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Extreme sea ice events in the Chinese marginal seas during the past 2000 years

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ABSTRACT: We used Chinese historical literature to examine extreme records of sea ice events in the Chinese marginal seas during the past 2000 yr. We identified a total of 6 sea ice events that occurred in the sea areas to the south of 35° N. These extreme events occurred in the winters of AD 821/822, 903/904, 1453/1454, 1493/1494, 1654/1655 and 1670/1671. According to the historical records, the southern limit of sea ice in the Chinese marginal seas should be in Hangzhou Bay (30–31° N), and most probably near Haiyan County in Zhejiang Province (30.5° N). The sea ice events of 1453/1454 and 1654/1655 were synchronous with the freezing events of Taihu Lake, and the sea ice event of 1670/1671 was synchronous with the freezing event of the lower reaches of the Yangtze River. However, none of the sea ice events was synchronous with the abnormally early freezing dates of Suwa Lake in Japan or the extreme freezing events of Venice Lagoon in Italy. Although all of the sea ice events occurred in a cold climate on a 30 yr timescale, they were not synchronous with the extreme cold winters of other sites in the northern hemisphere. However, the sea ice event of 1453/1454 may have been related to the ca. 1453 Kuwae eruption. Our findings increase our understanding of both regional environmental change in the Chinese marginal seas and the regional nature of global climate change.

KEY WORDS: Southern limit · Hangzhou Bay · Historical record · Volcanic eruption

1. INTRODUCTION

Sea ice events are unique palaeo-environmental indicators which provide valuable high-resolution records about marine and coastal winter temperature changes. Sea ice is controlled by the atmosphere and ocean. The study of its variability may provide a clue to a better understanding of the global climate system (Divine & Dick 2006). Sea ice records during the past 2000 yr may be classified into 2 types: alternative indicators (e.g. chronologies for marine sediments, ice cores and tree rings) and historical records. Alternative indicators are developed in order to reconstruct the variability of sea ice on decadal and quasi-annual scales (Grumet et al. 2001, Bonnet et al. 2010, Macias Fauria et al. 2010, Kinnard et al. 2011). Historical records of sea ice events provide evidence of sea ice variation over the past 2 millennia, thus improving our knowledge of historical sea ice fluctuations at a high spatial and temporal resolution, and help to refine relevant models and improve predictions (Massé et al. 2008). In addition, sea ice is a major marine hazard, and the study of sea ice events during the past 2 millennia will help towards a better understanding of the long-term evolution of this type of hazard.

Significant research progress has been achieved in this field in Europe and North America. Fragmental

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historical records of sea ice events can be traced back to more than 1000 yr ago in Europe and North America, whereas systematic records date back to 1500–1800 (Koch 1945, Bergthórsson 1969, Lamb 1977, Catchpole & Faurer 1983, Jevrejeva 2001, ACSYS 2003, Divine & Dick 2006).

The Chinese marginal seas include 4 parts from north to south: the Bohai Sea, the Yellow Sea, the East China Sea and the South China Sea. In modern times, the tip of the north bank of the mouth of the Yangtze River is the dividing point of the Yellow Sea and the East China Sea (Fig. 1).

According to modern marine observations (1949–present) in China, sea ice events commonly occur in the northern part of the Yellow Sea and the Bohai Sea, and the southern limit of sea ice events is Laizhou Bay (37.2–37.8° N; Sun et al. 1981, Yang 1994, Sun 2006). Sea ice events to the south of 35° N have not yet been recorded (Sun et al. 1981, Yang 1994, Sun 2006). We therefore asked whether the southern limit of sea ice events in the Chinese marginal seas over the past 2000 yr differed from that in modern times.

The Chinese have a strong tradition of studying climatic change and natural disasters over the past 2000 yr using historical records and various alternative indicators (Chu 1973, Liu et al. 2001, Yang et al. 2002, Ge et al. 2003, Zhang et al. 2008, Lee & Zhang 2010). However, few scientific studies have analysed historical records of Chinese coastal sea ice. Here we report the results of an investigation into the sea ice events in the sea areas to the south of 35° N in the Chinese marginal seas over the past 2000 yr, using historical records in the Chinese literature. According to these records, the southern limit of sea ice events in the Chinese marginal seas over the past 2000 yr is inferred to be circa 30.5° N.

