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SHORT COMMUNICATION

Deriving Lamb weather types suited to regional climate studies: A case study on the synoptic origins of precipitation over Ireland

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The Lamb weather type (LWT) categorization system is one of the best known procedures for summarizing the synoptic circulations that regulate daily weather. Traditionally, it is applied to daily sea level pressure, centred on a domain over the British Isles (BI), which is classed into one of 27 types (or 7 main types). The available register of LWT_{BI} extends to the mid-19th century and has provided a valuable context for understanding the reasons for temporal and spatial variations in recorded weather elements, especially precipitation. Much of what is known of the synoptic origins of precipitation in Ireland has been based on the LWT_{BI}, although it lies in the western part of this domain. While the original classification was based on manual assessment of weather maps, numerical methods can now be employed to objectively classify a pressure field into a LWT. As a result, it is possible to redefine the region of interest. In this study we applied the objective method to a new domain centred on Ireland (LWT_{IR}). The article compares the catalogue of LWT created for the new domain with that available for the original domain; while the overall synoptic climatology does not change, the sequence of LWT classes differs considerably. As a result, the interpretation of the synoptic origins of precipitation over Ireland is modified and this directs research to new areas of enquiry. This new LWT register that is focused on Ireland provides a more useful context for studying Irish climate and demonstrates the value of the objective method.

KEYWORDS

Ireland, modified Lamb weather types, rainfall, storm tracks, synoptic origins

1 | INTRODUCTION

The Lamb weather types (LWT) scheme is probably the best known synoptic classification of daily weather patterns. It recognizes 27 types of flow and circulation (7 main types) and has been used extensively to analyse the seasonal and annual variations of climate across the British Isles (BI) (Jones *et al.,* 2013). It has also been widely applied in a range of broader environmental and ecological based studies (e.g., Dunnett *et al.,* 1998; Hallett *et al.,* 2004; George *et al.,* 2010; Pope *et al.,* 2016). In Ireland, LWT have been employed to derive maps of precipitation patterns and allocate rainfall amounts to weather types (e.g., Houghton and ÓCinnéide, 1976; Sweeney, 1985; Sweeney and O'Hare, 1992) and to provide a framework for discussing the implications of climate change (e.g., Broderick and Fealy, 2015). As one example, "Southerly circulations, especially in autumn when the sea offshore is warmest, are the highest rainfall-yielding airflows in Ireland, and this confirms the role of sea temperatures as the root cause of the autumn and winter maximum in most of the island" (Sweeney, 1997, p. 269). However, these studies have relied on the application of the LWT scheme to a domain centred on the BI (LWT_{BI}) and, while the overall character of circulation may be appropriate to Ireland, the daily sequence of associated weather may not.

In this article we generated a LWT classification for a domain of the same extent as LWT_{BI} but centred on Ireland (LWT_{IR}) and propose it as a more appropriate synoptic classification for studying weather conditions in Ireland. We compared the corresponding frequencies of LWT_{BI} to LWT_{IR} over the period 1948–2016 and evaluate the relative abilities of each to discriminate between rainfall regimes. We used the temporal variations of LWT_{IR} to examine the synoptic origins of precipitation over time and evaluate the insights obtained using other data that describes cyclone tracks and sea surface temperatures (SSTs) off Ireland.

2 | DATA AND METHODS

Traditionally, synoptic classification systems relied on the manual classification of circulation patterns on synoptic maps by experts but numerical methods that measure the properties of pressure fields are now widely used. Jenkinson and Collison (1977) devised an objective scheme for automatically categorizing gridded fields of mean sea level pressure (mslp) into LWT by measuring six components of flow and circulation. Subsequent comparisons between records of LWT obtained by manual and automatic means for a 110-year period showed a high correlation; where discrepancies arose these differences were attributed to changes in the methodology used in the manual classification (Jones *et al.,* 1993). The automatic approach overcomes the subjectivity of the manual approach but it also allows the domain itself to be modified to be more appropriate to the regional climate under study (e.g., McElwain, 2004).

2.1 | British Isles and Irish LWT

The objective method of classifying flow and circulation types uses mean sea level pressure data at noon (UTC) from the NCEP/NCAR Reanalysis (Kalnay *et al.,* 1996), on a $2.5 \times 2.5°$ latitude-longitude grid. LWT_{BI} was obtained from the Climate Research Unit (Jones *et al.,* 2013) for the period 1948–2016 using the Jenkinson–Collison (JC) technique (Jenkinson and Collison, 1977), which employs a 16 point grid covering a domain centred over the BI (45°–65°N and 20°W–10°E, Figure 1). Mean sea level pressure at each grid point is used to automatically calculate the components of flow and circulation (Appendix). To create LWT_{IR}, the same re-analysis data sets were used for a similar sized domain but shifted westwards by 5° longitude so that its focus is on the island of Ireland (Figure 1).

The LWT scheme of 27 types can be summarized into seven main types for longer periods, like months, seasons and years. The main types are anticyclonic (A), cyclonic (C), northerly (N), easterly (E), southerly (S), westerly (W), northwesterly (NW) and the unclassified type (U). The summary is constructed by partitioning hybrid types into their constituent types, so that, for example, the frequency of the A type is increased by 1 if a "pure" A occurs but by one-third if ANE occurs.

2.2 | Precipitation data

Daily rainfall data from Shannon Airport was obtained for the period 1948–2016 from the Irish meteorological service, Met Éireann. The station was selected due to the period of record, which overlapped with the LWT analysis period and its central location, relative to the domain. A monthly series of homogenized rainfall data was also obtained from Noone *et al.* (2015) from the Island of Ireland Precipitation (IIP) data set. The IIP data obtained consist of monthly nationally averaged data for the period 1850–2010, derived from 25 stations distributed across the island. These data were subsequently used to calculate annual water year (October through September) accumulated deviations of precipitation; the deviations were calculated as the departure from the annual average for the designated normal period (1961–1990). Wilby *et al.* (2016) indicated that the 1961–1990 period was a relatively dry period in their analysis of IIP; years showing negative anomalies with respect to this baseline indicate especially dry periods.

