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ORIGINAL PAPER

An assessment of the Jenkinson and Collison synoptic classification to a continental mid-latitude location

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Abstract A weather-type catalogue based on the Jenkinson and Collison method was developed for an area in south-west Russia for the period 1961–2010. Gridded sea level pressure data was obtained from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis. The resulting catalogue was analysed for frequency of individual types and groups of weather types to characterise long-term atmospheric circulation in this region. Overall, the most frequent type is anticyclonic (A) (23.3 %) followed by cyclonic (C) (11.9 %); however, there are some key seasonal patterns with westerly circulation being significantly more common in winter than summer. The utility of this synoptic classification is evaluated by modelling daily rainfall amounts. A low level of error is found using a simple model based on the prevailing weather type. Finally, characteristics of the circulation classification are compared to those for the original JC British Isles catalogue and a much more equal distribution of flow types is seen in the former classification.

1 Introduction

Techniques in synoptic climatology have long been effective in the classification of atmospheric circulation patterns (or *weather types*) at a variety of locations. One of the aims is to relate large-scale circulation variability to temperature and precipitation variability at point scales and therefore

downscale the surface pressure field output of general circulation models (Jones et al. 2013). Results can then be used to bias adjust the temperature and precipitation output of climate models. Synoptic classifications have been created using a number of techniques ranging from simple subjective pattern identification of the surface pressure field, for instance Lamb weather types (LWTs) (Lamb 1972), to catalogues based on multivariate statistical analysis (Yarnal 1993). The objective method of Jenkinson and Collison (1977) (JC), which replaced the LWT system, was originally developed for the British Isles region; however, Jones et al. (2013) comment that the JC method can be applied to any mid-to-high-latitude region (~30°–70°). Indeed, several applications can be found in the literature, for example, for the Netherlands (Buishand and Brandsma 1997), Portugal (Trigo and DaCamara 2000), Sweden (Chen 2000), Spain (Spellman 2000), Estonia (Post et al. 2002), Chile (Espinoza et al. 2014) and the Western Mediterranean (Grimalt et al. 2013). All of these authors have investigated mid-latitude maritime regions with a significant proportion of open water upwind. In fact, many other synoptic classifications have also focused on locations in coastal regions such as Norway (Fitzharris and Bakkehøi 1986) and New Zealand (Kidson 1994). Less assessment of the value of synoptic climatological approaches has been undertaken deep within continental areas, although Petrone and Rouse (2000) and Spence and Rausch (2005) employed the use of a weather-type classification to explain precipitation patterns in Central Canada and a number of studies have been undertaken in Iran by Alijani and Harman (1985) and Jahanbakhsh and Zolfaghari (2002).

The study area is situated in Russia north of western Kazakhstan roughly within a rectangular grid with north-west coordinates of 60° N, 50° E, and south-east coordinates of 50° N, 60° E (Fig. 1). It includes the republics of Bashkortostan and Tatarstan and the cities of Samara and

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Fig. 1 Location of the study area
(points identify the locations of
meteorological stations used in
this study)
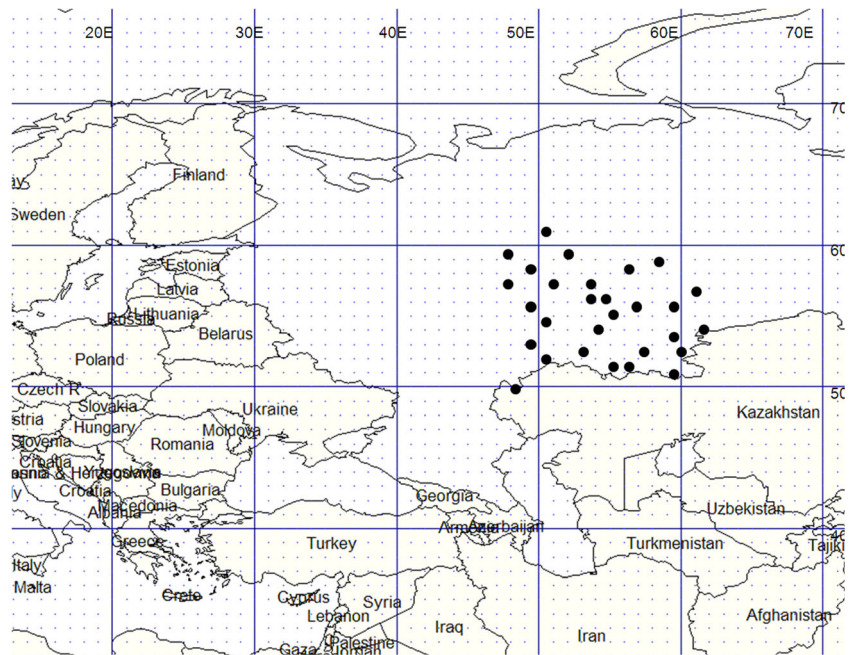
Perm. Topography slowly rises from low-altitude plains in the west to the southern Urals in the east (<600 m), although altitude rarely rises above 300 m. The northern coasts of the Caspian Sea and the Black Sea (the only significant sources of surface moisture) lie 1000 and 1500 km, respectively, from the centre of the study area. According to the Köppen-Geiger climate classification, it is defined as the *Dfb* (*humid continental*) climatic type (Barry and Chorley 2009). Thermally, this type is characterised by large seasonal temperature differences with warm to hot summers and cold (sometimes severely cold) winters. Most Dfb types exhibit rainfall that is well distributed throughout the year, although some areas have a seasonal rainfall regime of dry winters and a peak of largely convective rainfall in early summer. The *humid* designation of this type does not mean that the humidity levels are necessarily high, only that the climate is not dry enough to be classified as semi-arid or arid.

The purpose of the current study was to develop a weather typing scheme for an area of south-west Russia using the Jenkinson and Collison method. A daily catalogue of surface circulation was created for a 50-year period from 1961 to 2010. This extensive record permits the investigation of the key modes of variability of atmospheric circulation, and the main features of this catalogue can be compared to other locations at the same latitude but in a different longitudinal sector and hence subject to different long-term circulation patterns. The maritime JC catalogue for the British Isles (JCBI) provides a good contrast to this continental classification. Finally, the catalogue was used to determine the extent to which daily precipitation amount is controlled by the weather type in this area and, subsequently, to evaluate if this relationship is strong enough to form the basis of a predictive model of mean station rainfall.