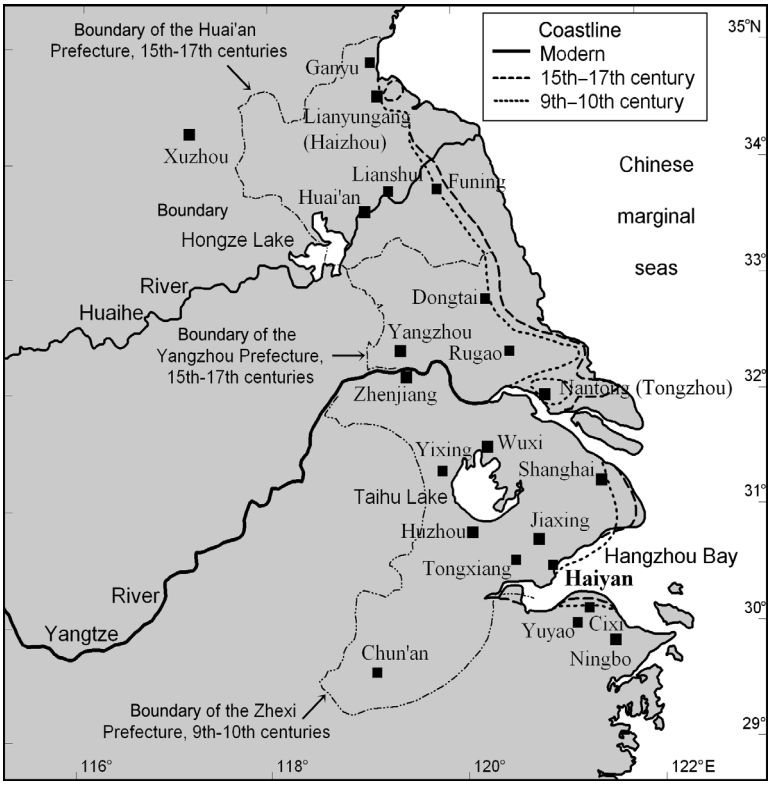

Fig. 1. Study area and the locations mentioned in the text. The historical coastlines and administrative boundaries are modified after Tan (1996)

2. MATERIALS AND METHODS

China has abundant historical literature. Official histories are available for every dynasty, and a number of private dynastic histories have been recorded ever since the Western Han Dynasty (206 BC to 24 AD). China also possesses a series of books on regional history and geography, i.e. local chronicles (or '*di fang zhi*' in Chinese Hanyu pinyin). The earliest local chronicle dates back 2000 yr, and since the early 15th century, it has been common practice for provinces, prefectures and counties to compile such chronicles.

There are specific volumes recording unusual natural phenomena and disasters in dynasty histories and local chronicles. Extreme sea ice events, as they were unique natural events, should therefore be recorded in the local chronicles and dynasty histories.

For the period prior to the 14th century, most of the historical records were found in dynasty histories, and since the 15th century, they could be found in both local chronicles and dynasty histories. We examined historical records on the sea ice events spreading to the extreme south of their range (to the south of 35° N) in the Chinese marginal seas over the past 2000 yr. Such records are rather rare.

3. RESULTS

From the records, we identified a total of 6 sea ice events, which occurred in the winters of 821/822, 903/904, 1453/1454, 1493/1494, 1654/1655 and 1670/1671 (Table 1). The 6 events are described below.

Table 1. Sea ice events in the sea areas to the south of 35° N in the Chinese marginal seas during the past 2000 yr

Year	Historical place name	Modern place name	Latitude (°N)	Source
821/822	Haizhou City	Lianyungang City	34.6	Song & Ouyang (1060)
903/904	Haiyan County	Haiyan County	30.5	Song & Ouyang (1060), Fan (1624), Wu (1669), Wei (1718)
1453/1454	Tongzhou City	Nantong City	32.0	Zhu (1467), Li (1618), Yu (1684), Zhang (1739), Wang (1755), Zhou (1816)
1493/1494	Andong County; Funing County	Liangshui County; Funing County	33.8	Xue (1518), Yu (1827), Jiao (1934)
1654/1655	Haiyan County	Haiyan County	30.5	Liu (1660), Peng & Tong (ca. 1673)
1670/1671	Ganyu County	Ganyu County	34.8	Yu (1673)

3.1. Sea ice event of the winter 821/822

One record was identified for this winter: '1st month, 2nd year, Changqing Reign Period (i.e. 27 January to 25 February 822) the sea was frozen in Haizhou Prefecture' (Song & Ouyang 1060). Haizhou Prefecture is the modern Lianyungang City of Jiangsu Province, whose latitude is 34.6° N (Fig. 1).

