



Characteristics of Extreme Snowfall–Wind-Gust Events in Finland (1960–2024): Frequency, Duration, and Intensity

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Abstract.

Compound weather events involving both strong wind gusts and intense snowfall can have significant impacts on critical infrastructure and public safety. This study analyses the frequency, duration, and intensity of such events in Finland using
10 ERA5 reanalysis data for 1960–2024. Extreme wind gust and snowfall conditions were identified using spatially varying 95th and 98th percentile thresholds. Events with both snowfall and wind gust exceeding these thresholds simultaneously were classified as compound events (SWG). SWGs were most frequent along Finland’s south facing coastal regions and eastern Finland. Increasing the threshold from 95th to 98th reduced the number of SWGs but emphasized the dominance of coastal areas and highlighted more severe cases. Approximately half of the events were short-lived (<5 h) and involved limited
15 accumulation of snow water equivalent (<5 mm). However, a few prolonged SWGs were identified, characterized by wind gusts >20 m s⁻¹, hourly snowfall rates >2.5 mm h⁻¹, and total snowfall >20 mm. Although rare, these high-impact SWGs can create substantial operational challenges for energy production and other critical infrastructures. The results underscore the importance of incorporating compound-event analysis into hazard assessments and preparedness strategies for regions exposed to severe winter weather.

20 1 Introduction

Extreme events such as high wind gusts and intense snowfall are not only natural phenomena but also significant factors that play a crucial role in the safety and operational integrity of critical infrastructure and economic losses (Rutgersson et al., 2022). From a societal perspective, high wind gusts and intense snowfall can severely disrupt transportation networks, cause widespread power outages, and limit access to emergency services (Räisänen et al., 2026; Láng-Ritter et al., 2025; Laurila et
25 al., 2025b; Rauhala and Juga, 2010; Niinimäki, 2008). Understanding and mitigating the impacts of such conditions is vital for societal resilience, as well as for ensuring the uninterrupted functioning of essential services, including energy production.

Nuclear power plants (NPP) must adhere to strict safety protocols and are designed with multiple layers of safety features. NPPs must account for external environmental stresses including possible consequences of extreme weather. Strong winds



30 causing snow and ice buildup on ventilation and cooling systems have been identified as potential risks that could reduce operational efficiency or even lead to unplanned shutdowns (Jylhä et al., 2018).

Recently, two strong mid-latitude cyclones affected large areas of Finland within a short time range, storm Lyly on 1 November 2024 (Laurila et al., 2025b; Punkka and Láng-Ritter, 2024) and storm Jari on 20–21 November 2024 (Lehtonen 2024; YLE, 2024; Trimble, 2024). High wind speeds and gusts, co-occurring with heavy snowfall caused severe power 35 outages and traffic accidents, forest damages and cancelled or delayed public transport systems. In addition, two large power line poles fell as a result of the hurricane-level winds during storm Lyly in Eurajoki in western coast of Finland. Understanding and mitigating the impacts of such conditions are vital for societal resilience, as well as for ensuring the uninterrupted functioning of essential services, including energy production.

In Finland in winter, the lowest level of wind gust warnings is issued when gusts exceed 20 m s^{-1} , while the second level of 40 warning is triggered at gusts exceeding 25 m s^{-1} in land areas (FMI, 2025a). The snowfall intensity has no exact threshold for warnings in Finland similarly as the rainfall has. For rainfall the extreme thresholds when warning is issued are 20 mm h^{-1} and 50 mm day^{-1} (<https://www.ilmatieteenlaitos.fi/sadevaroitukset>). For snowfall, the intensity is commonly described as visibility, not the precipitation rate. Rasmussen et. al. (1999) has studied the relation between snowfall rate (as water equivalent) and visibility. In their field experiments, a moderate snowfall rate (estimated by Rasmussen et. al. (1999) to be 1– 45 2.5 mm h^{-1} , 1 mm of snowfall corresponding roughly 1 cm of snow depth) corresponded to visibilities between 0.3 km and 2.0 km, while a heavy snowfall rate ($> 2.5 \text{ mm h}^{-1}$) resulted in visibilities from 0.2 km to 0.8 km, for temperatures less than 0°C .

From a societal perspective the compound nature of wind gust and snowfall events is crucial, since it is their concurrence that can lead to cascading impacts and amplified risks. Operational services, such as road weather warnings, have 50 acknowledged the danger of combined hazards. The Finnish Meteorological Institute (FMI) issues road weather warnings divided to four categories (normal, bad, very bad, extremely bad) based on the severity of possible impacts (FMI, 2021). In addition to snowfall, blowing snow also reduces visibility and poses hazard to traffic when snowfall coincides with wind gusts exceeding $15\text{--}20 \text{ m s}^{-1}$ (FMI, 2025b). Nevertheless, no specific numerical threshold is provided for snowfall in the warnings; the category only refers to “extreme snowfall” or “low visibility”.

55 Knowledge of the statistical characteristics of co-occurring strong winds and heavy snowfall is crucial for evaluating their possible impacts and devising effective response strategies. In Finland, winter storms typically arrive from the southwest (Láng-Ritter et. al., 2025), crossing the Baltic Sea before reaching the mainland. When the sea is ice-free, these storms can acquire additional heat and moisture, which enhances precipitation and may result in heavy snowfall along coastal areas (Olsson et al., 2023). Since Finland’s nuclear power plants are located on the shoreline, understanding storm impacts over 60 the sea as well as over land is crucial. However, direct observations of air temperature or wind gusts over the sea are sparse or entirely absent, making reanalysis data a more feasible source of information in such cases.

Temporal and spatial occurrence of strong winds and large snow load amounts in Finnish land areas based on weather station observations have been assessed by e.g., Gregow et. al. (2008) and Niinimäki (2008). Based on Gregow et al. (2008) the



strongest wind speeds were observed most often along the coastline and over the lakes in Finland during 1961-2000 but the
65 wind speeds rarely exceeded 17 m s^{-1} . Niinimäki (2008) found eight snowstorms in southern and southwestern Finland
during the period 1965–2005 for which 10-minute wind speed, daily precipitation amounts and daily increase in snow depth
simultaneously exceeded the selected thresholds of 21 m s^{-1} , 15 mm, and 15 cm, respectively. Niinimäki (2008) speculated
that jointly occurring high winds and intense snowfall are likely to have been more numerous.

The frequency of severe weather events including snowfall, wind gust and blizzards (snowfall $> 10 \text{ cm day}^{-1}$ and wind gust
70 $> 17 \text{ ms}^{-1}$) in Europe in past and future climates have been investigated by Vajda et al. (2014). They used 30 years of data
from E-OBS observational and ERA-Interim reanalysis data as well as ENSEMBLES climate model data to produce
statistics of the event frequencies of daily time resolution. They concluded that the number of snowfall days is decreasing in
the future, but the number of heavy snowfall days might even increase in the Northern Europe.

There is no recent statistics in Finland of how intense and frequent these compound events are. The present study addresses
75 this gap by examining extreme snowstorms for which both snowfall and wind gusts reach high levels. By focusing on these
compound extremes, the study provides quantitative evidence on their frequency and temporal characteristics, thereby
contributing to a more comprehensive understanding of winter hazards in northern Europe. Such knowledge is essential for
improving risk assessment frameworks and supporting societal preparedness in the face of severe winter weather.

Because the observation stations providing information on precipitation type is sparse, we utilize hourly ERA5 reanalysis
80 data to study these extreme events. The hourly data enables sub-daily and event-based studies. In addition, the usage of
snowfall instead of precipitation ensured that we included only snowfall events without a need to use a temperature threshold
for classifying precipitation events into rain or snow. As ERA5 is known to underestimate extreme winds (Laurila et al.,
2025a), the use of percentiles instead of an absolute threshold value was utilized. In addition, a short comparison between
two observation stations and corresponding ERA5 grid points was performed to examine the differences between observed
85 and ERA5 wind gusts and snowfall on hourly basis (Section 3.1).

The co-occurrence of extreme hourly snowfall and wind gusts was investigated using spatially varying high percentiles as
thresholds to define hourly extreme events, accounting for the spatial variability and distinct climatological characteristics of
the regions. The primary research questions we addressed are: (i) What are the frequency and geographical distribution of
co-occurring high winds and heavy snowfall (Section 3.2), (ii) What is the duration of consecutive hours during which
90 compound events persist (Section 3.3), and (iii) What is the intensity of these compound events (Section 3.4).

2 Data and methods

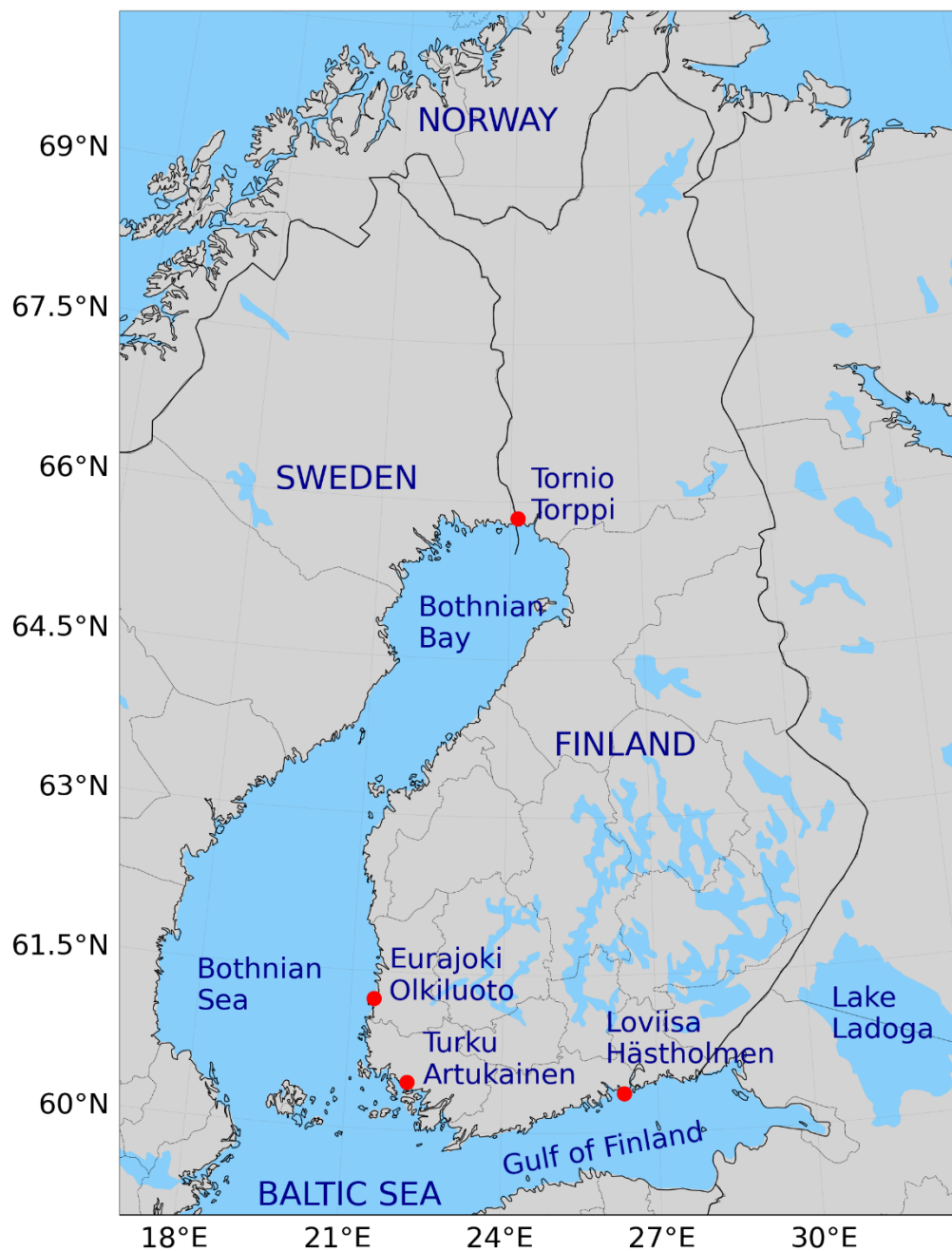
2.1 Study locations

Four locations in Finland were selected for detailed analysis of compound events involving high wind gusts and intense
snowfall. All the selected locations (Figure 1, Table 1) are coastal since apart from some mountain stations in the north, the
95 strongest wind gusts in Finland occur along the coastline (Laurila et al., 2025a). Two of the locations were chosen because



they host nuclear power plants (Eurajoki Olkiluoto and Loviisa Hästholmen), while the remaining two (Tornio Torppi and
Turku Artukainen) represent areas with a relatively high frequency of hours with snowfall $> 1 \text{ mm h}^{-1}$ (not shown). The
selection was further guided by the availability of concurrent observation stations measuring wind gusts, precipitation
amount, and precipitation type, as such stations are relatively scarce. Population density was also considered to include
100 regions of societal relevance.