To investigate if any differences in the synoptic origins of precipitation occur between LWT_{BI} and LWT_{IR}, the daily rainfall data from Shannon Airport was analysed for the seven main types over the period of record. The relative proportion of rainfall for each day was attributed to each of the main types, based on the contribution of the type to that day's circulation.

3 | RESULTS AND DISCUSSION

Figure 2 shows the relative distribution of the 27 LWT types for the period 1948–2016 using the objective method applied to both domains. Table 1 shows the frequency of the seven main types over the period. Overall, there are small differences between LWT_{BI} and LWT_{IR} in terms of their frequency. The small proportional differences mean however that LWT_{IR} has about three more A-type days per year, about six fewer C-type days and five more W-type days. Overall, this result is expected as the domains capture much of the same sequence of weather so that the aggregate frequencies of LWTs are similar.

The impact of the domain shift is to be seen in the comparison of daily classifications. Table 2 is a cross-tabulation of the relative frequencies of LWT types according to both the BI and IR domains based on the daily types. Each column shows what proportion of that LWT_{BI} type was categorized into each of the LWT_{IR} types; if there were perfect agreement, the values in the grey diagonal would all be 100%, indicating that a day classified using LWT_{BI} received the same classification using LWT_{IR}. Of the six most frequent types the match rates were 64% (A), 56% (C), 47% (W), 55% (SW), 31% (S) and 30% (NW). Composite maps based on mslp were constructed to examine selected mismatch cases and Figure 3 shows those cases with the largest number of mismatch days. Figure 3a shows an anticyclone centred over the United Kingdom and northern France that results in an A type according

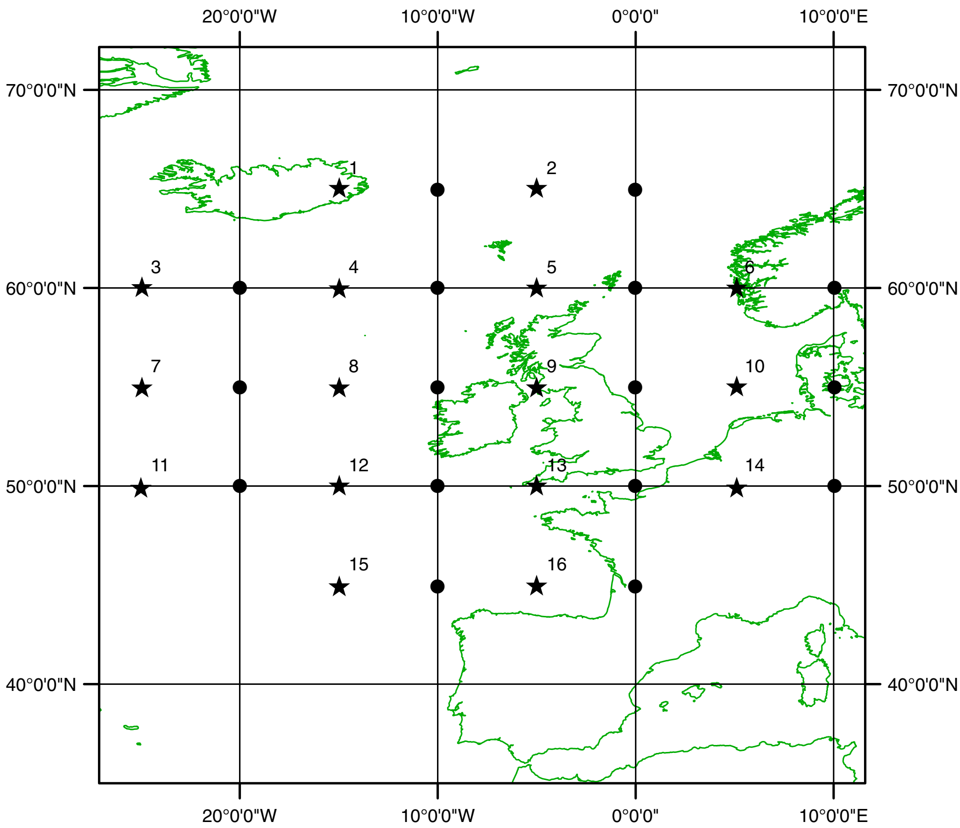

FIGURE 1 Location of the domain and grid points employed by (1) Jones *et al.* (1993) to calculate the LWT_{BI} (●) and (2) this study to calculate the LWT_{IR} (★) [Colour figure can be viewed at wileyonlinelibrary.com]

to LWT_{BI} but southerly airflow over Ireland and an S type in LWT_{IR}. Similarly, Figure 3b shows circumstances where the LWT_{BI} designation is C but LWT_{IR} type is CNW. Figure 3c shows LWT_{BI} S types that are classed as LWT_{IR} SW types and Figure 3d shows LWT_{BI} E types that are classed as CE in the LWT_{IR} scheme. These mismatches are the result of a spatial and temporal offset owing to the movement of circulation systems within the mid-latitude westerlies that pass through the Irish (IR) domain first and then subsequently through the BI domain.