3.2. Sea ice event of the winter 903/904

A total of 4 sea ice records were identified for this winter:

(1) '3rd month, 3rd year of the Tianfu Reign Period, there was over 3 *chi* [1 *chi* = 0.3 m] of snow in Zhexi Prefecture [north Jiangsu Province and northwest Zhejiang Province in modern times; Fig. 1]… 12th month [22 December 903 to 20 January 904], it snowed heavily again. Rivers and the sea were frozen' (Song & Ouyang 1060).

(2) '12th month, 3rd year of the Tianfu Reign Period, there was heavy snow in the Zhexi Prefecture. Rivers and the sea were frozen' (Wei 1718).

(3) '…12th month, 2nd year of the Tianfu Reign Period [2 to 31 January 903], it snowed heavily again. The sea and rivers were frozen [in Zhexin Prefecture]'. There is a footnote in the original literature: 'or the 12th month of the 3rd year' (Wu 1669).

(4) '12th month, 3rd year of Tianfu Reign Period [22 December 903 to 20 January 904], a heavy snow, sea ice occurrence [in Haiyan County, Zhejiang Province]' (Fan 1624).

In items 1, 2 and 3, the region of the sea ice event is recorded as Zhexi Prefecture, whose capital is the modern Zhenjiang City, Jiangsu Province. However, the coast of Zhexi Prefecture extends from 32° to 30° N (Fig. 1). In the chronicle of Haiyan County, it is recorded as Haiyan County, whose latitude is 30.5° N (Fig. 1).

The year of the sea ice event that was recorded in the 'History of the Ten Kingdoms' (Wu 1669) is somewhat ambiguous (item 3). However, it is unambiguously recorded as the 3rd year of the Tianfu Reign Period in the other 3 sources. Therefore, it is reasonable to infer that the sea was frozen in the northern part of Hangzhou Bay in the winter of 903/904 AD, and the southern limit of this sea ice event was probably in Haiyan County (30.5° N), Zhejiang Province.

3.3. Sea ice event of the winter 1453/1454

A total of 6 records were identified for this winter, although some very similar records were merged and are discussed together here.

(1) '*Wuchen* day, 11th month of the 4th year of the Jingtai Reign Period [30 November to 29 December 1453], it snowed heavily in Shandong, Henan, Zhejiang Provinces and the Huai'an and Xuzhou Prefectures of the Zhili Province [modern Jiangsu and Anhui Provinces]. The sea was frozen and extended to over 40 *li* [1 *li* = 0.5 km] off the coast. Tens of people and herbs died of coldness' (Zhang 1739).

(2) 'There was several *chi* of snow since the 16th day of the 11th month of the last year [15 December 1453] until the 1st month of this year [29 January to 26 February 1454]. North wind blew fiercely, and even blew off tiles and blew down walls. The Huaihe River was frozen, and the sea was frozen and extended to over 40 *li* off the coast. Tens of people and herbs died of coldness' (Zhu 1467).

(3) 'In the beginning of the 5th year of the Jingtai Reign Period, it snowed heavily in the Yangzhou Pre-

fecture [modern Yangzhou City and the surrounding area]. Waters froze to 3 *chi* deep and the sea was also frozen' (Yu 1684).

(4) '1st month of the 5th year of the Jingtai Reign Period (29 January to 26 February 1454), it snowed heavily and the bamboos and trees were frozen to death. 2nd month, it snowed heavily again. Water froze to 3 *chi* deep and the sea was also frozen. Grasses and trees were frozen to death' (Wang 1755). The location of this record is Tongzhou Prefecture, modern Nantong City. In addition, similar records appear in the chronicles of Rugao County and Dongtai County (Li 1618, Zhou 1816).

It is recorded in the 'History of the Ming Dynasty' (Zhang 1739) and the 'Chronicle of the reign of Emperor Ming Yingzong' (Zhu 1467) that the sea near the mouth of the Huaihe River was frozen (items 1 and 2). The mouth of Huaihe River lay to the north of modern Funing County during the 15th century (Fig. 1).

In the 'General chronicle of Jiangnan Province' (Yu 1684), it was recorded that the sea in Yangzhou Prefecture was frozen. The coastline of Yangzhou Prefecture is quite long and extends from 32.0 to 33.2° N (Fig. 1). In the chronicles of Tongzhou County, Rugao County and Dongtai County, it was recorded that sea ice appeared in the sea in these 3 cities and counties, of which the southern end of the coastline is 32.0° N. By synthesizing these records, the southern limit of the sea ice event in the winter of 1453/1454 was at 32.0° N.

