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Development of a spatial synoptic classification scheme for western Europe

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Abstract:

This paper presents a new spatial air-mass climatology for western Europe (WE) based upon the analysis of daily data for 48 climate stations for the period 1974–2000. Referred to as the spatial synoptic classification for western Europe (SSCWE), the new air-mass climatology not only facilitates the examination of both spatial and temporal climate variations but also provides, for the first time, a physically based synoptic classification for a wide variety of applications at the western European scale. The SSCWE is based on the philosophy of the spatial synoptic classification (SSC), which was first introduced to the synoptic climatological community in the mid-1990s and later refined as the SSC2 for application across North America. As for the SSC2, establishing the physical characteristics for six generic air masses is the basis of the SSCWE. In this paper, the procedures for identifying air-mass characteristics are described and an analysis of the spatial and temporal variation of the six generic air-mass types across western Europe is presented. Copyright © 2007 Royal Meteorological Society

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INTRODUCTION

Synoptic climatological classification in Europe, based on either manual or semiautomated methods, has been traditionally dominated by surface and upper air pressure map pattern classification (Yarnal, 1993; El-Kadi and Smithson, 1996). For example, Grosswetterlagen (GWL) (Hess and Brezowsky, 1952), which is a circulation pattern classification based on the work of Baur *et al.* (1944), has been used extensively to characterize the atmospheric circulation over western and central Europe (e.g. Bardossy and Caspary, 1990; Werner *et al.*, 2000; Kyselý, 2002; Domonkos *et al.*, 2003). In the GWL classification, three groups of circulation types (zonal, half-meridonal and meridonal) are divided into 10 types and 29 circulation patterns. Similarly, the map pattern based Lamb Weather Type (LWT) classification, developed originally for weather analysis in the region of the British Isles, is compromized of 7 major and 27 hybrid weather types. Although the GWL and LWT have proved useful in numerous studies of the association between the atmosphere and the surface environment (e.g. Bardossy and Plate, 1992) the number of map patterns or weather types is often found to be too large for practical application, thus, pattern groups are often merged prior to analysis (Bardossy and Plate, 1992; Post and Tuulik, 1999; Stahl and Demuth, 1999a,b). Furthermore, despite a general belief that the GWL classification is valid for the whole of Europe, it has been found that the GWL does not produce homogeneous descriptions of the weather in the peripheral regions of Europe (Post and Tuulik, 1999). Moreover, while a kinematic view of the atmosphere, as offered by the GWL and LWT classifications and more recent semiobjective classifications based on pressure patterns (Hewitson and Crane, 2002; Kassomenos, 2003; Esteban *et al.*, 2006), provide information on atmospheric dynamics, little is revealed about the nature of air masses associated with the main modes of atmospheric circulation as portrayed by composite pressure map patterns. Accordingly, there has been increasing interest in the development of air-mass based synoptic classifications as these allow interpretation of surface environmental processes and patterns in terms of variations in the synergistic effects of atmospheric thermal and moisture characteristics.

Synoptic-scale air-mass classifications are based on the concept of air masses. These are defined as large volumes of air with 'homogeneous' thermal and moisture characteristics (Barry and Perry, 1973). Air masses usually take on the characteristics of the underlying surface in their source region. On moving from its source region

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an air-mass can be subject to warming, cooling, and the addition/removal of water. However, when an air-mass crosses the same area at a similar speed and time of year, its characteristics will be similar. It is this characteristic that allows days with similar weather characteristics to be classified as the same air-mass type (Davis and Kalkstein, 1990a).

Air-mass classifications were first introduced in the 1950s (e.g. Belasco, 1952) for the purpose of relating the thermodynamic characteristics of the atmospheric circulation to surface environmental processes (Yarnal, 1993). Because air-mass classifications are based on identifying the covariant behavior of daily thermal and moisture characteristics, they are fundamentally different to map pattern based classifications such as the GWL and LWT, which distinguish between groups of days with 'homogeneous' pressure patterns. Notwithstanding the differences associated with their development, synoptic classifications based on air masses may have some practical advantages over those based on map patterns (Barry and Perry, 1973; Kalkstein *et al*., 1996). This is because variations in such things as agricultural production (Jones and Davis, 2000), air pollution (Kalkstein and Corrigan, 1986) and health (McGregor, 1999; Kyselý and Huth, 2004) can be related directly to air-mass thermal and moisture characteristics as opposed to pressure map patterns indirectly.

Although approaches such as trajectory analysis (Belasco, 1952) and partial collective methods (Bryson, 1966) have been used in the past, more recently, studies have employed principal component analysis (PCA) in conjunction with cluster analysis (CA) for developing air-mass classifications (Davis and Gay, 1993; Huth *et al*., 1993; Smoyer *et al*., 2000). Typically a P mode PCA is used to reduce the dimensionality of a large multivariate climate data set, the outcome of which is a number of principal components (PCs) that describe the main modes of covariation between the original climate variables (Yarnal, 1993). Subsequently, CA is applied to a matrix of PC scores in order to identify groups of days with similar meteorological, and thus, air-mass type characteristics (McGregor and Bamzelis, 1995). The resultant daily catalogue of air-mass types is termed the temporal synoptic index (TSI) (Kalkstein and Corrigan, 1986). Although the TSI possesses a demonstrable utility for environmental analysis, a drawback of this approach is that the resultant daily air-mass catalogue is only applicable at the location for which it was developed, or at best, a limited number of adjacent locations. To overcome this problem, Kalkstein *et al*. (1996) developed the spatial synoptic classification (SSC).

The SSC was first developed for eastern and central USA but later refined as the SSC2 and extended by Sheridan (2000, 2002) to include Canada and the western USA. The SSC/SSC2 differs from the TSI since it is able to describe air masses at a single station while facilitating the comparison of air masses between stations over a very large region (Kalkstein *et al*., 1996). At the heart of the SSC/SSC2 methodology is the classification of daily observed (surface) weather conditions on a station-by-station basis into one of six general air-mass types, the physical characteristics of which are defined *a priori.* The six air masses are: (1) dry polar (DP); (2) dry moderate (DM); (3) dry tropical (DT); (4) moist polar (MP); (5) moist moderate (MM); and (6) moist tropical (MT) which describe theoretical combinations of moisture and temperature characteristics at each station. The SSC, which uses the same six air masses for all locations, offers an advantage over other approaches since it enables the understanding of spatial variations of air-mass characteristics, unlike previous classifications which are generally location specific (e.g. Kalkstein and Corrigan, 1986; Huth *et al*., 1993) and restrict inter-station comparisons. In the SSC approach, air masses are based on the identification of homogeneous groups of weather variables, rather than distinct source regions (Sheridan, 2002) thereby ensuring days with similar meteorological characteristics are grouped together. This suggests that there is potential for the SSC/SSC2 to increase understanding of spatial variations in environmental variables, which is more difficult using map pattern and single station air-mass classifications.

Given that the SSC approach is grounded in the climatological theory of air masses, plus the fact that it overcomes the problem of classifying air-mass conditions over large geographical scales and lends itself to both spatial and temporal analyses of climatic variability, an evaluation of its applicability for constructing an air-mass climatology for western Europe (WE) seems warranted. Further, the fact that the few air-mass classifications that have been developed in Europe cannot be applied at the continental scale because they are regionally specific, use different methodologies and variables, classify different numbers of air-mass types and are based on different time-periods also provides strong motivation for exploring the transferability of the SSC approach to WE.

The purpose of this paper then is to apply the SSC2 approach of Sheridan (2002) to the development of a new air-mass classification for 48 locations across WE, since a classification that will facilitate examination of spatial and temporal climate variations at the western European scale does not currently exist. For a successful application of the SSC2 approach, *a priori* knowledge of the major air-mass types and their physical characteristics at each station is critical. Such knowledge, codified in the form of seed days, is required for classifying all days at each location into one of six air-mass types. Further, as the air-mass seed day criteria developed for North America cannot be directly transferred to Europe, these must be identified. Consequently, a subsidiary aim of this paper is to further develop the SSC2 methodology through using a climate regionalization as an organizational framework for identifying seed day characteristics for each of the air masses at each of the 48 locations.

In the following section, the SSC2 methodology of Sheridan (2002) is briefly reviewed in order to provide a context for what follows. In Section 3, data and the methodological developments associated with the

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application of the SSC to Europe are detailed. In Section 4, information on the physical characteristics of the air-mass types is presented and the utility of the SSCWE for analyzing the spatial and temporal variability of climate across Europe is outlined. Conclusions are drawn in Section 5.

THE SSC2

The SSC requires the manual identification of representative days (seed days) for each of the six theoretical air-mass types. This is followed by the automated classification of all days based on the characteristics of the seed days. Key stages of the SSC2 methodology are outlined in Figure 1. The identification of seed days is a crucial stage in the development of the SSC(2) air-mass calendar for a station. Seed days are those that represent the typical surface meteorological characteristics of the six air masses (i.e. DP, DM, DT, MP, MM and MT) at a station. These can only be selected from 6-week windows for each season, since air-mass characteristics may vary over the course of the year, for example a summer DT air-mass will be warmer than its winter counterpart.

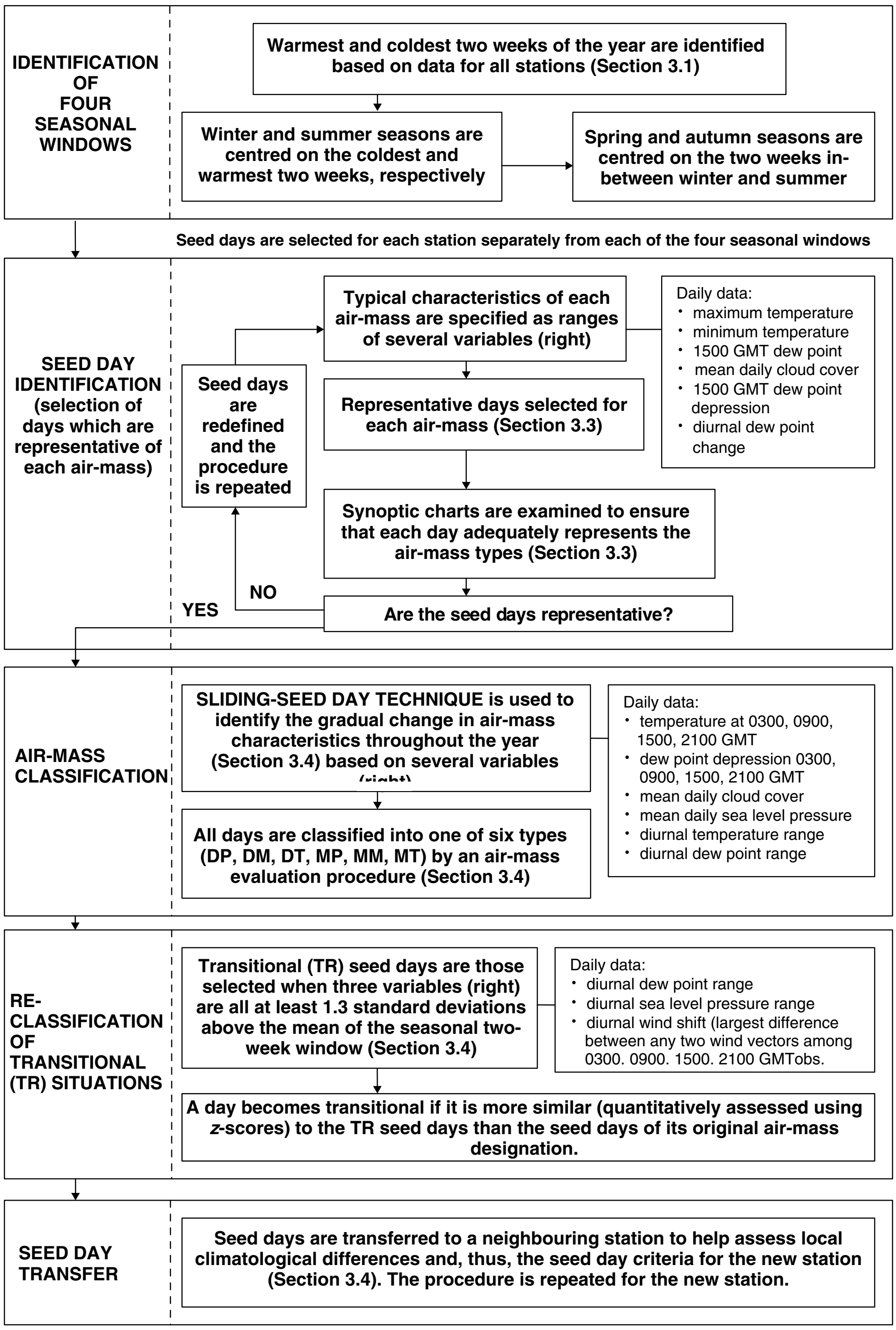

Figure 1. General stages involved in the development of the SSC2.