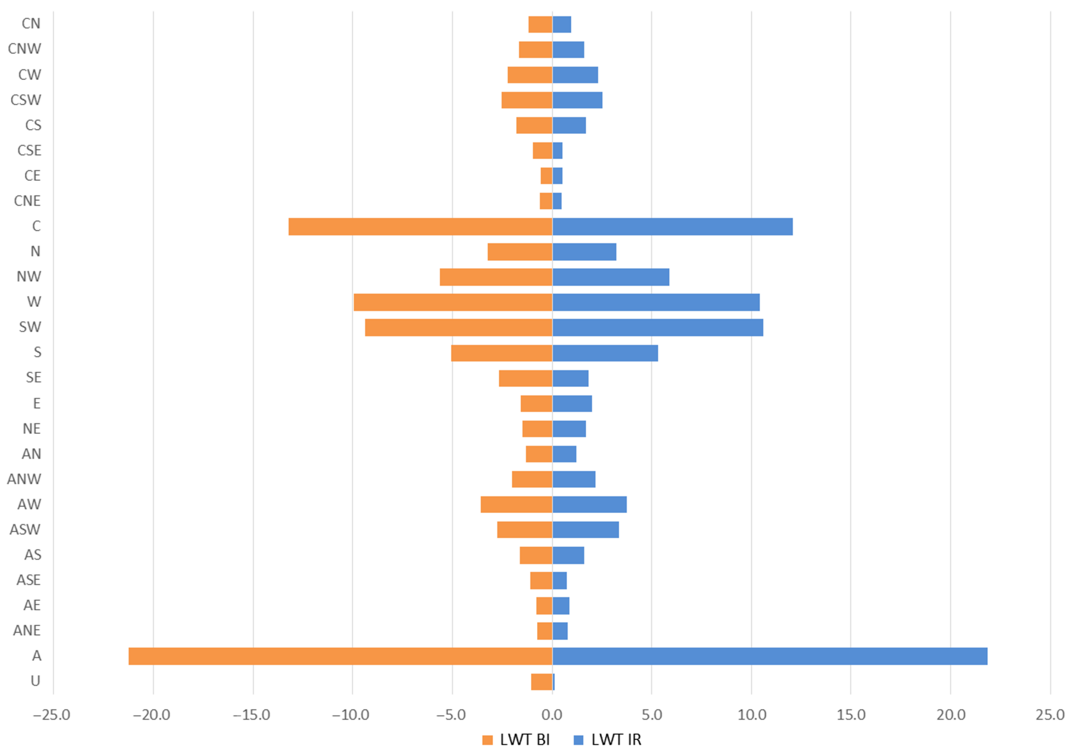

FIGURE 2 The relative frequency of the 27 LWT using the BI (LWT_{BI}) and IR (LWT_{IR}) domains [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 The frequency of the seven basic LWT categories using the BI (LWT_{BI}) and IR (LWT_{IR}) domains over the period 1948–2016. The number in parentheses represents the percentage of the 25,203 days classified into that type. The final column shows the annual average difference between the frequency counts for LWT_{BI} and LWT_{IR}

Type	LWT_{BI}	LWT_{IR}	Difference
A	6919.2 (27.5)	7125.2 (28.3)	−3.0
C	4622.3 (18.3)	4224.2 (16.8)	5.9
N	1438.3 (5.7)	1396.3 (5.5)	0.6
E	1369.3 (5.4)	1327.2 (5.3)	0.6
S	3836.7 (15.2)	3913.5 (15.5)	−1.1
W	4870.2 (19.3)	5222.2 (20.7)	−5.2
NW	1877.0 (7.4)	1959.5 (7.8)	−1.2
U	270.0 (1.1)	35.0 (0.1)	3.5

3.1 | The synoptic origins of precipitation

Table 3 shows a range of statistical measures to quantify daily rainfall according to each circulation type for LWT_{BI} and LWT_{IR}. Days on which no rainfall occurred (<0.1 mm/day) were excluded from the analysis. The results show differences of note between LWT_{BI} and LWT_{IR}, which reflects both the relative frequencies of weather types and the average daily rainfall associated with each type (Table 3).

The majority of precipitation (>80%) at Shannon is associated with three main types: cyclonic (C), westerly (W) and southerly (S). This is a result of both the frequency of occurrence and the daily rate (mm/day) associated with each. In terms of the domain differences, the allocation of rainfall to each varies. For LWT_{BI}, the C type generated 3.5 mm/day (31%), W 2.66 mm/day (26%) and S 2.86 mm/day (25%). The equivalent values for LWT_{IR} are C type 4.1 mm/day (33%), W type 2.92 mm/day (32%) and S type 2.34 mm/day (18%). The remaining types contributed little to the overall totals. The other difference is the roles of cyclonic (C) and anticyclonic (A) circulations. The LWT_{BI} C type produced an average 3.5 mm/day, compared with the LWT_{IR} C type of 4.1 mm/day. Similarly, the LWT_{BI} scheme produced an average of 1.4 mm/day for the A type and was responsible for 6% of precipitation at Shannon, while the equivalent values for LWT_{IR} are 1.0 mm/day and 5%.

The directional shifts in the allocation of synoptic origin are evident when the precipitation is plotted against the full 27 LWT categories. Figure 4 illustrates the mean daily rainfall associated with each domain decomposed into the four seasons. The importance of rain bearing mechanisms associated with the cyclonic (C) type is highlighted in all seasons in both LWT_{BI} and LWT_{IR}. However, differences are evident on a seasonal basis in terms of the relative importance of the different weather types between the classification schemes. This difference is most marked in the summer months of June, July and August (JJA). It also highlights the importance of cyclonic (C), westerly (W) and cyclonic westerly (CW) types in producing precipitation during autumn and winter in LWT_{IR}, in contrast to cyclonic southerly (CS) and southerly (S) in autumn and cyclonic southwesterly (CSW), southwesterly (SW) and southerly (S) in winter in LWT_{BI}.

The time series of LWT_{IR} can be used to explore the spatially averaged precipitation across Ireland using the IIP data set for the period 1948–2010. Figure 5 shows the annual (October through September) accumulated sum of deviations of precipitation; the deviations are calculated as the departure from the annual average for the designated normal period (1961–1990) and the series starts with the annual deviation for the October 1948 to September 1949 period. This form of plot was selected to remove the year-to-year variations and identify periods where there is a tendency towards wetter/drier conditions; these periods have obviously less significance at the beginning of the series when there is little accumulated information, hence the following discussion focusses on the period from 1961. The normal period (1961–1990) is characterized by a "wetting" and a "drying" sequence but after the mid-1980s the time series shows a trend of increasing wetness (Kiely, 1999; Mills, 2001).

