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ORIGINAL PAPER

The role of short-wave troughs on the formation and development of sea-effect snowbands in the western Black Sea

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Abstract

The short waves (less than 6000 km) embedded within the long waves and the resulting short-wave troughs have an effect on the sea-effect snow (SES). The short-wave troughs, which accompany most of the SES events, directly affect the formation and intensity of the bands, especially along their trajectories. In this study, the structure and characteristics of short-wave troughs and long waves during the occurrence of SES bands over the western Black Sea during nine winter periods (2010–2018) were investigated. A total of 48 short-wave troughs and long waves that concurred with snow events were detected in the period. In the classification made according to the movement direction followed by the short-wave troughs, it was determined that the western movement was dominant. This was mostly observed due to the latitudinal movements of the long waves. The average duration of the short-wave troughs over the region was found to be 27.8 h, while the longest duration trough lasted 60 h (LWT-Type). The most obvious effects of long waves were in the form of handling short waves. Apart from these, it also played a critical role in lowering arctic and polar air longitudinally to the south. The short-wave troughs allowed the convection to increase and contributed to the formation of severe SES bands by playing a role in the deepening of the convective boundary layer. The SES bands mostly had more than one parallel band formation in longitudinal direction. Movement directions of short-wave troughs and long waves mostly concurred with the SES bands (77–79%). Therefore, it is possible to talk about the effects of short and long waves not only in the change of boundary layer properties, but also in the direction of the upper atmospheric level (sub-inversion wind directions) movements.

1 Introduction

Sea/Lake-effect snow (SES-LES) is a meteorological phenomenon that occurs simply as a result of air-sea interaction, causing extreme instability and snowfall (e.g., Niziol et al. 1995; Bard and Kristovich 2012; Laird et al. 2017). As the cold air mass passes over the warmer water surfaces (e.g., lake and sea), a temperature gradient occurs between the water surface and the air mass. The temperature gradient allows the transfer of heat and moisture fluxes from the water surfaces to the upper atmosphere. Thus, an unstable boundary layer is formed at the lower tropospheric levels due to the cold air mass destabilized by fluxes and thermal energy (Niziol 1987). This boundary layer is shaped by the lower atmospheric level wind direction/intensity, the shape of the water body, the water surface temperature, the upper-atmospheric-level air temperature, the convection intensity, and the presence of a layer limiting the convection (Hjelmfelt 1990; Niziol et al. 1995; Markowski and Richardson 2010). All these aforementioned parameters directly affect the shape and trajectory of the SES/LES bands and the amount of precipitation they cause (Niziol et al. 1995; Yavuz et al. 2021a). The size of the water body increases the distance (fetch) traveled by the cold air mass. Accordingly, more time is created for the transfer of heat and moisture fluxes from the water surfaces, which increases the intensity of the SES bands (Wiggin 1950; Dockus 1985; Smith and Boris 2017). Local winds due to topographic structure (e.g., mountain-valley breezes) and winds due to intraday atmospheric variations (land-sea breezes) help increase coastal convergence.

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In this context, convection increases in the mixed layer and intensifies the existing SES/LES bands (Pike and Webb 2020). Synoptic-scale structures (low–high pressure centers, short-long-wave troughs, fronts, etc.) play an important role in increasing the severity of the existing SES/LES. In the SES/LES bands that occur under the influence of these systems, a significant increase is observed in the intensity of the bands, their duration, and the amount of precipitation they cause (Özdemir and Yetemen 2019; Yavuz et al. 2021a). Finally, the limitation of the unstable convective layer formed with meso- and/or synoptic-scale systems at the upper atmospheric levels is important for cloud/band formations. For this reason, the presence of inversion layer(s) between 850–700 and 700–500 hPa is vital for band formation (Niziol 1987; Mahoney and Niziol 1987; Kunkel et al. 2002). The fact that this layer does not form at the first 150 hPa from the surface (surface-850 hPa) is also important in terms of not restricting convection at an early stage and increasing the intensities of SES/LES bands (Steenburgh et al. 2000).

In the studies conducted for the Great Lakes Region of America, the Japan Sea, and water bodies influencing Europe, most changes in the lower atmospheric levels were analyzed in the SES/LES analyses. Although the lower atmospheric level conditions are important in the formation phase of the SES/LES bands, the changes in the upper atmospheric level also play a role in the formation of the bands, the trajectory it follows, and the amount of precipitation it causes (Ellis and Leathers 1996; Notaro et al. 2013). The presence, type, and position of a long wave of 500 hPa over a region affect the SES bands (Yavuz et al. 2021b). Similarly, short-wave troughs that occur due to long waves play a more active role (Metz et al. 2019). Atmospheric waves are of two types, long (Planetary or Rossby) and short waves (AMS 2021). Rossby waves are slow-moving waves with a length of about 6000–8000 km, which develop due to atmospheric circulation and westerly winds. Short waves are shorter than 6000 km in length and move faster (37–55 km.h^{-1}) than long waves (e.g., AMS 2021). It is seen that long and short waves have different effects on the synoptic characteristics of heavy snowfalls. Long-wave troughs and cut-off-low (COL) can affect the severity and duration of existing SES/LES systems. Most importantly, the short-wave troughs located within these long waves directly affect the SES/LES systems with their movement depending on the long wave orientation. In addition, short waves contribute to cyclogenesis (e.g., Kocin et al. 1995). On the other hand, long waves, including those associated with different configurations of blocking (e.g., Rex blocking, Omega blocking, blocking high) has an effect on the formation of extreme precipitation (e.g., Sousa et al. 2017; Rabinowitz et al. 2018; Efe et al. 2019). In studies on heavy snowfalls, a systematic relationship was found between the amount of precipitation and the vorticity maxima of 500-hPa level (Goree and Younkin 1966; Hanks et al. 1967). The presence and trajectory of the 500-hPa level vorticity maxima have been one of the most important indicators in determining the presence and position of the short-wave troughs that form due to the long wave (Younkin 1968). The cyclonic vorticity advection occurring just in front of the short-wave trough increases the upward forcing at the lower tropospheric level and causes the atmosphere to destabilize at these levels (Niziol et al. 1995; Holton and Hakim 2013). Depending on the deepening of the convective boundary layer and the rise of the inversion layer, the amount of precipitation increases where the vorticity maxima is observed (Niziol et al. 1995). Therefore, short-wave troughs are among the most important synoptic-scale structures that provide upstream support to existing SES/LES systems. Although studies on this subject are limited in the literature, Metz et al. (2019) revealed the climatology of seven cold season short-wave troughs and their relationship with LES. As a result, he stated that short waves survived on the Great Lakes for an average of 24 h, and 65% of these waves were found on at least four lakes during the times of LES. In addition, it has been determined that the number of short-wave troughs being much higher in some years is due to the presence of long waves that are effective on the region for a long time.