2 Data and methodology

Gridded daily mean sea level pressure data for 12 h UTC was obtained from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) project. The NCEP Reanalyses (Kalnay et al. 1996) are available at the relatively high spatial resolution (2.5° by 2.5° latitude/longitude) that provides the necessary data for the JC method grid. The latitude/longitude resolution used here is extracted for the 16-point grid shown in Fig. 2 so the computed variables represent surface airflow for this region. The JC method classifies daily map patterns using three basic variables that define circulation features over the study area: the direction of mean flow (*D*), the strength of mean flow (*F*) and the vorticity (*Z*). A set of daily index values are calculated using the equations in Appendix 1 and identify the following flow features:

W	The zonal component of geostrophic (surface) wind, calculated as the pressure gradient between 45° N and 65° N
S	The meridional component of geostrophic (surface) wind, calculated as the pressure gradient between 40° W and 70° W
D	The wind direction (azimuth degree) derived from *S* and *W* above
F	The wind speed (ms^{-1})

ZW   The zonal vorticity component
ZS   The meridional vorticity component
Z   The total vorticity derived from ZW and ZS.

The JC method was devised to capture objectively the 27 atmospheric circulation patterns that exist in the Lamb weather type system. Jones et al. (1993) showed how the objective method was effective in replicating the LWT classes. LWTs comprise eight pure advective (or *directional*) types based on wind direction (e.g. SE or *southeast*); A and C types which represent anticyclonic and cyclonic pressure patterns, respectively, but no coherent flow direction; and 16 *hybrid* types that represent directional types with either anticyclonic isobaric curvature (e.g. AN or *anticyclonic northerly*) or cyclonic curvature (e.g. CSE or *cyclonic southeasterly*). The final type undetermined (U) represents patterns that have weak pressure gradients, and thus, neither flow direction nor vorticity can be identified. Examples of some of the more frequent types in the catalogue are shown in Fig. 3.

3 Results: atmospheric circulation catalogue

Eighteen thousand two hundred sixty-two days were classified according to the JC classification (Table 1). In the resultant catalogue for south-west Russia (hereafter termed 'JCSWR'), there is a considerable variability in surface circulation without domination by any individual weather type. This is typical of mid-latitude atmospheric circulation. It contrasts with the lower-latitude Mediterranean region where Grimalt et al. (2013) found that three types alone (U, A and C) account for 68 % of all days. They reported a 27 %

mean occurrence of undetermined flow (the most frequent type) in their annual catalogue. These are termed 'barometric swamps' (Jorba et al. 2004) and are a key feature of summer circulation in the Mediterranean area. In contrast, U types only constitute 4.46 % of all days in JCSWR; however, there is a notable rise in June (9 %) and July (10 %). The most frequent type is A with an annual average of 85 days (23.3 %). It is followed by C (43.6 days, 11.9 %) and then W (26.6 days, 7.3 %). The two most frequent types record annual maxima of 132 days (A) and 62 days (C). Hybrid types are unusual and, in some instances, do not even occur at all in any one year. CS, for example, which features on only 96 days in the entire 50-year period, is absent in 10 of these years and only reaches a maximum occurrence of 5 in 2006. None of the hybrid types are recorded more than 25 times in any year. Seasonal differences can be seen in type occurrence with westerly component types (e.g. W, ANW, CW) being significantly more frequent in winter and those with north and easterly components occurring more often in the summer months.

Simple analysis of the 2-day persistence of each weather type reveals that the probability of an A type being followed by another A type is 0.531 which is considerably greater than that associated with a 2-day spell of the next most persistent weather type SE (0.313). Directional types tend to persist longer than any of the hybrid types with infrequent cyclonic types such as CSW being the most transitional (0.049). The A types regularly persist for 7 days or more, the longest run being 18 days in September/October 1974.

In their analysis of a weather typing in the Western Mediterranean, Grimalt et al. (2013) facilitated the description of atmospheric circulation by examining groups of weather

Fig. 2 The 16-point grid used to calculate the circulation index values
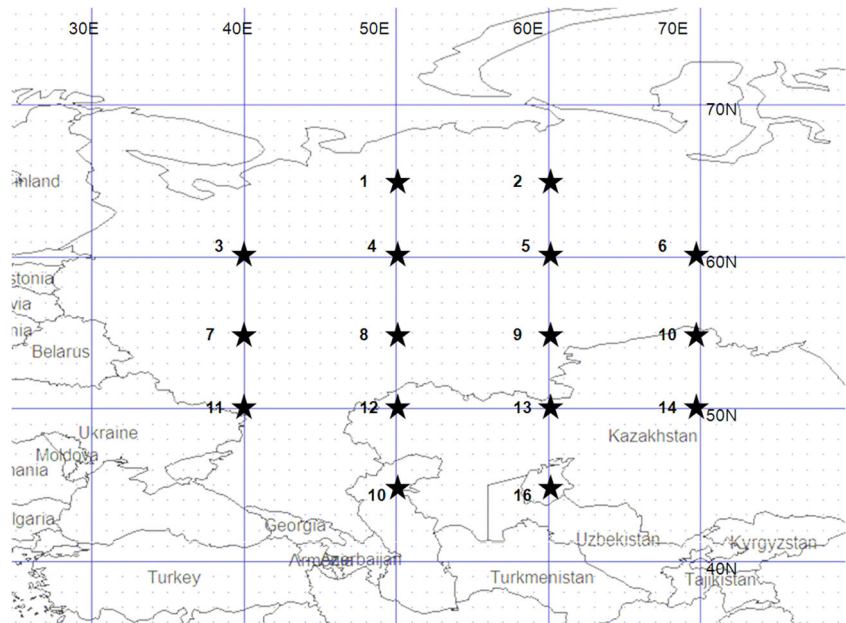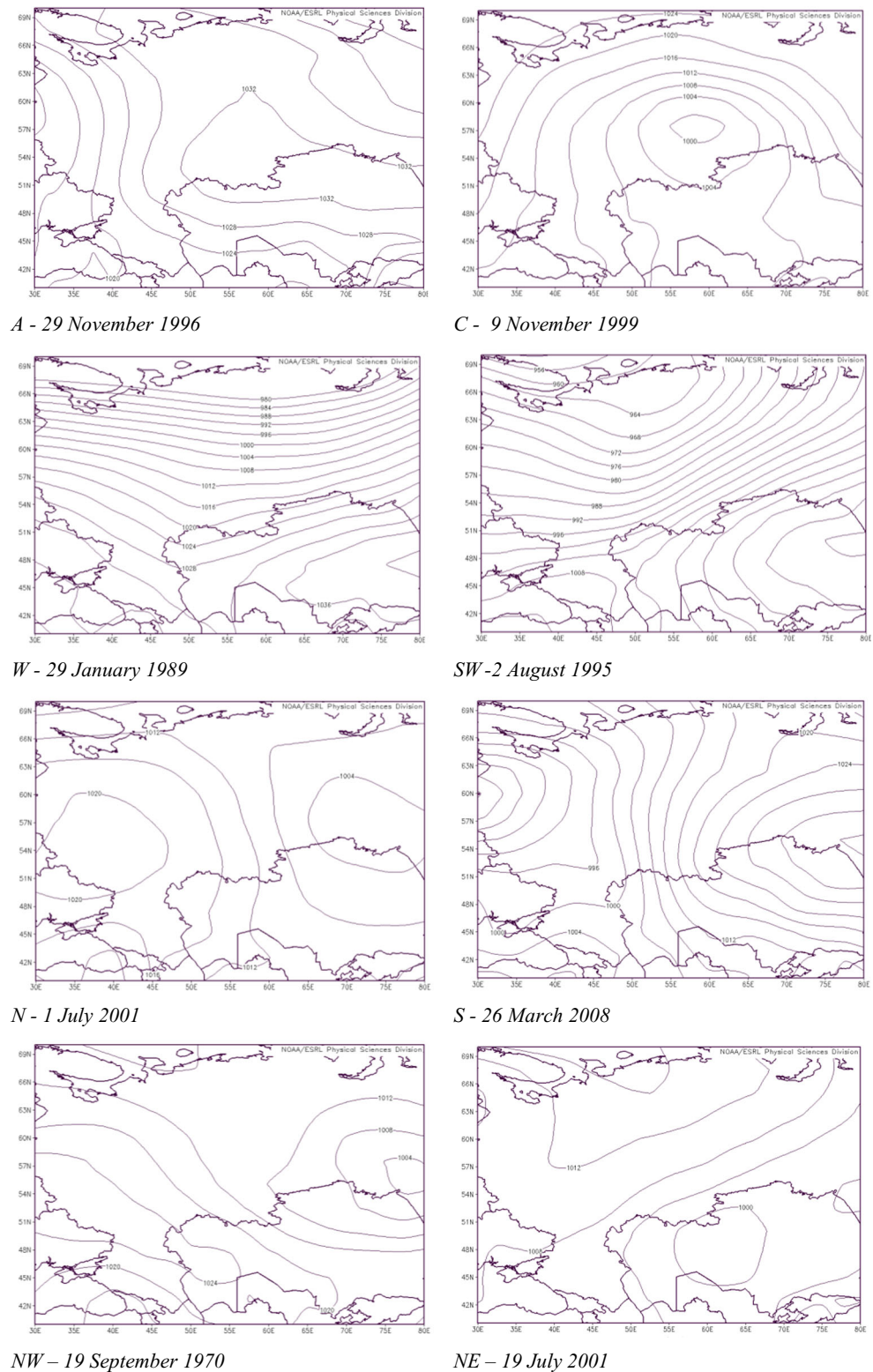
Fig. 3 Typical examples of main weather types