The sea ice event of 1453/1454 occurred near the mouth of the Huaihe River, and we speculate that the river contributed to the formation of sea ice. The possible mechanisms would be that (1) the Huaihe River carried snow and ice into the sea and accelerated the development of sea ice; and (2) the inflow of the fresh water of the Huaihe River decreased the salinity of the sea water, thus increasing the freezing point, which also accelerated the development of sea ice.

3.4. Sea ice event of the winter 1493/1494

A total of 3 records were identified for this winter: (1) '10th - 12th month [9 November 1493 to 5 February 1494], it snowed continuously. The sea was frozen due to the hard weather. The event was similar to that of the 2nd Year of Changqing Reign Period when the sea ice spread 200 *li* [1 li = 0.5 km]' (Xue 1518). The location of this record is in Huai'an Prefecture, namely modern Huai'an City and its surrounding area.

(2) 'Winter [of 1493/1494], it snowed continuously for 60 days. Firewood was in short supply. The sea was frozen due to the hard weather' (Yu 1827). The location of this record is Andong County, i.e. modern Lianshui County.

(3) 'Winter [of 1493/1494], it snowed continuously for 60 days. Firewood was in short supply. The coastal sea was frozen [Jiao 1934]. The location of this record is Funing County.

The coastline of Huai'an Prefecture extends from 33.3 to 35.1° N; therefore, it is not possible to deduce the exact southern limit according to the record in the chronicle of the Huai'an Prefecture (Fig. 1). According to the records in the chronicles of Andong County (modern Lianshui County) and Funing County, sea ice appeared in these 2 counties, which are located at about the same latitude, 33.8° N. Therefore, the southern limit of the sea ice event in the winter 1493/1494 was likely no further north than 33.8° N.

3.5. Sea ice event of the winter 1654/1655

One sea ice record was identified for this winter: '12th month, 11th year of the Shunzhi Reign Period [8 January to 5 February 1655], it snowed heavily. The sea was frozen' (Peng & Tong ca. 1673). The location of this record is Haiyan County, whose latitude is 30.5° N. (Fig. 1).

In addition, there is a sea ice record in Haizhou City (modern Lianyungang City, 35° N; Liu 1660): '2nd day of the 11th month [10 December 1654], the East Sea [modern Yellow Sea] was frozen for 6 days and shipping was discontinued' (Liu 1660). The location of this record is in Haizhou City, modern Lianyungang City, whose latitude is 34.6° N (Fig. 1).

The sea ice event is verified by other relevant records. There are more than 20 records about extreme ice conditions of Taihu Lake (e.g. Chen 1684, Chen et al. 1747, Pan et al. 1879) and the rivers in the vicinity of Haiyan County, including Jiaxing City, Ningbo City, Shanghai City, Wuxi City, Chun'an County, Cixi County, Jiashan County, Tongxiang County, Yixing County and Yuyao County (Wei & Zhu 1669, Liu et al. 1673, T. Li et al. 1683, Ren & Fan 1685, Kang 1693, Wang & Hao ca. 1700, Wang & Hua 1751, X. Li et al. 1797, Qin 1805, Yan 1887, Yang & Feng 1888, Jiang & Gu 1894; Fig. 1). For example, (1) In Huzhou City, it was 'very cold. Taihu Lake was frozen for twenty days, and the ice cover reached 2 *chi* [1 *chi* = 0.3 m] in thickness'. (2) In Ningbo City, there was a 'hard winter. The

rivers were frozen, and the water transportation was discontinued for a month. Innumerable trees were frozen to death'.

The above records verify that the winter 1654/1655 was extremely cold, and that the sea ice record in Haiyan County should be reliable. It is unambiguous that there was a sea ice event in the winter 1654/1655 in Haiyan County (30.5° N), Zhejiang Province.

3.6. Sea ice event of the winter 1670/1671

One record was identified for this winter: 'It snowed heavily for 20 days. Waters were frozen hard. The offshore sea ice piled up for tens of *li* [1 *li* = 0.5 km]. It looked like a mountain range, and could be seen from a very far distance. People died of coldness. Birds and animals rushed into houses to forage for foods' (Yu 1673). The location of this record is Ganyu County, whose latitude is 34.8° N. According to this record, it can be inferred that the southern limit of sea ice event in the winter 1670/1671 was 34.8° N.

