ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 40, MARCH 2023, 447–463

• **News & Views** •

Historic and Future Perspectives of Storm and Cyclone

Gang FU*[1,2], Pengyuan LI[1], Lijia CHEN[1], Yongmao PENG[1], and Jing NI[1]

[1]*Department of Marine Meteorology, Ocean-Atmosphere Interaction and Climate Laboratory, Key Laboratory of Physical Oceanography, Ocean University of China, Qingdao* 266100, *China*

[2]*Division of Oceanic Dynamics and Climate, Pilot National Laboratory for Marine Science and Technology (Qingdao), Qingdao* 266000, *China*

(Received 13 July 2022; revised 28 September 2022; accepted 17 October 2022)

ABSTRACT

In weather sciences, the two specific terms "storm" and "cyclone" frequently appear in literature and usually refer to the violent nature of a number of weather systems characterized by central low pressure, strong winds, large precipitation amounts in the form of rain, freezing rain, or snow, as well as thunder and lightning. But what is the connection between these two specific terms? In this paper, the historic evolutions of the terms "storm" and "cyclone" are reviewed from the perspective of weather science. The earliest recorded storms in world history are also briefly introduced. Then, the origin of the term "meteorological bomb", which is the nickname of the "explosive cyclone" is introduced. Later, the various definitions of explosive cyclones given by several researchers are discussed. Also, the climatological features of explosive cyclones, as well as the future trends of explosive cyclones under global climate change, are discussed.

Key words: weather sciences, storm and cyclone, the origin of explosive cyclone, climatological features, global climate change, future trends

Citation: Fu, G., P. Y. Li, L. J. Chen, Y. M. Peng, and J. Ni, 2023: Historic and future perspectives of storm and cyclone. *Adv. Atmos. Sci.*, **40**(3), 447−463, https://doi.org/10.1007/s00376-022-2184-1.

Article Highlights:

- The historic evolutions of the terms "storm" and "cyclone" are reviewed, and the origin of the term "explosive cyclone" is introduced.
- The earliest recorded storms in world history are briefly introduced.
- The climatological features and future trends of explosive cyclones under global climate change are presented.

1. Introduction

In weather sciences, the term "storm" usually refers to the violent nature of a number of bad weather events that occur within Earth's atmosphere. Feser (2018) stated that "Storms are characterized by high wind speeds; often large precipitation amounts in the form of rain, freezing rain, or snow; and thunder and lightning (for thunderstorms). Many different types exist, ranging from tropical cyclones and large storms of the mid-latitudes to small polar lows, medicanes, thunderstorms, or tornadoes. They may lead to extreme weather events like storm surges, flooding, high snow quantities, or bush fires. Storms often pose a threat to human lives and property, agriculture, forestry, wildlife, ships, and offshore and onshore industries". This statement suggests that the term "storm" has evolved with human history. Now, the word "storm" refers not only to a natural phenomenon, but also to something that reflects the long history of human interaction with the natural world. The word "storm" has history in politics, military, economy, culture, religion, music, painting, and almost every aspect of human social life. Some scholars even believe that storms can be closely linked with the fates of nations. For example, Emanuel stated that "Were it not for two typhoons, Japan might be part of China today" (Emanuel, 2005, p. 3). Thus, it is of great significance to review the history of storms.

Although a summary of the influences of "storms" on human beings would be very interesting, it would be difficult to discuss the full spectrum of storms in a short paper. Since rapidly intensifying cyclones have attracted more and more attention

* Corresponding author: Gang FU
Emails: fugang@ouc.edu.cn, fugangouc@qq.com

under the background of global climate change, the use of “storms” [a] in this paper will reference only rapidly intensifying cyclones. The aim of this paper is to briefly introduce the historic and future usage of the terms “storm” and “cyclone” from the weather science perspective. The rest of this paper is organized as follows. Section 2 will present our understanding of the terms “storm” and “cyclone”. Section 3 will briefly introduce the earliest recorded storms in world history. Section 4 will introduce the origin of the term “meteorological bomb”, which is a nickname for the “explosive storm”. Section 5 will present the various definitions of explosive storm. Section 6 will describe the climatological features of explosive cyclones. Section 7 will discuss the projected future trends of explosive storms under global climate change. Finally, concluding remarks will be given in section 8.

2. Understanding the meanings of the terms “storm” and “cyclone”

2.1. *Overview of “storm” and “cyclone”*

According to the *Oxford Advanced Learner’s Dictionary,* the word “storm” is a noun with the meaning “very bad weather with strong winds and rain, and often thunder and lightning”. The word “explosive” is an adjective with the meaning “increasing suddenly and rapidly”. It also refers to a noun with the meaning “an explosive device (= a bomb)”.

The term “cyclone” was first used in 1848 in the field of meteorology by Henry Piddington (Piddington, 1848). Unlike “hurricane” or “typhoon”, “cyclone” is an English version of a word from another language. When proposing this general term for tropical revolving storms, Piddington (1848) said “… I suggest that we might perhaps for all class of circular or highly curved winds adopt the term ‘Cyclone’ from the Greek ‘Kuklws’ (which signifies among other things the coil of a snake)…” (Sen Sarma, 2013). And since the term “cyclone” is less than 200 years old, European nations prefer to use the term “storm” to document severe weather events in history.

2.2. *Naming storm systems*

People like to name things so that they can recognize and remember them more easily. Although the tradition of recording the weather may date back to the Renaissance times, the tradition of naming high and low pressure systems started much more recently. Since the 1950s, meteorological organizations have been naming storm systems. This change has been welcomed by the public, media, and weather forecasters. Naming storm systems in a cooperative way based on meteorological data is a good way to aid clear communication about disastrous impacts. But because severe weather occurs frequently, most events are currently identified by date and region, as providing a name for each event could be a challenging issue.

During World War II, the weather service of the United States began naming typhoons over the Pacific Ocean with female names. Therefore, it was easier for them to track the current weather situations and distinguish several severe weather systems. This program was so useful and satisfactory that it was later applied to hurricanes over the Atlantic Ocean.

In Germany, since 1954, storms have been unofficially named by the Institute of Meteorology at Free University of Berlin. At that time, Karla Wege was a student at the Institute of Meteorology at Free University of Berlin, and she later became an on-air meteorologist with the ZDF (German Second Television Station). She suggested that all vortices in central Europe, including both lows and highs, should be named. Thus, since 1954, the Institute of Meteorology has been naming lows with female names and highs with male names so that it is easier to track low and high pressure systems on weather maps. Ten lists of names starting with letters cycling through the alphabet were created for highs, and ten similar lists of names were created for lows, totaling 260 female and 260 male names. If the total list ran out, it would be used again from the beginning. Until the 1990s, this practice was exclusively used by Berlin newspapers, local radio stations, and TV media. Severe storms such as “Vivien” and “Wiebke” have changed this habit, and since then, these names have been commonly used by the German media.

In 1998, a debate began concerning whether it was discriminatory to name highs with “good weather” by using male names and lows with “bad weather” by using female names. So, it was decided to use male names for lows in odd years and female names for highs in even years.

The UK and Ireland started naming storms for the first time in 2015. Led by the Met Office and Met Éireann, “Name Our Storms” was a pilot project to name storms that may have a significant impact on the UK and/or Ireland but have not yet been named by the United States. The public had the opportunity to submit storm names for the UK and Ireland.

According to the National Oceanic and Atmospheric Administration, the United States began to officially name storms in 1951 by using the phonetic alphabet (e.g., Alpha, Bravo, Charlie, etc.), and they began giving female names to storms in 1953 based on a list from the National Hurricane Center. It was not until 1978 that both male and female names were given to storms over the Northeastern Pacific; the new standard was adopted in 1979 for the Atlantic and Gulf of Mexico.

By using a quantitative method called IMPACT (Integrated Meteorological Population and Area Calculation Tool), the

[a] In this paper, the terms “explosive storm” and “explosive cyclone” are used interchangeably.

TV Weather Channel in the United States began unofficially naming significant winter storms in 2012. Their method compared population counts with the winter weather warnings of the National Weather Service. Today, the naming of storms is managed by an international committee of the WMO (World Meteorological Organization). The committee is composed of regional meteorological agencies, which are responsible for naming storms in corresponding areas.

3. The earlierst recorded storms in world history

3.1. *The earliest recorded storms in Chinese history*

A vast number of Chinese historical documents in the form of "Fang Zhi" (semi-official local gazette) provide a high-resolution historical dataset of typhoon landfall frequency. By using the data compiled from "Fang Zhi", Liu et al. (2001) reconstructed a 1000-yr time series of typhoon landfalls since AD 975 in the Guangdong Province of southern China. Although the 571 typhoon landfall records contained in the historical documents perhaps were not enough to represent the total number of typhoons affecting Guangdong, the calibration of the historical data against the observations taken during the instrumental period from 1884 to 1909 showed that these two datasets had a significant correlation coefficient of 0.71, confirming that the time series reconstructed from the historical documents contained reliable records of typhoon landfall variability (Liu et al., 2001).

3.1.1. *Storms recorded in ancient Chinese documents*

Chinese historical documents contain a tremendous amount of information about storms. In a well-known book titled *Science and Civilization in China*, authored by Joseph NEEDHAM and Ling WANG , the topic "meteorology" is discussed in Section 21 of Volume 3, "Mathematics and the Sciences of the Heavens and the Earth" (Needham and Wang, 1959, p.462–p.494). The authors thought that "China's succession of passing weather is the product of the seasonal monsoon circulation, the occasional tropical cyclones, and the procession of continental cyclonic storms, all modified by the relief of the subcontinent" (Needham and Wang, 1959, p.462–p.463). They also indicated that "The third element in the Chinese climate is the tropical typhoon, a small but very intense disturbance with extremely low pressure at the center, steep barometric gradients, and wind velocities up to 165 miles an hour. Though the typhoon as a whole moves fast (often several hundred miles a day), the total area under the sway of its damaging winds is frequently not more than 100 miles in diameter. The typhoon originates in the Pacific, and after travelling westward tends northward as it strikes the China coast, eventually dying out in the interior provinces" (Needham and Wang, 1959, p.463). The feature of [颶母] (speaks as "chümu", typhoon-mothers) was also described (Needham and Wang, 1959, p.470, line 19).