A - 29 November 1996

C - 9 November 1999

W - 29 January 1989

SW - 2 August 1995

N - 1 July 2001

S - 26 March 2008

NW – 19 September 1970

NE – 19 July 2001

types based on vorticity and directional characteristics. Grouping is also undertaken by Espinoza et al. (2014) for their catalogue of weather types in Central Chile. In this research, two sets of groups are identified (Table 2).

Set 1 In this set, three groups assess the overall strength of vorticity over the region: (i) negative termed 'anticyclonic' or 'ANT' (A, AN, ANE, AE, ASE, AS, ASW, AW, ANW), (ii) positive vorticity termed 'cyclonic' or 'CYC' (C, CN, CNE,

Table 1 Total number of days, annual mean and percentage, annual maximum and minimum and coefficient of variation (CV) of the JC classification types

JC type	Days	Mean	Percent	Max	Min	CV	Summer %	Winter %
N	705	14.1	3.86	25	6	33.79	*5.34*	2.37
NE	465	9.30	2.55	18	3	41.91	*4.00*	1.09
E	367	7.34	2.01	22	1	58.04	*2.62*	1.39
SE	601	12.02	3.29	22	3	35.48	*3.70*	2.88
S	653	13.06	3.58	26	3	34.22	3.10	*4.05*
SW	1407	28.14	7.70	42	12	25.50	4.28	*9.89*
W	1332	26.60	7.29	46	12	29.82	4.71	*5.08*
NW	977	19.54	5.35	30	7	27.55	*5.62*	5.08
C	2178	43.56	11.93	62	25	20.3	*13.10*	10.74
A	4254	85.08	23.29	132	49	20.4	22.85	*23.74*
CN	331	6.62	1.81	14	1	40.59	*2.35*	1.27
CNE	190	3.88	1.04	8	0	54.1	*1.48*	0.60
CE	123	2.80	0.67	7	0	61.03	*0.93*	0.42
CSE	131	2.91	0.72	7	0	51.69	0.71	*0.72*
CS	96	2.4	0.53	5	0	50.64	0.36	*0.69*
CSW	225	4.79	1.23	10	0	52.44	0.69	*1.78*
CW	343	6.86	1.88	17	2	40.27	1.44	*2.32*
CNW	352	7.04	1.93	17	2	46.00	*1.95*	1.91
AN	202	4.30	1.11	11	0	56.56	*1.56*	0.65
ANE	161	3.35	0.88	12	0	59.47	*1.33*	0.43
AE	171	3.56	0.94	10	0	57.88	*1.31*	0.56
ASE	330	6.6	1.81	14	1	42.85	*2.08*	1.54
AS	377	7.54	2.06	15	2	43.88	1.57	*2.56*
ASW	674	13.48	3.69	24	6	30.17	2.34	*5.05*
AW	498	9.96	2.73	23	3	41.52	2.00	*3.46*
ANW	325	6.63	1.78	12	2	42.50	1.75	*1.81*
U	794	4.26	4.35	29	8	33.09	*6.81*	1.88
Total	18,262							

Values in italics mean more common in this season

CE, CSE, CS, CSW, CW, CNW) and (iii) weak vorticity termed 'advective' or 'ADV' (N, NE, E, SE, S, SW, W).

Set 2 In this set, eight groups describe the directional component of circulation. For instance, the northerly direction group [N] includes N, CN and AN days; the westerly direction groups include W, AW and CW; and so on. The *northerly* component (<N>) sums the days N, CN, AN, NE, CNE, NW, CNW and ANW; the westerly component (<W>) counts W, CW, ASW, NW, ANW, CNW, SW, CSW and ASW; and so on.

Adding the number of pure C type days to the cyclonic hybrids yields 3974 days with cyclonic curvature or positive vorticity. CYC types represent 21 % of all days, but this is greatly exceeded by the number of ANT days with negative vorticity (6992 or 38.3 %). The monthly pattern in the mean numbers of CYC and ANT days (Fig. 4) depicts an increase in vorticity in late spring and early summer, a reduction in August

and a further rise in autumn. The rise in vorticity reflects the extension of influence of the two large high pressure areas in Asia: the subtropical high to the south in summer and the Siberian high in the northeast in winter. On the other hand, increases in cyclonicity in autumn accompany the renewal of enhanced westerly flow at this time of year.