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Seed days are identified by specifying ranges of meteorological variables for each of the air masses determined by climatological knowledge of an area and the analysis of synoptic charts. Despite seed days only being selected from a station's record for limited periods of the year, the SSC2 enables the year-round classification of air masses by employing a sliding seed day technique. This calculates the gradual change in air-mass characteristics throughout the year and thus allows each day of a time-series to be classified based upon idealized air-mass characteristics associated with a specific day of the year. In subsequent stages, some of the air masses may be reclassified if they are found to represent a transitional situation. A transitional situation is one for which there is a change from one air mass to another. Once all days are classified for an initial station, the procedure is repeated for a nearby station. To aid the process of seed day identification at a 'new' station, a seed day transfer procedure is used to help assess local climatological differences between a station for which the classification has already been performed and the 'new' station. For example the original SSC2, developed for over 300 stations across North America, started by producing an air-mass classification for two initial stations in Philadelphia and Wilmington. Seed days were then transferred, by radiating outwards, to all other stations allowing assessment of climatological differences between stations.

DATA AND METHODOLOGICAL DEVELOPMENTS

Six meteorological variables [air temperature, dew point temperature, mean sea level pressure (MSLP), wind direction, wind speed and cloud cover], recorded at six-hourly intervals (0300, 0900, 1500, 2100 GMT) are required for the application of the SSC2 approach (Sheridan, 2002). Requisite data for the 48 western European stations used in this analysis (Figure 2), for the period 1974–2000 were obtained from the MetOffice. Wind speed and direction were converted to u- (east–west) and v- (north–south) components. Since many of the 48 stations have short periods of missing data, all missing values were estimated using one of the following three methods: (1) linear fill, (2) linear regression or (3) the long-term daily value. The technique employed for replacing missing values was determined by the number of missing data points and the availability and strength of the relationship with neighboring stations, as summarized in Figure 3. Approximately 3.8% of all data was estimated.

Climate regionalization

As an organizational framework for the selection of seed day criteria and the development of the SSCWE, a climate regionalization for WE, based on the identification of the covariant behavior of climate variables at the 48 stations was performed. Station climate was described by the same nine variables as used by Sheridan (2002) for seed day selection and air-mass evaluation. These are listed below:

- mean cloud cover (average of values at 0300, 0900, 1500, 2100 GMT)
- mean sea level pressure (MSLP) (average of values at 0300, 0900, 1500, 2100 GMT)
- afternoon dew point depression (1500 GMT)

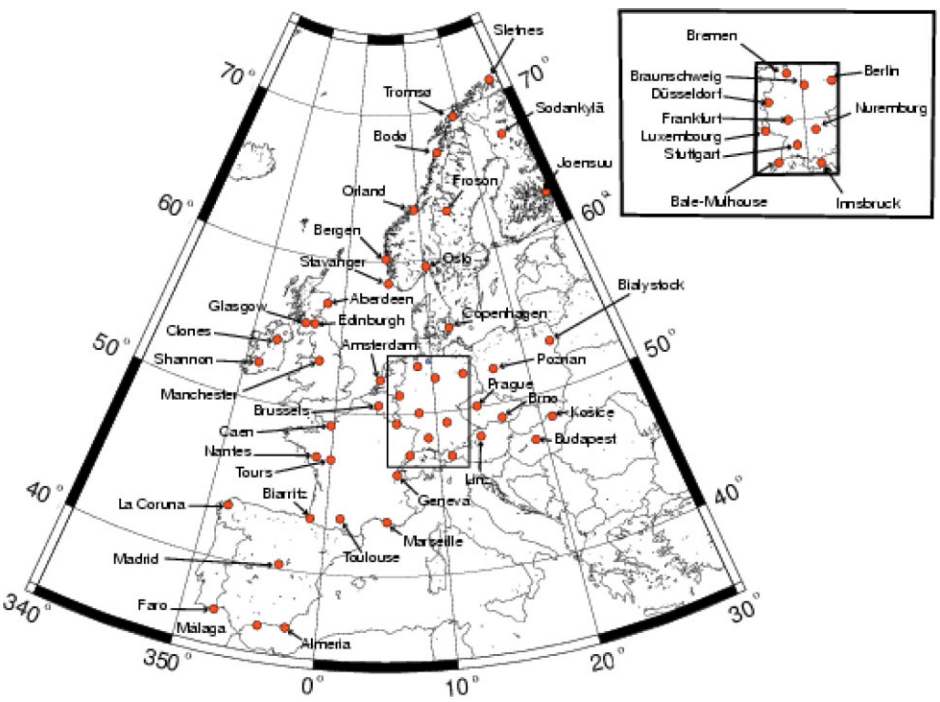

Figure 2. The 48 Western European climate stations used in this study. This figure is available in colour online at www.interscience.wiley.com/ijoc

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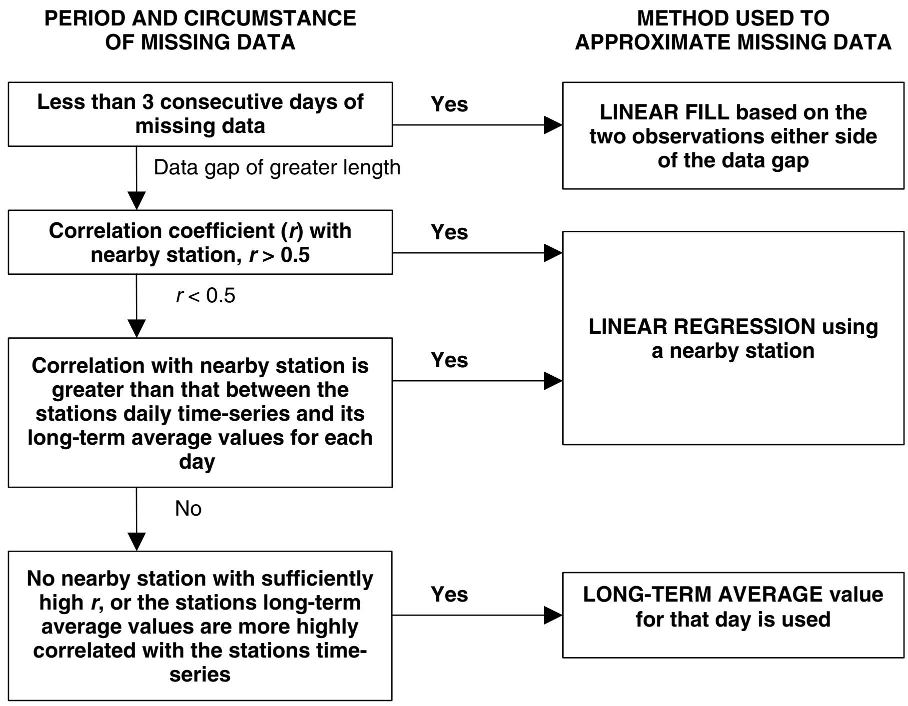

Figure 3. Procedure for replacing missing data values.

- maximum temperature (of values at 0300, 0900, 1500, 2100 GMT)
- minimum temperature (of values at 0300, 0900, 1500, 2100 GMT)
- diurnal range of dew point (of values at 0300, 0900, 1500, 2100 GMT)
- diurnal range of temperature (of values at 0300, 0900, 1500, 2100 GMT)
- maximum daily dew point depression (of values at 0300, 0900, 1500, 2100 GMT)
- minimum daily dew point depression (of values at 0300, 0900, 1500, 2100 GMT)

A separate regionalization was conducted for each season, since groups of stations with similar climates may vary on a seasonal basis. The dates for each season were defined climatologically using the mean temperature of four daily observations (0300, 0900, 1500, 2100 GMT). The winter (summer) dates were specified by the coldest (warmest) 2-week period based on the mode across all 48 stations for all years of record. The mode was used to ensure the coldest (warmest) 2-week period at the majority of stations was identified. Spring and autumn were taken as the mid-point between the coldest and warmest 2 weeks (Figure 1 shows the identification of four seasonal windows). Each window was then extended to 6 weeks (42 days) centerd on the initial 2-week period, to increase the chance of all six air-mass types occurring in each of the four seasonal windows. Sheridan (2002) used a 2-week window to identify the seed days during each season, but extended this to a 6-week window when no seed days could be identified during the shorter period. Defining a longer period from the outset increases consistency of the approach, whereas Sheridan (2002) took the view that using a shorter window decreases the opportunity for seed day criteria to change considerably. The 6-week windows are as follows:

Winter: 18 December–28 January (centered on Julian day 07)
Spring: 31 March–11 May (centered on Julian day 119)
Summer: 13 July–23 August (centered on Julian day 211)
Autumn: 5 October–15 November (centered on Julian day 298)

Regionalization was achieved using a three-stage procedure: PCA, then hierarchical, agglomerative cluster analysis using Ward's method and the squared Euclidian distance followed by nonhierarchical, *k*-means CA to reorganize groups (Bower, 2005). Nine S-mode PCA (Richman, 1986; Yarnal, 1993) were conducted to identify groups of stations with similar climatic characteristics for each of the nine climate variables and for each season. Correlation matrices were used to standardize each variable between stations (Davis and Kalkstein, 1990b; Yarnal, 1993). The PCs were rotated (Varimax) to isolate groups of stations displaying similar covariation of the individual climate variables (Richman, 1986; White *et al.*, 1991; Drosdowsky, 1993; Jolliffe, 1993). PCA followed by HCA and CA was preferred to straight HCA and CA of all variables because PCA reduces the dimensionality of the data matrix and in doing so, standardizes the variables so that all variables have equal impact on the computation of cluster distances. Further, the emergent PCs are orthogonal (independent) which is an underlying assumption of both HCA and CA (Everitt *et al.*, 2001; Kaufmann and Rousseeuw, 2005). Although the number of PCs produced in a PCA is equivalent to the number of

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original variables, only those PCs with a large eigenvalue and, thus likely to contain a climatological signal, (Huth, 1996) should be retained for analysis. Consequently, only PCs with eigenvalues greater than one for each of the nine separate PC analyses were retained (Jolliffe, 1993; Yarnal, 1993). PC loadings for all nine variables were then clustered on a seasonal basis using HCA and CA (Veal, 2001), to produce four seasonal regionalizations. The number of climate regions by season was determined by the inspection of a scree plot of a cluster agglomeration coefficient and the associated dendrogram. The emergent climate regions were then used as a basis for identifying centroid stations and subsequently seed day criteria.

Selection of centroid stations

The selection of centroid stations is an expedient means of reducing the time and effort required for the specification of seed day selection criteria. This is achieved by identifying the seed day criteria for a set of centroid stations in each climate region and then using a seed day transfer procedure (Figure 1) to determine seed day selection criteria for the remaining stations in each region. This differs from the approach used for the transfer of seed days in the original SSC2 developed for North America (Sheridan, 2002). For example, in the original SSC2, seed days were identified for Philidelphia and