3.7. Possible sea ice event of the winter 1892/1893

In the winter of 1892/1893, the sea near the mouth of the Huaihe River may have been frozen. A record was found in a poem entitled *'bitter cold'* (Wang 1922). In the poem, Wang (1922) wrote that: 'It is heard that the sea near the mouth of the Huaihe River was frozen hard, and the sea ice stretched to the horizon'. Similar to the sea ice event of 1453/1454, this event also occurred near the mouth of the Huaihe River. As discussed above, the ice event could also be related to the hydrology of the river.

However, no relevant records were found in the local chronicles of the relevant areas, thus the record cannot be confirmed. Moreover, the author of the poem had apparently only heard of the sea ice, but had not seen it himself. Therefore, we are uncertain about the reliability of this record, although the winter of 1892/1893 was bitterly cold in southern China, and Taihu Lake was frozen (Gong et al. 1987).

4. COMPARISON WITH OTHER DATA

The sea ice events in Hangzhou Bay are considered extreme, as its latitude is very low (30.5° N), and in particular, the bay is known for strong tides. Sea ice events are affected by various hydrometeorological factors. There is no doubt that low temperature is the primary cause, but hydrological factors, including tides, currents, salinity and the effects of rivers, complicate the formation of sea ice in the Chinese marginal seas.

The coast to the north of the Yangtze River mouth changed greatly, and the general trend is a gradual eastward shift of the coastline (Fig. 1). The coast to the south of the Yangtze River mouth and Hangzhou Bay has also changed significantly (Fig. 1). This coastal evolution also complicates the interpretation of historical sea ice events.

Another factor that further complicates the interpretation of the historical sea ice events is the course change of the Yellow River. The river is the second largest river in China and one of the largest rivers in the world, and its water is known for the enormous load of fine silt. Before the 12th century, the Yellow River flowed into the Bohai Sea, and would not have affected the ice condition of the Yellow Sea. However, from the 12th century to 1855, the Yellow River moved southward and flowed into the sea via the mouth of the Huaihe River. This greatly increased the input of water and silt into the sea near the river mouth, thus further complicating the interpretation of the historical sea ice events. After 1855, the Yellow River moved northward, thereby no longer affecting ice conditions in the Yellow Sea.

To answer the question of whether the sea ice events were local, regional or hemispheric climatic-hydrological phenomena, we compared the events to ice condition data sets from the vicinity (Lake Taihu [see Section 4.1] and the lower reaches of the Yangtze River [see Section 4.2]), from the other side of the Chinese marginal seas (Suwa Lake in Japan [see Section 4.3]) and from the other side of the Eurasian continent (Venice Lagoon in Italy [see Section 4.4] and the northern Baltic Sea [see Section 4.5]). In addition, we compare our sea ice events to palaeo-temperature chronologies [see Section 4.6], in order to analyze the climatic background [see Sections 4.6 and 4.7].

4.1. Comparison to winters when Taihu Lake was frozen

Taihu Lake (30.9–31.6° N, 119.9–120.6° E), the third largest freshwater lake in China, lies to the north of Hangzhou Bay (Fig. 1). It occupies an area of over 2.4×10^3 km^2, and has not changed significantly over the past 1000 yr. Abundant historical records docu-

ment the freezing of Taihu Lake over the past 1000 yr. By synthesizing previous research results and supplementing new records (Chu 1973, Gong et al. 1987), we obtained a total of 20 winters when Taihu Lake was frozen: 1111/1112, 1329/1330, 1353/1354, 1453/1454, 1474/1475, 1476/1477, 1502/1503, 1512/1513, 1513/1514, 1517/1518, 1568/1569, 1580/1581, 1654/1655, 1665/1666, 1683/1684, 1700/1701, 1761/1762, 1861/1862, 1877/1878 and 1892/1893.

Four sea ice events occurred during the past 1000 yr, i.e. 1453/1454, 1493/1494, 1654/1655 and 1670/1671. The sea ice events of 1453/1454 and 1654/1655 were synchronous with the winters during which Taihu Lake was frozen. These 2 sea ice events were more extreme than those of 1493/1494 and 1670/1671. The possible sea ice event of 1892/1893 was also synchronous with freezing of Taihu Lake. In general, the sea ice events in the Chinese marginal seas correlate to a certain extent with the winters during which Taihu Lake was frozen.

4.2. Comparison to winters when the lower reaches of the Yangtze River were frozen

The Yangtze River is the largest river in China and the third largest river in the world. Here we examine the records on the freezing of the lower reaches of the Yangtze River (from Hukou County to the river mouth; Fig. 1) over the past 2000 yr.