There are studies on the climatology of the atmospheric blocking events in association with temperature, including extreme temperature, and precipitation conditions for Turkey. The result of these studies is that many times long-term blockings are effective throughout the country, especially in the winter season (Efe et al. 2019; Efe et al. 2020a, 2020b). It is thought that blocking may influence the development and formation of SES bands that develop due to longitudinal flows to the northern parts of Turkey over the western Black Sea.

Yavuz et al. (2021a) classified the SES bands on the western Black Sea according to their formation. Five types of band structures were detected, and the most common band type found was type-2 (85%). Type-2 is a band type with a width of 5–20 km and a length of 20–50 km, in which more than one band occurs over a long fetch distance parallel to the wind. The difference from the type-1 band is that it has a longer fetch distance and more than one parallel band. Type-3 is a hybrid band type that is a mixture of type-1 and type-2 (Niziol et al. 1995). Yavuz et al. (2021a) determined that the bands formed almost 95% parallel to the wind (type-1 and type-2). Therefore, it is obvious that short-wave troughs and long waves will have an important role on SES bands. In the studies examining the relationship between atmospheric circulation types and precipitation for the Marmara Region, it was revealed that the northern circulation types (NW, N, NE) are dominant for the region in terms of both precipitation frequency and amount in winter season (Baltaci et al. 2015, 2017). Also, Baltaci et al. (2021) revealed the effect of synoptic-scale systems in heavy SES in Istanbul province, located in the northwest of Turkey. Besides, many case studies (Kindap 2010; Özdemir and Yetemen 2019; Yavuz et al; 2021b) and climatological analyses (Yavuz et al. 2021a; Baltaci et al. 2021) were carried out for western Black Sea effect snowfalls, but no study was found regarding the support of the upper atmospheric level in SES band formation.

The aim of this study is to determine the upper-level mechanisms in the formation of SES bands in the western Black Sea region. In this context, various statistics were made of short-wave troughs and long waves on the western Black Sea in the presence of SES bands between 2010 and 2018 using the SES band climatology determined by Yavuz et al. (2021a). Short-wave troughs were divided into five classes depending on the direction of movement and long wave relations, and analyses were carried out on a monthly and annual basis for each class. Then, their durations were examined and their relationship with long waves was examined. Statistical analyses were also carried out for long waves. The importance of each short-wave trough in the air-sea interaction was investigated, and the effects of short-wave trough and long waves on SES band types were revealed.

2 Data and methodology

2.1 Data

The western Black Sea (also known as the Danube Sea Area) is the western part of a closed inland sea (the Black Sea) located in the north of the Marmara Region, where Turkey's most industrially and economically developed provinces are located, on the longitudinal transit route of polar and arctic air masses in winter. Heavy snowfalls occurring in many provinces (not only in the Marmara Region, but also in the Black Sea Region), especially in Istanbul, occur due to the SES bands of western Black Sea origin with a long fetch distance. Its length in the north–south direction is approximately 600 km and its width is approximately 450 km (Fig. 1).

In the study, first, sounding data was used to obtain upper-level atmospheric information. In this direction, the data of the Istanbul Kartal Radiosonde Station was provided within the period (University of Wyoming 2021). These data were used in the determination of inversion layers and in the analysis of meteorological parameters at certain levels (e.g., 850, 700, and 500 hPa). The 500-hPa charts were analyzed to determine upper atmospheric level long and short waves (University of Wyoming 2021; Wetter3 2021).

Finally, sea surface temperature (SST) information was examined to determine the air-sea interaction. The daily average temperature values for the western Black Sea surface were analyzed using National Oceanic and Atmospheric Administration (NOAA) High-Resolution Blended Analysis data. The data has a latitude–longitude resolution of $0.25° \times 0.25°$ (APDRC 2021).

2.2 Methodology

The SES band type climatology introduced by Yavuz et al. (2021a) was used in the western Black Sea SES band analyses. Upper atmospheric level analyses were carried out based on the data set of the SES bands, which were put forward for the snowy periods in the Marmara Region between 2010 and 2018 and classified according to their formations. In the first stage of the study, geopotential heights, wind-height fields, and absolute vorticity parameters of 500-hPa level were analyzed in order to determine the short-wave troughs. Since all products were produced at intervals of 6 h, analyses were made at this interval. Several criteria set forth in the literature were used to determine short-wave troughs. These are as follows: (a) the cyclonic curvature is visible in 500-hPa wind and height fields; (b) the curvature width is limited to a maximum of 1500 km; and (c) the maximum absolute vorticity amount in the curvature is minimum $18 \times 10^{-5}\ s^{-1}$ (Tuttle and Davis 2013; Metz et al. 2019). In the examination of the atmospheric charts of 500-hPa level at 6-h intervals, no short-wave trough definition was made if any of the abovementioned criteria was not met. These criteria and the determination of short-wave troughs were made on the western Black Sea. After the short-wave troughs were determined in this way, their durations and orientations were determined. In determining the direction of short-wave trough movement, the temporal variation of the point where the vorticity maximum and the axis of the trough intersect was examined. Based on the direction the short-wave trough comes from, it was classified into five different categories. "W" type for troughs coming from the west, "NW" type for troughs coming from north-west, "SW" type for troughs coming from the south-west, "LWT" type for troughs with variable movement due to the long wave, and the "COL" type troughs that meets the three aforementioned criteria (also known as cut-off-low). Monthly annual analyses and the durations of troughs were determined for each trough type.

