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Classifications of Atmospheric Circulation Patterns

Recent Advances and Applications

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We review recent advances in classifications of circulation patterns as a specific research area within synoptic climatology. The review starts with a general description of goals of classification and the historical development in the field. We put circulation classifications into a broader context within climatology and systematize the varied methodologies and approaches. We characterize three basic groups of classifications: subjective (also called manual), mixed (hybrid), and objective (computer-assisted, automated). The roles of cluster analysis and principal component analysis in the classification process are clarified. Several recent methodological developments in circulation classifications are identified and briefly described: the introduction of nonlinear methods, objectivization of subjective catalogs, efforts to optimize classifications, the need for intercomparisons of classifications, and the progress toward an optimum, if possible unified, classification method. Among the recent tendencies in the applications of circulation classifications, we mention a more extensive use in climate studies, both of past, present, and future climates, innovative applications in the ensemble forecasting, increasing variety of synoptic–climatological investigations, and steps above from the troposphere. After introducing the international activity within the field of circulation classifications, the COST733 Action, we briefly describe outputs of the inventory of classifications in Europe, which was carried out within the Action. Approaches to the evaluation of classifications and their mutual comparisons are also reviewed. A considerable part of the review is devoted to three examples of applications of circulation classifications: in historical climatology, in analyses of recent climate variations, and in analyses of outputs from global climate models.

Key words: **classification; atmospheric circulation; circulation types; synoptic climatology; cluster analysis; principal component analysis; climate change; climate modeling; historical climatology; statistical climatology**

1. Introduction

In general terms, classification is a task of grouping entities (cases) so that they share common features (are similar) within each group,

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Address for correspondence: Radan Huth, Institute of Atmospheric Physics, Boční II 1401, 141 31 Praha 4, Czech Republic. Voice: +420-2 72 76 43 36; fax: +420-2 72 76 37 45. huth@ufa.cas.cz while being dissimilar between groups. In the context of this paper, the word "group" has a meaning similar to "class," "cluster," or "type"; all these terms are used interchangeably. The degree of (dis)similarity may be quantified by a variety of metrics, usually based on distance measures. The term "classification" is somewhat confusing since it refers both to the process, during which the groups of cases are formed, and the result of such a process. Wherever a misunderstanding might occur throughout the paper in this respect, we specify more clearly what we mean, by expressions like "classification result" or "classification procedure."

Classifications have had a long history in meteorology and climatology. Since the dawn of meteorology when it constituted an independent science until a few decades ago, classifications (in those days usually called "catalogs of synoptic types") were used mainly in weather forecasting. The usage of classifications has widened in recent decades, especially after the advance of computers, which made it possible to develop and routinely apply objective methods based on processing large amounts of data. The advance of computers led at the same time to a change in the methodology of weather prediction, which lost its interest in classifications. As a consequence, the main driver of the progress in classifications in the atmospheric sciences turned from weather prediction to climatology. At present, various classification methods are used in many fields of the atmospheric sciences for a large spectrum of purposes, making classification one of the most important fields in synoptic and statistical climatology.

We are not aware of any comprehensive review of classifications in atmospheric sciences during the last 10 years. In a review of recent developments in synoptic climatology,[188] classifications were given only a limited space. Therefore, we find it useful to provide a review of this specific topic, emphasizing recent tendencies and developments in both the methodology and applications. Since the field of classifications in meteorology and climatology is quite wide and coverage is difficult in a single paper, we limit ourselves in this review to the issue of classification of atmospheric circulation patterns. Classifications of other atmospheric entities and phenomena are mentioned only briefly with the intention of providing a broader context.

We first overview and systematize the existing classification methods in Section 2, which also discusses relationships of the concept of circulation types to other concepts, such as weather types, air mass types, circulation regimes, and modes of variability. Recent methodological developments in classification techniques are presented in Section 3, while recent tendencies in their applications are given in Section 4. Section 5 summarizes the circulation classification procedures and applications in Europe. Next, methods of comparison and evaluation of classifications are described in Section 6. Three examples of the topical applications of circulation classifications are presented in more detail in Section 7. The review paper is finalized by concluding remarks in Section 8.

2. Overview and Systematization of Classification Methods

2.1. General Concepts

Many climatological studies and applications need the data set to be simplified by dividing datapoints into a relatively small number of distinct categories. Classification is thus a tool used frequently in climatology and for varied purposes. There are several typical settings of climatological classifications, whose brief description follows. Regionalization studies divide a geographical area (commonly of subcontinental to country-wide size) into regions in which the time development or other statistical properties of the classified variable(s) are similar. The similarity is sought between spatial sites, such as stations or grid points. Classified variables most frequently include precipitation, temperature, or combinations of several elements. It is also possible to classify variables in an attempt to group them according to a similarity in their spatio–temporal behavior; this type of study is fairly rare (e.g., Ref. 124).

In the remaining classification approaches mentioned here, the individual time realizations (instantaneous values, daily, monthly, or annual means, etc.) are grouped together. The entities to be classified differ widely. If multiple surface weather variables from a single site (or, more generally, from a few sites) are classified, one gets a weather classification. The variables typically include temperature, humidity, cloud cover or sunshine duration, wind speed, and air pressure and may be measured several times a day to also capture the diurnal cycle. This kind of classification has been used in climate change studies[102] and in bioclimatological investigations, e.g., in relating human mortality to climatic factors.[100,118,172] They are sometimes referred to as air mass classifications; however, they reflect surface conditions only and, as such, do not truly describe air mass properties (the term *weather classification* being more appropriate). True air mass classifications are, on the other hand, based on multiple variables defined at several lower- and mid-tropospheric levels, possibly also including surface variables.[169] Over large (continental and subcontinental) areas, spatial synoptic classifications[18,101,171] are usually more useful, e.g., in bioclimatological studies, although their drawback is that representative (seed) days must be identified manually, which involves a large degree of subjectivity. Also vertical atmospheric profiles can be a subject of classification.[191]

Atmospheric circulation can be described in many different ways, and this variety is naturally reflected in the number of different sorts of circulation-based classifications. For example, classified can be backward air trajectories,[57,179] cyclone tracks,[17] and wind fields.[105] For the latter, a smaller temporal (hourly) and spatial (regional to local) scale is characteristic, allowing diurnal in addition to annual cycles to be captured. The bulk of circulation-based classifications are nevertheless those of circulation patterns. A circulation pattern in this context means a field of sea level pressure (SLP), geopotential height, or possibly another variable describing atmospheric circulation that is defined for each time instant of the analysis (e.g., hour, day, month) and usually on a regular grid. We refer to such classifications as "circulation classifications," and individual groups (classes) are referred to as "circulation types." Another frequently used term is "synoptic types," which is somewhat interchangeable with "circulation types" but used usually in connection with subjective classifications (see below). In the remaining text, we limit ourselves to discussing circulation classifications only, unless explicitly stated otherwise. It is, however, important to note that the distinction among various kinds of classifications is not sharp and that they overlap to a certain extent. For example, a classification of geopotential heights and temperature at the same level can be seen as circulation-based as well as, at least partly, an air mass one. The vast majority of circulation classifications use SLP and/or geopotential heights in lower to middle troposphere (up to 500 hPa) defined on a regular latitude–longitude grid. Usually one level is used as an input; the few studies using multiple levels[109,158] indicate that, owing to a high degree of dependence among individual levels, the inclusion of additional levels yields only little extra information over using a single level. A common temporal resolution is daily, although a few circulation classifications have been performed for monthly means (e.g., Ref. 10). Nevertheless, there is no methodological distinction between daily and monthly analyses: the same methods can be used to classify patterns on any reasonable temporal scale—from subdaily to monthly or even seasonal.

Atmospheric circulation constitutes more a continuum than a system with several, clearly defined, well-separated states. Any classification of circulation patterns should therefore be viewed as a purpose-made simplification of reality rather than a physical reality itself. For this reason, there is no single classification that might be considered a truth; the same holds for the number of classes. On the other hand, classifications can be compared with each other according to various criteria, both general and application-specific, and potentially be ranked with respect to them. This means that although there is no true, "absolutely correct" classification, we may flag individual classifications as more or less suited for particular purposes, or possibly even "better" or "worse" in general, if they succeed or fail in all or most of the criteria. However, a detailed intercomparison of many circulation classifications is an outstanding issue, which is discussed in more detail in Section 6.

Now it may be useful to mention the relation of the concept of circulation types to two related concepts, circulation regimes and modes of variability. The theory of circulation regimes is originally based on the chaos theory[125] where attractors (the regimes) pull the system of circulation states onto preferred paths around them.[136] Circulation regimes (frequently called *weather regimes*, which is somewhat misleading since their definition has nothing to do with weather) are defined on larger spatial scales (typically continental or hemispheric) and time scales longer than daily (typically on 5-day to monthly means or on low-pass-filtered data). They are manifestations of low-frequency atmospheric dynamics, their main properties being stationarity (they last for a relatively long time) and recurrence (they appear repeatedly).[136,146] Whereas in most circulation classifications, all (or almost all) daily patterns are classified, a typical feature of circulation regimes is that a considerable part of days are transitional, that is, remaining outside of regimes. A typical number of regimes is up to four on a continental scale, which is smaller than the number of types in the majority of circulation classifications. The distinction between the concepts of circulation classifications and regimes is blurred by the fact that similar methods of cluster analysis may be used to detect both of them (for circulation regimes, refer to e.g., Refs. 136, 139, 140, 141, 189; for classifications, references can be found in the following text). Nevertheless, the circulation regimes are more commonly defined as persistent anomalies[136] or local maxima in the multidimensional probability distribution function, e.g., Refs. 40, 111. However, the physical realism of the circulation regimes has been placed into doubt recently by questioning their statistical distinguishability from a multinormal distribution.[33,178] If these doubts proved true, the sets of circulation regimes would lose their physical basis and would, in fact, become nothing more than mere circulation classifications with a very low number of types.

Modes of low-frequency circulation variability are usually defined by means of principal component analysis (PCA), e.g., Ref. 7. Owing to the variance maximization property of PCA, the bulk of variability of circulation patterns is concentrated in the first few (on a hemispheric scale typically about 10) components (modes), which in fact means that individual circulation patterns can, to a good approximation, be reconstructed by a few leading modes. A circulation field at each time instant can thus be approximated by a linear combination of several modes of variability; modes of variability can thus be seen as main building blocks, of which the atmospheric circulation is composed. There is no reason to suppose that the modes of variability resemble individual circulation patterns; therefore, they cannot be considered as typical patterns or circulation types. More details on this topic are presented below in the discussion of a proper use of PCA as a classification tool.

2.2. Methodological Approaches

There is a wide variety of approaches and methodologies to classify circulation patterns. Table 1 and the following text attempt to systematize them.

Each classification consists of two major steps: the definition of types and the assignment of individual cases to the types. Concerning the definition of types, there is a main distinction between the approaches where the types

TABLE 1. Overview of Classification Methods

Main characteristic	Definition of types	Assignment to types	Method	Selection of references (definition and recent applications)
Subjective	expert knowledge	subjective	Hess–Brezowsky catalog	11, 65, 71
			Vangengeim–Girs	66, 182
	physical/geometrical	subjective	Lamb	120
			Schüepp	168
Mixed	expert knowledge	distance	objectivized Hess–Brezowsky	94
	physical/geometrical	threshold criteria	objectivized Lamb (Jenkinson–Collison)	95, 98
	prototypes	distance	prototypes	15
Objective	correlation-based		correlation	21, 126
			sums of squares of differences	52, 112, 134, 162, 163, 167
	cluster analysis		average linkage	142
			Ward	32, 57, 184
			k-means	20, 38, 39, 54, 55, 61, 161, 173, 175, 190
			simulated annealing	150
	PCA		T-mode PCA	10, 79, 81–83, 90, 143
	multi-step		various methods	84, 108, 158, 166
	neural networks		self-organizing maps	26, 27, 73, 76, 131, 135, 153, 164
	other nonlinear		classification and regression tree	25
	mixture models		mixture models	184
	fuzzy		fuzzy	5, 6, 177

In the list of references, we provide the original paper where the method was introduced and described and a selection of its recent applications in the last approximately 15 years. Abbreviations: PCA, principal component analysis.

are defined prior to the assignment stage and where the types are derived and evolve during the process of classification itself. The a priori definition of types can be guided by (i) expert knowledge (or, somewhat derogatively, a rule of thumb), as in the Hess–Brezowsky catalog[71] or (ii) physical or geometrical considerations, such as a direction of airflow, its strength, and degree of cyclonicity, as in the Lamb catalog.[120] All of such classifications require choices that are arbitrary to a large extent; therefore, it is reasonable to refer to them as subjective. The method-driven definition of types is guided by more or less objective criteria, which are method dependent and include, *inter alia,* a measure of (dis)similarity (maximization/minimization of within-/between-type similarity in cluster analysis) and variance maximization (in a PCA-based classification). Although these criteria are fully objective, the whole procedure cannot be thought of as fully objective since several subjective decisions enter it, e.g., the choice of the (dis)similarity measure and the number of classes. Concerning the assignment of cases to the types, the two basic approaches can be described as (i) subjective, consisting of a visual attribution of individual patterns by a trained expert, and (ii) numerical, either based on minimizing distance from the a priori-defined types or being a more or less iterative process within the numerical algorithm.

Putting together the approaches to the two classification stages, one gets three major groups of classifications. The first group is commonly referred to as subjective or manual classifications. Their types are subjectively defined a priori, and the assignment of individual cases to the types is also subjective. Two most widely known and used examples are the Hess–Brezowsky catalog and the Lamb classification. The catalog, named after P. Hess and H. Brezowsky, was originally developed by Baur *et al.*,[11] then improved and revised[71] and recently updated.[63,65] It consists of 29 types plus one small group of unclassified days. The Hess–Brezowsky catalog was developed for Germany and has been applied in a fairly wide area of central Europe for many different purposes. Lamb[120] created the catalog for the British Isles in which the types are defined by the direction of air flow and (anti)cyclonicity. The catalogs differ in the size of the area they focus on: whereas the Lamb classification relates to circulation over and near the British Isles, the Hess–Brezowsky catalog captures large-scale characteristics of atmospheric circulation over Europe.[94] Another difference is in the temporal scale: unlike the Lamb classification where there is no limit on the duration of periods with the same type, the Hess–Brezowsky catalog requires each type to last at least 3 consecutive days (except the unclassified days). There are many other subjective catalogs, which typically are application-specific and most of them have gained only regional relevance; many of them are national derivatives of the Hess–Brezowsky catalog. Among those having attained international recognition are the classification of hemispheric circulation patterns by Vangengeim[182] and Girs[66] and Schüepp's classification[168] focusing on Switzerland; all of them have been used in climatological studies, those by Vangengein and Girs especially in Russia and the former Soviet Union.

The classifications in which the types are defined subjectively a priori, while the cases are assigned by objective criteria, are referred to as hybrid or mixed. In general, different approaches may be used for classifying cases with predefined types. They include setting threshold criteria, using a distance measure, and means of artificial intelligence, such as decision trees and neural networks. However, only the former two have been used in practice, most notably in the objectivization of the two major subjective catalogs. The objectivization of the Lamb catalog consists in setting numerical criteria for the direction, intensity, and vorticity of airflow,[98] whereas the Hess–Brezowsky catalog requires a more complex procedure involving pattern correlation as a distance measure.[94] A correlation-based assignment of cases subsequent to a manual designation of initial seed patterns was also used in Ref. 60. Neural networks have not been used for the objectivization of subjective catalogs, although their architecture most widely used in the atmospheric sciences, multilayer perceptron, can be applied to pattern classification and is superior to traditional classification approaches.[62] Another example of a mixed classification, developed by Beck and Beck *et al.*,[13,15] is based on the similarity (in terms of pattern correlations) of daily patterns with three prototypical flow patterns, viz. zonal, meridional, and cyclonic. Using Euclidean distance as a dissimilarity measure, the classification results in two central low/high pressure types and eight main directional types, which can be further subdivided into a total of 18 types.

The classifications where both the types are defined and cases assigned by a numerical procedure are usually referred to as computer-based, computer-assisted, automated, or objective. We emphasize that the word "objective" does not imply the objectivity of the whole classification process because the objective procedures involve subjective decisions to be taken by the classifying subject that may considerably affect classification outputs. Although the term "computer assisted" may seem more appropriate from this point of view, we will stick to the term "objective" because of its simplicity and generally wider use.

TABLE 2. Evaluation of Objective Classification Methods Based on Results from Ref. 80

Method	Consistency	Separability	Temporal and spatial stability	Structure of clusters	Reproduction of predefined types
Correlation	poor	good	poor	snowballing	poor
Sums-of-squares	poor	good	poor	snowballing	poor
Average linkage	excellent by definition	good	very poor	snowballing	moderate
k-means	poor	very good	good	equal-sized	moderate
T-mode PCA of full data	good	poor	good	no deficiency	excellent
T-mode PCA of anomalies	good	poor	good	no deficiency	poor

For more details see text.

