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Climatological Note No. 21

CLIMATE DATA FOR USE IN BUILDING DESIGN – PAST AND FUTURE WEATHER FILES FOR OVERHEATING RISK ASSESSMENT

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Contents

1 Introduction

The climate of Ireland is changing. Consequently, the Department of Housing, Local Government and Heritage funded this project to update 'Climate maps and data to support building design standards in Ireland'. The motivation of this particular work was to produce a set of representative 'weather files' for use in the building energy modelling sector.

The warming climate is a challenge for society which requires both adaptation and mitigation in order to deal with its impacts, as was highlighted by the recent IPCC report (Masson-Delmotte et al., 2021). One area which has the potential to be substantially impacted is the built environment (Bamdad et al., 2021), as increasing temperatures will lead to either more overheating or greater cooling demands in buildings. Which might lead to either more negative health outcomes for occupants (Holmes et al., 2016; Lomas and Porritt, 2017; Santamouris, 2020) or would lead to higher costs due to greater energy consumption (Dodoo and Gustavsson, 2016; Santamouris, 2020). The use of building energy models are an important process in designing new buildings and researching new design methods (Brembilla et al., 2020; Virk et al., 2015). The conditions experienced within a building are the result of a variety of different influences. Building energy models simulate the interaction of these factors and return output that represents the expected ambient conditions within the building. This can include the heating and ventilation from the building's own infrastructure, but also can be influenced by the external environment, including the weather. Providing realistic input data for these models is important to accurately assess the ability of a building to cope with typical conditions experienced in the recent past, as well as conditions which are projected to occur in the future (Herrera et al., 2017). These weather-based input files (often referred to as simply "weather files") comprise of 365 days of hourly data from a range of weather variables that have the potential to have an impact on the ambient conditions within a building. These include temperature, humidity, solar radiation, wind and pressure. Previously the only weather files that existed in Ireland were the CIBSE files for Belfast. This work aims to rectify this by providing the relevant data for a number of locations around the country. This will allow building designers/modelers to simulate building performance more accurately using weather data which is representative of Irish locations and help Irish building designers to meet sustainability goals, such as the EU Taxonomy (TEG, 2020a, 2020b).

These 'weather files' typically come in two forms: a Test Reference Year (TRY), which represents a single year of the representative average conditions, and Design Summer Years (DSYs), which are a collection of three years with summers that contained significant overheating events. For the TRY file each month is chosen individually based on a selection criteria from the overall dataset, which determines which was the closest to 'average' conditions, using some form of a statistical metric. This is repeated for all 12 months to produce the final file. In this case the Finkelstein-Schaefer statistic (Finkelstein and Schafer, 1971) was used, having been widely used previously for this purpose elsewhere globally (Eames et al., 2016; Lam et al., 1996; Lee et al., 2010). Meanwhile the DSY files are selected as an entire single year based on an extreme value analysis of an overheating metric. DSYs enable building designers and modelers to simulate building performance during periods of extreme overheating. The Static Weighted Cooling Degree Hours (SWCDH) has been used as an overheating metric in the UK (Eames, 2016), and the same method was employed for this work also. As well as representations of weather conditions based on past data, which are likely to be relevant in the short term, there is also a need to consider the projected affects of climate change. To produce future TRYs and DSYs, climate model output is used to simulate future scenarios. This comes with challenges, as the requirement to have TRYs and DSYs at hourly resolution remains, but the majority of climate model data is not stored at such a high temporal resolution. Different methods have been used in the past to navigate this issue, such as 'weather generators' (Eames et al., 2011) or the 'delta-change' method (Jylhä et al., 2020; Velashjerdi Farahani et al., 2021; Wehrli et al., 2022). The delta-change approach was employed here to produce the future files under 27 different climate scenarios (combinations of time periods, emission scenarios and model sensitivities) for both TRY and DSYs.

The principal deliverable from this work was to produce a suite of TRYs and DSYs, for both past and future scenarios, at a representative collection of six Irish locations. These can be used when designing buildings to ensure that they are capable of coping with current conditions, as well as those that are projected in the future due to climate change. The remainder of this report presents an overview of the data and methods used the generate these files, along with a brief description of some results.

2 Methodology

The following section will present an overview of the data and methods used in this work. This includes the choice of stations and data used, the methods used to calculate the respective weather files and the methods used to generate the future weather files using climate model output.

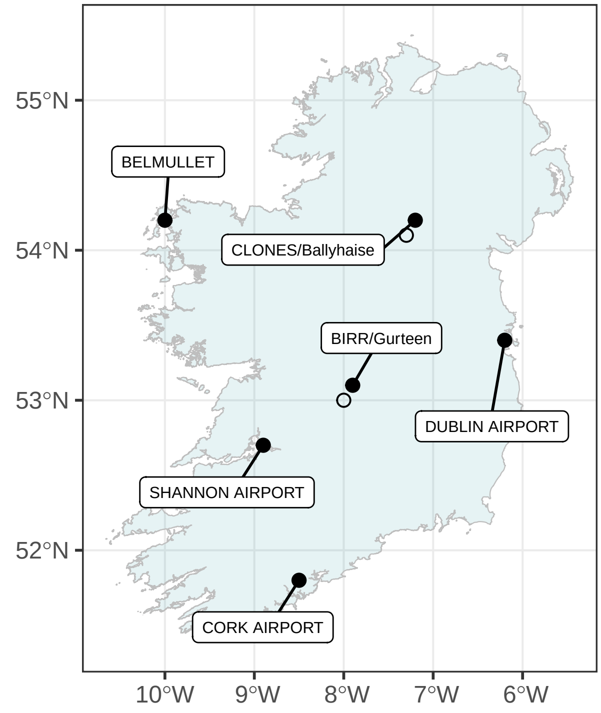

Figure 1: Map of six locations where TRY and DSYs were produced. Unfilled circles represent replacement stations that were used when the two stations in the midlands closed.

