REVISE Alpha Phase

Work Package 4: Understanding Worst Case Weather Scenarios

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Executive Summary

This report summarises the work undertaken by the Met Office for Work Package 4 of the REVISE (Revisiting and Evaluating Environmental Inputs on Line Ratings) project alpha phase. This work package has two main aims; to deliver weather observation data to our partners for the methodology development for line ratings, and to explore weather scenarios which could lead to high overhead line temperatures and reduced line ratings.

The provision of observation data included the quality control of the data to remove anomalous readings due to sensor malfunctions or logger errors. The focus was on low wind speed events and high temperature events as these are more likely to cause high line temperatures and lower line ratings. After data quality control, 14 years of observation data with measurements every minute is available with an availability of at least 94% for wind and temperature. Solar irradiance data is not available beyond 2022 resulting in only 12 years of data. The data was resampled to 30 minute intervals and shared with our partners.

The observation data was explored to answer several key questions:

- How does the frequency and severity of low wind speed high temperature events vary over time?
- How does the frequency and severity of low wind speed high temperature events vary by season?
- How does the frequency and severity of low wind speed high temperature events vary by location?
- How does the frequency and severity of low wind speed high temperature events vary with the sampling frequency of the weather data?

Low wind speed and high temperature events were identified within the observation data using a variety of thresholds appropriate to each season. The duration of each event along with the event average temperature were recorded. The main findings were:

- There is a large interannual variation in the frequency and severity of events. Several years of data, ideally at least 10 years, will be required to adequately assess the risk associated with overhead line ratings. A longer dataset is required to understand the impact of climate change on the low wind speed and high temperature events.
- The most severe events occur in the summer, although severe events are also possible in the spring and autumn. Optimal groupings of months into periods of similar risk for overhead line ratings may not follow traditional season groupings.

- The severity of events observed varied across the UK, with more severe and longer events identified in Southern England than Scotland. Further work should be undertaken to fully explore how events vary across the UK and by different types of geography (e.g. coastal compared to inland, hilly or mountainous compared to flat areas).
- Similar severity and duration events were seen in data sampling the 10 minutes preceding each hour as in 30 minute frequency data. Events observed in the 1 minute frequency data were typically shorter duration and had higher temperatures due to more frequent fluctuations that are smoothed out in the longer duration events

1 Introduction

This report outlines the findings of work package 4 of the alpha phase of the Revisiting and Evaluating Environmental Inputs on Line Ratings (REVISE) project, carried out by the Met Office. This work package has two main aims:

- Provide observation data of weather parameters for at least one location in the UK. This was to enable the development of line rating methodologies by the University of Strathclyde and to allow Energyline to explore the impact of humidity on line rating calculations.
- Develop an understanding of the frequency and severity of weather events which could cause high overhead line (OHL) temperatures.

This work package was informed by findings from the Discovery Phase of the REVISE project. Work by the University of Strathclyde showed that line temperatures are particularly sensitive to low wind speed events, with higher line temperatures observed when the wind speed is low (Berdygozhin & Stewart, 28th May 2024). High air temperature events especially combined with low wind speed also increase the line temperatures. Solar irradiation also increases line temperatures although the line temperatures are less sensitive to changes in solar irradiance.

Weather data measured at observing sites across the UK can include anomalous readings, for example due to sensor malfunctioning or logger errors. Work was carried out to quality control the observation data to remove anomalous readings before providing final observation data to our partners. The information from the Discovery Phase on the types of weather events that lead to high line temperatures informed the priorities for the quality control process. The quality control focused on removing artefacts in the wind speed and temperature data, focussing on low wind speeds and high temperatures. More limited quality control was carried out on the solar irradiance data, focussing on removing unrealistic high values. The quality control of these observations will also be important for Work Package 5 where we will be comparing sources of modelled weather data to the site observations.

The exploration of the observation data to understand the frequency and severity of weather events also focussed on low wind speed and high temperature events. This work focussed on finding events in the observation data that met a set of low wind speed and high temperature thresholds. The data analysis aimed to develop an initial understanding of several different aspects of how the weather data behaved and therefore could influence the final line ratings:

- **How does the frequency and severity of low wind speed high temperature events vary over time?** This will help develop an understanding of any interannual variability in the frequency of high impact events and lead to recommendations on the length of the timeseries of weather data needed to provide robust line ratings. It may also identify any climate change signal in the data – although longer timeseries of model data may be required to identify climate change signals robustly.
- **How does the frequency and severity of low wind speed high temperature events vary by season?** This will help develop an understanding of whether different times of year are more high risk for line ratings and whether the high risk times of year are the same at different locations. This could also lead to further work to explore whether traditional season definitions are the best way to split up line ratings for different times of year or whether different month groupings would better capture the times of year where consistent line ratings are appropriate.
- **How does the frequency and severity of low wind speed high temperature events vary by location?** This will help to develop an initial understanding of how the line ratings may vary across the UK. It will also enable the exploration of how much different geographic conditions impact the frequency and severity of low wind speed and high temperature events. These geographic differences include how mountainous the surrounding terrain is and the proximity to the coast.
- **How does the frequency and severity of low wind speed high temperature events vary with the sampling frequency of the weather data?** This will provide additional evidence for how important sub-hourly weather data may be for producing robust line ratings. However other partners will also be investigating how much sub-hourly fluctuations in weather data may impact the line temperatures.

The observation data used is described in section 2 including a description of the sites chosen for the data exploration. Section 3 describes the observation data quality control process and section 4 outlines the results of the data analysis. Section 5 presents the conclusions of the data analysis and section 6 provides recommendations including ideas for further exploration in the rest of the alpha project phase.

2 Observation data

Each day the Met Office assimilates millions of observations data into its weather models, recorded by many types of instruments. These include orbiting, airborne and ground based sensors, and those taking measurements both in-situ and remotely. The most appropriate observations to the Revise project are those recorded by the network of in-situ surface weather stations owned and operated by the Met Office.

2.1 Meteorological data description

The three meteorological variables used by the current line rating standards are ambient air temperature, horizontal wind speed, and global solar radiation. As part of work package 2, (moving closer to real world application), Energyline are investigating whether the effect of relative humidity should be included in the line rating calculations. Therefore, as part of this work package relative humidity observations have also been extracted but these data have not been processed.

2.1.1 Air temperature

Air temperature above the immediate vicinity of the ground may be assumed to vary only slowly with height above ground, typically reducing at a rate of 0.5 to 1 °C per 100m above ground level, depending how stable or turbulent the air is. Also in horizontal space, air temperature tends to be homogeneous over an area, though perhaps with more variation where air is advected over changes in surface types – for example the differences between air over tarmac and grassland. However, it is expected that there may be less variation at OHL heights, further from surface effects. At surface weather stations air temperature is measured by a thermistor at 1.5m above surface, housed within a screen such that it is not affected by solar radiation.

2.1.2 Wind speed

Wind speed displays much greater variability, in both space and time. Its drivers are both dynamic (large scale weather systems) and thermal (local sea breezes or thermals). On the microscale it is affected by sheltering from trees or buildings, and on the mesoscale it varies with terrain elevation – in general being higher on higher ground. However, its greatest variation in space is with height above the surface. Below a quasi-physical “displacement height” above the surface the wind speed is zero, but then increases logarithmically to its geostrophic speed, unaffected by surface friction, at around 1km altitude. The displacement height in forest may approach low OHL heights, whereas over open grassland it may be a few centimetres. In gusty thermal winds, there may be significant variation from calm to mild breezes from minute to minute.

The standard meteorological measurement of wind speed is at 10m height above ground level, at locations that are generally better exposed to the wind. As standard it is measured by a low-friction cup anemometer, which generally has a starting speed (minimum recordable speed) of approximately ¼ ms^{-1}. While their calibration is checked for conformity on a regular basis, the focus for their accuracy is given to higher wind speeds rather than the very low speeds pertinent to OHL ratings.

2.1.3 Solar radiation

Solar radiation is a cover term for various disparate types of solar irradiance. The type measured by pyrometers at surface weather stations is global horizontal irradiance (GHI)[1], and is the sum of radiation direct from the sun and diffuse radiation reflected from the rest of the sky. While its time-averaged level may be fairly constant for a broad area, localities may be further affected, for example, by local cloud and fog at high altitude or near-coast locations. More generally, while the direct radiation is physically constrained parabolic functions of time-of-day and day-of-year, the radiation reaching the surface may vary greatly from minute to minute with the passage of cloud. Further, the addition of diffuse radiation reflected by nearby cloud may result in GHI significantly exceeding the constrained direct radiation.

2.2 Surface weather station network

The operation of a network of surface weather stations formed the basis of original weather forecasts and preceded the era of computational numerical weather prediction (NWP), but has since been reduced as alternative, more effective sources of weather observations have become available. Historically, Met Office weather stations were manned by a human observer who would follow a standard process to take measurements once per hour. In the case of wind speed, this would be an average of wind speed recorded over the 10 minutes preceding the hour. Therefore, while many UK weather stations have very long archives of hourly readings from which an observed climatology may be derived, the sub-hourly minimum and maximum values of (particularly) wind speed may not be represented.

Since the advent of automated weather stations (AWS) sending recordings back to a central data centre, sub-hourly data of weather observations have become available. The AWS roll-out occurred over a period of several months, with 1-minute average recordings, 60 recordings per hour, becoming available at a subset of weather stations from early 2011.

While the spatial distribution of Met Office weather stations covers all of the UK, they are sparsely distributed compared to the resolution of the weather models they inform. However, they are sufficiently numerous, and with sufficient archives of 1-minute recordings, to provide

[1] https://www.sciencedirect.com/topics/engineering/global-horizontal-irradiance

important insights into the variability of sub-hourly weather throughout the UK, and in a variety of geographical situations. The temporally coherent data give ground-truth information on coincident extremes of the weather variables pertinent to OHL conductor temperatures.

2.3 Site selection process

The basis for the choice of weather stations to use in this work package was:

- A sufficient period of good quality observation data with a sufficient proportion of valid observations ("availability") to consider that the meteorological climate of the location is well represented. In particular, this relates to the representation of the coincident extreme conditions of the relevant variables.
- A requirement that all the required variables are recorded concurrently for the sufficient period.
- A sufficient geographic dispersion of stations throughout Great Britain to demonstrate the variation in meteorological conditions across its different regions.

The regions of Great Britain were selected based primarily on the electricity transmission system operator of the area, e.g. SSEN and SPEN in Scotland (Figure 1 - left). In the case of the NGET region covering England, further division was based approximately on the local county:

- Surrey: Includes sites nearby to Leatherhead, where meteorological data for the 1980s calculation of static line ratings were collected (Price & Gibbon, 1983).
- Lancashire: Representing a cooler and wetter region of Great Britain.
- Cambridgeshire: Representing a warm and drier region of Great Britain
- Devon: Representing a warm and sunny, but wetter region of Great Britain.

Due to the varying topography of Great Britain and the sparse distribution of weather stations within regions of different sizes, there was variation in the typical relationships between neighbouring sites within the regions. For example, the Surrey group are comparatively closely spaced and in similar topography, so their weather records are well correlated. Conversely, the Lancashire and Scottish regions are larger with more variation in geography, and their weather is less correlated during many weather conditions.

The Met Office land surface network comprises over 1900 weather stations opened between 1794 and the present. Of these, 484 remain open with over 10 years' records that may provide information useful to the project (Figure 1, left - blue). For the current task of producing estimates of static line ratings based on weather station observations, 76 stations have recorded all four variables of interest at some time since 2010 (Figure 1, left - green). The inclusion of relative humidity, which is not a part of current standard calculations, does not impact this figure as temperature and relative humidity are recorded together.

2.3.1 Quality control sites

From the 76 stations, five were selected from each of six regions across Great Britain to include in the data quality control process, totalling 30 stations to be used in the data quality control process. The selection was based on the period the station has been recording, the distance from a location of interest, and the topographic similarity to that location. For example:

- In the Surrey region the Wisley station is just 10km from Leatherhead, and so was expected to deliver calculated static line ratings similar to the 1980s calculations (Price & Gibbon, 1983), to provide a reference against which to compare other stations.
- In the SSEN region the Tain Range and Loch Glascarnoch stations are closer to the line temperature field study at Lentran (Karam, 2023).
- In the Lancashire region the Hawarden Airport station is closer and more similar to the area surrounding the Penwortham – Kirkby dynamic line ratings trial (National Grid, 2022), should the data of line temperature observations become available later in the project.

