The vortex species were involved with multiple intensity and size,
and were not restricted to tropical or extratropical cyclones. To guarantee the reliability of conclusions, the primary results were calculated with ERA40 data, and then compared with NRA data. When the two results were similar, further analysis and discussion were performed.

2. Data and methods

2.1 Data

Two reanalysis datasets, ECMWF 40-yr reanalysis (Simmons and Gibson, 2000) and NCEP/NCAR reanalysis data (Kalnay, 1996), were used in this paper. The vortex surveys were implemented during 1985–2002 summer (JJA for the Northern Hemisphere and DJF for the Southern Hemisphere), over five selected regions, i.e., northwestern Pacific (NWP; 5\degree–40\degree N, 110\degree–180\degree E), northwestern Atlantic (NWA; 5\degree–40\degree N, 95\degree–50\degree W), northeastern Pacific (NEP; 5\degree–40\degree N, 180\degree E–110\degree W), northeastern Atlantic (NEA; 5\degree–40\degree N, 50\degree–5\degree W), and Australia-South Pacific (ASP; 5\degree–40\degree S, 110\degree–180\degree E). On simple investigations, vortex activity was found most remarkable in the lower troposphere, and thus all results in this article were taken at the 850-hPa level. Both datasets are with a resolution of 2.5\degree \times 2.5\degree lat./long. and 4 times daily.

2.2 Analysis methods

For a long time, most vortex detection methods require the calculation of physical quantities (e.g., pressure, helicity, or vorticity) at each point in a flow field and then make the classification of the values based on thresholds. The assumption behind this is that characteristics of the flow patterns in an infinitesimal area around a point can be determined by quantities at that point. Recently, Hoskins and Hodges (2002) indicated that this category of vortex detection criterion has several flaws: If the methods based on pressure thresholds are used, then weak cyclones could not be detected because of the influence of the background field; If the methods based on vorticity thresholds are used, then other structures (e.g., trough or shear line) would be mistaken for vortex structures. Those defects are getting more serious for subtropical vortices. Sadarjoen and Post (2000) proposed another vortex detection criterion, based on the vorticity field and geometric characteristics of streamlines. This method used in this paper is no longer affected by background field and can detect weak or small vortices accurately.

The spatial distribution of vortex activities is the main content of vortex climatology. A general way to construct spatial patterns is using the center point as whole vortex to calculate the frequency in each grid cell. This method is easy to lose the intensity and size information of vortices, and the results strongly depend on the map project and grid interval. For overcoming these shortcomings, we have designed a new statistical variable, vortex relative vorticity ($V_{vor}$), to represent the strength of vortex activities. The steps are as follows: Firstly, centers and edges of all vortices are determined by the Sadarjoen’s method; secondly, all points inside the vortex edges remain their vorticity and others are set to zero; finally, we obtain the $V_{vor}$ field, in which the vortex is composed of a group of points. In this way, all structures but vortices are removed from the vorticity field, while the geometry, intensity, and size properties of vortices are kept. The mean $V_{vor}$ field ($\overline{V}_{vor}$) can be calculated by averaging $18(\text{years}) \times 92(\text{days}) \times 4(\text{times}) = 6624$ pieces of $V_{vor}$ field. In the-obtained $\overline{V}_{vor}$ field, higher values reflected the intense vortex activities.

For analyzing the interannual variation of vortex activities, we have also developed an area-averaged $V_{vor}$ index ($\overline{V}_{vor}$). Specifically, the $V_{vor}$ field at a given time is averaged over one region to obtain its area mean value denoted by $V_{mvor}$, i.e., the total $V_{vor}$ values of all grids are divided by the number of grids. Next, the 92(days)$ \times 4(\text{times}) = 368$ $V_{mvor}$ values are averaged to result in the $\overline{V}_{vor}$ of one summer. The $\overline{V}_{vor}(t)$ for 18-yr constructed a time series which is used to reflect the interannual vortex behavior in that region.