2.1 Location selection and data

Weather files are produced for specific locations, with a particular focus on large population centres. To capture a broad range of areas around Ireland the six locations shown in Figure 1, and also listed in Table 1, were chosen for analysis. These were chosen to give the broadest spatial coverage, including large population centres (the three airport locations) and a mix of both coastal and inland locations. Additionally stations were also chosen to make the best use of stations with long-term records of all variables required for producing weather files, particularly incoming solar radiation.

The two inland stations, Birr and Clones, were closed in the late 2000s. Both stations had long term records of all the variables required, Table 1, and as a result it was decided to merge them with the nearby stations of Gurteen and Ballyhaise respectively. This method of merging stations has been previously used for similar work in the UK where station closures have occurred (Eames, 2016; Eames et al., 2016). Each weather file has a prescribed set of weather variables that are required, namely: present weather code, cloud cover, 2m dry bulb temperature, 2m wet bulb temperature, relative humidity, mean sea-level pressure, 10m wind direction, 10m wind speed, global solar radiation and diffuse solar radiation. Each weather files is comprised of a 365 day year of data at an hourly resolution. The present weather code is allowed to have missing values (marked as "-999"), but all other variables need to have a complete set of 365 × 24 hours of data values in each weather file.

Table 1: List of six locations, with stations used and missing variables, where applicable.

Location	**Station(s)**	**Missing Variable(s)**
Belmullet	Belmullet (manual)	None
	Belmullet (automatic)	Cloud Cover
Birr	Birr	None
	Gurteen	Cloud Cover, Radiation
Clones	Clones	None
	Ballyhaise	Cloud Cover, Radiation
Cork	Cork Airport	Radiation
Dublin	Dublin Airport	None
Limerick	Shannon Airport	Radiation

Two particular challenges emerged with this criteria. Firstly some variables were not observed at certain stations and secondly some stations had data gaps at the site, which is common due to instrument calibration or similar station upkeep. The stations that had missing variables are listed in Table 1. The two airports in the south (Cork and Shannon Airports) do not have pyranometer measurements of radiation. Also the station at Belmullet became automated in 2012, when this happened the station no longer produced observations of cloud cover. Similarly the two replacement stations for Birr and Clones (Gurteen and Ballyhaise respectively) lacked both cloud cover and radiation observations. The general practice for dealing with data gaps when constructing weather files is to either interpolate or replace the data. As most data gaps encountered were typically over a number of hours, in which case interpolating across these gaps would offer little value, the decision was taken to fill all data gaps using reanalysis data for both scenarios described above.

The ERA5 reanalysis (Hersbach et al., 2020), produced by the European Centre for Medium-range Weather Forecasting, was selected for this purpose as it has been demonstrated to model these weather variables well (Babar et al., 2019; Doddy Clarke et al., 2021). Data from the reanalysis was bilinearly interpolated using the nearest surrounding grid-points to the station and used as a proxy for observations when required. This ensured a continuous series of hourly observations to be used when selected and constructing the resulting weather files.

Aside from meteorological data, weather files also require information on solar angles, namely the solar altitude and declination. A Microsoft Excel-based solar calculator produced by NOAA (NOAA, 2022) was adapted into an R function and used to calculate the relevant angles, based on station coordinates and the year being considered. With these, all the necessary data were in place to generate the representative weather files from past data.

2.2 Test Reference Year (TRY)

As mentioned in Section 1, the TRY is used to capture average climatic conditions that will be influencing the building externally (Eames et al., 2016). In order to create this file, each month is considered in isolation and a representative example of this month is selected from a 30-year reference period. In this case for the past TRY, the period 1991-2020 was used. For example, the January that represents the "most average" conditions is selected from the 30 different Januarys from 1991-2020 . In order to select a given month, a measure is required to assess how far a given month is away from its average conditions. One such metric is the Finkelstein-Schaefer (FS) statistic (Finkelstein and Schafer, 1971) which has been widely used for this particular application (Eames et al., 2016; Lam et al., 1996; Lee et al., 2010). This measures the difference in the cumulative density function (CDF) of daily mean values of a weather variable within a given month and year versus the CDF of values for all years of that given month.

When selecting a month for the TRY, the FS statistic was calculated for temperature, relative humidity, global radiation and wind speed. The mean of the FS values for 2m temperature (FS_T), relative humidity (FS_H) and global solar radiation (FS_R) were calculated. This combined FS score (FS_C) was defined as follows:

$$FS_c = \frac{FS_T + FS_H + FS_R}{3}. \tag{1}$$

The selection of a TRY month was then made using a two step process. Firstly the three years with the lowest values of FS_c were selected. Of those three years, the year with the lowest FS value for 10m wind speed was then selected as the month to be included in the TRY. This was then repeated for all months to select the 12 months to make up the TRY.