Details of the 30 quality control sites are provided in Appendix A.

2.3.2 Priority stations

A shortlist of priority stations was required on which to focus the study during the project's Alpha phase. Met Office weather stations are typically located in areas of less rugged terrain, at medium to lower altitude, and in positions of better exposure to the weather. Given its historical association with aviation, many stations are located at present or former airfield sites. So that variation in meteorological climate between regions could be assessed with less influence of individual station's local characteristics, in each region an airfield site was selected from the 30 quality control sites. These were paired with a second station from the region which would give a measure of the variability within the region due, for example, to either terrain altitude, ruggedness, or proximity to the coast.

Further information on the selected 12 priority weather stations are presented in Table 1.

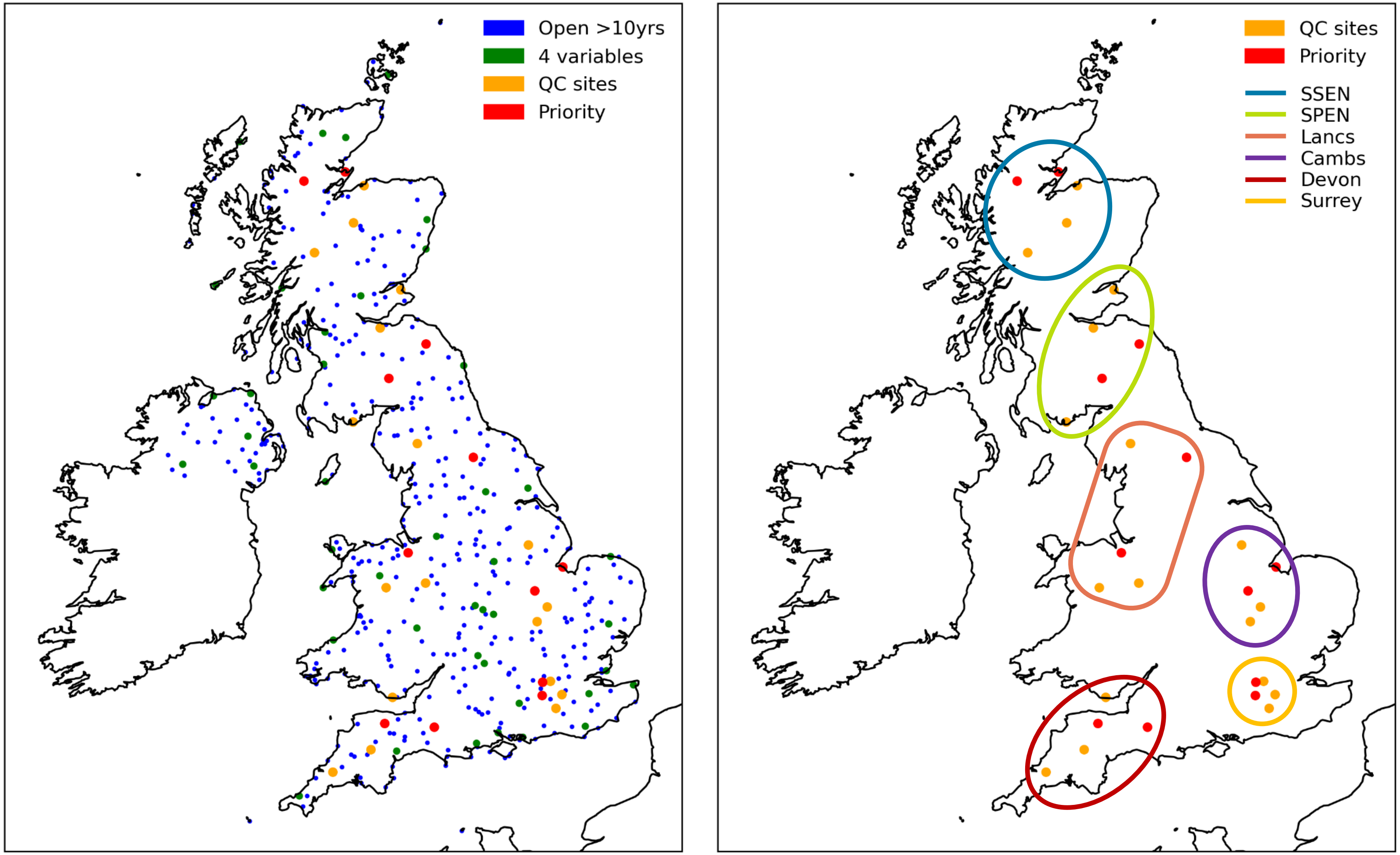

Figure 1: Selection of priority weather stations for the calculation of static line ratings representative of regions of Great Britain. [left] 484 sites with at least 10 year's archive (blue), of which 76 have some period of records for each variable (green), from which 30 were selected (orange) for the quality control of 12 priority weather stations (red). [right] 30 sites used in the quality control of data from 12 priority weather stations in 6 regions of Great Britain.

Table 1: Weather stations in each region of Great Britain prioritised for detailed study

Region/ Station	Detail
SSEN	
Tain Range	Former airfield, rural, close to the coast, 45km from Lentran test site
Loch Glascarnoch	Valley site, rural, in more mountainous terrain, 44km from Lentran test site
SPEN	
Charterhall	Airfield site on flat, more elevated terrain, rural
Eskdalemuir	Valley site in rolling hills on elevated terrain, rural
Lancashire	
Hawarden Airport	Airfield site, semi-urban, 34km from Penwortham-Kirby test line
Leeming	Airfield site, open, flat, rural terrain
Cambridgeshire	
Wittering	Airfield site, open, flat, rural terrain
Holbeach No2	Open, flat, near-coast site bordering salt marshes
Devon	
Yeovilton	Airfield site, open, flat, rural terrain
Liscombe	Open, rural, site in rolling terrain of Exmoor, positioned on a slope
Surrey	
Heathrow	Airport site, flat, urban, surrounded by concrete structures within London heat sink.
Wisley	Relatively flat site within horticultural gardens nearby to orchard and buildings. 10km from Leatherhead measurement site.

2.4 Availability of unprocessed data

Data availability relates to the proportion of measurement periods within an archive for which valid data are available. The station archives of 1-minute temporal resolution meteorological data begin on 1st February 2010, except Hawarden Airport which began on 3rd March 2010. All stations remain open and recording observations and have accrued almost 15 years' data (at the time of extraction), mostly with annual availability of unprocessed data exceeding 90%.

However, the solar radiation data at all stations cease in early 2022, and therefore there are at best approximately 12 years archives of coincidence of the three main variables from which to calculate observations-based line temperature calculations that include solar radiation.

3 Data Quality Assurance

The unprocessed weather station observations are mostly robust and accurate measurements of meteorological variables, but are occasionally prone to anomalies due to:

- Data logger malfunctions,
- Meteorological variable sensor malfunctions,
- Artificial influences that affect readings of the natural environment,

Since the occurrence of anomalies is generally infrequent, statistics such as the mean or median of a variable are reliable measures. However, in the case of the frequency of line temperature exceedances it is the extremes of the distribution of values of the variables that are of interest. It is necessary to ensure that anomalies of high temperature, low wind speed, and high solar radiation are removed from the dataset to mitigate the over-estimation of extreme scenarios. Relative humidity was not included in the quality assurance process as it does not feature in current line temperature calculations.

At the same time that anomalous occurrences of extreme (or less extreme) measurements need to be removed from the dataset, it is important that true naturally occurring extremes are not removed. The quality assurance process seeks to:

- Maximise the number of “Hits” of true anomalies,
- Minimise the number of “Misses” of true anomalies that bias results,
- Minimise the number of “False Alarms” where an important, naturally occurring extreme value is classed as an anomaly and is removed from the dataset, biasing the results.

3.1 Automated data flagging

A 15 year archive of 1-minute period observations is a time series of approximately 7.9 million records, per variable, per site. It was necessary to implement an automated data flagging process to review the ~378 million records from the 12 priority weather stations before they were resampled into a longer averaging period – which would hide anomalies within plausible but incorrect extreme values.

An initial review of the data explored:

- Metrics derived from the 1-minute data, such as the difference in a variable from one minute to the next, which is a valuable descriptor for its natural variation

- Review of time series of a shorter period of data, comparing the variation of a variable at a site to its four neighbouring sites in the region, to generate a list of typical anomalies that affected each variable.

It was noted during the initial review that as well as variation between sites in the anomalies to which they were susceptible, there was significant variation between the characteristics of meteorology that would impact the application of rule-based data flagging. Where some sites' data could be effectively flagged using a constrained threshold on a metric, the application of the same threshold at other sites would cause the occurrence of excessive false alarms and the removal of important extreme events or large numbers of mundane data.

Over a number of iterations, rule based data flagging of individual variables (that is, not taking information from concurrently occurring variations in other variables) was developed for a set of typical anomalies. Care was required to ensure that rules effective in one part of a dataset (for example, a season, or time of day) did not impact another part with excessive false alarms. Once a set of rules was developed, a single iteration of varying its numerous settings of thresholds and periods to achieve site specificity was applied.

3.1.1 Air temperature

Extreme high values of air temperature were of concern for the flagging process, where high temperatures are not bounded by a physical upper limit. Data were flagged for removal where:

- Data were missing from the unprocessed archive
- Unphysical extreme values were recorded beyond what was considered plausible, caused by data logger or sensor errors
- Unlikely values of 0°C where the value remained unchanged for several minutes; an occurrence often representing a measurement error retained by the logger
- Anomalous changes in temperature from one minute to the next
- Spikes in temperature values of several degrees within a few minutes
- Unexplained "Table" events with an anomalous increase in temperature over one or two minutes is followed by unusually constant temperature, followed by a similarly anomalous drop to the preceding "natural" value
- A site's temperature reading was anomalously divergent from its typical relationship with its four neighbours in its region
- A 1-minute reading preceded, or was preceded by, a period flagged by another rule, to account for malfunctions occurring within the minute which may result in a plausible but incorrect value.

Some additional flagging of specific periods during October 2013 was applied to the SPEN/Charterhall data to ensure periods of clear sensor malfunction where entirely removed.

3.1.2 Wind speed

The frequency of low wind speed is important for static line ratings, where wind speed is physically bounded at zero. As well as electrical malfunctions in the data measurement and logging process, during freezing conditions cup anemometers can become stuck with frost resulting in ongoing zero values that might otherwise be measured above the low wind speed threshold by a sonic anemometer. Fortuitously, such freezing incidents do not coincide with the high ambient temperature events of interest to static line ratings. A rule combining zero wind speed readings with freezing temperatures to identify those events was not implemented in this phase. Data were flagged for removal where:

- Data were missing from the unprocessed archive
- Unphysical extreme values were recorded beyond what was considered plausible, caused by data logger or sensor errors
- Ongoing values of 0 m/s where the zero period was preceded by a large drop to zero from a value exceeding a threshold, to represent the impact of higher friction from frost. The rule misses the flagging of frozen anemometers where the wind was calm beforehand.
- A site's wind speed reading was anomalously divergent from its typical relationship with its four neighbours in its region. Further site specific tuning of the rule is advised at a late project phase to reduce the occurrence of false alarms.
- Anomalous values of constant, unvarying wind speed above a threshold for a period of time
- A 1-minute reading preceded, or was preceded by, a period flagged by another rule, to account for malfunctions occurring within the minute which may result in a plausible but incorrect value.

3.1.3 Solar radiation

The frequency of high solar radiation is of interest for static line ratings, where GHI is physically bounded at zero, and also has a constrained upper bound. GHI is a combination of direct solar radiation, which can be calculated accurately for given date, time, and latitude, and diffuse radiation that is reflected from the remaining sky to the pyrometer. Thus, as well as decreasing solar radiation, the presence of cloud can increase GHI by up to approximately 300Wm^{-2} above the direct radiation.