Finally, an area-averaged intensity index ($\overline{I}_{vor}$) is defined to analyze the interannual variability of
individual vortex intensity. One summer $I_{\text{vor}}$ can be calculated by the total center vorticity ($I_{\text{vor}}$) divided by the number of vortices ($N_{\text{vor}}$) occurring in that summer.

3. Spatial distributions of the activity of summer subtropical vortices

As stated above, the $\nabla \text{vor}$ field averaged from 1985 to 2002 synthesizes the information on the frequency and intensity of vortices. Figure 1 shows the summer spatial distribution $\nabla \text{vor}$ averaged from 1985 to 2002 in the NWP and NWA regions. Prominent characteristics are as below.

1. According to the results obtained from ERA40 dataset, the high $\nabla \text{vor}$ areas are located in the adjacent coastal areas of both NWP and NWA regions.

![Figure 1](image1.png)

**Fig. 1.** The summer geographic distribution of vortex relative vorticity $\nabla \text{vor}$ averaged from 1985 to 2002 in NWP and NWA. (a) and (c) for NWP; (b) and (d) for NWA. (a) and (b) are computed by ERA40, (c) and (d) by NRA. Contour values are $1.0 \times 10^{-6} \text{ s}^{-1}$ and $3.0 \times 10^{-6} \text{ s}^{-1}$. Line-filled areas are $\nabla \text{vor} \geq 1.0 \times 10^{-6} \text{ s}^{-1}$, and solid-filled areas are $\nabla \text{vor} \geq 3.0 \times 10^{-6} \text{ s}^{-1}$.

![Figure 2](image2.png)

**Fig. 2.** As in Fig. 1, but for NEP ((a) and (c)) and NEA ((b) and (d)); (a), (b) are computed by ERA40, and (c) and (d) by NRA.
where to the land or the open sea $\overline{V}_{\text{vor}}$ decreases gradually, as shown in Figs.1a, b. This indicates that vortex activities, no matter in northwestern Pacific or northwestern Atlantic, are intense in adjacent sea areas. This is a notable feature of those two regions.

(2) In northwestern Pacific, there are two closed centers with higher $\overline{V}_{\text{vor}}$ values (solid-filled area). One is located over the South China Sea, and the other is over the adjacent sea area from the east side of Philippines to Japan. In contrast with northwestern Atlantic, the higher $\overline{V}_{\text{vor}}$ values centers span larger areas in northwestern Pacific (Figs.1a, b).

(3) Above-mentioned features can also be obtained from the results calculated with NRA dataset.

In other three regions (NEA, NEP, and ASP), a majority of high $\overline{V}_{\text{vor}}$ values lie over the adjacent sea area or the junction of land and sea (Figs.2a-d), with low $\overline{V}_{\text{vor}}$ values located in the open sea or inland (e.g., Australian outback, figure omitted). These attributes are analogous with those in Fig.1.

The correlation coefficients between ERA40’s $\overline{V}_{\text{vor}}$ and NRA’s $\overline{V}_{\text{vor}}$ fields are 0.94 for the NWP, 0.84 for the NWA, 0.71 for the NEP, 0.83 for the NEA, and 0.76 for the ASP region. All the five correlations are statistically significant at 95% confidence level and present a good agreement between ERA40 and NRA datasets.

4. Interannual variations in the activity of summer subtropical vortices

Figure 3 shows interannual variation curves of the area-averaged vortex vorticity index anomaly $\Delta \overline{V}_{\text{vor}}$ in the NWP and NWA regions. The correlation coefficients between the curves in Fig.3a (3c) and Fig. 3b (3d) reach 0.89 (0.83) and they are statistically significant at 95% confidence level.

Remarkable stage characteristics are dominated in the interannual variation of vortex activities in both regions. As in the NWP, vortex activities were strengthened during 1988–1991, weakened during 1993–1999 and increased from then to 2002 (Figs.3a, b). In the NWA, vortex activities were increased during 1987–1990 after a weakened year of 1987, followed by weak signals in two periods of 1991–1993 and 1995–2002, and strong signals from 1993 to 1995 in between. Evidently, different subtropical region has their unique interannual variation of vortex activities.