Consecutive months that make up a TRY are generally unlikely to come from the same year, therefore the end of a given month might not match up to the start of the next month; e.g. if the January TRY might be from 1993 and the February TRY from 2004. This may lead to non-physical jumps in the data at these month boundaries. To accommodate this, smoothing functions were employed. A time window of ±12 hours around the month boundary were chosen for smoothing using local regression (LOESS: locally estimated scatterplot smoothing) method (Cleveland et al., 1992) in the event that the two months came from different years.

2.3 Design Summer Years (DSYs)

The DSYs are weather files which are used to capture the weather from years that contain particularly warm summers, which may stress a building from the perspective of overheating (Eames, 2016). Unlike the TRY, the DSYs are not a composite of months from different years. A single year is selected based on some selection criteria using metrics of overheating. Initial work in this area selected a single year to represent the DSY with a moderate overheating event (CIBSE, 2002). Further work found that more intense DSYs would also be needed to capture the extremes that can occur (Eames, 2016; Jentsch et al., 2014). As a result three DSYs are now produced for a given location as standard practice (Eames, 2016). DSY1 represents a typical overheating event, it was initially classified as being the 3rd warmest summer in a 20 year period (Jentsch et al., 2014). This was later updated to be defined as the summer with a return period of 7 years, when past overheating data were fitted to a generalised extreme value (GEV) distribution, as outlined in (Eames, 2016). The DSY2 and DSY3 were then chosen from the remaining years with greater return periods than the DSY1 and are characterised by short/intense and long overheating events respectively (Eames, 2016).

Analysis of DSYs in the UK considered a range of overheating metrics, namely the Weighted Cooling Degree Hours (WCDH), Threshold Weighted Cooling Degree Hours (TWCDH) and Static Weighted Cooling Degree Hours (SWCDH). Both WCDH amd TWCDH are calculated using a “comfort temperature” (T_c), which is based on an adaptive thermal comfort model. In the UK, it was found that WCDH produced too few overheating events at temperate locations like Belfast and Edinburgh, which made fitting the GEV distribtuion problematic (Eames, 2016). This was also found for the Irish locations. Therefore the SWCDH was exclusively used for DSY selection. The SWCDH is defined as follows:

$$SWCDH = \sum_{T > T_{rt}} (T - T_{rt})^2, \tag{2}$$

where T_{rt} is the regional threshold temperature. This is calculated as the 93rd percentile of two-day rolling mean of daily maximum temperature, as done in Eames, 2016. This was interpreted from Armstrong et al., 2011, based on adverse health outcomes during heatwaves. The thresholds are listed in Table 2.

Table 2: Regional threshold temperatures (T_{rt}) for calculating SWCDH at each location.

Station	Threshold (°C)
Belmullet	18.7
Birr	20.6
Clones	20.1
Cork	19.3
Dublin	20.3
Limerick	20.8

The year for DSY1 was established by calculating annual sums of SWCDH across all hours in the year, according to Equation (2). The values for a 30 year period (1991-2020) were used to fit a GEV distribution, using a maximum likelihood estimation approach (Virtanen et al., 2020). Return periods were then calculated for all years in the dataset. The year with a return period closest to 7 was then selected as DSY1. The remaining years with a return period greater than 7 were then isolated and the individual overheating spells within each year were examined. A spell was considered a prolonged period where the daily sum of SWCDH was greater than 0. If two spells are separated by two days or less of zero SWCDH, they are considered part of the same spell. From this set of spells, they were sorted by accumulated SWCDH and the spell duration and average intensity were calculated. The spell with the highest average intensity and the longest duration were assigned as DSY2 and DSY3 respectively.

2.4 Climate projections

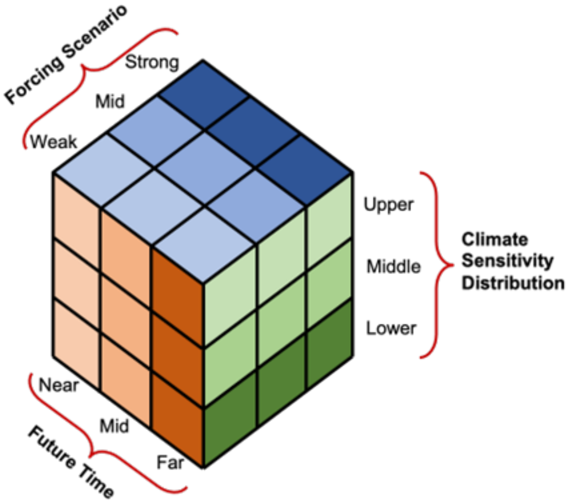

Figure 2: "Rubik's Cube" representation of TRANSLATE climate scenarios, with different axes for emissions, time periods and model sensitivities. Taken from (O'Brien, Enda and Nolan, Paul, in press).