A preliminary study of the solar radiation data extracted each hour of each day of the year from the 15 year archive, from which a high percentile of radiation readings was calculated. Following smoothing of peaks and troughs, this provided a parabolic near-maximum value of GHI to which a value could be added to arrive at an upper threshold of plausible solar radiation for each hour of each day of the year, varying from Surrey to Scotland.

Data were flagged for removal where:

- Data were missing from the unprocessed archive
- Unphysical extreme values were recorded beyond what was considered plausible, caused by data logger or sensor errors
- Global radiation exceeded the near-maximum calculated in pre-processing plus an additional threshold margin.
- Anomalous values of constant radiation above a threshold for a period of time
- A 1-minute reading preceded, or was preceded by, a period flagged by another rule, to account for malfunctions occurring within the minute which may result in a plausible but incorrect value.

3.2 Quality Assurance process review

To appraise the effectiveness of the automated process at each iteration of rule development, batches of all sites' events flagged under each rule were plotted for review. Where more than thirty events of a given length occurred in a batch, just thirty were plotted as a sample representative of the rule. The plots provided information on the "Hits" and "False Alarms", and effectiveness of general rules, where they were causing unexpected impacts elsewhere in the data, and how thresholds could be altered on a site specific basis.

Once a final set of rules and site specific settings had been developed the final set of quality controlled data were reviewed to assess occurrence of the "Missed" anomalous events at the Surrey/Wisley site. The top 100 unique days were extracted that gave the:

- Highest 1-minute temperature value
- Highest 1-minute solar radiation value
- Highest count of 1-minute wind speed of zero ms^{-1}.

It was found that there were no anomalies in temperature or solar radiation extremes that had been missed by the automated data flagging process on those days, though a miss of a moderate anomaly in solar radiation was known to have occurred at Heathrow on 8th March 2011. This single anomaly event did not exceed the maximum plausible threshold for that day.

The top few of the top 100 days for wind speed at Wisley showed extensive flagging of zero wind speeds, even while the neighbouring sites were also recording low winds below 2ms^{-1}. While these may be considered a false alarm, the events were triggered by the large drops to zero rule and occurred mostly during winter months. Generally the flagging appeared appropriate in the context of Wisley's neighbours. There were no incidents in the sample of clearly anomalous events having been missed by the process.

3.3 Availability of Quality Assured data

A review of the availability of quality assured data was undertaken to identify significant gaps in the processed 1-minute records that might impact the validity of regional comparisons of the frequency of extreme meteorological events. A whole-period summary for each priority station and variable is presented in Table 2. The monthly availability values on which the values are based are presented in Appendix B.

Table 2: Availability of Quality Assured data at prioritised stations, measured on a scale 0-1.

		Quality controlled data availability (0-1)		
Region	Station	Temperature	Wind speed	Solar radiation
SSEN	Tain_Range	0.96	0.96	0.80
	Loch_Glascarnoch	0.96	0.96	0.77
SPEN	Charterhall	0.95	0.94	0.80
	Eskdalemuir	0.96	0.94	0.80
Lancs	Hawarden	0.96	0.95	0.77
	Leeming	0.96	0.96	0.81
Cambs	Wittering	0.95	0.95	0.81
	Holbeach_No2	0.96	0.96	0.80
Devon	Yeovilton	0.96	0.95	0.81
	Liscombe	0.96	0.95	0.79
Surrey	Heathrow	0.96	0.96	0.82
	Wisley	0.95	0.95	0.78

The values in Table 2 indicate that the temperature and wind speed availability is consistently high, exceeding 94% in all cases, and with little variation between sites. The availability of solar radiation data is lower, ranging from 77% to 82%. The lower values are caused largely by the cessation of records at the start of 2022, rather than issues with the measurements.

The plots in Appendix B show that all data were missing from all stations for the months December 2010, February 2011, and April 2012. The cause of these gaps in the archive is not known, but it is expected that this will not influence the results of the study. The next most common characteristic is the occurrences at all stations where all variables are similarly lower availability at the same time as a result of temporary station outages. A seasonal tendency for these outages that might impact results is not identified. Similarly, the gaps in individual variables' records do no show seasonality at any sites.

Due to project constraints a detailed investigation of the performance of the rule-based data flagging process was conducted only for the Surrey stations. In other regions data anomaly events may have been missed, or true extreme events may have been incorrectly excluded. However, the final data availability values in all regions are consistent with expectations. Further investigation is only planned if cause is found in later (Beta) project phase.

4 Data exploration

4.1 Methods

We chose to investigate the observation data for periods of low wind speed that coincided with periods of high temperature, conducive to a situation where an OHL would be vulnerable to overheating due to the high ambient temperature and the lack of cooling by wind. Exploring the frequency and severity of such events across space and time provides context for how often the weather conditions may threaten the safety of a particular line rating with a certain baseline operating temperature; the suggestion of different line ratings for different regions of the UK, and different seasons of the year, is anticipated. Furthermore, investigating occurrence of, and variability in, these events over time will help inform the final weather data that is used in the methodology being developed to convert weather data into suitable line ratings, for example ensuring that a long enough dataset is used to capture year-to-year variability in conditions.

Multiple thresholds for temperature and wind speed were used in combination to investigate different extremities of events. Wind speed threshold options were held constant at 0.5, 1 and 2m/s, while temperature thresholds were varied across seasons, with yearly thresholds also chosen (Table 3). These wind and temperature thresholds were chosen both as a result of discussions with project partners, and from investigating the distribution of temperatures for low wind speed events to ensure that the thresholds would capture a reasonable number of events of concern, in the high temperature tail (example in Figure 2). Seasons were split using traditional three-month groups (spring: March-May; summer: June-August; autumn: September-November; winter: December-February). The 12 priority sites identified in section 2.3.2 were focused on in this exploration.

Table 3: The temperature thresholds used in combination with low wind speed thresholds to identify high risk weather events for OHLs. They are varied by season such as to capture a reasonable number of events.

		Temperature threshold (°C)		
Season	Months	Low	Medium	High
Spring	3,4,5	10	14	18
Summer	6,7,8	18	20	22
Autumn	9,10,11	10	14	18
Winter	12,1,2	4	6	8
Full year	All	8	13	18

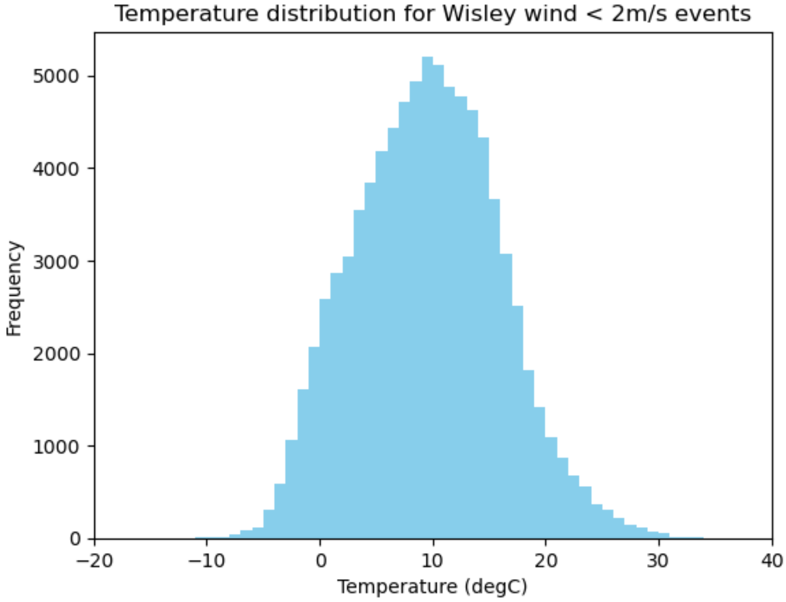

Figure 2: The distribution of temperatures for Wisley across timesteps where wind is < 2m/s. The high-risk events will be found in the high temperature tail.

After QA, the 1-minute observation data was resampled to produce datasets at 30-minute and 60-minute intervals. 30-minute data is required for the method to calculate line ratings from weather data, but 1 minute and hourly data were also investigated in order to understand the impact of choice of data interval on the identification of events. The 30-minute data was produced by taking the mean over each 30-minute period of the 1-minute data where there was at least 80% valid data, otherwise the 30-minute period in question was dropped; this was done such as to prevent extremes appearing in the data from bias in periods of limited data. The hourly data was produced by just looking at the 10 minutes before each hour, producing a dataset which is more comparable to the hourly gridded model data to be explored in Work Package 5. The 30-minute data will be focused on in the results, and compared to the 1-minute and hourly results when appropriate.

Initially, individual timesteps were identified with wind speeds below the wind threshold. Then, these were filtered further to timesteps with temperatures that were also above the temperature threshold. A compound “event” was then identified by combining consecutive timesteps that met both criteria, and the duration and average temperature were calculated for each event, which were considered its severity metrics. The frequency of events was calculated as the number of timesteps that met the threshold requirements as a percentage of the number of timesteps with valid observation data.

Plots were then produced to display the results; line graphs of frequency of compound events over time, and scatter plots of the severity metrics per site, which were also investigated for seasonal and yearly trends. Further plots of temperature distributions under different wind speed thresholds were also produced to facilitate site and seasonal comparisons.

4.2 **Results**

4.2.1 Yearly variability

Firstly, the frequency of compound low-wind speed and high temperature events was plotted for each year in the timeseries. Figure 3 shows the frequency of these compound events for different extremities of thresholds for full years of data, while Figure 4 shows the frequencies separately by season, using the medium-strict thresholds. Generally, there is a lot of year-to-year variability in the occurrence of the events. For example, 2014, 2018 and 2021 are particularly high occurrence years, then typically followed by a subsequent low occurrence year; for example, 2015 has low frequencies across all seasons for the vast majority of sites, as shown in Figure 4. Some sites/seasons were missing data for 2022, hence it appears that there is no data/a drop to an extremely low frequency for many sites in that year – although sites that do have records for 2022 display a drop in frequency after the 2021 peaks.

Stricter thresholds produce lower event frequencies with a smaller variation range, as shown in Figure 3. There is comparable variability across seasons, and, across regions, the yearly variabilities are most closely correlated for the season of autumn. For winter, the Surrey, Devon and Lancashire regions display increases in event frequency in recent years, as shown in the lower right panel of Figure 4, which could be a climate change signal of warmer UK winters – however, a longer dataset would be required to establish whether this is the case or if this is just a more significant variation.

From the yearly variation in frequency, regional trends are apparent; the Surrey region tends to have the highest event frequencies, and the SSEN and Cambridgeshire regions the lowest. From further investigation of the data, the low occurrences in SSEN reflect low temperatures, whereas the low occurrences in Cambridgeshire reflect low occurrence of low wind speed.

The Cambridgeshire sites are quite exposed however we have not yet explored whether the level of exposure at the observation sites is typical of the level of exposure experienced by overhead lines. Further work could look at finer resolution features and the impact of sheltering, such as from trees, on appropriate line ratings.

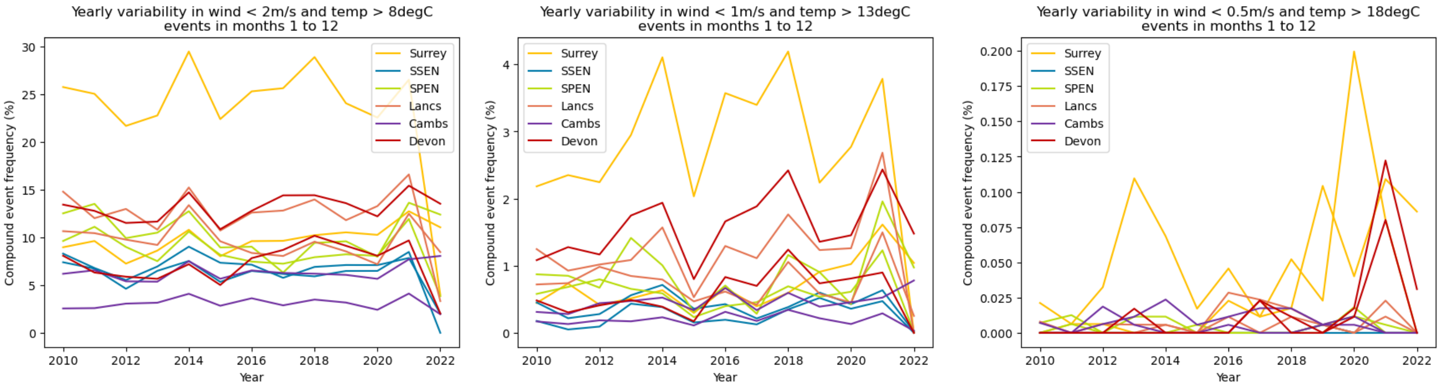

Figure 3: Yearly variability in compound events with increasingly strict thresholds. Left: wind <2m/s and temperature >8°C, middle: wind <1m/s and temperature >13°C, right: wind <0.5m/s and temperature >18°C.