In the second stage of the study, the effects of the upper atmospheric level support on the SES band formations were investigated. Analyses of the temperature difference between the upper atmospheric levels and sea surface (SS) were carried out to examine the change in air-sea interaction in the presence of short-wave troughs. The presence and level of a high-level limiting mechanism due to increasing baroclinity

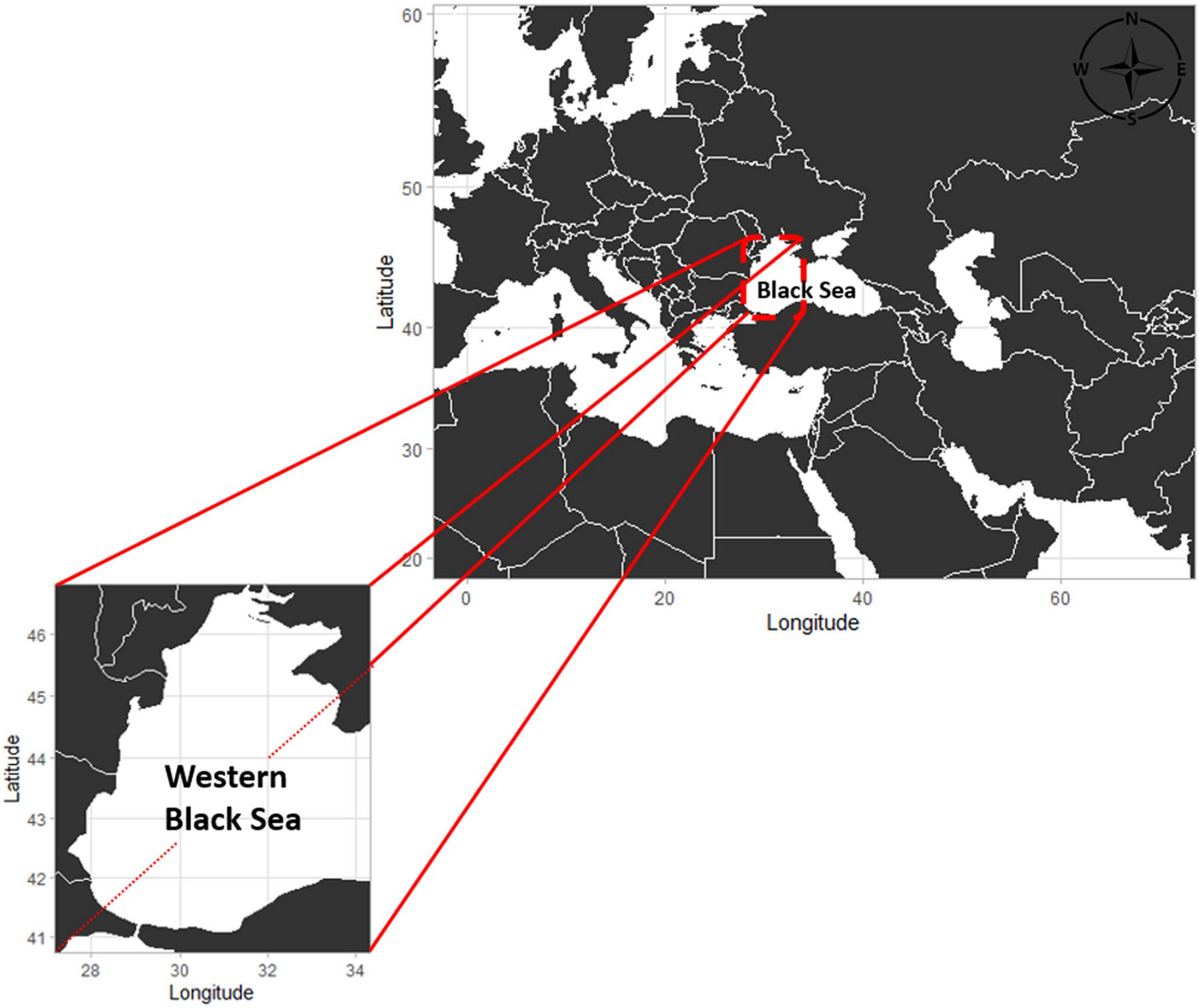

Fig. 1 The study area

(increase in instability and temperature gradient) and convection in the transitions of short-wave troughs, which are characterized by their maximum absolute vorticity were also analyzed.

In the last stage of the study, analyses of long waves were carried out. For each event, the average geopotential charts were prepared to cover the period, and analyses were made. The National Centers for Environmental Prediction (NCEP) Reanalysis II was used as the data set. This data is provided free of charge by the NOAA Physical Sciences Laboratory four times a day at 17 pressure levels (NOAA 2021). Unlike the analyses made in short-wave troughs, the types of long waves were determined by looking at their formations on the western Black Sea for each event. Apart from the long-wave troughs, atmospheric blockings were also observed, and these were also classified according to their types. In this context, long waves are evaluated in five different classes. These are as follows: positive tilted trough (PPT), negative tilted trough (NTT), and blocking anticyclone or cut-off-low (COL). The axis of the PTT is in the northeast-southwest direction, and the NTT is in the northwest-southeast direction. Atmospheric blocking is typically characterized as Rex-type or Omega-type events. The Omega blocking was named because it resembles the Greek letter omega (Ω). It consists of a combination of two COL and a blocking-high. The Rex blocking is characterized by a high-pressure system located over a low-pressure system. The COL refers to stable low-pressure areas disconnected from the main flow (NWS 2021).

3 Results

3.1 Classification, frequency, and duration of the short-wave troughs

In the analyses made for the western Black Sea between 2010 and 2018, a total of 48 short-wave troughs were determined. "NW"-type short-wave troughs were observed at the highest rate, while cut-off-lows were the least observed type. "LWT"-type troughs, whose direction of movement changed due to long waves, dominated the region in the presence of a significant amount of SES band (Fig. 2). In similar analyses for the Great Lakes Region, Metz et al. (2019) determined that the "W"-type short-wave troughs mostly occurred, and attributed the main reason for this to the direction of the upper-level jet streams throughout the region. Similarly, in this study, it was expected that westerly and north-westerly short-wave trough movements were observed due to the fact that the upper level jets and the general prevailing wind direction of the region are north-west.

