Historical extreme winters of Istanbul: the factors that contributed to severe winters during the 20th and 21st centuries

Veli Yavuz*

Department of Meteorological Engineering,
Faculty of Aeronautics and Astronautics,
Istanbul Technical University,
ITU Maslak Campus,
34469 Maslak, Istanbul, Turkey
Email: yavuzv@itu.edu.tr
and
University of Missouri,
332 ABNR Building,
Columbia MO 65211, USA
Email: veliyavuz@missouri.edu
*Corresponding author

Mervegül Özdaş, Anthony R. Lupo and Neil I. Fox

University of Missouri,
332 ABNR Building,
Columbia MO 65211, USA
Email: mozdas@mail.missouri.edu
Email: lupoa@missouri.edu
Email: foxn@missouri.edu

Ali Deniz

Department of Meteorological Engineering,
Faculty of Aeronautics and Astronautics,
Istanbul Technical University,
ITU Maslak Campus,
34469 Maslak, Istanbul, Turkey
Email: denizali@itu.edu.tr

Abstract: In this study, the analysis of the extreme winters that occurred in Istanbul between the years 401–2022 was carried out. Until the 21st century, the extremely low temperatures and heavy snowfalls in the province sometimes lasted for days, sometimes for weeks, which adversely affected daily life and especially transportation. In the 21st century, snow depths measured between half a metre and 1 metre have been effective rather than low temperatures. By examining the extreme events that took place between the 18th and 21st centuries as reference, the statistics for the future occurrence of these events until 2050 and 2100 are presented. The most important factor in the occurrence of four events in only 22 years in the 21st century has been the positive trend in sea surface temperature (SST) anomalies.

Keywords: extreme winter; severe weather; snowfall; SST; sea surface temperature; extreme weather; Bosphorus; Golden Horn; Istanbul; Turkey; Black Sea.

Reference to this paper should be made as follows: Yavuz, V., Özdaş, M., Lupo, A.R., Fox, N. and Deniz, A. (2023) 'Historical extreme winters of Istanbul: the factors that contributed to severe winters during the 20th and 21st centuries', *Int. J. Global Warming*, Vol. 29, No. 4, pp.350–361.

Biographical notes: Veli Yavuz is working on his Doctoral thesis in the Department of Atmospheric Sciences. He is also working as a Research Assistant at Istanbul Technical University. His research interests are extreme weather, air-sea interactions, and lake/sea effect snowfalls.

Mervegül Özdaş is doing her Master's in Atmospheric Sciences at University of Missouri. Her research interests are radar meteorology and precipitation.

Anthony R. Lupo is an academician in Atmospheric Sciences at the University of Missouri. His research interests are atmospheric dynamics, atmospheric thermodynamics, long-range forecasting, atmospheric general circulation, chaos theory, and tropical meteorology.

Neil I. Fox is an academician in Atmospheric Sciences at the University of Missouri. His research interests are radar meteorology, physical meteorology, micrometeorology, radiation in atmosphere, and now casting.

Ali Deniz received his PhD in Atmospheric Sciences from Istanbul Technical University. His research interests are synoptic meteorology, aviation meteorology, and atmospheric dynamics.

1 Overview of Istanbul's historical extreme winters

Istanbul is located in a unique geopolitical position in the world. The province, which has a piece of land on the continents of Asia and Europe, connects the Black Sea and the Marmara Sea with a narrow S-shaped channel (throat-also known as the Bosphorus) (Figure 1). In order to examine the extreme winters of Istanbul and to compile the records of these winters, it is necessary to divide the period the last 1,700 years into three sub-periods. These periods are the Byzantine Empire period (330–1453), the Ottoman Empire period (1453–1922), and the Turkish Republic (1923–continue). The first important event related to the extreme winter conditions in the history of Istanbul occurred in 401. It was stated that the Bosphorus and the Golden Horn were completely frozen during the time of the Byzantine Emperor Arkadius, and ice floes were observed even in March (Yavuz et al., 2007). Since this date, there was a period of harsh winter in almost every century (except the 9th century). In the 9th century, although there were very harsh winters in Europe in six different years and even the Adriatic Sea and the Danube Rivers froze, no written records of extreme winters for Istanbul or the freezing of the Bosphorus could be found.