Considerable variation exists in the occurrence of directional groups; however, over the longer term, the most important flow is westerly. On the whole groups of easterly types are least frequent, yet its importance is significant in mid-summer (Fig. 5) during which it can exceed both northerly and southerly components. This is a consequence of the large-scale pressure fall to the east, particularly the development of the Tibetan low-pressure system. Monthly frequencies of all directions follow distinct seasonal patterns with southerly and westerly groups showing a strong association with the winter half of the year.

4 Comparison to JCBI record

Differences between the mid-latitude circulation catalogues for this continental area to the well-established JCBI record can be examined. In order to do so, the same period (1961–2010) is summarised for the JCBI catalogue. The centre of the JCBI grid lies at 5° W and some at 60° or 3700 km from the mid-point of the Russian grid. In the long term, differences in the importance of weather types should be a response to hemispheric-scale patterns of sea level pressure, that is the mean longitudinal positions of the main axes of troughs and ridges. Furthermore, given that mean surface pressure in the Northern Hemisphere is strongly influenced by the distribution of land and sea, then the main differences between the two catalogues should reflect their maritime or continental locations. Notwithstanding this, there is a similar pattern in the relative frequency of types between the two records. In the JCBI system, A is the most frequent type (21.4 %), followed by C (13.2 %) and then W (10 %) and SW (9 %). The greatest percentage difference of the numbers of individual types is the U type which is 3 times more common in the south-west Russia area than the British Isles. U types in the Russian catalogue are most frequent in the summer months of May, June and July when slack pressure gradients are observed. This is similar (but not as extreme) as that reported by Jorba et al. (2004) for Mediterranean latitudes.

Applying the JC method to the south-west Russia area results in a more equal distribution of days across the 27 weather types. A way of quantifying this spread is to calculate the deviation in the total numbers of days classified under each weather type from the value if there were equal numbers of days in each of the 27 weather types (676 days) and then divide the sum of these deviations by 18,262. This indicative value would therefore range from 0, if there were equal numbers of days in each weather type, to 1.93, if all days were classified in the same category. In this case, the value suggests marginally more clustering in the case of the JCBI record (0.84) than for JCSWR (0.76).

Gross circulation differences can be illustrated by the groupings of weather types. With respect to the vorticity groups, CYC and ANT, there are less cyclonic days (on average, 11 less per year) and more anticyclonic circulation types (on average, 11 more per year) in the JCSWR catalogue. This indicates the stronger control on circulation of the polar front directing travelling depressions in the British Isles area. Furthermore, patterns of cyclonicity differ during the year (Fig. 6) and, hence, the average timing of cyclonic rainfall will differ between locations.

Considerable differences can also be seen in the number of days within each directional group (Table 3). There are significantly greater amounts of days with the compared northerly and easterly components in Russia and southerly and westerly components in the British Isles ($\chi^2 = 249.8$, $p < 0.001$). These differences occur in all seasons. Northerly and easterly flow direction is a response to relatively frequent location of anticyclonic centres over north-west Russia and Scandinavia (Fig. 7), whereas to the north-west of the British Isles, there is a far greater likelihood of troughs directing SW and W flow.

5 Precipitation in the study area

5.1 General characteristics

Rainfall data were obtained from the 518 station datasets of Bulygina and Razuvaev (2012) made available by the Carbon Dioxide Information Analysis Center (CDIAC 2014). Thirty stations were extracted from within the classified grid (appendix 2). There is a significant latitudinal decrease in annual precipitation amounts from north to south within this sample window ($r = 0.648$, $p < 0.05$) and also a significant correlation with altitude ($r = 0.490$, $p < 0.05$). These geographical relationships are stronger in the summer than in the winter months. Variability of rainfall, as measured by the coefficient of variation of monthly rainfall amounts, also significantly increases with decreasing altitude and latitude. Examination of the mean rainfall per event suggesting a relatively small number of convective storms explains the peak in rainfall amounts in summer months (Fig. 8). For instance, at Kushnarenkovo (55.13° N, 55.35° E), a simple ratio of the 'number of dry days (<0.2 mm)' to the 'number of days with

Table 2 Total number of days, annual mean and percentage of the groupings of advective types

	Northerly direction [N]	Easterly direction [E]	Southerly direction [S]	Westerly direction [W]	Northerly component <N>	Easterly component <E>	Southerly component <S>	Westerly component <W>
Total	1240	666	1131	2173	3955	2536	4487	6190
Mean	24.80	13.32	22.62	43.46	79.10	50.72	89.74	123.80
%	6.79	3.65	6.19	11.90	21.66	13.89	24.57	33.90
Max	12	3	9	24	51	30	53	77
Min	39	30	34	69	122	76	117	154
CV	25.57	37.57	27.63	22.89	17.69	20.85	13.53	14.14
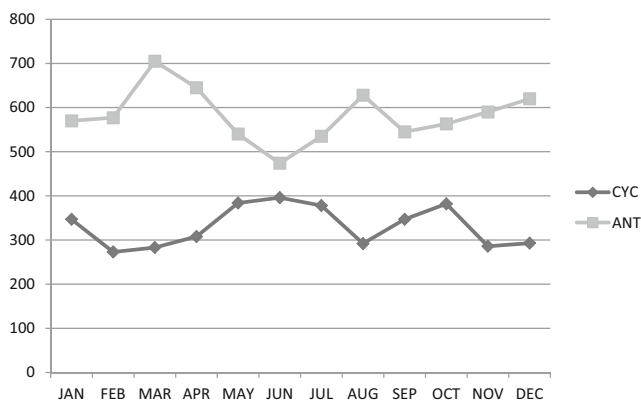
Fig. 4 Monthly regimes of cyclonic (*CYC*) and anticyclonic (*ANT*) groupings

Fig. 6 Total monthly cyclonic (CYC) days

falls over 10 mm' yields a value of 92 in mid-winter in January (739:8) but 11 in July (944:86).