In the annual analyses, it was determined that an annual average of 5.3 short-wave troughs crossed over the western Black Sea during the period (each year is evaluated as January start and December end). No short-wave trough was observed in 2014 when SES bands were observed (this is because the SES band only occurred once this year), and the highest number of troughs (11 short-wave troughs) observed in 2012. While "NW"-type short-wave trough was observed in all years except 2014, it was determined that "LWT"-type troughs, whose direction of movement was determined by long wave, were observed at least once in all years except 2018 (Fig. 3). When the "COL"-type short-wave trough was detected in 2012, a meso-scale vortex SES band, also known as type-5, was observed over the western Black Sea.

In monthly analyses, it was determined that short-wave trough occurred mostly in January (56%), followed by February (23%), December (17%), and March (4%), respectively. According to Yavuz et al. (2021a), since there was no snowfall in the other months and there was no SES band analysis, the analyses related to the short-wave trough were made only for the specified months in this study. While all five types of troughs were observed in January, all types were observed in February and December, except for the "COL" type. In March, only two short-wave troughs were detected, and they were of the "NW" type (Fig. 4). Metz et al. (2019) observed short-wave trough and LES bands for six months of the year in the Great Lakes Region, and found that "W"- and "LWT"-type troughs were dominant in all of these months. Generally, an increase trend was observed from October to December and then a decreasing trend towards March. In this study, similarity could not be found due to the fact that far fewer SES events occurred compared to the Great Lakes Region.

In the western Black Sea, the average duration of short-wave troughs was 27.8 h during the periods when SES bands were observed. While the shortest duration of trough was 6 h, the longest duration of trough was 60 h. On average, the

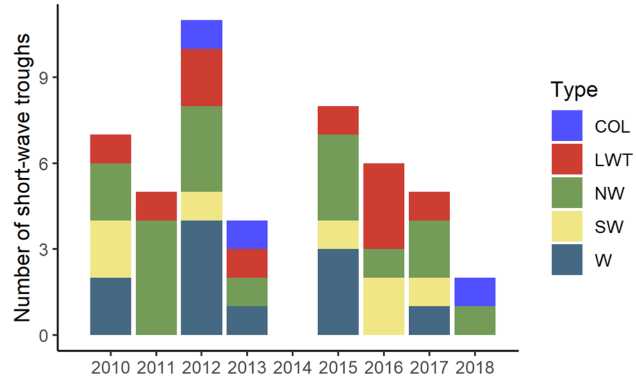

Fig. 3 Annual number of each type of the short-wave troughs in the western Black Sea

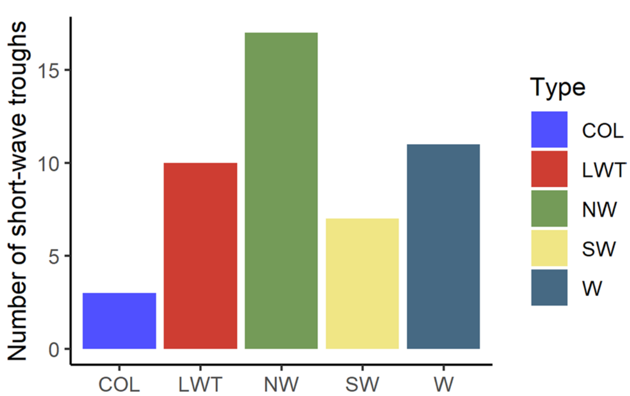

Fig. 2 The total number of each type of short-wave trough in the western Black Sea

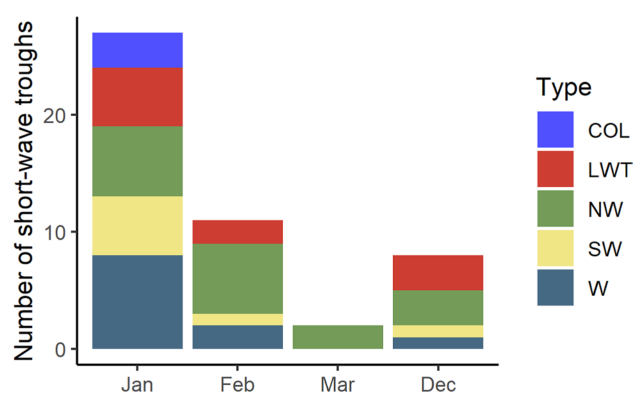

Fig. 4 Monthly number of each type of the short-wave troughs in the western Black Sea

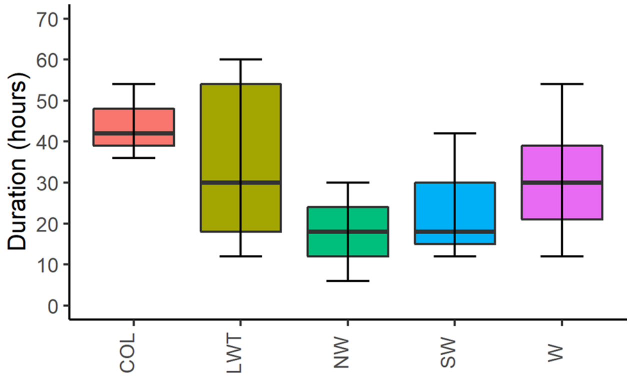

Fig. 5 The duration of each type of the short-wave troughs in the western Black Sea

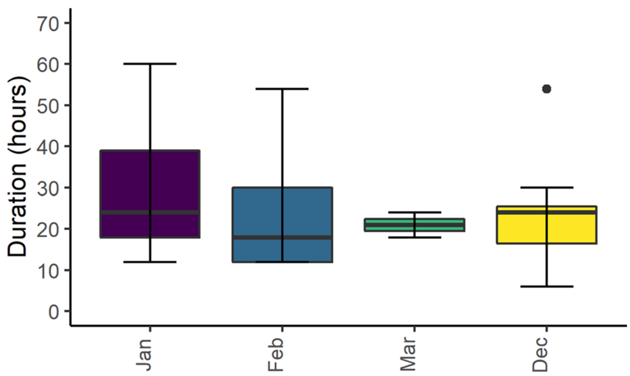

Fig. 6 The duration of each type of the short-wave troughs during each month in the western Black Sea

longest durations were observed in the "COL" type (44 h); on the other hand, the lowest durations were observed in the "NW" type (21.2 h) and "SW" type (23.1 h). The "LWT" type with a maximum duration of 60 h was also the short-wave trough with the widest distribution in terms of durations (Fig. 5). Metz al. (2019) found the average duration for the Great Lakes Region to be 24 h, and observed short-wave troughs lasting a minimum of 6 h and a maximum of 123 h. The short-wave trough type that lasted 123 h was the "COL" type. In this study, the average durations were determined close to Metz al. (2019) found; moreover, the longest duration similarly was seen in the "COL" type.