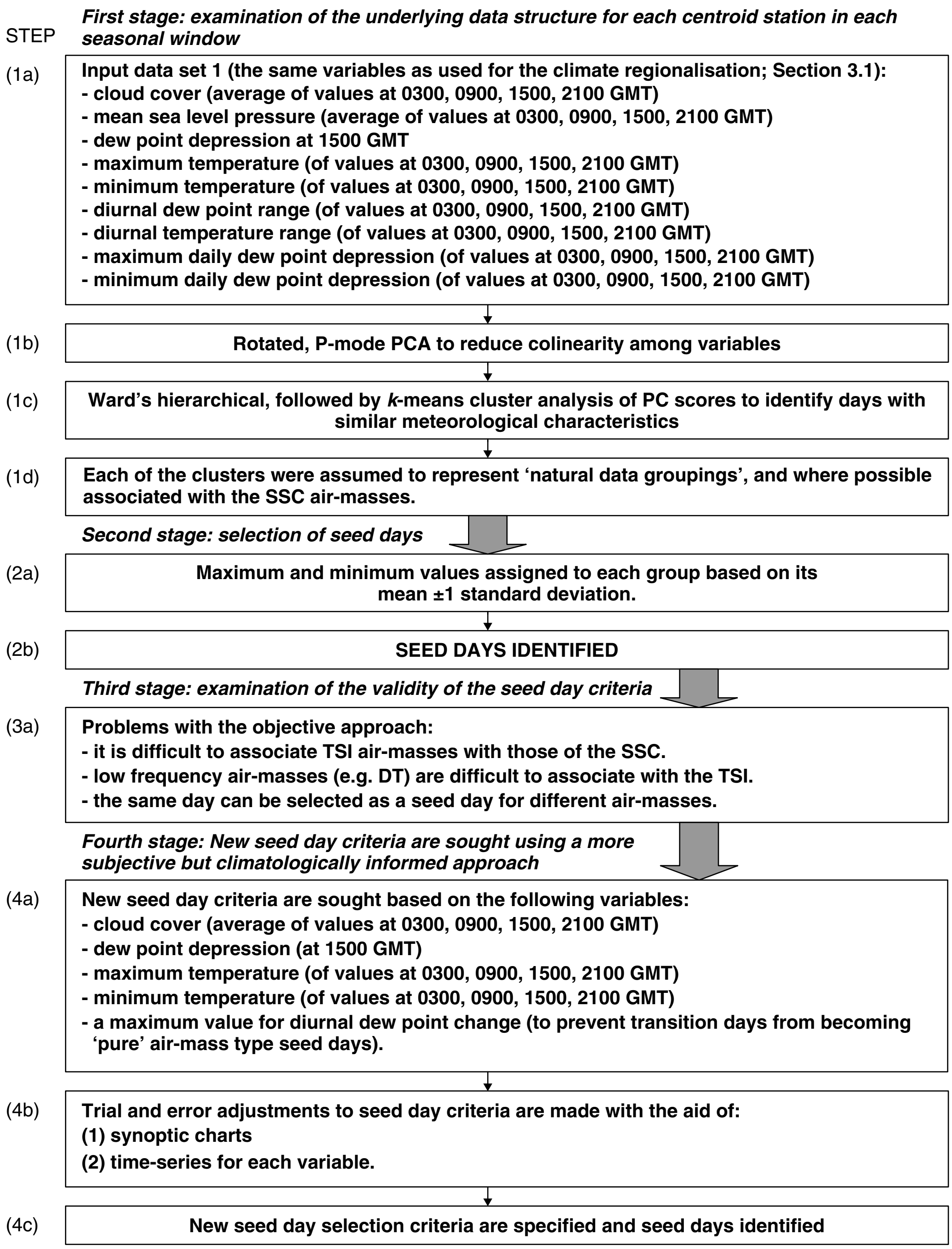

Figure 4. Methods used to determine seed day selection criteria at each centroid station.

Wilmington and then transferred via routes that radiated outwards from these initial stations. In contrast, a starting point within each climate region is used here. The centroid stations are defined as those closest to the mean climate conditions for each region and were identified as follows.

$$d = \left|\frac{\overline{PC_{1(P1)}} - PC_{1(P1)}}{\sigma}\right| + \left|\frac{\overline{PC_{2(P1)}} - PC_{2(P1)}}{\sigma}\right| + \left|\frac{\overline{PC_{3(P1)}} - PC_{3(P1)}}{\sigma}\right| + \cdots + \left|\frac{\overline{PC_{n(Pn)}} - PC_{n(Pn)}}{\sigma}\right| \quad (1)$$

where; d = standardized distance from cluster centroid
$\overline{PC_{n(Pn)}}$ = mean cluster PC loading (PC_n) for each parameter (Pn)
PC_n = observed PC loading
σ = standard deviation of PC loading

Seed day selection criteria

Having located the centroid station in each climate region, seed day selection criteria for the air masses occurring at each centroid station are identified. These are then transferred with adjustment to the other stations in the same climate region in order to establish their air-mass seed day criteria.

In the original SSC2, seed day criteria were identified for the six air-mass types across North America. While on a theoretical level, the six generic air-mass types used for North America should be applicable to the European situation since they represent possible combinations of thermal and moisture characteristics at the general level, the absolute values assigned to the seed days will differ because of the contrasting climate setting. Figure 4 outlines the combination of objective and subjective methods used to identify the air-mass seed day characteristics that form the basis of the SSCWE. These differ from the largely subjective methods used in the original SSC2 for North America. Firstly, the underlying structure of the variables observed at each centroid station was examined in order to establish the validity of a six air-mass type approach (Figure 4(1a)). To examine the nature of the air masses, a TSI Kalkstein and Corrigan, 1986 was constructed for each of the centroid stations. The number of emergent air masses for each of the centroid stations ranged between five and eight, but six was frequently found to be the optimum, as indicated by a cluster agglomeration coefficient and dendrogram (Kaufmann and Whiteman, 1999). However, since it is appealing to assign each day into one of a series of air masses that facilitate comparison of the air-mass climatology between stations, six *a priori* clusters were retained for all stations. This is based on the assumption that these map onto the air-mass groupings of the SSC and thus allow the SSC2 to be evaluated. (Figure 4(1d)).

As a first approximation of the seed day criteria, the mean ±1 standard deviation for each variable was taken to represent typical characteristics of each air mass (Figure 4(2a)), and thus, days satisfying these criteria were selected as representative seed days (Figure 4(2b)). Although intuitively appealing, three key problems were identified with using the TSI approach to identify the seed day criteria as outlined in Figure 4(3a). Consequently an alternative approach for defining seed day criteria was developed. This involved focusing on those variables that emphasize the thermal and moisture characteristics of air masses, namely, cloud cover, dew point depression and maximum and minimum temperatures (Figure 4(4a)). Further to these, a maximum value was specified for diurnal dew point change to prevent transitional days from becoming ‘pure’ air-mass type seed days. Accordingly, the number of variables used in the exploratory TSI analysis was reduced from nine to five (compare Figure 4(1a) and (4a)). Ladd and Driscoll (1980) encourage focusing on such a limited set of variables, as they found descriptors of dew point and temperature are the most important for characterizing day to day weather and that other variables such as wind and pressure are relatively unimportant. Cloud cover is included as it describes moisture in the upper atmosphere and is therefore considered a key air-mass descriptor. Further, Davis and Kalkstein (1990a) found that the inclusion of this variable gave greater definition to their synoptic categorization for the US.

In addition to the outcomes of the TSI analysis, synoptic charts and variable time-series were used as a guide to determine seed day criteria (Figure 4(4b)). Air-mass specific maximum and minimum criteria for each

Table I. Example of seed day selection criteria for Edinburgh (Region 3) for the winter window.

	Cloud cover (oktas)		Dew point depression at 1500 GMT (°C)		Maximum temperature (°C)		Minimum temperature (°C)		Diurnal dew point change (°C)
	Min	Max	Min	Max	Min	Max	Min	Max	Max
DP	0	7	5	10	−8	2	−17	−4	99
MP	6	8	0	4	−2	5	−4	2	5
DM	0	7	5	10	4	8	−4	3	7
MM	6	8	0	4	8	11	3	8	6
DT	0	7	7	14	14	17	3	13	99
MT	5	8	0	4	12	17	6	12	6

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variable were stipulated (Figure 4(4c)) to prevent seed day characteristics deviating outside physically realistic bounds. As an illustration, seed day criteria for Edinburgh are presented in Table I.

As the seed day criteria identified for an air mass at a station are for a particular day within a predefined season, seed days for each day of the year need to be determined because the physical characteristics of an air mass will change over the seasonal cycle. Determination of seed days for an individual calendar day is performed so that each day of record may be classified into one of the six air-mass types. For a situation that a day is not classifiable as belonging to a 'pure' air-mass, a day may be re-classified as transitional. To achieve the identification of daily theoretical seed day criteria for each air mass, a sliding -seed day calculation was performed. This produces a sliding seed day curve that describes the seasonal evolution of air-mass characteristics at the daily time scale and thus allows the seed day criteria for each day to be determined Sheridan (2002).

Seed day transfer

Once the seed day criteria have been established and the seed days selected for a station, a seed day transfer technique is used as the method to help specify seed day criteria for a nearby station (Figure 4). It is assumed that on a day when the same air-mass is present over two stations, the difference in the meteorological observations between the two stations can be used to help establish local meteorological differences. The climate regions established via the regionalization process are used to help guide the seed day transfer, ensuring that this is based on both geographical proximity and similarities of climate. This contrasts with the approach originally used by Sheridan (2002) and represents a methodological advance over the SSC2. The seed days (but not criteria) are directly transferred between stations within the same climate region. An example of the routes followed for summer seed day transfer is shown in Figure 5. The seed day transfer route followed from the centroid station (Figure 5) is determined by climatological similarity, as established by the statistical or Euclidian distance between stations belonging to the same climate region. In all cases, this was related to geographical proximity. Only the same days were retained as seed days at the new station if they were deemed to be sufficiently similar. If not similar, a new seed day was selected using the criteria outlined above. Once seed days have been transferred to the 'new' station, this enabled air masses at the 'new' station to be evaluated. Climatological differences between the air masses at the 'old' and 'new' stations are assessed and thus, allow the initial seed day selection criteria of the 'new' station to be modified based on these differences. 'New' seed days are selected based on the modified seed day selection criteria and the process of air-mass evaluation is repeated producing a revised daily air-mass classification for the 'new' station.

To establish the sliding seed day curve for each air-mass at each station, seed days are required for each of the four seasonal windows. However, the same station is rarely selected as the region centroid for all four seasons. To overcome this, a new cross-seed day technique was developed to facilitate the transfer of seed days between centroid stations.

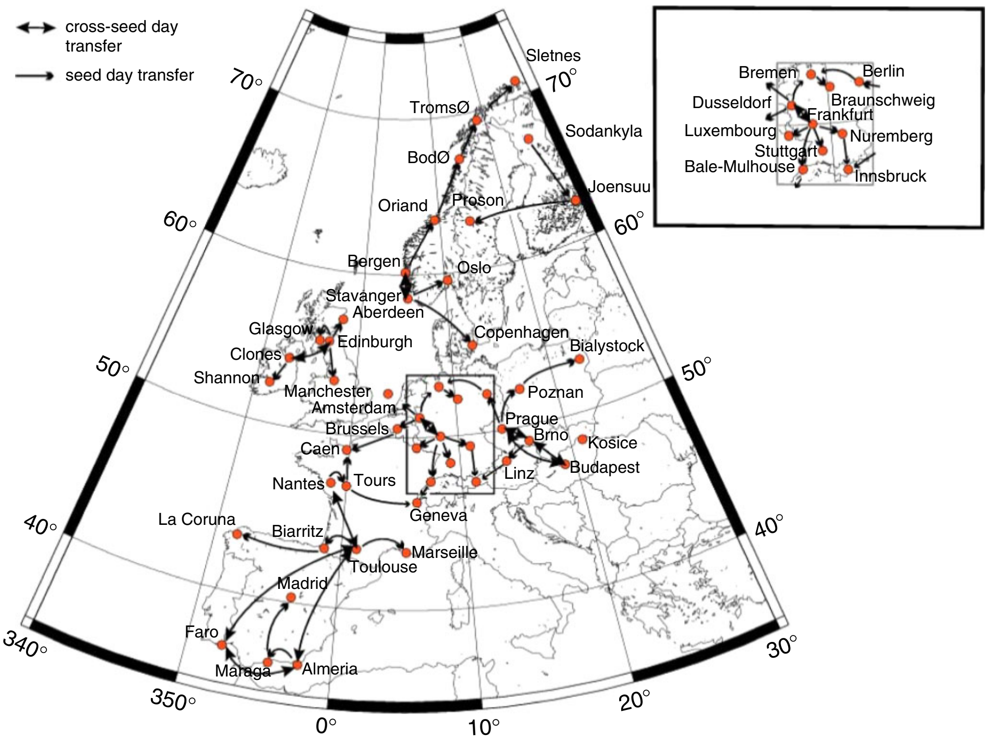

Figure 5. Route for the transfer of seed days. This figure is available in colour online at www.interscience.wiley.com/ijoc

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Cross-seed day technique

In the new cross-seed day procedure, a station's seed day criteria are used for the seasons in which it is the region centroid, with dummy variables used for the season(s) in which another station is the region centroid (e.g. spring and summer). For example, for Edinburgh, Clones' spring and summer seed day selection criteria are used as dummy values. This allows the following steps to be taken to estimate seed day selection criteria for spring and summer at Edinburgh: (1) Edinburgh's sliding seed day curve is established (using real and dummy values), (2) the seed days identified for Edinburgh are transferred to Clones, to allow Clones' seed day criteria to be evaluated for spring and summer, (3) Clones' spring and summer seed days are transferred to Edinburgh to allow climatological differences between the two stations to be assessed, and thus, Edinburgh's spring and summer seed days to be reevaluated based on the climatological differences identified. This cross-seed day technique was used for the stations shown in Figure 5.