Figure 1 Study area (see online version for colours)

Notes: The black small square represents Istanbul. In the upper right corner, the S-type formation separating the two continents is the Bosphorus.
In the lower right corner, the Golden Horn with connection to the Bosphorus can be seen.

Table 1 The years of Istanbul's extreme winters and the consequences

Years	*Effects and consequences*
401, 472	The Black Sea was partially frozen, and the ice masses coming from here blocked the Bosphorus and caused it to freeze for 20 days.
545	There was a one-day winter in summer (in August), the waters of the Bosphorus swelled due to the tidal wave, and all the Bosphorus villages were flooded.
660	Extreme colds were observed and Istanbul was covered with snow for months.
739, 753, 755, 756, 763	The Bosphorus and Golden Horn partially frozen, extreme cold and strong winds were observed in 753.
9th century	-
905, 928, 934, 993	In 905, the Bosphorus was frozen, in 928 the Golden Horn was partially frozen and ice masses were observed in the Bosphorus, in 934 ice blocks were observed floating in the Marmara Sea, and in 993 freezing temperatures occurred.
1011	The Bosporus was frozen.
1124	Very low temperature values were encountered in Europe and Istanbul.
1232, 1297	The Bosphorus and the Golden Horn were partially frozen.
1341, 1342, 1343	Freezing temperatures in Europe and Istanbul showed themselves three winters in a row.
1402	Icebergs were observed in the Bosphorus.
1573	Snowfalls and freezing temperatures were observed for at least a month.

Table 1 The years of Istanbul's extreme winters and the consequences (continued)

Years	*Effects and consequences*
1620, 1621, 1669	In 1620, thick ice masses connected the two continents, in 1621 the Bosphorus and the Golden Horn were covered with ice, and in 1669 partial freezing occurred in the Bosphorus.
1754, 1755, 1778, 1779, 1782	In 1754, it snowed for two months without interruption and the Bosphorus was frozen, in 1755 there were frosts in places in the Bosphorus, and in 1778, 1779 and 1782, very severe winter conditions occurred.
1808, 1823, 1849, 1857, 1862, 1878, 1893	In 1808, snow depths of 1.5 men heights were observed between the neighborhoods, in 1823, the long and harsh winter conditions froze part of the Sea of Marmara and the water flowing from the taps. The Golden Horn was frozen during the years 1849, 1857, 1862, 1878 and 1893, and the Bosphorus was partially frozen in 1862, 1878 and 1893.
1928	The Bosphorus and the Golden Horn partially frozen.
1929	Heavy snowfalls and colds occurred all over Europe and Istanbul, and it snowed nonstop for two months. Every day, a few people froze to death, the ceilings of many houses collapsed due to the snow load, the Bosphorus was partially frozen, many of the dam lakes that supplied the city with water were completely frozen, the water pipes burst, hungry wolves and wild boars came to the city.
1942	Long-term freezing cold prevailed.
1954	The Bosphorus was covered with ice floes from the Black Sea. Freezing cold and snow stopped transportation in the Bosphorus. There was a shortage of bread and wood.
1963	Terkos Dam froze and water could not be supplied to the city for days. Freezing temperatures observed.
1969	Three dams in Istanbul were frozen and water could not be supplied to the city.
1987	In March, snowfall continued during the days under the influence of blocking and cyclones, and freezing temperatures were present. Metre-thick snow heights were measured.
2004	Electricity and water were cut off, natural gas could not be supplied.
2012	One of the coldest days in the last 33 years was experienced.
2017	The heaviest snowfall was observed after 1987. Snow heights exceeding 1 metre were measured in some places.
2022	Snow heights were measured in metres from places under the effect of sea-effect snow bands and cyclones.

According to Yavuz et al. (2007), the Bosphorus and the Golden Horn were frozen and the periods when severe cold were experienced were discussed during three historical periods. These extreme conditions were encountered between the 400s, 700–250 and 1600–2000. It was stated that since the first century AD, the Bosphorus froze 12 times completely and six times in parts, and the Golden Horn was frozen 15 times completely and six times in parts (Yavuz et al., 2007). In the same study, it was stated that the climatic conditions of the region changed depending on the North Atlantic Oscillation (NAO) and the Siberian High-Pressure Centre and these effects were observed between 1621–1954. As a result of the analyses carried out through various newspaper news, literary sources, books, and publications, it was determined that a total of 48 extreme winters occurred in Istanbul between the years 401–2022. In this context, the information obtained about the events and the problems experienced are given in Table 1.