After examining relevant records in a compendium of Chinese historical meteorological records, we found that the lower reaches of the Yangtze River were frozen over in only 2 winters during the past 2000 yr, i.e. the winters of 985/986 and 1670/1671 (Zhang et al. 2004). The latter agrees with a sea ice event in the marginal sea of China. However, no evidence shows that the Yangtze River was frozen in other winters concurrently with sea ice events. It thus seems that the extreme sea ice events in the Chinese marginal seas are not closely related to the freezing of the lower reaches of the Yangtze River.

4.3. Comparison to the freezing dates of Suwa Lake, Japan

Suwa Lake (36.1° N, 138.1° E) lies in central Japan and covers an area of 14.7 km^2 (Arakawa 1955). The quasi-continuous records of the freezing dates of the lake, i.e. the first dates on which the water body was observed to be totally ice covered, can be traced back to as early as 1443 (Arakawa 1955, Magnuson et al. 2000; Fig. 2). However, none of the 4 sea ice events (1453/1454, 1493/1494, 1654/1655 and 1670/1671) was synchronous with abnormally early freezing dates of Suwa Lake during the overlapping period (1443–present; Fig. 2). In winter, both east China and Japan are dominated by the winter monsoon. The poor correlation between the sea ice events in Chinese marginal seas and the freezing events in Suwa Lake in Japan indicates that local climatic conditions were more influential for these events than the winter monsoon, assuming that these events were controlled by climate.

4.4. Comparison to winters when Venice Lagoon was frozen

Lengthy records of ice condition over the past 1200 yr are available for Venice Lagoon, Italy (44.2–44.6° N,

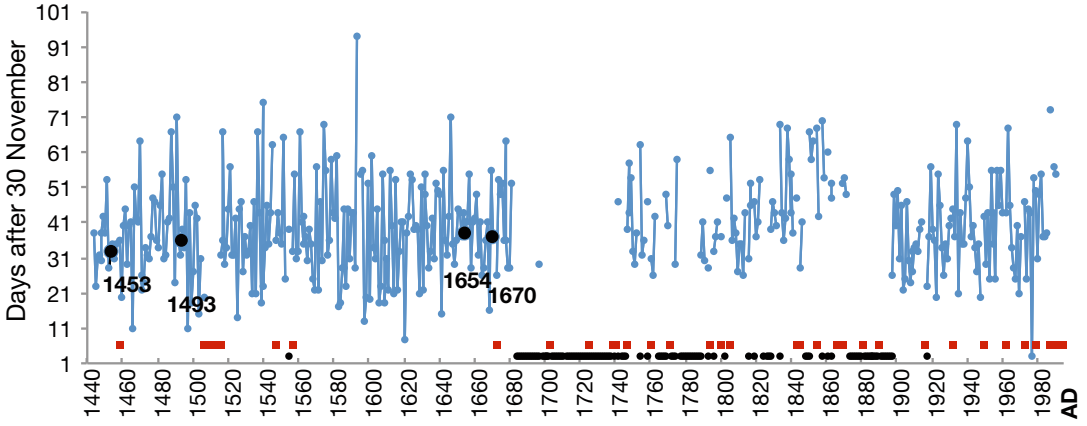

Fig. 2. Timing of the first day of the year when the surface of Suwa Lake, Japan, was fully frozen during 1443–1993 (data from Magnuson et al. 2000). The first day is defined as the day on which the water body was observed to be completely covered by ice. The *y*-axis denotes the number of days after 30 November, e.g. '1' denotes 1 December, '32' denotes 1 January of the next year, etc. Red squares: years when the lake was not totally frozen; small black dots: years when the lake was fully frozen but the freezing date is unknown. Large black dots: years with sea ice events in the Chinese marginal seas

12.1–12.7° E) (Camuffo 1987). According to the records, freezing of the lagoon to a thickness that can support a person occurred in the winters of 859/860 (possible), 860/861, 1118/1119, 1122/1123, 1234/1235, 1432/1433, 1443/1444, 1487/1488, 1491/1492, 1549/1550, 1709/1710, 1716/1717, 1740/1741, 1755/1756, 1758/1759 (possible), 1789/1790, 1864/1865, 1929/1930, 1965/1966 and 1985/1986 (Camuffo 1987). It is interesting that none of these events was synchronous with the sea ice events in the Chinese marginal seas. This poor correlation suggests that these events are local, not global, if they are controlled by climate.