Also plotted in Figure 5 are the accumulated annual deviations for the C, W and S types. These three types are responsible for the most precipitation and account for nearly 65% of days over this period. The A type, which generates little precipitation and accounts for 28% of days, is also shown. Inevitably, many of the changing LWT patterns correspond as the synoptic conditions change over the period causing a shift in frequency from one type to another. The most obvious correspondence is that between the C- and A-type series, which is clearest from the mid-1990s onwards as A types become less frequent and Ireland becomes wetter. However, different combinations of C, W and S types over sub-periods correlate to the precipitation patterns, notably:

1. The cumulative sum of W declined from the mid-1960s to the mid-1980s after which it increased.
2. The cumulative sum of S types shows comparatively little change over the entire period but its increase/decrease matches closely the trends of accumulated precipitation.
3. The wetting period from the mid-1980s onwards corresponds with increases in W and S types mostly as the C type declines initially, until the mid-1990s, before increasing over the remainder of the period.

Also evident is the increase in A types during the prolonged dry period experienced from October 1974 to August 1976 (O'Laoghog, 1979). A types are the lowest precipitation producing types; coupled with the associated frequency reductions in "wet" types is likely to partly explain the drier than normal conditions experienced during this period.

These changes in LWTs (and precipitation) suggest that the change from dry to wet periods may be associated with a shift in the tracks of cyclones southwards that increases the frequency of C types but is also likely

TABLE 2 Cross-tabulation of the percent of days for the period 1948–2016 classified according to the 27 LWT using the BI (LWT_{BI}) and IR (LWT_{IR}) domains. The percentages add to 100% along the columns which represent LWT_{IR}; the rows represent LWT_{BI}. The totals indicate the number of days of occurrence for each type

LWT	U	A	ANE	AE	ASE	AS	ASW	AW	ANW	AN	NE	E	SE	S	SW	W	NW	N	C	CNE	CE	CSE	CS	CSW	CW	CNW	CN	Total
U	14	1	0	0	0	0	0	1	1	2	3	2	1	1	1	1	1	3	1	3	2	4	2	1	1	1	1	270
A	23	64	36	73	90	82	30	3	1	9	4	21	32	26	4	0	0	1	0	1	1	2	1	0	0	0	0	5,360
ANE	0	1	22	7	1	0	0	0	0	1	8	4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	186
AE	3	0	9	8	2	0	0	0	0	0	5	19	4	0	0	0	0	0	0	2	1	1	0	0	0	0	0	199
ASE	6	0	2	1	4	1	0	0	0	0	1	9	27	4	0	0	0	0	0	1	0	1	1	0	0	0	0	272
AS	3	0	0	1	1	6	0	0	0	0	0	0	4	20	2	0	0	0	0	0	0	1	2	1	0	0	0	406
ASW	9	1	0	0	0	7	27	2	0	0	0	0	0	5	9	0	0	0	0	0	0	0	0	0	0	0	0	696
AW	0	9	0	0	0	1	17	17	4	0	0	0	0	0	3	1	0	0	0	0	0	0	0	0	0	0	0	908
ANW	3	7	1	0	0	0	1	3	6	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	503
AN	3	4	9	2	0	0	0	0	1	11	2	1	0	0	0	0	0	2	0	0	1	0	0	0	0	0	0	333
NE	0	0	11	3	0	0	0	0	0	3	46	5	0	0	0	0	0	7	0	18	3	0	0	0	0	0	2	375
E	0	0	2	3	0	0	0	0	0	0	15	28	4	0	0	0	0	1	1	21	55	7	0	0	0	0	0	395
SE	11	0	0	0	1	0	0	0	0	1	1	9	22	5	0	0	0	0	7	3	27	69	18	0	0	0	1	667
S	0	0	0	0	1	2	0	0	0	0	0	0	2	31	9	0	0	0	5	0	1	7	61	25	1	0	0	1,272
SW	3	0	0	0	0	1	12	4	0	0	0	0	0	6	55	17	0	0	1	0	0	0	2	24	6	0	0	2,368
W	3	3	0	0	0	0	11	56	12	0	0	0	0	0	10	47	9	0	0	0	0	0	0	2	2	1	0	2,505
NW	3	5	0	0	0	0	1	13	61	11	0	0	0	0	1	5	30	5	0	0	0	0	0	0	0	0	1	1,415
N	6	3	8	0	0	0	0	0	10	58	8	0	0	0	0	0	4	36	0	0	0	0	0	0	0	0	3	819
C	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	6	21	12	58	11	2	0	2	10	54	89	71	3,337
CNE	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	7	1	22	1	1	0	0	0	0	13	157
CE	3	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	3	14	5	2	0	0	0	0	2	139
CSE	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	7	1	1	4	2	0	0	0	1	238
CS	3	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	10	0	0	1	6	11	2	0	0	455
CSW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	6	0	0	3	0	0	0	1	23	25	1	0	644
CW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	13	7	0	0	0	0	0	0	1	9	1	0	561
CNW	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2	21	2	0	1	0	0	0	0	1	4	1	421
CN	3	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	5	22	0	3	2	1	0	0	0	1	5	302
Total	35	5,507	194	217	184	400	848	948	543	311	422	505	456	1,338	2,667	2,630	1,485	808	3,040	116	130	135	424	639	578	406	237	25,203

