Quasi-Stationary and Transient Periods in the Northern Hemisphere Circulation Series

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ABSTRACT

In this paper, persistence characteristics of the Northern Hemisphere (NH) extratropical circulation have been studied. A simple method, based on the speed with which the atmosphere moves in the phase space (PSS, measured by 2-day lag distances), was adopted to partition the circulation data series into 5-day or longer quasi-stationary periods (QSP) and alternating transition periods (TP). The method is based on the assumptions that large-scale circulation regimes often develop abruptly and that during their development transient activity is either unchanged or enhanced. The partitioning results reveal that a whole cycle of QSP and TP on the hemisphere has an average duration of 20 days with considerable amount of variability. The average length of a QSP-TP cycle is not sensitive to changes of a relatively wide range in the PSS limit value employed in the method. In this range of limit values, the average length of the cycle changes less than 17%, while the ratio between the length of QSP and TP increases dramatically from 0.73 to 4.42.

The partitioning results are statistically very similar for three complementary sectors of the hemisphere. However, we found very little synchronicity in the changes in the three sectors. The correlation between changes in any of the three sectors and on the whole hemisphere is at a much higher level, around 0.75. Although the length of the cycle on height values at individual grid points is in the range we can expect from a red-noise process, this cycle length is considerably (20%) shorter than that in a larger region or on the whole hemisphere. This is an indication that the persistence characteristics of larger-scale circulation, due to spatial interactions, show more persistence than, and cannot be well modeled by, a simple autoregressive process.

Statistical tests indicate that the hemispheric QSPs are largely temporally uncorrelated and cannot be results of a random partitioning method. All these results suggest that the basic assumption about the regime-like behavior of the atmosphere is at least partially true: large-scale regime changes are indeed accompanied with higher speed of changes in the circulation phase space.

Further evidence is presented that the circulation patterns in the phase space are distributed as a multivariate normal distribution in a phase-average sense (i.e., as a function of distance from the mean). Hence, the characteristic distance between neighboring circulation patterns is smaller close to the climate mean than farther away from it. As a consequence that had to be considered in this study, the day-to-day changes in the circulation (an inverse measure of persistence) are also smaller close to the climate mean. It is also argued that phase-average multnormality is the primary characteristic of the distribution of circulation patterns in the phase space and any secondary characteristic (local density maximum) should be searched for and interpreted in this context.

1. Introduction

In meteorology, as in many other sciences working with time series of different variables, the need for time filtering often arises. Sometimes the filters are applied simply to remove noise associated with the measuring technique. At other times, we want to distinguish changes in the data that are related to different time scales. In either case there are at least two options. The first is to apply Fourier analysis to the original data, after which the variability in certain frequency ranges may be eliminated. This kind of approach is especially convenient when the data are periodic or close to periodic in nature, but is also useful in studying the less regular meteorological series (see, e.g., Barry and Perry 1973). Another and simpler method is to time average the data, which, if applied as a running mean (Burrough 1978), gives equivalent results to those of some Fourier filters. However, for practical purposes the use of non-overlapping time means is common in meteorology. Different lengths of time averages have traditionally been used, such as 90-, 30-, 15-, 10-, or 5-day means. These time means also act as crude time filters. Since in the atmosphere most of the motions are nonperiodic, it is not surprising that these time averages, created strictly by the “calendar,” often mix warm and cold, dry and wet, or, in the circulation field, zonal and meridional flows. The resulting time averages are usually not clear-cut pictures of various aspects of the atmosphere but rather mixtures of those that we would like to see separately. This problem has frequently been
noted (see, e.g., Barry and Perry 1973; Lau 1988; Nakamura and Wallace 1990) and there have been a variety of attempts to overcome it.

Obviously, it is desirable to identify persistent or quasi-stationary periods that exhibit little change in the large-scale circulation. Among a variety of studies is that of Dole and Gordon (1983), who systematically investigated Northern Hemisphere (NH) height values. They identified periods during which the height anomaly at a particular grid point was continuously higher/lower than a predefined positive/negative limit value over a minimum period of 5, 10, or 15 days. Of course, by choice, they did not identify nonanomalous persistent cases that are close to the climate mean. Also, some of their results are dependent on the choice of the parameters in their technique. Oerlemans (1978) introduced a somewhat different and perhaps more general approach to study the persistence characteristics of univariate variables. Instead of focusing on the persistent periods, he identifies the breaks in the time series (and their intensity). He defines an analytical function that broadly represents the typical changes in the series. Then he fitted this function to the data series, point by point, and computed the parameters of the prescribed analytical function that gave the best fit. The series of these parameters then served as indices for quantifying the “break quality” in the original data series. Note that for partitioning the data series here we also need to arbitrarily set a limit value for the break-quality index. Oerlemans’ method was recently applied by Yang and Reinhold (1991) on 500-hPa height values at selected grid points.