2 Istanbul's extreme winters in the 20th and 21st centuries

The occurrence of one or more of the following criteria has been taken into account in the determination of extreme winter conditions:

- Partial or complete freezing of the Bosphorus or Golden Horn (especially for the first half of the 20th century).
- Freezing of dams in the province.
- More than half a metre of snow depth and this situation adversely affects aviation activities, sea transportation, land transportation and energy/water supply for several days.
- The occurrence of the coldest days of at least the last 30 years, which do not freeze the Bosphorus, Golden Horn or Dams.

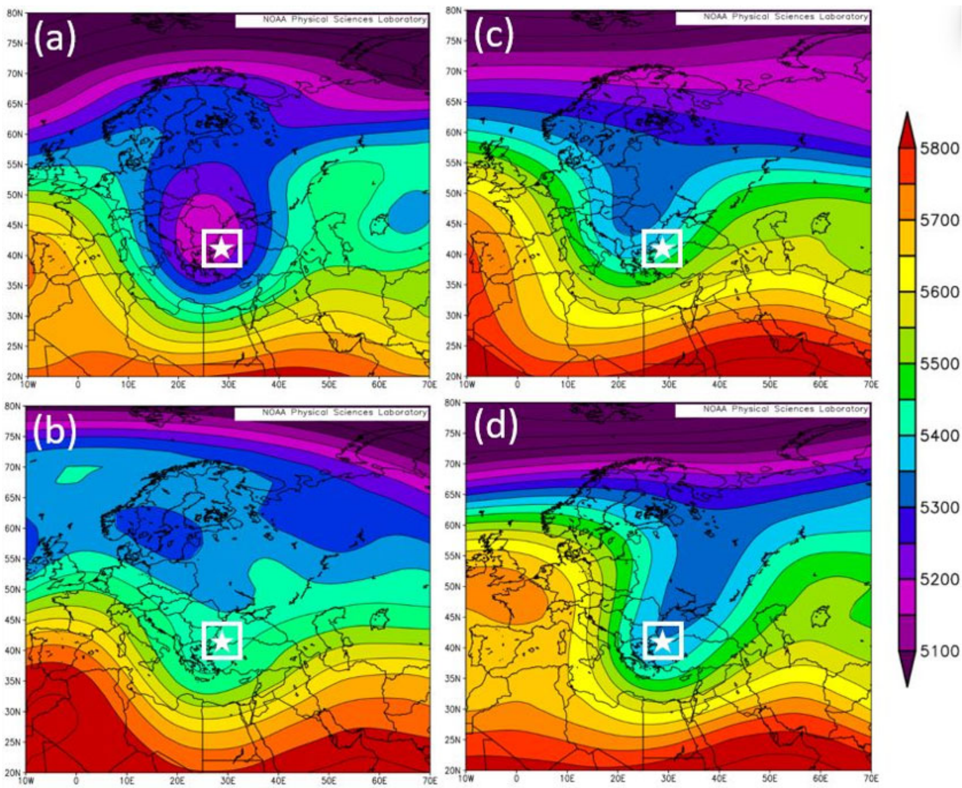
A total of seven winters in the 20th century and four severe or extreme winters in the 21st century up to 2022 were determined in Istanbul. In the 20th century, the Bosphorus and the Golden Horn were partially frozen only in 1928, and in some years, partial or complete freezing occurred in the dams and lake/stream type formations that only supplied water to Istanbul. Images of the Bosphorus, snowfall and freezing throughout Istanbul in the 20th century are given in Figure 2 (TRT, 2022).

Figure 2 Istanbul winter landscapes of the 20th century (see online version for colours)

Source: Vatan (2022), Milliyet (2022) and Kanalistanbul (2022)

Following 1928, the year 1929 was the year when the severe winter conditions were observed both in Istanbul and in Europe. In 1942, temperatures were measured below 0°C for ten days, 1°C for 14 days, 3°C for 27 days and below 5°C for 44 days at the meteorological station in Goztepe district, located on the Anatolian side of the province. In 1954, the highest daily temperatures remained below 0 °C for days, and after 1929 and 1942, it was the year in which the most severe winter conditions were experienced. At this date, the ice masses coming from the Black Sea covered the Bosphorus, and people were able to walk on these masses in the Bosphorus. The cold temperatures that froze the dams in Istanbul in 1963 and 1969 were also effective in Europe. Mostly the NAO was in the positive phase, causing relatively warm waters to come over Europe from the Atlantic. Longitudinal movements of the Arctic and Polar air masses to the south, the Siberian High-Pressure Centre being located further south, and the blocking effect that lasted for days over Europe caused severe winter conditions to be effective for days.