In ancient China, although the topic of storms was not the specific subject of any official book, knowledge about storms ("Jufeng" or "Typhoon") can be found in some unofficial documents such as gazettes, essays, personal dairies, travel logs, and poems written by individual scholars. The earliest mention and scientific description of storms (typhoons) in ancient China were recorded in a book titled *Nan Yue Zhi* ([南越志], *Gazette of the Southern Yue Region)*, written around AD 470.

As weather phenomena, typhoons were often mentioned and discussed in the 9th century in works such as history books, poems, and government documents. In AD 816, a typhoon which hit the coastal city of Mizhou in Shandong Province of northern China was the earliest recorded landfalling tropical cyclone in China, and perhaps in the world (Louie and Liu, 2003).

The ancient Chinese people recognized the violent nature of storms and used (created) a specific word [颶] to describe these storms. *Kangxi Dictionary*[b], one of the most authoritative dictionaries for the study of Chinese characters, includes detailed documents and explanations for the Chinese character [颶] (see Fig. 1).

Basically, the Chinese character [颶] consists of two parts: the left part [風](wind) + the right part [具] (fearful), which is spelled as "jù" in Chinese Pinyin. *Kangxi Dictionary* says that throughout the history of China, one of the earliest texts discussing storms that formed over seas might be traced to *Nan Yue Zhi*, compiled by Huaiyuan SHEN[c] during the period from 453 AD to 463 AD. Shen's work includes the earliest recording of so-called "the mother of storm" [颶母]. Shen also thought that the character [颶] meant "fearful wind." The original excerpt from *Nan Yue Zhi* (see Fig. 2) was translated from Chinese into English as follows: "Among the local people, there are many 'Jufeng' (violent storms). The so-called 'Jufeng' means winds coming from four directions. These storms occur frequently in June or July of lunar calendar which corresponds with July or August of solar calendar, respectively. When those storms come, cocks and dogs usually keep no sound for three days. The big storms may last for seven days, and the small storms may last for one or two days. The foreign

[b] In Chinese [康熙字典]. In the Qing Dynasty, the compilation of *Kangxi Dictionary* was started in 1710 and was completed in 1716, lasting for six years. It contains a total of 47 035 Chinese characters and is regarded as one of the key and most powerful tools in the world to study Chinese characters.
[c] Chinese name is [沈懷遠].

Fig. 1. The Chinese character [颶] included in *Kangxi Dictionary*.

countries regard these storms as black winds.” [d]

The shape of Chinese character [颶] was disputable. According to Tong DAI [e] of the Southern Song Dynasty of China, who wrote the *Liu Shu Gu*[f] (*Ancient Stories from Six Books*), the character [颶] (see Fig. 3) was the earliest term used to describe a big storm. Later, this character was erroneously passed down as [颶]. “This character [颶] meaning disastrous winds from the sea. However, it was mis-written as [颶] by popular books.”[g]

In the Tang Dynasty of China, a poem titled “*Poem to Jiangling*”[h] authored by Yu HAN[i] was written as “The ‘Jufeng’ storm is the most terrible, sweeping the hills with roar.”[j] In the Southern Song Dynasty of China, the great poet You LU[k] once said that “There were massive miasma air over the surface of hills. Initially it looked to be dark and circular, but later it became wider gradually. It was called as “mother of ‘Jufeng’ storm.”[l]

The “typhoon” is a well-known weather phenomenon, and its etymology has been debated for more than 300 years. Based on all available ancient and modern documents around the world, Wu (2020) discussed the historical evolution of the Chinese word “Tai Feng” and the English word “typhoon”. Wu (2020) pointed out that the debate on the etymology of typhoon started from the publication of “The Voyages and Adventures of Ferdinand Mendez Pinto” in 1560. Wu (2020) also indicated that European researchers did not give convincing evidence to support the Greek origin of typhoon, nor the Greek origin of typhoon in Arabic and the languages of countries around the Indian Ocean. He thought that if the word “typhoon” in the languages of these countries came from Greek, and the word “typhoon” was transmitted to China through the ancient maritime silk road that began in the Han Dynasty of China, there should be some records in ancient Chinese documents. However, there were only some records in ancient Chinese books of foreigners calling typhoon “black wind.” Therefore, the existing documents do not support the transmission route map of typhoon from the Greek language through the Arabic language and to the Chinese language, although it is possible that the evolution of the English word “typhoon” was influenced by the Greek language. There is no convincing evidence that the word “typhoon” came from Greece or Arabia. On the contrary, its origin might be traced back to dialects in coastal regions of southeastern China beginning in the Song Dynasty, although “Jufeng” (hurricane) was officially used for more than 1000 years. This word is pronounced as “Fengchi” in the southern Zhejiang dialect (Chinese Wu dialect), as “Chi Feng” in the Fujian dialect (Chinese Min dialect), and as “Fengtai”

[d] In Chinese [南越志曰熙民間多颶(具音)風颶者其四方之風也一曰懼風言怖懼也常以六七月興未至時三日雞犬為之不鳴大者或七日小者一二日外國以為黑風].

[e] Tong DAI [戴侗] (1200–1285 AD), courtesy name Zhongda, was a famous writer in the Southern Song Dynasty of China. It took Tong Dai about 30 years to complete the 33 volumes of *Liu Shu Gu* [六書故]. *Liu Shu Gu* were divided into 9 parts on astronomy, geography, and human affairs, which were further subdivided into 479 sections. *Liu Shu Gu* corrected many errors in *Shuo Wen Jie Zi* [說文解字], which has an important position in the history of textualexegetics. Tong Dai is a philologist who made outstanding contributions in the history of Chinese philology. *Liu Shu Gu* is a reference book with high achievements and unique characteristics in the history of Chinese philology.

[f] The book is titled [六書故] in Chinese.

[g] In Chinese 《六書故》曰：補妹切，海之災風也，俗書誤作颶.

[h] In Chinese 《赴江陵诗》.

[i] Yu HAN [韩愈] lived from 768 AD to 824 AD and was regarded as an outstanding writer, thinker, philosopher, and politician in the Tang Dynasty of China.

[j] In Chinese “颶起最可畏，訇哮簸陵丘”.

[k] You LU [陆游], who lived from 13 November 1125 AD to 26 January 1210 AD and has the courtesy name Wuguan and the literary name Fangweng, was a greatest writer, historian, and poet in the Southern Song Dynasty of China. He wrote about 10 000 poems in his sixty-year life. More than 9300 of his poems were passed down to later generations.

[l] In Chinese “嶺表有瘴母，初起圜黑，久漸廣，謂之颶母”.

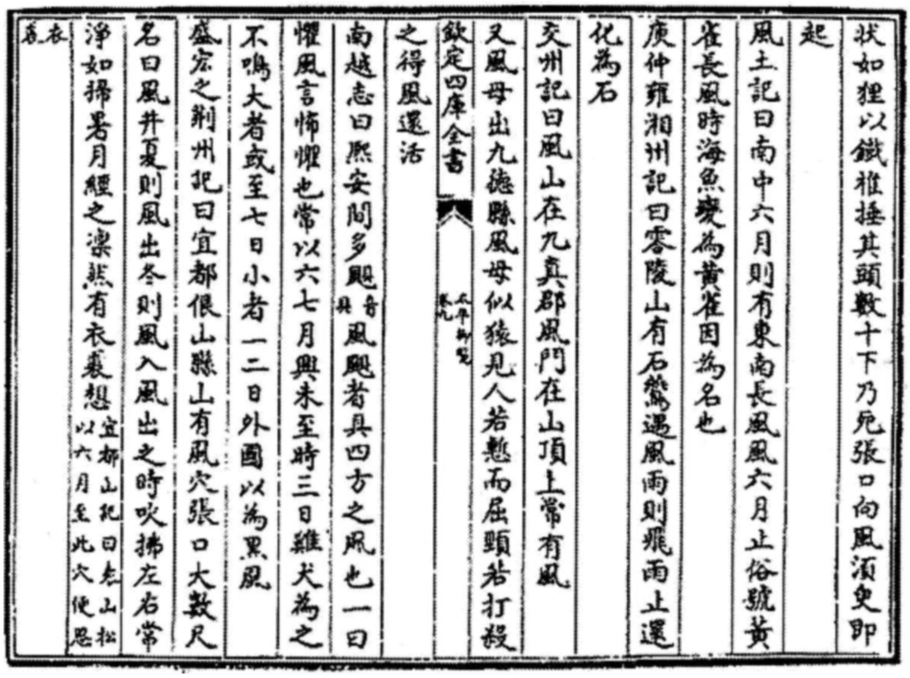
狀如狸以鐵椎插其頭數十下乃死張口向風須臾即
起
風土記曰南中六月則有東南長風風六月止俗號黃
雀長風時海魚變為黃雀因為名也
庚仲雍湘州記曰零陵山有石鷰遇風雨則飛雨止還
化為石
交州記曰風山在九真郡風門在山頂上常有風
又風母出九德縣風母似猿見人若慙而屈頸若打殺
欽定四庫全書
之得風還活
南越志曰熙安間多颶音具風颶者具四方之風也一曰
懼風言怖懼也常以六七月興未至時三日雞犬為之
不鳴大者或至七日小者一二日外國以為黑風
盛宏之荊州記曰宜都佷山縣山有風穴張口大數尺
名曰風井夏則風出冬則風入風出之時吹拂左右常
淨如掃箸月經之凜然有衣裘想宜都山記曰老山松以六月至此穴便思

Fig. 2. Excerpt from *Nan Yue Zhi* containing the earliest mention of storms (“Jufeng”) in the world.

Fig. 3. The Chinese character [颶] collected in *Kangxi Dictionary*.

or “Taifeng” in the Fujian dialect, because “Chi” and “Tai” have similar pronunciations in the Fujian dialect. The history of the word “typhoon” reflects the significant changes during the long history of China, as well as the long history of communication between China and the coastal countries of the Indian Ocean as well as European countries. A lot of information was preserved in vast historical documents, and many details need further verification.