4.5. Comparison to sea ice records in the northern Baltic Sea

Jevrejeva (2001) presented the reconstructed severity of winter seasons in the northern Baltic Sea during 1529–1990, and identified 23 severe winters during 1529–1720. However, none of these severe winters was synchronous with the sea ice events in the Chinese marginal seas.

4.6. Climatic background

Here we compare the sea ice events to winter temperature chronologies and discuss the climatic background of these events.

Most of the palaeo-temperature chronologies record annual and summer temperature, and very few chronologies record winter temperature changes. Ge et al. (2003) reconstructed a chronology of winter temperature in East China over the past 2000 yr, with a resolution of 30 yr (Fig. 3). It is interesting that all of the sea ice events occurred during cold periods of this chronology. In particular, the coldest 30 yr period over the past 2000 yr, viz. 1651–1680, includes the sea ice events of 1654/1655 and 1670/1671.

Rutherford et al. (2005) reconstructed the northern hemisphere winter temperature (October to the following March) chronology from 1400–1960 (Fig. 4). After a comparison of the overlapping period of the chronology with the sea ice records, we found that on a 30 yr timescale, all sea ice events occurred in relatively cold periods, whereas on an annual timescale, none of the sea ice events occurred in the years with significant cold anomalies (Fig. 4). The driving force of sea ice events are complex, and cold winters do not necessarily result in sea ice events.

4.7. Possible relationship with volcanic eruptions

Volcanic eruption is a major cause of abrupt climatic cooling (Lamb 1970, 1977, Crowley 2000, Robock 2000, Zielinski 2000). We considered the connections between volcanic eruptions and these sea ice events in the Chinese marginal seas.

After a careful survey of major historical volcanic eruptions, the sea ice event of the winter 1453/1454 was found to occur concurrently with a major volcanic eruption, the Kuwae eruption (16.8° S, 168.5° E) in Vanuatu. Pang (1993) first suggested that the abnormally cold winter of 1453/1454 in China could be a possible climatic result of the Kuwae eruption. Volcanology and ice core studies confirmed that the date of the Kuwae eruption should be circa 1453, and this eruption ranks among the largest volcanic eruptions over the past 2000 yr

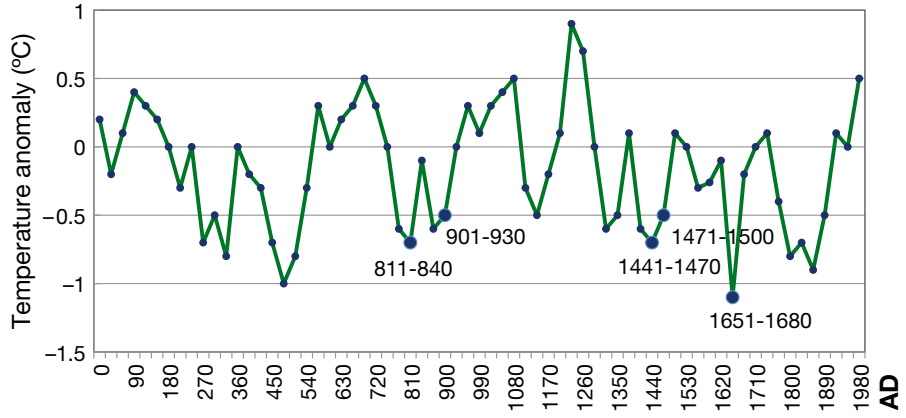

Fig. 3. Winter half year (October to April of the following year) temperature anomaly with respect to the mean of 1951–1980 in eastern China with 30 yr resolution over the past 2000 yr (modified after Ge et al. 2003). Large dots: years with sea ice events in the Chinese marginal seas