Artificial seed days

For some stations no air-mass specific seed days may be identified using the seed day transfer procedure. This presents a potential problem, as a requirement for the SSC2 is that at least one seed day for each of the air masses in each of the seasonal windows must exist (Sheridan, 2002). This is because the sliding seed day curve is a continuous function and is unable to operate with missing data points. On occasions, when no actual days can be identified as seed days for a particular air-mass, an artificial seed day is created. The characteristics of the artificial seed day are taken to be the same as the mean conditions for the closest station at which this air-mass is found. This is based on the fact that if an air mass was to move toward an adjacent station its characteristics would be unmodified. Fortunately, the number of times that required the substitution of artificial for actual days was fairly limited, but not trivial (Table II). Stations for which no artificial seed days were required included Berlin, Braunschweig, Bremen, Düsseldorf, Frankfurt, Luxembourg, Bale-Mulhouse, Nuremberg, Geneva, Nantes and Toulouse.

Table II. The total number of artificial seed days made for all stations.

	Winter	Spring	Summer	Autumn
DP	4	*None*	12	4
MP	1	*None*	4	5
DM	*None*	*None*	*None*	*None*
MM	*None*	*None*	*None*	*None*
DT	25	11	2	16
MT	19	15	3	10

RESULTS

Climate regionalization

Figure 6 illustrates the regionalization of seasonal climate across WE with climate region centroid stations indicated for each season. For the winter, spring and autumn, seven climate regions may be identified, while six exist for the summer (Figure 6). Although K-means CA was used to reorganize station groups and thus regions (following HCA), no stations switched regions in any season, demonstrating the robustness of the regions originally identified by HCA. However, on an inter-seasonal basis, some stations switch regions. Table III presents the mean daily climate characteristics for each of the seasonal climate regions. The five most temporally persistent regions are: (1) UK and Ireland, (2) northern Scandinavia, (3) southern Scandinavia, (4) southern Spain, and (5) France and northern Spain. In summer, the climate at stations in groups (4) and (5) show greater similarity, and a single region encompasses much of France and Spain (Figure 6). There are two further regions in Central Europe, but the similarities/differences between these stations vary interseasonally. In spring, summer and autumn, stations in the west and east of this area form two distinct climate regions (Figure 6) associated with the drier spring and cooler summer and autumn climates in the east (Table III). In winter, stations in the northwest and southeast of central Europe form two distinct climate regions. At the southeastern-most locations, temperatures during winter are lower than at other entral European locations (Table III).

The emergent climate regions bear out climatological expectations and confirm the general geographical distribution of climate portrayed by the Koeppen climate classification (McGregor, 2005) such that WE is generally colder in the north, and wetter and cloudier in the north and west (Table III). Differences in the maximum and minimum temperatures between the seven regions are greatest during winter and autumn. Interregional differences in MSLP and diurnal dew point range are greatest during winter, probably reflecting the more southerly position of wintertime storm tracks. Each of the remaining climate variables display smaller seasonal variations, with interregional climate variations least during summer (Table III).

Physical nature of air-mass types

Table IV and Figure 7 describe how the six air-mass types of the SSC manifest themselves in Europe. Because the air-mass types are generic in nature, in relative terms their characteristics are comparable to those identified by Kalkstein *et al*. (1996) and Sheridan (2002) for North America. However, in absolute terms, the physical properties differ from those of their trans-Atlantic counterparts; generally the tropical types are cooler whereas the polar types are warmer. This relates to geographical contrasts in the large-scale environmental setting between WE and North America. For example, although summer tropical maritime air masses arriving over WE have a long ocean fetch and originate from low latitudes,

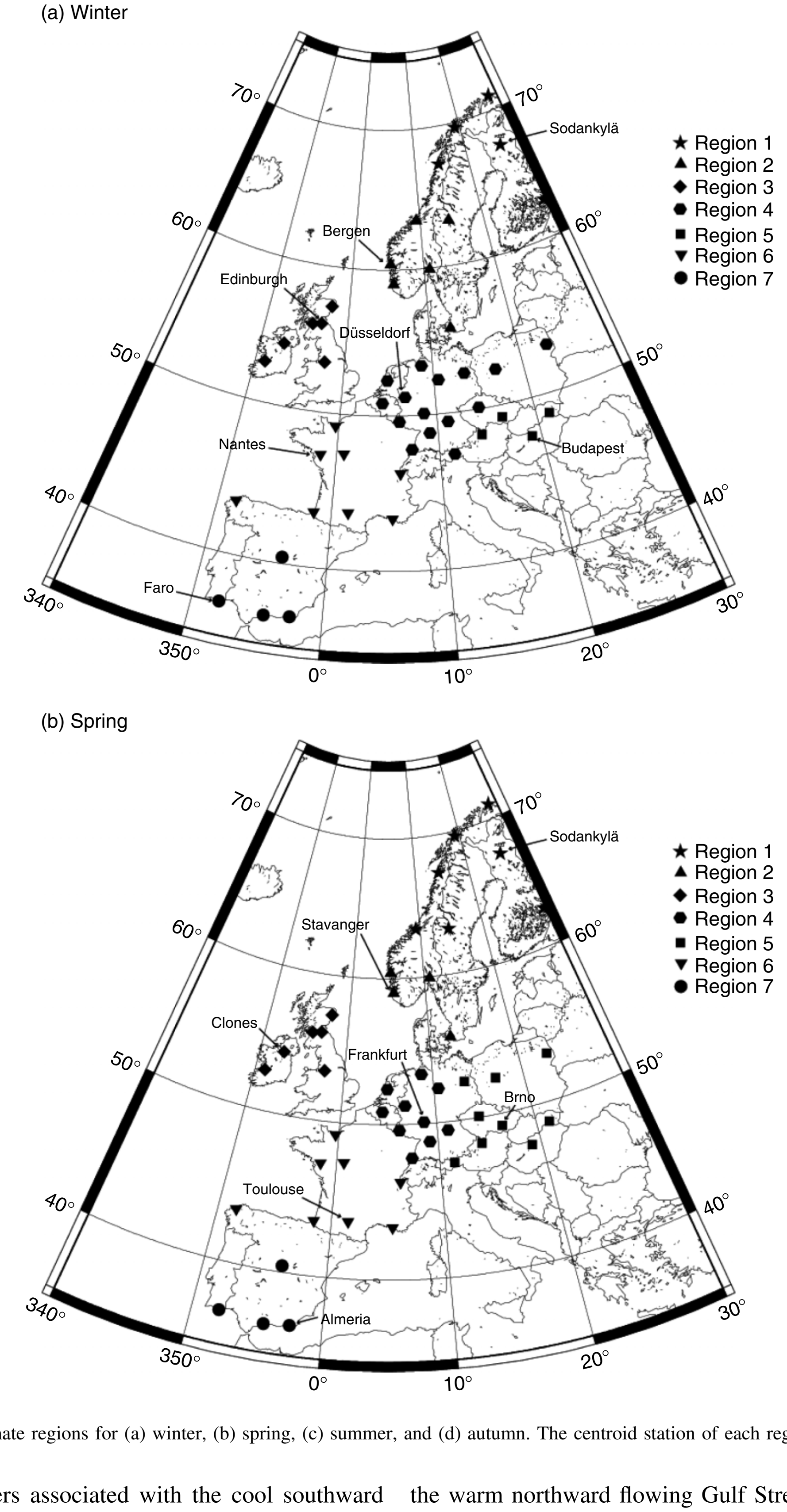

Figure 6. Climate regions for (a) winter, (b) spring, (c) summer, and (d) autumn. The centroid station of each region is labelled.

cool surface waters associated with the cool southward flowing Canary current moderate their thermal properties. This contrasts with the situation for North America, especially for the southeastern regions and along the Atlantic seaboard, as air masses besides originating from low latitudes, sequester heat and moisture from the warm northward flowing Gulf Stream current. Similarly, the more extreme conditions associated with North American DT air mass types relate to the fact that DT air masses originating over the desert regions of North America maintain a long slow trajectory over dry land surfaces. On the contrary, DT air masses arriving over

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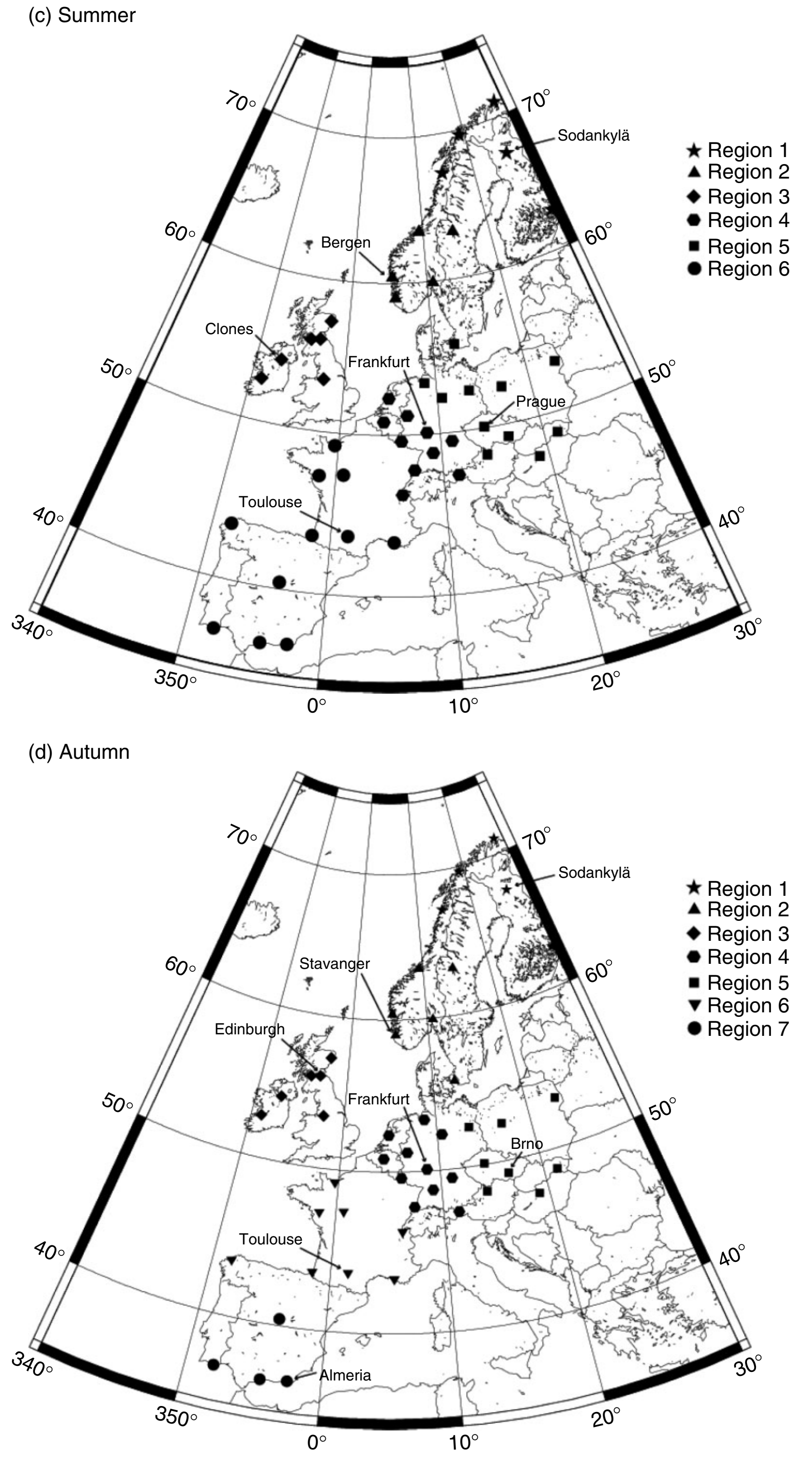

Figure 6. (*Continued*).

WE from North Africa have been modified by heat and moisture exchanges with the relatively cool and moist surface of the Mediterranean Sea. Winter polar air masses also demonstrate contrasts due to different surface atmosphere exchanges. In the case of WE, polar air-mass trajectories are predominantly over open ocean surfaces whereas sea ice or terrestrial snow and ice typify the surfaces over which polar air is advected from high North American latitudes. Consequently western European polar air masses possess higher minimum temperatures and moisture contents than their North American equivalents.

Spatial and temporal variability of air masses

Air-mass frequencies and their variations between locations provide a valuable means of understanding spatio-temporal variations in western European climate. This section examines the salient aspects of the SSCWE in terms of air-mass spatial and temporal variability.

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Table III. Mean daily climate characteristics for stations in each of the seasonal climate regions.