In addition, from the evolution of the English word “typhoon”, it can be seen that typhoon is not an English spelling (Typhon), and it is directly borrowed from the ancient Greek myth. From 1560, when Ferdinand Mendez Pinto proposed “tufaŏ”, to the end of the 19th century, more than 300 years has passed. There have been a lot of spellings such as “Touffon, Tuffon, Tufon, Tuffin, Tuffoon, Tayfun, Tiffoon, Typhawn, Tyfoong, Typhoon, Toofan, Tiffon, Touffan, Tyfoon, and Tuphan”. *Journal of the Franklin Institute*, published in the United States in 1839, mentions the typhoon that affected Macao during 5–6 August 1835. Typhoon was spelled “tyfoon”. In the book *The Philosophy of Storms*, which was published by James Pollard Espy (Espy, 1841), the spelling “typhoon” was used again.

3.1.2. *Storm studies by modern Chinese researchers*

During the earlier part of the 20th century, the pioneering meteorologists of China investigated storms over the East Asian region. On 21 March 1916, Co-Ching CHU[m], when he was working toward his doctorate degree with the department

[m] Chinese name is [竺可楨].

of geology and geography at Harvard University in Cambridge, Massachusetts, United States, submitted a paper titled "Rainfall in China, 1900–11" to *Monthly Weather Review*. In May 1916, this paper was published in Volume 44 Issue 5 of *Monthly Weather Review* from page 276 to page 281 (Chu, 1916). By using the meteorological data from the period of 1901 to 1910 observed at Zi-Ka-Wei (Xu-Jia-Hui) observatory station, Shanghai, Co-Ching CHU found that there were three main cyclone tracks: (a) those originating from Siberia, Mongolia, and Manchuria, (b) those originating from China and Tibet, and (c) those originating from the Pacific, East China Sea, and Yellow Sea.

A total of 626 storms were investigated individually and classified into three groups according to their origins. Siberian storms, which belong to the first group, usually originated in the west of Irkutsk and moved eastward, passing through eastern Mongolia, southern Manchuria, and then to northeastern China or Shandong, or more directly entering into the Japan Sea from Manchuria and then to the Okhotsk Sea. Their moving direction changed from southeast to northeast, and the average passing time was about six days. These storms could have also originated in Mongolia or Manchuria. The low centers of the second group of storms usually appeared first in the southern part of Tongting Lake or in Sichuan (Szechuang) Province and then arrived at nearby Nanjing (Nanking) on the second day, leaving it on the third day and heading for the East China Sea, later entering the Okhotsk Sea by way of the Japan Islands. Usually, the moving direction of these storms was eastward while they were over the continent. The centers of low pressure that originated in the Pacific were mostly what were known as typhoons or baguios. In winter, the storms were usually far from the continental coast and exerted little or no influence on the rainfall in China, while in summer and early autumn, they brought heavy rainfall. The storms in summer, which make up the third group, developed near or in eastern part of the Philippine Islands, passed the eastern Chinese coast and moved northwestward over the Japan Sea or Japan Islands toward Kamchatka. In summer, no storm tracks could be traced over the Bering Sea or the extreme northeast Pacific coast.

The meteorological data collected at Zi-Ka-Wei also contained the daily rainfall records of 41 stations in China for the years 1901 to 1905 and of an additional 70 stations for the years 1909 to 1910. Some of the additional stations are Japanese stations. The number of storms recorded increased with later years, and the locations of the low centers were more clearly indicated in the later years as a result of the increasing number of stations.

Some of the storms reported by the Zi-Ka-Wei Observatory were too far offshore to affect the rainfall in China, and a few passed too far north in Siberia. The total 626 storms, which passed across or near China proper, Manchuria, and the neighboring seas, were classified according to their origins (see Fig. 4). The storms were well distributed between the months of the year. There were two maxima, one in spring and the other in late fall. The first was due to the frequency of Siberian and China proper storms, and the second was due to the great number of typhoons in the autumn. The translation speeds of these storms increased from summer to winter. For the storms of the first two types, the translation speeds vary from 20 mph to 40 mph (9–18 m s^{-1}) in winter and from 15 mph to 25 mph (7–12 m s^{-1}) in summer. For all the typhoons, the average translation speed is about 20 mph (9 m s^{-1}) in winter and about 18 mph (8 m s^{-1}) in summer. The storms that originated in the East China Sea and Yellow Sea were not typhoons, but belonged to the second group, as could be easily seen

TABLE 2.—*Classification of 626 storms that passed across or near China.*

Month.	Siberian type.	China proper type.			Typhoons.		
		North China.	South China.	Eastern Sea.	In ocean.	On coast.	Total.
January	12	3	23	7	0	0	45
February	9	7	16	5	4	0	41
March	20	4	21	7	4	0	56
April	28	7	25	3	4	0	67
May	26	11	19	1	12	0	69
June	17	5	26	3	9	4	64
July	6	6	8	3	14	14	51
August	1	5	2	1	16	20	45
September	7	2	5	3	19	13	49
October	11	5	11	2	19	8	56
November	18	4	9	3	10	1	45
December	16	5	12	1	4	0	38
Total	171	64	177	39	115	60	626

Fig. 4. The hard copy of "Table 2-Classification of 626 storms that passed across or near China" on page 277 of the paper (cited from Chu, 1916). It is vital to indicate that in the original table in the rightmost column for row "September", there was tiny error in which the count given was previously "48".

by their monthly distribution.

Pingjan TSIANG[n] was another pioneering Chinese scholar who investigated typhoons over the Pacific. In 1925, he published a paper titled "On Typhoons over the Shandong Peninsula" in *Chinese Journal of China Meteorological Society* (Tsiang, 1925). He indicated that the typhoons over the Pacific often affected the coast of China between July and August of every year. But their landfall locations were mostly in Fujian, Zhejiang, and Guangdong provinces. To the far north, they could reach the coast of Jiangsu and even move into the Yangtze River basin. As these storms might have moved northward, far beyond 34°N or 35°N, most of them then moved eastward and then into the Japan Sea. A typhoon impacting the Shandong coast was quite rare. Based on historic data, Tsiang (1925) summarized the monthly tracks of typhoons that occurred over the Pacific (see Fig. 5)[o]. He even documented a rare typhoon case that impacted the Shandong Peninsula during 12–13 July 1924 (see Fig. 6)[p]. He also recorded the related meteorological parameters of air pressure, wind direction, wind speed, air temperature, and air humidity from 11 to 13 July at the station of Tsingtao[q] and from 12 to 14 July at the stations of Zhi-Fu[r], Wei-Hai[s], and Lü-Shun[t]. To the knowledge of the present authors, this typhoon case seems to be the first with recorded weather maps for the region over the Northwestern Pacific.

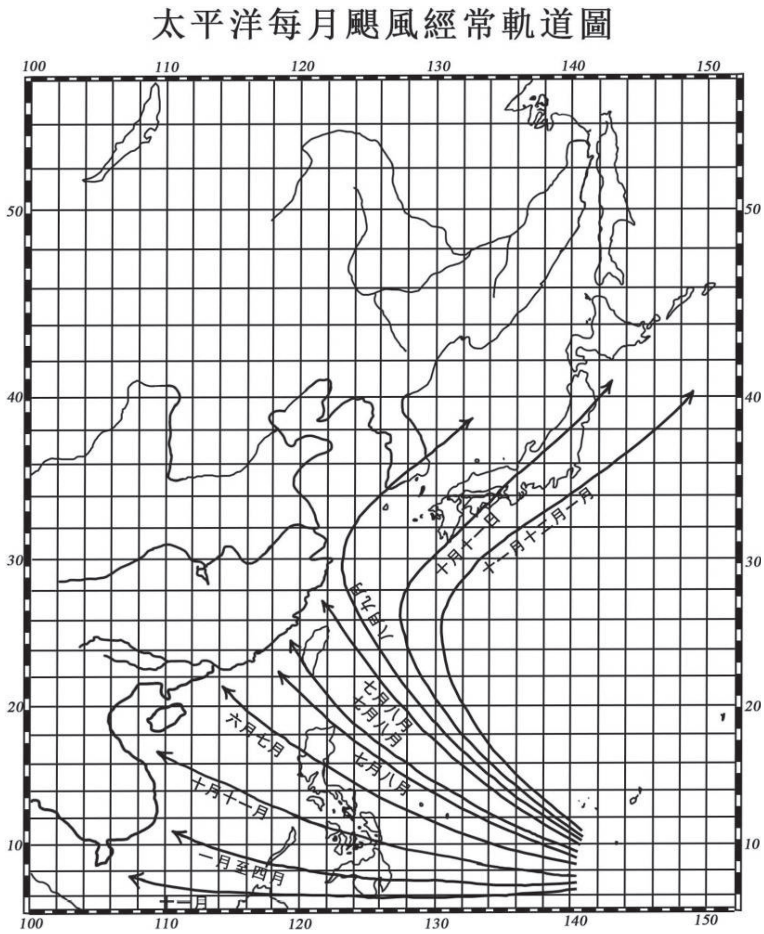

Fig. 5. The monthly tracks of typhoons that occurred over the Pacific (cited from Tsiang, 1925). The Chinese labels located near the ten tracks (from bottom to top) are "November", "January to April", "October to November", "June to July", "July to August", "July to August", "August to September", "October to November", "November, December, January", respectively.

[n] Chinese name is [蒋丙然].
[o] The map title [太平洋每月颶風經常軌道圖] means "The monthly moving tracks of typhoons occurred over the Pacific".
[p] The map title [中華民國十三年七月十二日天氣圖] means "The weather chart on 12 July 1924".
[q] In Chinese [青岛].
[r] In Chinese [芝罘].
[s] In Chinese [威海].
[t] In Chinese [旅顺].