There is also a need to produce a set of future weather files to consider the conditions that are expected to be experienced by buildings in the future due to the warming climate. To do this a collection of TRYs and DSYs were generated for future climate scenarios through the use of climate model output. Future weather files, just like their past equivalents, require data to be at an hourly resolution. Typically, climate model data are not stored at such fine temporal resolution. Previous work in the UK has made use of "weather generators" to temporally downscale climate model output using a statistical approach (Eames et al., 2011). This typically relates a single variable in the climate model output (e.g. daily mean precipitation) to a range of other variables (temperature, pressure etc), through the use of a statistical model. An alternative method called "delta-change" has been demonstrated as a viable method to generate hourly future projections from climate model data at a daily resolution (Michel et al., 2021). Different versions of this methodology have been employed previously for similar building energy applications (Jylhä et al., 2020; Velashjerdi Farahani et al., 2021; Wehrli et al., 2022). In this case day of year (DOY) averages are calculated for both historic and future climate runs of a given variable, which are then smoothed using a Fourier series. For temperature the delta is calculated as the difference between the future and historical smoothed DOY averages. While for all other variables, the delta is the ratio of these two quantities. These are then applied to a set of hourly observations, either by addition for temperature or scaling for other variables, to generate an hourly representation of future weather conditions for a given climate scenario. This was employed here at the 6 locations.

Output from Met Éireann's TRANSLATE project was used to form the input data for this work (O'Brien, Enda and Nolan, Paul, in press). TRANSLATE is a multi-institutional project which produced a standardised set of climate projections for Ireland, pooling together and post-processing a large number of regional climate model simulations with domains over the country. A combination of a high-resolution downscaled dataset produced by the Irish Centre for High-End Computing (Nolan and Flanagan, 2020) and the Euro-CORDEX ensemble (Jacob et al., 2014) were used as input for TRANSLATE. These datasets are formed of different combinations of regional climate models applied to downscale a collection of global climate models from CMIP5. These data have been categorised in a 3 × 3 × 3 matrix (or "Rubik's Cube"), with each axis representing the time period, emission scenario or model sensitivity, see Figure 2 for an illustrative overview. The three time periods considered were "near-term" (2021-2050), "mid-century" (2041-2070) and "end-century" (2071-2100) conditions, along with historical values for 1976-2005. The emission scenarios are based on representative concentration pathways (RCPs) and are categorised as low (RCP2.6), medium (RCP4.5) and high (RCP8.5) emission scenarios. Lastly the model sensitivity was selected based on the temperature change produced over Ireland by each of the individual global models that comprised the TRANSLATE ensemble. These are accordingly classified as "low", "mid" and "high" sensitivity. Models which use the MPI (Max Planck Institute) global climate model were classified as low sensitivity, models driven by the UK Met Office's HadGEM2-ES global climate model were classified as high sensitivity and the remaining models were classified as mid sensitivity. Temperature data from this climate ensemble have been de-trended (within each 30 year period), bias-corrected (using a quantile mapping approach) and re-gridded onto a common grid to produce a standardised set of projections.

The historical period for the TRANSLATE ensemble was 1976-2005, therefore the previously discussed delta-change method was applied to hourly observations from this same 30-year period at the same 6 locations, see Figure 1. The future "deltas" were calculated for each of the variables required for the files, with differences used for temperature and ratios used for the other remaining variables. These differences or ratios were then applied to the set of hourly observations, e.g. the difference/ratio for DOY = 1, would be applied to all 24 hours of 1st of January for each year from 1976-2005. This is repeated for all 365 days of the year to produce a representation of an hourly future climate projection. This was repeated for all 27 elements of the TRANSLATE "Rubik's cube" scenarios, to generate the full set of future scenarios. These data were then used to calculate a future TRY and DSYs, following the methods outlines in Sections 2.2 and 2.3, for each given climate scenario. While all 27 scenarios were calculated, a subset of 18 scenarios will be released. These align with the scenarios considered in the CIBSE future output. The final dataset produced comprises of 4 future weather files (1 TRY + 3 DSYs) per scenario, leading to a total of 72 future weather files per location.

3 Results

This section presents some findings from the production of both past and future TRYs and DSYs for locations in Ireland. Outlining the application of methods outlined in Section 2 and highlighting the projected changes in overheating for different future climate scenarios.

3.1 Past TRY

Table 3: Constituent months for each of the past TRYs at the six locations.

Month	Belmullet	Birr	Clones	Cork	Dublin	Limerick
Jan	2003	2013	2006	1995	2006	1999
Feb	2004	2008	2008	2003	2003	2008
Mar	1993	2007	2009	1993	2004	1993
Apr	2005	2002	2019	2003	2004	2018
May	2006	2009	1991	2017	2002	1993
Jun	2008	2000	2013	2008	2000	2005
Jul	2008	2008	1996	1996	2005	2005
Aug	2013	1999	2001	2018	2006	2007
Sep	2003	2001	2010	2005	2001	2020
Oct	1994	1999	1994	2010	2010	1999
Nov	2009	1998	2009	2003	2004	2006
Dec	2019	2017	2014	2019	2017	2019

The methods outlined in Section 2.2 for selecting the months in a Test Reference Year were applied at all six locations. The resulting collection of months making up the TRY at each location are summarised in Table 3.