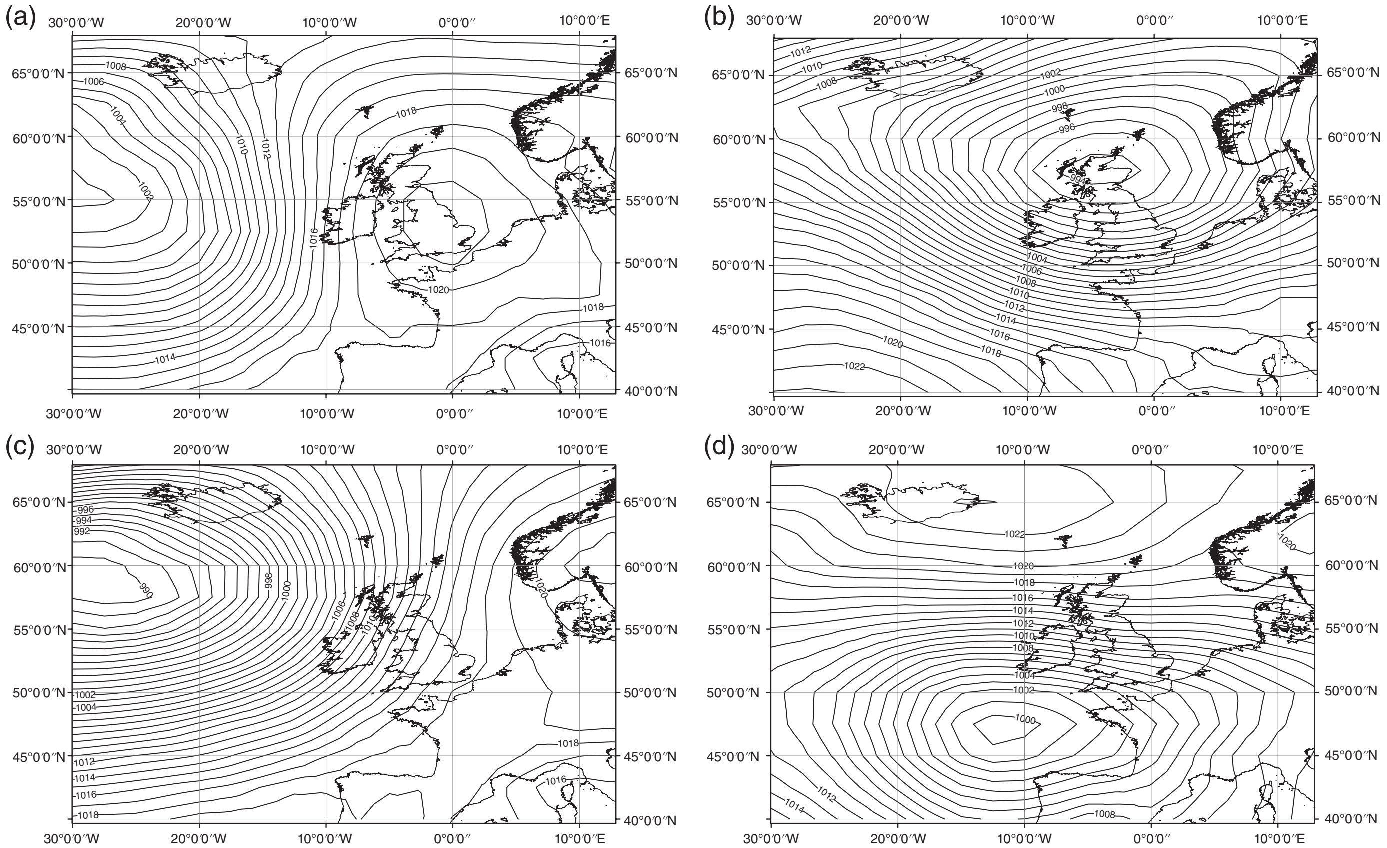

FIGURE 3 Composite mean sea level pressure for a selection days classified as different LWT between LWTBI and LWTIR (Source: Images provided by the NOAA/ESRL Physical Sciences Division, Boulder, CO from their website at http://www.esrl.noaa.gov/psd/). (a) A type in LWT_{BI} and S type in LWT_{IR} ($n = 342$); (b) C type in LWT_{BI} and CNW type in LWT_{IR} ($n = 360$); (c) S type in LWT_{BI} and SW type in LWT_{IR} ($n = 227$); (d) E type in LWT_{BI} and CE type in LWT_{IR} ($n = 72$)

to create sequences of S and W types created by the passage of storms. In the following we evaluate this proposition in conjunction with changes in SSTs west of Ireland.

3.2 | Cyclone tracks and SST

Cyclone tracks over the LWT domain for the period 1961–2010 were extracted from the Northern Hemisphere Cyclone Locations and Characteristics data set, which were

TABLE 3 Statistical values of daily rainfall derived from Shannon Airport for the period 1948–2016. Daily rainfall is proportioned and categorized according to the contributory counts of the seven basic types. Over the entire period the total precipitation was 64,200 mm (approximately 944 mm/year). Days on which no rainfall occurred were excluded from the analysis

Domain	Statistic	A	C	N	E	S	W	NW	U
BI	Mean	1.4	3.5	0.9	2.0	2.8	2.6	1.9	3.0
	Median	0.5	2.1	0.5	0.8	1.7	1.6	0.9	1.5
	Range	27.9	52.4	37.9	26.3	47.7	35.1	25.7	22.2
	Minimum	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Maximum	28.0	52.5	38.0	26.4	47.8	35.2	25.8	22.3
	Sum	3901.4	20030.1	811.9	2759.2	16221.0	16850.3	3161.8	503.2
	Percent	6.07	31.18	1.26	4.30	25.25	26.23	4.92	0.78
	Count	2,752	5,601	895	1,348	5,662	6,327	1,655	166
IR	Mean	1.0	4.1	1.3	1.6	2.3	2.9	2.3	4.5
	Median	0.5	2.4	0.6	0.5	1.4	1.8	1.4	3.6
	Range	19.4	52.4	22.0	48.6	35.2	35.9	22.2	13.5
	Minimum	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3
	Maximum	19.5	52.5	22.1	48.7	35.3	36.0	22.3	13.8
	Sum	3215.0	21081.3	1359.7	1248.6	11524.9	20852.3	4829.7	73.1
	Percent	5.01	32.84	2.12	1.95	17.96	32.49	7.52	0.11
	Count	3,217	5,045	1,038	752	4,916	7,132	2,041	16