(a) Winter

Variable	1	2	3	4	5	6	7
Cloud cover	6.0	5.8	5.8	6.0	6.0	5.3	3.7
Mean sea level pressure	1003.5	1007.7	1011.7	1017.6	1020.4	1019.9	1021.7
Dew point depression at 1500 GMT	2.6	2.9	3.0	3.1	2.8	4.5	7.3
Maximum temperature	−4.5	0.5	6.1	2.8	0.4	8.6	14.4
Minimum temperature	−8.9	−2.9	2.4	−0.9	−3.0	3.9	7.5
Diurnal dew point range	5.0	3.8	3.5	3.2	3.0	3.5	4.4
Diurnal temperature range	4.4	3.3	3.6	3.6	3.4	4.7	6.9
Maximum daily dew point depression	3.8	4.0	3.6	3.6	3.3	5.0	7.8
Minimum daily dew point depression	1.6	1.4	1.3	1.2	0.9	1.5	2.2

(b) Spring

Variable	1	2	3	4	5	6	7
Cloud cover	5.5	5.0	5.7	5.0	4.7	4.9	3.6
Mean sea level pressure	1012.4	1013.4	1013.1	1014.3	1013.9	1015.0	1015.0
Dew point depression at 1500 GMT	6.6	8.3	6.8	9.3	10.9	8.1	10.2
Maximum temperature	4.3	9.4	11.2	13.3	14.0	14.8	19.3
Minimum temperature	−1.0	3.3	5.4	5.5	5.3	8.0	11.7
Diurnal dew point range	3.8	3.7	3.4	3.5	3.8	3.4	4.2
Diurnal temperature range	5.4	6.1	5.9	7.7	8.7	6.8	7.6
Maximum daily dew point depression	7.4	9.0	7.2	9.6	11.3	8.5	10.9
Minimum daily dew point depression	1.9	2.3	1.7	2.1	2.3	2.1	3.3

(c) Summer

Variable	1	2	3	4	5	6
Cloud cover	5.7	5.4	5.9	4.3	4.4	3.1
Mean sea level pressure	1011.6	1012.0	1013.8	1015.4	1016.7	1016.5
Dew point depression at 1500 GMT	6.0	7.2	6.5	10.7	10.9	10.9
Maximum temperature	15.1	17.3	18.1	22.9	23.1	26.3
Minimum temperature	9.7	11.6	12.2	13.9	14.2	18.1
Diurnal dew point range	2.8	3.1	3.0	3.3	3.4	3.6
Diurnal temperature range	5.3	5.7	5.9	8.9	8.9	8.2
Maximum daily dew point depression	6.7	7.7	6.8	11.1	11.2	11.5
Minimum daily dew point depression	1.4	1.9	1.4	1.9	1.9	3.3

(d) Autumn

Variable	1	2	3	4	5	6	7
Cloud cover	6.2	5.7	5.8	5.4	5.2	4.9	3.6
Mean sea level pressure	1007.4	1009.8	1011.9	1016.6	1018.3	1017.8	1017.7
Dew point depression at 1500 GMT	3.0	4.2	4.1	5.3	5.1	5.9	8.3
Maximum temperature	2.7	7.5	11.0	11.4	10.0	15.3	20.5
Minimum temperature	−0.4	4.2	6.6	5.9	4.6	9.4	13.6
Diurnal dew point range	3.5	3.2	3.3	3.2	3.3	3.3	4.0
Diurnal temperature range	3.1	3.2	4.4	5.6	5.4	5.9	6.9
Maximum daily dew point depression	4.1	5.0	4.5	5.5	5.5	6.3	8.9
Minimum daily dew point depression	1.6	1.7	1.3	1.1	1.2	1.5	2.5

Table IV. General characteristics of the six SSC2 air-mass types and the 'typical' synoptic situation.

Air-mass	General air-mass characteristics	The 'typical' synoptic situation
Dry Polar (DP)	Cool or cold dry air, with little cloud cover.	Advection of cold polar air into Europe frequently along the eastern flank of an anticyclone. In winter, the synoptic situation may be characterized by cold anticyclonic conditions.
Dry Moderate (DM)	Mild and dry	Typically associated with a slow moving high-pressure system. Blocking situations prevent moist westerly and cold northerly airflows over western Europe. For northern and western locations this air-mass maybe associated with the flow of air around a well-developed high-pressure zone located over central Europe.
Dry Tropical (DT)	Hot and dry, with little cloud cover.	Typically associated with a ridge of high pressure stretching from Africa into Europe. Warm, dry air is advected northwards.
Moist Polar (MP)	Cold, cloudy and humid.	Associated with the advection of moist air from the Polar region. For stations at lower latitudes this air-mass is frequently characterized by circulation around a low-pressure center over the UK, thus, allowing air to pick up moisture before reaching these stations. In autumn and winter, the synoptic situation maybe characterized by blocking to the west of a station, allowing the advection of cold northerly airflows.
Moist Moderate (MM)	Warm, humid air and cloudy skies	Frequently associated with moist westerly airflows.
Warm Tropical (MT)	Warm and very humid, cloudy in winter and partially cloudy in summer	Typically associated with south-westerly airflows that advect heat and moisture into Europe from high pressure centred over Africa and/or southern Europe

Spatial variability. Spatial variations are considered here for the core winter and summer months of January and July only. Figures 8 and 9 map the mean frequency of occurrence of each air-mass across the SSCWE region for these months. The air-mass frequency maps were produced using the generic mapping tool (GMT) software (Wessel and Smith, 1991). Frequency contours were plotted by transforming station locations onto a grid using a tension factor and a Laplacian operator and then tracing each contour through the grid as described by Wessel and Smith (2004). All maps are plotted with a contour interval of five units (representing the % of days in each month) to facilitate comparison. As noted by Smith and Wessel (1990), and as seen in Figures 8 and 9, using a tension factor to contour data can generate false maxima and minima outside the observational area. Despite this idiosyncracy, air-mass frequencies are accurately represented within the study area.

January. As might be expected, the highest frequencies of the polar air masses (DP and MP) are found in the north, but high frequencies are also found in continental locations (Figure 8(a), (b)). For example, at Innsbruck (Austria) the frequency of the DP air-mass is 23%, since continental locations allow the air to cool appreciably during winter. The MP air-mass is most frequent in northeastern areas, but frequencies of this air-mass show high spatial variation across the study area (0–61%). The DM air-mass is most frequent in the south (Figure 8(c)), since mild sub-Saharan air is more frequently advected over southerly locations. The MM air-mass dominates much of WE during January (Figure 7(d)). High frequencies of this air-mass, ranging from 15 to 48%, are associated with frequent eastward tracking storm systems from the Atlantic that advect relatively warm and moist air over WE (Figure 8(d)). Tropical air- mass (DT and MT) frequencies are low during winter (Figure 8(e), (f)), although MT air masses reach Almeria (Southeastern Spain) on 23% of days. At the majority of stations, the frequency of DT during winter is very low, but frequencies reach 10% at Málaga (southern Spain). The high frequency of occurrence of allied air masses such as MP and MM over Scotland and DM and MM over southern Germany in winter are clear indicators of the intraseasonal variations experienced over these regions because of their position relative to the Polar Front Jet and the upper westerlies. The frequencies of transition situations (approximately 10% of all days) are not presented in Figures 8 and 9.

July. By July, the frequency of the DP air-mass has decreased at nearly all stations (Figures 8(a) and 9(a)). The local maxima of DP recorded at Caen in northern France, is at odds with climatological expectations and may be the result of the absence of stations from this analysis for eastern Scandinavia where the maximum summertime DP frequencies might be expected to be found. From January to July, the frequency of MP also declines at the majority of stations, but frequencies at some central European stations show only minor changes (Figures 8(b) and 9(b)). In the south of the study area there is little change in the frequency of DM, but there is a greater decline in the north (Figures 8(c) and 9(c)).

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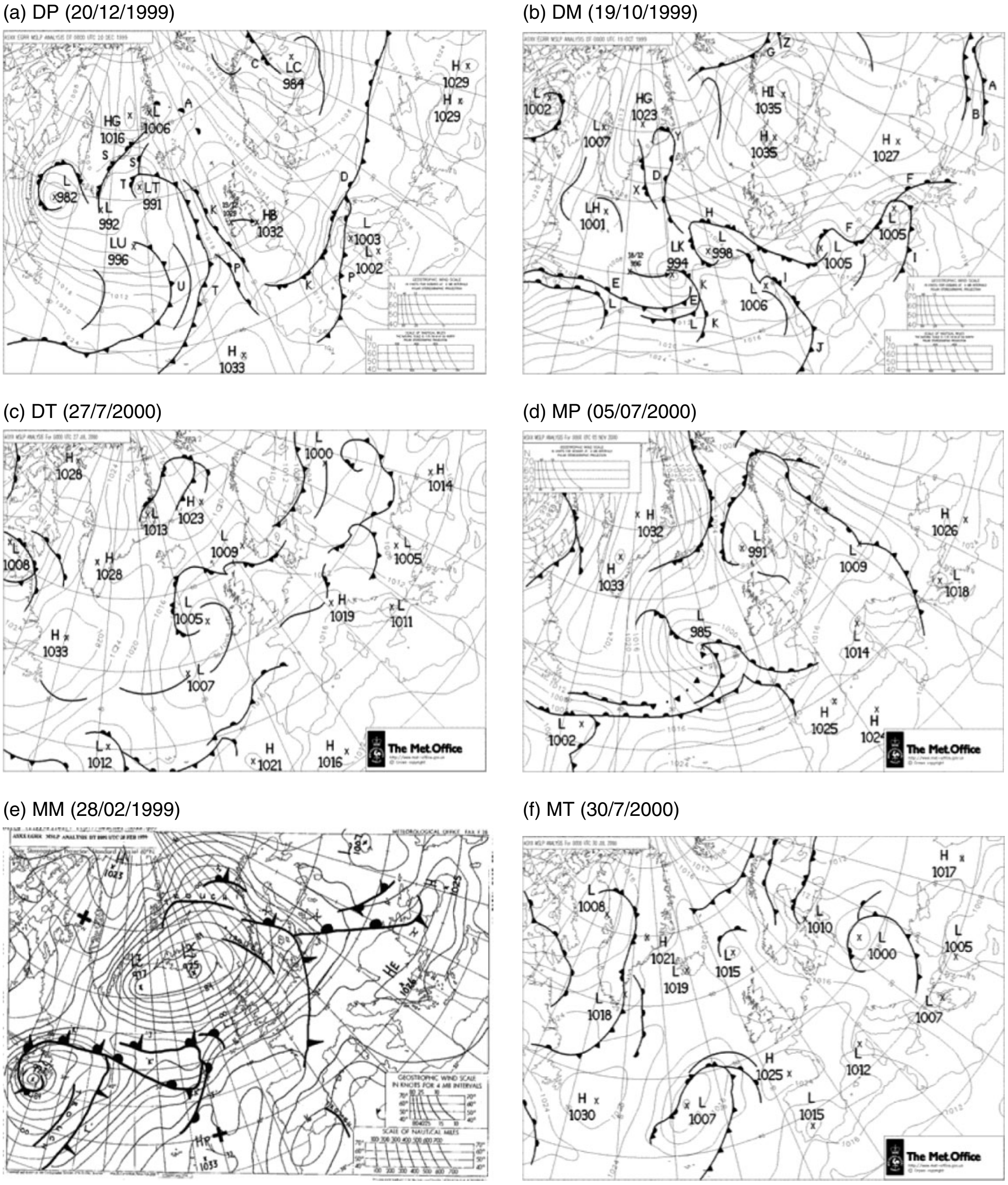

Figure 7. Synoptic charts representative of the 'typical' synoptic situation of each of the six SSC2 air-mass types at Edinburgh (a) DP, (b) DM, (c) DT, (d) MP, (e) MM, (f) MT (Source: Wetterzentrale, http://www.wetterzentrale.de/topkarten/tkfaxbraar.htm).

MM increases in frequency by midsummer (Figures 8(d) and 9(d)). Notable, is the strong spatial gradient in the frequency of the MM air-mass across the Iberian peninsula. This corresponds with the strong gradient of annual precipitation with the lowest values in the southeast and highest values in the northwest (Rodriguez-Puebla *et al*., 1998). Tropical air masses (DT and MT) are most prominent in July (Figures 8 and 9), particularly in the south of the study area. The high frequency of DT at Madrid (56%; Figure 9(e)) is particularly striking, most likely caused by the intense heating and subsequent drying of air over the central regions of the Iberian landmass and the consequent development of the Iberian heat low.