Naturally it is always more difficult to study physical systems that require a multivariate approach, such as circulation systems. Among the first objective studies in this area was Horel’s (1985) work on the persistence of the wintertime NH circulation. He defined two criteria for persistence periods. First, the correlation between all the possible pairs of daily maps within a persistent period should exceed a certain limit value (0.5), and second, the period should have a duration of at least 7 (or other predefined number of) days. Horel noted two drawbacks of this technique. First, it does not give a unique solution since persistent periods sometimes overlap and require further subjective inspection. More importantly, the results are sensitive to the choice of the limit values (i.e., pattern correlation and minimum duration) used in the definition of a persistent period.

The purpose of the present paper is to improve the methodology for studying quasi stationarity in circulation time series by reducing the role of some of the undesirable characteristics of previous studies. More specifically, a method is sought to identify different long quasi-stationary periods that would later serve as descriptors of low-frequency, large-scale changes in the hemispheric circulation. Such a method could be considered as a flexible time filter, where the length of the time-averaging period (i.e., length of quasi-stationary periods) would depend on the actual persistence characteristics of the flow.

Identifying the breaks in circulation series just as Oerlemans did for univariate data would be ideal for the aforementioned purpose; however, fitting an analytical break function to multidimensional circulation data is probably impossible. Therefore, the basic method of Oerlemans was changed. Instead of fitting an analytical function and computing its parameters each day, in this study only a 2-day lag (leapfrog) distance is computed as an indicator of the “speed” with which the atmosphere changes in the phase space. This indicator is then used to identify quasi-stationary and transient periods in the atmosphere.

The preceding method is analogous to that used by Vautard and Legras (1988) and especially Vautard (1990). To identify weather regimes in observational data series the latter study searched for quasi-stationary large-scale flows. To achieve that goal a time filter (low-pass filter) and a “phase-space filter” (averaging circulation analogs) were applied on the data. No such filters are applied in the present study since they would be counterproductive in identifying “breaks” in the data series. As a consequence of these changes, local minima in the daily series of phase-space speed (PSS) (and not zero values, as in Vautard 1990) are identified as quasi-stationary periods. These periods of consecutive days with low PSS are used in subsequent studies (Toth 1991a, b) to assess the dimensionality and density characteristics of the hemispheric circulation.

This paper is organized as follows. First we present the characteristics of the dataset used along with the basic distance functions applied to this data (section 2). Section 3 contains the details and further justification of the method used for identifying quasi-stationary periods in circulation data series. In section 4 are presented some results for NH circulation data series. These results were statistically tested to determine whether they are different from a random partitioning. The outcome of the statistical tests and some other applications of the method on regional and on generated random data are also reported in section 4. The conclusions and discussion are found in section 5.

2. Data and distance functions

a. Database

This study uses the twice-daily Northern Hemisphere 700-hPa height series compiled at the National Meteorological Center (NMC). Instead of the original 541-point grid, a 358-point nearly equal-area grid (designed by Barnston and Livezey 1987) was used. This grid covers the Northern Hemisphere poleward of 20°N, excluding some areas over Africa and Eurasia. (When estimating gradients the data over the North Pole were also used.)
Averaging the two analyses each day, daily analyses were created spanning 14 October 1949 through 13 October 1982. Then, after Kirchhofer (1973), each map’s spatial mean height value was removed from all the original gridpoint height values and only the departures from this mean value (which we will call anomalies) were kept.\(^1\) If \(z_i\) stands for the height at grid point \(i\) \((i = 1, 358)\) and at time point \(j\) \((j = 1, 12 \ 053)\), then the map anomaly is

\[
a_{i,j} = z_{i,j} - \frac{1}{358} \sum_{i=1}^{358} z_{i,j}. \tag{1}
\]

b. Circulation similarity measures

As in any other circulation study, we need to define a distance function that measures the similarity of two circulation maps. Based on earlier results (Toth 1991c) we chose the differences in gradient of height (DGH) as a distance function:

\[
\text{DGH}_{i,j} = \frac{1}{358} \sum_{i=1}^{358} \left[ (\Delta_x a_{i,j} - \Delta_x a_{i,j})^2 + (\Delta_y a_{i,j} - \Delta_y a_{i,j})^2 \right]^{1/2} \tag{2}
\]

where \(\Delta_x a_{i,j}\) is the zonal and \(\Delta_y a_{i,j}\) is the meridional gradient of the height field, estimated from the height values. DGH gives results quite similar to what would be obtained if root-mean-square (rms) values of wind differences were evaluated. This measure, a close analog for the rms vector error used at the National Meteorological Center (NMC) for model verification, performed considerably better than other distance functions in earlier experiments.

All the results that follow, except where noted otherwise, are with DGH. However, most of the experiments were checked using root-mean-square difference (RMSD) as a similarity measure:

\[
\text{RMSD}_{i,j} = \left[ \frac{1}{358} \sum_{i=1}^{358} (a_{i,j} - a_{i,j})^2 \right]^{1/2}. \tag{3}
\]

3. Procedure

a. Basic method

After a considerable amount of experimentation, we adapted the following simple procedure for partitioning the extratropical NH circulation data series into alternating quasi-stationary periods (QSP) and transition periods (TP). To determine whether a particular day belongs to a QSP we computed the phase-space speed (PSS) that is the difference (either in DGH or RMSD) between the circulation on the day before and after that day (i.e., the 2-day change centered around the day in question). If 1) this difference was below a limit value and 2) there were at least five such consecutive days in the data series, the day was assigned to a QSP. Otherwise the day was designated as part of a transition period. No limit on the length of TPs was introduced.

Numerous experiments were performed using 1-day, 4-day, and 6-day lag changes instead of 2-day lags. These experiments gave very similar partitioning results, showing that the method is not particularly sensitive to the choice of a particular interval over which PSS is calculated. (A nearly red-noise process would show similar insensitivity.) Of course, changing the minimum length requirement for QSPs (5 days) changes the results in that range, showing that the choice of 5 days is somewhat arbitrary. The use of the 5-day limit for QSPs is justified partly by synoptic experience and partly by our results. When no minimum requirement is introduced for QSPs, the majority of TPs (more than 91% of the cases) are 4 days long or shorter.\(^2\) If a period with small day-to-day changes has a maximum duration in the same, 1–4-day range, we do not consider it as a separate QSP but rather a part of a TP with a temporary drop in PSS.

b. Underlying assumptions

There are two basic assumptions behind the foregoing method. First, it is assumed that changes that result in new large-scale, quasi-persistent patterns are fast, and hence, when they occur, project heavily on 2-day lag differences that serve as a proxy for PSS. The second assumption is that all other changes, especially those in the small scales, have a projection on 2-day lag differences that is smaller over QSPs than it is over TPs (or at least of comparable magnitude).

As to the first assumption, increasing evidence has been presented in the literature that large-scale features develop and disintegrate quite abruptly, at the time scale of baroclinic changes, within a few days. Dole (1989) found that positive or negative persistent height anomalies often fully develop within a week. The analysis of the onset and decay of selected teleconnection patterns by Nakamara and Wallace (1990) indicates a similar time frame. Vautard (1990), in accordance with earlier studies, also found that the onset of blockings is explosive in nature. In Yang and Reindhold’s (1991) study of geopotential height transitions, the most frequent time interval over which large transitions (fol-

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\(^1\) The transfer to map anomalies removes a large part of the seasonal cycle from the data series that is connected to seasonal changes of the average height value over the hemisphere. However, if the same circulation configuration (except a difference in the map average height) occurs in different seasons of the year, they will be found identical in terms of map anomalies but they would not be identical if the whole seasonal cycle had been removed by converting the height values to anomalies from the seasonally changing climate. This advantage of using map anomalies will be utilized in follow up studies; in the present study anomalies from the map mean or from the climate mean would yield basically identical results.

\(^2\) This is true for a 2-day lag limit value that maximizes the number of QSP–TP cycles in the data series.
lowed by quasi persistence) occur is between 5 and 6 days. The long-favored and recently revitalized concept of weather or circulation regime based on similar synoptic experience, namely, that large-scale circulation changes over a region or sometimes over the whole hemisphere occur quite abruptly (e.g., see Reinhold 1987). Interested readers can find further references and theoretical considerations in support of the "rapid-change" assumption in the latter two studies.