The objective classification techniques fall within several major families, which are briefly characterized below. A more extensive review can be found e.g., in Ref. 80 where their performance is also assessed. A brief evaluation of selected methods is provided in Table 2. The evaluation criteria include: (i) *consistency*, i.e., the degree to which the classifications based on close values of parameters that are set a priori agree or differ; (ii) *separability*, i.e., the degree of similarity among the cases within the same cluster and dissimilarity between the clusters; (iii) *stability* in time and space, i.e., the degree of similarity of groupings based on temporal subsamples of data and on a slightly different grid; (iv) *structure* of the clustering, i.e., whether the method tends to produce a biased structure; and (v) *reproduction of predefined types*, which reflects the ability of a method to detect the known underlying structure of data. A more detailed discussion on the evaluation criteria follows in Section 6.

Correlation-based methods use the similarity between daily patterns as a criterion. The similarity is expressed in term of correlations[126] or sums of squares of differences.[112] Blair[16] found that the original description of the latter is not correct and suggested its improvement. The main idea of the correlation method is that the pattern with the largest number of correlations with all other patterns exceeding the threshold is assigned as the first keyday pattern; the highly correlated patterns are classified with it, removed from the data set, and the pattern with most numerous correlations over the threshold with the remaining patterns is sought. The procedure continues until all days are classified or the size of classes drops below a prespecified value. The sums-of-squares method performs analogously; the patterns with the sums-of-squares of differences below the prespecified threshold are sought. The main disadvantage of the correlation-based methods is their tendency to produce one huge group accompanied by many small ones and, depending on the variant of the method, even many individual unclassified cases. On the other hand, they yield a good separation between clusters.

Cluster analysis is a mathematical methodology designed to produce classifications,[104] hence it is the approach most natural for classifying circulation patterns and, in fact, also the most commonly used one. There is a great variety of clustering algorithms. The hierarchical ones start with each case (daily pattern) in its own cluster, creating a nested sequence of partitions, and finally form one cluster containing all cases. Several hierarchical clustering algorithms have been used in climatology, the average linkage and Ward methods, e.g., Ref. 102, having gained the widest popularity. The nonhierarchical algorithms need the number of types to be determined a priori and assign cases to cluster centroids, usually in an iterative procedure. Their typical representative is the k-means technique. Cluster analysis is frequently preceded by PCA to remove colinearity from the input variables since their linear dependence may negatively affect results of a clustering procedure, mainly by giving excessive weight to strongly correlated variables, e.g., Refs. 45, 59. Another reason for the use of PCA is its data-compression ability, i.e., a considerable reduction of the number of variables. A comparison of several clustering techniques was performed by Kalkstein *et al.*,[102] for the classification of weather types, and by Gong and Richman,[67] for regionalization. Gong and Richman[67] also evaluate different methodological choices, such as the distance measure and determination of preliminary cluster centroids. The average linkage frequently produces the snowballing effect, that is, forms one huge cluster to which more and more other groups are attached in later stages of the clustering, accompanied by small clusters and unclassified days. Such a tendency can be partially eliminated by stopping the clustering process at different levels of dissimilarity in different parts of data.[87,170] On the other hand, the k-means procedure tends to produce equally-sized groups, which may be unrealistic, the groups being very well separated.

As an improvement over the k-means clustering method, simulated annealing was developed, e.g., Ref. 150. Its main advantage is the elimination of the instability of the k-means technique, which is demonstrated by the dependence of the classification output on the preliminary selection of centroids.

The potential of PCA to also be used as a classification tool was proposed by Richman.[154] For classification of circulation patterns, the data matrix must be organized so that grid point values are in rows and cases (time realizations) in columns, e.g., Refs. 36, 79; this kind of PCA is referred to as T-mode.[154] Another prerequisite for PCA to be used for classification purposes is that principal components should usually be rotated.[79,81] There is a fairly common misunderstanding related to the application of PCA to circulation patterns, stemming probably from the fact that another configuration of the data matrix, grid points being organized in columns and cases in rows (S-mode), is more widely used. Unlike T-mode, S-mode results in the detection of the modes of variability, discussed earlier in this section, e.g., Ref. 7. The distinction between the two matrix configurations is sometimes neglected, and results of S-mode PCA are referred to as "circulation types" or "typical circulation patterns," which is definitely not appropriate (for a discussion, see, e.g., Refs. 35, 36). Discussing reasons why the application of S-mode PCA for the classification of circulation patterns is incorrect would reach beyond the scope of this paper; an interested reader is referred to Refs. 36, 79, 154.

We feel that the use of cluster analysis and PCA should be better clarified because of occasional misunderstandings of their role in classification. The use of PCA in classification is twofold: it is applied either as a data-preprocessing tool prior to cluster analysis (in S-mode in such a case) or as a classification tool (in T-mode). If PCA in S-mode is used prior to cluster analysis, it cannot be considered a classification tool simply because it is the subsequent cluster analysis that accomplishes the classification. Therefore the inclusion of cluster analysis preceded by PCA among the "eigenvector-based" classification methods, as in the widely cited book by Yarnal[187] and repeated in several other papers, is highly misleading. A different case is a two-stage (or even more stage) clustering when a preliminary classification is performed in the first step, which is refined by another classification in the final step. The rationale for making the procedure more complex by putting together two classification procedures is the belief that their negative properties may be eliminated. In the second step, a nonhierarchical technique is used, while in the first step hierarchical clustering, e.g., Ref. 166, or T-mode PCA[158] is employed. The use of T-mode PCA in this context is methodologically different from the use of S-mode PCA as a mere preprocessor: in the former case, PCA is a classification tool and the whole procedure can be regarded as eigenvector-based, contrary to the latter case.

A specific group of classification approaches are nonlinear methods, of which neural networks are the most prominent example. In climatological classifications, one specific architecture of neural networks, self-organizing maps (SOMs), is used exclusively. The classification by SOMs consists of a two-dimensional array of maps portraying typical patterns, with the most dissimilar pairs of patterns being located at the opposite ends of the main diagonals. The SOM methodology differs from cluster analysis in that it is not primarily concerned with grouping data; it rather attempts to find points in the physical space that are representative of nearby observations. More information on SOMs in climatological classifications can be found in the papers referenced in Table 1.

The last group of objective classification approaches to mention here are fuzzy methods. The underlying concept of fuzzy classifications is that each case (daily pattern) may belong to more types than a single one, with a different intensity of membership. Although this seems to be well in line with the fact that circulation patterns are only weakly structured and do not form clearly distinct classes, the multiple membership of cases is counterintuitive and difficult to work with. It can also be seen as a compromise between PCA and a distinct classification technique and, as such, may not be considered a classification in the pure sense. As a consequence, fuzzy classifications still remain at the edge of interest of the climatological community.

Occasionally, other classification methods than those listed above have been used. None of them have been applied in more than a single paper on circulation classifications. Such methods include classification and regression trees[25] and mixture models.[184]

2.3. Geographical Distribution of Classifications

Finally, we address the geographical distribution of classifications and their development. For historical reasons related to the developments in synoptic meteorology and weather forecasting techniques, the majority of subjective classifications are rooted in Europe. The development of mixed and objective classifications was driven more by scientific than weather forecasting interests and proceeded together with the advance of computers. The regions where circulation classifications were developed and applied include almost all of Europe (more details are provided in Section 5), as well as North America (where the Great Lakes region and California are among those most targeted), southern South America, South Africa, Australia with New Zealand, and the Arctic. Naturally, the interest in circulation classifications appears in the regions where the day-to-day synoptic variability is the most important driver of local weather conditions, that is, in the mid and high latitudes of both hemispheres. Somewhat surprisingly, very little if anything has been done in the field of circulation classifications in Asia, and particularly striking is the lack of classification studies published in international literature in Japan, Korea, and China.

3. Recent Methodological Developments and Tendencies

The daily gridded circulation data sets are quite large, and some of the classification techniques are highly computer demanding. Therefore, the methodological developments in circulation classifications are conditioned by the computer power available and go hand in hand with the advance of computers. We briefly mention developments and tendencies in five methodological aspects of classifications, which include nonlinear methods, objectivization of subjective catalogs of circulation types, various efforts to optimize classifications, the increasing need for intercomparison studies, and a struggle to find an optimum universal classification methodology.

3.1. Introduction of Nonlinear Methods

The progress in computer power has made it possible to routinely use mathematical techniques that would have been inapplicable only a decade ago. One such example is nonlinear methods, which are computationally much more demanding than standard linear techniques. In circulation classifications, this role is played mainly by SOMs, a specific architecture of neural networks. The introduction of SOMs into the atmospheric sciences was pioneered by Hewitson, Crane, and Cavazos.[28,29,42,72,73] SOMs benefit from their easy interpretation, namely from the fact that the types (modes) are organized on a rectangular array. The display of frequencies of the types, their trends, differences between data sets, and in general of any property for which each class can be characterized by one number is then easy and intuitive since it can be presented as a single map on a rectangle. The density of the nodes reflects the density of observations, which can be thought of as a desirable property of a classification but is not trivial and not met by other techniques, especially those producing a snowballing effect. Such techniques yield outputs with an opposite behavior: where the data density is large, one huge cluster is formed, accompanied by many small clusters where the data density is small. Recent applications of SOMs demonstrate their potential in climate studies; they include analyses of causes of increasing drought in southwestern Australia,[76] analyses of circulation in global climate simulations for current and future climates,[27,75,131] and statistical downscaling.[74] Reusch *et al.*[153] demonstrate that SOMs are related to the leading two principal components (modes of variability). Although SOMs are becoming more popular, they have not undergone any intercomparison with other methods; so little is known at present about how their performance in fundamental qualities of classifications, like those shown in Table 2, relates to the performance of standard and well-established techniques.

3.2. Objectivization of Subjective Catalogs

The rapidly evolving field of climate modeling necessitates the development of advanced techniques for evaluation of global climate model (GCM) outputs. The analysis of circulation types is one of several potential approaches for evaluating past, present, and future simulated climates. Two counteracting facts are relevant in this context: First, the subjective catalogs of Hess–Brezowsky and Lamb are widely used, accepted, and their characteristics are well known. Second, it would be extremely time consuming to use the subjective classification methods in analyses of climate model outputs because of the immense number of daily patterns to be manually analyzed. An objectivization of the subjective catalogs appears as a logical and promising solution. The objectivization of the Lamb catalog was performed by Jenkinson and Collison[95] and refined by Jones *et al.*[98] Its smaller scale nature and fairly easy definition make the objectivized Lamb catalog transferable to other regions (it was developed for Scandinavia[31,123] and the Iberian peninsula[69,181]). The Hess–Brezowsky catalog waited for its objectivized version[94] longer, probably because the definition of its types relies more on synoptic experience and is difficult to algorithmize. It is important to stress that the goal of the objectivized catalogs is not to replace the original subjective ones[98] and to exactly reproduce the original series of subjective types.[94] Instead, the goal is to produce "an acceptable surrogate for the original, that might readily be applied."[98]

3.3. Efforts to Optimize Classifications

3.3.1. *Classification of Sequences of Patterns*

One of the ways to improve classifications for specific applications is to consider the history of a circulation pattern by including information on preceding days in the description of the entity to be classified. The idea behind this approach is that one and the same circulation pattern can have different consequences for surface conditions (temperature, precipitation, etc.) depending on the patterns that preceded it. This can be connected to e.g., different degree of persistence or different typical forms of dynamical development, which may justify the assignment of actually similar patterns to different classes. A subjective version of this approach was presented in Ref. 37. The first objective implementation of the concept of extending circulation patterns to pattern sequences for classification was presented by Compagnucci *et al.*[34] who applied T-mode PCA to sequences of daily patterns [the procedure is called principal pattern sequence analysis or extended principal component analyis (EPCA)]. The implementation for cluster analysis (extended cluster analysis) and a comparison to EPCA has been published recently in Ref. 149, showing that pattern sequence classification is able to considerably improve the skill of classifications, e.g., for downscaling purposes.

3.3.2. *Reducing Within-type Variability*

Within-type variability of climate variables within circulation types is a major problem shared by all circulation classifications because of the categorization of continuous data, e.g., Ref. 187. Within-type variability gains particular importance when using circulation classifications as a downscaling tool, e.g., Ref. 162, or for analyzing long-term circulation–climate relationships, e.g., Ref. 15. Several attempts toward the reduction of within-type variability of large-scale circulation types with regard to related regional surface climate variables were made by Brinkmann.[19–21] The approaches comprise the shift of the spatial domain used for the determination of circulation types[19] and varying methods to account for small-scale circulation components that are relevant for associated weather regimes but are missed by the automated classification methods. The most promising approaches use additional information on circulation features (e.g., 700 hPa vorticity) for a further subdivision of circulation types[19] or increase the sensitivity of a correlation-based classification approach for small-scale circulation components by raising correlation thresholds in the relevant geographical sectors.[21] Although leading to some reductions of within-type variability, these extensions and modifications share one major drawback as they are adjusted to very specific regional synoptic conditions and may not be easily transferred to other regions.

3.3.3. *Enhancing Cluster Algorithms*

Two developments within standard clustering algorithms are mentioned here. A new, though seldom used, way to extract clusters is to overcome the principle of finding symmetric spherically shaped clusters in the phase space. This principle is already realized in hierarchical cluster analysis, e.g., in single linkage clustering where it, however, leads to undesirable effects, like snowballing. Hannachi and Legras[70] presented a way to find clusters with varying and irregular boundaries by solving the traveling salesman problem for connecting points in the phase space. Even though this method did not gain ground until now, it is a remarkable new development and offers a different way to classifications and a new sight on them. Another noteworthy step in the recent development of classifications was the introduction of the simulated annealing technique.[1,6,150] It effectively overcomes the unstable character of conventional k-means cluster analysis, one of the most widespread methods used for classification. Especially for large data sets, ignoring the instability of k-means can significantly affect the classification output since the iterative process of optimization in conventional k-means is quickly trapped by a local, not global, optimum by chance. Analyzing such a suboptimal classification may, therefore, lead to highly unreliable results.[150]

3.3.4. *Finding an Optimum Number of Types*

A central question when dealing with classifications is how many types should be defined in order to capture important features of the varying atmospheric state.

For the early subjective classifications, there was no need to address the problem explicitly because the authors simply defined as many types as they thought were necessary to describe synoptic conditions. The number of types, therefore, was a secondary result of subjectively differencing between meteorological situations. For some objective methods the definition of the number of classes is still a minor task since it is implicitly derived by the specific concept of the classification. The situation is, however, totally different when objective methods, like PCA and cluster analysis, are considered. For those methods the two main factors driving the decision are, on one hand, the maximization of homogeneity within classes, which is generally increasing with the number of classes, and, on the other hand, the goal to reduce the variety of atmospheric states to a number of classes that is small enough to easily conceive their differences.

The ways to determine the number of classes mainly differ by the use of different statistical measures. A new aspect in the discussion on the number of classes was brought by the introduction of the regime theory.[125] Even though daily circulation types should be clearly distinguished from circulation regimes (see Section 2), the idea of naturally existing types (attractors) with higher persistence and higher frequencies than other states, which are interpreted as transitions between the regime states, had some influence on circulation classifications, leading to a fairly small number of circulation types, frequently two to four, in several studies, e.g., Ref. 178. Some of these studies use statistical quantities, such as a "reproducibility" and "classifiability" index, to support the existence of a low number of significantly separated preferred types.[40,136]

On the other hand, more and more recent studies raise doubts whether there is a significantly predetermined number of types in circulation data sets[33,56,150,178] and show that some of the statistical methods used to confirm them may be questionable.[150,178]

3.4. Increasing Variety of Classifications and a Need for Their Mutual Comparison

A typical feature of the last decade is a growing number of papers in which the investigators produce their own classifications for specific regions and purposes, unfortunately without any comparison with other already existing classifications or classification techniques. The lack of a verification of the new classifications against a benchmark method implies that the essential information is lacking on whether the new method brings a real improvement over the existing approaches, hence whether it is worth dealing with. This, among others, precludes a wider distribution and use of the newly developed classifications. We take this opportunity to emphasize the important role of intercomparison studies; although in general these studies are not able to rank the methods or to select the single optimum one, they may point out specific strong and weak points of each method. However, the number of intercomparison studies does not grow as fast as the number of classifications that should have been subjected to them.

3.5. Toward a Universal Objective Classification Method

In response to the undesirable tendency to producing new and new classifications, as described above, an awareness of the necessity to proceed in the opposite direction has grown among climatologists and meteorologists concerned with classifications. It was recognized that (i) circulation classifications are needed for an increasing range of applications, (ii) it is undesirable that so many different classifications are available, (iii) there is a need for developing criteria for mutually comparing circulation classifications, and (iv) there is no common reference circulation classification. Based on these premises, the European-wide international activity entitled "Harmonisation and Applications of Weather Types Classifications for European Regions" was launched, which is supported by the COST (European Cooperation in the Field of Scientific and Technical Research) program. Its aims include, among others (adapted from Ref. 49), (i) to overview the existing circulation classification methods and their applications in Europe, (ii) to enhance the knowledge on linkages of the atmospheric circulation to weather, climate, and environmental variables, (iii) to analyze strengths and weaknesses of the classification methods for different applications, (iv) to provide tools for comparison and evaluation of different classifications, and (v) to assess different methodologies for the comparison of circulation classifications. The declared ultimate goal of the activity is to achieve a general objective method for assessing, comparing, and classifying synoptic situations in European regions, which would be scalable to any European (sub)region with daily time scales and spatial scales of 200–2000 km. For more details on the COST733 Action, an interested reader can refer to webpage http://www.cost733.org.