Temporal variability. This section considers the inter-annual variability and trend of air-mass frequencies at the centroid stations for the various climate regions for winter (D-J-F) and summer (J-J-A). In cases where the centroid station of a region differs between seasons, the centroid for the greater number of seasons is selected. The centroid stations considered here are: (1) Sodankylä, (2) Bergen, (3) Edinburgh, (4) Frankfurt, (5) Bruno, (6) Toulouse and (7) Almeria.

Winter. Winter air-mass inter-annual variability is described using the coefficient of variation (standard deviation/mean) as shown in Table V. Overall interannual variability is high with most locations possessing

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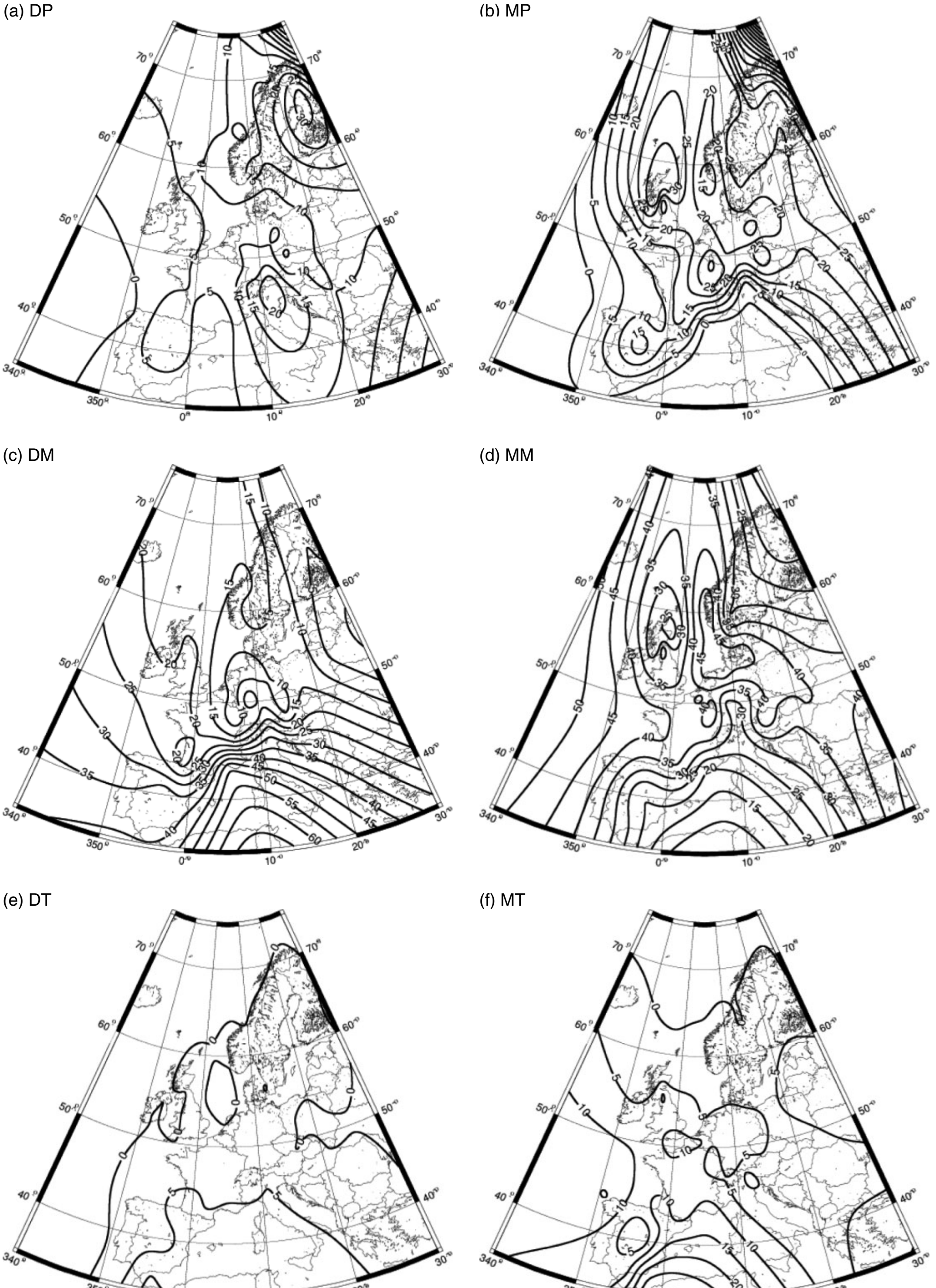

Figure 8. Map illustrating the mean frequency (as a %) of occurrence of the air-mass types in January.

interannual standard deviations in excess of 40% of the mean winter (annual) air-mass frequency.

Generally high values of the coefficient of variation (CV) for a particular air-mass occur for those locations most distant from the air-mass source. For example, the southern locations of Toulouse and Almeria possess high CV values for DP and MP air which has its origins in sub-arctic latitudes while the northern locations of Edinburgh and Bergen display high interannual variability for DT and MT, as such air masses originate over subtropical latitudes (Table V(a)). The contrasting CV for DP at Sodankylä and Bergen, is also a result of distance from air-mass source. This is because DP air originates from the general area of the Siberian high. For this reason DP air on an interannual basis often reaches Sodankylä but only occasionally does so at Bergen located much further

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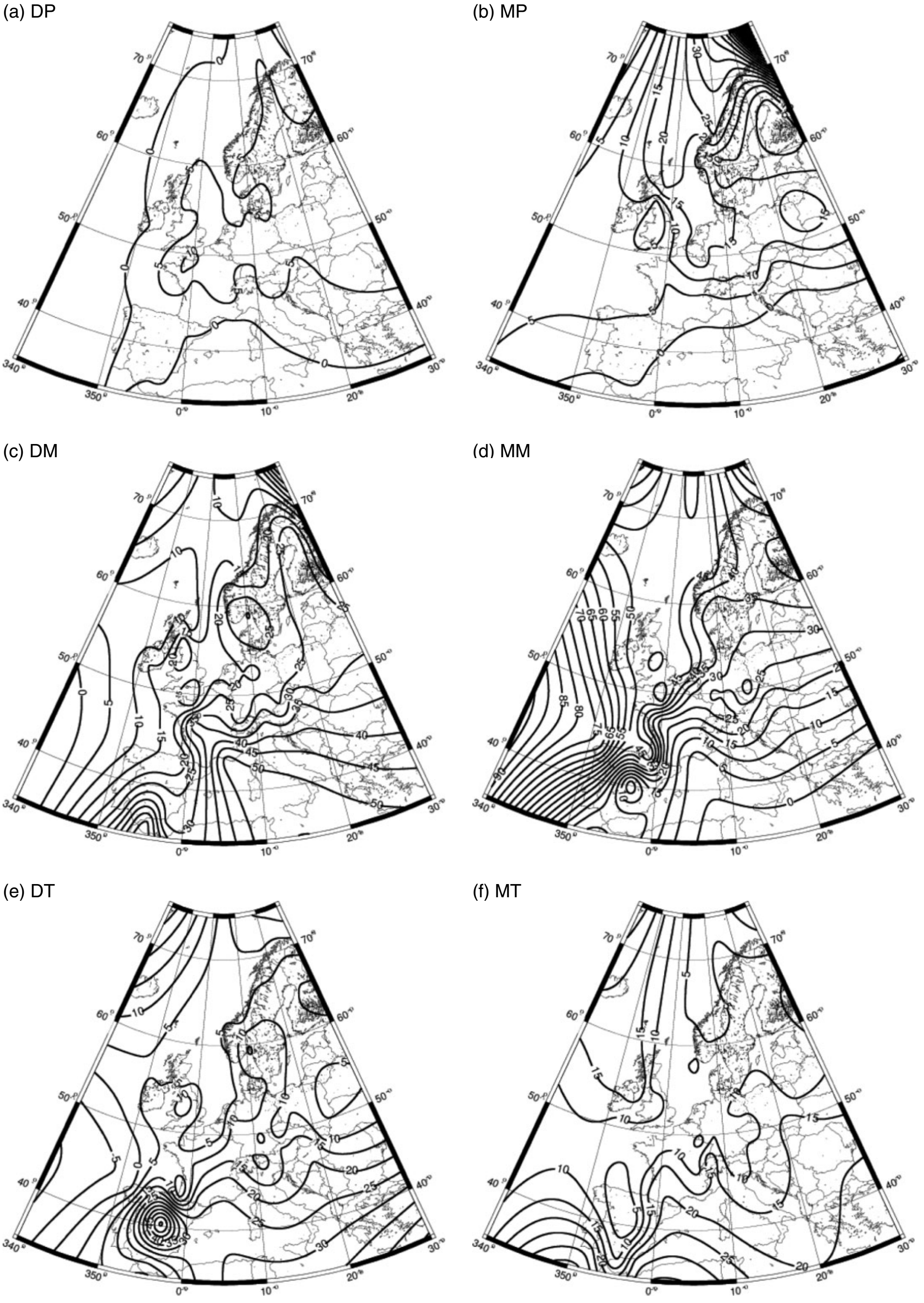

Figure 9. Map illustrating the mean frequency (as a %) of occurrence of the air-mass types in July.

to the south and west. An additional factor explaining the high variability at Bergen may be topographic blocking of DP air from the east as Bergen lies downwind of the Jotunheimen mountains with elevations in excess of 2000 m. A similar explanation relating to distance and topographic blocking may also apply to the occurrence of winter DP air masses at Almeria and Toulouse, both of which have extensive mountain barriers between themselves and the source of DP air.

A possible determinant of the interannual variation of winter air-mass frequency is alterations in the configuration of the wintertime North Atlantic atmospheric circulation as represented by the North Atlantic Oscillation Index (NAOI) (Hurrell, 1995; Jones *et al*., 1997; Osborn, 2004, Raible *et al*., 2005). Notwithstanding the strength of the statistical association between the wintertime NAOI and air-mass frequency, it would appear that a positive (negative) phase of the NAO results in a

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Table V. Winter and summer air-mass frequency coefficient of variation[a] (%) 1974–2000. NA represents non-occurrence of a particular air-mass.

	Toulouse	Almeria	Bergen	Brno	Edinburgh	Frankfurt	Sodankylä
Air-mass				(a) Winter			
DM	29	33	43	38	26	30	66
DP	92	91	68	60	64	55	36
DT	55	43	255	130	NA	185	350
MM	20	42	33	21	13	29	38
MP	57	415	47	54	40	36	25
MT	39	34	166	81	48	51	7
TR	44	45	48	41	39	34	44
				(b) Summer			
DM	30	33	30	21	34	26	35
DP	101	275	87	60	46	44	54
DT	52	44	74	68	90	69	57
MM	34	42	27	32	26	27	35
MP	91	520	59	59	60	61	44
MT	42	41	105	44	230	52	79
TR	45	57	51	38	41	54	47

[a] Coefficient of variation is standard deviation/mean (sample size is 26 years) expressed as a %.

Table VI. Association between North Atlantic Oscillation Index (http://www.cru.uea.ac.uk/cru/data/nao.htm) and air-mass frequency. ***, ** and * indicate significance at the 0.01, 0.05 and 0.10 levels respectively. + and − indicate the direction of an insignificant statistical association. Blank indicates indiscernible direction of statistical association ($r < 0.1$) while NA indicates nonoccurrence of air-mass, for example no DT occurs at Edinburgh in winter.

	Toulouse	Almeria	Bergen	Bruno	Edinburgh	Frankfurt	Sodankylä
Air-mass				(a) Winter			
DM	−0.54***	0.39**	−0.43**	−0.55***	+	+	+
DP	−	+	−0.60***	−0.37*	−	−0.41**	−0.46**
DT	+	+	−	0.38*	NA	+	+
MM	+	−0.34*	0.55***	+	+	−	0.37*
MP	−	+	−0.35*	−0.46**	−0.41**	−0.37*	−
MT	−	−	+	0.35*	+	0.53***	+
TR	−	−0.38*	0.42**	+	0.59***	0.36*	+
				(b) Summer			
DM	−		−0.38*	−	+	+	−
DP	−	−	−0.35*				−
DT		+	−	0.53***	−0.40**		
MM	+		0.34*	−	0.40**		0.38*
MP	−	+	+	−0.42**		−	−
MT	+			−	−		
TR	+		+	−		+	

frequency reduction (increase) of polar air masses (DP and MP) at all locations apart from the southern-most location of Almeria (Table VI(a)). The overwhelming influence of a positive NAO on polar air-mass occurrence is a result of the dominance of zonal flows associated with a strong Azores high and an intense Icelandic low. Positive NAO phase related decreases (increases) in transitional situations noted for the southern (northern) locations of Almeria and Toulouse (Bergen, Bruno, Edinburgh, Frankfurt, Sodankylä), are most likely related to an expanded Azores high. Consequently, eastward tracking North Atlantic storms will be steered northwards across middle to high middle latitudes where a high inter-daily variability of air-mass occurrence will be experienced as reflected by the positive associations between the NAOI and transitional situations for Bergen, Edinburgh and Frankfurt. Comparatively, Almeria and Toulouse will experience prolonged periods of stable conditions with the persistence of DM air most likely (see significant positive correlations for DM in Table VI(a) for these two locations).