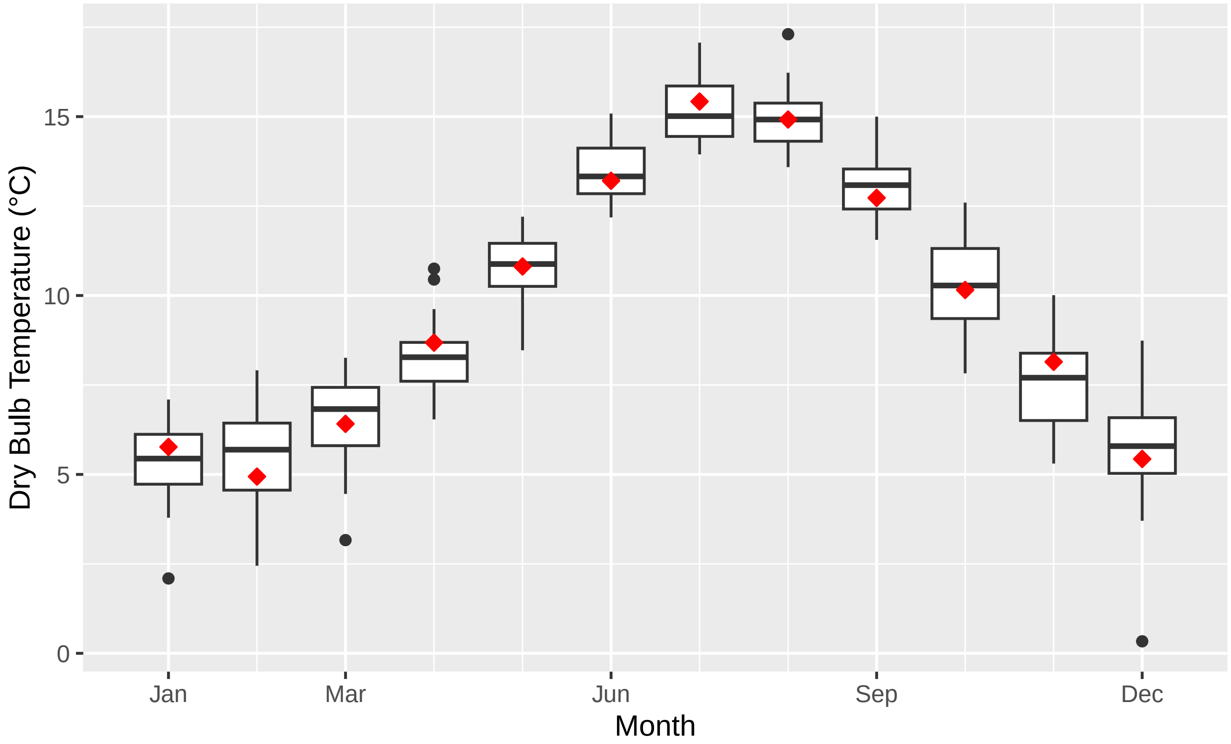

Figure 3: Boxplots of monthly mean 2m dry bulb temperature at Dublin Airport for 1991-2020. The monthly mean dry bulb temperature for each TRY month is shown by the red diamond markers.

The aim was to select months which best captured the most average conditions across the variables of interest, temperature, humidity, solar radiation and wind speed. This is shown in Figure 3 for dry bulb temperature at Dublin Airport, where the TRY month (red diamond) is generally close to the median value for the month as a whole (central line in boxplot), based on 30 years of data.