4. Recent Tendencies in Applications

4.1. More Extensive Use in Climate Change Studies

During the last decade, climate scientists recognized the utility of circulation classifications as an exploratory tool in climate change research. Below we list three different areas of such applications of classifications related to reconstructions of the past climate, analysis of variability of the present climate, and evaluations of future climate simulations by GCMs.

4.1.1. *Reconstructed Past Climates*

Until recent years the application of objective circulation classifications in climate change studies has been confined to the 20th century because of the lack of reliable gridded data for periods reaching farther into the historical past. Although automated classifications have been applied to subjectively reconstructed pressure fields for outstanding historical periods, like the Late Maunder Minimum,[127] only the development of objectively reconstructed gridded SLP data for the North Atlantic–European region[3,97,99,128,130] with varying temporal and spatial resolution and covering varying periods of the historical past gave rise to thorough investigations of long-term circulation variations by means of objective classifications. The application of nonhierarchical clustering to reconstructed SLP data for the Late Maunder Minimum[128] and observed SLP data for the 1961–1990 period was used as a tool for comparing circulation dynamics between the two periods.[129] In Ref. 165, correlation-based circulation typing was applied to reconstructed monthly SLP fields for the period 1785–1994 in order to detect major circulation changes. Based on an improved version of SLP reconstructions for the 1780–1995 period,[97] several investigations dealing with circulation changes and their relationship with surface climate variability were carried out using different classification methods, including T-mode PCA,[14] nonhierarchical cluster analysis,[88] and a prototype-based classification.[15,89] All these studies were based on monthly data; only the recent availability of reconstructed, gridded, daily SLP data back to 1850[3] enabled daily SLP fields and their sequences to be classified.[56,149]

4.1.2. *Recent Observed Changes*

The property of circulation types that is most frequently analyzed in the studies on recent changes in circulation patterns is the frequency of their occurrence. Various classifications have been used for this purpose. They include the subjective ones of Hess–Brezowsky,[4,9,103] Lamb,[144] Vangengeim–Girs,[151] and Schüepp.[176] The objectivized Hess–Brezowsky catalog was also analyzed in such a manner,[94] as were the objectivized versions of the Lamb catalog over Scandinavia[31] and the Iberian peninsula.[68] Changes in the objectively defined circulation types were evaluated in outputs from the cluster analysis,[55,173] T-mode PCA,[10,90] and SOMs.[73] The persistence of atmospheric circulation, expressed in terms of the lifetime of events of circulation types, was studied mainly for the Hess–Brezowsky catalog. There are indications that atmospheric circulation has become more persistent recently[114,117,185]; however, whether this is a real feature or a manifestation of an inhomogeneity in the subjective catalog has yet to be determined.[119] The potential importance of a changing persistence for the severity of temperature extremes was also examined.[50,114,115] A broader discussion on the circulation persistence follows in Section 7.2.

As can be seen from the reference list, studies on changes in properties of circulation types focus on Europe, with only a few studies devoted to South America and the United States. Since the studies focus on different areas and different seasons, use different classification techniques, and, especially the objective ones, do not use intuitive nomenclature (in the sense that the types in objective classifications are usually described by mere numbers, not by abbreviations reflecting the character of the pattern), any judgments on whether they are mutually in accord and any attempts to create a unified continental-scale view of the changes are difficult. Nevertheless, it is clear that the frequencies of at least some circulation types have been changing; whether the increases in persistence are real remains an open question.

4.1.3. *Future Climates*

With more and more GCM runs becoming available, the analyses of changes of circulation types under future climate conditions are getting more numerous. Changes in the frequency of circulation types from the current climate conditions to future conditions (usually to the end of the 21st century) are examined as the primary characteristic in all studies of this kind.[27,39,75,82,83,110,131,133,162,167] A few of these studies also examine changes in the patterns themselves (e.g., weakening or strengthening of troughs/ridges and shifts of a jet stream axis) and related changes in precipitation. Any generalization of the results is unfortunately impossible because of a wide variety of GCMs used and regions covered (Europe, North America, Australia, New Zealand, Arctic, Antarctic).

Circulation classifications have also been used in studies of future climate in the context of statistical downscaling. Statistical downscaling is a methodology that bridges the spatial mismatch between GCM outputs and local scale. Classifications enter statistical downscaling in three different ways. First, data are stratified by circulation classification and the downscaling model is built within each class separately, e.g., Refs. 28, 53, 122. The idea behind this approach is that the relationship between the large-scale predictor and local predictand may vary depending on the type of synoptic pattern. Huth *et al.*,[86] however, find that a stratification does not improve the performance of a downscaling procedure. Second, the mean value of a type is calculated and attributed to each member of that class.[162,163] This approach implicitly assumes that future changes in the climate element considered are solely because of changes in atmospheric circulation, which is unrealistic; therefore, its outputs are at least questionable. Third, the monthly or seasonal frequencies of daily circulation types serve as predictors of monthly/seasonal mean values of a climatic variable.[68]

4.2. "Back to Weather Prediction"

Circulation classifications developed as an auxiliary tool in the field of weather prediction, their focus having later turned to climatology. Now a promising application in weather prediction, namely ensemble forecasting, has reappeared. As is well known, the basis of ensemble forecasting is running many forecasts from a given starting time, each with slightly modified initial conditions. The ensemble forecasts may be difficult to interpret, mainly because a very large amount of information is generated. Circulation classifications may provide a convenient tool to condense the information and transform it into an intuitive output easy to comprehend. The idea is to classify the predicted circulation patterns in all ensembles for all forecast leading times, which allows the likelihood of occurrence of individual circulation types to be determined for each day in the forecast range. This is beneficial for several reasons: (i) it can indicate probable dates for major changes in synoptic conditions, (ii) it facilitates identification and description of multiple trajectories of forecasts, and (iii) it communicates the ensemble outcomes to synoptic meteorologists in a very effective and understandable way. The application to ECMWF medium-range forecasts proved the utility of this approach.[92]

4.3. Increasing Variety of Synoptic Climatological Applications

Another notable tendency in the circulation classifications is an increasing variety of their applications. In addition to numerous synoptic climatological studies aimed at studying characteristics of climate variables (especially precipitation and temperature) under circulation types and analyses of climate variability, there are many other applications, for which we list a few illustrative examples: air pollution, including surface ozone (please note that some of the referenced papers are more weather than circulation classifications[12,37,43,44,58,160,179]); a comparison between radiosondes and atmospheric reanalysis[166]; surface frosts[143]; melting of Greenland ice sheet[142]; snow avalanches[54]; and wine quality.[96] More examples, such as forest fires, wind atlas, and fish captures, can be found in nonrefereed literature.

4.4. Above the Troposphere

All the classifications mentioned so far are confined to the troposphere and especially to the lower and middle troposphere at or below 500 hPa. However, we are convinced that there is also a potential for using circulation classifications in studies of the upper atmospheric levels, especially of the stratosphere. The utility of classifications in stratospheric research was proven in Ref. 85; this study analyzed monthly mean potential vorticity in the lower stratosphere and managed to identify in the resultant types such events as sudden midwinter warmings and the impact of El Niño–Southern Oscillation.

5. Inventory of Circulation Classifications in Europe

The first task of the COST733 Action, introduced in Section 3.5, was to compile an inventory of the classifications existing in Europe. We believe its results are of interest for a wider scientific community. Although the inventory was not able to identify all the classifications and their applications in Europe, it provides a good overview and may be considered a reasonable representation of the existing classification activities. The inventory was based on a questionnaire, which was sent out to relevant persons and institutions. Its aim was to cover circulation classifications used for both research and operational purposes in as many European countries as possible. The inventory was closed in early 2006, so it contains only the classifications that were available at that time.

The overview of countries from where the responses to the questionnaire arrived is provided in Figure 1. One can see a varied involvement of individual countries in the work on circulation classifications: e.g., Spain and Germany are highly active in this field.

The inventory is based on more than 80 responses to the questionnaire. In addition to true circulation classifications, other kinds of classifications (e.g., weather and air mass) were also reported; it is, however, important to note that their share is certainly underestimated because the main interest in circulation classifications was announced in advance. The share of circulation classifications, i.e., those classifications based on SLP, geopotential height, or wind fields, was 84%, one additional classification

Figure 1. Numbers of classifications reported from European countries in the responses to the questionnaire: subjective/objective/mixed or unknown. (In color in *Annals* online.)

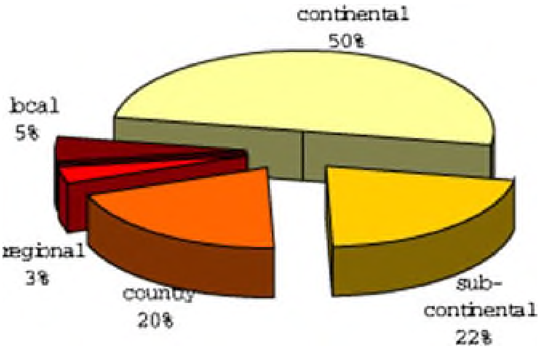

Figure 2. Percentage of classification methods reported in the inventory stratified by their spatial scale. (In color in *Annals* online.)

being based on cyclone trajectories and one on both circulation and weather variables.

Concerning the temporal resolution of the classifications, the large majority (84% of reported classifications) operate on a daily basis. Altogether 9% of classifications operate on a shorter time scale, viz. 12 h and 6 h. However, the difference is not because of a specific methodology but results mainly from data availability. Only 5% of classifications are operated on a monthly basis but all with a remark that a daily time step is also possible or has already been applied.

The information on the horizontal scale, spatial resolution, and geographical coordinates of the classifications was somewhat subjectively transformed into general qualitative information on the spatial scale, which was keyed into five different classes (Fig. 2): continental (involving whole Europe with adjacent parts of the Atlantic Ocean or at least a major part of Europe—typically more than 30° of latitude by 40° of longitude), subcontinental (involving large parts of Europe—typically of about 20° by 20°), country (involving a single country or a group of small countries, possibly including a close neighbor), regional (only a part of a single country), and local (single station). Larger-scale classifications prevail; half of all classifications are of a continental scale, about 20% of them

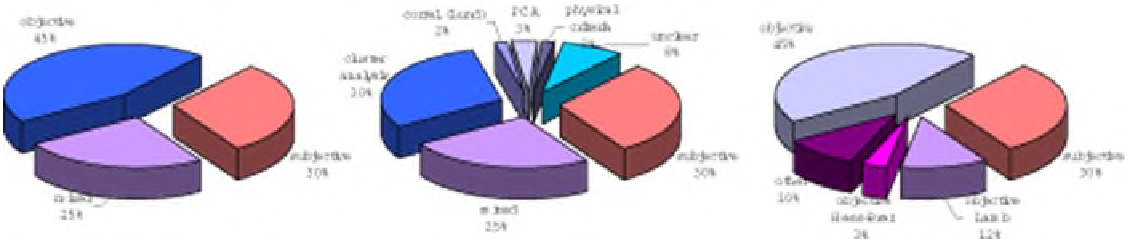

Figure 3. Percentage of classification methods reported in the inventory by the method (*left*), with objective methods subdivided (*middle*), and with mixed methods subdivided (*right*). (In color in *Annals* online.)

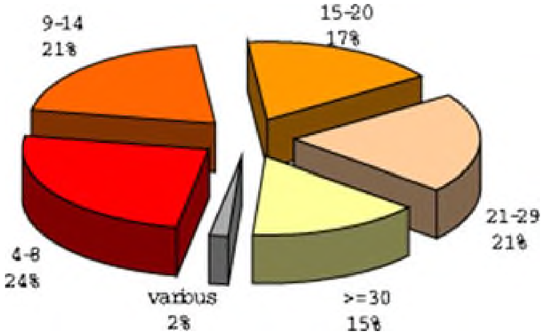

Figure 4. Percentage of classification methods reported in the inventory by the number of classes. (In color in *Annals* online.)

are of subcontinental scale and 20% country scale. The rest (8%) includes regional and local scales. All the local-scale classifications are indeed based on weather, not circulation variables.

The distribution of the classifications according to the approach and methodology is shown in Figure 3. Of the classifications, 30% are subjective, 25% are mixed, and 45% are objective (Fig. 3 left). Several objective methods are used in classification studies (Fig. 3 middle). Cluster analysis (most frequently k-means method is used but also hierarchical methods of average linkage are reported) has the largest share (30% of the total). Other methods are represented by PCA (two responses), correlation method (one response), and classifications based on threshold criteria (one response). In 8% of cases, the objective method is not clearly specified or is complex. The mixed methods (Fig. 3 right) include the objectivized Lamb catalog (Jenkinson–Collison method and its derivatives; 12%), two are objective versions of the Hess–Brezowsky catalog, and another 10% are based on the authors' own subjective classifications.

The number of types varies widely from four to 40 (Fig. 4). Some of the methods allow also subtypes to be determined, of which the largest number is 209. Several objective methods produce variable numbers of clusters, depending on the data set subject to classification; their respondents either do not specify possible numbers of classes or indicate their usual range. The numbers of types are distributed fairly evenly in the groups of classifications with 4 to 8, 9 to 14, 15 to 20, 21 to 29, and over 30 classes.

The purposes for which the classifications were developed or to which they were applied cover many areas of meteorology and climatology. The responses indicate that circulation classifications are still (or already again?—see Section 4.2) used in weather prediction. Nevertheless, the applications in climatology are definitely more numerous.

6. Comparison and Evaluation of Commonly Used Classifications

The evaluation and intercomparison of circulation classifications can be performed in several ways focusing on different aspects. One very pragmatic way of evaluating and comparing circulation classifications is to analyze how they perform when used in a specific application. This was done by several authors within the framework of climatological studies.[22,145,149] Several authors compared

TABLE 3. Selected Measures for Determining the Quality of Classifications

Measure	Description	Reference
Explained variation (EV)	$= 1 - \frac{ss_i}{ss_t}$	-
Within-type standard deviation (WSD)	$= \frac{1}{k} \sum_{i=1}^{k} sd_i$	102
Pattern correlation ratio (PCR)	$= \frac{pc_o}{pc_i}$	80
Pseudo-F (PF)	$= \frac{ss_b/(k-1)}{ss_b/(n-k)}$	24
Silhouette index (SI)	$= \frac{1}{n} \sum_{i=1}^{n} \frac{b_i - a_i}{\max(a_i, b_i)}$	159

ss_i = sum of squares within classes

ss_b = sum of squares between classes

ss_t = total sum of squares

sd_i = standard deviation within class

pc_i = mean pattern correlation between cases from the same class

pc_o = mean pattern correlation between cases from different classes

n = number of cases

k = number of classes

a_i = average distance between case i and all other cases in the same class

b_i = average distance between case i and all other cases in the closest class

objective and subjective classifications by evaluating their various characteristics.[51,98,177,186] More systematic comparison studies of several commonly used objective classification methods have been performed[80,107]; the main results of Huth[80] are summarized in Table 2.

The important features of circulation classifications that can easily be evaluated in a quantitative way are the separability between classes (discriminatory power) and the variability within each class (within-type variability).[64] There are various measures used to evaluate the ability of a classification to stratify the variable used for classification. Several of these criteria (see Table 3 for a brief list of selected measures) are also commonly used for estimating the most appropriate number of classes when performing a classification (Section 3.3.4). A more extensive overview and an evaluation of procedures that may be used for estimating and comparing the quality of classifications are given in Ref. 137. However, different measures may give different hints on the quality of a specific classification and, if used in the frame of intercomparison studies, on the "ranking" of classifications. This fact is illustrated in Table 4, which summarizes several selected criteria determined for a sample of circulation classifications for the North Atlantic/European region investigated within the framework of the COST733 Action.

With respect to the application of circulation classifications in different fields of climatological research, it is of major importance to investigate the above mentioned criteria not only for the variable that is used for circulation classification (in most cases baric fields) but also for associated fields of important climatic variables (e.g., surface temperature and precipitation).

Evaluation criteria, as shown in Tables 3 and 4, may be determined not only by integrating over a whole temporal and spatial domain, thus providing an overall view of each characteristic. Determining respective values for individual grid points, small regions, and/or temporal subsets can give more detailed information on seasonal or spatial variations in the ability of a classification to stratify the variable used for classification as well as associated climatic parameters. Thus, results of such basic evaluations can help in deciding which classification approach is most appropriate for a specific application or for a specific region.

A number of properties of classifications that are easy to determine (e.g., the number and frequency of classes, the number and characteristic of parameters used for classification) are, however, hard to assess and, moreover, impact results of statistical evaluations (e.g., the more classes are defined, the better would be the discriminatory power of a classification). In addition, there are characteristics of classifications that cannot be quantified (e.g., the degree of subjectiveness involved in the classification procedure) and can only be assessed subjectively. Thus, an objective overall ranking of circulation classifications, taking into account all characteristics, will remain impossible.