Before the analysis of extreme events based on ERA5 a short comparison between station observations and ERA5 data was
performed for two of the selected study locations; Tornio Torppi and Turku Artukainen. ERA5 values at the nearest grid
point are used for each study location.



105 Figure 1. Map of Finland. The four study locations; Tornio Torppi, Eurajoki Olkiluoto, Turku Artukainen and Loviisa Hästholmen, are marked with red dots.



2.2 Reanalysis

This research seeks to advance the understanding of compound extreme events involving snowfall and wind gusts through analysing ERA5 hourly data for 65 years. ERA5 is the fifth generation ECMWF (European Centre for Medium Range Weather Forecasts) atmospheric reanalysis of the global climate and is openly available online in the Climate Data Store (Hersbach et al., 2023). ERA5 is a globally complete and consistent dataset which covers the Earth on a 30 km (0.25° x 0.25°) grid spacing with 137 vertical model levels up to a height of 80 km. ERA5 covers the period from January 1940 to the present with a time lag of approximately one week. ERA5 provides hourly estimates of many atmospheric climate variables.

In this study, the hourly maximum of instantaneous wind gust data at 10 m level and accumulated snowfall at hourly time steps during the period of 1960–2024 were used. Our research domain covers Finland and northern Baltic Sea from 55° N to 70° N and 17° E to 32° E. High percentiles of the variables were used as threshold values to investigate the frequency and intensity of compound events.

2.3 Observations

For making a short comparison between two observation stations and corresponding ERA5 grid points, it was essential to have co-located observations of precipitation type, precipitation amount, and wind gust speed. In 2025, Finnish meteorological institute operates 175 automatic weather stations, which carry out a variety of meteorological observations. Precipitation gauges were installed at 118 weather stations, an anemometer at 132 stations, and a present weather sensor, which detects precipitation type, at 79 stations. Only 51 out of 175 weather stations have all three sensors.

Automated weather stations report their instantaneous observations every 10 minutes. In addition, they produce various hourly values (e.g. means, maxima and sums) of the observed variables. The observations used here are the hourly precipitation accumulation (mm h^{-1}), the hourly maximum wind gust speed (3-second average of the speed in m s^{-1}), and the hourly most significant weather phenomenon (present weather codes).

For the comparison of ERA5 and observations, we use a ten-year period from 2014 to 2023. The weather stations Tornio Torppi and Turku Artukainen (Table 1), located near the coasts, were chosen as the weather stations to be compared against ERA5 because these stations had adequately long time series (ten years) of the three necessary quantities and the observations of the stations, especially precipitation observations, have been found to be climatologically representative.

2.4 Methods

In meteorological studies, percentiles are commonly used to define extreme weather conditions (Rutgersson et al., 2022). Here, the 95th and 98th percentiles were employed as thresholds to identify extreme values and to test the suitability of the high percentiles in a compound event study. High percentiles used as threshold values for hourly snowfall and wind gusts are summarized in Table 1. The use of location-specific percentile thresholds (e.g., 95th and 98th percentiles) allows for the



140 characterization of extreme events relative to the local climatological distribution. Since climatic conditions such as snowfall and wind gusts vary significantly across different geographic regions, applying a uniform threshold would not adequately capture what constitutes an "extreme" event at each site. By employing percentiles derived from historical data at each grid point, the approach ensures that the detection of extremes is normalized to the local variability and mean state.

Using hourly meteorological data from cold season months (October to March) during 1960-2024, the frequency, duration, and intensity of concurrent extreme snowfall and wind gust events were assessed. Events were considered "compound" when 145 both snowfall and wind gust (SWG) parameters exceeded their percentile thresholds (Table 1) simultaneously within the same hour and grid point. From here on, when hourly snowfall and wind gust exceed their 95th percentiles, the compound is called SWG95, and correspondingly for 98th percentile SWG98. A compound event can last one or several consecutive hours.

In addition to the percentile-based thresholds, absolute metrics were used to showcase the most extreme events with 150 comparable values between the four study sites. Extreme compound events were assessed more closely using thresholds of i) 1 mm h⁻¹ for moderate and 2.5 mm h⁻¹ for heavy snowfall rate; ii) 20 mm per event for large snowfall accumulation; iii) 20 m s⁻¹ and 25 m s⁻¹ for strong and extreme wind gusts, respectively, and iv) blizzard conditions (extreme blizzard conditions) where maximum wind gust exceeds 17 m s⁻¹ (or 20 m s⁻¹) and snowfall accumulation is larger than 10 mm per event (or 20 mm per event).

155 Because only compound events were of interest in this study, this analysis does not take into account if e.g. the snowfall has continued longer than the compound event. Thus, the total snow accumulation might have been larger during the course of the day(s) when compound event occurred. In all the tables extreme values exceeding the 2.5 mm h⁻¹ for heavy snowfall rate, 20 mm event⁻¹ for large snowfall accumulation and 25 m s⁻¹ for extreme wind gusts are bolded.

160 **Table 1. Thresholds for extreme values for hourly snowfall (mm h⁻¹) and wind gust (m s⁻¹) in study locations for October-March 1960-2024 based on ERA5. The 95th and 98th percentiles of hourly values were used as thresholds for compound events.**

| | Tornio Torppi | Eurajoki Olkiluoto | Turku Artukainen | Loviisa Hästholmen |
|--|--|-----------------------|--|-----------------------|
| Observation station | WMO station ID 02880, 65.84733°N, 24.17369°E, 8 m AMSL | | WMO station ID 02773, 60.45439086°N, 22.17869509°E, 8 m AMSL | |
| ERA5 gridpoint | 24.25° E, 65.75° N | 21.5° E, 61.25° N | 22.25° E, 60.5° N | 26.25° E, 60.5° N |
| Snowfall 95 th as water equivalent (mm h ⁻¹) | 0.42 | 0.33 | 0.40 | 0.40 |
| Snowfall 98 th as water equivalent (mm h ⁻¹) | 0.68 | 0.58 | 0.70 | 0.65 |



| | | | | |
|---|-------|-------|-------|-------|
| Wind gust 95 th (m s ⁻¹) | 14.32 | 16.58 | 14.11 | 16.14 |
| Wind gust 98 th (m s ⁻¹) | 16.15 | 18.61 | 16.08 | 17.89 |

3 Results

3.1 Comparison between station observations and ERA5

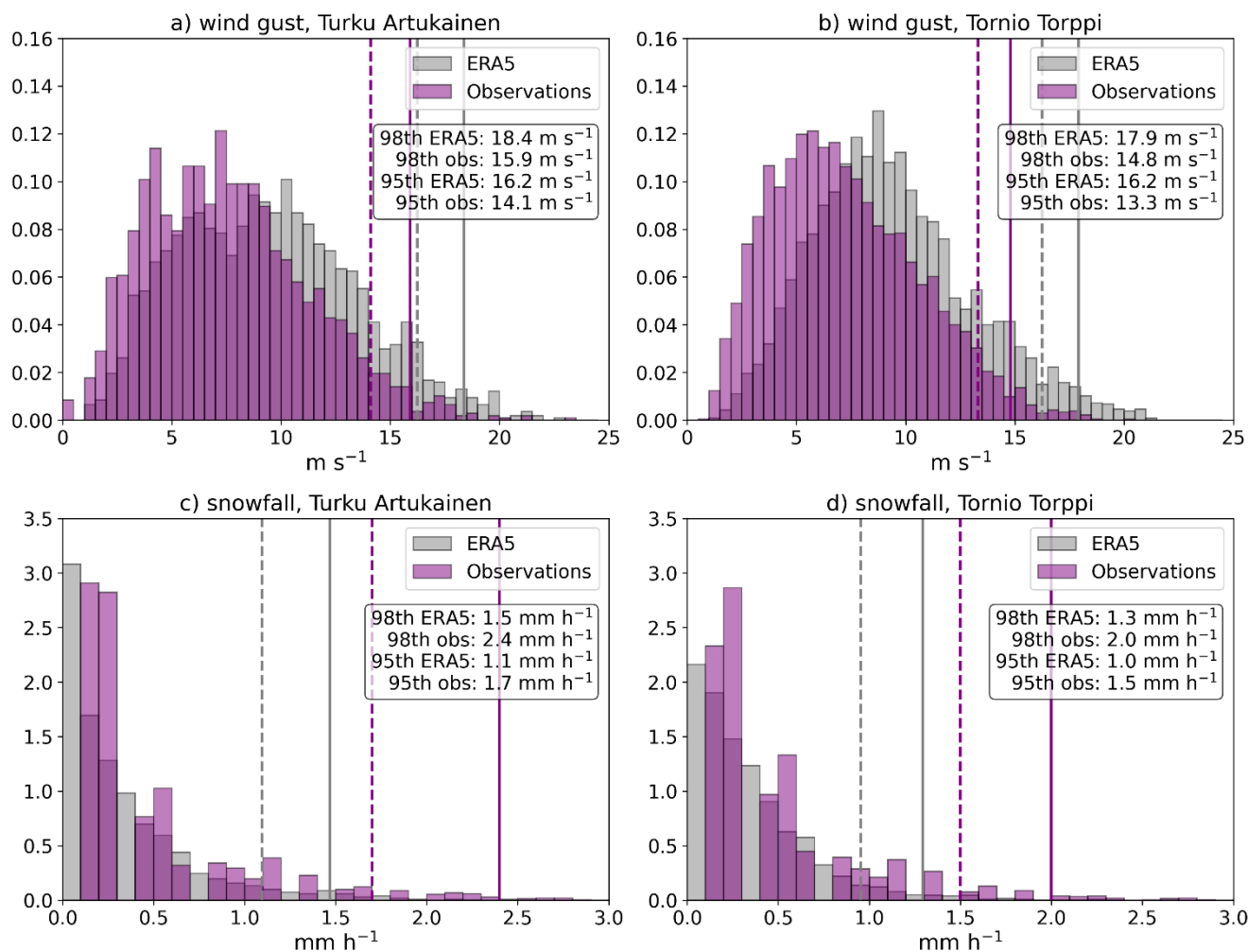
165 For validation purposes, ERA5 hourly wind gust and snowfall are compared to weather station observations in Turku
Artukainen and Tornio Torppi for the period of 2014-2023 during the cold season (October to March). Only those time steps
are included in the comparison when snowfall is recorded on observation station.

The distributions of wind gusts (Figure 2a,b) show that overall, the wind gust distribution is shifted more to right in ERA5
than in the observations. The 95th and 98th percentiles are somewhat higher in ERA5 than the observed values in both Turku
170 and Tornio (ERA5 minus observed wind gust difference ranges from 2.1 m s⁻¹ to 3.1 m s⁻¹). This finding contrasts with
results from coastal stations in Finland, where ERA5 tends to underestimate high wind gusts (Laurila et al., 2025a). It is
important to note that this comparison focuses exclusively on cold season data and time steps with observed snowfall,
whereas Laurila et al. (2025a) include all hourly observations throughout the year. Their findings indicate that the ERA5 bias
is more pronounced during summer months and the lower wind gust values (below 10 m s⁻¹) are overestimated by EAR5.
175 Moreover, the underestimation is the largest with much higher wind gusts (over 25 m s⁻¹) than for wind gusts between 15
and 20 m s⁻¹ (Laurila et al., 2025a) which is the category for the 95th and 98th percentile values in this study.

The distributions of snowfall (Figure 2c,d) show similar shapes with a long right tail and a peak in small snowfall amounts.
Notably, the 95th and 98th percentiles of snowfall are smaller in ERA5 compared to observations at both Turku Artukainen
and Tornio Torppi. This discrepancy arises from the measurement accuracy of observations, which is limited to 0.1 mm h⁻¹,
180 while ERA5 treats snowfall amounts as a continuous variable. Additionally, observational data represents point
measurements, whereas ERA5 provides a mean over grid point areas, smoothing out extreme values.