Figure 3 The structure and positions of the long waves at 500 hPa level on, a) 22–25 January 2004 b) 19-–3 December 2012 c) 4–13 January 2017 d) 22–27 January 2022 (see online version for colours)



Note: The star in the white square indicates Istanbul.

The first specially prepared study in the literature on the hard winter conditions observed in Istanbul was conducted for the 1987 Istanbul winter (Tayanç et al., 1998). Blocking observed at 250- and 850-hPa geopotential levels over northern Europe contributed to cyclogenesis and led to heavy snowfall. Atmospheric mechanisms showed similarity in the severe winter conditions that took place in the 21st century. The polar cold air, which descends from the north, over central Europe, and sometimes to the Mediterranean, allows the pressure centres to descend continuously with the blocking effect, allowing cyclones to be produced and to pass over Istanbul. In addition, the high temperature differences between sea surfaces and air masses at upper atmospheric levels activate the sea-effect snow (SES) mechanism. These bands, which are currently formed with cyclone and frontal transitions, support the formation of enhanced-sea effect snowfall. Especially in the northern parts of Istanbul, snow depths in the order of metres have been observed from time to time in places where SES bands were impactful.

Yavuz et al. (2021a) determined that SES mechanisms occurred during 75 of the 186 snow events that occurred within the borders of the Marmara Region between 2009 and 2018. In addition, it was determined that these SES bands were formed due to the high temperature differences between the western Black Sea surface and the polar and arctic air masses as a result of the longitudinal movements of these to the south. These bands were stated to be effective in the northern parts of Istanbul in the north-south direction of more than one parallel band with a rate of 85%. According to Yavuz et al. (2021b), it was stated that the heavy snowfalls that took place in 2012 occurred due to the high temperature difference between the sea surface and the air parcels at the level of 850/700 hPa. In addition, it was determined that vortex-type SES bands observed in the western Black Sea region left heavy snowfalls to Istanbul with north-northeast flows during the long fetch distance. For this reason, cyclogenesis, the passage of frontal systems connected to pressure centres over the region, the location and survival times of long waves (predominance of blocking types), short-wave troughs, and SES mechanisms played an important role in the heavy snowfalls and severe cold periods of the 21st century.

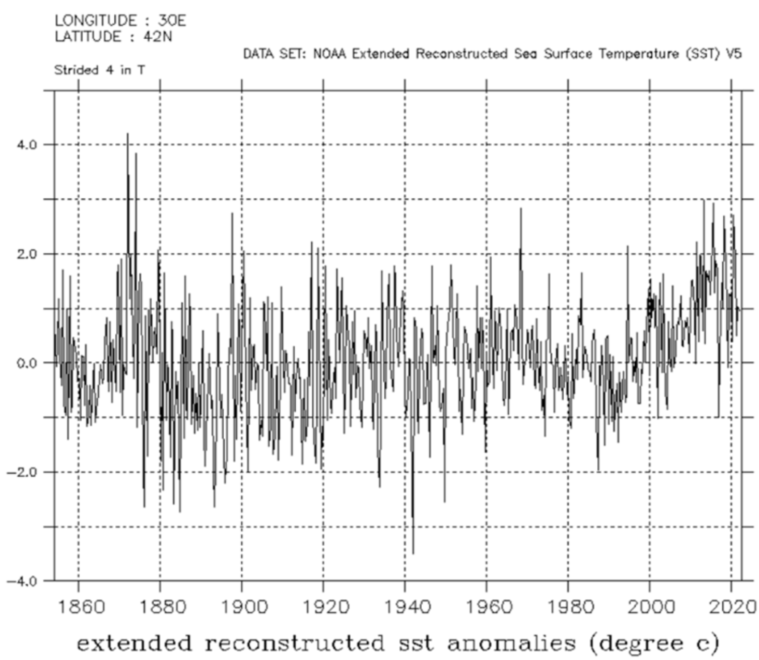
3 Atmospheric circulation types and effects on snowfall