In order to examine the spatial and temporal variability of rainfall across the area, groups of covarying locations can be identified. A multivariate technique, used for instance by Romero et al. (1999), can determine *rainfall affinity areas* (RAAs) by applying principal component analysis to the full dataset and then grouping locations with similar component scores using the *k*-means clustering algorithm. Application of this regionalisation technique results in four distinct RAAs which have marginally different group memberships in summer and winter months (Fig. 9). The rainfall regime of at least one *key* representative station within each RAA can be used to illustrate the findings of this research. The general rainfall regime for each of these stations is listed in Table 4. Groups 1, 2 and 3 display regimes with a peak in totals in June and July and are differentiated by the influence of the latitude and altitudinal control (the mean altitude of stations in each group is 144, 105 and 452 m, respectively). The southerly group 4 is much drier with a reduced summer peak and a second relatively wet spell in late autumn.
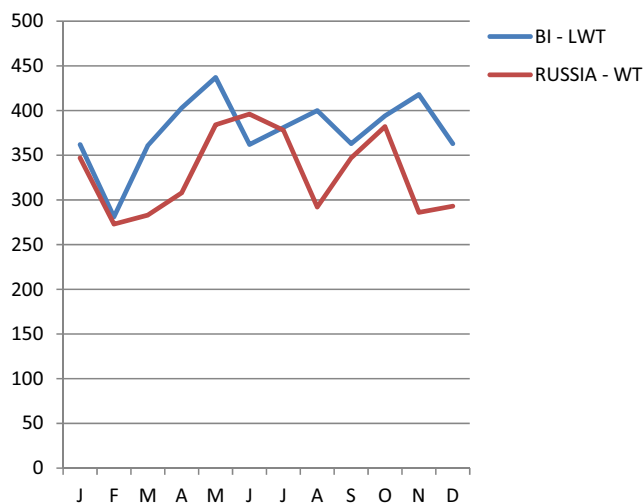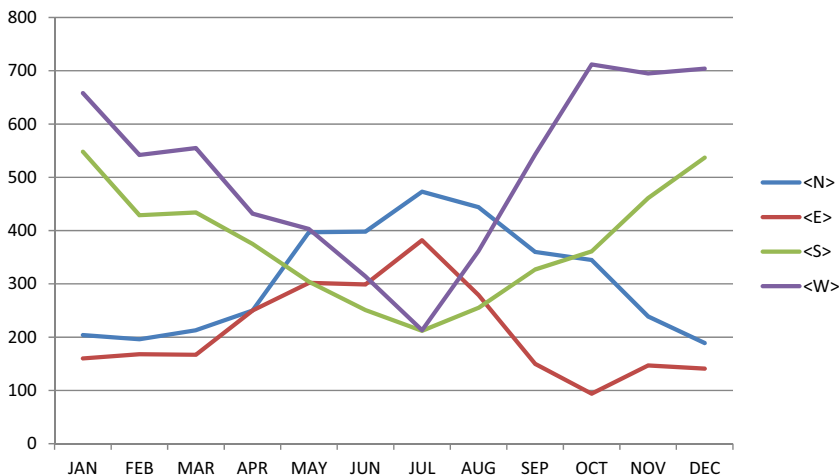
5.2 Daily rainfall distribution

Establishing a statistical model to capture the behaviour of precipitation systems has long been a topic of interest (Hanson and Vogel 2008), but due to the complex nature of precipitation processes, these models have been selected by goodness-of-fit criteria rather than being derived from knowledge of the underlying physical processes (Duan et al. 1998). There are many probability distributions that have been seen to successfully parameterise rainfall distributions, and the critical component is that they are flexible enough to represent a variety of rainfall regimes. The gamma distribution is often used to model the distribution of daily rainfall amounts as it suits the distribution of daily rainfall and accommodates the lower limit of zero which constrains rainfall values (Wilks 2006). Other distributions include the Weibull distribution (e.g. Boulanger et al. 2007), the log-normal (e.g. Shoji and Kitaura 2006) and the mixed exponential distribution (e.g. Wilks 1999). Studies that have compared the suitability of two or more different distributions such as Boulanger et al.

Fig. 5 Monthly mean for directional component groups

Table 3 Number of days within each direction group for JCBI and JCSWR Russia 1961–2010

	JCBI	JCSWR	χ^2	p
[N]	1071	1238	160.9	<0.001
[E]	558	661		
[S]	1769	1126		
[W]	2864	2173		
<N>	3311	3708	249.7	<0.001
<E>	1939	2539		
<S>	5025	4494		
<W>	7187	5136		

(2007) have found that no single distribution consistently suits all regions, seasons and climates better than others. In this study, daily station precipitation distribution was fitted to a number of probability distributions. Although the differences between performances were not considerable, the Weibull distribution repeatedly provided the best-fit probability distribution for rainfall.

5.3 Rainfall and weather type

Should a significant synoptic control on rainfall be established, then consideration of the prevailing weather type should improve the accuracy of modelled rainfall over the simulation of a rainfall regime based on features of a probability distribution alone. The synoptic classification was, therefore, first examined to determine if consistent stable relationships between weather types and precipitation could be identified. The fundamental assessment of how dry or how wet a weather type is summarised by the following simple relative performance index (RPI) which can be calculated for each weather type at each location:

$$RPI = \frac{WTRF}{RF}$$

In this equation, RPI is the *relative performance index* of each weather type, WTRF refers to the mean rainfall for the weather type, and RF refers to the mean rainfall at that location under all the weather types. The resulting value can be used to determine if a type is wet (<1.00), dry (>1.00) or non-distinct (1.00). The RPI values are listed in Table 5. Positive (wet) values are shown in italics. As expected, negative vorticity types and groups (A, ANT), as a result of their atmospheric stability, result in dry conditions whereas CYC days are universally wet. The relationship between directional types and rainfall is less easy to interpret and depends on the location of the station considered; nevertheless, rainfall amounts in the southern half of the study area are more associated with northerly and easterly flow whereas westerly types are important drivers of precipitation in the north. In the summer months, actual rainfall amounts show a high degree of variability under