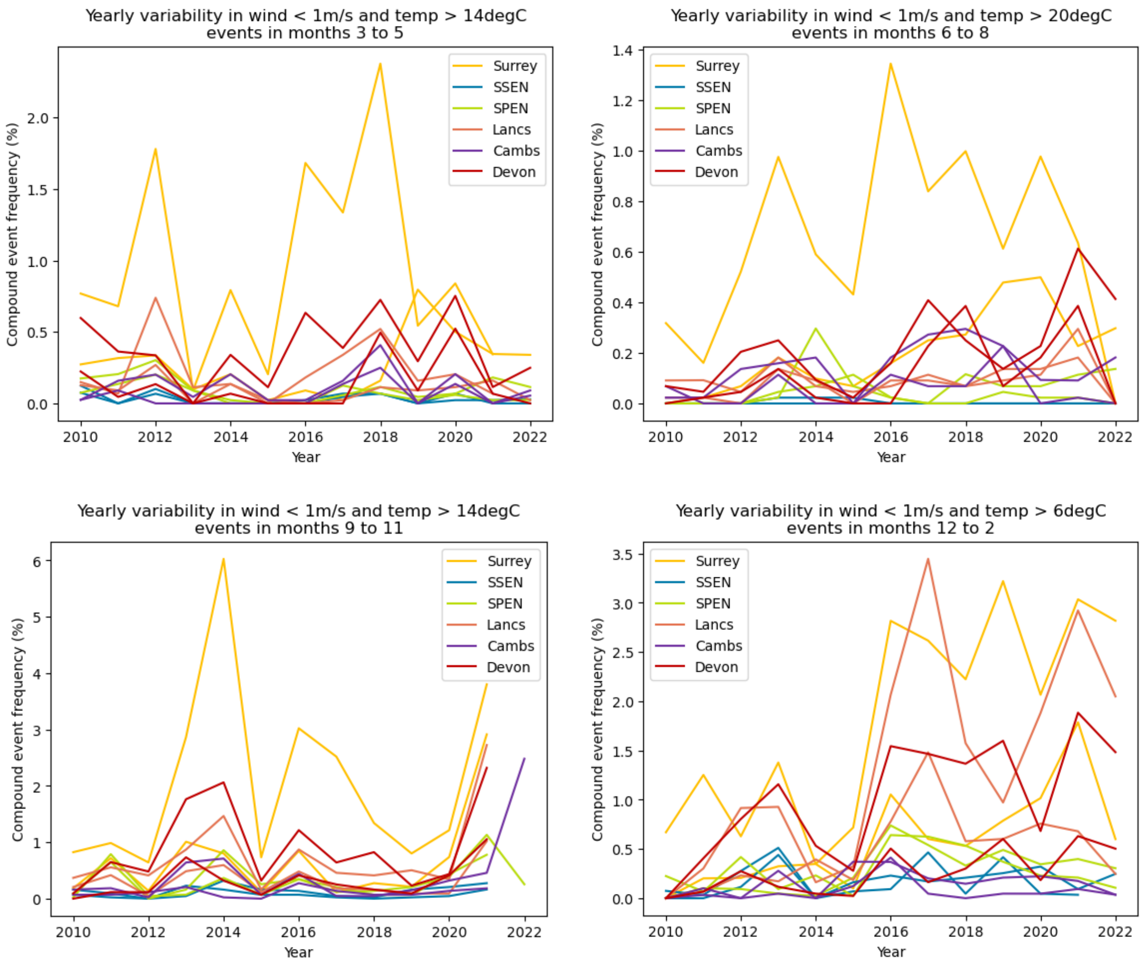

Figure 4: Yearly variability in compound events for mid-thresholds, for each season.

4.2.2 Temperature distributions of low wind speed events

In order to understand seasonal variations, and how it varies by region, plots of the full temperature distribution in each season for wind speeds below 2m/s were produced. Inspection of these plots partially informed the selection of the seasonal thresholds in Table 3. Wisley (Surrey; Figure 5) and Tain Range (SSEN; Figure 6) were selected for initial site comparisons, being in distant regions of the UK.

Wisley has a much higher number of low wind speed events, and notably higher temperatures than Tain Range in all seasons except winter, where the temperature distributions look very similar between sites. Surrey therefore has a stronger seasonality, so would be more at risk in warmer months if an average line rating was applied year-round rather than varied across seasons. Temperature distributions for all priority sites are provided in appendix C to further illustrate the regional variability in seasonality.

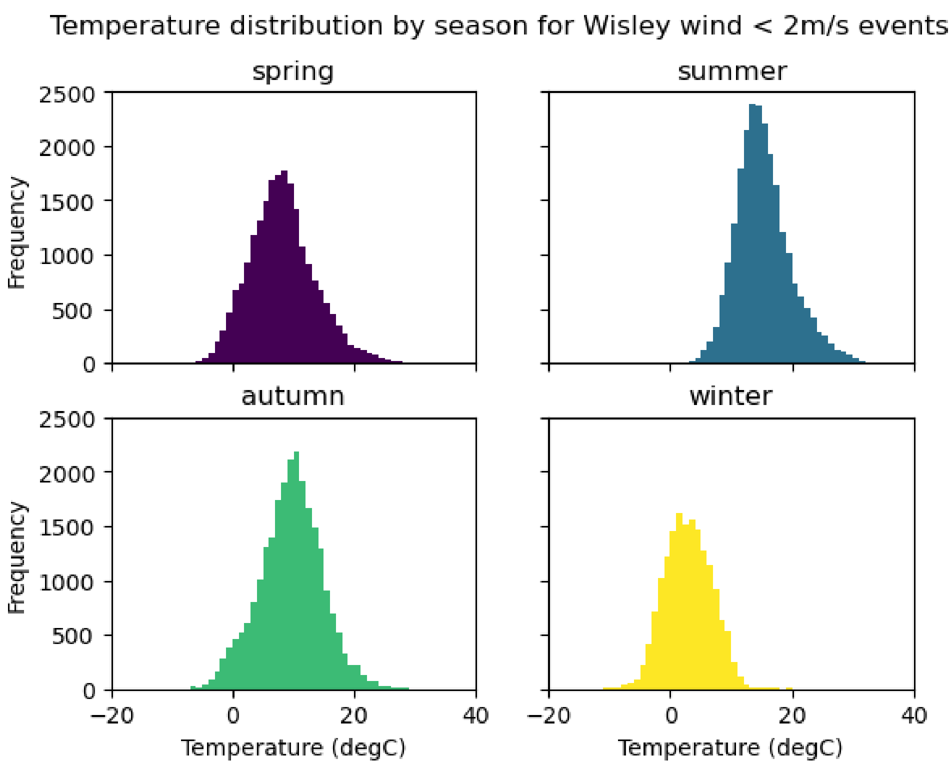

Figure 5: Temperature distribution of timesteps where wind speed <2m/s, by season at Wisley. Season split defined in Table 3.

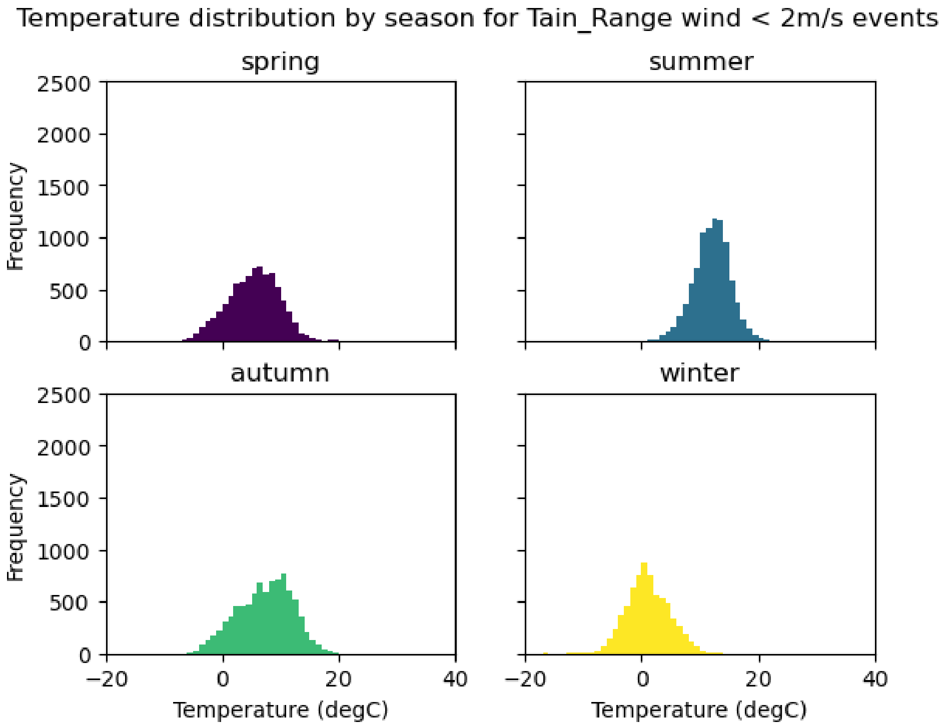

Figure 6: Temperature distribution of timesteps where wind speed <2m/s, by season at Tain Range. Season split defined in Table 3.

4.2.3 Event severity

For a given combination of low wind speed and high temperature thresholds, the duration and average event temperature for all events were plotted to illustrate event severities. Figure 7 shows a clear trend in event severity by season, with average event temperatures increasing from lowest in winter, to spring, to autumn, to the hottest events occurring in summer. This is partially facilitated by the variable thresholds, but interestingly, there is more overlap of spring/autumn event temperatures into the summer range than of winter event temperatures into the spring/autumn range. This indicates that the seasonal split of months across spring, summer and autumn would be interesting to vary, and looking at summer in isolation would likely miss some severe events in autumn and spring. Indeed, the longest duration events occur in autumn, and the fewest long duration events occur in summer, despite them being of the highest temperature.

Figure 7 illustrates that Wisley has more severe events than Tain Range, reaching average event temperatures of up to ~10C higher, with durations often up to 4x longer. Filtering down to the medium-strict wind threshold and the highest yearly temperature threshold further highlights the regional difference. Figure 8 shows that exceedances at Tain Range occurred for only one or two 30-minute periods, only in the summer months, and reaching much lower average event temperatures than Wisley. Not only were there many more exceedance events at Wisley, but they also occurred in spring and autumn as well as summer. Figure 9 and Figure 10 show more detail on event severity by month; across all seasons, the majority of events occur for short durations, and decline in occurrence as higher event average temperatures are reached.

Like with event frequency, there is a lot of variability in event severity over time. Figure 11 illustrates the lack of trend in event duration or average temperature with year. By region, event frequencies and severities indicate the highest risk to OHLs being in Surrey, which will likely require lower regional ratings for them to remain operationally safe. With current ratings across the country being based on data from the Leatherhead area, this suggests that there is higher capacity on OHLs elsewhere in the country since Surrey weather is often conducive to OHL risk through high temperatures. However, the climate change experienced since the 1980s, when these original ratings were established, will likely require the ratings to be scaled down as ambient temperatures are now higher; this may trade off with potential rating increases in other regions. The role of climate change should be explored in Work Package 5 using a longer timeseries of observation data. Plots of event severities for more sites are provided in appendix C to provide a more complete picture of variability around the UK – there appears to be more events recorded for the same thresholds in more southerly regions, implying temperature to be a prevailing factor here – and also begin to consider the impact of geographic setting (flat/upland, coastal/inland, rural/urban). While this would benefit from further investigation, initial findings suggest that more complex, less exposed sites have fewer events of longer durations.