In the duration of the short-wave troughs on a monthly basis, the longest average duration was found in January (average 29.1 h), February (average 25.6 h), December (average 24 h), and March (average 21 h), respectively. The longest duration occurred in January (60 h), while the shortest duration occurred in December (6 h) (Fig. 6). Metz al. (2019) stated that shorter durations occur in November and December, while the longest durations occur in October and March. While no large differences were observed in terms of average duration in this study, a wider range was observed in January and February.

3.2 Short-wave troughs and vertical atmospheric changes

The effects of each type of short-wave trough on air-sea interactions (the temperature difference between upper atmospheric levels and sea surface) and on inversion levels due to baroclinity (increase in instability and convection) were analyzed. Different average values and oscillations stand out for each trough type between the air temperatures in the upper atmosphere (T_{850} and T_{700}) and sea surface temperatures (SST). The $\Delta T_{850\text{-SS}}$ has the highest value (18 °C) in "COL" type, also the narrowest oscillation occurred in this type. In the "LWT" type, both the highest $\Delta T_{850\text{-SS}}$ value (21.2 °C) and the widest oscillation were observed. The average $\Delta T_{850\text{-SS}}$ value was 17.7 °C. The lowest average $\Delta T_{850\text{-SS}}$ value was observed in the "NW" type (16.3 °C), while the average values similar to "LWT" were observed in the "SW" and "W" types. In the $\Delta T_{700\text{-SS}}$ analysis, the highest average value was found in the "LWT" type (25.7 °C), and the lowest average value was found in the "NW" type (23.1 °C). The largest change in terms of oscillation was again in the "LWT" type. The highest value was observed in the "W" type (30.7 °C). The increase in the temperature difference between the upper atmospheric levels and sea surfaces has been stated in many studies as a factor that both intensifies the SES bands and increases the amount of precipitation (Jiusto and Kaplan 1972; Niziol 1987; Hjelmfelt 1990, 1992; Niziol et al. 1995; Yavuz et al. 2021a, 2021b). This value should be a minimum of 13 °C for $\Delta T_{850\text{-SS}}$ and a minimum of 17 °C for $\Delta T_{700\text{-SS}}$ (Hjelmfelt 1992; Niziol 1987; Niziol et al. 1995). In this study, the minimum values in the literature were fully met. The average $\Delta T_{850\text{-SS}}$ value was 17.3 °C and the average $\Delta T_{700\text{-SS}}$ value was 24.8 °C. These average values made heavy SES band formations and heavy precipitation possible (Fig. 7).

The inversion layer is of great importance in limiting the increased convection above and providing this criterion necessary for the formation of SES bands. While the presence of inversion layer in the first 150 hPa (from the surface) is stated as a negative factor as it restricts convection early (Hjelmfelt 1990; Steenburgh et al. 2000), it is known that inversion layers at higher levels from 850 hPa level increase the strength of the SES bands and have a positive effect on the precipitation amount (Rothrock 1969; Niziol 1987; Hjelmfelt 1992; Reinking et al. 1993). In the analysis of the short-wave troughs and the levels where the first inversion layer was seen, it was found that the first inversion occurred at an average of 781.8-hPa level in all trough types. Except for the "COL" type, the average values in other types showed oscillation in the range of 770–790 hPa levels. In the "COL"

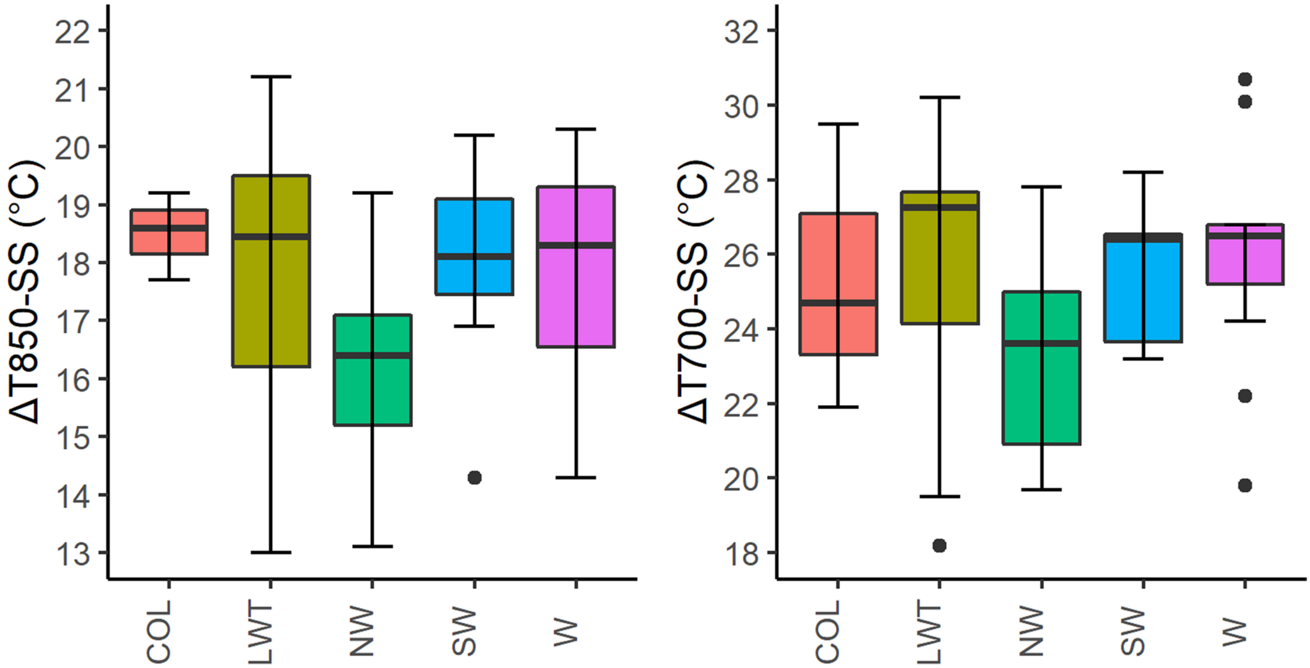

Fig. 7 Temperature difference between upper atmospheric levels and sea surface (850 and 700 hPa) during the observation of each type of the short-wave troughs