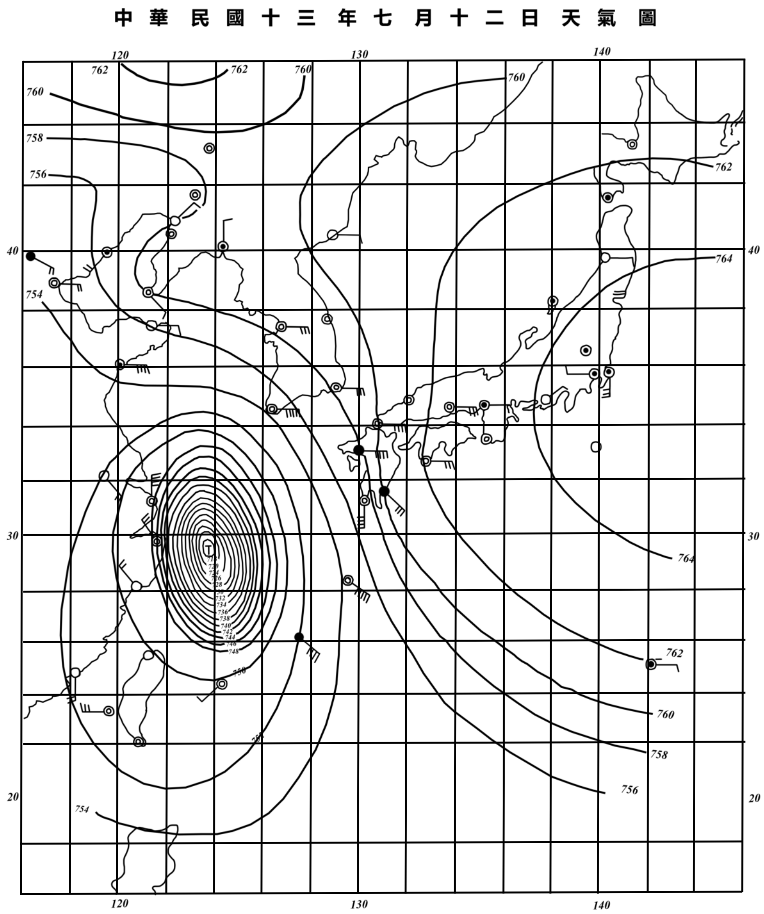

Fig. 6. The weather chart on 12 July 1924. The unit of isobaric contour is the millimeter of mercury (cited from Tsiang, 1925). 1 millimeter of mercury is roughly equal to 1.333 hPa.

3.2. *Historic storms in Japan*

Some historic documents imply that Japanese history has a close connection with the evolution of the term storm. The term “divine wind”[u] (spelled as “Kamikaze” in Japanese) has played a very special and unique role in Japanese history. Emanuel even held the following point of view: “Were it not for two typhoons, Japan might be part of China today” (Emanuel, 2005, p.3). He suggests that the course of Japan’s history was closely related to two violent storms (“Kamikaze” of 1274 and 1281) that occurred during two of Mongol’s wars on Japan, which took place in November 1274 and August 1281, respectively, when Kublai KHAN (1260–94) sent two huge fleets from Korea and China. These two storms wrecked the Mongol fleets attempting to invade Japan in 1274 and 1281. Most of the Mongol ships were destroyed, and the rest were dispersed, forcing the attackers to abandon their plans, fortuitously saving Japan from foreign conquest.

3.2.1. *The first Mongol War of Japan*

Around November 1274, the Mongols launched their first war against Japan, known as the Battle of Bun’ei. An estimated 500 to 900 ships and 40 000 fighters (mostly Chinese and Koreans) arrived on the shores of Hakata Bay, where the two forces met. The Mongols destroyed the Japanese army who had begun to retreat. However, fearing that the Japanese were ready to return with reinforcements, the Mongols retreated to their ships. That night, as the ships were moored in Hakata Bay, a violent storm (possibly a typhoon) struck. By daybreak, there were only a few ships left. The rest were destroyed, taking the lives of thousands of Mongols with them.

3.2.2. *The second Mongol War of Japan*

Although the Japanese had a lucky escape in 1274, the war was not over yet. The Mongols were now more determined than ever to conquer Japan. They prepared diligently to rebuild their fleets and recruit more warriors. At the same time, the Japanese constructed two-meter high walls to protect themselves from the future attacks of Mongols.

---

[u] In Japanese 神風.

Seven years later, in 1281, the Mongols returned with an enormous fleet of 4400 ships and about 70 000 to 140 000 soldiers. One army set out from Korea and another set sail from southern China, converging near Hakata Bay in August 1281. Unable to find any suitable landing beaches due to the walls, the fleet drifted over sea for months, depleting their supplies while searching for a suitable area for landing. On 15 August, the Mongols prepared to attack the much smaller Japanese forces defending the island. However, a massive typhoon struck again, destroying the Mongol fleet, and once again foiling the Mongols' invasion attempt.

The Japanese believed that their gods had dispatched the storms to preserve Japan from the Mongols. They called these two storms "Kamikaze" (divine winds). Later, the term "Kamikaze" was coined in honor of the two storms, as it was perceived to be a gift from the gods, supposedly granted after a retired emperor went on a pilgrimage and prayed for divine intervention. Kublai KHAN seemed to agree that Japan was protected by supernatural forces, thus giving up the idea of conquering this island nation. Now it is quite hard to overstate how vital the two wars are to Japan and their influences on the nation. The entire glorious episode, which mixed divine intervention with martial heroism, would gain and hold mythical status in Japanese culture forever after.

3.3. *Historic storms in Europe*

European countries traditionally recorded their impactful storms. In 1991, Lamb published his book "*Historic Storms of the North Sea, British Isles and Northwest Europe*" (Lamb, 1991). This book is a unique study of storms over the past 500 years that have affected the British Isles as well as the seas and coasts of northwestern Europe. This is a specific region for which there was enough information available in the archives to make such a review possible. Almost all storms since about 1700 had been reported by using meteorological maps and wind strength estimates and measurements. The book also looked at the trends and long-term changes, as well as the impact of these great storms on seafarers, local populations, and the landscapes.

In 1703, the British Isles experienced one of the most severe storms in their history (Wheeler, 2003). This great storm attracted widespread attention not only for its severity, but also for its impact on shipping around the coasts, where thousands of people lost their lives and hundreds of ships were destroyed. Another interesting point about the storm of 1703 is that it seemed to be the first one for which there existed a lot of "scientific" evidence—a claim based on barometric data. The mercury barometer was invented less than a century earlier by Evangelista Torricelli (1608–47), and barometric data became very valuable for gauging the passage of a violent storm. Lamb's (1991) exhaustive reconstruction of historical storm events drew heavily on these data. He placed great emphasis on evidence obtained from ships' logbooks. He had long recognized the value of this source of data.

One of the most striking aspects of the 1703 storm was not wholly ascribed to its severity but was that it marked the conclusion of a two-week period of increasingly stormy weather conditions. That age was an age of navigation, and the westerly winds throughout this period made it possible for ships from the Atlantic and the Mediterranean to reach their anchorages smoothly. The book "*Historic Storms of the North Sea, British Isles and Northwest Europe*" (Lamb, 1991) should always be referred to on matters of the detailed meteorology of the 1703 storm.

3.4. *Historic storms in the North American and Caribbean regions*

In 1963, David M. Ludlum published his famous book "*Early American Hurricanes 1492–1870*" (Ludlum, 1963). By using private diaries, logbooks of ships, chronicles, military reports, and early newspapers, Ludlum (1963) developed the most comprehensive archive of hurricanes prior to 1870 that either closely approached or actually crossed the Atlantic and Gulf coastlines of the United States. Starting with the experiences of Columbus, Ludlum (1963) divided history into three periods: 1501–1700, 1701–1814, and 1815–70. He also discussed, in more detail, three significant tropical cyclones that affected the United States in 1850.

Stuart B. Schwartz is a professor of history at Yale University. In 2015, he published his book "*Sea of Storms: A History of Hurricanes in the Greater Caribbean from Columbus to Katrina*", which spanns more than five centuries and draws on extensive archival research performed in Europe and the Americas (Schwartz, 2015). He believes that the diverse cultures of the Caribbean region have been shaped as much by hurricanes as they have by diplomacy, commerce, or the legacy of colonial rule. In this panoramic book of social history, Schwartz (2015) examines how Caribbean society has responded to the dangers of hurricanes, and how these destructive storms have affected the history of the region. From the voyages of Columbus to the devastation of Hurricane Katrina in 2005, Schwartz (2015) shows readers the ethical, political, and economic challenges that hurricanes have posed to the Caribbean region.

4. The origin of the term "meteorological bomb"

Among the various kinds of extratropical cyclones, one undergoes such significant rapid deepening that it has the potential to bring more destructive effects than even tropical cyclones.

In 1954, Tor Bergeron noticed the phenomenon of rapid intensification of extratropical cyclones (Bergeron, 1954). In the paper "*Reviews of Modern Meteorology-12. The Problem of Tropical Hurricanes*," Bergeron (1954) discusses not only the "rapid development" of tropical cyclones, but also five typical extratropical hurricanes[v]. They were: (1) "the famous cyclone which on the 23 October 1921 reached southern Scandinavia" (Fig. 15 on p.156). (2) "An analogous case, occurring within the period from 30 September to 2 October 1912" (Fig. 16 on p.157). (3) "the Scandinavian Low of 25–30 July 1950" (Fig. 17 on p.158). (4) "Baltic summer hurricane from 7 to 8 July 1929" (Fig. 18 on p.159). (5) "Baltic summer hurricane from 10 to 11 July 1882" (Fig. 19 on p.160), respectively. When describing the cyclone on 23 October 1921, he also mentioned that "It could be expected to move eastward, occlude and cause a rather strong deepening of the Low. In such a case one may generally expect a pressure fall of about 1 hPa h^{-1}." Although Bergeron (1954) outlined the phenomena of the rapid development of tropical cyclones, he did not give a clear definition of explosive cyclones.

The 1979 Fastnet Yachting Race from 10 to 13 August 1979 held in the UK and Ireland was the 28th annual yachting race of the Royal Ocean Racing Club. This race was impacted by one of the most devastating "killer storms" (Rice, 1979) in history for the North Atlantic region. A rapidly deepening storm with the force of 10 gale resulted in 18 deaths and caused huge property losses. The story of the devastating 1979 Fastnet Race was dramatic and tragic, and the ramifications for yachting continued to unfold for several decades[w]. Only 86 of the original 303 yachts completed the race, and more than half of the original 303 yachts competing went missing in a vast area of the Irish Sea. A massive search and rescue operation began on 13 August 1979. About 4000 people were involved in the rescue operation, which included British Royal Navy warships, lifeboats, helicopters, and Royal Dutch Navy destroyers. A total of 80 yachts and 136 sailors were rescued, making it the UK's biggest ever peacetime rescue operation.