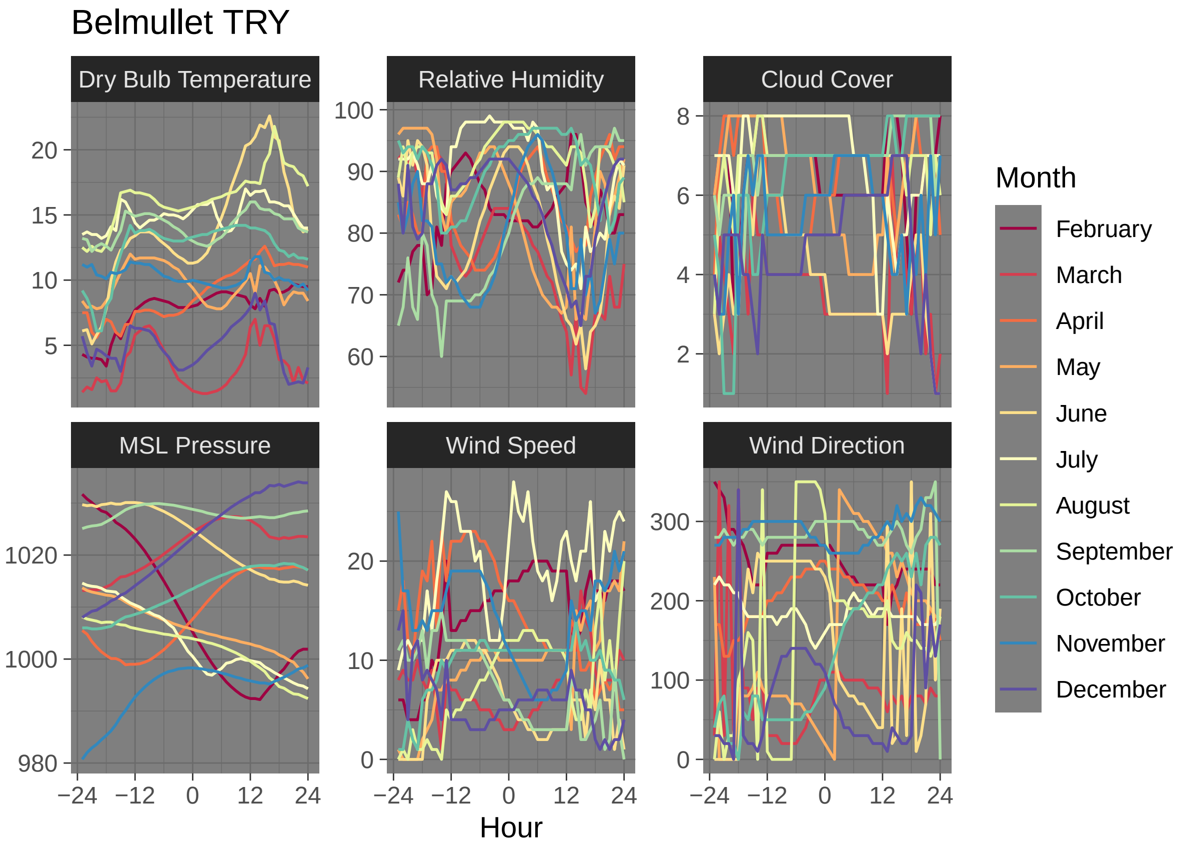

Figure 4: Month boundary data for different months (colours) in the past TRY at Belmullet within a 48 hour window around the month change for dry bulb temperature , relative humidity, cloud cover, mean sea-level pressure, wind speed and wind direction.

The smoothing of data between months was performed when consecutive months were taken from different years to avoid large non-physical jumps in the data. This is shown for Belmullet in Figure 4. Notably, the month boundary for July (light yellow) has not been smoothed as the months of June and July in the TRY at Belmullet come from the same year (2008, see Table 3), as a result smoothing was not required.

3.2 Past DSYs

Annual values of SWCDH were calculated at all six locations, using equation (2) and corresponding thresholds in Table 2. The resulting SWCDH values were then fitted to a GEV using a maximum likelihood estimate method, and return periods were calculated for the different observed values. These are shown for Belmullet, Dublin Airport and Shannon Airport in Figure 5, in a similar format to what was shown in Eames, 2016.

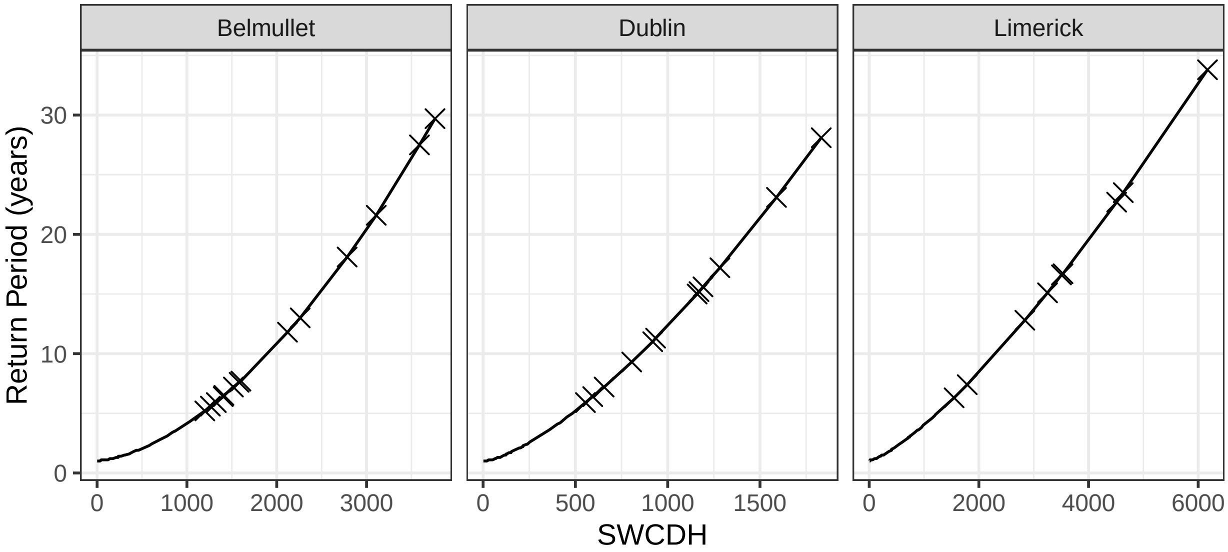

Figure 5: Plot of annual total SWCDH versus return period, based on fitted GEV distribution, at Belmullet, Dublin Airport and Shannon Airport.

Table 4: Annual SWCDH and associated return periods at Dublin.