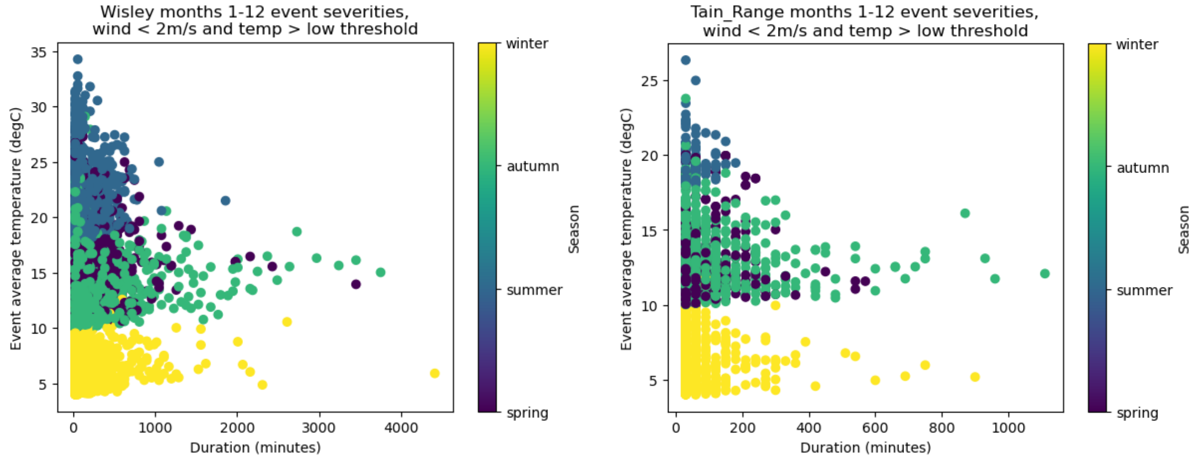

Figure 7: There is a clear trend with season of event average temperature, shown here for the least strict thresholds at Wisley (left) and Tain Range (right).

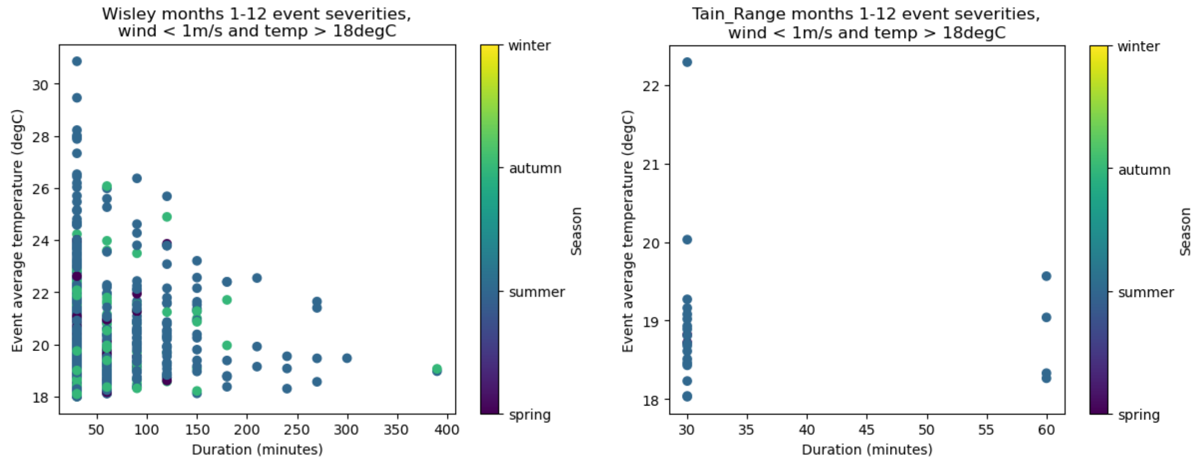

Figure 8: Wisley (left) has much more severe events than Tain Range (right); of higher average temperatures, longer durations, and with the most extreme occurrences happening in more seasons.

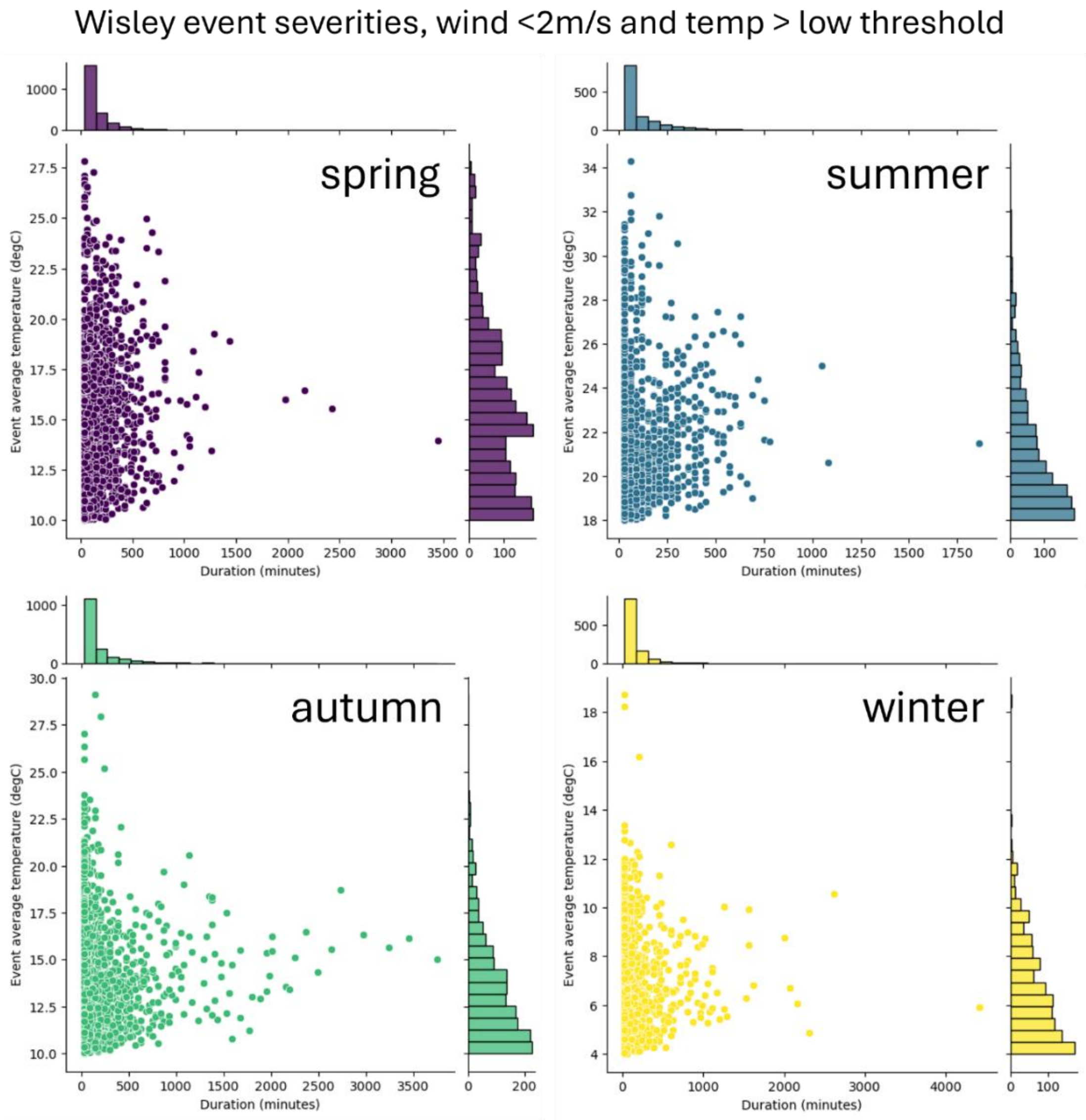

Figure 9: Wisley event severities across seasons, where wind <2m/s and temperature is above the low threshold for the season (Table 3). Above and to the right of the scatter plots are histograms showing the distribution of the durations and average temperatures, respectively, for the events.

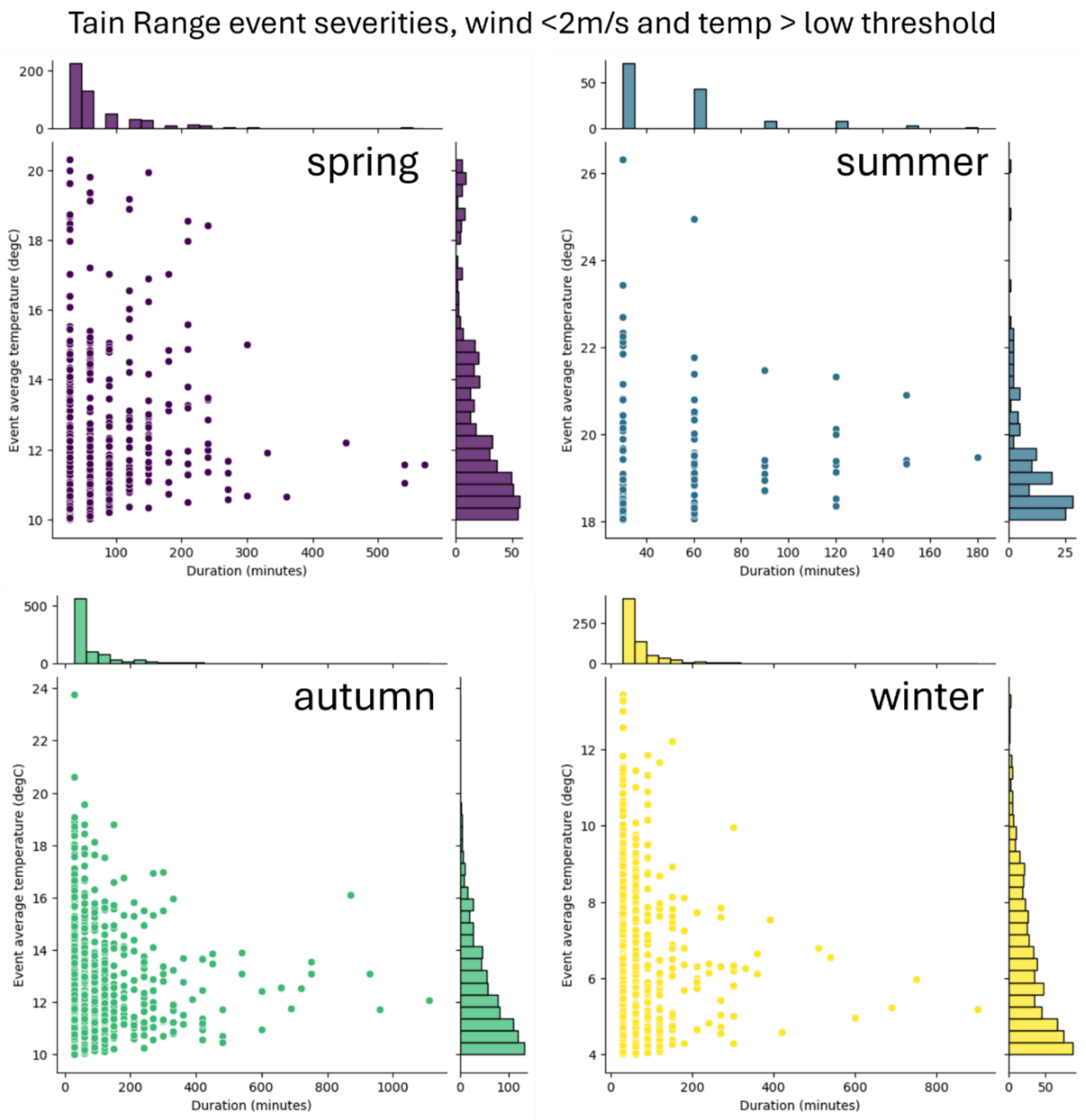

Figure 10: Tain Range event severities across seasons, where wind <2m/s and temperature is above the low threshold for the season (Table 3). Above and to the right of the scatter plots are histograms showing the distribution of the durations and average temperatures, respectively, for the events.