As to the second assumption, we are learning more and more about how high-frequency transients interact and influence the low-frequency behavior of the atmosphere (e.g., see Hoskins et al. 1983; Andrews 1990). By no means could we contradict our second assumption and say that the high-frequency variability is suppressed during regime transitions. Evidence is accumulating that at least in certain cases and in certain regions, the transients play a major role in forming or triggering changes in the large-scale flow (e.g., see Lau 1988; Cai and Van den Dool 1991; and Nakamura and Wallace 1990). Reinhold and Yang (1992) postulate and show examples from a simple model that there are two basic mechanisms through which weather regimes change, and one of these is based on intensifying transients. Although there is considerable evidence supporting our assumptions, only the results of the application of the method will show whether these assumptions are, at least partially, true.

There is another conceptual question to address. It is not about the method, but rather the domain of the data to which it is applied. Namely, is it reasonable to search for QSPs on a hemispheric basis, as opposed to regional studies? This question is related to another question about the existence of recurring hemispheric circulation patterns. If, as studies applying rotated principal component analysis indicate (e.g., Barnston and Livezey 1987), most of the important circulation patterns have a regional character, then there is little reason to study persistence on a hemispheric basis either. But if the opposite is true, as argued, for example, by Molteni et al. (1990), who, using a cluster analysis technique, found that the hemispheric patterns have a major role in the atmospheric circulation, then the choice of a hemispheric domain would be more justified. Since the question about the role of hemispheric patterns is still unsettled, our results on both hemispheric and regional domains can serve as further evidence for or against the case.

c. Refinements

Returning to the technical aspects of the method, there are two points worth mentioning. First, as can be seen from Fig. 1, there is a pronounced seasonal cycle, both in the average value and the variability of the 2-day changes. We estimated the variability for each month and after a spline interpolation, standardized the 2-day change data series. As a result, the variability of the data series became uniform throughout the year. As a next step, the values of the 2-day lag change data series were adjusted so that the resulting new series had uniform seasonal averages. With these changes the 2-day lag change data series do not reflect seasonal changes. It was expected that the use of a single PSS limit value would yield meaningful results in any season and that results from different seasons would be comparable to each other.

However, experiments with the new 2-day change data series revealed another problem. Using a particular PSS limit value, QSPs with time-averaged patterns that were close to the climate mean (generally, with zonal flow prevailing over most of the hemisphere) had considerably longer lifetimes than those farther away from the mean (characterized with large departures from the climatological mean in one or more regions of the hemisphere). The reason for this is that PSS, on the average, is considerably larger far away from the climate mean than close to it (see Fig. 2 for winter cases). The same is true not only for PSS measured over 2-day but also over 1-day, 4-day, or 6-day periods. (It is interesting to note that changes in a simple red noise process also depend on the magnitude of the current anomalies.) To understand this result we turn to Fig. 3, where we show how the characteristic distance between the closest winetime analog circulation patterns increases with the distance of the analogs from the climate mean. As shown in Toth (1991d), this is an indication that the circulation patterns in the phase space are distributed as a multivariate normal distribution in a phase-average sense (i.e., when only one dimension, the distance from the mean is considered without accounting for phase differences). A statistical test comparing the density properties of the circulation data (distances between neighboring circulation patterns in the phase space) to that expected from a multinormal distribution, as a function of distance from the climate
mean, found no significant discrepancy. That means that distances between neighboring circulation patterns, in rms or DGH sense, are larger farther away from the climate mean, thus implying that longer 2-day trajectories and larger PSS values are needed to get from one pattern to another. We argue that when studying the persistence characteristics of the atmosphere, this dependence of PSS on the distance from the climate mean does not represent a real difference in persistence but rather reflects only the statistical properties of the distribution of circulation patterns in the phase space. Consequently, we decided to standardize the data series in this respect, too. This standardization was performed by dividing the 2-day lag change values by their corresponding average value at the distance from the climate mean of the circulation on the center day of the change. For interpolating the average 2-day lag changes in Fig. 2, a spline curve has been used. After this standardization the data series of 2-day changes had an average value and standard deviation of approximately 1.0 without any dependence either on the distance from climate mean or on season.