TABLE 4. Selected Evaluation Criteria (See Table 3 for Their Definitions) Derived for a Sample of Circulation Classifications Available from the COST733 Inventory of Classifications for the European Region

Classification/ reference	Number of classes/method	SLP				2 m temperature			
		EV (%)	WSD	PCR (%)	PF	EV (%)	WSD	PCR (%)	PF
CEC 53	40 k-means	35.9	7.6	44.0	235.8	10.3	3.2	98.9	48.4
ESLPC30 -	30 correlation-based	18.1	9.4	39.6	125.0	4.6	3.7	96.9	27.5
GWT 15	18 hybrid	26.4	8.1	43.1	346.2	5.3	3.4	98.6	54.2
HBGWL 71	29 manual	21.3	8.4	48.0	159.0	7.3	3.3	98.4	46.5
LUND 126	10 correlation-based	30.2	7.9	36.4	788.6	5.6	3.3	98.8	107.4
LWT2 93	26 objectivized Lamb catalog	30.0	7.9	41.9	281.5	6.2	3.3	98.7	43.4
OGWL 94	29 objectivized Hess–Brezowsky catalog	33.8	7.8	38.9	299.0	9.5	3.3	98.1	61.8
P27 113	27 subdivision according to S-mode PCA-scores	28.1	8.1	46.0	246.6	10.8	3.2	98.1	76.7
PCACA -	11 k-means	24.5	8.2	44.2	533.1	5.2	3.3	98.7	90.4
PCAXTR 55	17 k-means	29.4	8.0	40.9	427.5	6.8	3.3	98.6	75.1
PECZELY 147	13 manual	11.5	8.9	63.0	178.3	4.2	3.4	99.0	60.3
PERRET 148	31 manual	19.2	8.6	52.5	130.3	6.8	3.3	98.4	39.7
PETISCO -	14 correlation-based	28.4	8.0	39.8	500.3	6.6	3.3	98.7	89.5
SANDRA 150	18 simulated annealing	42.2	7.7	37.6	706.0	8.4	3.4	98.1	89.0
SANDRAS 149	30 simulated annealing (3-day sequences)	35.7	8.0	42.9	314.8	14.4	3.2	97.5	95.4
TPCA07 79	7 T-mode PCA	19.4	8.6	50.3	658.7	7.9	3.3	98.5	235.5
TPCAV 79	12 T-mode PCA	19.4	8.6	52.5	359.4	8.8	3.3	98.5	144.8
WLKC733 48	40 subdivision according to multi-parameter thresholds	19.7	8.3	52.8	103.4	8.1	3.3	98.4	37.3

Annual measures were estimated on the basis of 1° by 1° ERA-40 sea level pressure (SLP) and 2 m temperature data for the domain 30°N–76°N/37°W–58°E and the period September 1958 to August 2002. For a description of the resolution criteria, refer to Table 3.

Besides evaluating the above-mentioned properties of individual circulation classifications, the similarity of individual classifications is of interest. Several measures have been developed in order to determine the similarity between two partitions (classifications) of one set of observations. Commonly used indices are the Rand index,[152] the adjusted Rand index (ARI),[77] the Jaccard index,[174] and the mutual information/normalized mutual information.[180] All these indices are based on the contingency matrix between partitions to be compared. However, as circulation classifications may comprise differing numbers of types (classes), it is feasible to use a similarity index that accounts for varying numbers of classes in partitions. Thus, the ARI appears to be the most appropriate quantity to be used for estimating the similarity among circulation classifications.[138] Figure 5 illustrates the degree of similarity between selected circulation classifications for the North Atlantic–European region as estimated by ARI separately for summer and winter, showing distinct differences in similarity between pairs of classifications and also pronounced seasonal variations concerning the most similar/dissimilar classifications.

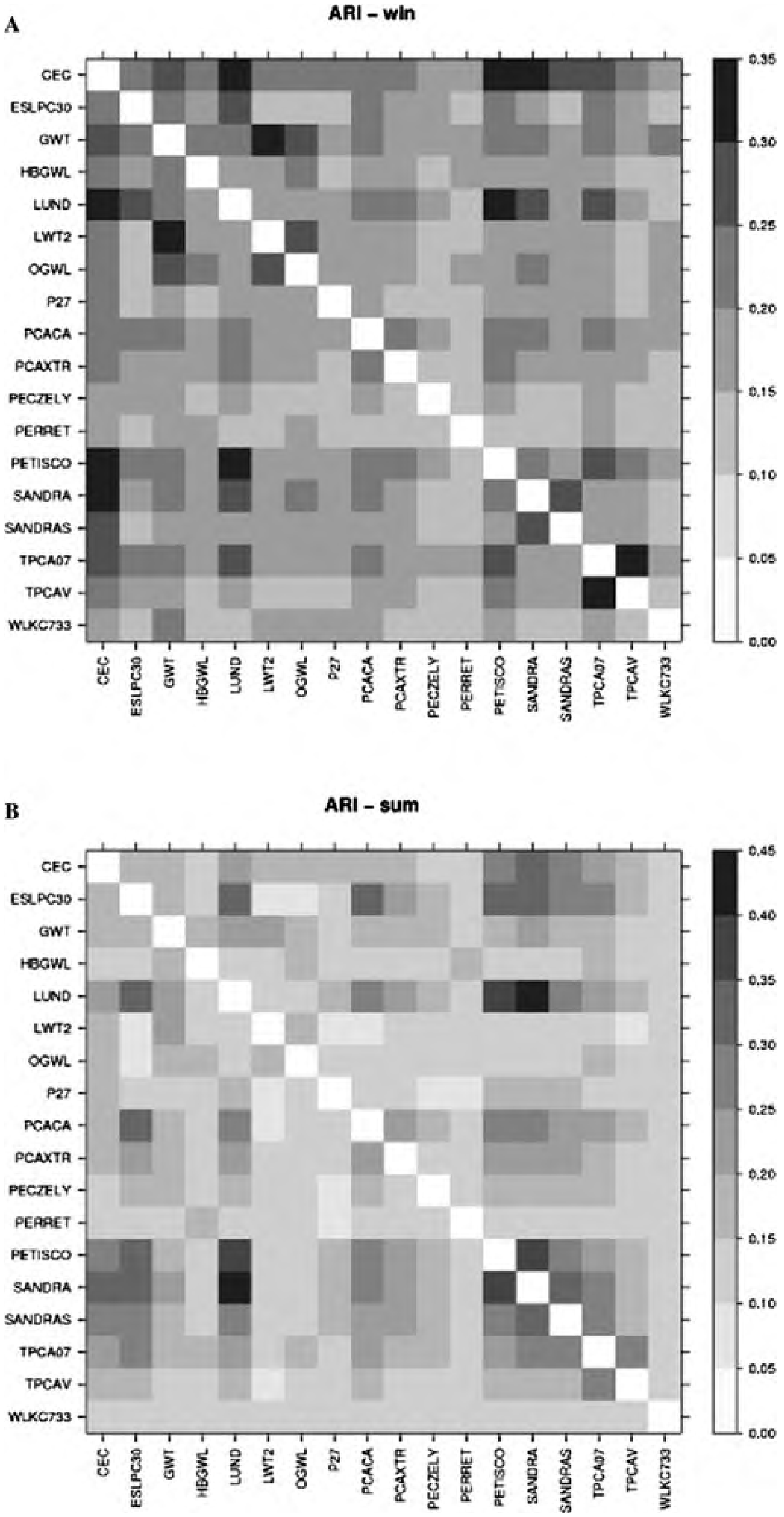
A
ARI - win
CEC
ESLPC30
GWT
HBGWL
LUND
LWT2
OGWL
P27
PCACA
PCAXTR
PECZELY
PERRET
PETISCO
SANDRA
SANDRAS
TPCA07
TPCAV
WLKC733
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
B
ARI - sum
CEC
ESLPC30
GWT
HBGWL
LUND
LWT2
OGWL
P27
PCACA
PCAXTR
PECZELY
PERRET
PETISCO
SANDRA
SANDRAS
TPCA07
TPCAV
WLKC733
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00

Figure 5.

Although a comparison of circulation classifications based on different evaluation criteria may not lead to a clear-cut ranking of classifications in a sense that one classification appears as a generally superior method, such evaluations and comparisons are a useful tool for characterizing strengths and weaknesses of individual methods and thus help to decide which classification methods are probably the most appropriate for a specific application. With respect to the planned investigations within the framework of the COST 733 Action, such evaluations and comparisons may provide hints towards the development of an optimized classification method.

7. Examples of Classifications and Applications

7.1. Historical Climatology

The development of an improved data set of reconstructed gridded monthly SLP data for the period 1780–1995[97] within the framework of the EU funded research project ADVICE (Annual to Decadal Variability In Climate in Europe) offers the opportunity to expand synoptic climatological analyses well beyond the 20th century. Moreover, as the SLP data were reconstructed using solely station pressure data and thus can be assumed to be independent of surface climate variables (temperature, precipitation), it makes it possible to analyze long-term variations in the relationship between large-scale atmospheric circulation and regional-scale surface climate over time scales that include distinct periods of negligible (later decades of the so-called Little Ice Age) and increased (20th century) anthropogenic global-scale climate forcing.

Beck *et al.*[15] analyzed the low-frequency variability of the importance of frequency and within-type changes of atmospheric circulation types for central European climate variations on the basis of the circulation classification scheme from Ref. 13. Using classification results and mean central European temperature and precipitation time series, both available for more than 200 years, temperature and precipitation changes in central Europe were broken down into frequency changes of circulation types and changes attributable to within-type changes of the circulation types. The "decomposition" was performed for moving 31-year time windows with annual time steps by comparing each 31-year period to its adjacent 31-year periods shifted by 1 year, thereby using the decomposition scheme according to Barry and Perry.[8] This approach resulted in time series of the total, the frequency induced, and within-type related variations in central European temperature and precipitation over the whole 1780–1995 period, as depicted for selected months and variables in Figure 6.

The most remarkable overall finding is that only about 50% of the climatic variations can be explained by varying frequencies of circulation types. The remaining part of variations is from changing within-type characteristics of major circulation types. Percentages of frequency-related and within-type-induced changes not only differ between seasons and climate variables (a substantially higher importance of within-type variability is observed during summer and for precipitation) but also vary on decadal to multidecadal time scales (Fig. 7), the latter pointing to nonstationarities in circulation–climate relationships, which are relevant for the application of downscaling approaches.

←

Adjusted Rand Indices (ARI) between selected circulation classifications available from the COST733 inventory of circulation classifications (see Table 4), derived for the (A) winter [December, January, February (DJF)] and (B) summer [June, July, August (JJA)] season, respectively. Higher ARI values denote a higher degree of similarity between classifications (maximum attainable ARI is 1.0).

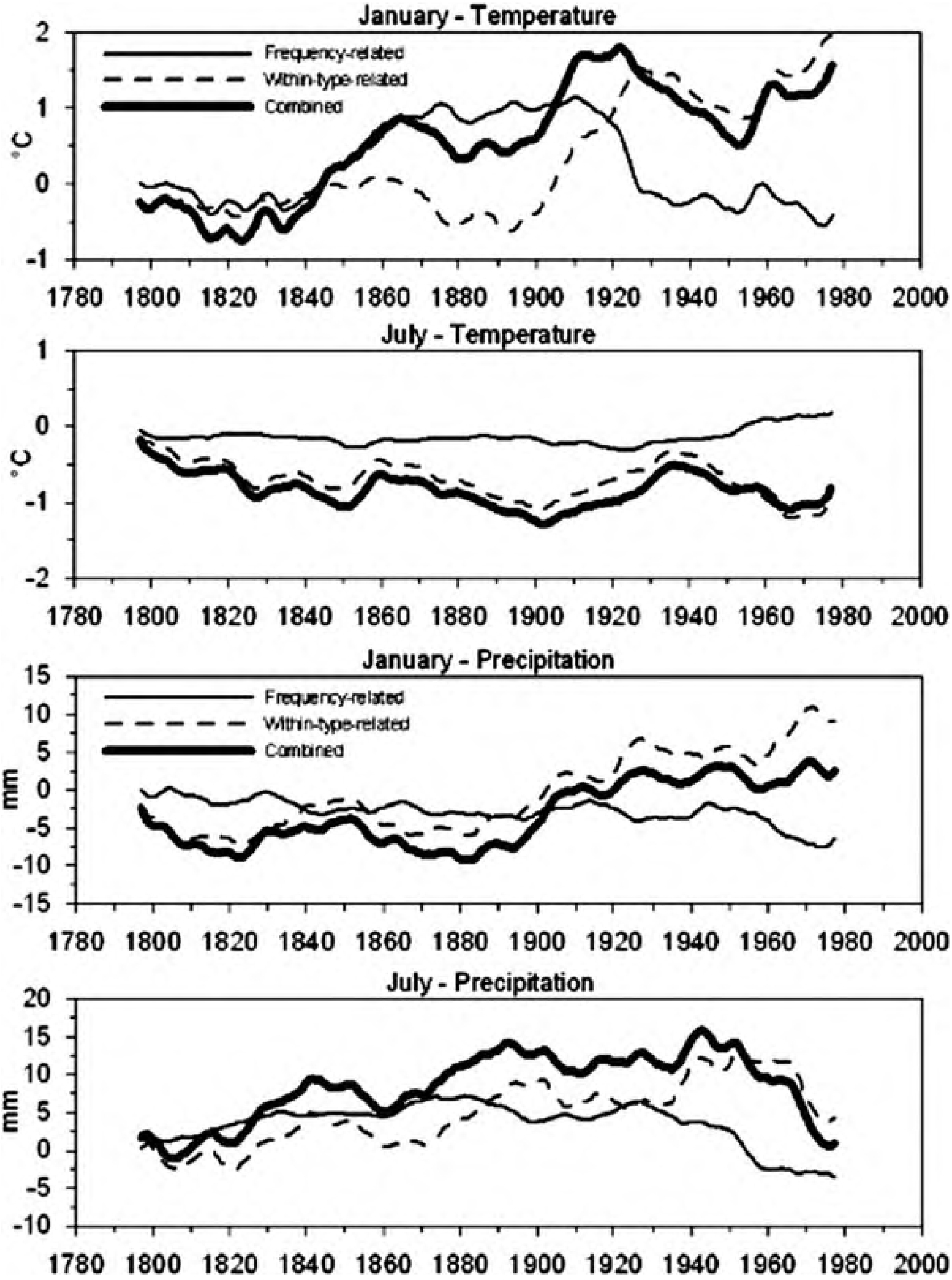

Figure 6. Time series of cumulated central European January and July temperature (*upper two panels*) and precipitation (*lower two panels*) differences between consecutive moving 31-year periods. Time series within each panel reflect changes from frequency changes (*solid*) and within-type related changes (*dashed*) of 18 North Atlantic–European circulation types as well as the combined variations (*bold*) in the 1780–1995 period.