Fig. 7 Synoptic pattern of 2 October 2010, leading to NE flow in the study area
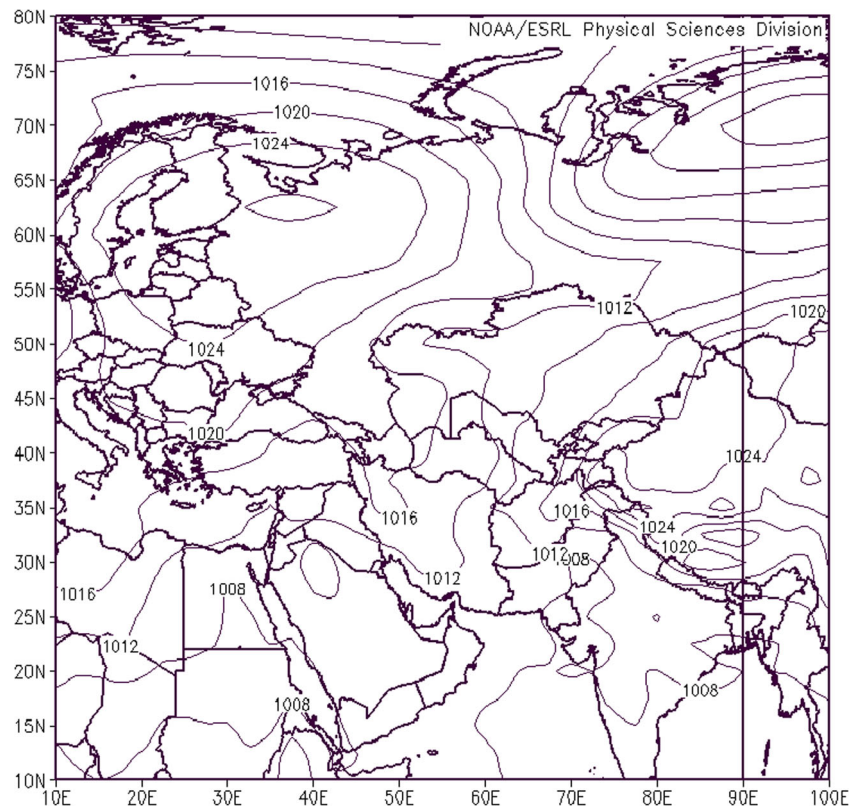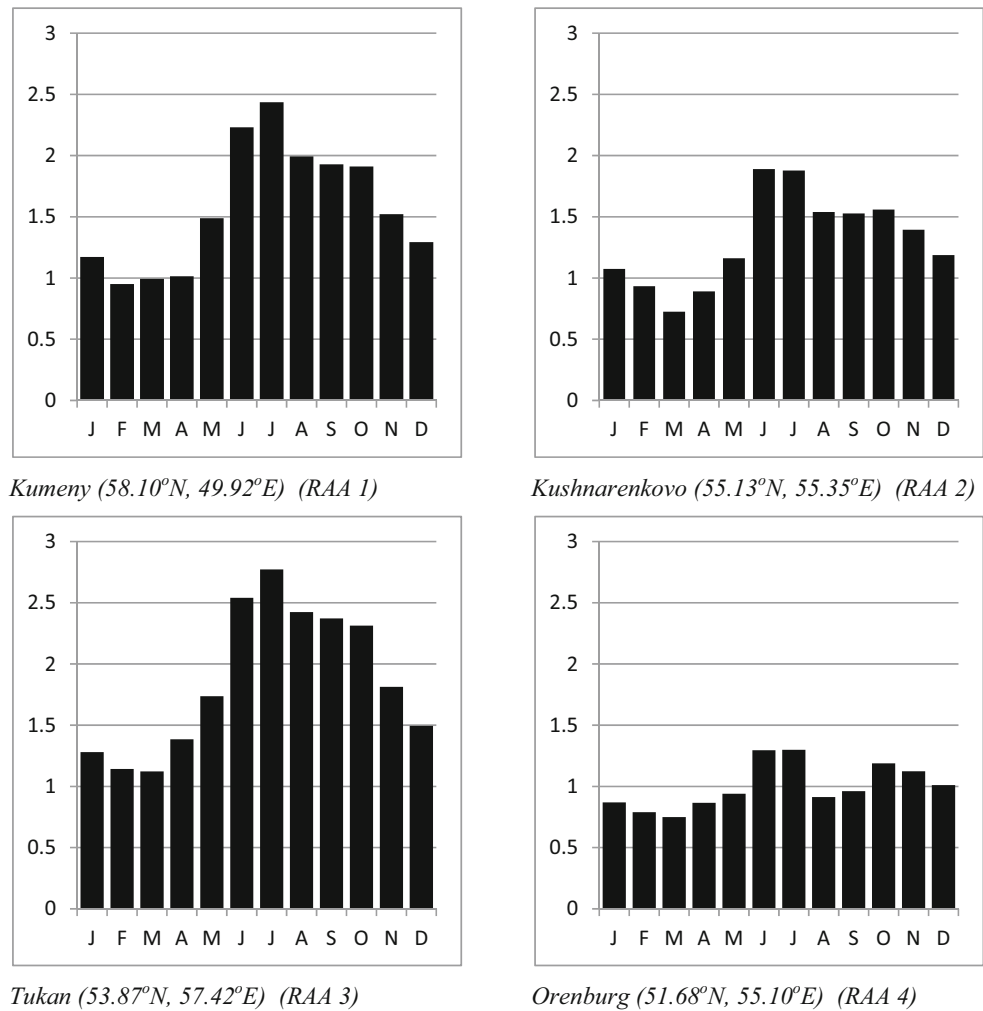
Fig. 8 Mean daily rainfall (mm) by month for representative stations in each RAA

Kumeny (58.10ºN, 49.92ºE) (RAA 1)

Kushnarenkovo (55.13ºN, 55.35ºE) (RAA 2)

Tukan (53.87ºN, 57.42ºE) (RAA 3)

Orenburg (51.68ºN, 55.10ºE) (RAA 4)

each weather type. This is consistent with findings by other authors (e.g. El-Kadi and Smithson 1996) who identify the stronger synoptic control on rainfall amounts in winter due to the high variability in the spatial nature and the depth of rainfall from summer convective mechanisms.

To determine if there is effective statistical differentiation of rainfall amounts by weather types, a non-parametric test of

Fig. 9 Regionalisation of meteorological stations in the study area for winter half of the year
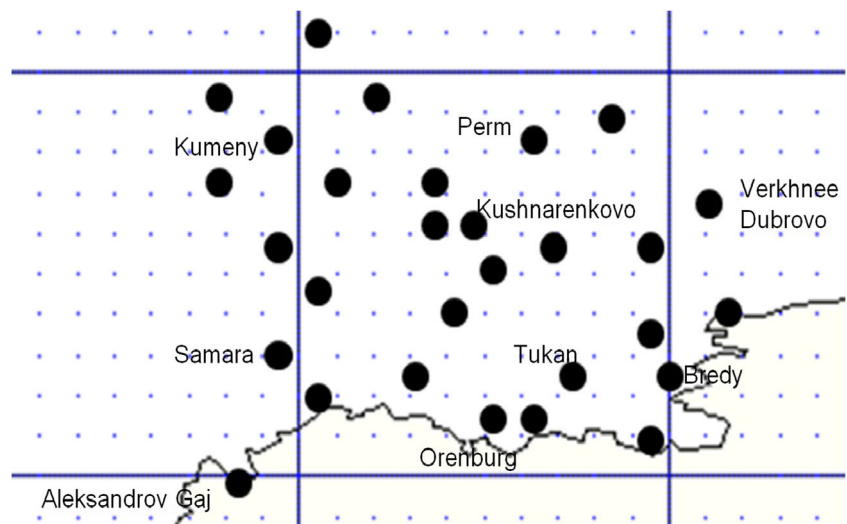
difference was applied to daily rainfall regimes under each of the most frequent types. Kruskal-Wallis one-way analysis of variance determines the probability that daily rainfall recorded under each of the main weather types originates from the same distribution. The test identifies a significant difference between at least two of the groups at each station for all years, summer and winter periods at $p < 0.001$. Further analysis (Mann-Whitney U test) using pairs of weather types for all groups indicates a statistically significant weather type-based distinction between rainfall regimes. Only the southerly types (SW, SE and S) in group 4 and SW and W in group 2 stations do not exhibit clear differences at the 0.05 level.