Year	SWCDH	Return Period (years)
2017	593.8	6.4
2016	655.7	7.2
1976	805.2	9.3
1990	918.9	11.0
2013	934.5	11.3
2021	1159.7	15.0
2006	1169.7	15.2
1983	1191.3	15.6
1989	1283.0	17.2
2018	1589.4	23.1
1995	1832.0	28.1

These data were then used to make the selection for DSY1 at all locations, selecting the year with a return period that is closest to seven, as outlined in Section 2.3. This is shown in Table 4 for Dublin Airport, where 2016 was selected as DSY1 based on this criteria. The individual overheating spells that constituted the

Table 5: Individual overheating spells used to calculate DSY2/3 at Dublin, for years with higher return period than DSY1.

Year	Start	Duration (days)	SWCDH	Intensity
1995	1995-07-24	39	1399.3	35.9
2021	2021-07-13	12	1084.1	90.3
1989	1989-07-02	27	1019.6	37.8
2013	2013-07-05	28	873.3	31.2
2006	2006-07-15	15	830.3	55.4
1983	1983-07-02	13	816.7	62.8
2018	2018-06-23	17	754.8	44.4
1990	1990-07-23	11	608.3	55.3
1976	1976-06-21	17	526.4	31.0

Table 6: Past DSY years selected for all six locations.

DSY	Belmullet	Birr	Clones	Cork	Dublin	Limerick
DSY1	2018	1984	1975	2005	2016	2006
DSY2	2021	1976	2021	1983	2021	2021
DSY3	1995	1995	1995	1995	1995	1995

remaining years with a higher return period than DSY1 were then considered and are shown in Table 5. The years of 2021 and 1995 contained the overheating events with the highest average intensity and duration respectively. These years were selected as the DSY2 and DSY3 at Dublin Airport. This process was repeated to produce the 3 Design Summer Years at all six locations, with the resulting set of years shown in Table 6.

3.3 Future weather files (TRY and DSYs)

The delta change method was used to calculate deltas for all variables for all scenarios, as described in Section 2.4. An example is shown in Figure 6. An additive approach was used for 2m temperature, as shown in Figure 6, while a ratio/multiplicative method was used for all other variables. These ratios and differences were used to map the hourly observations from the historical period (1976-2005) to each of the 27 future climate scenarios. These were then used to calculate a corresponding TRY and set of DSYs for each scenario, using the same methods outlined in the previous sections.

To consider the impact of climate change, the annual total SWCDH was calculated for both the 3 past DSYs and 81 future DSYs at the six locations, Figure 6.

4 Discussion

The projected impact of warming due to climate change is evident Figure 7, with future values predicted to be higher than the past DSYs in all circumstances. The low emission scenario (RCP2.6, top row) produces a peak in overheating in the mid-century, with a small reduction for the end of century period (2071-2100). In the two other scenarios SWCDH is still increasing at the end of the century. There is a broad range of uncertainty, between model sensitivity and emission scenarios. In particular, the most pessimistic scenario scenario of high emissions (RCP8.5, bottom row) and high model sensitivity (the upper limit of the error bars, based on UK Met Office Had-GEM2 model) leads to substantial increases in the magnitude of overheating events.

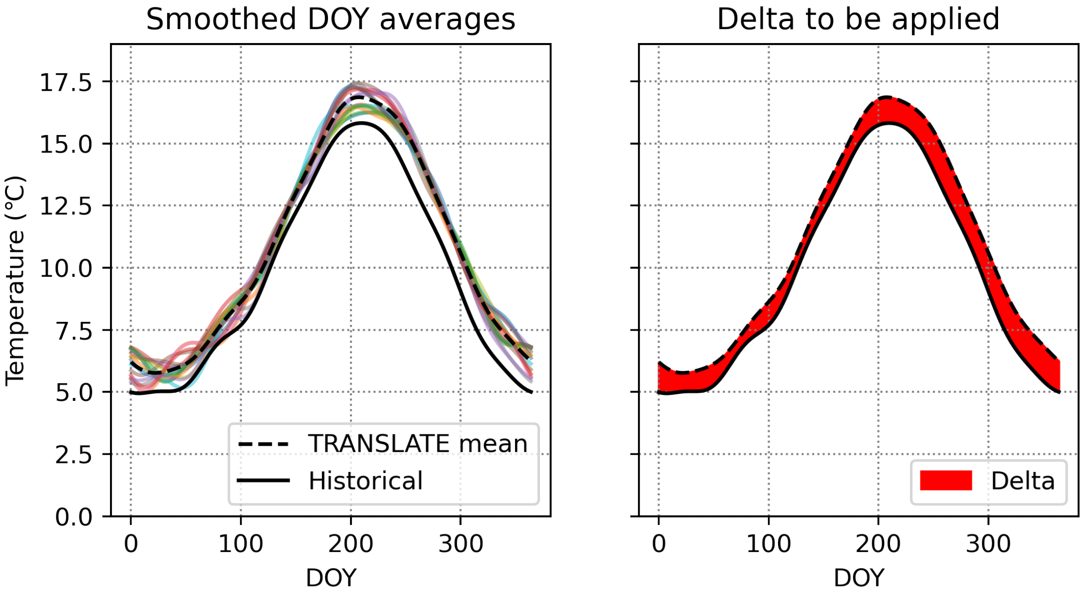

Figure 6: Example of delta change method for 2m temperature at Dublin Airport under RCP4.5 emission scenario for the period of 2041-2070 and models classified as mid sensitivity. Data has been day of year (DOY) averaged and smoothed using a Fourier series. Colours represent individual ensemble members. The black dashed line is the ensemble mean of the projections, with the historical values shown by the solid black line. The difference between the solid black line and the dashed black line (red shading in the right plot) is the “delta” which is applied to past obsevations to produce the hourly future projections.