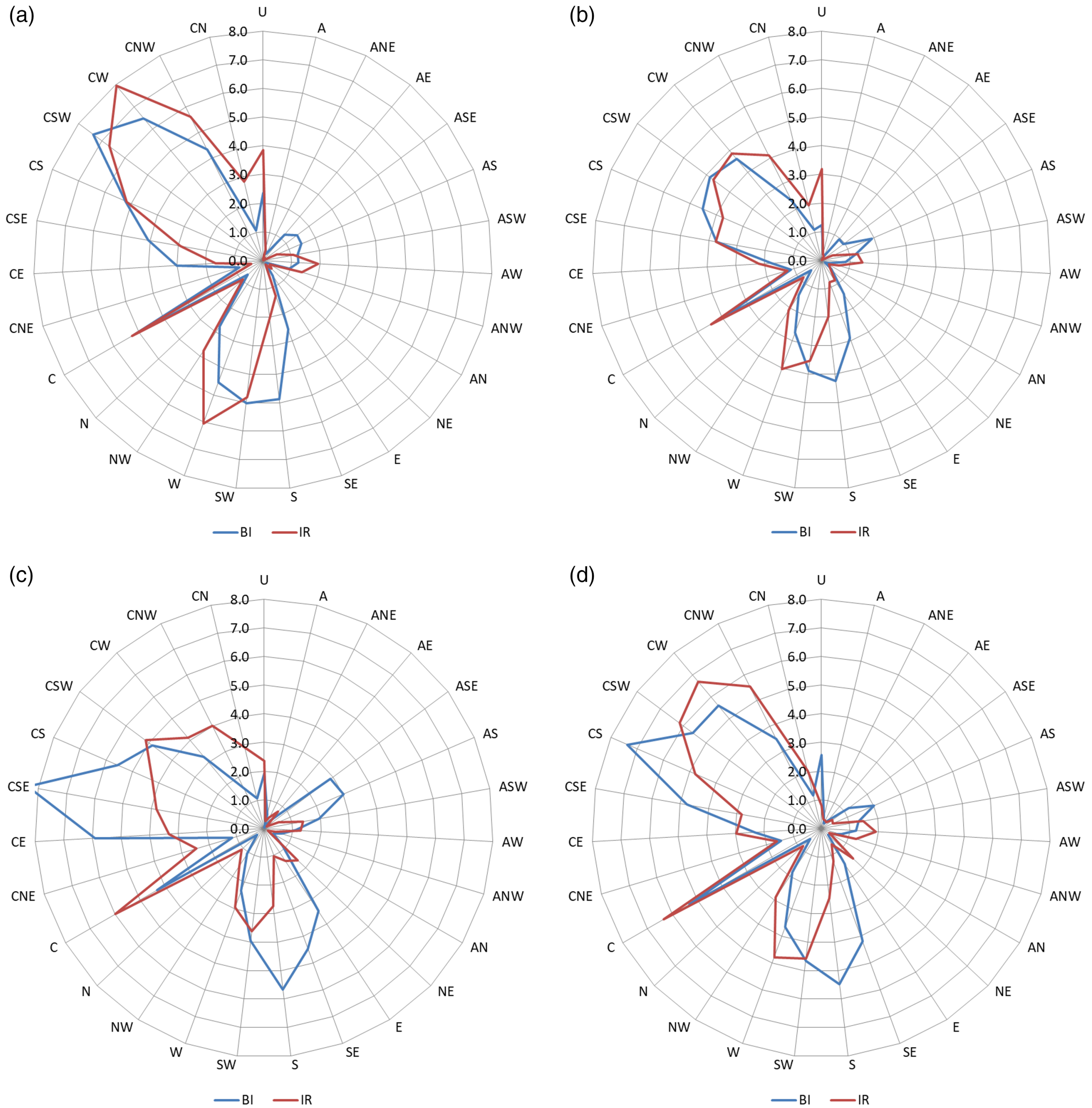

FIGURE 4 Seasonal mean daily precipitation (mm/day) by weather type for the LWT_{BI} and LWT_{IR} at Shannon Airport for the period 1948–2016. (a) Seasonal mean DJF rainfall (mm/day) by type; (b) seasonal mean MAM rainfall (mm/day) by type; (c) seasonal mean JJA rainfall (mm/day) by type; (d) seasonal mean SON rainfall (mm/day) by type [Colour figure can be viewed at wileyonlinelibrary.com]

derived from the NCEP/NCAR Reanalysis Data (Serreze, 2009). The parameters gathered include the position and central pressure of each cyclone. The data for a domain over the North Atlantic region were extracted and short-lived systems were removed following the recommendations of Serreze and Barrett (2008). Figure 6 shows the mean annual counts of cyclones for the normal period, 1961–1990 ($Count_{61–90}$). The dominant cyclone track over this period is shown as an elongated area of high frequency extending northeastwards and located to the south and west of Iceland. Also plotted on this map are symbols showing the differences in the annual cyclone counts since 1990, that is, $Count_{61–90} – Count_{91–10}$. Negative values are clustered near Ireland to the west and north of Ireland, indicating a more southerly cyclone track during this period, which supports the LWT analysis.

It is well accepted that the precipitation regime in Ireland is closely linked to SST in the North Atlantic (Logue, 1984), which experiences periods of cooling and warming described by the Atlantic Multidecadal Oscillation (McCarthy *et al.,* 2015). It follows then that part of the explanation for the tendency towards increased wetness in Ireland evident from the mid-1990s (Figure 5) may be attributed to changing SST. To explore