In October 1979, about two months after the 1979 Fastnet Race disaster in August 1979, Rice (1979) published a two-page paper titled "Tracking a Killer Storm" in *Sail*, a professional international sailing journal. In this paper, he unconsciously used the following description: "The weather map for 2100 GMT (Fig. 3) shows the truly explosive development that was under way within the decelerating storm system" (lines 22–25 in the right column of page 107), which opened a new door to storm researches within the meteorological community.

Later, Sanders and Gyakum (1980) creatively coined a new term, "meteorological bomb", because only a "bomb" would have "explosive" properties. From reading the inconspicuous paper by Rice (1979), Professor Fred Sanders from the Massachusetts Institute of Technology and his Ph.D student J. R. Gyakum became keenly aware of the risks of this type of rapidly intensifying extratropical cyclone system and named it the "meteorological bomb" or "explosive cyclone." In June 1980, they jointly published a paper titled "*Synoptic Dynamic Climatology of the 'Bomb'*" in *Monthly Weather Review* (Sanders and Gyakum, 1980). They mentioned that "Even pleasure craft are endangered by these storms; the tragic loss of life in the 1979 Fastnet yacht race was attributable to a rare summer example of the meteorological 'bomb' (Rice, 1979)" (lines 2–5 in the right column on page 1589). Since that time, the international meteorological community has investigated this type of rapidly deepening cyclone system extensively and in great detail. The number of published papers on this topic has increased greatly, just like an "avalanche." Broadly speaking, the "storm of Fastnet 1979" not only left its mark in the "history book" of international yachting races, but it also prompted the international meteorological community to widely study "explosive cyclones."

5. Definitions of "explosive cyclone"

Explosive cyclones have been widely investigated across the world because of their great impacts and significant role in the poleward transports of moisture, heat, and momentum. However, as explosive cyclones can develop in different ways, some being confined to lower levels while others extend through greater heights, they have no commonly accepted scientific definition. There exists a wide range of ideas and concepts regarding how to identify and track explosive cyclones. In this section, we introduce these ideas and concepts.

Based upon the pioneering studies on rapidly deepening cyclones of Bergeron (1954), Jalu (1973), Böttger et al. (1975), Rice (1979), and so on, Sanders and Gyakum (1980) not only firstly coined the term "explosive cyclone," but also put forward its quantitative definition. Sanders and Gyakum (1980, p.1589–p.1590) indicated that "As Bergeron's characterization probably referred to the latitude of Bergen (60°N), a geostrophically equivalent rate was obtained for arbitrary latitude φ by multiplying his rate by ($\sin\varphi/\sin 60°$). The resulting critical rate, which we denote as 1.0 Bergeron, varies from 28 hPa $(24\ h)^{-1}$ at the pole to 12 hPa $(24\ h)^{-1}$ at latitude 25°N, the southern limit of the phenomenon in our sample."

By using the definition of an explosive cyclone given by Sanders and Gyakum (1980), some researchers (Roebber, 1984; Gyakum et al., 1989; Chen et al., 1992; Wang and Rogers, 2001; Yoshida and Asma, 2004) have made statistical analyses

[v] Although he used the term "hurricane," he clearly recognized that those five cyclones were not real hurricanes, as with the present climatic conditions, true hurricanes would never occur at such high latitudes.

[w] Even 40 years afterward, on 11 October 2019 (Friday), the Royal Navy held a remembrance service for the 40th anniversary of the Fastnet Race disaster.

of explosive cyclones in different regions. Their results show that explosive cyclones occur most often in the midlatitude region (30º–60ºN). It could be seen that the geostrophical adjustment latitude of 60°N used by Sanders and Gyakum (1980) deviated from the latitude of most frequent occurrence of explosive cyclones. Therefore, based on the scheme proposed by Sanders and Gyakum (1980), some researchers have modified the geostrophical adjustment latitude in the definition of explosive cyclone. Roebber (1984) pointed out that since explosive cyclones occurred most often near 42.5°N, the latitude of 42.5°N should be selected in the calculation of the geostrophically equivalent rate. Thus, the deepening rate *R* of central sea level pressure (SLP) is calculated as follows:

$$R = \left[\frac{P_{t-12} - P_{t+12}}{24}\right] \times \left[\frac{\sin 42.5°}{\sin\phi}\right]. \quad (1)$$

Here, *P* is the SLP of the cyclone center, *t* is the analysis time in hours, and φ is the latitude of the cyclone center.

Gyakum et al. (1989) took 45°N as the geostrophical adjustment latitude in the definition of explosive cyclone; thus, the deepening rate of central sea level pressure *R* becomes:

$$R = \left[\frac{P_{t-12} - P_{t+12}}{24}\right] \times \left[\frac{\sin 45°}{\sin\phi}\right]. \quad (2)$$

With the improvement of temporal resolution of observational data, some researchers have revised the time interval in Sanders and Gyakum's (1980) definition of explosive cyclone. Yoshida and Asuma (2004) adopted a 12-hour time interval, which may describe some explosive cyclones with short periods of rapid development, but the geostrophical adjustment latitude was kept as 60°N. Yoshida and Asuma (2004) calculated the deepening rate of central sea level pressure in the following way:

$$R = \left[\frac{P_{t-6} - P_{t+6}}{12}\right] \times \left[\frac{\sin 60°}{\sin\frac{\phi_{t-6} + \phi_{t-6}}{2}}\right]. \quad (3)$$

Fu et al. (2020) performed a systematic investigation of these explosive cyclones by using ERA-Interim data from January 1979 to December 2016, and summarized the common and widely accepted features of explosive cyclones as follows: "(1) a rapid drop of central pressure; (2) fast cyclogenesis; (3) strong winds; and (4) heavy rainfall/snowfall. Usually, these features are integrated, and cannot be isolated. Among these four features, strong wind associated with explosive deepening is the most dominant factor that may cause severe damage, just like a tropical cyclone."

Based on the explosive cyclone definition given by Sanders and Gyakum (1980), Fu et al. (2020) calculated the deepening rates of central SLP of cyclones by using ERA-Interim data and selected all cyclones whose deepening rates were greater than or equal to 1.0 Bergeron. They indicated that there was a total of 6392 explosive cyclones over the whole Northern Hemisphere (NH) (20°–90°N) from January 1979 to December 2016. In order to examine the wind speeds in the definition of explosive cyclone, the ERA-Interim wind speeds associated with explosive cyclones at 10-m height were analyzed in detail. The results showed that, for some explosive cyclones, although their central SLP deepening rates were greater than 1.0 Bergeron, their wind speeds were sometimes very weak, and the maximum wind speeds associated with those cyclones were even near to 8.2 m s^{-1}. Since the major shipping safety threat caused by explosive cyclones over oceans is strong winds, and the WMO recommends that gales over oceans greater than Force 8 (17.2 m s^{-1}) should constitute a gale warning, it is reasonable and acceptable to choose the wind speed of 17.2 m s^{-1} as the threshold in the revised definition of explosive cyclone. A total of 1112 cyclones with maximum wind speeds less than 17.2 m s^{-1} were eliminated.

According to Fu et al. (2020), an explosive cyclone is currently defined as a surface low pressure system whose deepening rate of central SLP falls at least 1.0 Bergeron within 12 hours, lives longer than 24 hours, and maintains a maximum wind speed at 10-m height greater than 17.2 m s^{-1}. The deepening rate of an explosive cyclone is calculated as follows:

$$R = \left[\frac{P_{t-6} - P_{t+6}}{12}\right] \times \left[\frac{\sin\phi_s}{\sin\frac{\phi_{t-6} + \phi_{t-6}}{2}}\right], \quad (4)$$

where ϕ_s is the mean latitude.

As pointed out by Neu et al. (2013), "Identifying and tracking extratropical cyclones might seem, superficially, to be a straightforward activity, but in reality it is very challenging." Although most studies identify explosive cyclones based on the minimum of sea level pressure, there are different methods, such as using the maxima of 850-hPa vorticity. Neu et al. (2013) compared 15 cyclone detection and tracking methods by using the same input data to assess their similarities and differences and found that the consistency across various methods was generally higher for deep (or strong) explosive cyclones than for shallow (or weak) ones.

Despite qualitative consistency in the spatial distribution and characteristics of cyclones identified across different methods, there were great differences in the total numbers of explosive cyclones in the two hemispheres. In winter (December to February), the total numbers of explosive cyclones over the NH ranged from 6000 to 21 000. In summer (June to August), the range was roughly between 5000 and 28 000. Since there is no universal agreement on the definition of an explosive cyclone, these results might look somewhat discouraging when considering the importance of extratropical cyclones and their impacts.

6. Climatological features of explosive cyclones

A lot of previous studies have revealed that there are obvious differences in the tracks, lifetimes, and development mechanisms of explosive cyclones in different regions. Therefore, in order to study explosive cyclones more deeply, it is necessary to assign categories of explosive cyclones.

6.1. *Classification*

According to the maximum deepening rate of the central SLP of an explosive cyclone, Sanders (1986) classified cyclones that occurred over the central and Northwestern Atlantic from January 1981 to November 1984 into three categories: “strong bomb” (>1.80 Bergeron), “moderate bomb” (1.30–1.80 Bergeron), and “weak bomb” (1.00–1.20 Bergeron). Wang and Rogers (2001) statistically analyzed the explosive cyclones that occurred in the NH from January 1985 to March 1996. The explosive cyclones were divided into three categories: “strong cyclone” (⩾1.80 Bergeron), “moderate cyclone” (1.40–1.79 Bergeron), and “weak cyclone” (1.00–1.39 Bergeron), based on the maximum deepening rate of the central SLP of those cyclones. There was no significant difference in the classification criteria between Wang and Rogers (2001) and Sanders (1986), but there were slight differences between “moderate cyclone” and “weak cyclone,” against “moderate bomb” and “weak bomb”. In addition, they did not cite the reasons for their classification of cyclones.