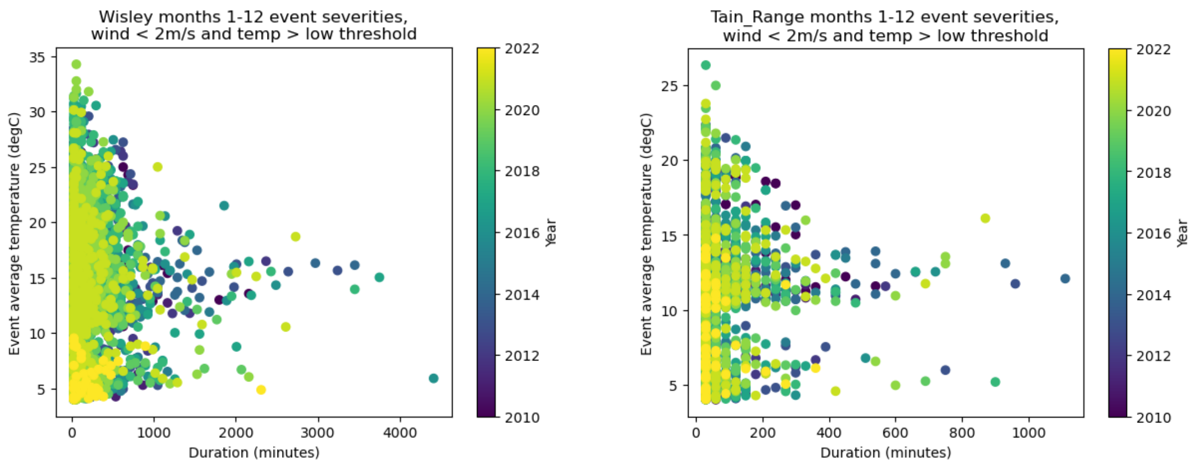

Figure 11: There is no clear trend in event severity with year, shown here for Wisley (left) and Tain Range (right).

4.2.4 Impact of sampling frequency of observation data

To assess the impact of using 30-minute data versus a different frequency on the identification and severity of low wind speed high temperature events, results from using 60-minute and 1-minute data were compared to the 30-minute results. Figure 12 shows that using different frequency observation data has negligible impact on the percentage of timesteps in which events occur and displays almost identical variability over time. This is an encouraging implication that even though the raw number of events will be lower, their frequency of occurrence is equally represented across data intervals. Data at 30-minute intervals can therefore be deemed suitable for investigating these events.

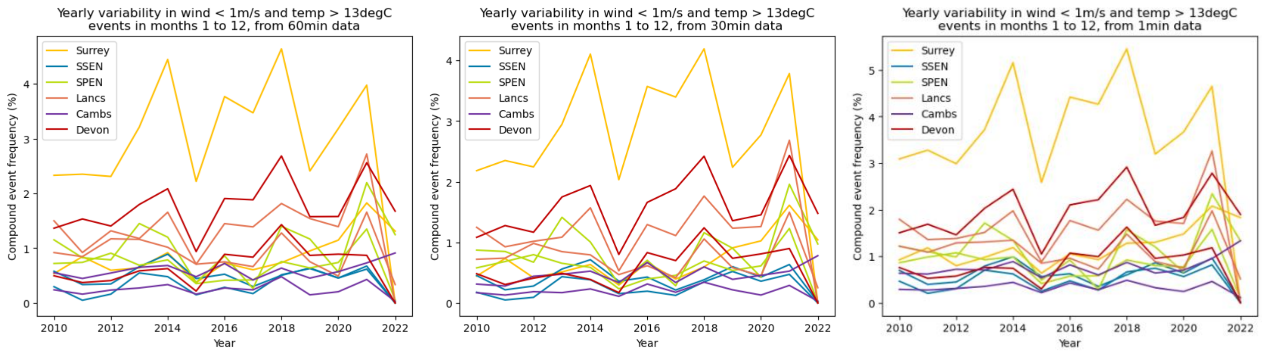

Figure 12: The medium-strict yearly thresholds produce yearly variability plots that look extremely similar across sampling frequencies. Left: hourly data, middle: 30min data, right: 1min data.

Higher frequency observation data identifies a higher number of individual events, where wind and temperature values that exceed their thresholds have not been smoothed out by the resampling to lower frequencies. At all frequencies, the majority of events are of low duration (**Error! Reference source not found.**).

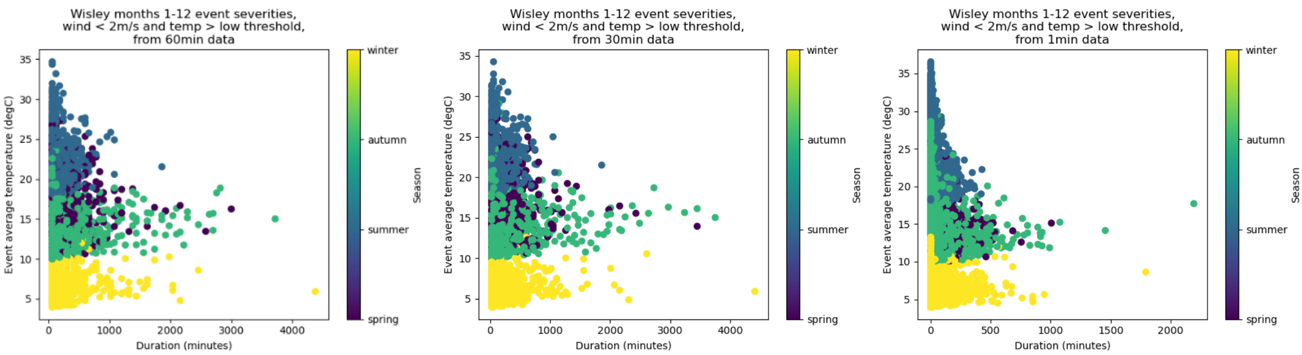

Figure 13: Comparing Wisley event severity metrics across sampling intervals, where wind <2m/s and temperature is above the low thresholds for each season (Table 3). Smaller sampling frequencies return a few higher temperature events, and events of lower duration.

At 60- and 30-minute frequencies, the distribution of event average temperatures and durations is most similar. 1-minute frequency data means any short-duration high temperatures are captured, rather than smoothed out. This also means that the winter event temperatures overlap more into the autumn and spring event temperature range than is seen for more coarse sampling frequencies. Durations also tend to be shorter for the 1-minute data since it has more fluctuations than longer interval data will, making it more likely that there will be a non-occurrence over consecutive timesteps.

5 Conclusions

The main findings from the data exploration with regards to the initial aims of the data exploration are outlined below:

How does the frequency and severity of low wind speed high temperature events vary over time?

- There is large interannual variability in the frequency and severity of the events. This indicates that using the full length of our dataset is important as looking at a few years in isolation may not represent the full variability in event frequency and severity that should be considered when determining line ratings. Ideally, a dataset even longer than 12 years would be used to characterise the current climatology, for which at least 20, or 30, years is typically recommended.
- A longer dataset would be required to fully investigate the impact of climate change on these events since the current ratings were established in the 1980s. There is a hint at a possible climate change signal of warmer winters in the south of the UK in recent years, but a much longer dataset would be required to establish whether this may be just a large natural variation.

How does the frequency and severity of low wind speed high temperature events vary by season?

- Independently, both low wind speed events and high temperature events occur most frequently in summer, and least frequently in winter. As a compound event, these are therefore also most frequent in summer. The choice to use different temperature thresholds per season was to capture the high-risk end of the temperature distributions in each season.
- The most severe events, quantified by event duration and average temperature, occur in the summer months. However, there is also high risk in autumn and spring, with high average event temperatures still being reached, and autumn in particular having many long duration events. This indicates that looking at summer in isolation is not a suitable approach for considering what conservative line ratings may be required.

How does the frequency and severity of low wind speed high temperature events vary by location?

- Temperature distributions between regions are offset most in summer, and least in winter. This suggests that uniform line ratings across the country would be safer in winter than they would be in summer.
- More severe events are more likely in autumn and spring in more southerly regions, such as Surrey, than sites further north, where the most severe events mostly occur in the summer.
- There is also more seasonality in more southerly regions, implying that a yearly average line rating for a region would be more risky if applied there.
- Some regions, such as Cambridgeshire, have fewer low wind speed events. Further investigation into the exposure of the location of OHLs, would be beneficial to understanding whether the results from the stations investigated are fully representative of the occurrence of events in locations of OHLs.
- Further work should be conducted looking at the impact of site geography in more detail to isolate any effect of flat vs mountainous, inland vs coastal, and urban vs rural site status on event frequency and severity.

How does the frequency and severity of low wind speed high temperature events vary with the sampling frequency of the weather data?

- Sampling frequency does not have a notable impact on event frequency, returning very similar yearly variability patterns.
- Shorter sampling frequencies return more shorter events, since there is more fluctuation in the data.
- Shorter sampling frequencies capture shorter-lived higher temperatures that are smoothed out by longer sampling frequencies. However, this may not matter if the line temperature does not react quickly enough to high frequency temperature fluctuations – this is one of the questions being explored by Energyline.

6 Recommendations

Based on this initial exploration there are some important findings that should influence how the weather data is used in the line rating calculations. There are also several aspects which require further investigation during the rest of the alpha phase of this project, or potentially in the beta phase of the project. These can be summarised as:

- There is a large amount of interannual variability so multiple years of weather data should be used. We recommend at least 10 years of data should be used. We should consider whether up to 30 years of data should be used.
- Using the longer dataset available from gridded models of weather data to explore any climate change signal during the beta phase of the project.
- We recommend that line ratings should vary throughout the year, but that the traditional season definitions are unlikely to be the optimal split of months into periods of similar risk for line rating definitions. We recommend that further investigation into how to group months into periods of similar risk is carried out in the beta phase of the project.
- Regional variations in line ratings are likely to be possible and we will continue to develop our understanding of how regional line ratings could be implemented during the project. We recommend that we continue to investigate regional variations as we develop the methodology for line ratings. We also recommend that other geographic conditions are considered, including proximity to coast, the local terrain, and any sheltering a site experiences.
- The initial data exploration has shown that similar low wind speed and high temperature events are seen in the 30 minute and one hour frequency data. Further recommendations on the frequency of weather data that we should use should be available from work package 2 and further exploration of the weather data on different temporal frequency may be required.
- We recommend refining the wind and temperature thresholds used to identify high risk events based on modelling of overhead line temperatures by the University of Strathclyde. Refined thresholds could be used to look for events in the model datasets in comparison to the observation data in during work package 5 of the alpha phase.

7 References

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Karam, M. (2023). *Application of Adaptive Neural Network (ANN) to Estimate and Assess the Validity of Present Practices whilst Assessing Real Time Conductor Rating.* University of Strathclyde.

National Grid. (2022, 10 20). National Grid trials new technology which allows more renewable power to flow through existing power lines. Retrieved from https://www.nationalgrid.com/national-grid-trials-new-technology-which-allows-more-renewable-power-flow-through-existing-power

Price, C., & Gibbon, R. (1983). *Statistical approach to thermal rating of overhead lines for power transmission and distribution.* IEE proceedings.