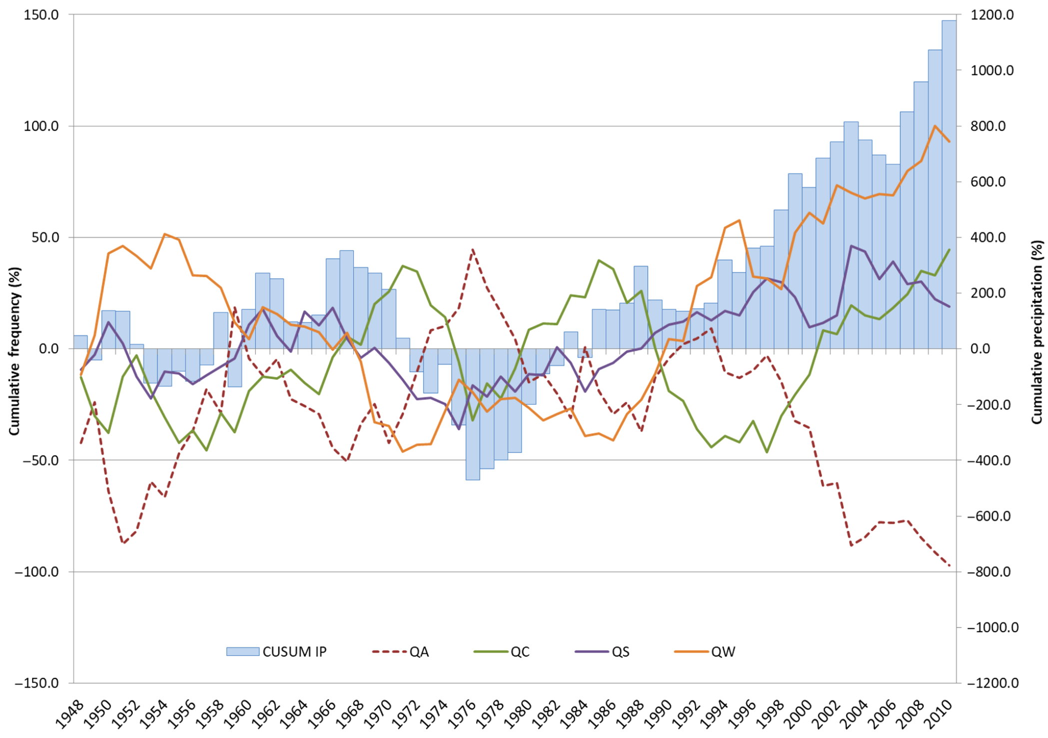

FIGURE 5 Cumulative sums (CUSUMS) of annual deviations of precipitation derived from the IIP data (mm) and annual deviations of counts of LWT_{IR} A, C, S and W types, relative to the 1961–1990 period. Annual deviations were calculated on the basis of the months from October to September [Colour figure can be viewed at wileyonlinelibrary.com]

this proposition, we used the COBE-SST2 SST data provided by the NOAA/OAR/ESRL PSD (Hirahara *et al.*, 2014) as monthly means on a 1 × 1° grid resolution. The monthly SST data for an area located off the west coast of Ireland (Figure 6) was extracted and averaged to produce an annual SST series from 1961 to 2010 (Figure 7). Consistent with previous studies,

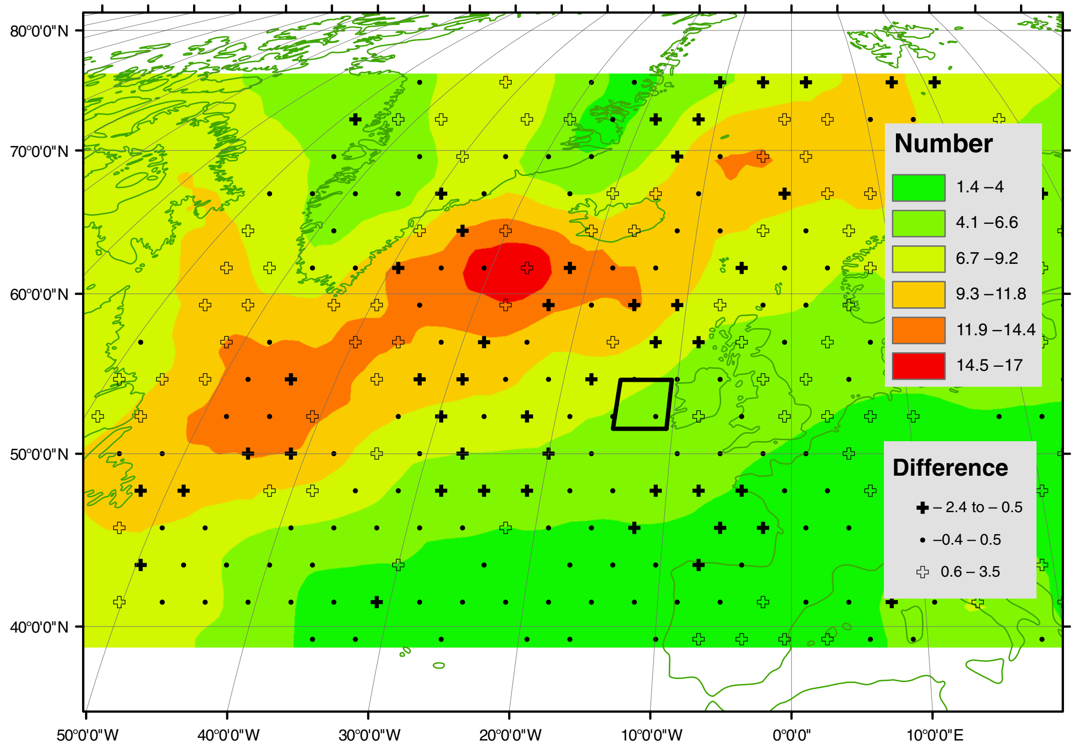

FIGURE 6 Mean annual counts of cyclones identified from the NCEP/NCAR Reanalysis data for the period 1961–1990 (contours). The difference in the mean annual counts between the 1990–2010 and 1961–1990 periods are shown using symbols; negative values indicate an increase in cyclone counts over the 1990–2010 period, relative to 1961–1990. The box area (15°–10.5°W and 51.5°–54.5°N) to the west of Ireland was used to calculate mean SSTs [Colour figure can be viewed at wileyonlinelibrary.com]