By using the reanalysis data of National Centers for Environmental Prediction (NCEP), Zhang et al. (2017) analyzed the explosive cyclones that occurred over the Northern Pacific (October to April of the next year) from 2000 to 2015 and pointed out that it was reasonable to divide explosive cyclones into four categories, namely: “weak cyclone” (1.00–1.29 Bergeron), “moderate cyclone” (1.30–1.69 Bergeron), “strong cyclone” (1.70–2.29 Bergeron), and “super cyclone” (⩾ 2.30 Bergeron).

Sun et al. (2018) used final reanalysis data to analyze the explosive cyclones that occurred over the Northern Atlantic in the cold season (October to April of the next year) from 2000 to 2015 and found that the explosive cyclones over the Northern Atlantic might be divided into four categories according to their deepening rate of central SLP, namely: “weak cyclone” (1.00–1.44 Bergeron), “moderate cyclone” (1.45–1.74 Bergeron), “strong cyclone” (1.75–2.14 Bergeron), and “super cyclone” (⩾2.15 Bergeron).

6.2. *Spatial distribution*

Sanders and Gyakum (1980) analyzed the climatology of explosive cyclones in the NH during the cold season from 1977 to 1979 and pointed out that explosive cyclones occurred most often over the Northwestern Pacific and the Northwestern Atlantic. Roebber (1984) and Rogers and Bosart (1986) also indicated that the Northwestern Pacific and the Northwestern Atlantic were the regions with most frequent occurrences of explosive cyclones. Lim and Simmonds (2002) pointed out that the Northwestern Pacific was one of the most densely populated regions of explosive cyclones of all the global oceans. Since the Northwestern Pacific is an important shipping region, a great number of researchers have carried out in-depth studies on explosive cyclones over the region.

Li and Ding (1989) statistically analyzed explosive cyclones that occurred over the Northwestern Pacific from August 1984 to August 1985 and found that most of the explosive cyclones concentrated in the region (35°–55°N, 140°–165°E). Chen et al. (1992) indicated that there were two main genesis locations of explosive cyclones over East Asia, one being downstream of the Eurasian continent and the other being the region from the East China Sea to the Japan Sea.

According to Yoshida and Asuma (2004), explosive cyclones over the Northwestern Pacific are mainly concentrated in the region (20°–60°N, 120°E–180°). Although different researchers have used different data, they all have pointed out that the Northwestern Pacific is the region where explosive cyclones occur most frequently.

Wang and Rogers (2001) analyzed the spatial distribution of explosive cyclones over the Northern Atlantic based on the cyclone center and the maximum deepening rate of central SLP. They found that there were three high-frequency regions, which allow explosive cyclones to be categorized based on location as NWA (the Northwest Atlantic), NCA (the North-Central Atlantic), or NEA (the Extreme Northeast Atlantic) explosive cyclones. Yoshida and Asuma (2004) investigated explosive cyclones over the Northwestern Pacific and found that there were three types of explosive cyclones according to their geographical locations of formation. The first type is the Okhotsk–Japan Sea type (OJ type), which form over the Eurasia mainland and develop over the Okhotsk Sea and Japan Sea. The second type is the Pacific Ocean–Land type (PO–L type). The third type is the Pacific Ocean–Ocean type (PO–O type), which form over the Western Pacific and develop over the central Pacific. Wang and Rogers (2001) classified the explosive cyclones over the Northern Atlantic according to the spatial distribution of their maximum deepening locations, while Yoshida and Asuma (2004) classified the explosive cyclones over the Northwestern Pacific according to the formation location of the explosive cyclones.

Zhang et al. (2017) indicated that explosive cyclones over the whole Northern Pacific might be divided into five categories according to their locations of maximum deepening rate of central SLP, namely, Japan–Okhotsk Sea (JOS), the Northwestern Pacific (NWP), the West–Central Pacific (WCP), the East–Central Pacific (ECP), and the Northeastern Pacific (NEP) explosive cyclones.

Sun et al. (2018) found that the explosive cyclones over the Northern Atlantic mainly occurred over four regions: the North American region, the Northwestern Atlantic region, the Central–Northern Atlantic region, and the Northeastern Atlantic region. The number of explosive cyclones over the whole Northern Atlantic region decreased with the increase of the maximum deepening rate of central SLP of cyclones, and their intensities increased from west to east. The main tracks of the cyclones were from southwest to northeast.

6.3. *Favorable environmental conditions*

6.3.1. *Atmospheric baroclinicity*

Many previous studies (Sanders, 1986; Manobianco, 1989; Wash et al., 1992), as well as Fu et al. (2021), have conclusively indicated that the rapid intensification of explosive cyclones might be driven by the atmospheric baroclinicity. Yoshida and Asuma (2004) comprehensively analyzed three types of explosive cyclones over the Northwestern Pacific and pointed out that the invasion of cold air from Eurasia was favorable for the generation and development of explosive cyclones, and there were strong baroclinicities in the middle and lower levels of explosive cyclones. Iwao et al. (2012) analyzed the development process of explosive cyclones over the Northwestern Pacific in winter for 30 years and found that the increase of occurrence frequency of explosive cyclones was caused by the enhancement of baroclinicity of the lower atmosphere.

6.3.2. *Upper-level trough*

Fu et al. (2021) summarized that there were three favorable weather conditions for the development of explosive cyclones in the NH: the upper-level trough catching up with the surface cyclone center, the surface vortex meeting with the upper-level trough, and the low pressure system meeting with the upper-level trough (Sanders and Gyakum, 1980). It suggested that the development of explosive cyclones was significantly related to an upper-level trough. The center of the surface cyclone was usually located downstream of the upper-level trough.

6.3.3. *Upper-level jet stream*

Fu et al. (2021) stated in summary that explosive cyclones tended to occur north of the westerlies (Sanders and Gyakum, 1980). Wash et al. (1988) thought that the superposition of positive vorticity in the upper-level jet stream exit and the surface cyclone center was favorable for the rapid development of explosive cyclones. Numerous studies (Uccellini and Kocin, 1987; Wash et al., 1988; Cammas and Ramond, 1989; Nakamura, 1993) have shown that the strong divergence field, advection of positive vorticity, and ascending field in the left side of the upper jet stream exit might provide upper-level dynamic forcing for the rapid development of explosive cyclones. Yoshida and Asuma (2004) pointed out that there were strong jet streams in the upper level of the three types of explosive cyclones.

6.3.4. *Sea surface temperature (SST)*

Some previous studies (Sanders and Gyakum, 1980; Roebber, 1984; Gyakum et al., 1989; Chen et al., 1992; Yoshida and Asuma, 2004), as well as Fu et al. (2021), pointed out that explosive cyclones over the Northwestern Pacific mostly occurred over the Kuroshio region. Sanders and Gyakum (1980) found that explosive cyclones were most likely to occur near the strong gradient region of SST. Sanders (1986) showed that the moving distance of a “strong explosive cyclone” when passing through warm current was longer than that of a “weak cyclone” and a “moderate cyclone.” Hanson and Long (1985) and Sanders (1987) found that there was a significant statistical correlation between the rapid development of explosive cyclones and the cyclones’ passing through the strong SST gradient region. Chen et al. (1992) indicated that explosive cyclones gradually concentrated near the Kuroshio and Kuroshio extension region. Ueda et al. (2011) pointed out that SST had an important influence on the vertical movement of the atmosphere during the rapid development of explosive cyclones. In an analysis of severe storm Xynthia, Liberato et al. (2013) indicated that SST in subtropical waters made a significant contribution to the explosive development of storm Xynthia. Davis and Emanuel (1988), Kuwano-Yoshida and Asuma (2008), and Kuwano-Yoshida and Enomoto (2013) also pointed out that when an explosive cyclone passed through a warm current region, the warm ocean not only transmitted sensible and latent heat to the atmosphere, but also reduced the stability of the lower atmosphere, which might promote the rapid development of the cyclone.

6.4. *Seasonal variations*

Fu et al. (2021) clarified in summary that explosive cyclones occurred mainly in the cold season (Sanders and Gyakum, 1980; Carleton, 1981; Physick, 1981; Roebber, 1984; Gyakum et al., 1989; Chen et al., 1992; Yoshida and Asuma, 2004) and the occurrence frequency of explosive cyclones in the cold season was much higher than in the warm season (Roebber, 1984; Chen et al., 1992). Chen et al. (1992) analyzed the explosive cyclones over East Asia from 1958 to 1987 and found that only 13 of 363 explosive cyclones occurred in the warm season, while the other 350 cases occurred in the cold season. It was also seen that the occurrence frequency of explosive cyclones in the cold season had obvious monthly variation. Sanders and Gyakum (1980) pointed out that the peak frequency of explosive cyclones in the cold season of the NH was January, and there were two explosive cyclones every three days on average. There were more explosive cyclones in November, December, and February, but there were fewer explosive cyclones in September, October, March, and April. Chen et al. (1992) analyzed the seasonal variation characteristics for occurrence frequency of explosive cyclones over East Asia and found that the peak occurrence frequencies were in January and March, respectively. Explosive cyclones mainly occurred from December to March, with few cases in other months. Yoshida and Asuma (2004) analyzed the seasonal variation characteristics of occurrence frequency of three types of explosive cyclones over the Northwest Pacific and found that there were obvious differences in their seasonal variation characteristics. The peak frequency of the OJ type of explosive cyclone was in November, and that of the PO–L type of explosive cyclone was in December and February. The peak frequency of the PO–O type of explosive cyclone occurred in January.

7. Future trends of "explosive cyclones" under global climate change

Recently, the topic of how climate change will affect explosive cyclones has become one of the hottest points in the scientific community. As indicated by Ulbrich et al. (2009), "This increase in interest of the scientific community is partly due to the availability of basically homogeneous gridded datasets for the observational period, which in conjunction with the numerical schemes for the identification of cyclones and the quantification of their activity allow detailed studies that were not possible in earlier times. In addition, many GCM simulations both for present-day climate and climate scenarios have recently become available. Their evaluation with respect to cyclone activity can in principle serve to give confidence in the simulated effects of increasing greenhouse gas forcing on the mid-latitude climate."