The fractions of long-term climate variations originating from within-type climatic changes can at least be partly attributed to variations in dynamical properties (pressure gradients, vorticity) of these types. For example, within-type climatic changes of the zonal westerly circulation type, substantially contributing to an increase in central European January

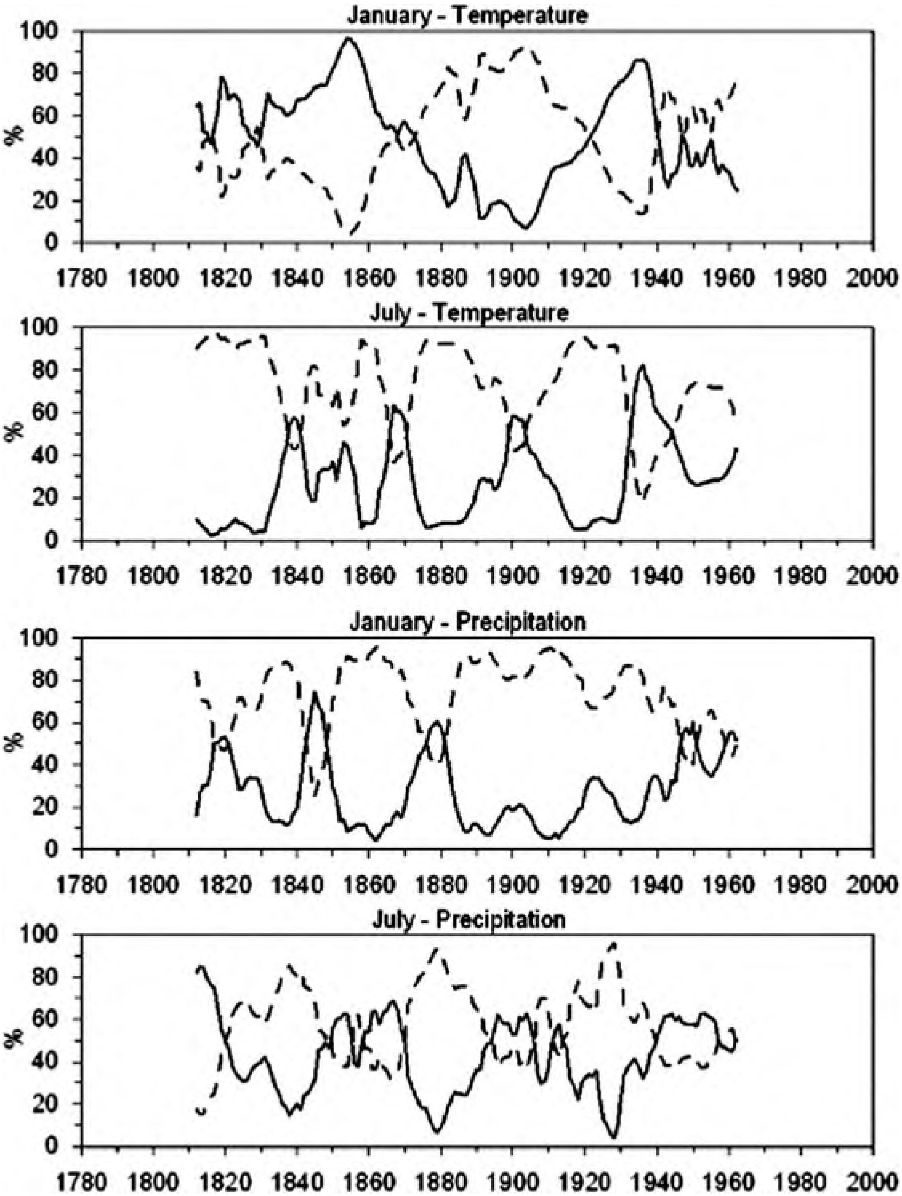

Figure 7. Time series of percentages of central European January and July temperature (*upper two panels*) and precipitation (*lower two panels*) differences between consecutive 31-year periods that can be attributed to frequency changes (*solid*) and within-type changes (*dashed*) of 18 North Atlantic–European circulation types.

temperature and precipitation from the late 19th to the early 20th century, can be attributed to the increasing meridional pressure gradient and increasing vorticity (see Fig. 8). However, the unexplained part of within-type climatic variations may be attributed to insufficiencies of the reconstructed SLP data and the classification approach, concerning, for example, spatial and temporal resolution, and also to variations in climatic boundary conditions modifying climate characteristics of the circulation types.

In the course of examination of historical circulation variability, the development of a gridded SLP reconstruction data set for

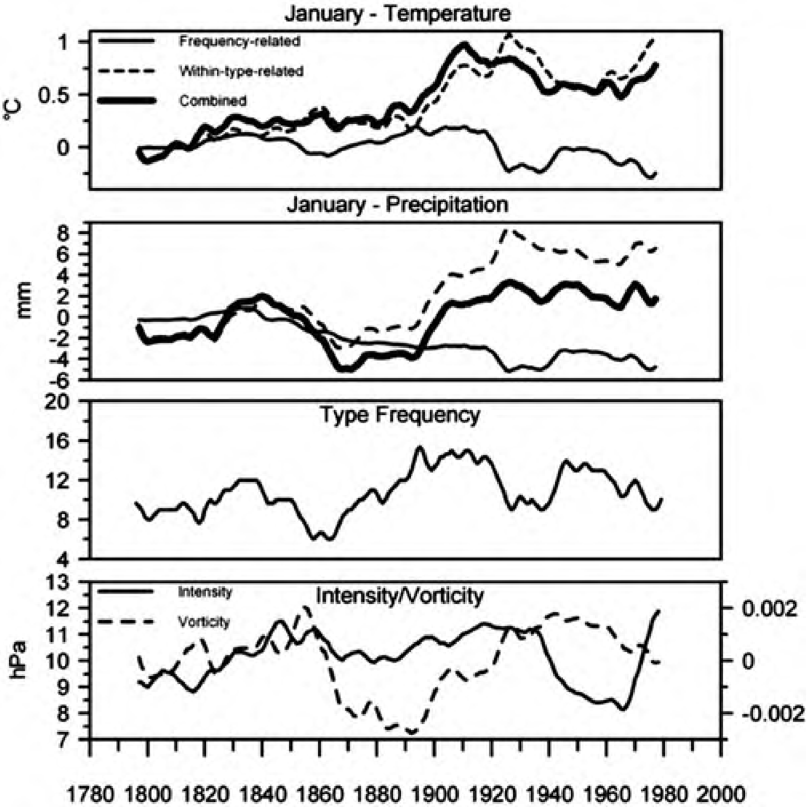

Figure 8. *Upper two panels*: Time series of cumulated central European January temperature and precipitation differences between consecutive moving 31-year periods; as in Figure 6 but for the zonal westerly type, W. *Lower two panels*: Time series (31-year running means) of the frequency and within-type characteristics (intensity, meridional pressure gradient between the North Atlantic pressure centers; vorticity, estimated over central Europe) of type W.

the European and North Atlantic domain on a daily basis back to 1850[3] was an important milestone. Within the EU-funded project EMULATE (European and North Atlantic Daily to Multidecadal Climate Variability), detailed studies on circulation changes covered in this data set were undertaken, making intensive use of circulation-type classification.

The conventional k-means clustering was found to be unstable; therefore, an enhanced clustering algorithm was developed using Simulated ANnealing and Diversified RAndomisation (SANDRA), which is much more stable, especially for large data sets (see also Section 3.3.3.; for details refer to Ref. 150). In contrast to classifications of recent circulation data (see next subsection), data reconstruction errors have to be considered. For the EMULATE reconstruction, the confidence on reconstruction quality is given by the RSOI (Reduced-Space Optimal Interpolation) error. Therefore, the original data were weighted (besides applying latitude weights) by the reconstruction-error weights, which results in putting more emphasis on western and central Europe. The classification scheme was applied to 12 2-month and four 3-month seasons separately with different numbers of clusters ranging between five (in summer) and 11 (in spring).

Screening for significant circulation changes showed that significant trends in interannual variability of the cluster frequencies between 1850 and 2003 can be observed in all seasons.

In winter a remarkable result is that a significant overall increase in the frequency of westerly patterns is manifested mainly for a pattern describing cyclones north of the British Isles (Figs. 9 middle panel and 10 middle panel), while a NAO-like circulation type, which has been increasing in frequency since 1985, also showed high frequencies in the relatively cold period between 1850 and 1870 (Figs. 9 top panel and 10 top panel). This means that there is no significant increasing trend in frequency for the positive NAO state over the whole $1\frac{1}{2}$-century-long period, contrary to what was assumed before, e.g., Ref. 78. At the same time a significant decrease in frequency of continental cold highs is confirmed for the whole period 1850–2003 (Figs. 9 bottom panel and 10 bottom panel).

Altogether the classification approach shows that changes in the daily circulation-type frequencies have clearly contributed to the long-term warming in Europe. The NAO does not seem to be the only driver of circulation-dependent warming in central Europe but mainly has contributed to the enhanced warming since about 1985.

One feature of the long-term warming in central Europe is the increasing number of extremely warm days in winter, which may be defined as days with the mean daily air temperature above the 95th percentile for the time series constructed by averaging long-term records of 16 stations throughout Germany. While the total number of extremely warm days was 59 within the period 1850–1899 and 60 for 1900–1949, it increased to 117 for 1950–1999. The changing relevance of the NAO-like pattern (cluster 1, Fig. 9 top panel) for these extremely warm winter days in Germany can be seen in Figure 11. While 20.3% of all extremely warm days fall to circulation type 1 in the historical period 1850–1899, this portion increases to 26.7% in 1900–1949 and further to 35.9% in 1950–1999. Also the westerly pattern of cluster 4 (Fig. 9 middle panel) gains percentages of warm days increasing from 9.8% (1850–1949) to 13.0% (1950–1999). In the same time cluster 5, a strong Scandinavian low (not shown) showed much more extremely warm days in historical times (27.1% in 1850–1899) than it did recently (12.8% in 1950–1999). The reason for the latter seems to be a slight change in the shape of this circulation type, while the increasing incidence of warm days for the former two clusters (1 and 4) might be more a hint of warming independent of circulation-type frequency changes. This means that even on the daily scale, there is a considerable amount of within-type variability.

All in all, circulation-type frequency on the daily scale can explain at least about 60% of winter temperature variability in central Europe,[150] which is around 10% more than that reached with classifications of monthly circulation fields (see above). But the fraction of explained variance might still be increased (reaching over 70% for continental regions) if a pattern sequence classification is used.[149]

Thus the exact contribution of changes in atmospheric circulation to the observed climate change in historical times is still an open question, but circulation-type classifications have been proven to be a useful tool to narrow down the lack of knowledge and therefore are subject to ongoing improvements. However, the data quality for the early instrumental period, even if remarkable advances in reconstructions are made, is still limited. More reliable conclusions are possible when using more recent data of a higher quality, which is discussed in the following section.

7.2. Recent Climate Variability

In research on recent climate variations, the utility of circulation classifications is much wider than merely studying changes in the frequencies of types. We bring two examples of such an "advanced" application: In the first, the changes in the lifetime of circulation types are analyzed, together with their possible implications for the severity of temperature extremes; while in the second, the effect of changes in

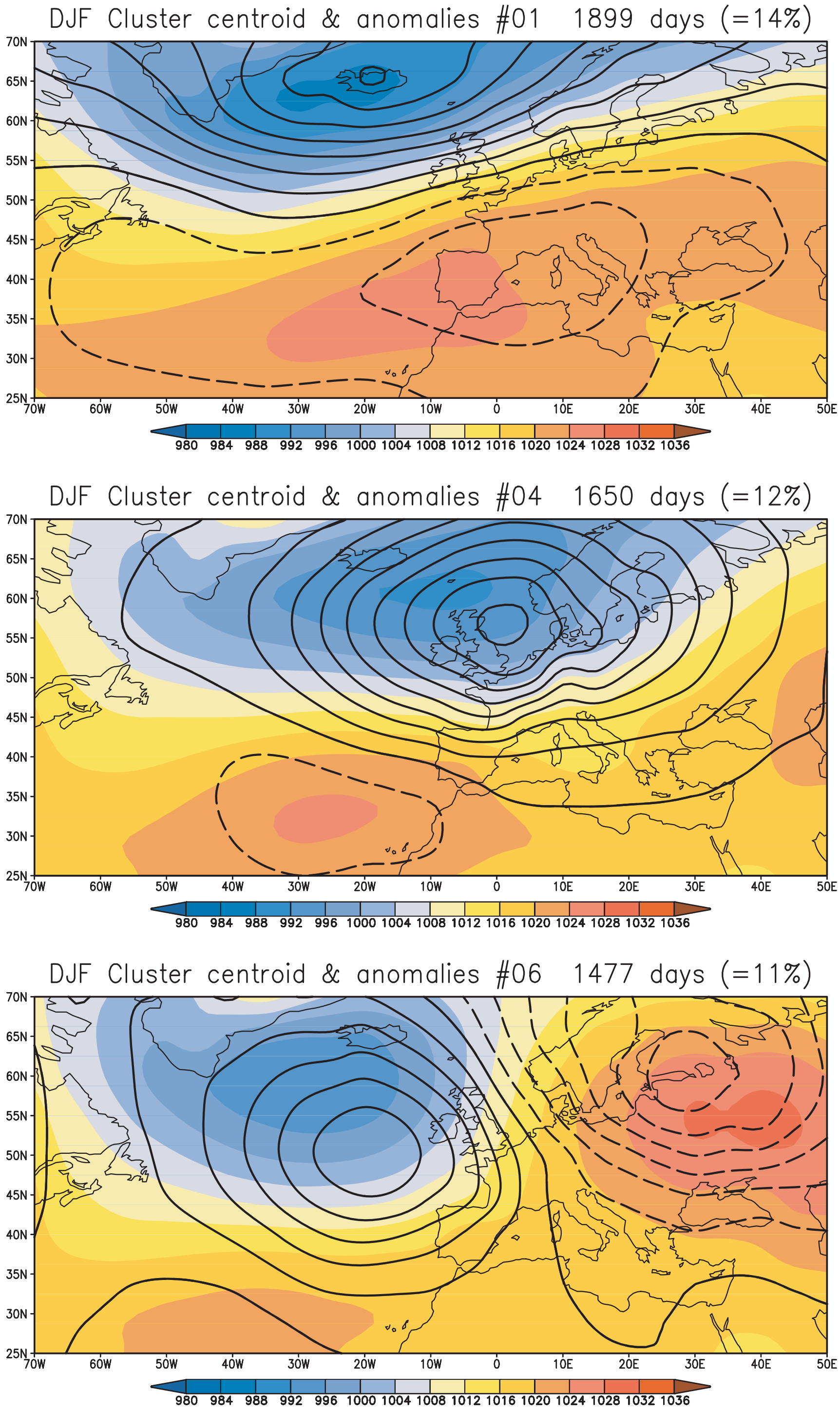

Figure 9. Centroid patterns for three of nine circulation types in winter (DJF) for the period 1851–2003 in the Euro–Atlantic domain obtained by SANDRA cluster analysis (see text) of daily reconstructed sea level pressure (SLP) fields. *Contours* represent the SLP field in hPa while *solid/dashed lines* represent anomalies less than/greater than or equal to the SLP mean for 1850–2003 in DJF (interval 2 hPa). The number of days and percentage of days in the cluster are shown in the header.

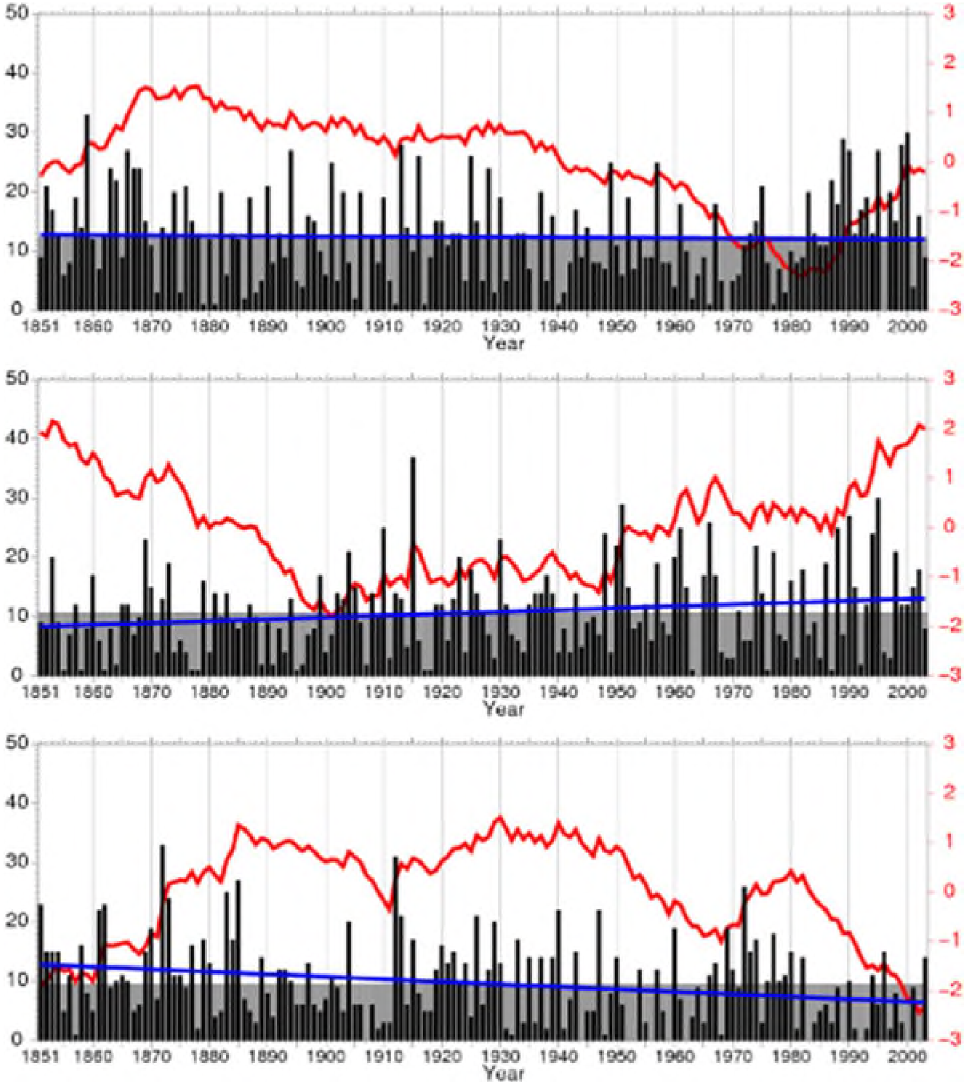

Figure 10. Seasonal frequencies (*bars*), linear trend (*blue line*), and normalized cumulative anomalies (*red line*), for the circulation types shown in Figure 9. The long term mean is indicated in gray. Cumulative anomalies indicate periods of prevailing positive/negative anomalies by sections of line increase/decrease.

the frequency of circulation types on trends in surface climate elements is examined, similarly to the analysis conducted above for the reconstructed data.