There are comparatively large discrepancies in the other three regions (Fig.4). The correlation coefficients between ERA40 and NRA $\Delta \overline{V}_{\text{vor}}$ datasets in

![Fig.3.](image)

Fig.3. The 1985–2002 interannual variations of summer vortex relative vorticity anomalies $\Delta \overline{V}_{\text{vor}}$ (unit: $10^{-7}$ s$^{-1}$) averaged over NWP and NWA. (a) and (b) for the NWP; (c) and (d) for the NWA. (a) and (c) are computed by ERA40; and (b) and (d) by NRA.
NEP, NEA, and ASP regions are 0.12, 0.46, and 0.41, respectively, but none of them reaches statistically significant at 95% confidence level, indicating that the consistency between two datasets changes with regions. To sum up, there are better consistencies between ERA40 and NRA resulting in the NWP and NWA regions.

Figure 5 displays temporal changes of the

**Fig. 4.** The 1985–2002 interannual variations of summer vortex relative vorticity anomalies $\Delta V_{vor}$ (unit: $10^{-7}$ s$^{-1}$) averaged over NEP, NEA, and ASP. (a) and (b) for NEP; (c) and (d) for NEA; (e) and (f) for ASP. (a), (c), and (e) are computed by ERA40; (b), (d), and (f) by NRA.

**Fig. 5.** The interannual variations of summer mean vortex intensity anomalies $\Delta \bar{I}_{vor}$ (unit: $10^{-6}$ s$^{-1}$) over NWP and NWA from 1985 to 2002. (a) and (b) for the NWP; (c) and (d) for the NWA. (a) and (c) are computed by ERA40, and (b) and (d) by NRA.
area-averaged intensity index anomaly $\Delta I_{vor}$ during 1985–2002 summer over the NWP and NWA. Since the middle 1980s, $\Delta I_{vor}$ has been strengthened in two research regions, especially significant in the NWP, where has experienced a decreasing trend since 1997. Moreover, the results calculated by both ERA40 and NRA data are similar.

Figure 6 shows the 5-yr smoothed area-averaged SST anomaly (SSTA) during 1985–2002 summer over the NWP and NWA, indicating an increased SST trend in both areas, which is more notable in the NWP region. Details of SST dataset may be found in Reynolds et al. (2002).

5. Conclusions and discussions

Vortices are dominant features in the atmospheric flow field. Intense vortex structures, such as typhoon or extratropical cyclone, will produce disastrous weather events. Previous studies of vortex climatology were frequently limited by geographic coverage, vortex detection method and data used to extract vortices. In this article, by using a new vortex detection method and the ECMWF 40-yr and NCEP/NCAR reanalysis data during 1985–2002 summer, the climatology of summer vortices has been investigated in the five subtropical regions, i.e., NWP, NEP, NWA, NEA, and ASP. The analysis characteristics may be drawn as follows.

(1) Northwestern Pacific has the most dramatic vortex activities in subtropical regions. In the NWP, there are two centers in which the number, size, and strength of vortices are larger than other regions. One is located over the South China Sea, and the other is over the adjacent sea area from the east side of the Philippines to Japan.

(2) In all the five selected regions, the areas of high vortex activities are mainly located in the adjacent sea area or the junction of land and sea. This is the basic feature of subtropical vortex climatology.

(3) In NWP and NEA, remarkable stage characteristics are dominated in the interannual variation of vortex activities.

(4) In NWP, individual vortex intensity has been strengthened since middle 1980s. This means that vortex activities will be increased in that area under the background of global warming.

The vortex climatology is a complex topic and lots of issues demand further study, e.g., in this article only the single layer data (850 hPa) were used to investigate vortex behaviors, and the three-dimensional distributions of vortex are still unclear.

REFERENCES