Ulbrich et al. (2009) found that there were two distinct regions of high cyclonic activity over the NH, which could be detected in reanalysis data and modeling results: one over the Northern Pacific and one over the Northern Atlantic, with the secondary center over the Mediterranean. The representation of the latter center was particularly dependent on the spatial resolution of the data and model considered. Under anthropogenic climate change conditions, the number of all cyclones will be decreased in winter, but over some specific regions (the Northeastern Atlantic and British Isles, as well as the Northern Pacific), the number of intense cyclones increases in most models. On average over the hemisphere, the number of extreme cyclones is found to increase only when "extreme" is defined in terms of core pressure, while there is a number decrease in several models when defining "extreme" from the Laplacian of surface pressure or vorticity around the core.

Seiler and Zwiers (2016) analyzed how explosive cyclones responded to climate change in the extratropical region of the NH. An objective-feature tracking algorithm was used to identify and track cyclones from 23 CMIP5 climate models for the recent past (1981–99) and future (2081–99). Explosive cyclones are projected to shift northwards by about 2.2° latitude on average over the Northern Pacific, with fewer and weaker events south of 45°N, and more frequent and stronger events north of this latitude.

Catto et al. (2019) reviewed the research progress on the structure, characteristics, dynamics, and impacts of explosive cyclones in the future and pointed out that multiple properties of the global climate system might influence the occurrence frequency, location, and intensity of explosive cyclones. Catto et al. (2019) had higher confidence in the future changes of three properties: (1) The atmospheric moisture content will increase due to the increase of temperature. (2) The lower-tropospheric meridional temperature gradient will decrease due to polar amplification in the NH in the winter. (3) The enhanced warming in the tropical upper troposphere and cooling in the high-latitude stratosphere will lead to an increased meridional temperature gradient in the vicinity of tropopause slope around 30°–40° latitude in the north and south. However, they had lower confidence in how these three factors would interact and contribute to future changes in explosive cyclones and the aggregated storm tracks. Finally, Catto et al. (2019) summarized the main features of explosive cyclones that were expected to change in the future.

All these features listed in Table 1, were summarized as follows:

(1) Atmospheric baroclinicity and thereby storm development will be impacted by the increased upper-tropospheric temperature gradient (feature 1), decreased lower-tropospheric temperature gradient (feature 2) (over the NH only), and increased static stability (feature 3), as well as increased latent heat release (feature 4). These factors did not change monotonically with warming, and so there were still uncertainties around the precise impact.

(2) The precipitation intensity within explosive cyclones is expected to increase (feature 5), but there are mixed results

Table 1. Eight features associated with extratropical cyclones.

	Features							
	1	2	3	4	5	6	7	8
	increased upper-tropospheric temperature gradient	decreased lower-tropospheric temperature gradient	increased static stability	increased latent heat release	increase in intensity (extent)	intensity of the winds	intensity of the central pressure	precipitation and moisture transport increases
Confidence	High	High	High	High	High (Low)	Low	Medium	Low

in terms of how this feeds back onto the intensity of winds (feature 6) or the central pressure (feature 7).

(3) Due to the increase of precipitation and moisture transport, inland floods are projected to increase (feature 8), but there is a lack of catchment-specific information. Coastal floods from storm surge are likely to increase in the future, mainly associated with the sea level rising.

(4) Although the projections of wind strength are uncertain (feature 6), there are expected future increases in storm-related costs.

8. Concluding remarks

Čampa and Wernli (2012) indicated that "Extratropical cyclones are the most important actors in determining daily weather in midlatitudes because of the strong winds and intense precipitation typically associated with them." In the autumn and winter seasons, there occur a great number of rapidly intensifying extratropical cyclones over middle- and high-latitude oceans, which have been identified as "explosive cyclones". Extratropical cyclones may also be regarded as the "cousin sisters" of tropical cyclones. Although they are born in different families at different times (autumn-winter season vs. summer season), their mothers' hometowns are over the same oceans, and their mothers are seen to be sisters. The two types of cyclones develop in different environments and are driven by different energy sources (fuel). So, why are they seen to be sisters and not brothers? Because their "faces" look to be similar, with beautiful "eyes", when they are mature. They are usually named by using various female names, not male names. They usually dance ballet on the "earth stage," dressing in spiral-shaped clouds, which may be regarded as "long skirts."

Since the first appearance of the term "meteorological bomb" in 1980, more than 40 years have passed. Although research on explosive cyclones has progressed greatly (Schultz et al., 2019), there are still many problems which remain unsolved. For example, there is no unified and widely-accepted definition of explosive cyclone. There are many theories on the mechanism of explosive cyclone development, but most of these theories are only based on the analyses of several cases. Since there are limitations in the spatial and temporal resolutions of data, the aforementioned theories are not strongly supported by observational facts, and some of the theories are speculative to a certain extent. Verification of these theories is a great challenge. Recent and fast developments in high spatial and temporal resolution reanalysis data, such as the fifth generation ECMWF (European Centre for Medium-Range Weather Forecasts) atmospheric reanalysis ERA5 data and ASR (Arctic System Reanalysis) data, as well as increased remote sensing at high altitudes, such as CloudSat, may provide high-resolution data to identify more features of explosive cyclones, and may contribute to significant improvements in our understanding of explosive cyclones.

Since the major threat from explosive cyclones to shipping safety is their strong winds, detailed temporal and spatial characteristics of explosive cyclone wind fields will be a future focus. Moreover, what are the relationships among the wind field structure of explosive cyclones, their central pressure, and the deepening rate of their central pressure? How should we classify the intensity of explosive cyclones considering the influence of wind speed? It is urgent and necessary to establish a consistent system of explosive cyclone intensity classification.

Finally, the first author of the present paper would like to use a small poem titled "Explosive Cyclone," written on 13 July 2019, to end this paper:

A small cyclone stands in front of upper-trough.
This vortex intensifies quickly just like a "bomb" explosion.
Deep snow is swept by its strong winds.
Huge and rough waves roll into the sky violently.
Upper-jet transfers large momentum downward.
And warmer sea water dispels the coldness of its body.
"Hook-shaped" potential vorticity is transformed into "treble clef".

Its great power causes the earth's shaking like winds blowing dead leaves away.

Acknowledgements. All authors are grateful for the financial supports of National Key R&D Program of China (2022YFC3004200) and National Natural Science Foundation of China (Grant Nos. 42275001 and 41775042) to this study.

REFERENCES

Bergeron, T., 1954: Reviews of Modern Meteorology-12. The problem of tropical hurricanes. *Quart. J. Roy. Meteor. Soc.*, **80**(344), 131−164, https://doi.org/10.1002/qj.49708034402.

Böttger, H., M. Eckardt, and U. Katergiannakis, 1975: Forecasting extratropical storms with hurricane intensity using satellite information. *J. Appl. Meteorol.*, **14**, 1259−1265, https://doi.org/10.1175/1520-0450(1975)014<1259:FESWHI>2.0.CO;2.

Cammas, J. P., and D. Ramond, 1989: Analysis and diagnosis of the composition of ageostrophic circulations in jet-front systems. *Mon. Wea. Rev.*, **117**(11), 2447−2462, https://doi.org/10.1175/1520-0493(1989)117<2447:AADOTC>2.0.CO;2.

Čampa, J., and H. Wernli, 2012: A PV perspective on the vertical structure of mature midlatitude cyclones in the Northern Hemisphere. *J. Atmos. Sci.*, **69**(2), 725−740, https://doi.org/10.1175/JAS-D-11-050.1.

Carleton, A. M., 1981: Monthly variability of satellite-derived cyclonic activity for the Southern Hemisphere winter. *J. Climatol.*, **1**, 21−38, https://doi.org/10.1002/joc.3370010105.

Catto, J. L., and Coauthors, 2019: The future of midlatitude cyclones. *Current Climate Change Reports*, **5**, 407−420, https://doi.org/10.1007/s40641-019-00149-4.

Chen, S. J., Y.-H. Kuo, P. Z. Zhang, and Q. F. Bai, 1992: Climatology of explosive cyclones off the East Asian coast. *Mon. Wea. Rev.*, **120**(12), 3029−3035, https://doi.org/10.1175/1520-0493(1992)120<3029:COECOT>2.0.CO;2.

Chu, A. M. C.-C., 1916: Rainfall in China, 1900-1911,. *Mon. Wea. Rev.*, **44**(5), 276−281, https://doi.org/10.1175/1520-0493(1916)44<276:RIC>2.0.CO;2.

Davis, C. A., and K. A. Emanuel, 1988: Observational evidence for the influence of surface heat fluxes on rapid maritime cyclogenesis. *Mon. Wea. Rev.*, **116**(12), 2649−2659, https://doi.org/10.1175/1520-0493(1988)116<2649:OEFTIO>2.0.CO;2.

Emanuel, K., 2005: *Divine Wind: The History and Science of Hurricanes*. Oxford University Press, 285 pp.

Espy, J. P., 1841: *The Philosophy of Storms*. Forgotten Books, 606 pp.

Feser, F., 2018: Constructing records of storminess. *Oxford Research Encyclopedia of Climate Science*, https://doi.org/10.1093/acrefore/9780190228620.013.5,Publishedonlineon28March2018.

Fu, G., Y. W. Sun, J. L. Sun, and P. Y. Li, 2020: A 38-year climatology of explosive cyclones over the Northern Hemisphere. *Adv. Atmos. Sci.*, **37**, 143−159, https://doi.org/10.1007/s00376-019-9106-x.

Fu, G., L. J. Chen, P. Y. Li, H. J. Pang, and S. Q. Zhang, 2021: Explosive cyclones: Past, present, and future. *Meteorological Monthly*, **47**(3), 261−273, https://doi.org/10.7519/j.issn.1000-0526.2021.03.001. (in Chinese with English abstract)

Gyakum, J. R., J. R. Anderson, R. H. Grumm, and E. L. Gruner, 1989: North Pacific cold-season surface cyclone activity: 1975-1983,. *Mon. Wea. Rev.*, **117**(6), 1141−1155, https://doi.org/10.1175/1520-0493(1989)117<1141:NPCSSC>2.0.CO;2.