Of the seven locations, winter air-mass frequency at Bergen appears to have the greatest sensitivity to variations in the atmospheric circulation state. At Bergen

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a positive (negative) phase of the winter NAO results in the reduced (increased) occurrence of DM, DP and MP air, with the opposite true for MM and transitional situations (Figure 10). This makes sense, as enhanced westerlies and a more northerly storm track during a positive NAO phase, will result in the advection of warm moist air over the southwestern regions of Norway and thus the reduction of the occurrence of continental air masses (DM and DP) and MP air masses originating from northern regions of the North Atlantic. Air-mass occurrence at Bruno is also noteworthy for its association with the NAO. Here, a positive NAO engenders a decrease in polar air masses (DP and MP), as is the case for Bergen, but an increase in both warm dry (DM and DT) and warm moist (MT) air masses. Similar associations to this can also be found for Frankfurt and to a lesser extent for Sodankylä and Edinburgh (Table VI(a).) indicating that while air-mass frequency in general is associated with the NAO, the sensitivity to this large-scale mode of atmospheric circulation varies geographically. A further characteristic of the interannual variation of air masses is frequency compensation such that strong inverse associations generally occur between dry and moist, and warm and cold air masses. This is seen clearly in the case of Frankfurt (Table VII)

Further to the notable interannual variability is evidence of trends in winter air-mass frequency (Table VIII(a)). Bergen is noteworthy for significant decreases (increases) in DM and DP (MM and TR) air masses (Figure 11). This is consistent with observed changes in the frequency and intensity of zonal flows across the wider study region (Marshall *et al.*, 2001; Brunetti *et al.*, 2002; Hanssen-Bauer and Førland, 2002; Lu *et al.*, 2004; Kyselý and Domonkos, 2006). Further south over southern France, there is also evidence of significant changes in moist air-mass frequency (MM and MT) as noted for Toulouse (Table VII(a)). Notwithstanding the statistical significance of the trend, the only location not to demonstrate an increase in MT air-mass frequency is Edinburgh, indicating that winter conditions over the study period became more influenced by warm maritime air masses.

In order to explore whether air-mass frequency has an impact on climate at the seasonal scale, winter air-mass frequency was correlated with a range of winter climate indices available through the European Climate Assessment project (http://eca.knmi.nl/) and as described by Klein Tank *et al.* (2002). Where possible, climate indices derived from variables independent of those used in defining the air masses were used. Accordingly, the majority of the indices used in this exploratory analysis are related to precipitation. Results are provided in Table IX. These reveal that the interannual variation of air-mass occurrence does have a discernible impact on various aspects of the winter precipitation climate of Frankfurt. For total winter precipitation, a low frequency of MP air masses in combination with a high frequency of transitional days appears important. A high frequency of transitional days, indicative of rapidly changing conditions often associated with fronts, in association with a low occurrence of DP days, are conducive to a high frequency of heavy precipitation days. Wet days appear dependent on the frequent (infrequent) occurrence of transitional (MP) days. Persistence of dry winter days is associated with a low frequency of moist moderate air masses and thus reduced advection of moisture (Kassomenos and McGregor, 2006). As might be expected, the strongest statistical associations between air-mass frequency and climate occur in the case of temperature indices as indicated by

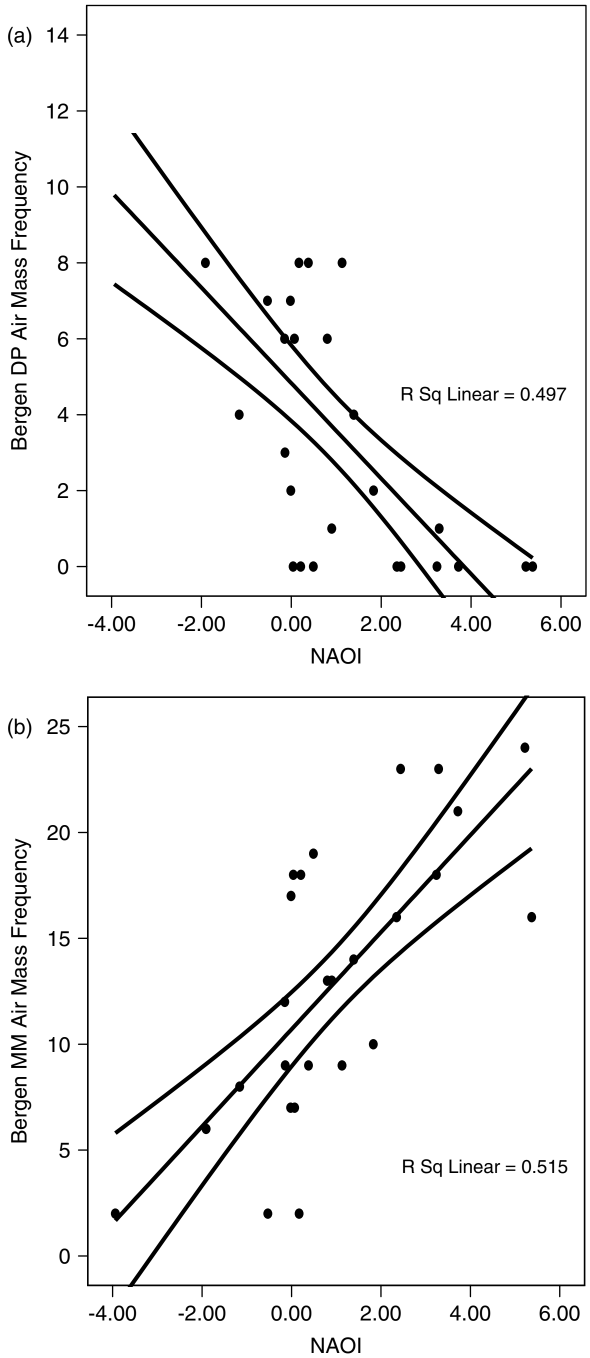

Figure 10. Relationship between winter NAOI and (a) DP air-mass and (b) MM air-mass frequency at Bergen, Norway. NAOI is from http://www.cru.uea.ac.uk/cru/data/nao.htm.

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Table VII. Inter-air-mass correlations for Frankfurt. ***, ** and * indicate significance at the 0.01, 0.05 and 0.10 levels respectively.

	(a) Winter						
Air-mass	DM	DP	DT	MM	MP	MT	TR
DM							
DP	-0.45^{**}						
DT	0.53^{***}	-0.32^{*}					
MM		-0.37^{*}					
MP	-0.45^{**}	0.46^{**}	-0.42^{**}				
MT		-0.60^{***}			-0.45^{**}		
TR						0.36^{*}	
	(b) Summer						
Air-mass	DM	DP	DT	MM	MP	MT	TR
DM							
DP							
DT							
MM	-0.34^{*}	-0.34^{*}	-0.60^{***}				
MP	-0.47		-0.63^{***}	0.32^{*}			
MT			0.36^{*}		-0.52^{***}		
TR						-0.42^{**}	

Table VIII. Correlation of air-mass frequency against time. Positive (negative) values indicate an increase (decrease) of air-mass frequency. ***, ** and * indicate significance at the 0.01, 0.05 and 0.10 levels respectively. + and − indicate the direction (increase/decrease) of statistically insignificant trend.

	Toulouse	Almeria	Bergen	Brno	Edinburgh	Frankfurt	Sodankylä
Air-mass				(a) Winter			
DM	+	−	-0.58^{***}	−	0.47^{**}	+	+
DP	−	−	-0.48^{**}	+	+	−	−
DT	+	0.42^{**}	+	+		−	−
MM	0.33^{*}	−	0.36^{*}	−	+	−	+
MP	−	−	+	+	-0.39^{*}	−	−
MT	0.46^{**}	+	+	+	−	0.46^{**}	+
TR	−	−	0.35^{*}	0.39^{*}	−	+	−
				(b) Summer			
DM	-0.63^{**}	-0.56^{**}	-0.58^{**}	-0.40^{*}	+	+	
DP	-0.45^{**}	−	-0.44^{**}	-0.38^{*}	+	−	−
DT	0.44^{**}	0.54^{***}	−	+	−	+	
MM	-0.38^{*}	-0.40^{*}	+	+	0.44^{**}		+
MP	−	+	+	-0.47^{**}	+	-0.46^{**}	−
MT	0.55^{***}	0.38^{*}	+	+	-0.34^{*}	+	−
TR	+	0.34^{*}	+	−	+	−	−

the strong positive (inverse) associations between the frequency of DP and MP (DM and MT) air masses and frost days. This arises partly because temperature is used to define both frost day occurrence and air-mass type. The inverse association between mean absolute day-to-day difference in daily temperature range (vDTR) and the frequency of transitional situations indicates that persistence of days with little change in temperature range is associated with a stable nonchanging air-mass situation.

Summer. As with winter, a good deal of interannual variability is evident for summer and this is related to distance from the origin of the air-mass. Toulouse and Almeria are notable for their low (high) CV for DT and MT (DP and MP) air masses in comparison to the other more northern locations (Table V(b)). For all locations, DM possesses the lowest CV indicating that relative to interannual variability, its annual mean frequency (25% of all summer days) is high, signifying its summertime climatological importance.

Relative to winter, the summer NAO pattern has less influence on the interannual variability of summertime air masses (Table VI(b)). However, if the statistical association between atmospheric pressures at the two NAO centers of action (Ponta Degarda and Reykjavik) and air-mass frequencies at all locations is considered (not

Table IX. Correlation between winter air-mass frequency and range of winter climate indices for Frankfurt*. ***, ** and * indicate significance at the 0.01, 0.05 and 0.10 levels respectively. + and − indicate the direction of an insignificant statistical association. Blank indicates no discernible direction of association (r < 0.1).

Air-mass	Total precipitation	Consecutive dry days	Wet days	Heavy precipitation days	Frost days	vDTR
DM		−	−	+	−0.34*	−
DP	−0.45**	+	−	0.44**	0.70***	+
DT	−		−	−	−	−
MM	+	−0.37*	+		−	−
MP	−	−	−0.42**	+	0.63***	
MT	+	+	+	+	−0.71***	
TR	0.47**		0.46**	0.41**	−	0.32*

* Total precipitation is the sum of daily precipitation for June, July and August. Consecutive dry days is the maximum number of consecutive days with daily precipitation less than 1 mm. Wet days are the number of days with daily precipitation greater than 1 mm. Heavy precipitation days are the number of days with precipitation greater than 10 mm. Frost days are the number of days with minimum temperature less than 0 °C. vDTR is the mean absolute day to day difference in the diurnal temperature range. For a fuller explanation of the indices see Klein Tank *et al*. (2002).