Due to the classification of observed data in 0.1 mm h⁻¹ increments, only values above this threshold are recorded,
potentially underrepresenting lighter snowfall events. In contrast, the continuous nature of the ERA5 data allows for the
inclusion of values closer to zero, leading to lower upper percentile estimates. Consequently, while ERA5 captures a more
185 comprehensive range of snowfall intensities, the observational data results in higher percentile values, which skews the
interpretation of snowfall severity in this comparison.

Overall, ERA5 effectively captures the main characteristics of wind gust and snowfall distributions during cold-season
snowfall events, although differences are present in the highest percentiles. These results indicate that ERA5 provides a
reliable and consistent representation of the conditions relevant to this study and can be used for the subsequent analyses.

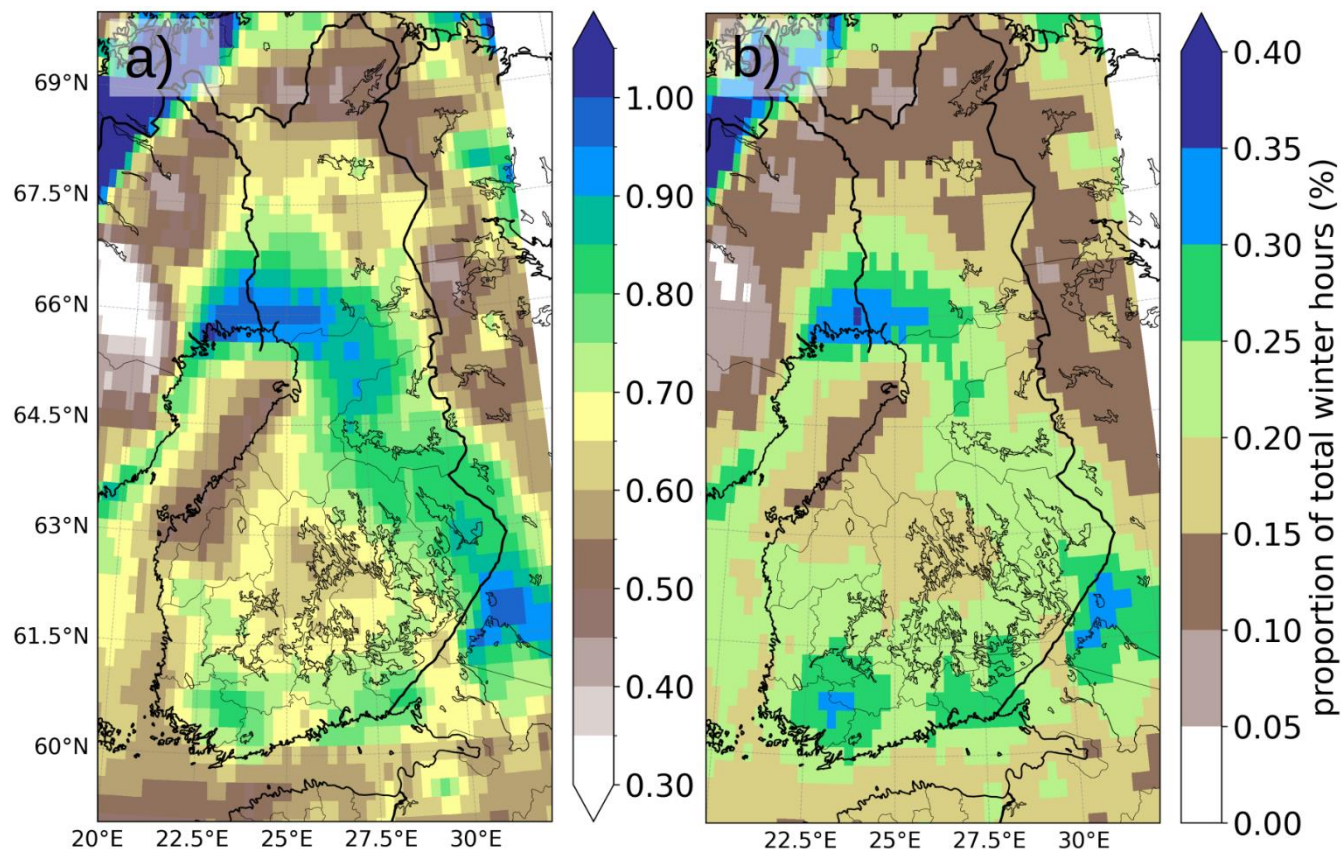


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Figure 2. The distributions of a,b) hourly wind gust and c,d) hourly snowfall in ERA5 (grey bars) and observations (purple bars) in a,c) Turku Artukainen and b,d) Tornio Torppi. Only time steps with snowfall are selected also for the wind gust. The vertical lines are percentiles: the dashed lines show the 95th percentiles and the solid line the 98th percentiles.

3.2 Co-occurrence of high wind gusts and heavy snowfall

195 High percentiles were used to detect extreme compound events for different regions. Although the extremeness of the events was defined for each grid point separately, the number of compound events varies largely spatially. Maps presenting the proportion of total winter hours with co-occurring extreme snowfall and wind gusts reveal that hot spots for these extreme SWG compound events differ depending on whether lower or higher percentiles are used as the threshold value (Figure 3).



200 **Figure 3. Proportion of total winter hours when co-occurring hourly snowfall and wind gust (SWG) exceeded their 95th (a) and 98th (b) percentiles from October to March in 1960-2024 based on ERA5. Note the different scaling in colorbars.**

When the 95th percentile was used as the threshold value for compound events, the largest number of hours were detected in a zone extending from the shores of the Bothnian Bay towards Lake Ladoga (Figure 3a). With 98th percentile as threshold, the largest number of compound events are located along south facing shores of the Baltic Sea and Lake Ladoga (Figure 3b).
 205 In contrast, the smallest amounts of compound events with both thresholds were detected in northern Finland and surrounding areas as well as in the northwest facing shore of the Bothnian Bay. The study locations, Tornio Torppi and Turku Artukainen (Figure 1), are situated within these regions of high event frequency (Figure 3).

The annual number of compound event days varied significantly from year to year in the study locations, ranging from zero to 12 days/year (Figure 4) with SWG98, and up to 19 days/year with SWG95 (Figure A1). There is no statistically
 210 significant increase or decrease in the annual SWG95 nor SWG98 days over time due to large year-to-year variations.

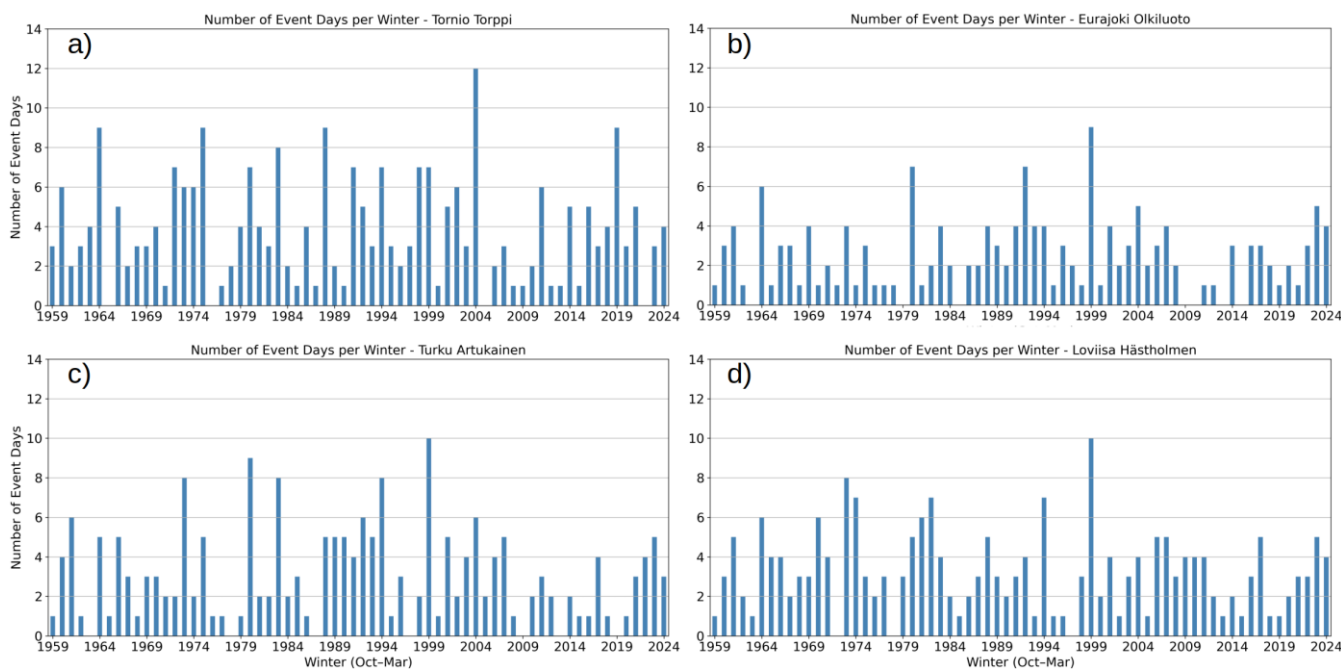


Figure 4. The annual number of days when wind gusts and snowfall exceeded their 98th percentile (SWG98) in Tornio Torppi (a), Eurajoki Olkiluoto (b), Turku Artukainen (c) and Loviisa Hästholmen (d) for each year from 1960 to 2024 based on ERA5 data. The annual number of events is calculated from October to March except for the first and last year of the data set when only January-March is calculated as year 1959 and October-December as year 2024 to cover the whole study period.

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When considering the SWG events (i.e. events with consecutive hours), one can see that the mean annual number of SWG events is similar between the four study locations, varying between 6-9 events for SWG95 and 2-4 for SWG98 (Table 2). The highest annual mean SWG95 event number was found in Tornio Torppi (9.1 events/year, Table 2). The slightly higher event number in Loviisa Hästholmen (8 events/year, Table 2) compared to Turku Artukainen (7.5 events/year) suggests that there is a larger number of shorter events in Loviisa Hästholmen, because the total amount of hours was larger in Turku Artukainen than in Loviisa Hästholmen (Figure 5).

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Table 2. The number of events of co-occurring wind gust and snowfall (SWG) exceeding their 95th and 98th percentiles in study areas in October-March 1960-2024, based on ERA5 data.

| Area | Tornio Torppi | | Eurajoki Olkiluoto | | Turku Artukainen | | Loviisa Hästholmen | |
|------------------------------------|---------------|------|--------------------|------|------------------|------|--------------------|------|
| | 95th | 98th | 95th | 98th | 95th | 98th | 95th | 98th |
| Mean annual number of events | 9.1 | 3.6 | 6.4 | 2.4 | 7.5 | 3.0 | 8.0 | 3.2 |
| Mean duration of event (h) | 4.5 | 3.9 | 4.0 | 3.4 | 4.0 | 3.7 | 4.2 | 3.4 |
| Mean annual number of long-lasting | 0.4 | 0.1 | 0.3 | 0.03 | 0.2 | 0.06 | 0.3 | 0.03 |