5.4 Modelling the association of circulation type and rainfall

The strength of the association between weather types and precipitation behaviour can be tested using a simple model. In order to do this, the whole dataset was divided into a calibration set, in which relationships between rainfall and weather types were established, and a validation set in which the rainfall was modelled using the relationships that exist in the calibration set. The success of this method depends on a consistent relationship between precipitation and the weather type—a situation termed 'stationarity'. In this study, the 18, 262 days are first divided into two subsets of data: the summer months (April to September, 9150 days) and the other the rest of the winter months (October to March, 9112 days). From each subset, only those days with the eight most recurring weather types in each season are retained (summer 63.6 % or 5821 days; winter 73 % or 6665 days). This is done to reduce the effect of the very infrequent hybrid types in the modelling process. Finally, the resulting two sets are further divided into calibration (90 %) and validation (10 %) sets. There is some discussion in the literature (e.g. Mourad et al. 2005) on the optimum size of calibration and validation sets for this type of model. Clearly, better calibration can be achieved when a large number of cases can be presented for model calibration yet, at the same time, better validation results will likewise be obtained using a large validation set. In this model, a relatively small validation set of 10 % of days was chosen for both the summer and winter validations. Days within this set were determined using random numbers.

After calibration, a daily rainfall prediction for the validation set was made using the following: (a) a distribution-based model in which a value for each day was drawn at random from a Weibull frequency distribution with scale and shape parameters based on the characteristics of the calibration data in each season and (b) a weather type model in which the mean value for each weather type was calculated from the calibration set in each season. The performance of each model is then determined by calculating the mean daily modelled rainfall for each key station for each season over the length

Table 4 Rainfall observed at key stations (1961–2010)

	Number of days used	Mean daily rainfall (mm)	Dry day (<0.3 mm) probability	Maximum daily amount (mm)	Mean annual rainfall (mm)	Max annual rainfall (mm)	Min annual rainfall (mm)
Kumeny (1)	18,133	1.582	0.534	74.2	579.2	782.6	407.3
Kushnarenkovo (2)	18,167	1.315	0.599	54.4	483.5	613.9	291.6
Tukan (3)	18,166	1.870	0.543	86.4	687.2	1030.0	461.7
Orenburg (4)	18,262	1.001	0.683	62.2	365.7	536.9	365.7

Table 5 Relative performance index of daily rainfall (all months) for pure types

	A	C	N	NE	E	SE	S	SW	W	NW	ANT	CYC
Kumeny	0.456	*1.518*	0.327	0.189	0.303	0.961	*1.856*	*2.19*	*1.280*	0.733	0.638	*1.342*
Kushnarenkovo	0.458	*2.258*	0.830	0.718	0.632	0.951	0.771	*1.070*	*1.026*	0.874	0.697	*1.654*
Tukan	0.336	*1.945*	*1.524*	*1.391*	*1.018*	0.713	0.400	0.713	*1.257*	*1.699*	0.409	*1.934*
Orenburg	0.456	*2.219*	*2.11*	*1.319*	*2.492*	*1.605*	0.708	0.737	0.637	0.568	0.515	*1.975*

Positive RPI values (relatively wet types) are presented in italics

of the validation set and then calculating the percentage error (Table 6).

Table 6 shows that in the winter months, although the modelled value performs reasonably well and the error in the mean daily amount is generally less than 10 %, the modelled data using the rather crude measure of the mean of each JC type performs better. This indicates the strong stability in the relationship between circulation type and rainfall amounts. As expected, the use of calibration set mean values fails to capture the variability in the daily data and, as a consequence, the variability of the rainfall is poorly represented and much better represented using the distribution that does not take into account the circulation. The prediction of summer rainfall is considerably less accurate, suggesting a lack of coherent response in rainfall totals with weather type. For instance, at Tukan (53.87° N, 57.42° E), the weather type model has a 15.77 % underprediction and the frequency model overpredicts by 20.7 % in the summer.

6 Conclusion

This study demonstrates that the JC weather typing method can successfully be applied to a mid-latitude region with a high degree of continentality. It demonstrates the key modes of atmospheric circulation and can be used to identify a clear association with precipitation behaviour despite the lack of apparent direction-based moisture contrasts in advected air.

A catalogue of sea level pressure patterns, and hence weather type, was created using the Jenkinson and Collison method for the 1961–2010 period for an area in south-west Russia. The continental location of the study area catalogue contrasts with other synoptic catalogues, yet Jones et al. (2013) have suggested that the JC method should be applicable to any mid-to-high-latitude region. In this case, there is not only a typical mid-latitude importance of A (23.3 %) and C (11.9 %) pure types but also a diversity of other weather types. There are relatively few hybrid types occurring in any one year. If types are grouped, the number of days with anticyclonic curvature (38.3 %) greatly exceeds that with cyclonic curvature (21 %); however, the difference is less marked in early summer.

The number of *undetermined* (~4 %) is less than that found in lower latitudes, but they are more frequent, particularly in the summer months, than at the western continental margin (i.e. the British Isles). Main differences are largely a consequence of the difference in location. There is a significant importance of easterlies in summer; for instance, in July, the total easterly component days is 126 in the British Isles against 382 for the Russian area. The resulting pattern shows some influence by well-known circulation features near this area and also the importance of the westerly flow associated with the polar front.