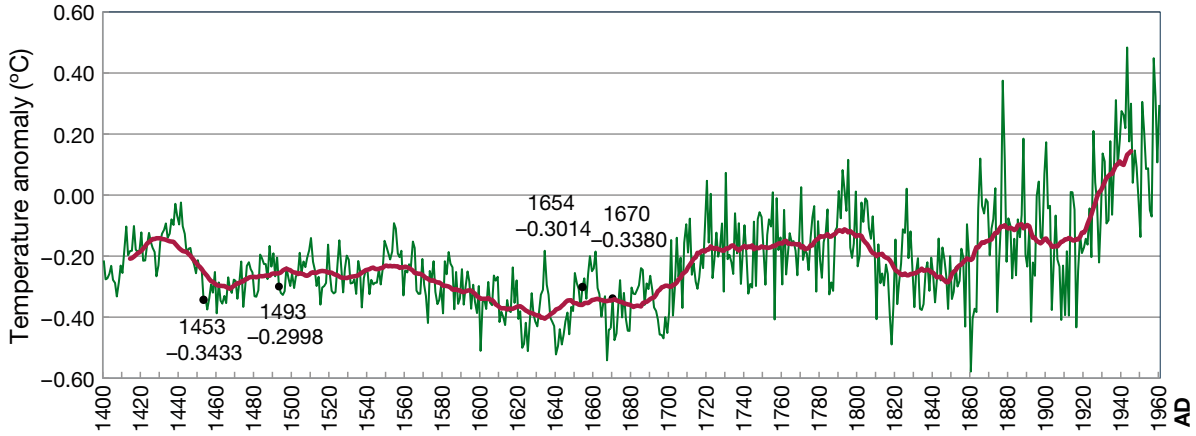

Fig. 4. Winter temperature (October to March of the following year) anomaly (°C) with respect to the 1900–1960 mean in the northern hemisphere over the past 600 yr (modified after Rutherford et al. 2005). Bold purple line: chronology that is smoothed by 30 yr Gauss low-pass filter. Years with sea ice events in the Chinese marginal seas are marked

(Monzier et al. 1994, Witter 1997, Briffa et al. 1998, Zielinski 2000, Gao et al. 2006, 2012, Witter & Self 2007).

According to a 4100 yr record of explosive volcanism from an East Antarctica ice core, explosive volcanic eruptions possibly occurred in 1653 and 1671 (Cole-Dai et al. 2000). Volcanic eruptions around 905 and 1668 were identified in a new ice core at the Amundsen-Scott South Pole Station, Antarctica (Budner & Cole-Dai 2003). The Greenland ice cores of Dye3 and GRIP also recorded a volcanic eruption at around 900–903 and 1667–1668 (Clausen et al. 1997). Significant volcanic eruptions around 822–823 and 900–902 are also recorded in the ice core of the Greenland Ice Sheet Project 2 (Zielinski et al. 1994). These ice core records of palaeo-volcanic eruptions indicate that the 822/823, 903/904, 1654/1655 and 1670/1671 sea ice events in Chinese marginal seas may also have been related to volcanic eruptions, with the 1493/1494 event as the only exception.

We should point out that several years of dating errors likely exist in the ice core records of volcanic eruptions, thus making the above comparison somewhat ambiguous. Moreover, the climatic impacts of volcanic eruptions should be hemispheric or global, and thus it is not clear why, if the sea ice events in the Chinese marginal seas are related to volcanic eruptions, similar events did not occur in Suwa Lake in Japan, Venice Lagoon in Italy and the northern Baltic Sea.

Further volcanology and climatology studies are necessary to confirm whether the relationship between volcanic eruptions and sea ice events really exists, and if so, what the mechanism is.

5. CONCLUSIONS

We conducted a comprehensive survey of the historical records of extreme sea ice events in the Chinese marginal seas. A total of 6 sea ice events in the sea areas to the south of 35° N were identified. These extreme events occurred in the winters of 821/822, 903/904, 1453/1454, 1493/1494, 1654/1655 and 1670/1671 (Table 1).

The 903/904 and 1654/1655 events occurred in Hangzhou Bay near Haiyan County. The southern limit of sea ice events in the Chinese marginal seas during the past 2000 yr is likely in Hangzhou Bay (30–31° N), and most probably near Haiyan County, Zhejiang Province (30.5° N).

The sea ice events of 1453/1454 and 1654/1655 were synchronous with the freezing of Taihu Lake, a large lake near Hangzhou Bay. The sea ice event of 1670/1671 was synchronous with the freezing event of the lower reaches of the Yangtze River. However, no sea ice events were synchronous with abnormally early freezing dates of Suwa Lake in Japan or the extreme freezing events of Venice Lagoon in Italy. All of the sea ice events occurred during cold 30 yr periods. However, they were not synchronous with the significant cold winters of the northern hemisphere. Assuming that the events were controlled by climate, the poor correlation suggests that the sea ice events may be local climatic events, rather than global phenomena. In addition, the sea ice event of 1453/1454 could be related to the ca. 1453 Kuwae eruption.

Our findings will help develop a better understanding of regional environmental changes in the Chinese marginal seas and the regional nature of global change.

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