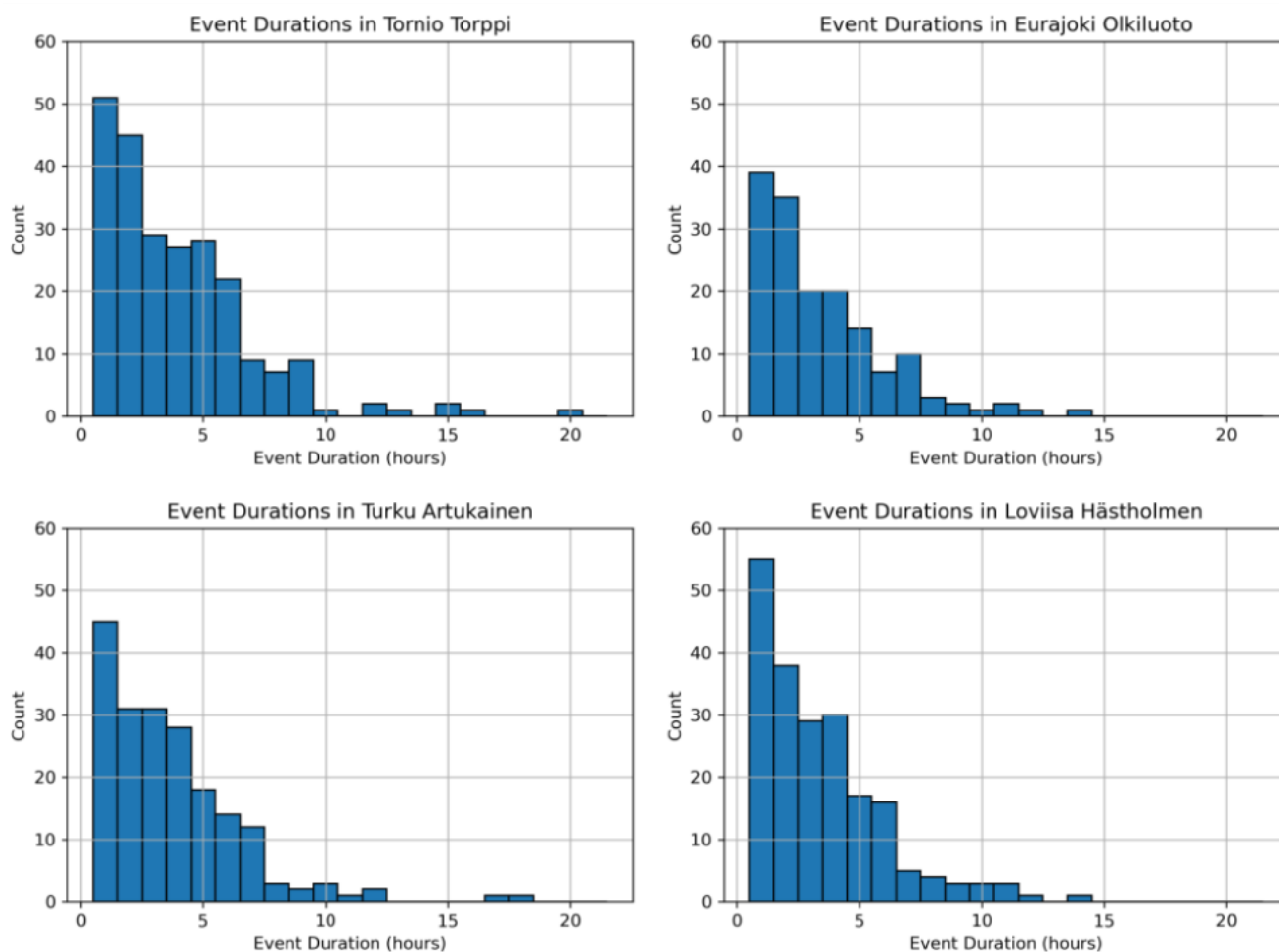


| | | | | | | | | |
|-------------------|----|----|----|----|----|----|----|----|
| (≥12 h) events | | | | | | | | |
| Longest event (h) | 35 | 20 | 21 | 14 | 20 | 18 | 33 | 14 |

3.3 Duration of SWG events

230 The duration of compound events is an important quantity because the longer the extreme conditions persist, the greater the potential risk for infrastructures is. Thus, consecutive hours of wind gusts and snowfall were investigated. In this section, only the four study locations are elaborated.

235 The duration of compound events varied from 1 up to 35 hours (Table 2, Figure 5). Compound events were mainly short-lived as the mean duration varied between 3.4 and 4.5 hours (Table 2). The selection of the threshold, either the 95th or 98th percentile, did not have a large effect on the mean duration as with SWG95 the event duration varied between 4.0-4.5 h and with SWG98 between 3.4-3.9 h. Regardless of the selected threshold value, short-lived (< 5 h) compound events dominated, 1-hour events being the most common (Figure 5, Figure B2).



240 **Figure 5. Histograms of compound event’s durations in Tornio, Torppi (a), Eurajoki Olkiluoto (b), Turku Artukainen (c) and Loviisa Hästholmen (d) for the threshold value of 98th percentile. Histograms show the number of consecutive hours when snowfall and wind gust exceeded their threshold value simultaneously during October-March 1960-2024 based on ERA5.**

The most prominent differences between SWG95 and SWG98 durations were observed among the longest-lasting events, with SWG95 events lasting considerably longer than SWG98 events. (Table 2, Figure 5, Figure B2). Because the longer lasting compound events are of more interest for end users, such as NPP companies, the duration of over 12 hours was selected as a threshold for a long-lasting (LL) event. These LL events were not detected annually or even every second year.

245 The annual mean number of the LL SWG95 events in 1960-2024 was 0.4 in Tornio Torppi, 0.3 in Eurajoki Olkiluoto and Loviisa Hästholmen and 0.2 in Turku Artukainen. When the 98th percentile was used as a threshold, the annual mean number of LL compound events were distinctly smaller, accounting for only 0.1 events in Tornio Torppi, 0.06 in Turku Artukainen and 0.03 in Eurajoki Olkiluoto and Loviisa Hästholmen. No statistically significant long-term change in event duration was found.



250 The maximum duration of SWG95 events in the study locations varied between 20 h in Turku Artukainen to 35 h in Tornio Torppi (Table 2). The extremely long SGW95 event in Tornio Torppi (35 h) was one single peak event, whereas Loviisa Hästholmen has faced two over 30 h long SWG95 events (33 h and 31 h, Figure B2, Table C3). When the 98th percentile was used as a threshold value, the maximum event duration varied between 14 h in Eurajoki Olkiluoto and Loviisa Hästholmen to 20 h in Tornio Torppi (Table 2 and 3).

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Table 3. The five longest lasting SWS compound events in each study location when the 98th percentile were used as a threshold value for hourly snowfall and wind gust from October to Marh in 1960-2024 based on ERA5. In addition, statistics for mean and maximum snowfall and wind gust values are given for each event.

| Date | Max duration (h) | Mean snowfall (mm h ⁻¹) | Max snowfall (mm h ⁻¹) | Accumulated snowfall (mm per event) | Mean wind gust (m s ⁻¹) | Maximum wind gust (m s ⁻¹) |
|--------------------|------------------|-------------------------------------|------------------------------------|-------------------------------------|-------------------------------------|--|
| Tornio Torppi | | | | | | |
| 18.12.1966 | 20 | 1.3 | 1.9 | 25.9 | 19.4 | 21.0 |
| 24.10.2014 | 16 | 1.3 | 1.8 | 20.3 | 18.0 | 19.0 |
| 28.11.1984 | 15 | 0.9 | 1.2 | 14.0 | 20.0 | 21.7 |
| 10.11.1998 | 15 | 1.0 | 1.1 | 15.1 | 17.1 | 18.2 |
| 01.01.1960 | 13 | 1.2 | 1.4 | 15.2 | 18.0 | 19.0 |
| Eurajoki Olkiluoto | | | | | | |
| 21.11.1971 | 14 | 1.6 | 2.1 | 22.5 | 21.5 | 23.8 |
| 31.10.2006 | 12 | 1.5 | 2.6 | 17.6 | 22.0 | 23.8 |
| 18.12.1966 | 11 | 1.9 | 2.8 | 21.4 | 24.0 | 26.1 |
| 06.12.1999 | 11 | 1.0 | 1.4 | 11.4 | 21.5 | 23.0 |
| 15.12.1982 | 10 | 1.1 | 1.5 | 11.5 | 22.1 | 23.9 |
| Turku Artukainen | | | | | | |
| 15.01.1974 | 18 | 1.5 | 2.7 | 26.6 | 18.3 | 19.2 |
| 12.01.2021 | 17 | 1.2 | 1.4 | 20.4 | 18.5 | 19.9 |
| 22.01.1962 | 12 | 1.2 | 1.4 | 13.9 | 18.2 | 19.2 |
| 15.01.1981 | 12 | 1.0 | 1.1 | 11.7 | 18.9 | 19.6 |
| 18.12.1966 | 11 | 2.0 | 3.0 | 22.4 | 23.0 | 24.6 |
| Loviisa Hästholmen | | | | | | |
| 20.12.1970 | 14 | 1.5 | 2.2 | 21.4 | 20.4 | 21.1 |
| 15.01.1974 | 12 | 1.2 | 1.7 | 13.9 | 20.5 | 22.0 |



| | | | | | | |
|------------|----|-----|-----|------|-------------|-------------|
| 05.12.1967 | 11 | 1.2 | 1.9 | 13.5 | 21.8 | 22.5 |
| 26.10.1980 | 11 | 1.2 | 1.8 | 13.7 | 20.1 | 21.9 |
| 30.11.2012 | 11 | 1.1 | 1.2 | 11.6 | 26.2 | 28.0 |

260 All the longest lasting events presented in Table 3 fulfill the blizzard definition (wind gust $> 17 \text{ m s}^{-1}$, accumulated snowfall $> 10 \text{ mm}$ per event). One of the most extreme event occurred simultaneously in Tornio Torppi, Eurajoki Olkiluoto and Turku Artukainen on 18th of December 1966 (Table 3). This SWG98 event lasted even 20 hours with mean hourly snowfall rate of 2 mm h^{-1} and the maximum snowfall rate of 3 mm h^{-1} with wind gust reaching 26 m s^{-1} . The snowfall accumulation was almost 26 mm during the event in the study locations.

265 3.4 Intensity of SWG events

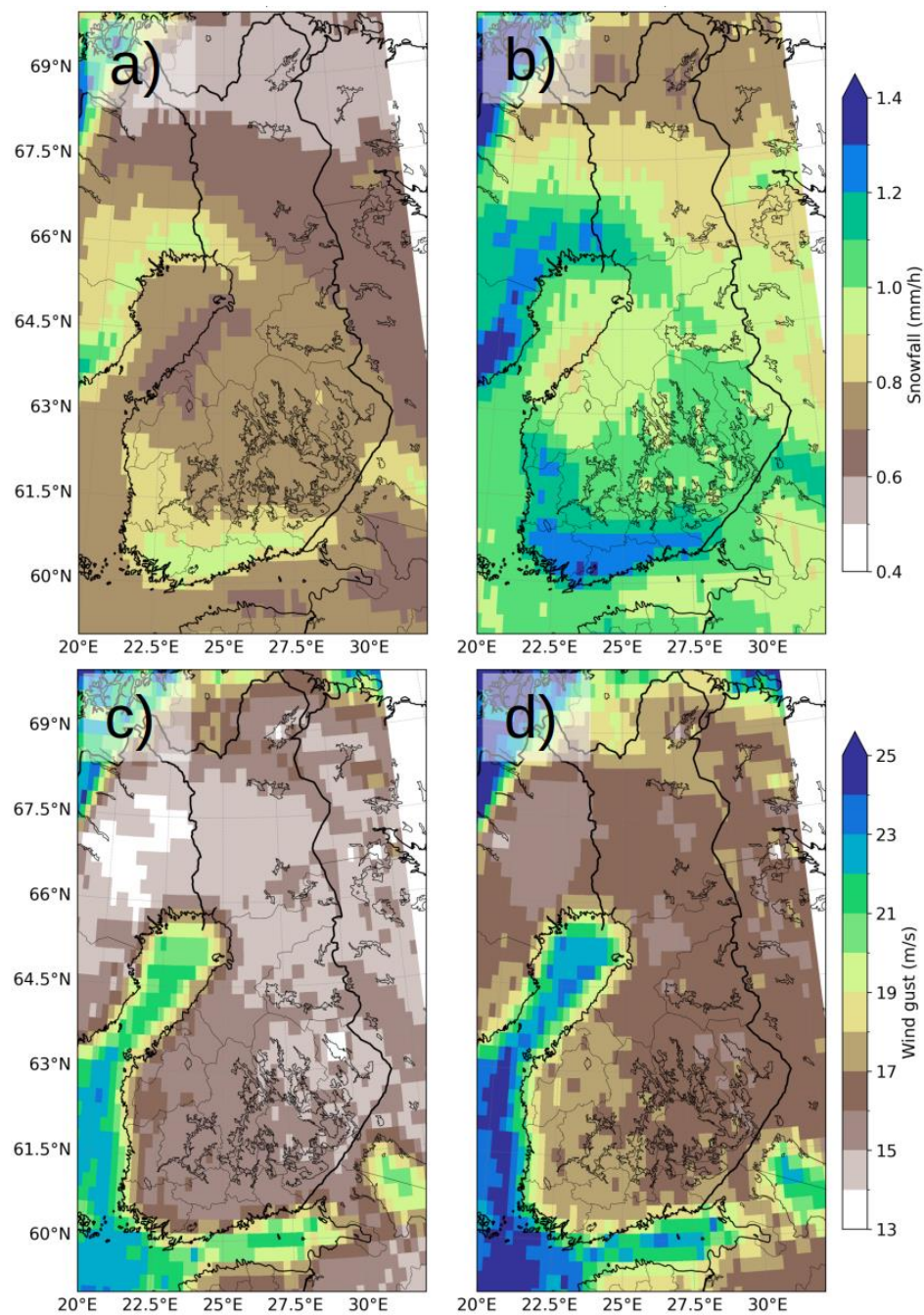
Mean values for hourly snowfall and wind gust during the detected SWG95 and SWG98 compound events in 1960-2024 are presented in Fig. 6. On average, the hourly mean snowfall as well as wind gusts are higher with SWG98 events than with SWG95 events. On average, the highest wind gust values during compound events occur over the Bothnian Sea (Figure 6 c and d), while the largest snowfall values are concentrated over the southern coast of Finland (and east coast of Sweden, Figure 6 a and b). This indicates that the western coast of Finland could be more affected by impacts caused by strong wind gusts and the southern coast by heavy snowfall during the SWG compound events.