In studies conducted for the Marmara Region, it has been stated that northern atmospheric circulation types (NW, N, NE) dominate the frequency and amount of precipitation in the region (Baltaci et al., 2015, 2017). Efe et al. (2019) analysed the atmospheric blocking and precipitation changes in Turkey for the period 1977-2016, and determined that Omega-type blocking dominates Turkey in the winter season. They also found that blocking increases the average precipitation frequency. Efe et al. (2020) found an anomaly of –2°C in the presence of blocking in the northern parts of the Marmara Region (in provinces close to Istanbul) in their study for a similar period. Therefore, it is seen that the winter season blocking systems may cause lower temperature values for the region. Yavuz et al. (2022) studied long waves and short-wave troughs in the formation of SES bands in the western Black Sea. It has been stated that short-wave troughs mostly enter the western Black Sea from western directions (due to long waves), and have high absolute vorticity values depending on the sea surface and upper atmosphere air temperature difference. It has been determined that long waves are effective on the region mostly in cut-off low (COL) and positively-tilted trough forms, and Omega- and Rex-type blocking structures were also observed in the presence of SES systems in addition to these forms. Therefore, the positions of the positively-tilted long-wave troughs, the structures and trajectories of the short-wave troughs acting on them, and ultimately the presence of the components that will form these systems play an important role in the activation, development and trajectory of SES mechanisms. The structure and positions of long waves at 500 hPa in heavy snowfalls that took place in Istanbul in the 2000s in four different years are shown in Figure 3, as the average values of the snowy period in those years. It was determined that the positive-tilted trough structure in the region in all figures and the north and north-east flows related to it, carried the cold air pool in the north over the region (Figure 3).

4 Black Sea surface temperature anomalies

It has been reported in many studies that changes in Black Sea surface temperatures have direct effects on the formation and effects of SES bands in provinces located in the north of Istanbul and the Marmara Region (Kindap, 2010; Yavuz et al., 2021a, 2021b; Baltaci et al., 2021). The high temperature differences between sea surface and upper atmosphere air contributes positively to the formation and intensification of SES bands (Niziol, 1987; Niziol et al., 1995). For this reason, increasing values of sea surface temperatures will make a positive contribution in terms of SES band formation. In order to analyse the changes in SSTs, the anomaly graph of SST values between 1860 and 2020 for the 30°E and 42°N point (corresponding to the western Black Sea) was obtained from the NOAA extended reconstructed sea surface temperature V5 data set (Figure 4). The anomaly values showed variations around 0°C until the 2000s, sometimes values above 4°C and sometimes below –3°C were detected. However, it is obvious that anomaly values that have increased on average since the 2000s. If the increasing trend in SST anomaly values continues, it can be said that SES bands with greater frequency and intensity will be effective throughout the region.

Figure 4 SST anomalies (°C) on the Black Sea



5 The possibility of extreme winter conditions in the period until 2050 and 2100

In this section, the probability of occurrence of these events from 2022 to 2050 and 2100 for Istanbul was analysed based on 23 extreme winter conditions that occurred in the

18th, 19th, 20th, and 21st centuries. First, all data between the 18th and 21st centuries were analysed as the first period, and then only the 20th and 21st centuries data were analysed as the second period. Although the average times between events were known, the Poisson distribution, one of the statistical methods used in event series where the exact timing of events is random, was preferred for analysis. In order to use the Poisson distribution, events must be independent from each other, and one event should not affect the other. At the same time, events should not be simultaneous. The Poisson distribution gives us how many (k) times an event is likely to be observed in a certain time period (the period from 2022 to 2050 and 2100 in this study), and the average duration (λ) of this event according to time. The equation of the Poisson distribution is as follows.

$$P(k;\lambda) = \frac{\lambda^k e^{-\lambda}}{k!}$$

Table 2 Projections made using data between the 18th and 21st centuries

2022–2050 projection			*2022–2100 projection*		
Number of occurrences	*Exact probability*	*Cumulative probability*	*Number of occurrences*	*Exact probability*	*Cumulative probability*
0	0.091	0.091	0	0.001	0.001
1	0.218	0.308	1	0.008	0.010
2	0.261	0.570	2	0.028	0.037
3	0.209	0.779	3	0.062	0.099
4	0.125	0.904	4	0.104	0.203
5	0.060	0.964	5	0.139	0.341
6	0.024	0.988	6	0.155	0.496
7	0.008	0.997	7	0.148	0.644
> 7	0.003	1.000	8	0.124	0.768
			9	0.092	0.860
			10	0.062	0.922
			11	0.038	0.959
			12	0.021	0.980
			13	0.011	0.991
			14	0.005	0.996
			15	0.002	0.998
			> 15	0.002	1.000