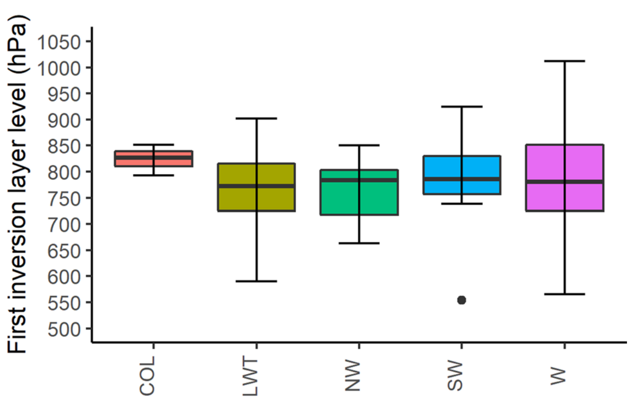

Fig. 8 First inversion layer levels (hPa) during the observation of each type of the short-wave troughs

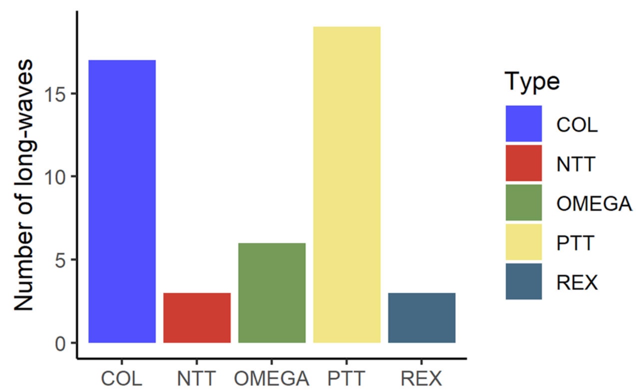

Fig. 9 The total number of each type of long wave in the western Black Sea

type, the average of 824 hPa was found. As a result, when the average values and oscillations of the heights where the first inversion layer was found in all types were examined, it was observed that the inversion layers cut the mixing layer (convective boundary layer) at the upper atmospheric levels (Fig. 8).

3.3 Long-wave types and their effects on short-wave troughs

Long waves affect the type and direction of travel of short waves. The centers and durations of short-wave troughs also vary depending on long waves. In this study, the long waves observed when there were SES bands were divided into five types (Sect. 2.2). "Omega" and "Rex" blockings in this classification are known as atmospheric blocking types. Atmospheric blocking is expressed as the presence of air parcels in a region for a long time (Aalijahan et al. 2019; Brunner et al. 2018). In the analysis made with long-wave numbers, it was observed that the least number of long waves was observed in blocking types and "NTT" type (Fig. 9). This may be one of the reasons why durations or lifespans of short-wave troughs were short on average. Because in the analysis made for each short-wave trough types, the average duration was calculated as 27.8 h, and in the presence of blocking type long waves, this duration was 31.5 h on average. In "PTT" and "COL" long-wave types, short-wave troughs mostly appeared in the northwest of the western Black Sea and continued their transition with western (north/southwest) movements.

3.4 The effect of short-wave troughs and long waves on the SES band type

According to Yavuz et al. (2021a), type-2 band was the most observed (85%) SES band type over the western Black Sea. It was determined that type-2 bands mostly occur in the north–south, northwest-southeast, and northeast-southwest directions. In this type, in which more than one parallel band was observed, the positions of the short-wave troughs and the long waves that manage them on the western Black Sea were highly similar to the detected band trajectories. In the presence of SES bands concurred with short-wave troughs, 79% of bands were found to be type-2. In the presence of SES bands concurred with long waves, 77% of bands were found to be type-2. These were followed by type-3 with 10% in both short-wave troughs and long waves (Table 1).

4 Discussion and conclusions

This is the first study to examine the short-wave trough and long-wave climatology of the western Black Sea region for sea-effect snow events. Although the direct effect of long waves on the formation and characteristics of SES bands is limited, short-wave troughs that arise due to these waves have important effects. These effects are generally as follows: the increase in instability in the atmospheric boundary layer (increasing baroclinity), change of position and structure of wind fields and restrictive upper level mechanisms in the layer, changes in the types, and orientation of SES bands depending on the aforementioned effects.

It was determined that short-wave troughs and long waves play an active role in the region in almost all times when the SES bands were observed in the western Black Sea. The most important effect of long waves was that they play a role in the formation of short-wave troughs on the region, and also carried arctic and polar air masses over long distances thanks to their length/oscillations. Therefore, most of the short-wave troughs that arose due to long waves on the region occurred within the cold air mass coming from the north. The movements of most short-wave trough types with western component were observed on the region (SW, W, NW). A part of it consisted of "LWT" type, which was exposed to direction changes due to long waves. The prevailing north-westerly wind direction of the region and upstream jets also play a major role in this distribution. Long waves have an effect on the determination of the average duration of short-wave troughs. Atmospheric blocking was observed in a small part of the long waves; mostly "COL" and "PTT" types were dominant. In the presence of atmospheric blocking, the average duration of short-wave troughs increased over the region; this was due to the long-term presence of an air parcel on a region due to the nature of blocking.