270 In the south facing coastal areas the mean hourly snowfall is $0.8\text{-}1.0 \text{ mm h}^{-1}$ with SGW95 and $1.1\text{-}1.3 \text{ mm h}^{-1}$ with SWG98. Over the Bothnian Sea, the mean wind gusts are $20\text{-}24 \text{ m s}^{-1}$ with SWG95 and $21\text{-}26 \text{ m s}^{-1}$ with SWG98. The difference between SWG95 and SWG98 originates from the threshold values which are approximately 0.2 mm h^{-1} higher regarding the snowfall and 2 m s^{-1} higher regarding the wind gusts when using the 98th percentile as threshold compared to 95th percentile (Table 1). What is notable is that even with SWG95 the mean snowfall amount is larger in south facing coastal areas than in the region from Bothnian Bay to Lake Ladoga (Figure 6a) where most of the events were found (Figure 3a). Thus, the hourly snowfall related to compound events is typically larger in coastal regions than inland. In addition, the mean values are higher during the SWG events (Figure 6) compared to the mean values during single extreme events (only snowfall or wind gust exceeding their percentile thresholds, Figure D4).

280 The annual mean and maximum hourly snowfall amounts during compound event days (SWG95 and SWG98) exhibited substantial interannual variability across the study sites. Analysis of hourly maximum snowfall intensities (mm h^{-1}) during these compound events showed no statistically significant long-term trends in the annual maxima at any of the four locations. When examining the number of all snowfall events (regardless of wind gust value), statistically significant ($p < 0.05$) decrease in events with at least 10 mm of accumulated snowfall was found across most coastal areas (0.1-0.4 events per decade, not shown), while northwestern Lapland showed an increase (0.2-0.4 events per decade, not shown). However, the number of SWG95 and SWG98 events that produced at least 10 mm of snowfall showed no change. This indicates that



although substantial snowfall events have become less frequent in southwestern Finland, the frequency of snowstorms accumulating substantial snowfall has not shown corresponding decline.



290

Figure 6. Average hourly snowfall (a and b) and wind gust (c and d) during SWG events when the 95th (a and c) and 98th (b and d) percentile was used as a threshold value from October to March in 1960-2024 based on ERA5.



Table 4 summarizes the number of extreme events with different thresholds elaborated in the Section 2.4, in the four study locations for the SWG95 and SWG98 compound events. Due to the low hourly snowfall values corresponding to the high percentiles (Table 1), only 30-48 % of all SWG95 compound events exceed the hourly threshold of 1 mm h⁻¹ for moderate snowfall (Table 4). With SWG98 events, the hourly maximum snowfall exceeds 1 mm h⁻¹ during slightly over half of the events (51-68 %, Table 4). In addition, because of the smaller hourly snowfall threshold, the SWG95 events accumulate more often less than 5 mm per event snow (73-80 % of events, not shown) than SWG98 events (64-76 % of events, not shown).

300

Table 4. The number of SWG compound events with the 95th (and the 98th in parentheses) threshold(s) in four study locations; Tornio, Eurajoki, Turku and Loviisa, during October-March in 1960-2024 based on ERA5. The table includes percentage of compound events with maximum hourly snowfall exceeding 1 mm h⁻¹ (1st row), total number of compound events exceeding snowfall of 2.5 mm h⁻¹ (2nd row) as well as 20 mm per event (3rd row), total number of compound events with maximum wind gusts exceeding 20 m s⁻¹ (4th row) and 25 m s⁻¹ (5th row), total number of SWG events exceeding maximum wind gust ≥ 20 m s⁻¹ and maximum snowfall 2,5 mm h⁻¹ (6th row), the total number of compound events with blizzard conditions (maximum wind gust ≥ 17 m s⁻¹, snow accumulation ≥ 10 mm per event, 7th row) as well as with stricter conditions (maximum wind gust ≥ 20 m s⁻¹, snow accumulation ≥ 20 mm per event, 8th row) are presented.

305

| Location | Tornio Torppi | Eurajoki Olkiluoto | Turku Artukainen | Loviisa Hästholmen |
|---|------------------|-----------------------|---------------------|-----------------------|
| Percentage (%) of SWG events with max snowfall ≥ 1 mm h ⁻¹ | 38 (60) | 30 (53) | 43 (68) | 30 (51) |
| Number of SWG events with max snowfall ≥ 2.5 mm h ⁻¹ | 7 (2) | 9 (7) | 17 (14) | 4 (4) |
| Number of SWG events with snowfall accumulation ≥ 20 mm per event | 4 (2) | 4 (2) | 3 (3) | 2 (1) |
| Number of SWG events max wind gust ≥ 20 m s ⁻¹ | 51 (44) | 129 (95) | 57 (47) | 119 (84) |
| Number of SWG events with max wind gust ≥ 25 m s ⁻¹ | 2 (0) | 12 (10) | 4 (4) | 12 (10) |
| Number of SWG events with max wind gust ≥ 20 m s ⁻¹ and max snowfall ≥ 2.5 mm h ⁻¹ | 1 (1) | 7 (7) | 10 (10) | 4 (4) |
| Number of SWG events with blizzard conditions (max wind gust ≥ 17 m s ⁻¹ and accumulated snowfall ≥ 10 mm per event) | 37 (18) | 21 (11) | 32 (20) | 25 (11) |
| Number of SWG events with extreme blizzard conditions (max wind gust ≥ 20 m s ⁻¹ and accumulated snowfall ≥ 20 mm per event) | 1 (1) | 4 (2) | 1 (1) | 2 (1) |

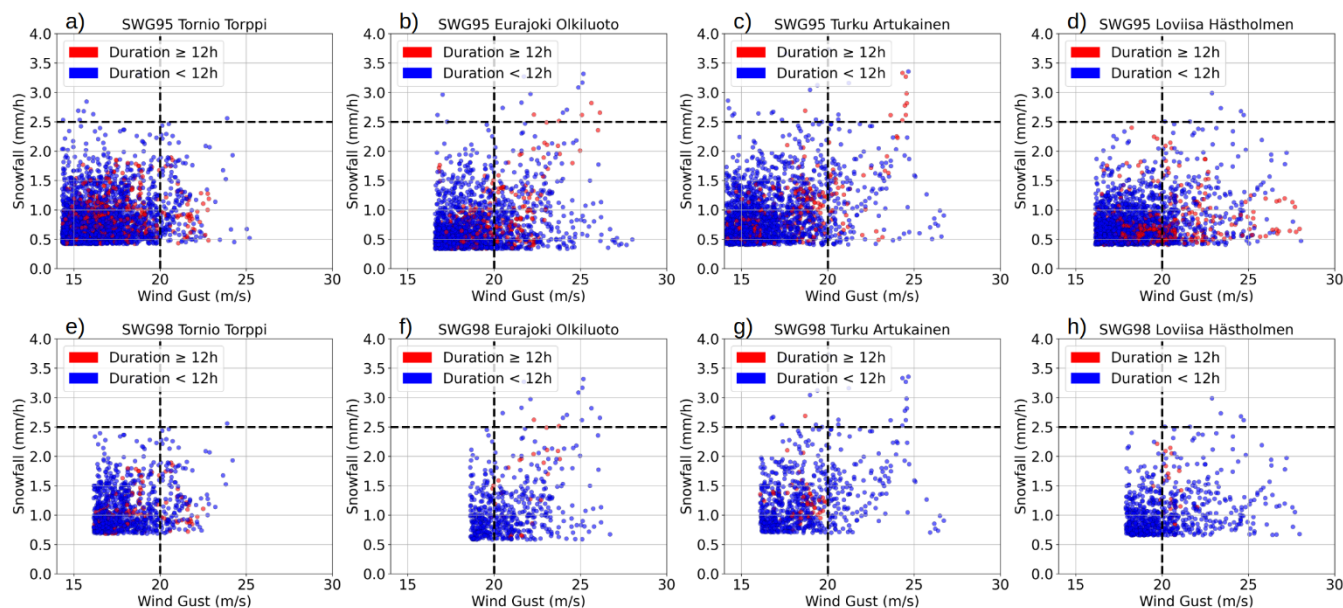


310 The severity of a compound event was first investigated based on the maximum hourly snowfall amount and accumulated
snowfall during the compound events. SWG events influenced by heavy snowfall rates of over 2.5 mm h^{-1} were rare; 4-17
SWG95 events and 2-14 SWG98 events were detected in the study locations in 1960-2024 (Table 4). The largest number of
events with heavy snowfall rate was found in Turku Artukainen. SWG events with large snowfall accumulation ($> 20 \text{ mm}$
per event) during the event were even more rare in all four study locations (Table 4). When considering SWG95 (SWG98), it
315 was found that accumulated snowfall exceeded 20 mm per event only in 4 (2) events in Tornio Torppi and Eurajoki
Olkiluoto and 3 (3) in Turku Artukainen and 2 (1) in Loviisa Hästholmen during 1960-2024 (Table 4).

On average, the SWG events with heavy snowfall rate ($> 2.5 \text{ mm h}^{-1}$) lasted slightly longer than the mean duration of all
events. The duration of these extreme events varied from 5 h in Tornio Torppi, 7h in Turku Artukainen and Loviisa
Hästholmen, to 8 h in Eurajoki Olkiluoto (not shown). No notable differences in event duration were found between SWG95
320 and SWG98. On average, these high-snowfall-rate events produced 9-14 mm of snowfall. The duration of these extreme
events was long enough to accumulate more than 20 mm of snowfall only at Eurajoki Olkiluoto (during 3 SWG events) and
at Turku Artukainen (during 2 SWG events).

SWG95 (SWG98) events experiencing maximum wind gusts of over 20 m s^{-1} were relatively common compared to extreme
snowfall amounts; 51-129 (44-95) events exceeding 20 m s^{-1} at the study locations. SWG95 (SWG98) events facing over 25
325 m s^{-1} wind gust were again only few; 2-12 (0-10) events. The largest numbers of SWG events with extreme wind gusts were
found in Eurajoki Olkiluoto and Loviisa Hästholmen (Table 4, Figure 7).

For short duration but extreme compound events were used the following fixed thresholds: maximum wind gust during an
event needs to exceed 20 m s^{-1} and maximum hourly snowfall rate to exceed 2.5 mm h^{-1} . With these fixed thresholds, 1-10
extreme SWG events were detected with most events in Turku Artukainen and least in Tornio Torppi. Those events can be
330 seen in Fig. 7 in addition to all SWG events. In Figure 7, lines for wind gust of 20 m s^{-1} and snowfall of 2.5 mm h^{-1} are
added to showcase the most extreme event hours. In addition, all SWG events for which duration exceeded 12 hours are
highlighted in red. Due to lower thresholds, more events exceeding 12-hour duration can be found with SWG95 events than
SWG98. Only in Eurajoki Olkiluoto and Turku Artukainen the most extreme events with maximum snowfall $> 2.5 \text{ mm h}^{-1}$
and wind gust $> 20 \text{ m s}^{-1}$ exceeded 12 h duration.