The increasing lifetime of circulation types, which would be indicative of increasing persistence of atmospheric circulation in general, was reported for the zonal types in the Hess–Brezowsky catalog in winter[185] and for most groups of its circulation types in summer, particularly for those supporting heat waves.[114] In Ref. 117, persistence was examined separately in individual seasons for 10 groups of Hess–Brezowsky types. The application of the standard normal homogeneity test[2] showed that 67% of the time series of lifetimes have a significant change point during the 1980s, while change points in the century-long period 1881–1980 were detected in 8% of series only. Reference 119 analyzed the lifetime changes for types in the Hess–Brezowsky catalog and in an objective classification based on T-mode PCA over the period from 1958 (Fig. 12). The lifetime of Hess–Brezowsky types increases rapidly from about 1980 and peaks about 1990 in both winter and summer, attaining durations that are about 2 days longer than any time before (since 1881). The objective types also get longer in winter, although the change is not as pronounced as for the Hess–Brezowsky catalog, and the values reached are not far from the high values in the 1960s and 1970s but change their duration very little after 1980 in summer. The difference in the lifetime changes between the Hess–Brezowsky and objective types can have several causes[119]: first, there may be an inhomogeneity in the subjective catalog, although it is stated to be homogeneous[65]; second, the Hess–Brezowsky catalog poses a limitation on the minimum duration of types (3 days), while for the objective one, short events of 1–2 days are typical; third, the objective catalog possesses a large number of unclassified days (about 20% in winter and 35% in summer), contrary to about 1% in Hess–Brezowsky; and fourth, the objective catalog is based solely on 500 hPa heights, whereas Hess–Brezowsky reflects both mid-tropospheric and near-surface circulation characteristics since the 1940s. A marked drop was found in the frequency of events of Hess–Brezowsky types lasting 3 days in the mid 1980s (Fig. 13); this drop is able to explain the enhanced lifetime of all types and seems to be of artificial rather than natural origin.[23] A final word on whether the lifetime of circulation types has increased since 1980 may be provided in the near future by analogous analyses planned within the frame of the COST733 Action, for which a large number of all kinds

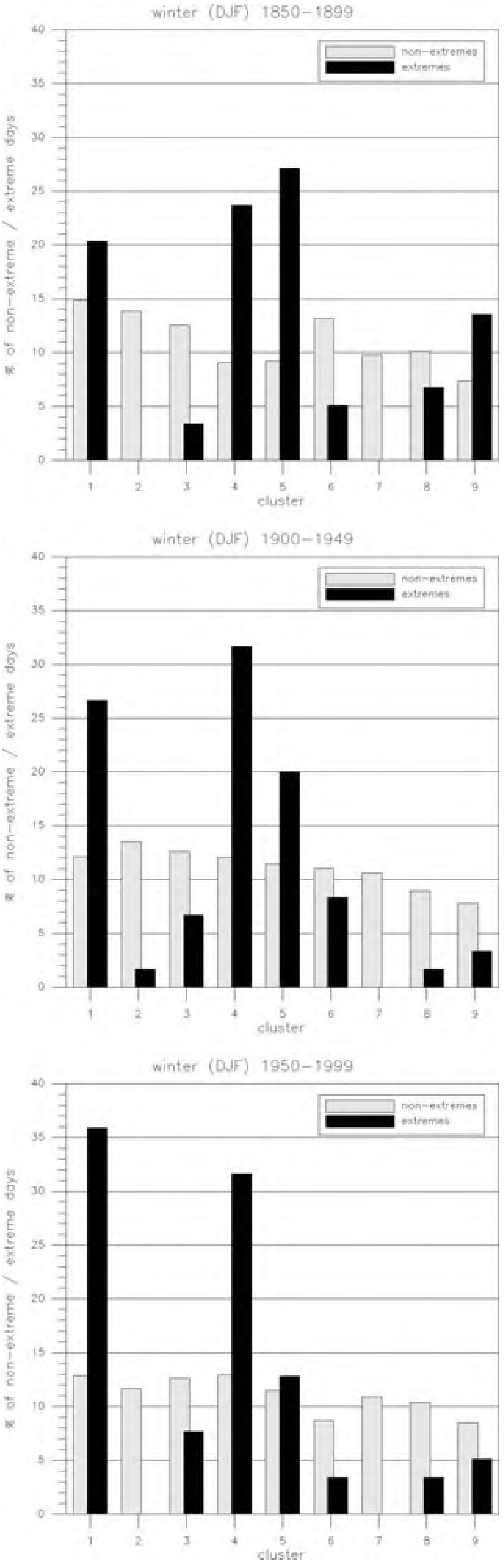

Figure 11. Relative frequency of days with nonextreme (gray bars) and extremely high (T-mean > 95th percentile; black bars) temperature in Germany for circulation types (nine clusters) in winter (DJF) for 50 year periods since 1850. The frequency is given in percent of the nonextreme and extreme days, respectively. The 95th percentile of the T-mean was calculated for the mean temperature time series of 16 stations in Germany with records back to 1850.

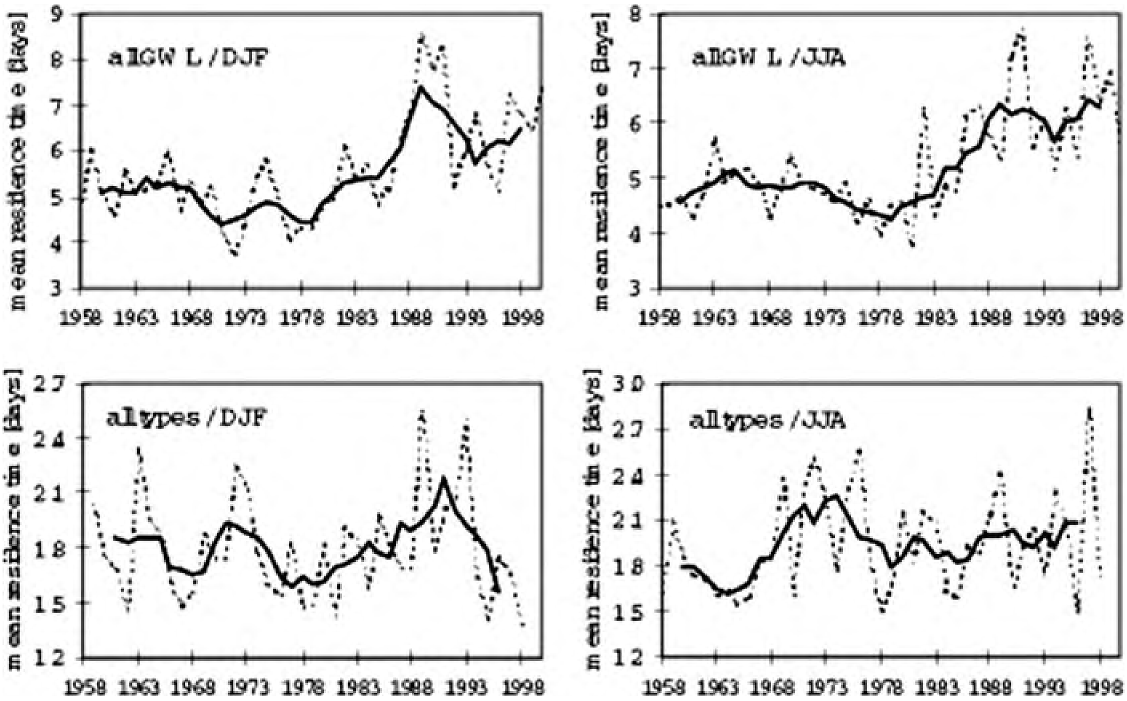

Figure 12. *Dashed line* shows temporal changes in the mean lifetime averaged over all circulation types in winter (*left*) and summer (*right*) for the Hess–Brezowsky types (*top*) and the objectively defined types (*bottom*). *Solid line* shows 5-year running means.

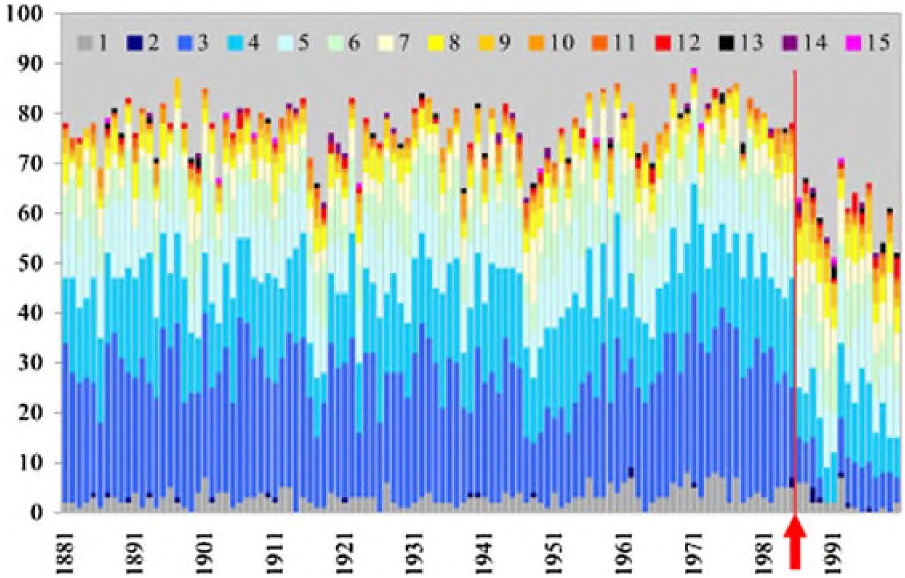

Figure 13. Annual numbers of events of Hess–Brezowsky types with respect to their lifetime (in days). The *vertical red line* and *red arrow* indicate the drop in the number of situations lasting 3 days between 1985 and 1986.

of classifications over several European regions will be available.

An enhanced persistence of atmospheric circulation appears to contribute to the severity of extreme temperature events of both signs.[115,116] Here we present results for the influence of Hess–Brezowsky types and their lifetime on summer heat waves over Europe. In line with Ref. 115, we characterize the relation between the types and the incidence of heat waves at each station by the efficiency coefficient, calculated as the ratio of the occurrence of the type under heat waves to the climatological occurrence of the type in summer. If the efficiency coefficient is significantly larger than one (the significance being determined by a block resampling procedure; for details see Ref. 115), then the type is considered as conducive to heat waves. The effect of persistence is evaluated by calculating the difference in mean temperature anomalies between the first 5 days of an event with a single type and the rest of the event. Figure 14 shows the effect of several Hess–Brezowsky types and their persistence on heat waves, full dots indicating where persistence contributes to the severity of heat waves. The figures confirm that there are two main causes of the formation of heat waves: warm advection (as in southerly types SWZ and SEA and southern areas for easterly type HFA; for the definitions of the types, see caption to Fig. 14) and anticyclonic conditions (as in types with central European high, HM and BM, northern areas for easterly type HFA, and areas where an anticyclone is effective in westerly type WA). Whereas the persistence of an anticyclone leads to an increase in temperature in the course of its duration, the warm advection does not generally have such an effect. This means that an enhanced severity of heat waves would result from increased lifetimes of situations with stationary anticyclones, where positive radiation balance and air mass stagnation (the absence or reduction of removal of locally heated air, e.g., by passages of atmospheric fronts) act as main physical mechanisms. On the other hand, changes in the lifetime of advective types would not tend to affect the severity of heat waves. A generalization of the effects of the lifetime of warm circulation types on the heat wave severity is provided in Figure 15. Here, the difference in temperature anomalies between the end of the circulation-type event (day 6 to last day) and the first 5 days, averaged over all warm types (defined as the types with a mean temperature anomaly in summer exceeding +1°C), is shown for each station. The temperature increase during the lifetime of warm circulation types is clearly observed; the difference ranges from +0.4°C to +1.5°C, with most values around +1.0°C, and does not seem to be geographically consistent. This is probably because the sets of warm circulation types differ between stations and so does the course of mean temperature during their events.

The question on whether atmospheric circulation is or is not an important driver of recently observed climate changes is becoming more frequently posed in scientific literature. Several recent studies examined the impact of changes in the frequency of circulation types on trends in surface climate elements. In this type of study, conditional mean values of climatic elements are calculated for circulation types, their trends (which imply that the circulation changes are the only source of the long-term changes) are evaluated, and these “hypothetical” trends are compared to the observed ones, e.g., Refs. 84, 106, 121. Changes in the frequency of circulation types were found to contribute to spring drying in Portugal,[38] drought in Spain,[183] and a dramatic precipitation decrease in southwestern Australia.[76] The studies based on reconstructed circulation data are discussed in the previous subsection and are not mentioned here.

The effects of atmospheric circulation changes on climate trends in the Czech Republic (located in central Europe) were analyzed using the Hess–Brezowsky catalog for 11 climate variables: daily mean, minimum and maximum temperature, precipitation amount and occurrence, relative humidity, cloudiness, sunshine duration, zonal and meridional wind

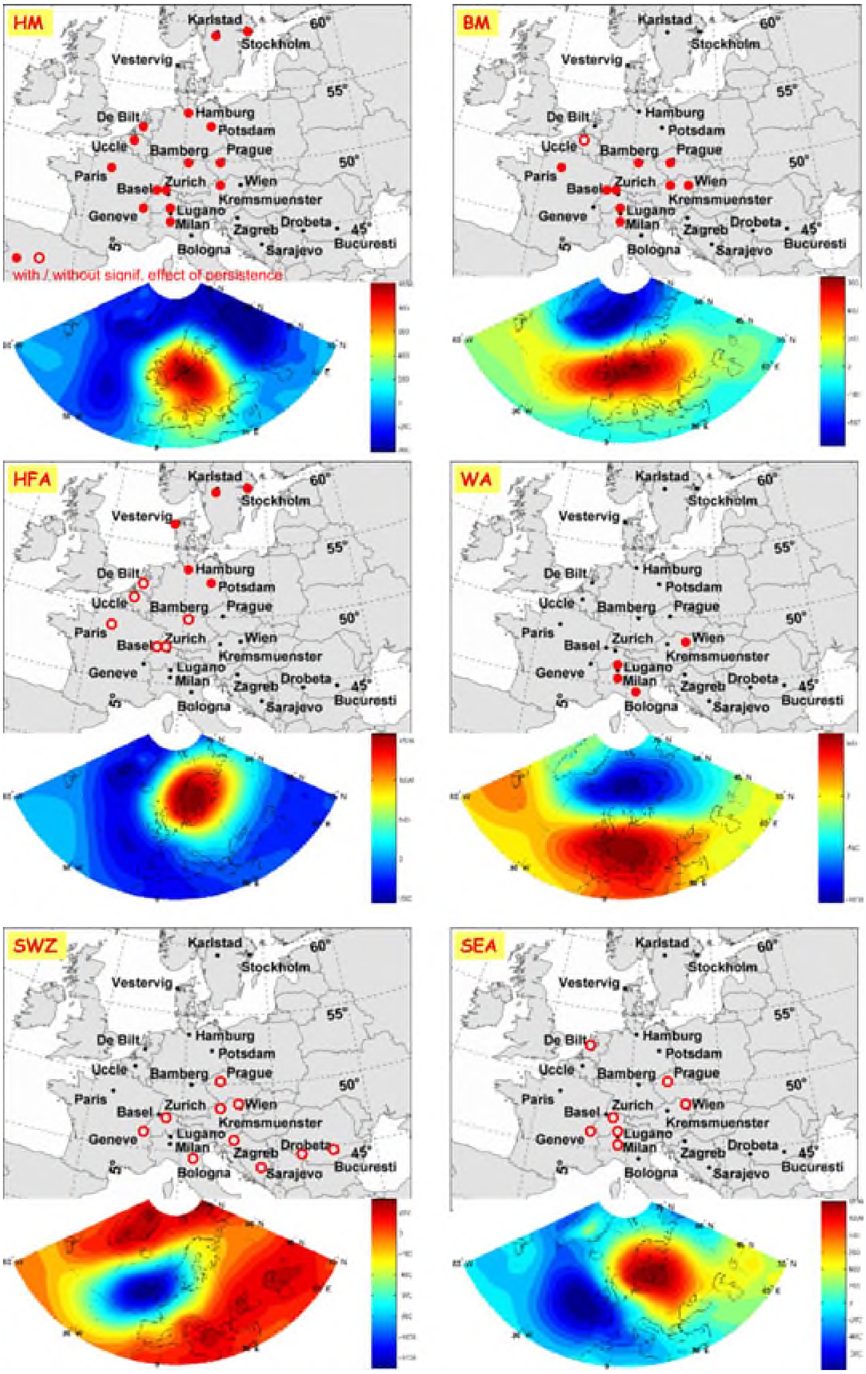

Figure 14. Large maps show effect of selected Hess–Brezowsky types on heat waves in Europe. Full and empty circles indicate where the circulation type is conducive to the heat wave occurrence; full circles indicate that temperature at the end (6th to last day) of the event of the type is significantly higher than in the first 5 days. Small maps show mean SLP anomalies of the types over the Euro–Atlantic region (taken from Ref. 30). The types selected for display are: central European high (HM), central European ridge (BM), Fennoscandian high anticyclonic (HFA), west anticyclonic (WA), southwest cyclonic (SWZ), and southeast anticyclonic (SEA).