The movements of the long-waves, mostly with a western component, caused the short-wave troughs that develop due to them to emerge especially in the northwest of the western Black Sea and moved towards the southeast. Accordingly, more than one SES band parallel to each other (parallel to the sub-inversion level wind direction) followed the north–south and northwest-southeast trajectories over the region. According to Yavuz et al. (2021a), it was found that 85% of the SES bands over the western Black Sea between 2009 and 2018 occurred as type-2 and 10% as type-3. In this study, 79% of the SES bands in the presence of short-wave troughs and 77% of the SES bands in the presence of long waves were type-2. In a case where a "COL"-type short wave was observed, a meso-scale vortex structure (Type-5), which did not reach the shore, was observed on the western Black Sea. This is a result of the positive contribution of short-wave troughs to baroclinity by increasing convergence.

Table 1 The SES band types detected over the western Black Sea for each event where short-wave troughs and long waves were observed

	Band type	Type-1	Type-2	Type-3	Type-4	Type-5
	COL	-	16	3	2	-
	NTT	-	3	-	-	-
Long waves	OMEGA		6	-	-	1
	PTT	-	19	3	-	-
	REX	1	2	-	1	1
	COL	-	3	1	-	1
	LWT	1	10	2	1	-
Short-wave troughs	NW	-	15	-	1	-
	SW	1	7	1	1	1
	W	-	10	2	-	-

Changes in the atmospheric boundary layer over the sea, depending on the increasing baroclinity, also determine the band structure and trajectories. Similarly, type-4 band, also known as shoreline parallel band, was formed by the effect of the "COL"-type long waves having a western component along the coast to cover the entire western Black Sea. A support was provided to the formation of a parallel band to the coast by contributing to coastal convergence. Similar structure was also observed in "Omega" blocking. In short-wave troughs, the parallel structure of the northwest and southwest components (NW, SW) and the movement of the "LWT" type along the "COL"-type long wave also contributed to the coastal convergence and the formation of type-4 bands.

In the presence of short-wave troughs, it was found that the convective boundary layer deepened and there were high temperature differences between the upper atmospheric levels and the sea surface. The occurrence of convection-restricting inversion layers at high levels increased the baroclinity and caused the bands to intensify. Also, the high temperature differences made it possible to transfer heat and moisture fluxes from the sea surfaces to the air mass above in greater quantities. Therefore, in the presence of these two conditions, a positive contribution was made to the SES bands. The most important mechanism triggering these situations was the high amount of vorticity and the associated cyclonic vorticity advection in regions with short-wave troughs.

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Neil I. Fox: supervision, writing—review and editing.
Ali Deniz: supervision, writing—review and editing.

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Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication The authors confirm that the study is original and abide within the regulations for publication.

Conflict of interest The authors declare no competing interests.

References

Aalijahan M, Salahi B, Rahimi YG, Asl MF (2019) A new approach in temporal-spatial reconstruction and synoptic analysis of cold waves in the northwest of Iran. Theor Appl Climatol 137:341–352. https://doi.org/10.1007/s00704-018-2601-7

AMS (2021) American Meteorological Society: Glossary of Meteorology. https://glossary.ametsoc.org/wiki/Long_wave. Accessed 12 October 2021

APDRC (2021) Asia-Pasific Data-Research Center: sea surface temperatures. http://apdrc.soest.hawaii.edu. Accessed 15 October 2021

Baltaci H, Gokturk OM, Kindap T, Unal A, Karaca M (2015) Atmospheric circulation types in Marmara Region (NW Turkey) and their influence on precipitation. Int J Climatol 35(8):1810–1820. https://doi.org/10.1002/joc.4122

Baltaci H, Kindap T, Unal A, Karaca M (2017) The influence of atmospheric circulation types on regional patterns of precipitation in Marmara (NW Turkey). Theor Appl Climatol 127:563–572. https://doi.org/10.1007/s00704-015-1653-1

Baltaci H, da Silva MCL, Gomes HB (2021) Climatological conditions of the Black Sea-effect snowfall events in Istanbul. Turkey Int J Climatol 41(3):2017–2028. https://doi.org/10.1002/joc.6944

Brunner L, Schaller N, Anstey J, Sillmann J, Steiner AK (2018) Dependence of present and future European temperature extremes on the location of atmospheric blocking. Geophys Res Lett 45:6311–6320. https://doi.org/10.1029/2018GL077837

Bard L, Kristovich DAR (2012) Trend reversal in Lake Michigan contribution to snowfall. J Appl Meteor Climatol 51(11):2038–2046. https://doi.org/10.1175/JAMC-D-12-064.1

Dockus DA (1985) Lake effect snow forecasting in the computer age. Natl Wea Dig 10(4):5–19

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

Efe B, Sezen İ, Lupo AR, Deniz A (2020) The relationship between atmospheric blocking and temperature anomalies in Turkey between 1977 and 2016. Int J Climatol 40(2):1022–1037. https://doi.org/10.1002/joc.6253

Efe B, Lupo AR (1898) Deniz A (2020b) Extreme temperatures linked to the atmospheric blocking events in Turkey between 1977 and 2016. Nat Hazards 104:1879. https://doi.org/10.1007/s11069-020-04252-w

Ellis AW, Leathers DJ (1996) A synoptic climatological approach to the analysis of lake-effect snowfall: potential forecasting applications. Weather Forecast 11:216–229. https://doi.org/10.1175/1520-0434(1996)011%3c0216:ASCATT%3e2.0.CO;2

Goree PA, Younkin RJ (1966) Synoptic climatology of heavy snowfall over the central and eastern United States. Mon Wea Rev 94(11):663–668. https://doi.org/10.1175/1520-0493(1966)094%3c0663:SCOHSO%3e2.3.CO;2

Hanks HH, de Harpporte DR Jr, Grueber EC (1967) Snow forecasting procedures in the central United States. Final Report, Contract, Cwb-11353, Atmospheric Research and Development Corp., Kansas City, MO, 33.