335

Figure 7. Hourly values of SWG compound events involving snowfall (vertical axis) and wind gust (horizontal axis) when the 95th (a,b,c,d) and 98th (e,f,g,h) percentiles for snowfall and wind gusts were used as threshold values in Tornio Torppi (a,e), Eurajoki Olkiluoto (b,f), Turku Artukainen (c,g) and Loviisa Hästholmen (d,h) in 1960-2024 based on ERA5. Hourly values related to SWG compound events that lasted over 12 h are highlighted with red dots. Black dashed lines are added to showcase snowfall exceeding 2.5 mm h^{-1} and wind gust exceeding 20 m s^{-1} .

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Blizzard conditions with maximum wind gust exceeding 17 m s^{-1} and snowfall accumulation exceeding 10 mm per event were detected from all four study locations. Blizzard conditions were fulfilled during 21-37 SWG95 events and 11-20 SWG98 events with most occurrences in Tornio Torppi and Turku Artukainen (Table 4). When considering a stricter threshold for blizzard conditions with maximum wind gust exceeding 20 m s^{-1} and snowfall accumulation exceeding 20 mm per event only a handful of events were detected from the study locations. With the 95th (98th) percentile, four SWG events were found in Eurajoki Olkiluoto (2), two in Loviisa Hästholmen (1), and one in Tornio Torppi (1) and Turku Artukainen (1). All these extreme events exceeded 11 h duration and can be regarded extremely hazardous based on the heavy hourly snowfall, accumulated snow amount and/or strong wind gusts.

345

Across the 65-year period and four study locations, the highest hourly snowfall rate (3.7 mm h^{-1}) as well as the largest snowfall accumulation (28.5 mm per event) during the SWG95 and SWG98 events occurred in Turku Artukainen. Somewhat surprisingly—given the patterns shown in Fig. 6—the strongest wind gust occurred in Loviisa Hästholmen with 29 m s^{-1} and 28 m s^{-1} during SGW95 and SWG98, respectively. Notably, the 28 m s^{-1} wind gust coincided with one of the longest SGW95 events (31 h) in Loviisa Hästholmen (Table C3). Although the snowfall intensities remained moderate ($< 1.2 \text{ mm h}^{-1}$) throughout this event, its long duration allowed nearly 23 mm of snowfall to accumulate.

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355

In general, the largest snowfall accumulations during SWG95 and SWG98 occurred during the longest SWG98 events, but not consistently during the longest SWG95 events. A comparison between, for example, Table 3 and Table C3 illustrates that SWG95 event duration does not necessarily determine the total snowfall accumulation.



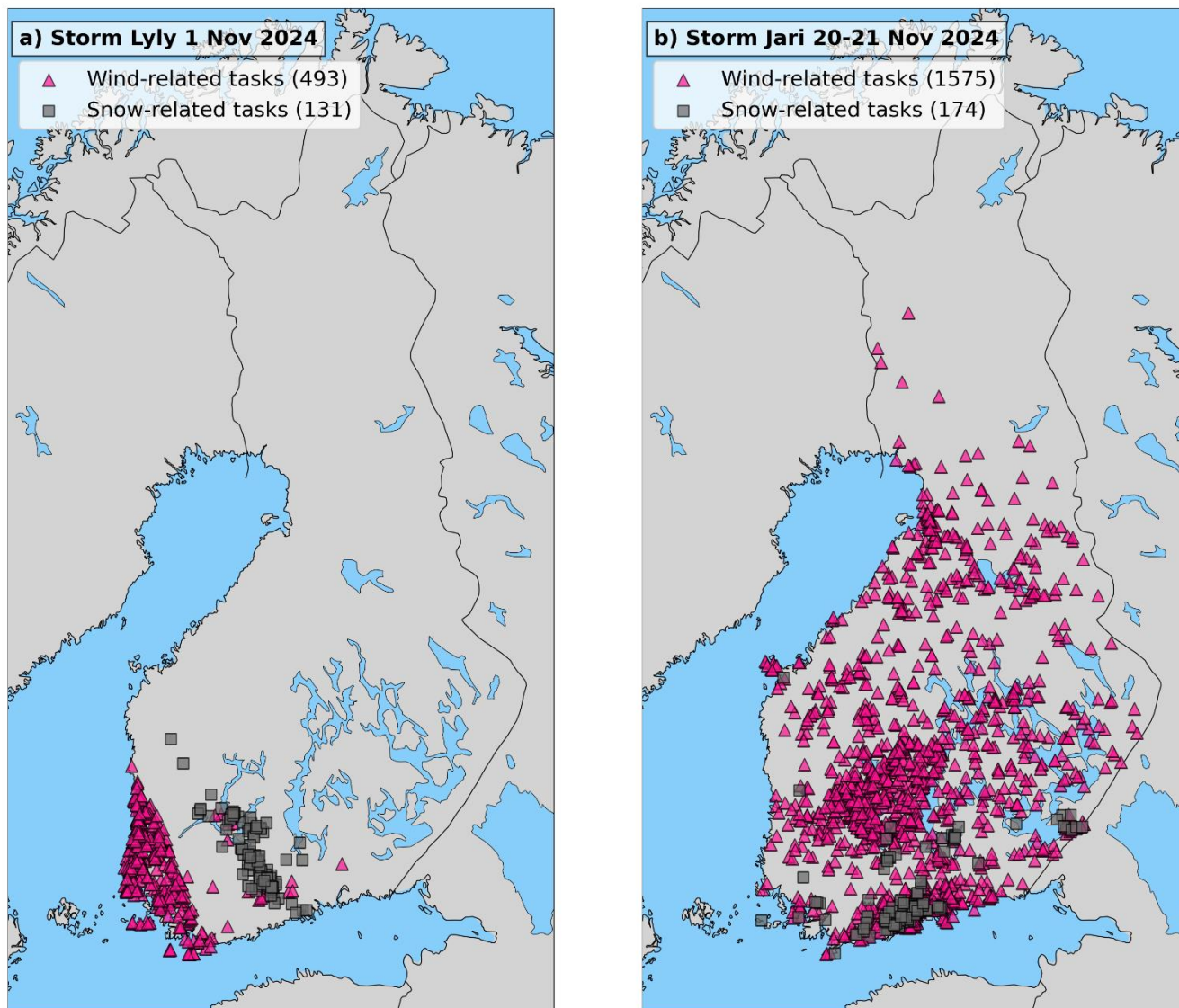
3.5 Case studies

In November 2024, Finland experienced two extratropical cyclones, Lyly and Jari, which together represented some of the most severe weather events recorded in the country in recent decades. These storms occurred within a three-week interval and caused extensive meteorological and socio-economic impacts across large parts of Finland.

The first event, known as the Lyly storm, developed over the North Atlantic and reached Finland on 1 November 2024. As the system moved across the western and southern parts of the country, it produced unprecedented wind speeds. At the Kylmäpihlaja lighthouse near Eurajoki Olkiluoto, the Finnish Meteorological Institute recorded a ten-minute mean wind speed of 33.5 m s^{-1} , marking the first time that officially hurricane-force winds had been observed in Finnish marine areas (Laurila et al., 2025b). Highest wind gust over coastline was 39.6 m s^{-1} and inland gusts reached up to 26 m s^{-1} , particularly in the Satakunta region. Snow depth increased 10-20 cm. The combination of strong winds and early-season snow led to widespread damage to trees and power lines. Approximately 67 000 customers were left without electricity, and emergency services reported hundreds of storm-related incidents (Figure 8a).

The second system, the Jari storm, affected Finland between 20 and 21 November 2024. Although its peak mean wind speeds and gusts were lower than Lyly's, Jari was characterized by a complex combination of hazards, including strong winds, heavy snowfall, and significant fluctuations in sea level. The highest recorded mean wind, 28.2 m s^{-1} , and gusts up to 34.2 m s^{-1} , were measured at Ulkokalla off the west coast of Finland in the Bothnian Bay (Lehtonen, 2024). In addition, relatively warm and ice-free sea enabled the formation of persistent snowbands over the open water. These snowbands repeatedly moved toward the southern and western coast bringing locally intense, long-lasting showers. As a result, snow depth increased 10-20 cm but in some areas even up to 28 cm. The storm caused widespread power outages—exceeding 70 000 households at the peak—and disrupted road and rail transport due to snow accumulation and fallen trees (Figure 8b). Along the coast of the Bothnian Bay, wind-driven surges and withdrawals of water produced rapid sea-level changes; in Kemi (near Tornio), for instance, the water level dropped by approximately 1.6 m below the seasonal average.

Lyly was exceptional for its record-breaking wind speeds, while Jari exemplified a compound event in which wind, snow, and hydrological extremes occurred simultaneously. Figure 9 illustrates the temporal and spatial extent of extreme wind gusts and snowfall exceeding their 98th percentile, and their co-occurrence during the two storms. During Lyly, periods of high wind speeds did not coincide with heavy snowfall (Figure 9a–b) and therefore it was not classified as an extreme compound event (Figure 9c). In contrast, during Jari, extensive areas over both land and sea experienced simultaneous wind gusts and snowfall exceeding the 98th percentile (Figure 9d–e). Consequently, large regions were subjected to compound extreme weather conditions (Figure 9f) although maximum wind speed and gust values were lower than during Lyly. Jari storm was noted also as one of the longest lasting SWG95 event in Eurajoki Olkiluoto (18 h, Table C3).



390 **Figure 8. Emergency response tasks during storms Lyly (a) and Jari (b). Wind related tasks are marked with pink triangles and snow related tasks with grey squares.**

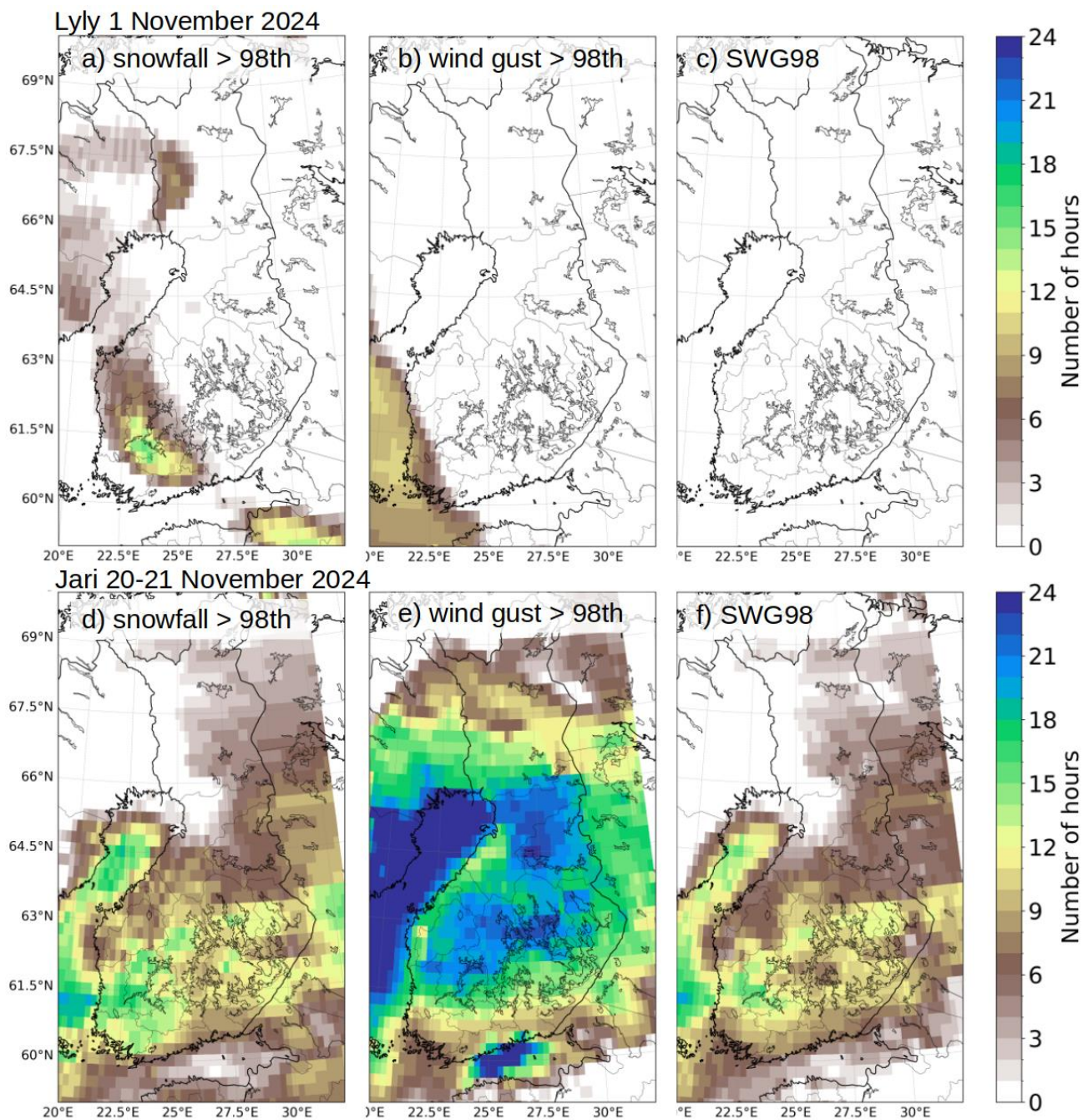


Figure 9. Number of consecutive hours when snowfall (a, d) and wind gust (b, e) 98th percentile thresholds were exceeded, and their co-occurrence (c, f) during storms Lyly (a, b, c) and Jari (d, e, f) based on ERA5.