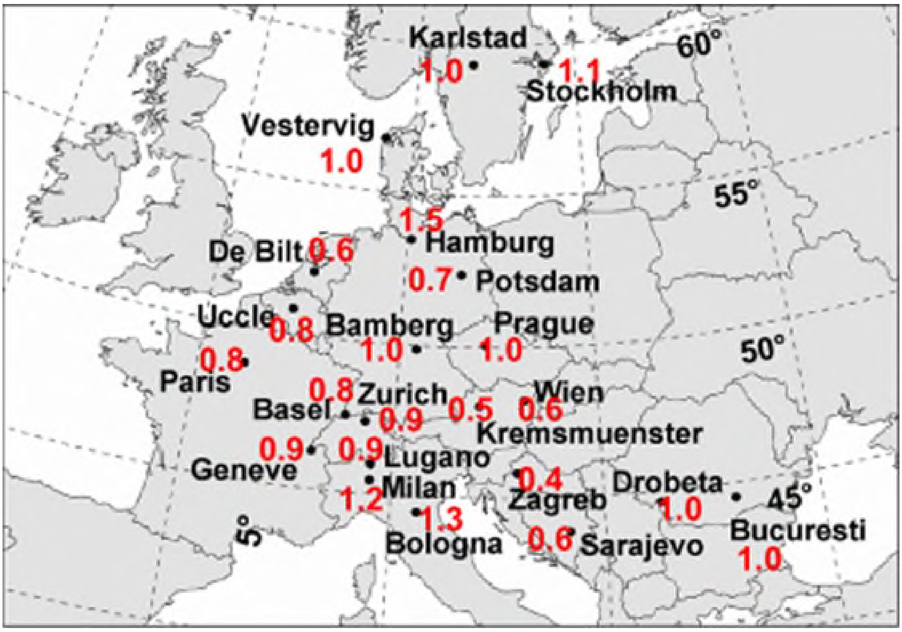

Figure 15. Difference in temperature anomalies (in °C) between the 6th to last day and the first 5 days of events of circulation types, averaged over all types with mean summer anomaly exceeding +1 °C at a particular station. (In color in *Annals* online.)

components, and wind speed. The analysis was conducted at 21 stations for the period 1961–1998. The trends are noted for warming, sunshine duration increases, and decreases in relative humidity and cloudiness in winter, spring, and summer, whereas cooling, shortening of sunshine, and increasing humidity and cloudiness took place in autumn (Fig. 16). The "hypothetical" trends, reflecting only changes in the frequency of Hess–Brezowsky types, were calculated for all variables at all stations and divided by the actual trends. The more this ratio approaches one, the more long-term circulation changes affect the trend in the particular surface element. Negative values of the ratio indicate that circulation changes act in the direction opposite to the observed changes. Figure 17 shows the ratio between the "hypothetical" and observed trends for the cases when the observed trend was significantly different from zero at the 5% level. Changes in the frequency of Hess–Brezowsky circulation types explain about half of the temperature trends and non-negligible portions of relative humidity, cloudiness, and sunshine duration trends in winter. In spring, circulation changes are partially effective in explaining trends in relative humidity, cloudiness, and sunshine duration, whereas for temperature variables, the share of explained trends is about 20% and less. In summer, circulation trends have a fairly negligible contribution to surface climate trends. In autumn, circulation explains considerable amounts of cooling trends (up to 50%) as well as the trends in precipitation occurrence, cloudiness, and sunshine duration. Note also that the ratio of trend explained by circulation changes has a large spread across stations for precipitation occurrence and wind speed. For precipitation amount and wind components, the number of stations with significant trends is very low and no conclusions can be made for them. Another subjective synoptic catalog was used for comparison in Ref. 23—the catalog of the former Czechoslovak Hydrometeorological Institute, named after its main author J. Brádka.

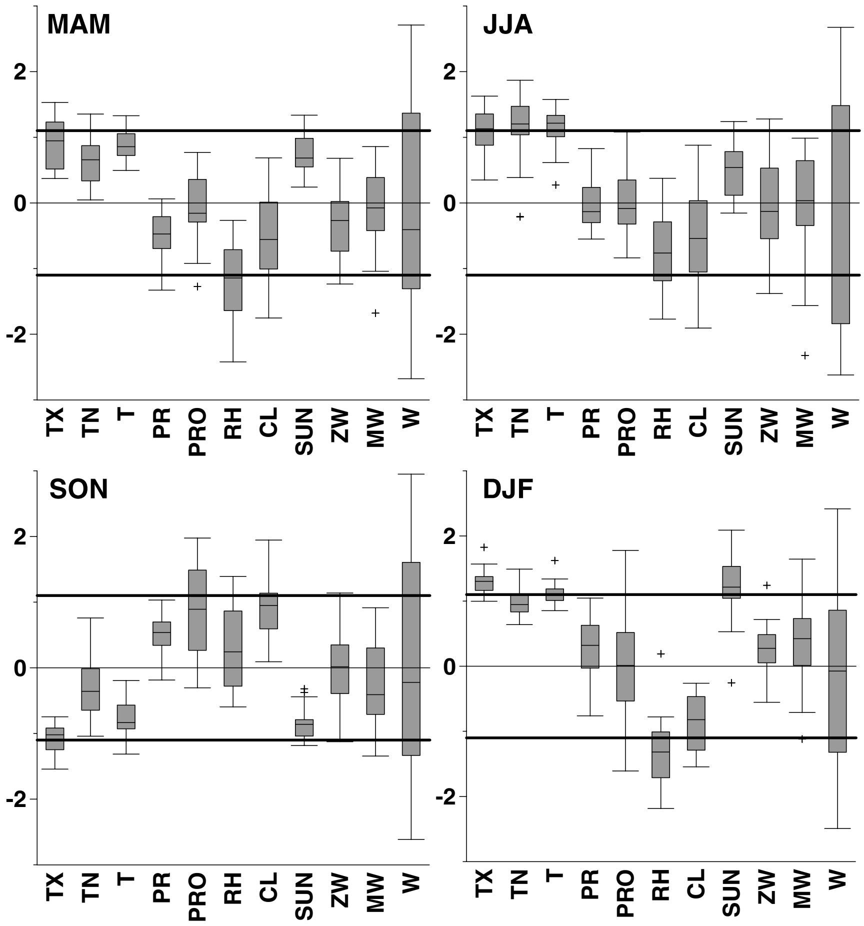

Figure 16. Box-whisker plots of seasonal trends in climatic elements at 21 stations in the Czech Republic during 1961–1998, normalized by standard deviation; trends significant at the 95% level are above/below the upper/lower thick horizontal line. The elements are daily maximum (TX) and minimum (TN) temperature, mean daily temperature (T), precipitation amount (PR) and occurrence (PRO), relative humidity (RH), cloudiness (CL), sunshine duration (SUN), zonal (ZW) and meridional (MW) wind components, and wind speed (W).

There are several considerable differences between results from the two catalogs (not shown here): Brádka's catalog indicates no circulation effect on trends, especially for temperature, in spring; circulation counteracting the observed warming in summer; and a considerably larger effect of circulation on autumn cooling and trends in humidity variables. This partial disagreement underlines the necessity to use multiple classifications for this purpose in order to exclude nonclimatic factors from the results.

7.3. Analysis of GCM Outputs

GCMs are important tools for climate simulations and creation of future climate scenarios. It is important that these models be able to properly represent large-scale circulations, and it is also important to know how atmospheric circulation will change in the future. In spite of this, the analyses of circulation types in GCM outputs are not numerous.

There are four approaches to comparing circulation patterns between two climates. The

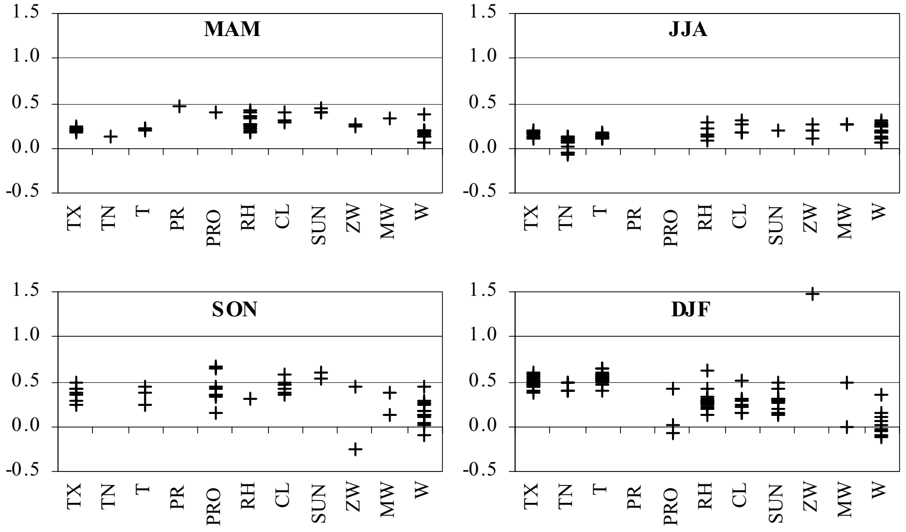

Figure 17. Ratio of "hypothetical" (from changes in the frequency of Hess–Brezowsky circulation types; see text) and observed seasonal trends at stations in the Czech Republic (1961–1998); only the values for the observed trends significantly different from zero are shown. TX, TN, T are maximum, minimum, and mean temperature, respectively; PR, PRO are precipitation amount and occurrence, respectively; RH, relative humidity; CL, cloudiness; SUN, sunshine duration; ZW, MW, W are zonal and meridional wind components and wind speed, respectively. (In color in *Annals* online.)

two climates can be the observed climate and a control GCM run for model validation or a control and perturbed run of a GCM (or alternatively two different time slices of a transient GCM simulation) for assessing future climate changes. The first approach is that the circulation types are determined in each data set separately, e.g., Ref. 41. Although this approach potentially allows the truly dominant types to be identified in either data set, its main disadvantage is implied by the nature of circulation patterns, which do not form distinct classes, and the classifications tend to be unstable. As a result, a comparison of classifications between the two climates may be misleading and may not reflect the real correspondence of circulation patterns. The other approach deals with the definition of the types prior to the classification, independent of the two climates to be compared. Typical examples are mixed methods in which individual patterns are assigned a priori to the types defined: in Refs. 91, 155, the objectivized Hess–Brezowsky catalog is used for this purpose, while in Ref. 162, the types are identified on a shorter period of observations. The potential drawback of this approach is that it may not reflect the real structure in either data set; on the other hand, an easy and fair comparison is secured. In the third approach, the circulation types are determined on one data set and projected onto the other. The projection can be performed in a way specific for each classification procedure, e.g., T-mode PCA,[82,83] nonhierarchical clustering,[110,133] and correlation-based method.[167] In the fourth approach, both data sets are concatenated into one, hence the types are determined simultaneously in both climates. This is a setting typical of the use of SOMs.[27]

We show two examples of analyses of circulation types in GCM outputs. The first one uses the T-mode PCA classification and serves as an illustration of projecting classifications from one data set to another in model validation.

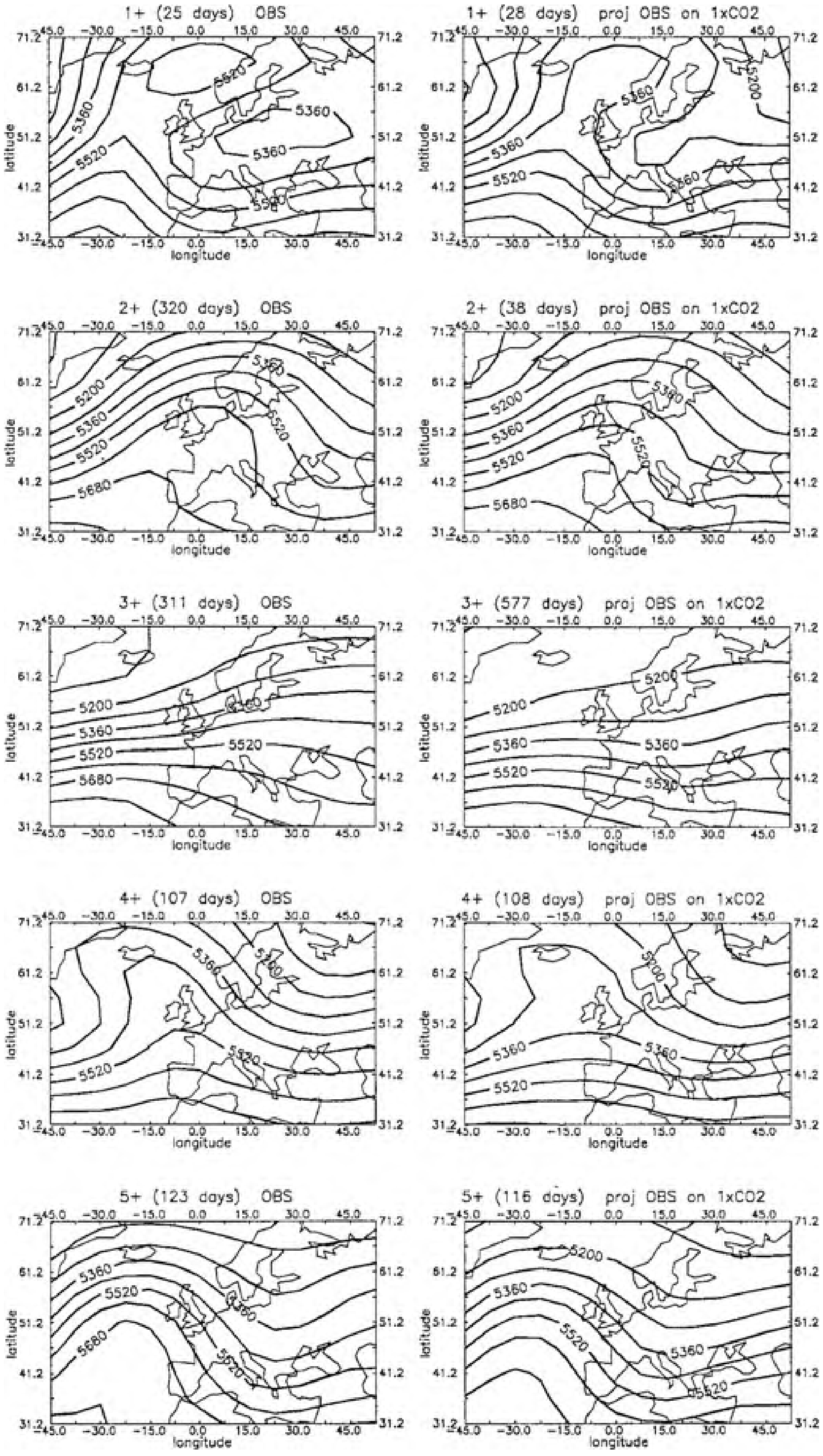

Figure 18. Mean 500-hPa height patterns of circulation types over Europe detected in observed data (*left column*) and their projections onto the United Kingdom Meteorological Office High Resolution (UKHI) global climate model (GCM) control run (*right column*). Each type is indicated by its number and frequency of occurrence (*in parentheses*). Contour labels are in meters; contour interval is 80 m.

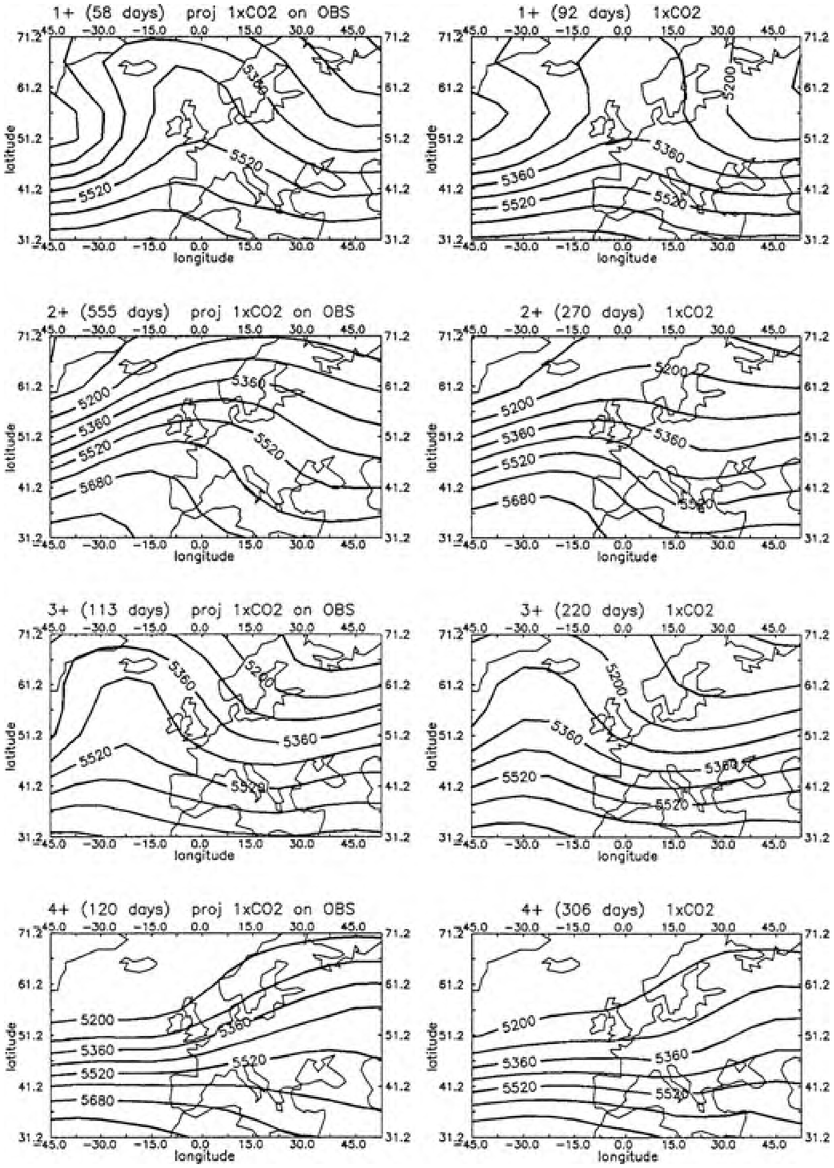

Figure 19. Mean 500-hPa height patterns of circulation types over Europe detected in the UKHI GCM control run (*right column*) and their projections onto the observations (*left column*); otherwise as in Figure 18.