Appendix A: Details of 30 stations in observations quality assurance

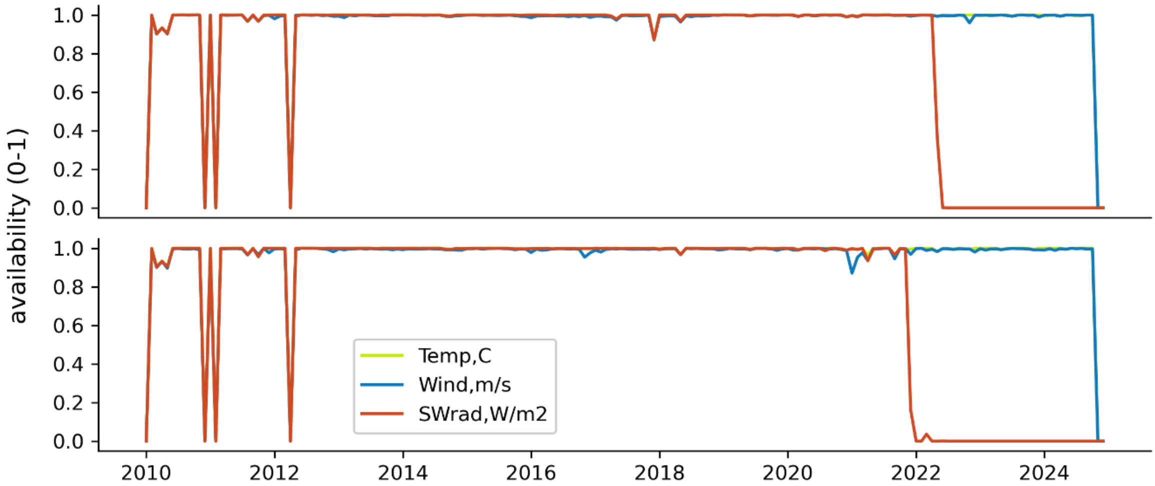
Region	Station	Latitude	Longitude	NGR	Elevation agl, m	Year opened
SSEN	Aviemore	57.2063	-3.8283	NH896143	228	1982
	Kinloss	57.6455	-3.5635	NJ067628	5	1950
	Loch Glascarnoch	57.7248	-4.8955	NH276742	269	1992
	Tain Range	57.8188	-3.9667	NH832827	4	1989
	Tulloch Bridge	56.8666	-4.7080	NN350782	249	1982
SPEN	Charterhall	55.7086	-2.3845	NT759461	115	1987
	Dundrennan	54.8033	-4.0079	NX710472	113	1983
	Edinburgh, Gogarbank	55.9283	-3.3443	NT161714	57	1998
	Eskdalemuir	55.3119	-3.2069	NT234026	236	1908
	Leuchars	56.3773	-2.8620	NO468208	10	1921
Lancs	Hawarden Airport	53.1754	-2.9863	SJ341647	11	1944
	Lake Vyrnwy No 2	52.7573	-3.4654	SJ012187	360	1988
	Leeming	54.2970	-1.5330	SE304891	33	1944
	Shap	54.5021	-2.6849	NY557120	263	1982
	Shawbury	52.7947	-2.6647	SJ552221	72	1944
Cambs	Bedford	52.2270	-0.4654	TL049598	85	1956
	Holbeach No 2	52.8733	0.1385	TF440327	3	1985
	Monks Wood	52.4016	-0.2370	TL200796	41	1963
	Waddington	53.1754	-0.5234	SK987652	68	1946
	Wittering	52.6118	-0.4679	TF038026	74	1955
Devon	Cardinham, Bodmin	50.5022	-4.6669	SX109703	200	1974
	Liscombe	51.0869	-3.6089	SS874331	348	1993
	North Wyke	50.7687	-3.9039	SX658983	177	1965
	St Athan	51.4054	-3.4407	SS998683	49	1988
	Yeovilton	51.0064	-2.6428	ST549231	20	1964
Surrey	Charlwood	51.1441	-0.2294	TQ239398	67	2002
	Heathrow	51.4795	-0.4532	TQ075767	24	1947
	Kenley Airfield	51.3040	-0.0915	TQ331578	170	1988
	Kew Gardens	51.4819	-0.2944	TQ185772	6	1910
	Wisley	51.3108	-0.4763	TQ062579	38	1904

____ Priority weather stations in flat, well exposed locations (yellow)

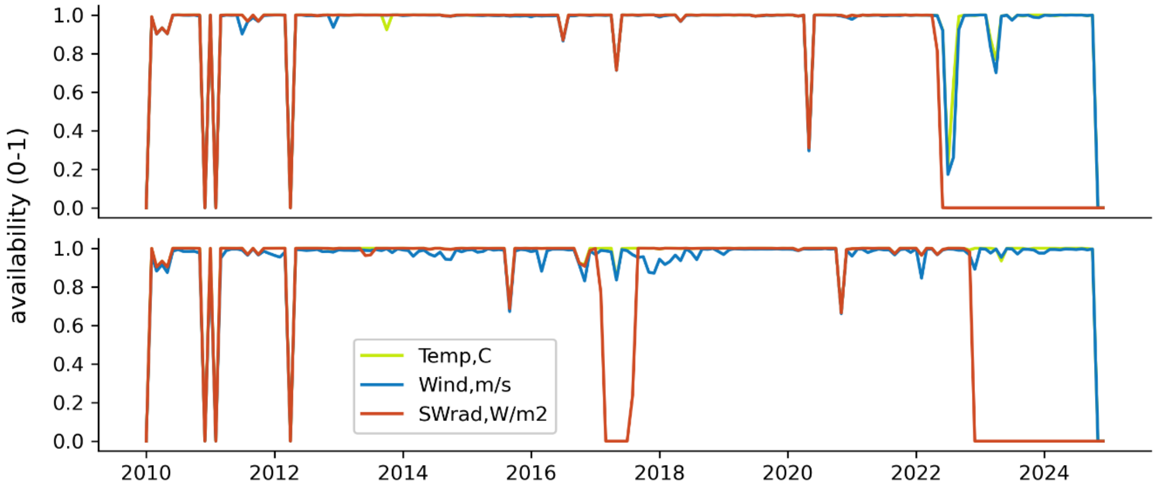
____ Priority weather stations in more rugged or less exposed locations (light green)

Appendix B: Priority sites' availability of quality controlled observations data

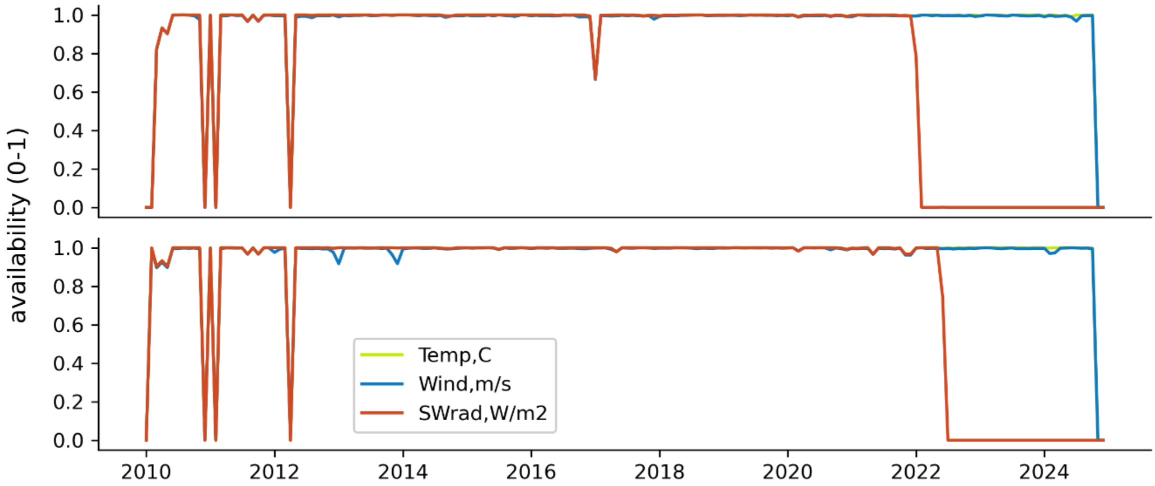
SSEN region: Tain Range (top) and Loch Glascarnoch (bottom)



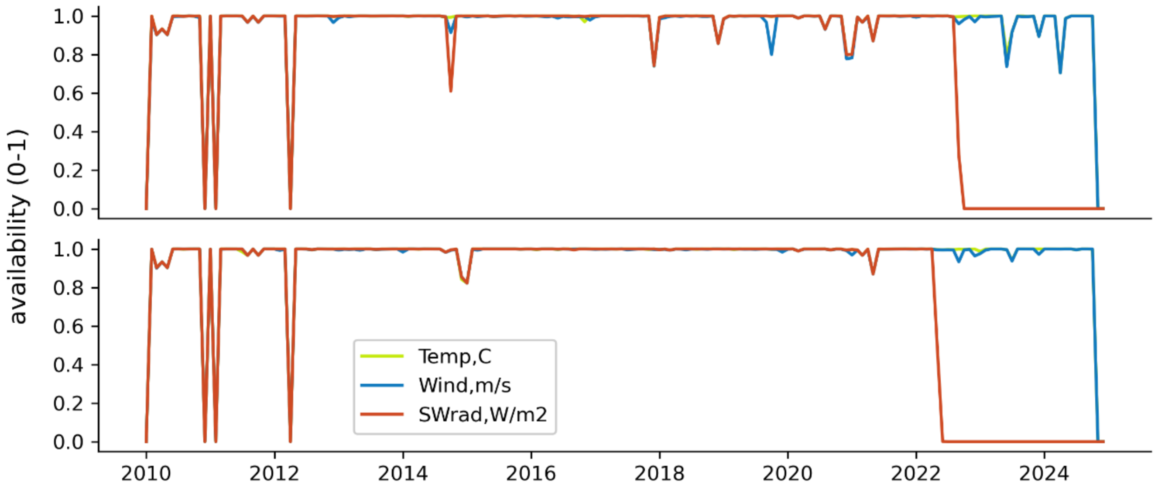
SPEN region: Charterhall (top) and Eskdalemuir (bottom)



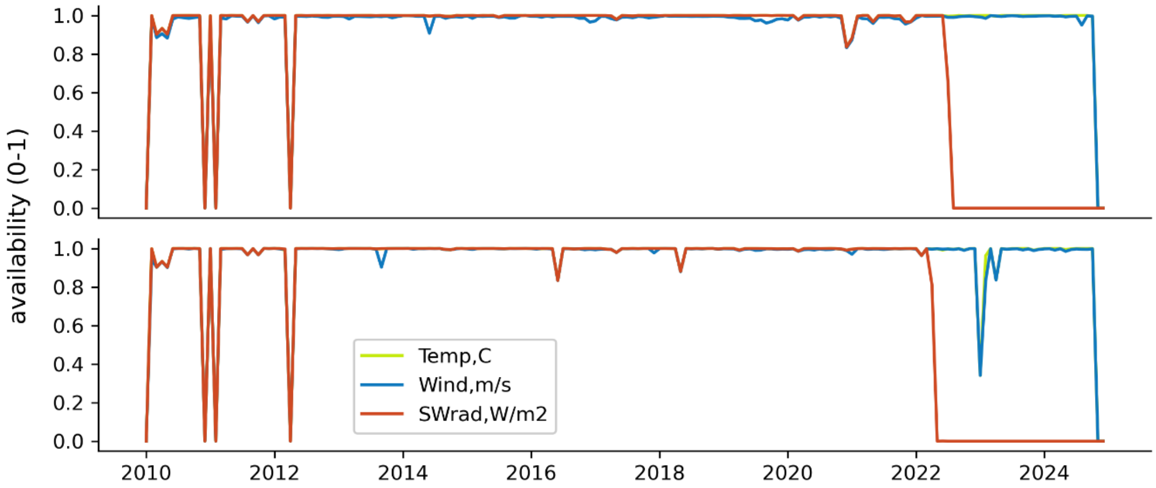
Lancashire region: Hawarden Airport (top) and Leeming (bottom)



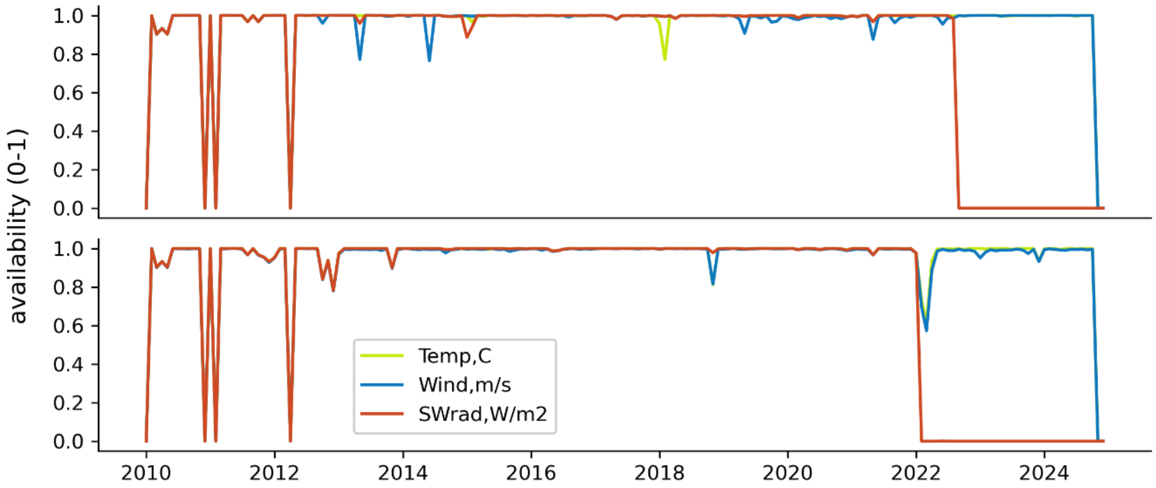
Cambridgeshire region: Wittering (top) and Holbeach No2 (bottom)