395 4 Discussion

A key challenge in identifying extreme events involving snowfall and wind gusts lies in the choice of threshold values. While the 95th and 98th percentiles provide a useful framework for identifying extremes, the impact of an event is not only a function of its frequency but also its duration and intensity. This is particularly important for snowfall, where long-lasting events identified using a lower percentile threshold (e.g. the 95th percentile) may lead to substantial snow accumulation, even if hourly snowfall rates are moderate. In contrast, events detected using a higher threshold (e.g. the 98th percentile) are typically more intense but shorter in duration and may result in less total accumulation. Therefore, absolute accumulation metrics were tested alongside percentile-based thresholds to compare the wind gust and snowfall values during the most extreme events (Table 4).

Using 95th percentile as a threshold increases the amounts of less intense events when compared to the use of 98th percentile. But it also increases the number of blizzard events in comparison to 98th percentile. This is due to the mismatch between heavy snowfall and high wind gust occurrences. By using the looser threshold of 95th percentile the compound events included also events where the snowfall was intense, but wind gusts were not as high and vice versa. This can be seen in the statistics of the events. All the SWG98 events are included in the SWG95 events but not all intense events in SWG95 are included in SWG98 events due to too weak wind gust or snowfall value (Figure 7).

The relevance of short-duration extremes should also be emphasized. One to a few hours of coincident high snowfall rates and strong wind gusts may not disrupt industrial operations or power generation but can still trigger severe traffic accidents, hinder emergency services, and overwhelm snow removal capacity. Thus, even relatively short-lived compound extremes can have significant societal consequences.

A few highly extreme events were identified in our analysis. Eurajoki Olkiluoto has experienced a larger number of extreme events than the other three locations. For example, the longest lasting SWG98 event in Eurajoki Olkiluoto produced the second-largest daily snow accumulation ever recorded in Finland (50 cm day⁻¹ on 21 November 1971, Table 3). This event has previously been attributed to sea-effect snowfall (Olsson et al., 2023), with moisture uptake from the ice-free sea enhancing precipitation over the coastal zone. Another example is the December 1966 snowstorm, which simultaneously affected Tornio Torppi, Eurajoki Olkiluoto, and Turku Artukainen. During this event, thresholds corresponding to the 98th percentile were exceeded continuously for at least 11 hours, the total snowfall accumulation exceeded 20 mm, and maximum wind gusts surpassed 20 m s⁻¹ at all three sites (and even 25 m s⁻¹ in Eurajoki Olkiluoto). This combination makes it one of the most extreme compound snowfall–wind events in the current record.

Recent storms in Finland further highlight the importance of compound-event analysis. For example, storm Jari qualified as an extreme compound event under our framework, while storm Lyly—occurring only two weeks earlier—did not (see Section 3.5). Although Lyly produced very high wind speeds and widespread warnings for heavy snowfall, the maxima of these two hazards did not coincide spatially or temporally. As a result, it did not meet the compound-event definition, despite



causing significant impacts across south-western Finland. This distinction demonstrates the value of compound-event methods, which help differentiate between co-occurring hazards and sequential but spatially separated ones.

Care should be taken when comparing ERA5 variables with observations, because observations are local to a particular point
430 in space and time, rather than representing averages over a model grid box and model time step (Hersbach et al., 2020).
Furthermore, observational practices (e.g., precipitation recorded at 0.1 mm resolution) differ from the continuous output of
reanalysis, where values $<0.1 \text{ mm h}^{-1}$ are retained. Such differences are also evident in histogram comparisons of snowfall
frequency distributions (Figure 2). Nevertheless, winter precipitation is commonly produced by extratropical cyclones, and
ERA5 resolves these large-scale atmospheric processes better than convective processes (Lavers et al., 2022). The smallest
435 differences between ERA5 and observed precipitation have been found to occur during winter in the Extratropics including
many stations in northern Europe (Lavers et al., 2022). Because of the ERA5 tendency to underestimate the snowfall and
wind gust values (Laurila et al., 2025a), percentile-based methods are more robust for extreme-event analysis in ERA5 than
fixed absolute thresholds.

Finally, the geographical location of observation stations strongly influences both snowfall and wind gust values. As shown
440 in Figure 6, large differences arise over short spatial scales, particularly in coastal regions where exposure to open sea versus
inland modifies event intensity.

5 Conclusions

This study addressed the frequency, duration and intensity of co-occurring high wind gust and intense snowfall events
impacting Finnish coastal areas with special focus on four study locations Tornio Torppi, Eurajoki Olkiluoto, Turku
445 Artukainen and Loviisa Hästholmen, with data spanning 1960–2024 from ERA5 reanalysis. High wind gusts and intense
snowfall were assessed using the 95th and 98th percentile thresholds for snowfall and wind gusts. The higher percentile
threshold shifted the focus of the spatial distribution of compound events from inland to coastal regions. Expectedly, the
number of events were smaller but the mean hourly snowfall and wind gust higher with the 98th percentile than the 95th
percentile.

450

Key findings:

1. Frequency and location: The highest number of hours exceeding the 95th percentile was found in southwestern
Lapland on the shore of the Bothnian Bay. With the stricter threshold of 98th percentile, also southwestern Finland
has a pronounced proportion of extreme event hours. Tornio Torppi experienced slightly more compound events
455 than the other study locations.
2. Duration: Most compound events were brief, lasting less than five hours. Long-duration events exceeding 12 hours
were rare, with only 16–28 events found over the 65-year period at the 95th percentile threshold, and 4–7 events at
the 98th percentile in the four study locations.



3. Intensity: Most of the events were moderate with hourly snowfall less than 1 mm h^{-1} and accumulation less than 5
460 mm per event. All four study locations faced compound events with heavy hourly snowfall ($> 2.5 \text{ mm h}^{-1}$), large
snow accumulation ($> 20 \text{ mm}$ per event) or high wind gusts ($> 20 \text{ m s}^{-1}$), but those events where all these three
components were exceeded simultaneously during one compound event were detected only from Eurajoki Olkiluoto
(3 events) and Turku Artukainen (1 event).

465 This study emphasizes the importance of understanding simultaneous extreme weather events for assessing the operational
safety and emergency preparedness of critical infrastructures and society. While most observed events were short-lived and
not particularly severe, a small number of prolonged and intense compound events were identified that could pose significant
risks to critical infrastructure.

Tornio Torppi experienced the largest number of simultaneous wind gust–snowfall events, including the longest-lasting
470 event and most frequent blizzard events ($\geq 17 \text{ m s}^{-1}$ wind gusts and $\sim 10 \text{ mm}$ snowfall per event). However, the most extreme
compound events—characterized by simultaneous long duration, heavy hourly snowfall ($> 2.5 \text{ mm h}^{-1}$), high total snow
accumulation ($> 20 \text{ mm}$ per event), and strong wind gusts ($> 20 \text{ m s}^{-1}$)—were found in Eurajoki Olkiluoto.

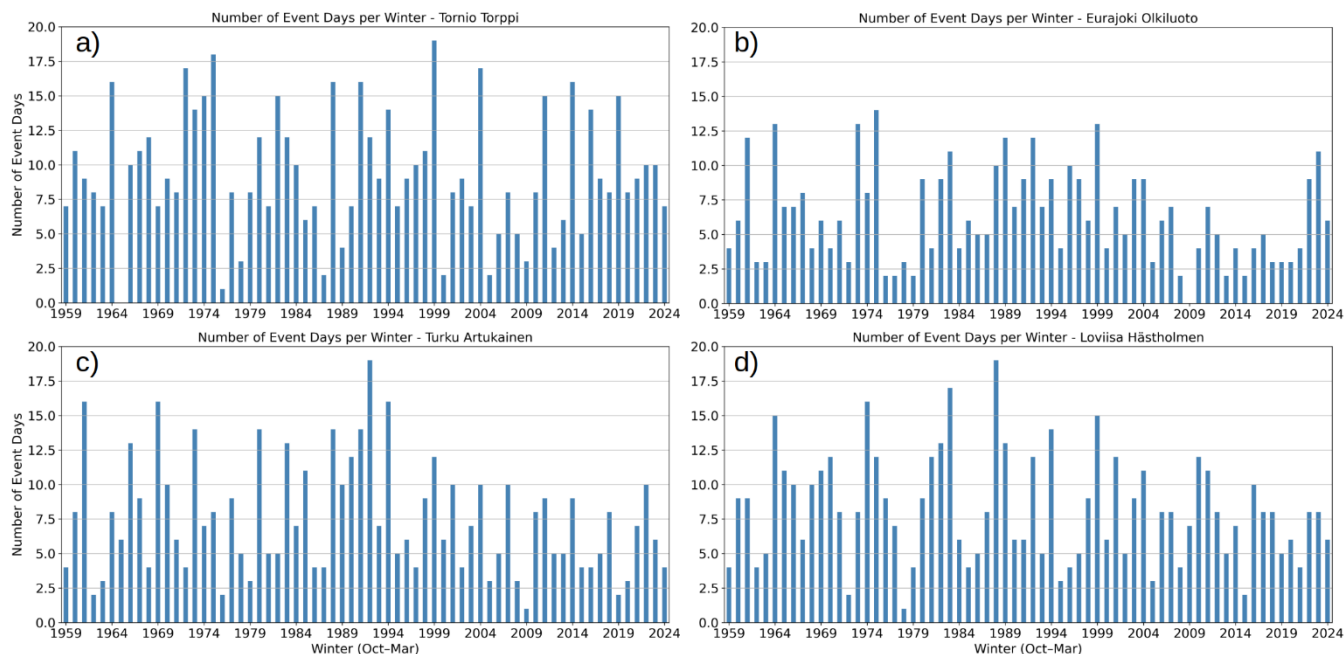
Because the primary focus of this study was on hazards to industry, particular attention was given to long-lasting events with
both high wind gusts and substantial snowfall. While blizzard events with $\sim 10 \text{ mm}$ snowfall per event can disrupt urban life
475 and city services, they are generally less critical for industrial operations. In contrast, a few extremely strong compound
events were identified where hourly snowfall exceeded 2.5 mm h^{-1} , wind gusts surpassed 20 m s^{-1} (and in some cases 25 m s^{-1}), and total snowfall accumulation exceeded 20 mm . Such conditions not only cause poor visibility and hazardous traffic
but also lead to drifting snow accumulation far greater than snowfall amounts alone would suggest. For nuclear power plants,
in particular, these conditions could block ventilation intakes and overwhelm snow removal operations during prolonged
480 events.

No statistically significant long-term changes were detected in the duration, intensity, or frequency of high–wind-gust and
heavy–snowfall compound events over the 65-year study period. However, the observed decrease in heavy snowfall events
($> 10 \text{ mm}$ per event), contrasted with the absence of change in heavy compound snowfall–wind gust events, suggests that
although substantial snowfall amounts may be declining, the occurrence of significant snowstorms has remained stable.

485 Overall, this study demonstrates the importance of examining wind–snowfall combinations as distinct meteorological
situations rather than treating them as isolated hazards. By characterizing how often such compound events occur and how
intense they can be, the analysis provides a more realistic basis for understanding the conditions that may challenge power
transmission lines, transportation systems, or areas susceptible to falling trees. Although these combined events are relatively
rare, their potential to create unfavourable circumstances highlights the value of incorporating compound-event perspectives
490 into risk assessments and preparedness planning.