The second example makes use of the objectivized Lamb classification, hence being an example of circulation types defined prior to the analysis.

The first analysis is used here as an instructive example of how the projection works for the T-mode PCA classification; it is based on the study from 1997[82] and therefore uses the GCM that is obsolete from the present point of view. Circulation types are determined in 10 winters (December to February) of 500 hPa height fields over the Euro–Atlantic domain in the observations and in the control run of the UKHI (United Kingdom Meteorological Office High Resolution GCM) (for more details on the data sets as well as procedures, the reader is referred to Ref. 82). First, the classification is developed on the observed data, with five

TABLE 5. Correspondence between the Observed and Simulated Frequencies of Circulation Types during the 1961–2000 Period is Described by χ^2 Statistics

	Year	Season	Month	Mean monthly bias (in days per month)
Dec	$0.55 \times 10^{-3**}$	0.20	0.33	0.91
Jan			0.98	0.65
Feb			0.60	0.90
Mar		0.25	0.82	0.59
Apr			0.62	0.68
May			$4.6 \times 10^{-2**}$	**1.24**
Jun		$4 \times 10^{-3**}$	0.11	**1.03**
Jul			$5.5 \times 10^{-2**}$	**1.26**
Aug			0.28	**1.02**
Sep		0.42	0.19	**1.01**
Oct			0.77	0.45
Nov			0.49	0.79

Values below 0.1 indicate the rejection of the hypothesis that ECHAM5 global climate model (GCM) is a good approximation of observations (i.e., both populations are significantly different) at the 5% level and are marked by two asterisks. Mean monthly bias presents the differences in monthly frequencies (days per month) averaged over all years for all types (ECHAM5 minus observations). Boldface indicates months excluded from further analysis because of low correspondence between the model and observations.

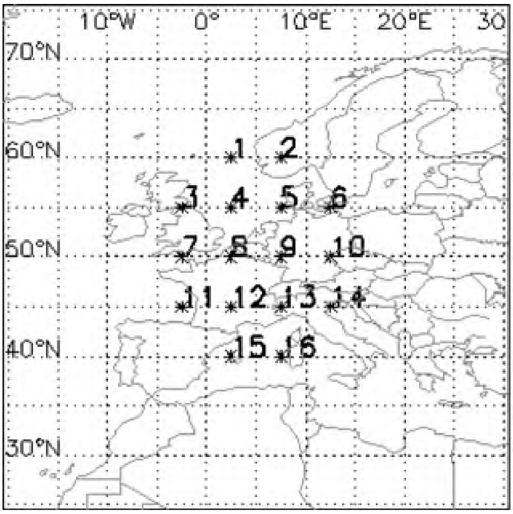

Figure 20. Location of the Jenkinson–Collison method grid points, covering western and central Europe.

resulting types, and then projected on the control GCM run (Fig. 18). One can see that the frequency of the zonal flow is overestimated in the GCM, whereas the number of situations with a zonal flow deflected northward by a ridge over western Europe is severely underestimated. Similarly, the shapes of the patterns, such as ridges and troughs, seem to be weaker in the control run. However, this may be an artifact of the projection methodology rather than a matter of fact. Therefore, another classification was developed on the control run and projected back to the observations (Fig. 19). We can see that the excessive number of westerly flows with a more southerly position in the control run at the expense of those more northerly positioned (i.e., a southward shift of the storm track in the model) is a real feature. There is also an indication of ridges and troughs being less pronounced in the control run (especially for type 1+), but the difference seems to be weaker than for the types based on the observed data set. This tells us that relying only on the projection in one direction (e.g., from observations to the control run) may result in an overestimation of the change in the intensity of ridges and troughs. If no projection were performed and only the original classifications of observations (left column in Fig. 18) and the

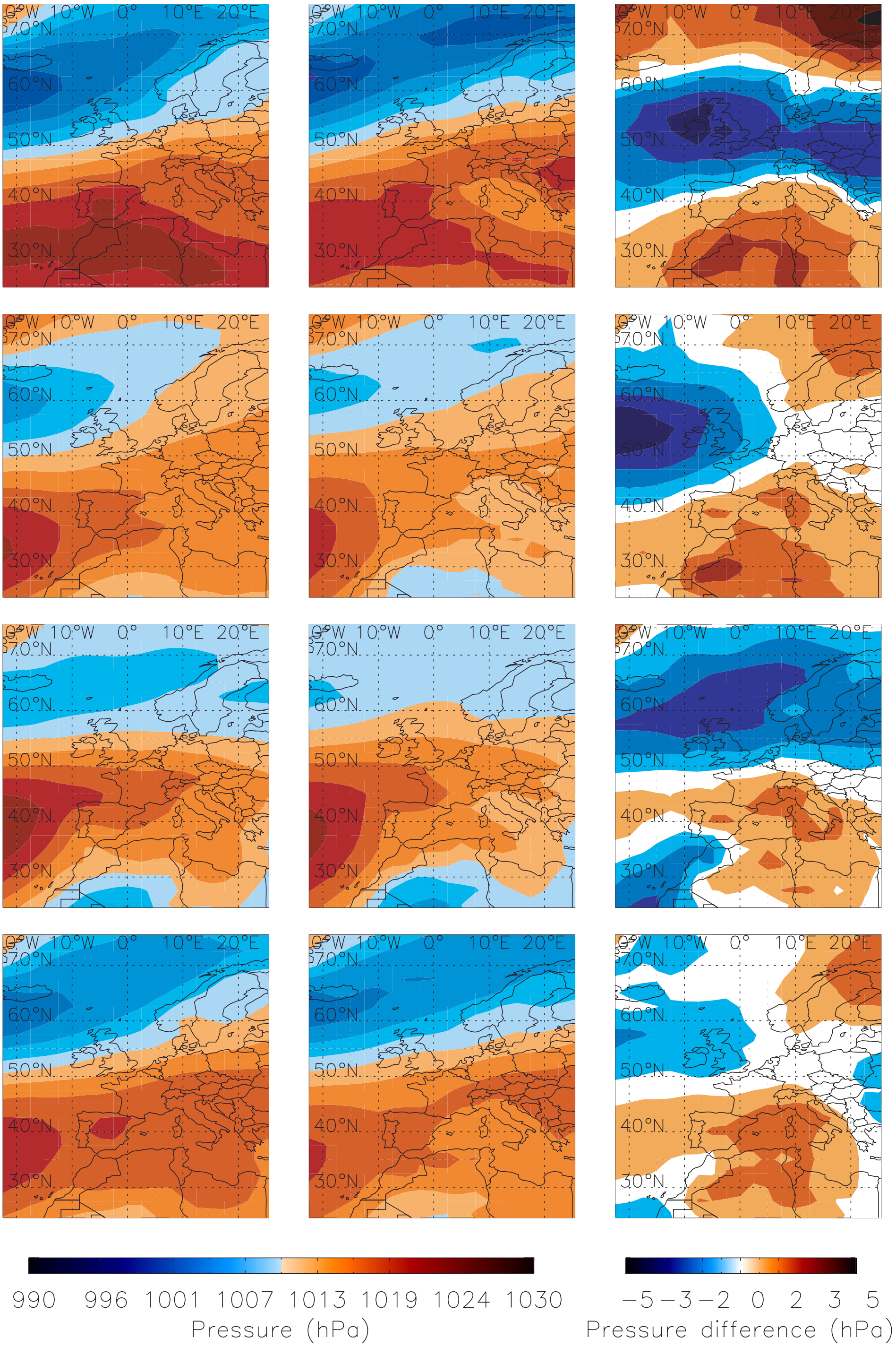

Figure 21. SLP composites (in hPa) for 1961–2000 based on the ECHAM5 GCM (*left column*), ERA-40 reanalysis (*middle column*), and the difference between the two (*right column*), for each season separately (*from top to bottom*: DJF, MAM, JJA, SON).

TABLE 6. Linear Trends in the Frequency of Circulation Types (in Days per 240 Years) and the Associated Mann–Kendall Statistic in the ECHAM5 Integration for the A1B Emission Scenario, 1860–2100, October to April

Type	C	A	N(d)	NE(d)	E(d)	SE(d)
Linear trend	−5.8	2.5	−0.1	−1.1	−4.3	−1.6
Mkprob	0.0001**	0.2522	0.2841	0.0251*	0.0023**	0.1277

Type	S(d)	SW(d)	W(d)	NW(d)	All West	All East
Linear trend	0.2	1.5	11.9	−1.2	12.2	−7.0
Mkprob	0.8780	0.3939	0.0003**	0.0666*	0.0011**	0.0017**

The 90% and 95% significance levels are indicated by one and two asterisks, respectively.

control run (right column in Fig. 19) were compared (i.e., if the first approach to comparing circulation patterns between two climates were employed), one would incorrectly conclude that there are no types with a strong ridge/trough dipole over central and northern Europe (type 1 in Fig. 18) in the GCM run since no such type is identified in Figure 19. However, the projection (right column in Fig. 18) demonstrates that such patterns are present in the control run, even with approximately the same frequency although with somewhat weaker features. Similarly, one could conclude that the GCM does not simulate types with a ridge over Britain (observed type 4), although the projection again tells us that this type is indeed present in the GCM output. This analysis provides a warning that performing separate classifications in the two compared climates is likely to result in wrong conclusions and should be avoided.

In the second example, which is based on Ref. 46, SLP fields from a coupled atmosphere–ocean model [ECHAM5/MPI-OM at T63L31 resolution in the framework of the 4th Intergovernmental Panel on Climate Change (IPCC) assessment report[132,156,157]] are evaluated using ERA-40 reanalysis data for 1961–2000. The trends in the frequency of circulation patterns in the GCM output are investigated for the period 2000–2100. Using the Jenkinson–Collison classification method,[47,95] centered over Belgium (Fig. 20), the circulation patterns for the western and central European region are derived.

To increase the sample size, the original 27 hybrid Jenkinson–Collison weather types are combined into a smaller number of groups according to their directional characteristics. For each month, the mean bias for all circulation types over the 10-year period is calculated. This bias represents the mean difference in the number of occurrence (days) between the control simulation of the ECHAM5 GCM and reality over all directional weather types, calculated for each month separately (Table 5). Biases are largest for May and July (1.24 and 1.26 days, respectively). For all months from May to September, biases exceed 1 day. This value is set as a threshold for a good correspondence; so we can conclude that the GCM satisfactorily reproduces the observed frequencies of circulation types for October to April. The lack of agreement of the GCM output with reality in May to September is because the frequency of especially westerly types is significantly overestimated by the model, while the easterly types are underestimated. This is confirmed by the seasonal SLP composites over the whole period that show cyclonic activity too strong over the northwestern Atlantic Ocean (Fig. 21).

As the trends for the circulation types between 2000 and 2100 using the three IPCC scenarios A1B, B1, and A2 are similar (not shown), circulation trends between 1860 and 2100 are shown here for the A1B scenario, as

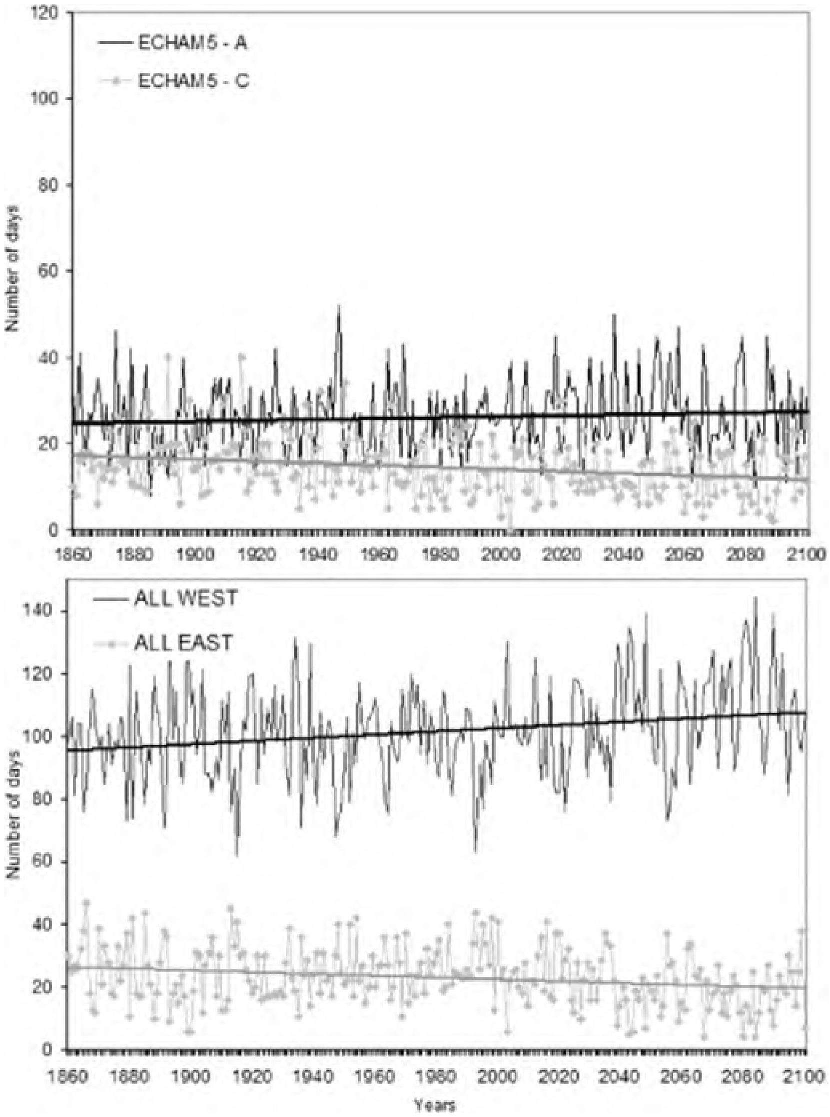

Figure 22. Interannual variations in the frequency of anticyclonic and cyclonic (*top panel, black and gray lines, respectively*), and west and east (*bottom panel, black and gray lines, respectively*) circulation patterns in 1860–2100, from the ECHAM5 run for the A1B emission scenario, October to April. *Straight lines* are linear fits.

a representative, for the October–April period only. The Mann–Kendall test (Table 6) shows that the trends in the frequency of the directional types are in general zero except for a significant increase (decrease) for the westerly (easterly) types (Fig. 22). This suggests that one may expect an increase in the influence of westerly circulation over central Europe during autumn and winter seasons.

In order to increase the use of GCMs in assessments of synoptic conditions in future climates—for downscaling, air quality monitoring, as boundary conditions for regional climate models, and in other applications—one has to ensure that the circulation patterns are simulated well in all seasons. The approach described here provides a rather simple methodology to accomplish this goal.

8. Conclusions

In this paper, recent developments and applications of classifications of circulation patterns are reviewed. We concentrate on the systematization of classification methods, select several recent methodological developments and tendencies in the applications, overview the approaches to comparisons and evaluations of classifications, and discuss three examples of the use of classifications in more detail.

We also introduce the international activity toward the intercomparison and harmonization of classifications, concentrated in the COST733 Action "Harmonisation and Applications of Weather Types Classifications for European Regions." Several of the examples of classifications introduced here suggest that future studies would benefit from analyses based on multiple different catalogs and classifications, mainly in that classifications with spurious or outlying features would be identified, properly analyzed as to their potential inhomogeneities or other drawbacks, and, if necessary, flagged as unsuitable to specific purposes.

The review demonstrates that the field of circulation classifications is evolving rapidly and their applications in climatology and meteorology are becoming more and more numerous. The focus of classifications has changed from a mere description of atmospheric states to a tool for understanding and interpretation of atmospheric processes and modeling the linkage between circulation and surface climate. Circulation classifications will, in the future, certainly continue playing an important role in many areas of atmospheric sciences.

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Conflicts of Interest

The authors declare no conflicts of interest.

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