Hjelmfelt MR (1990) Numerical study of the influence of environmental conditions on lake-effect snow-storms on Lake Michigan. Mon Wea Rev 118:138–150. https://doi.org/10.1175/1520-0493(1990)118%3C0138:NSOTIO%3E2.0.CO;2

Hjelmfelt MR (1992) Orographic effects in simulated lake-effect snowstorms over Lake Michigan. Mon Wea Rev 120:373–377. https://doi.org/10.1175/1520-0493(1992)120%3c0373:OEISLE%3e2.0.CO;2

Holton JR, Hakim GJ (2013) An introduction to dynamic meteorology. Academic Press, Waltham, MA. https://doi.org/10.1016/B978-0-12-384866-6.00001-5

Jiusto JE, Kaplan ML (1972) Snowfall from lake-effect storms. Mon Wea Rev 100(1):62–66. https://doi.org/10.1175/1520-0493(1972)100%3c0062:SFLS%3e2.3.CO;2

Kindap T (2010) A severe sea-effect snow episode over the city of Istanbul. Nat Hazards 54:707–723. https://doi.org/10.1007/s11069-009-9496-7

Kocin PJ, Schumacher PN, Morales RF Jr, Uccellini LW (1995) Overview of the 12–14 March 1993 superstorm. Bull Americ Met Soc 76(2):165–182. https://doi.org/10.1175/1520-0477(1995)076%3c0165:OOTMS%3e2.0.CO;2

Kunkel KE, Wescott NE, Kristovich DAR (2002) Assessment of potential effects of climate change on heavy lake-effect snowstorms near Lake-Erie. J Gt Lakes Res 28:521–536. https://doi.org/10.1016/S0380-1330(02)70603-5

Laird NF, Metz ND, Gaudet L, Grasmick C, Higgins L, Loeser C, Zelinsky DA (2017) Climatology of cold season lake-effect cloud bands for the North American Great Lakes. Int J Climatol 37(4):2111–2121. https://doi.org/10.1002/joc.4838

Mahoney EA, Niziol TA (1997) BUFKIT: a software application tool kit for predicting lake-effect snow. Preprints, 13th Int. Conf. on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology, Long Beach, CA, Amer Meteor Soc 388–391.

Markowski P, Richardson Y (2010) Mesoscale Meteorology in Midlatitudes. Wiley-Blackwell, 407 pp.

Metz ND, Bruick ZS, Capute PK, Neureuter MM, Ott EW, Sessa MF (2019) An investigation of cold-season short-wave troughs in the great lakes region and their concurrence with lake-effect clouds. J Appl Meteorol Climatol 58(3):605–614. https://doi.org/10.1175/JAMC-D-18-0177.1

Niziol TA (1987) Operational forecasting of lake effect snowfall in western and central New York. Weather Forecast 2(4):310–321. https://doi.org/10.1175/1520-0434(1987)002%3C0310:OFOLES%3E2.0.CO;2

Niziol T, Snyder W, Waldstreicher J (1995) Winter weather forecasting throughout the eastern United States. Part IV: lake effect snow. Weather Forecast 10:61–77. https://doi.org/10.1175/1520-0434(1995)010%3c0061:WWFTTE%3e2.0.CO;2

Notaro M, Zarrin A, Vavrus S, Bennington V (2013) Simulation of heavy-lake effect snowstorms across the Great Lakes basin by RegCM4: synoptic climatology and variability. Mon Wea Rev 141(6):1990–2014. https://doi.org/10.1175/MWR-D-11-00369.1

NOAA (2021) National Oceanic and Atmospheric Administration: NCEP/NCAR Reanalysis II. https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.pressure.html. Accessed 7 October 2021

NWS (2021) National Weather Service: Basic wave patterns. https://www.weather.gov/jetstream/basic Accessed 7 October 2021

Özdemir ET, Yetemen Ö (2019) Meteorological analysis of lake enhanced snow in Istanbul, on February 17–19, 2015. J Anatol Env Anim Sci 4(2):115–121 ((in Turkish))

Pike WS, Webb JDC (2020) The very deep cold pool, and lake-effect snowfalls of 27 February–1 March 2018. Weather 75(3):88–98. https://doi.org/10.1002/wea.3675

Rabinowitz JL, Lupo AR, Guinan PE (2018) Evaluating linkages between atmospheric blocking patterns and heavy rainfall events across the north-central Mississippi River valley for different ENSO phases. Adv Meteorol Article ID 1217830. https://www.hindawi.com/journals/amete/2018/1217830/

Reinking RF, Caiazza R, Kropfli RA, Orr BW, Martner BE, Niziol TA, Byrd GP, Penc RS, Zamora RJ, Snider JB, Ballentine RJ, Stamm AJ, Bedford CD, Joe P, Koscielny AJ (1993) The Lake-Ontario winter storms (LOWS) project. Bull Amer Meteor Soc 74(10):1828–1849

Rothrock HJ (1969) An aid in forecasting significant lake snows. Tech Memo WBTM CR-30, National Weather Service Central The Region, 16 pp.

Smith BB and Boris JP (2017) Lake snow parameter. National Weather Service Forecast Office, Gaylord, MI. https://www.weather.gov/apx/lake_snow_parameter. Accessed 15 October 2021.

Sousa PM, Trigo RM, Barriopedro D, Soares PMM, Ramos AM, Liberato MLR (2017) Responses of European precipitation distributions and regimes to different blocking locations. Clim Dyn 48(3):1141–1160. https://doi.org/10.1007/s00382-016-3132-5

Steenburgh WJ, Halvorson SF, Onton DJ (2000) Climatology of lake-effect snowstorms of the Great Salt Lake. Mon Wea Rev 128:709–727. https://doi.org/10.1175/1520-0493(2000)128%3C0709:COLESO%3E2.0.CO;2

Tuttle JD, Davis CA (2013) Modulation of the diurnal cycle of warm-season precipitation by short-wave troughs. J Atmos Sci 70:1710–1726. https://doi.org/10.1175/JAS-D-12-0181.1

University of Wyoming (2021) Upper-level atmospheric charts. http://weather.uwyo.edu/upperair/sounding.html. Accessed 9 October 2021

Wetter3 (2021) Archived data. http://www.wetter3.de. Accessed 9 October 2021

Wiggin BL (1950) Great snow of the great lakes. Weatherwise 3:123–126. https://doi.org/10.1080/00431672.1950.9927065

Yavuz V, Deniz A, Özdemir ET, Kolay O, Karan H (2021a) Classification and analysis of sea-effect snowbands for Danube Sea area in Black Sea. Int J Climatol 41(5):3139–3152. https://doi.org/10.1002/joc.7010

Yavuz V, Deniz A, Özdemir ET (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 108:819–846. https://doi.org/10.1007/s11069-021-04707-8