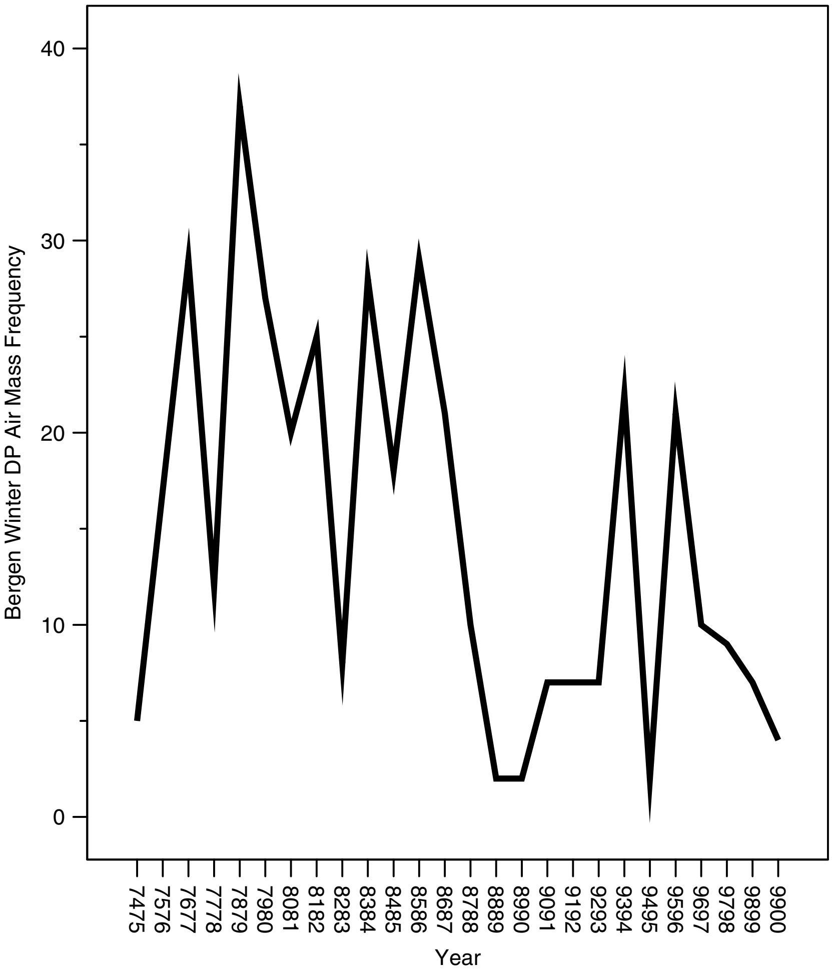

Figure 11. Trend in winter DP air-mass frequency at Bergen, Norway.

shown here) it emerges that atmospheric pressure at Reykjavik and by extension, the summertime dynamics of the polar trough, is a key determinant of summer air-mass frequency occurrences across the study area. For example, at Bergen a high frequency of moist moderate air masses is associated with anomalously low summer monthly pressure at Reykjavik (Figure 12(a)) whereas such pressure anomalies produce an anomalously high number of MP days at Frankfurt (Figure 12(b)). As with winter, clear frequency compensation occurs between air masses at the interannual scale as demonstrated for

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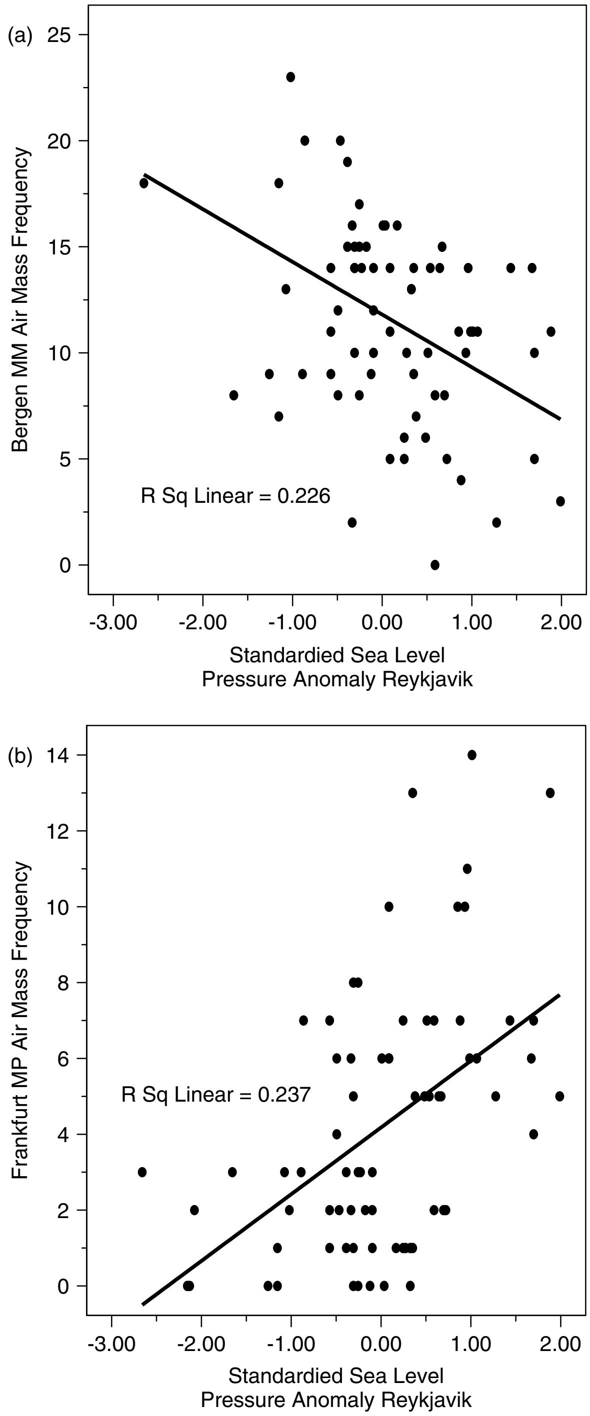

Figure 12. Relationship between standardized sea level pressure at Reykjavik and summer (a) MM air-mass frequency at Bergen and (b) MP air-mass frequency at Frankfurt.

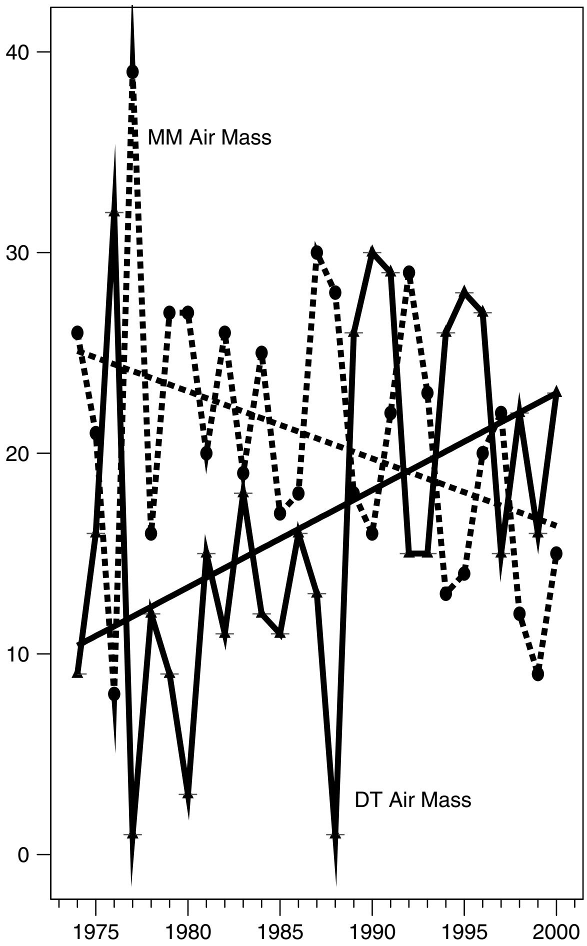

Figure 13. Relationship between and trend of summer MM (dashed line) and DT (solid line) air masses at Toulouse. Straight lines are statistically significant trend lines (Table VIII).

Frankfurt (Table VII(b)) where strong inverse associations between the frequency of DT and MM/MP air masses and between MP and MT air masses are observed. For this location, the annual occurrence of MM air masses is also inversely related to that of DM and DP air masses, which on an interannual basis, hold implications for the occurrence of warm moist and warm dry summers (Sartor *et al*., 1995; Rooney *et al*., 1998; Kyselý, 2002).

The number of statistically significant trends in summer air-mass frequency substantially outweighs those observed for winter (Table VIII(b)). Particularly noteworthy are the trends at Toulouse where MP air masses are the only ones not to demonstrate a statistically significant change in frequency. Important is the direction of the frequency trend at Toulouse. DM, DP and MM demonstrate falling frequencies while the opposite is obtained for DT and MT. As DT and MM are inversely related, the observed trends are suggestive of a displacement of MM by DT air masses (Figure 13). Concomitant inverse trends of DM/DT (decrease/increase) and MM/MT (decrease/increase) may also indicate that an increase in extreme events has taken place over the study period, because warm dry (DM) and moist moderate (MM) conditions have been gradually replaced by hot dry (DT) and hot moist (MT) conditions respectively. Similar trends to those observed for Toulouse also occur for Almeria, the only other southern European location considered here. On the basis of a consideration of inter-air-mass frequency correlations (not shown here) it would appear that the decrease in summer DM and DP air masses at Bergen are matched by possible increases in MM, MP and MT air masses while similar decreases at

Table X. Correlation between summer air-mass frequency and range of summer climate indices for Frankfurt*. ***, ** and * indicate significance at the 0.01, 0.05 and 0.10 levels respectively. + and − indicate the direction of an insignificant statistical association. Blank indicates no discernible direction of association ($r < 0.1$).

Air-mass	Total precipitation	Consecutive dry days	Heavy precipitation days	Days >25 °C	vDTR
DM	−	−	+	−	−
DP		−	−	−	+
DT	−0.57***	0.62***	+	0.85***	−
MM	0.52***	−0.47**		−0.53***	
MP	0.38*	−		−0.79***	−
MT			0.32*	0.63***	−
TR	−	−	−	−0.37*	0.50***

Days >25 °C are the number of days with maximum temperature greater than 25 °C. See Table IX for explanation of other variables.

Bruno are associated with increases in DT and MT air masses. Given this, it would appear that over the study period there has been moistening of the atmosphere over Bergen, while at Bruno, there was an increase in both hot dry and hot moist conditions.

The statistical association between summer air-mass frequency and a range of summer climate indices for Frankfurt is shown in Table X. Dry (wet) summers are clearly related to a high frequency of DT air-mass days as are the number of consecutive dry days, an indicator of persistent dry spells. Conversely, wet summers and a reduced number of consecutive dry days are related with a high frequency of occurrence of MM and MP days which occur as the result of the eastward progression of centers of low pressure across northern Europe that bring with them strong moist westerly flows (Figure 7). Interestingly, heavy precipitation days are not associated with MM or MP days but with moist tropical air advected from the south (Table X), which, when interacting with a warm summer land surface, may engender thunderstorm activity. The positive association between mean absolute day-to-day difference in vDTR and the frequency of transitional situations, indicates that rapidly changing air-mass conditions produce large differences in daily temperature ranges. As with winter, summer temperature extremes are closely associated with the prevalence of certain air-mass types. At Frankfurt, summers with a large number of hot days are associated with a high incidence of both dry and moist tropical air masses whereas cool summers are the result of the frequent occurrence of moist moderate and MP air masses with which cloudy and wet conditions are associated. The frequent occurrence of transitional situations, typified by rapidly changing atmospheric circulation conditions at the large-scale, also has a negative impact on summer temperatures (Table X).

CONCLUSIONS

The purpose of this paper was to apply the SSC approach, originally developed for North America (Kalkstein *et al*., 1996; Sheridan, 2002), to WE in order to provide a spatial synoptic air-mass classification that will facilitate air-mass comparisons and general climate analysis for WE. The key advantage of the SSC air-mass classification is that it facilitates comparison of the climate characteristics at different stations in contrast to previous approaches, which provide classifications specific to a location (e.g. Kalkstein and Corrigan, 1986; Huth *et al*., 1993), or use map patterns to describe the atmospheric circulation over large geographical areas. Further, the SSC places emphasis on air-mass meteorological characteristics and not geographical source regions, and facilitates the development of a daily calendar of air-mass types for an individual location.

While at the theoretical level the application of the SSC approach to Europe would appear nonproblematic, a number of modifications were required related to the correct specification of seed day criteria. These modifications represent methodological advances that could be applied in future applications of the SSC philosophy. Specifically the modifications to the original SSC methodology included (1) a climate regionalization to identify stations in climatologically distinct areas which would form the reference stations (centroid stations) for the establishment of seed day criteria; (2) a new cross-seed day technique to allow seed day criteria to be established for a station that is a region centroid for less than four seasons; and (3) the use of climate regions to determine the route for seed day transfer based on climatological similarity. Despite these improvements, it should be acknowledged that determining the initial seed day criteria at each reference station still remains a largely subjective exercise, despite efforts to increase the objectivity of this process. Further developments of the SSC should explore ways to address this deficiency.

The SSCWE provides a valuable tool for understanding spatio-temporal climatic variations across WE. It facilitates mapping of the frequency of individual air-mass types and thus, the analysis and understanding of the synoptic origins of spatial climatic variations, and allows the relative severity of climate for individual years, seasons and months to be understood in terms of physical air-mass characteristics. An exploratory analysis of the degree of statistical association between air-mass frequency and a range of climate indices has revealed the potential utility of the spatial synoptic approach for climate analysis

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across broad geographical areas. Furthermore, consideration of the interannual variability of the temporal and spatial patterns of air masses assists in understanding the synoptic origins and spatial extent of climate extremes. Finally, as the SSCWE is a generic classification, it may be applied to the analysis of the impact of climate variations on European biophysical systems and socioeconomic sectors that are climate-sensitive, such as, water resources, agriculture and health.

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