5 Conclusions

This work has produced a set of past and future weather files at a selection of six Irish locations, comprising of some major population centres and a mix of coastal and inland locations. These data will enable building energy modellers to assess the ability of buildings to cope with both current and future climatic conditions when designing new buildings. This will allow them to test both the performance of the building during average conditions and varying amounts of overheating, which are expected to become more severe in the future.

Should you wish to get a copy of these weather files contact Met Éireann - The Irish Meteorological Service - enquiries@met.ie. A full list of available products and further details on data access can be found by visiting https://www.met.ie/climate/available-data/climate-data-for-thermal-modelling-of-buildings/.

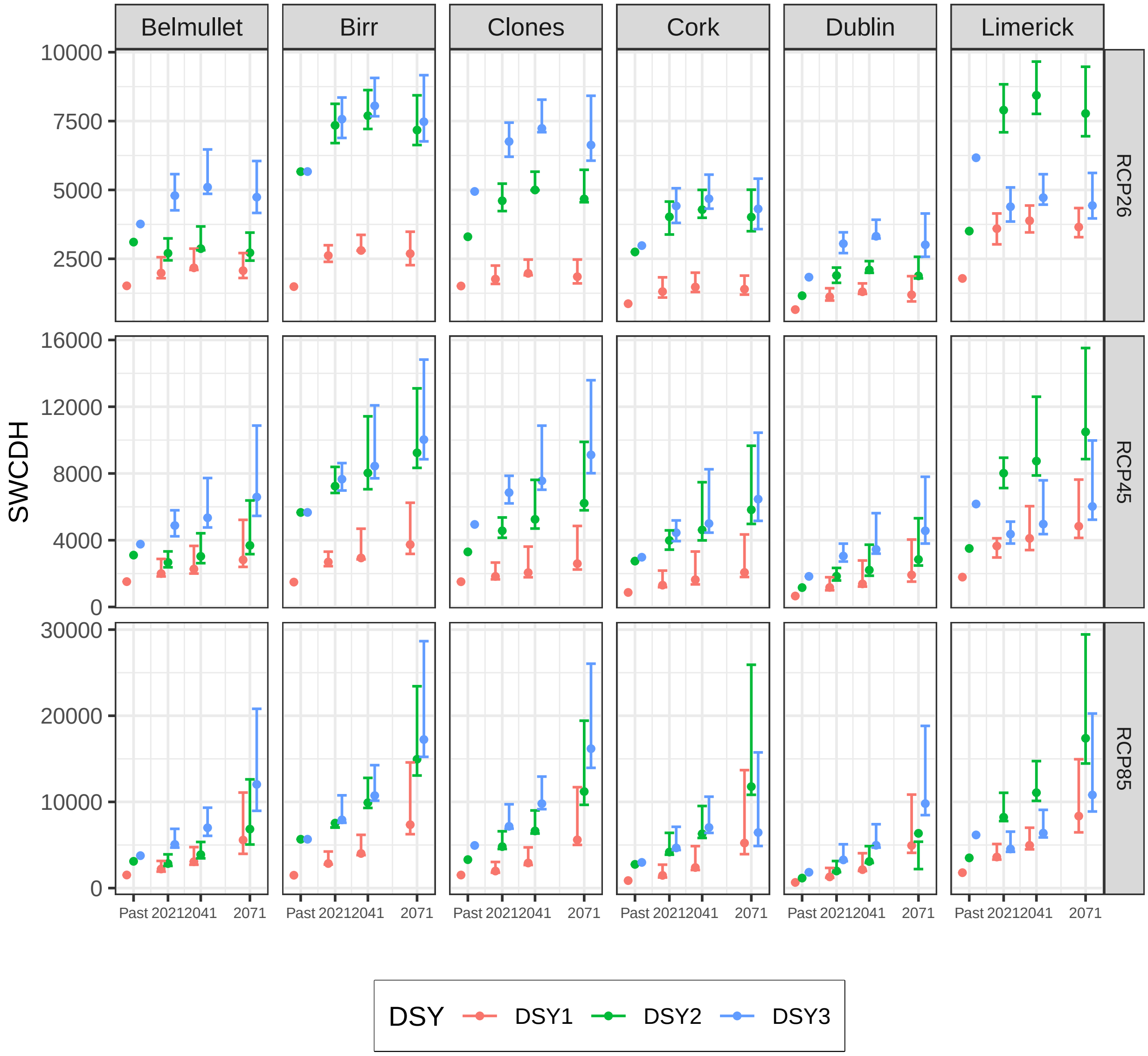

Figure 7: Annual total SWCDH for different DSYs (colours), emission scenarios (rows), locations (columns) and time periods, both past and future. Error bars on future projections signify the range between the low and high sensitivity climate models, with the dot representing the mid-sensitivity ensemble. Note there are different y-axis limits for each row.

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