The utility of the catalogue in explaining surface meteorology is explored with respect to daily rainfall amounts. A clear relationship can be found between circulation pattern and

Table 6 Performance of simple models of rainfall

	Observed mean (mm)	SD (mm)	Frequency model mean (mm)	SD (mm)	% error	Weather type model mean (mm)	SD (mm)	% error
Kumeny								
Perma	1.5691	2.56	1.5339	2.02	−2.24	1.5691	0.84	0.00
Verhnee Dubrovo	0.8293	1.81	0.8898	1.46	+7.29	0.8293	0.61	0.00
Samara	1.0542	2.23	1.1260	1.81	+6.81	1.0537	0.91	−0.05
Kushnarenkovo	1.1341	2.21	1.1873	1.87	+4.69	1.1355	0.62	+0.12
Tukan	1.4480	2.80	1.3767	2.08	−4.92	1.4436	0.92	−0.30
Alexsandrov Gaj	0.7226	1.89	0.9447	1.58	+30.74	0.7212	0.61	−0.19
Bredy	0.6443	1.86	0.6113	1.22	−5.12	0.6445	0.48	+0.03
Orenburg	0.8303	2.19	0.7372	1.42	−11.2	0.8302	0.73	−0.01

rainfall amount, and a significance test proves that different regimes exist under each type. In order to test these datasets, rainfall amounts can be tested using a small validation dataset with the relationship between weather type and rainfall being established with a much larger calibration set. Although methodologically unnecessary, the utility of the weather type model was repeatedly tested using different randomly selected calibration and validation sets and repeatedly produced accurate prediction which improved that from a frequency distribution model, but this was only observed in the winter. This is common with other authors (e.g. El-Kadi and Smithson 1996) who have found that the use of synoptic climatologically–

precipitation relationship is much stronger in winter. Inevitably, this is due to the significant amount of rainfall that derives from convective activity which has less of a coherent synoptic signal.

Appendix 1

The equations used to determine the airflow indices needed to generate a JC type for each day are as follows (the numbers in bold refer to the grid point reference in Fig. 3)

Westerly flow $(W) = 0.5(\mathbf{12} + \mathbf{13}) - 0.5(\mathbf{4} + \mathbf{5})$

Southerly flow $(S) = 1.74[(0.25(\mathbf{5} + 2.0 \times \mathbf{9} + \mathbf{13}) - (0.25(\mathbf{4} + 2.0 \times \mathbf{8} + \mathbf{12})]$

Resultant flow $(F) = \left(S^2 + W^2\right)^{0.5}$

Westerly shear velocity $(ZW) = 1.07[0.5(\mathbf{15} + \mathbf{16}) - 0.5(\mathbf{8} + \mathbf{9})] - 0.95[0.5(\mathbf{8} + \mathbf{9}) - 0.5(\mathbf{1} + \mathbf{2})]$

Southerly shear velocity $(ZS) = 1.52[0.25(\mathbf{6} + 2.0 \times \mathbf{10} + \mathbf{14}) - 0.25(\mathbf{5} + 2.0 \times \mathbf{9} + \mathbf{13}) - 0.25(\mathbf{4} + 2.0 \times \mathbf{8} + \mathbf{12})$

$\qquad\qquad\qquad +0.25(\mathbf{3} + 2.0 \times \mathbf{7} + \mathbf{11})]$Total shear velocity $= Z = ZW + ZS$

The flow units are geostrophic (each is equivalent to 1.2 knots) expressed as hectopascals (hPa) per 10° latitude at 55° N. The geostrophic vorticity units are expressed as hPa per 10° latitude also at 55° N; 100 units are equivalent to 0.55×10^{-4} which is 0.46 times the Coriolis parameter at 55° N. The constants in the equations account for the relative differences between grid point spacing in the east-west and north-south direction.

The equations use a number of coefficients, calculated by Jenkinson and Collison (1977) to take into account the different relative grid spacing at different latitudes. In order to be applied at different latitudes, the coefficients are explained below for latitude 55° (ψ)

S 1.74 is $1/\cos(\psi)ZW$ 1.07 and 0.95 are $\sin(\psi)/\sin((\psi) - 5°)$ and $\sin(\psi)/\sin((\psi) + 5°)ZS$ 1.52 is $0.5\left(\cos((\psi))^2\right)$

Jenkinson and Collison (1977) used the following rules to determine the appropriate LWT:

(i) The direction of flow is $\tan(W/S)$. Add 180° if W is positive. The appropriate direction is calculated on an 8-point compass allowing 45° per sector. Thus, W occurs between 247.5° and 292.5°.

(ii) If $|Z|$ is less than F, then the flow is essentially straight and corresponds to a Lamb pure directional type.

(iii) If $|Z|$ is greater than $2F$, then the pattern is strongly cyclonic ($Z > 0$) or anticyclonic ($Z < 0$). This corresponds to Lamb's pure cyclonic and anticyclonic type.

(iv) If $|Z|$ lies between F and $2F$, then the flow is partly (anti) cyclonic and this corresponds to one of Lamb's synoptic/direction hybrid types, e.g. AE.

(v) If F is less than 6 and $|Z|$ is less than 6, there is light indeterminate flow corresponding to Lamb's unclassified type U. The choice of 6 is dependent on the grid spacing and would need tuning if used with a finer grid resolution.

Appendix 2

Table 7 Details of 30 meteorological stations examined in this study

Station number	Station name	Latitude	Longitude	Altitude (m)	Opened	PAA (winter)	PAA (summer)
23904	Kojgorodok	60.45	50.97	124	1959	1	1
27083	Oparino	59.85	48.28	179	1940	1	1
27296	Kumeny	58.10	49.92	175	1940	1	1
27385	Jaransk	57.37	47.92	103	1940	1	2
27595	Kazanâ€™	55.73	49.20	116	1812	1	3
27995	Samara (Bezencuk)	52.98	49.43	45	1904	4	2
28009	Kirs	59.37	52.22	168	1940	1	1
28138	Biser	58.52	58.85	463	1888	3	3
28224	Permâ€™	58.02	56.30	171	1866	2	2
28312	Debessy	57.63	53.82	187	1940	2	2
28401	Kila	56.90	51.07	143	1940	2	2
28418	Sarapul	56.47	53.73	135	1940	1	2
28419	Janaul	56.27	54.90	98	1940	2	2
28445	Verhnee Dubroo	56.73	61.07	287	1959	2	3
28537	Duvan	55.70	57.90	337	1940	2	2
28624	Kushnarenkovo	55.13	55.35	98	1959	2	2
28630	Zlatoust	55.17	59.67	532	1936	3	3
28704	Culpanovo	54.50	50.42	76	1929	2	2
28719	Aksakovo	54.03	54.18	357	1940	3	2
28748	Troizk	54.08	61.62	192	1940	4	4
28823	Tukan	53.87	57.42	551	1959	3	3
28833	Verhneuralâ€™sk	53.88	59.20	401	1903	4	4
34391	Aleksandrov Gaj	50.15	48.55	23	1929	4	4
35007	Pereljub	51.87	50.33	72	1933	4	4
35011	Sorocinsk	52.43	53.13	122	1934	4	4
35026	Zilair	52.22	57.40	522	1940	4	3
35041	Bredy	52.43	60.35	309	1940	4	4
35121	Orenburg	51.68	55.10	115	1843	4	4
35127	Ak-Bulak	51.02	55.63	143	1927	4	4
35233	Dombarovskij	50.75	59.55	277	1937	4	4

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