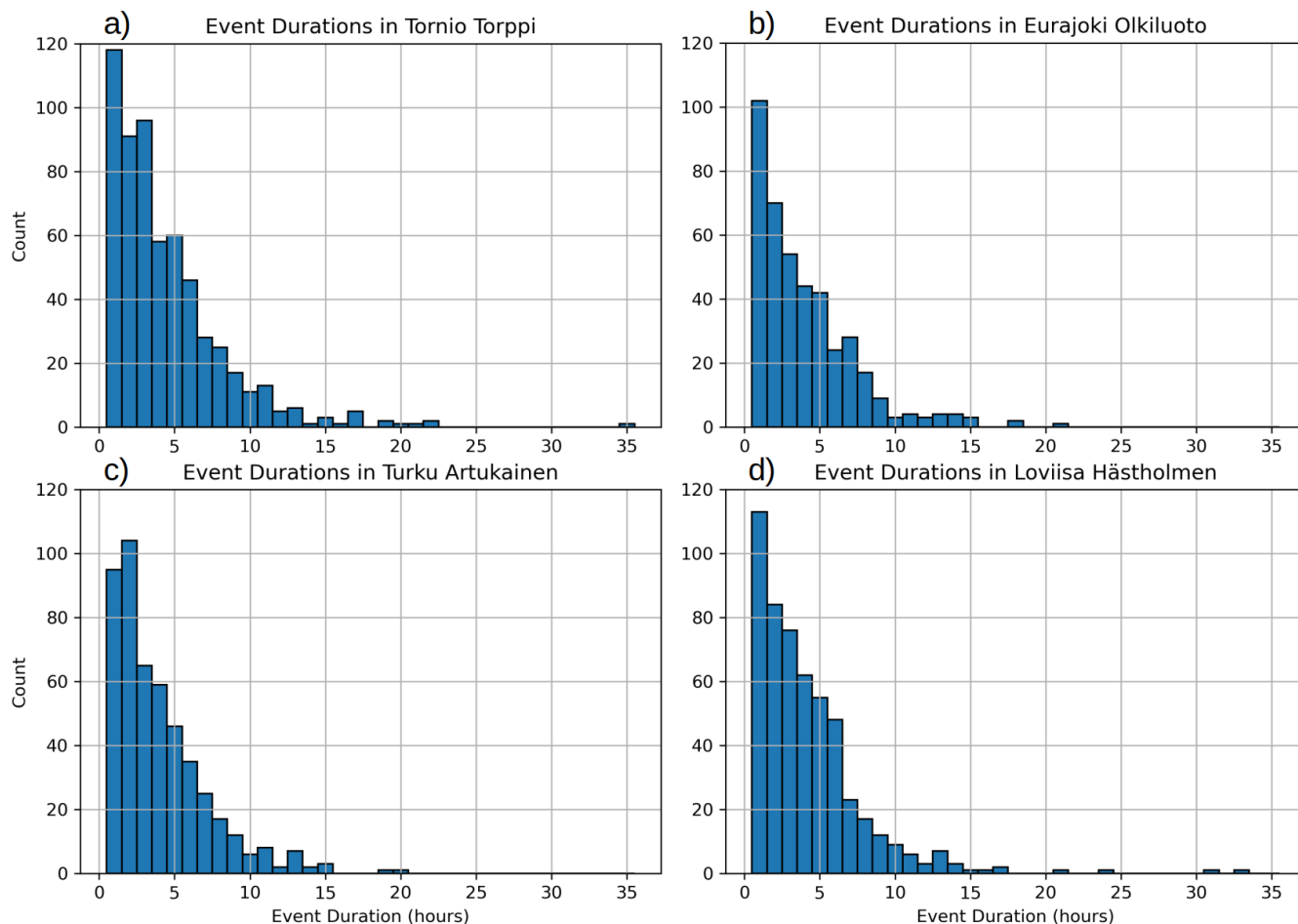


Appendices



Appendix A1. The annual number of days when wind gusts and snowfall exceeded their 95th percentile (SWG95) in Tornio Torppi (a), Eurajoki Olkiluoto (b), Turku Artukainen (c) and Loviisa Hästholmen (d) for each year from 1960 to 2024 based on ERA5 data. The annual number of events is calculated from October to March except for the first and last year of the data set when only January-March is calculated as year 1959 and October-December as year 2024 to cover the whole study period.

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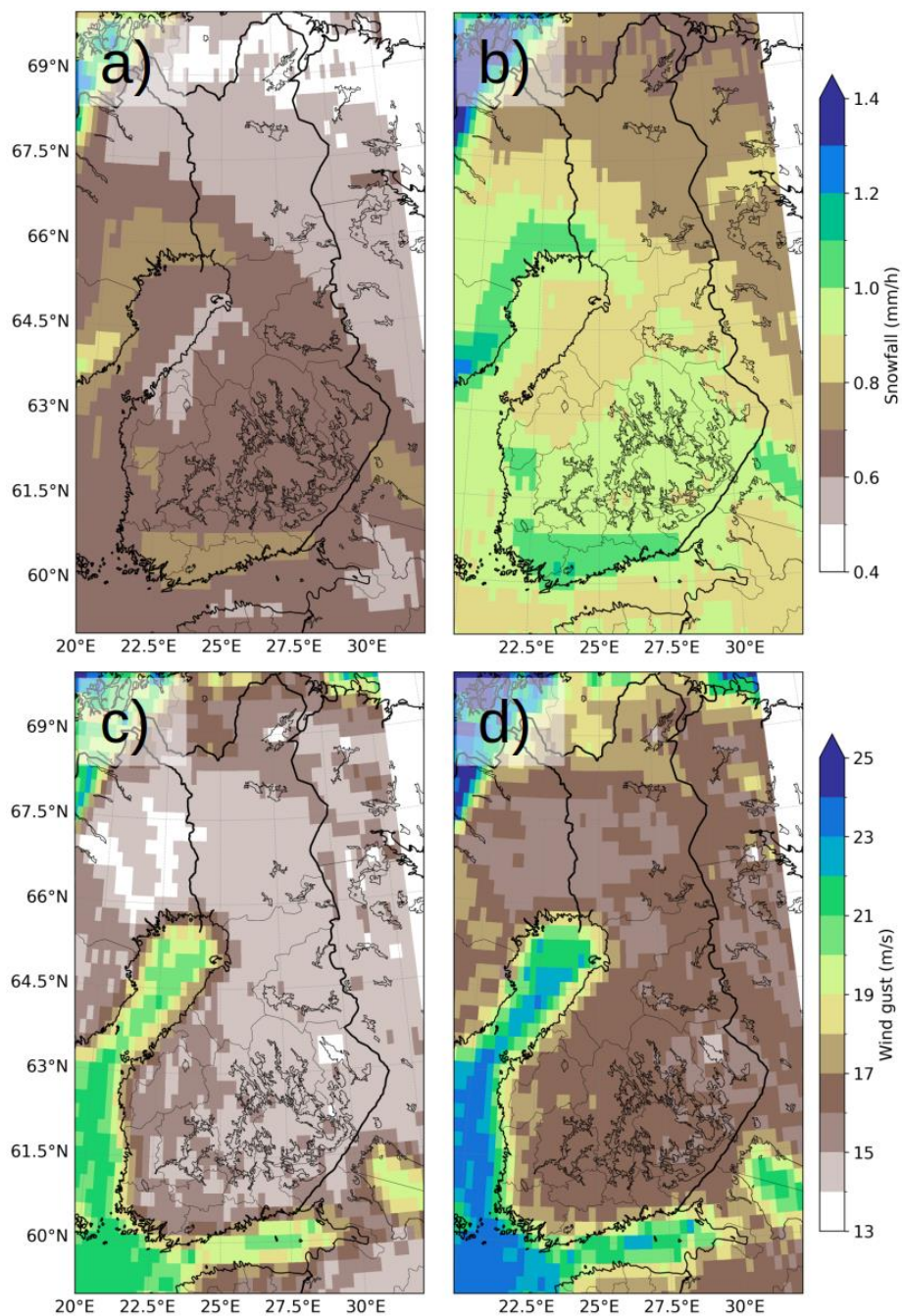
500 **Appendix B2.** Histograms of SWG compound event's durations in Tornio Torppi (a), Eurajoki Olkiluoto (b), Turku Artukainen (c) and Loviisa Hästholmen (d) for the threshold value of 95th percentile. Histograms show the number of consecutive hours when snowfall and wind gust exceeded their threshold value simultaneously during October-March 1960-2024 based on ERA5.

505 **Appendix C3.** The five longest lasting SWG compound events in each study location when the 95th percentile were used as a threshold value for hourly snowfall and wind gust during October to March in 1960-2024 based on ERA5. In addition, statistics for mean and maximum snowfall and wind gust values are given for each event.

| Start date | Max duration (h) | Mean snowfall (mm h ⁻¹) | Max snowfall (mm h ⁻¹) | Accumulated snowfall (mm per event) | Mean wind gust (m s ⁻¹) | Maximum wind gust (m s ⁻¹) |
|---------------|------------------|-------------------------------------|------------------------------------|-------------------------------------|-------------------------------------|--|
| Tornio Torppi | | | | | | |
| 12.02.1973 | 35 | 0.7 | 1.1 | 24.3 | 17.9 | 19.6 |
| 18.12.1966 | 22 | 1.2 | 1.9 | 27.2 | 19.3 | 21.0 |
| 10.11.1998 | 22 | 0.9 | 1.1 | 20.3 | 16.5 | 18.2 |



| | | | | | | |
|--------------------|----|-----|------------|-------------|-------------|-------------|
| 24.10.2014 | 21 | 1.1 | 1.8 | 23.8 | 17.5 | 19.0 |
| 23.03.1986 | 20 | 0.8 | 1.3 | 15.6 | 20.7 | 22.9 |
| Eurajoki Olkiluoto | | | | | | |
| 14.01.1981 | 21 | 0.6 | 1.0 | 12.6 | 19.3 | 21.8 |
| 11.01.2021 | 18 | 0.7 | 1.1 | 13.3 | 20.4 | 22.9 |
| 20.11.2024 | 18 | 0.8 | 1.2 | 13.7 | 20.2 | 22.0 |
| 31.10.2006 | 17 | 1.2 | 2.6 | 20.5 | 21.8 | 23.8 |
| 21.11.1971 | 15 | 1.5 | 2.1 | 23.1 | 21.4 | 23.8 |
| Turku Artukainen | | | | | | |
| 15.01.1974 | 20 | 1.4 | 2.7 | 28.5 | 18.1 | 19.2 |
| 11.01.2021 | 19 | 1.2 | 1.4 | 22.4 | 18.3 | 19.9 |
| 22.01.1962 | 15 | 1.1 | 1.4 | 15.9 | 17.7 | 19.2 |
| 17.11.1995 | 15 | 0.7 | 1.0 | 10.1 | 15.2 | 16.0 |
| 06.12.1999 | 15 | 0.9 | 1.4 | 13.4 | 19.3 | 21.2 |
| Loviisa Hästholmen | | | | | | |
| 07.11.2016 | 33 | 0.6 | 0.7 | 18.9 | 18.7 | 20.8 |
| 21.11.2012 | 31 | 0.7 | 1.2 | 22.6 | 25.1 | 28.0 |
| 12.01.2021 | 24 | 0.7 | 0.9 | 17.6 | 18.8 | 19.9 |
| 31.10.1976 | 23 | 0.6 | 0.7 | 13.9 | 18.5 | 20.1 |
| 25.12.2010 | 21 | 0.6 | 0.7 | 11.7 | 19.6 | 21.9 |



Appendix D4. Average hourly snowfall (a and b) and wind gust (c and d) during single events when the 95th (a and c) and 98th (b and d) percentile was used as a threshold value from October to March in 1960-2024 based on ERA5.



510 **Data availability**

ERA5 data was downloaded from Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: 10.24381/cds.adbb2d47. FMI weather observations are available from FMI open data (<https://en.ilmatieteenlaitos.fi/open-data>). Emergency response tasks show in section 3.5 are not publicly available data.

Author contribution

515 TO and TL contributed to the conceptualization of the study, performed the statistical analysis of the data, created the visualizations, and wrote the original draft of the manuscript. AA contributed to data acquisition and participated in reviewing and editing the text. KJ was responsible for funding acquisition and project administration and contributed to reviewing and editing the manuscript.

Competing interests

520 The authors declare that they have no conflict of interest.

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