Hanson, H. P., and B. S. Long, 1985: Climatology of cyclogenesis over the East China Sea. *Mon. Wea. Rev.*, **113**(5), 697−707, https://doi.org/10.1175/1520-0493(1985)113<0697:COCOTE>2.0.CO;2.

Iwao, K., M. Inatsu, and M. Kimoto, 2012: Recent changes in explosively developing extratropical cyclones over the winter Northwestern Pacific. *J. Climate*, **25**(20), 7282−7296, https://doi.org/10.1175/JCLI-D-11-00373.1.

Jalu, M., 1973: Étude des perturbations cycloniques extratropicale par l'imagerie des satellites. *Les Satellites Meteorologiques*, Centre National d' Études Spatiales, 409−422. (in French)

Kuwano-Yoshida, A., and Y. Asuma, 2008: Numerical study of explosively developing extratropical cyclones in the Northwestern Pacific region. *Mon. Wea. Rev.*, **136**(2), 712−740, https://doi.org/10.1175/2007MWR2111.1.

Kuwano-Yoshida, A., and T. Enomoto, 2013: Predictability of Explosive cyclogenesis over the Northwestern Pacific region using ensemble reanalysis. *Mon. Wea. Rev.*, **141**(11), 3769−3785, https://doi.org/10.1175/MWR-D-12-00161.1.

Lamb, H. H., 1991: *Historic Storms of the North Sea*, *British Isles and Northwest Europe*. Cambridge University Press, 204 pp.

Li, C. Q., and Y. H. Ding, 1989: A diagnostic study of an explosively deepening oceanic cyclone over the Northwest Pacific Ocean. *Acta Meteorologica Sinica*, **47**(2), 180−190, https://doi.org/10.11676/qxxb1989.023. (in Chinese with English abstract)

Liberato, M. L. R., J. G. Pinto, R. M. Trigo, P. Ludwig, P. Ordóñez, D. Yuen, and I. F. Trigo, 2013: Explosive development of winter storm Xynthia over the subtropical North Atlantic Ocean. *Natural Hazards and Earth System Sciences*, **13**(9), 2239−2251, https://doi.org/10.5194/nhess-13-2239-2013.

Lim, E. P., and I. Simmonds, 2002: Explosive cyclone development in the Southern Hemisphere and a comparison with Northern Hemisphere events. *Mon. Wea. Rev.*, **130**(9), 2188−2209, https://doi.org/10.1175/1520-0493(2002)130<2188:ECDITS>2.0.CO;2.

Liu, K.-B., C. M. Shen, and K.-S. Louie, 2001: A 1, 000-year history of typhoon landfalls in Guangdong, Southern China, reconstructed from Chinese historical documentary records. *Annals of the Association of American Geographers*, **91**(3), 453−464, https://doi.org/10.1111/0004-5608.00253.

Louie, K.-S. and K.-B, Liu, 2003: Earliest historical records of typhoons in China. *Journal of Historical Geography*, **29**(3), 299−316, https://doi.org/10.1006/jhge.2002.0453.

Ludlum, D. M., 1963: *Early American Hurricanes 1492−1870*. American Meteorological Society, 198 pp.

Manobianco, J., 1989: Explosive east coast cyclogenesis over the west-central North Atlantic Ocean: A composite study derived from ECMWF operational analyses. *Mon. Wea. Rev.*, **117**(11), 2365−2383, https://doi.org/10.1175/1520-0493(1989)117<2365:EEC-

COT>2.0.CO;2.

Nakamura, H., 1993: Horizontal divergence associated with zonally isolated jet streams. *J. Atmos. Sci.*, **50**(14), 2310–2313, https://doi.org/10.1175/1520-0469(1993)050<2310:HDAWZI>2.0.CO;2.

Needham, J., and L. Wang, 1959: *Science and Civilisation in China:* Vol. 3*, Mathematics and the Sciences of the Heavens and the Earth*. Cambridge University Press, 886 pp.

Neu, U., and Coauthors, 2013: IMILAST: A community effort to intercompare extratropical cyclone detection and tracking algorithms. *Bull. Amer. Meteor. Soc.*, **94**(4), 529–547, https://doi.org/10.1175/BAMS-D-11-00154.1.

Physick, W. L., 1981: Winter depression tracks and climatological jet streams in the Southern Hemisphere during the FGGE year. *Quart. J. Roy. Meteor. Soc.*, **107**, 883–898, https://doi.org/10.1002/qj.49710745409.

Piddington, H., 1848: *The Sailor's Horn-Book for the Law of Storms*. Smith Elder & Co., London.

Rice, R. B., 1979: Tracking a killer storm. *Sail*, **10**, 106–107.

Roebber, P. J., 1984: Statistical analysis and updated climatology of explosive cyclones. *Mon. Wea. Rev.*, **112**(8), 1577–1589, https://doi.org/10.1175/1520-0493(1984)112<1577:SAAUCO>2.0.CO;2.

Rogers, E., and L. F. Bosart, 1986: An investigation of explosively deepening oceanic cyclones. *Mon. Wea. Rev.*, **114**(4), 702–718, https://doi.org/10.1175/1520-0493(1986)114<0702:AIOEDO>2.0.CO;2.

Sanders, F., 1986: Explosive cyclogenesis in the west-central North Atlantic Ocean, 1981-84. Part I: Composite structure and mean behavior. *Mon. Wea. Rev.*, **114**(10), 1781–1794, https://doi.org/10.1175/1520-0493(1986)114<1781:ECITWC>2.0.CO;2.

Sanders, F., 1987: Skill of NMC operational dynamical models in prediction of explosive cyclogenesis. *Wea. Forecasting*, **2**(4), 322–336, https://doi.org/10.1175/1520-0434(1987)002<0322:SONODM>2.0.CO;2.

Sanders, F., and J. R. Gyakum, 1980: Synoptic-dynamic climatology of the "Bomb". *Mon. Wea. Rev.*, **108**(10), 1589–1606, https://doi.org/10.1175/1520-0493(1980)108<1589:SDCOT>2.0.CO;2.

Schultz, D. M., and Coauthors, 2019: Extratropical cyclones: A century of research on meteorology's centerpiece. *Meteor. Monogr.*, **59**, 16.1–16.56, https://doi.org/10.1175/AMSMONOGRAPHS-D-18-0015.1.

Schwartz, S. B., 2015: *Sea of Storms: A History of Hurricanes in the Greater Caribbean from Columbus to Katrina*. Princeton University Press, 439 pp.

Seiler, C., and F. W. Zwiers, 2016: How will climate change affect explosive cyclones in the extratropics of the Northern Hemisphere? *Climate Dyn.*, **46**, 3633–3644, https://doi.org/10.1007/s00382-015-2791-y.

Sen Sarma, A. K., 2013: On the word 'Cyclone'. *Weather*, **68**(12), 323, https://doi.org/10.1002/wea.2139.

Sun, Y. W., G. Fu, and S. Q. Zhang, 2018: Statistical characteristics of explosive cyclones over the Northern Atlantic. *Acta Meteorologica Sinica*, **76**(2), 169–181, https://doi.org/10.11676/qxxb2017.093. (in Chinese with English abstract)

Tsiang, P., 1925: On typhoons over the Shandong Peninsula. *Journal of China Meteorological Society*, **1**, 9–25. (in Chinese)

Uccellini, L. W., and P. J. Kocin, 1987: The interaction of jet streak circulations during heavy snow events along the east coast of the United States. *Wea. Forecasting*, **2**(4), 289–308, https://doi.org/10.1175/1520-0434(1987)002<0289:TIOJSC>2.0.CO;2.

Ueda, A., M. Yamamoto, and N. Hirose, 2011: Meteorological influences of SST anomaly over the East Asian Marginal Sea on Subpolar and Polar Regions: A case of an extratropical cyclone on 5-8 November 2006,. *Polar Science*, **5**, 1–10, https://doi.org/10.1016/j.polar.2010.11.002.

Ulbrich, U., G. C. Leckebusch, and J. G. Pinto, 2009: Extra-tropical cyclones in the present and future climate: A review. *Theor. Appl. Climatol.*, **96**, 117–131, https://doi.org/10.1007/s00704-008-0083-8.

Wang, C. C., and J. C. Rogers, 2001: A composite study of explosive cyclogenesis in different sectors of the North Atlantic. Part I: Cyclone structure and evolution. *Mon. Wea. Rev.*, **129**(6), 1481–1499, https://doi.org/10.1175/1520-0493(2001)129<1481:ACSOEC>2.0.CO;2.

Wash, C. H., J. E. Peak, W. E. Calland, and W. A. Cook, 1988: Diagnostic study of explosive cyclogenesis during FGGE. *Mon. Wea. Rev.*, **116**(2), 431–451, https://doi.org/10.1175/1520-0493(1988)116<0431:DSOECD>2.0.CO;2.

Wash, C. H., R. A. Hale, P. H. Dobos, and E. J. Wright, 1992: Study of explosive and nonexplosive cyclogenesis during FGGE. *Mon. Wea. Rev.*, **120**(1), 40–51, https://doi.org/10.1175/1520-0493(1992)120<0040:SOEANC>2.0.CO;2.

Wheeler, D., 2003: The great storm of November 1703: A new look at the seamen's records. *Weather*, **58**, 419–427, https://doi.org/10.1256/wea.83.03.

Wu, L. G., 2020: Historical evolution of the word "Typhoon". *Acta Meteorologica Sinica*, **78**(6), 1065–1075. (in Chinese with English abstract)

Yoshida, A., and Y. Asuma, 2004: Structures and environment of explosively developing extratropical cyclones in the Northwestern Pacific Region. *Mon. Wea. Rev.*, **132**(5), 1121–1142, https://doi.org/10.1175/1520-0493(2004)132<1121:SAEOED>2.0.CO;2.

Zhang, S. Q., G. Fu, C. G. Lu, and J. W. Liu, 2017: Characteristics of explosive cyclones over the Northern Pacific. *J. Appl. Meteorol. Climatol.*, **56**(12), 3187–3210, https://doi.org/10.1175/JAMC-D-16-0330.1.