Projections made until 2050 and 2100 with reference to the extreme winters that took place between the 18th and 21st centuries are given in Table 2, and projections made until 2050 and 2100 with reference to the events that took place in the 20th and 21st centuries are given in Table 3. In both projections, there were a possibility of a maximum of seven severe winters until 2050 and a maximum of 15 severe winters until 2100. In addition, in the projection made by taking the events that occurred in the 20th and 21st centuries as a reference, the probability of the occurrence of events was higher than the other. The probability of more than seven severe winters by 2050 and 15 or more severe winters by 2100 was found to be slightly higher. This shows the trend of increasing, albeit low, event rates in the 20th and 21st centuries within the entire period.

Table 3 Projections using only data from the 20th and 21st centuries

2022–2050 projection			*2022–2100 projection*		
Number of occurrences	*Exact probability*	*Cumulative probability*	*Number of occurrences*	*Exact probability*	*Cumulative probability*
0	0.038	0.038	0	0	0
1	0.124	0.162	1	0.001	0.001
2	0.203	0.364	2	0.005	0.006
3	0.221	0.586	3	0.014	0.019
4	0.181	0.767	4	0.031	0.051
5	0.119	0.886	5	0.057	0.108
6	0.065	0.951	6	0.087	0.195
7	0.030	0.981	7	0.114	0.309
> 7	0.019	1.000	8	0.130	0.439
			9	0.132	0.571
			10	0.120	0.691
			11	0.100	0.79
			12	0.076	0.866
			13	0.053	0.92
			14	0.035	0.954
			15	0.021	0.975
			> 15	0.024	1.000

6 Conclusions and discussion

Turkey's metropolitan city, Istanbul, has been exposed to many natural disasters over the centuries. Extreme precipitation and cold weather, which is one of the meteorological natural disasters, caused the Golden Horn to freeze from time to time, and sometimes even the Bosphorus. In the 20th century, it has been determined that Istanbul has experienced severe winter conditions seven times, on the other hand, in the 21st century, severe winter conditions have occurred only four times in 22 years. In 2012, the coldest day of the last 33 years was experienced, and snow depths exceeding 1 metre were measured in 2017. Projections for the future, based on Istanbul's extreme winter past, have shown that the megacity will be more exposed to these events in an increasing trend as a result of climate change. When the events that took place in the second half of the 20th century and the 21st century are analysed, the most important reason for the winter systems affecting Istanbul, and especially for the precipitation they leave, is the moisture transport originating from the Black Sea. SES mechanisms, which occur together with meso- and synoptic-scale systems, have become the main mechanism in recent events. The most important parameter that triggers the formation of SES bands over the Black Sea is the high sea surface temperatures (SSTs). The increase in SST anomalies, which was responsible for the occurrence of four events in a short time in the 21st century, draws attention. As can be seen from the statistical projections made for the coming years in the analysis section, it is expected that Istanbul will be exposed to extreme winter conditions more frequently in the future.

Acknowledgements

This work is funded by the Turkish Science Foundation (TUBITAK) with Grant Number 1059B142000051.

References

Baltaci, H., da Silva, M.C.L. and Gomes, H.B. (2021) 'Climatological conditions of the Black Sea-effect snowfall events in Istanbul, Turkey', *Int. J. Climatol.*, Vol. 41, No. 3, pp.2017–2028, https://doi.org/10.1002/joc.6944.

Baltaci, H., Gokturk, O.M., Kindap, T., Unal, A. and Karaca, M. (2015) 'Atmospheric circulation types in Marmara Region (NW Turkey) and their influence on precipitation', *Int. J. Climatol.*, Vol. 35, No. 8, pp.1810–1820, https://doi.org/10.1002/joc.4122.

Baltaci, H., Kindap, T., Unal, A. and Karaca, M. (2017) 'The influence of atmospheric circulation types on regional patterns of precipitation in Marmara (NW Turkey)', *Theor. Appl. Climatol.*, Vol. 127, pp.563–572, https://doi.org/10.1007/s00704-015-1653-1.