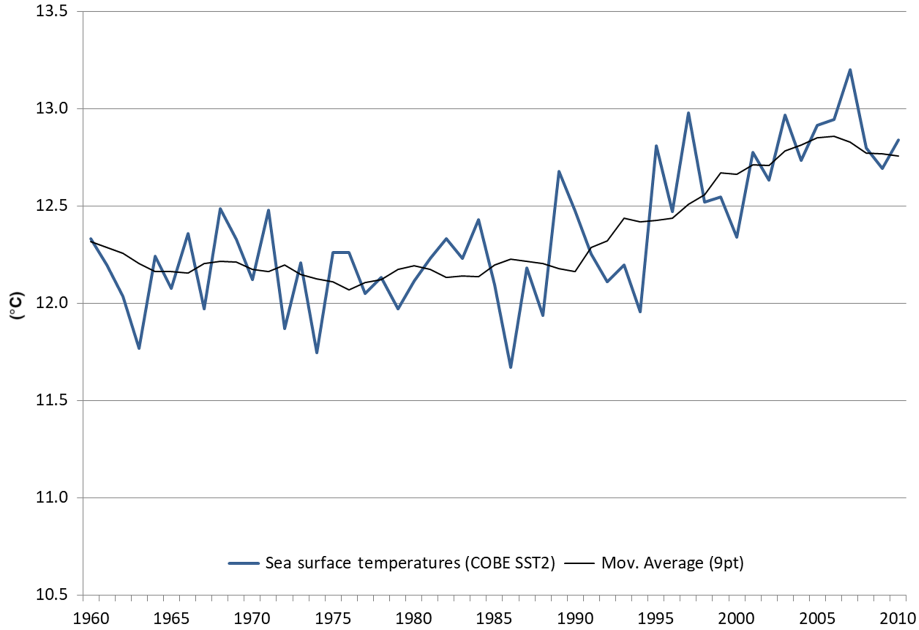

FIGURE 7 Mean annual SSTs, derived from a domain located off the west coast of Ireland (see Figure 6 for the period 1960–2010). Data derived from the COBE SST2 data. A 9-point moving average is also shown (1956–2014) [Colour figure can be viewed at wileyonlinelibrary.com]

SSTs in the selected domain are shown to increase; the increase in SSTs is coincident with the precipitation increases.

A more southerly located storm track coupled with an increase in SSTs, would indicate an increased potential for moisture availability (due to increased ocean heat content), decreased atmospheric stability and subsequent advection (increased cumulative frequency of W, but also S and C, types; Figure 5) over this period. The southwards shift in the storm tracks during this period has previously been associated with increased summer precipitation over the United Kingdom (Dong *et al.,* 2013), while Sutton and Dong (2012) found increased precipitation anomalies during summer and autumn across the United Kingdom which they attribute to increased SST anomalies. The link between the atmospheric circulation (represented by the register of LWT_{IR}) and SSTs off the coast of Ireland will be the subject of further research.

4 | CONCLUSION

The LWT_{BI} register has long been used as a system for characterizing the synoptic-scale circulation systems responsible for precipitation over Ireland although it is located west of the domain centre. The objective LWT method permits a more precise description of the circulations that affect regions. Here the LWT_{IR} has been shown to provide improved insights on the changing synoptic origins of IR precipitation that can direct research towards fruitful lines of enquiry.

The daily composite of mean sea level pressure illustrated for the six most frequently occurring types is shown in Figure S1, Supporting information and the complete catalogue of LWT_{IR} for the period 1948–2017 is available at www.icarus.ie.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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APPENDIX

FLOW AND CIRCULATION EQUATIONS

Equations to calculate flow and circulation for the automated LWT following Jones *et al.* (1993).

Flow is comprised of three scores:

- Westerly (W) flow is the average latitudinal flow across the domain based on mslp at western and eastern grid points (w scores <0 indicate easterly flow):

$$W = 0.5(\mathrm{G12}+\mathrm{G13}) - 0.5(\mathrm{G4}+\mathrm{G5}).$$

- Southerly (S) flow is the average meridional flow across the domain based on mslp at southern and northern grid points (s scores <0 are northerly),

$$S = 1.74\left[\tfrac{1}{4}(\mathrm{G5}+2x\,\mathrm{G9}+\mathrm{G13}) - \tfrac{1}{4}(\mathrm{G4}+2x\,\mathrm{G8}+\mathrm{G12})\right].$$

- Resultant flow (F) is then derived from the westerly and southerly components (only positive),

$$F = \left(S^2+W^2\right)^{1/2}.$$

Circulation is measured as:

- Westerly shear flow (zw) based on the meridional gradient in westerly flow,

$$zw = 1.07\left[\tfrac{1}{2}(\mathrm{G15}+\mathrm{G16}) - \tfrac{1}{2}(\mathrm{G8}+\mathrm{G9}) - 0.95\,\tfrac{1}{2}(\mathrm{G8}+\mathrm{G9}) - \tfrac{1}{2}(\mathrm{G1}+\mathrm{G2})\right].$$

- Southerly shear flow (zs) based on the latitudinal gradient in the southerly flow,

$$zs = 1.52\left[\tfrac{1}{4}(\mathrm{G6}+2x\,\mathrm{G10}+\mathrm{G14}) - \tfrac{1}{4}(\mathrm{G5}+2x\,\mathrm{G9}+\mathrm{G13}) - \tfrac{1}{4}(\mathrm{G4}+2x\,\mathrm{G8}+\mathrm{G12}) + \tfrac{1}{4}(\mathrm{G3}+2x\,\mathrm{G7}+\mathrm{G11})\right].$$

- Total shear vorticity (Z) is the sum of these shear components, positive Z corresponds to cyclonic and negative to anticyclonic circulation,

$$Z = zw + zs.$$

The grid numbers (e.g., G1, G2, etc.) refer to the indexed mean sea level pressure grids over the selected domain (Figure 1). The components of flow and circulation used to classify daily mslp over the domain into one of 27 LWT categories follow that of Jones *et al.* (1993).