Devon region: Yeovilton (top) and Liscombe (bottom)

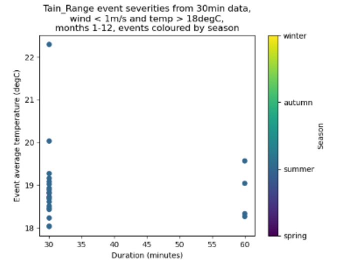
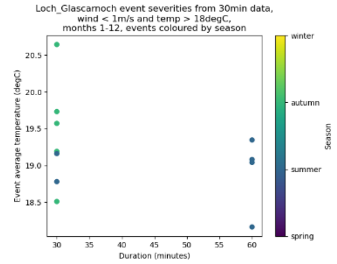
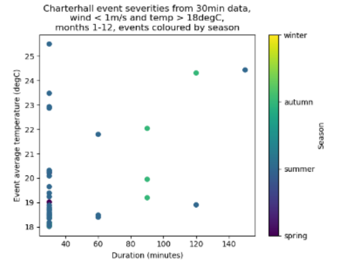
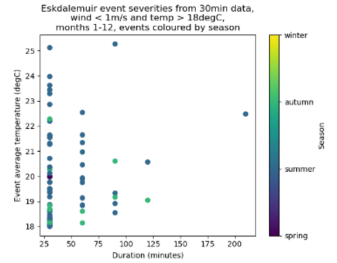
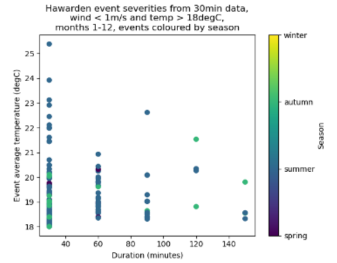
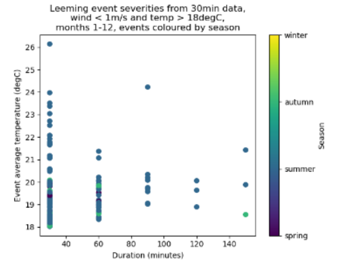
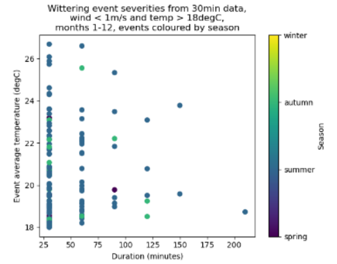
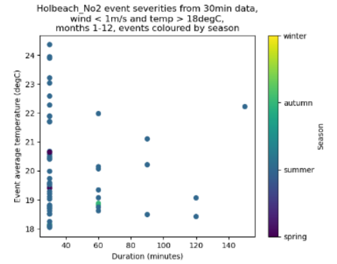
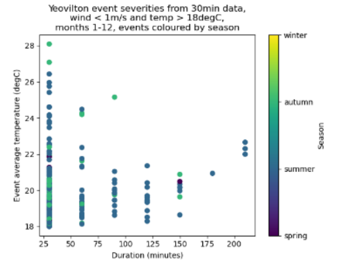
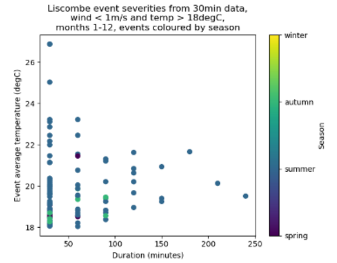
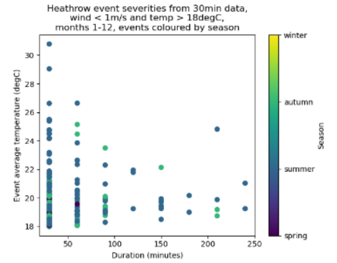
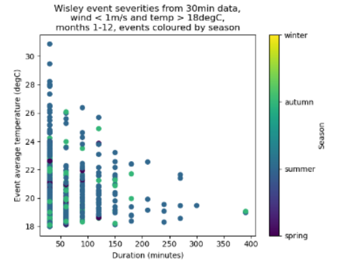


Surrey region: Heathrow (top) and Wisley (bottom)

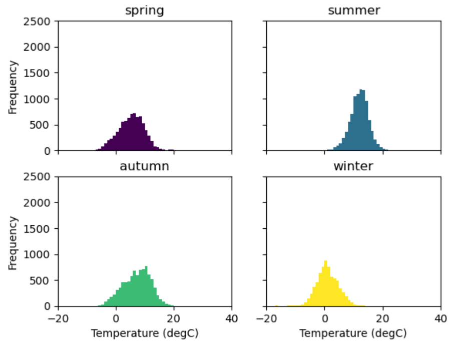
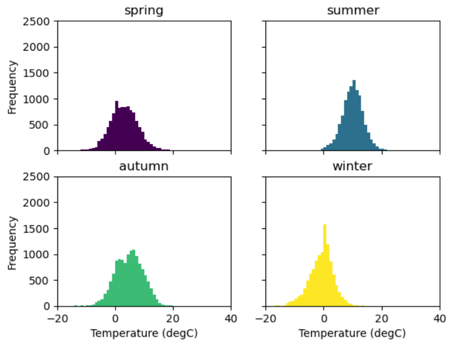
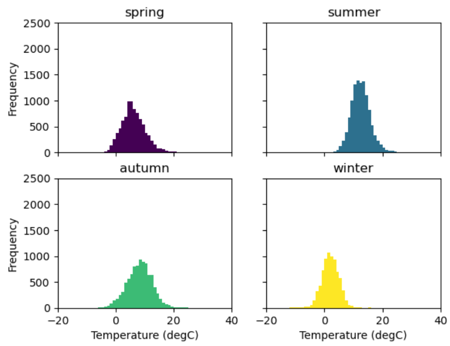
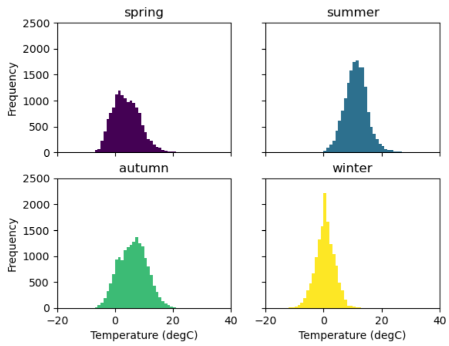
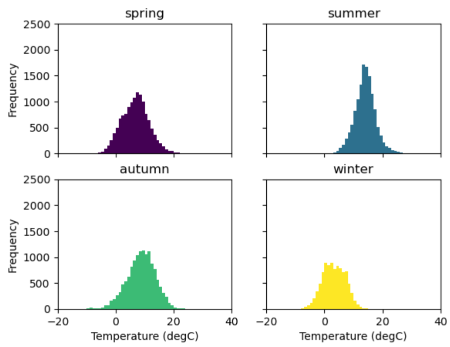
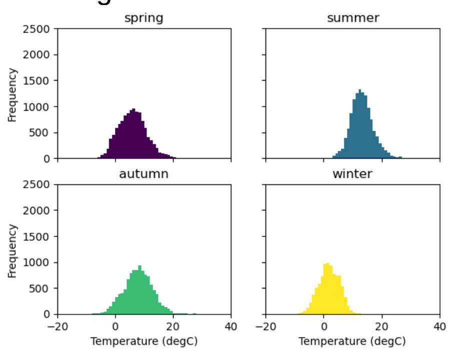
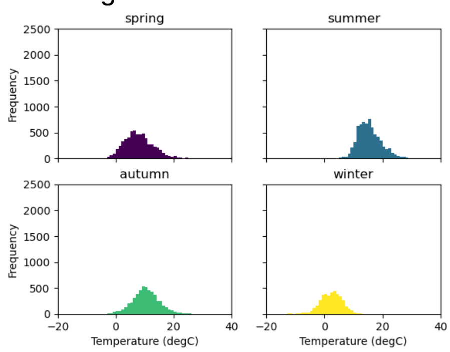
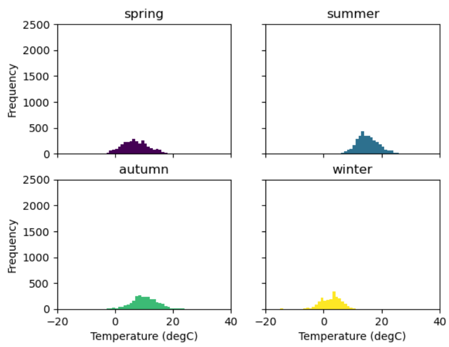


Appendix C: Data exploration extra plots

Event severities for wind speed < 1m/s and temperature > 18C

Region	Flat site	More geographically complex site
SSEN		
SPEN		
Lancashire (sites comparably flat/exposed)		
Cambridgeshire (sites comparable flat/exposed)		
Devon		
Surrey		

Temperature distributions for wind speed < 2m/s

Region	Flat site	More geographically complex site
SSEN	Tain Range 	Loch Glascarnoch 
SPEN	Charterhall 	Eskdalemuir 
Lancashire (sites comparably flat/exposed)	Hawarden 	Leeming 
Cambridgeshire (sites comparable flat/exposed)	Wittering 	Holbeach No2 
Devon	Yeovilton	Liscombe

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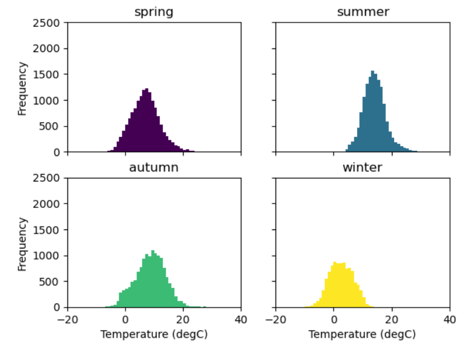
<td>
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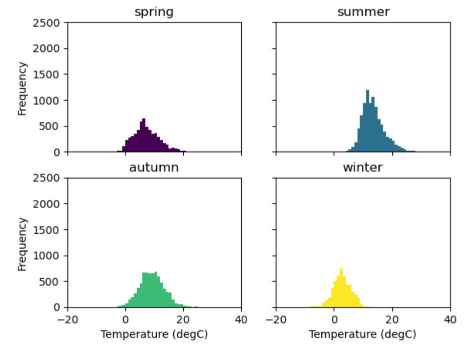
<td>
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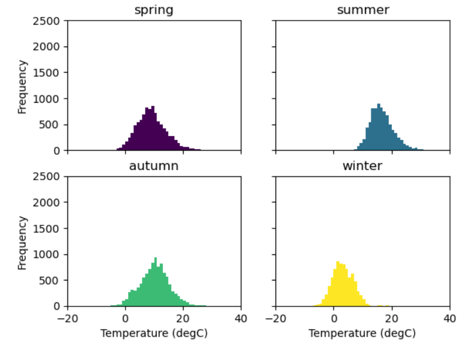
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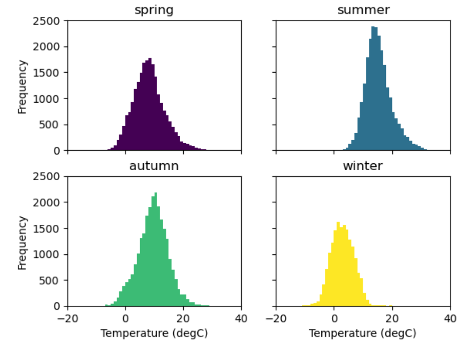
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