Efe, B., Lupo, A.R. and Deniz, A. (2019) 'The relationship between atmospheric blocking and precipitation changes in Turkey between 1977 and 2016', *Theor. Appl. Climatol.*, Vol. 138, pp.1573–1590, https://doi.org/10.1007/s00704-019-02902-z.

Efe, B., Sezen, İ., Lupo, A.R. and Deniz, A. (2020) 'The relationship between atmospheric blocking and temperature anomalies in Turkey between 1977 and 2016', *Int. J. Climatol.*, Vol. 40, No. 2, pp.1022–1037, https://doi.org/10.1002/joc.6253.

Kanalistanbul (2022) *The Year the Bosphorus Froze*, 21 February [online] http://www.kanalistanbul.com.tr/istanbul-bogazinin-dondugu-yil/ (accessed 15 January 2022).

Kindap, T. (2010) 'A severe sea-effect snow episode over the city of Istanbul', *Nat. Hazards*, Vol.54, pp.707–723, https://doi.org/10.1007/s11069-009-9496-7.

Milliyet (2022) *Istanbul Has Seen Very Dark Winters in 5 Thousand Years*, 22 February [online] https://www.milliyet.com.tr/gundem/istanbul-5-bin-yilda-cok-kara-kislar-gordu-1496801 (accessed 12 January 2022).

Niziol, T.A. (1987) 'Operational forecasting of lake effect snowfall in western and central New York', *Wea. Forecast*, Vol. 2, No. 4, pp.310–321, https://doi.org/10.1175/1520-0434(1987)002%3C0310:OFOLES%3E2.0.CO;2.

Niziol, T.A., Snyder, W. and Waldstreicher, J. (1995) 'Winter weather forecasting throughout the eastern United States. Part IV: lake effect snow', *Wea. Forecast*, Vol. 10, pp.61–77, https://doi.org/10.1175/1520-0434(1995)010%3c0061:WWFTTE%3e2.0.CO;2.

Tayanç, M., Karaca, M. and Dalfes, H.N. (1998) 'March 1987 cyclone (blizzard) over the Eastern Mediterranean and Balkan Region associated with blocking', *Mon. Wea. Rev.*, Vol. 126, No. 11, pp. 3036–3047, https://doi.org/10.1175/1520-0493(1998)126<3036:MCBOTE>2.0.CO;2.

TRT (2022) *Unforgettable Cold Winters of Istanbul*, 23 February [online] https://www.trthaber.com/haber/turkiye/istanbulun-unutulmayan-soguk-kislari-458541.html (accessed 10 January 2022).

Vatan (2022) *Istanbul's Coldest Winters! 20 Times Since 1621*, 18 February [online] https://www.gazetevatan.com/galeri/istanbulun-en-soguk-kislari-1621-yilindan-itibaren-20-kez-2016769/22 (accessed 15 January 2022).

Yavuz, V., Akcar, N. and Schlüchter, C. (2007) 'The frozen Bosphorus and its paleoclimatic implications based on a summary of the historical data', in Yanko-Hombach, V., Gilbert, A.S., Panin, N. and Dolukhanov, P.M. (Eds.): *The Black Sea Flood Question: Changes in Coastline, Climate, and Human Settlement*, Springer, Dordrecht, https://doi.org/10.1007/978-1-4020-5302-3_26.

Yavuz, V., Deniz, A., Özdemir, E.T. (2021b) 'Analysis of a vortex causing sea-effect snowfall in the western part of the Black Sea: a case study of events that occurred on 30–31 January 2012', *Nat. Hazards*, Vol. 108, pp.819–846, https://doi.org/10.1007/s11069-021-04707-8.

Yavuz, V., Deniz, A., Özdemir, E.T., Kolay, O. and Karan, H. (2021a) 'Classification and analysis of sea-effect snowbands for Danube Sea area in Black Sea', *Int. J. Climatol.*, Vol. 41, No. 5, pp.3139–3152, https://doi.org/10.1002/joc.7010.

Yavuz, V., Lupo, A.R., Fox, N.I. and Deniz, A. (2022) 'The role of short-wave troughs on the formation and development of sea-effect snowbands in the western Black Sea', *Theor. Appl. Climatol.*, Vol. 149, pp.501–510, https://doi.org/10.1007/s00704-022-04071-y.