4. Results

a. Hemispheric QSPs

The preceding partitioning method was first applied to 2-day changes computed for the entire extratropical NH. The PSS limit value for QSPs was set at various levels. As we increased its value, using less and less stringent criteria for quasi stationarity, QSPs became longer and longer while the length of transition periods shrank considerably. As can be seen from Fig. 4, there is a considerable range of limit values where the change in the length of a complete cycle of a QSP and the following TP changes less than 17%. The interesting feature is that despite the small changes in the average length of a QSP-TP cycle in the limit value range shown in Fig. 4, the ratio between the length of QSP and TP changes dramatically from 0.73 to 4.42. What that implies is that the majority of individual QSP-TP cycles are maintained within this range of limit values. The most notable change when we relax the QSP criterion is that some days around each QSP, days that were previously classified as part of a TP, now become part of a QSP. Comparison of these various long QSPs defined with different critical levels reveals that the addition of surrounding days results in very little change in the time-average circulation field. All these indicate that the partitioning method, at least in the presented limit value range, is not very sensitive to the choice of the limit value; it identifies, by and large, the same QSP-TP cycles and, with different critical values, changes only the assignment of peripheral days, leaving the core QS days unchanged. For further studies, we chose a limit value close to that producing the most cycles (i.e., shortest cycle length, 20.0 days). With limit value 1.11 (in standardized DGH units) we get a slightly longer cycle (20.3 days), while the assignment of QSP and TP days becomes, for some practical purposes (circulation classification, to be performed in later studies), more preferable with longer QSPs and with a QSP-TP duration ratio of 2.07. Of course, if we chose a limit value either below 1.05 or above 1.15, a

![Graph showing the dependence of 2-day lag changes on distance from climate](image1)

Fig. 2. Dependence of 2-day lag changes in the NH extratropical wintertime circulation on the circulation pattern's distance from the climate mean.

![Graph showing the dependence of distance from closest neighbor](image2)

Fig. 3. Dependence of the distance between best NH extratropical wintertime analogs on their distance from the climate mean.

![Graph showing the length of stationary and transition periods](image3)

Fig. 4. The length of stationary and transition periods as a function of PSS limit value. For further details, see text.
lot of cycles would not be identified any more, and we would soon get into a range where the limit value completely loses its effectiveness.

To illustrate the strong and weak points of this partitioning method we present the time-average 700-hPa height map anomalies for the first few QSPs found in the dataset using 1.11 as a limit value. If we look at the consecutive maps in Fig. 5, we find some surprisingly good "cuts" along with some other cases where the situation is not so clear. An example for the latter is the case of the first two QSPs. The first, 10-day-long QSP (predominant wavenumber 5 pattern) is, after a 4-day-long TP (not shown), followed by a 7-day QSP (wavenumber 4 pattern) that has quite similar characteristics to the first one on one-half of the hemisphere (west of 45°W), while it is dramatically different on the other half. Whether we consider the two patterns separate QSPs is a question of definition. The problem, of course, is related to the question about the regional or hemispheric character of the circulation itself. An-
other interesting example is the pair of fourth and fifth QSPs (Figs. 5d and 5e). With only a one-day TP separating them, they have remarkably different circulation characteristics (wavenumber 2 and 3 structures, respectively). These QSPs could be used as a good example for the case of quickly changing (but then long lasting) circulation regimes.

In Fig. 6 we present the distribution of the length of QSPs and TP’s with limit value 1.11. We can see that the duration of the majority of QSPs is in the 5–16-day range while TPs are most often 9 days long or shorter.

As discussed earlier, the length of QSPs or TPs is sensitive to the choice of PSS limit value. However, this is not so for the length of complete QSP–TP cycles. Hence, we will now analyze some statistical properties of these objectively identified cycles. Figure 7 shows the duration of whole QSP–TP cycles with limit value 1.11. When compared to the distribution of durations for other limit values (e.g., 1.05 or 1.15, not shown), the only notable difference is that partitioning with 1.11 limit value has more cycles in the 11–15-day duration range. For comparison, similar duration data are shown in Fig. 7 for a red-noise process, with an autocorrelation of 0.3, 0.79, and 0.9. The randomly generated univariate data were processed the same way as the circulation data. The two time-step distances were computed and subjected to the partitioning method, using the same limit in the three cases. It is quite surprising how close the three histograms for the different autocorrelation values are to each other. Note also that the

![Graph showing frequency distribution of QSP and TP lengths with a limit value of 1.11.](image)

**Fig. 6.** Frequency distribution of the length of QSPs and TP’s found with PSS limit value 1.11. Values for 43 days represent all cases with duration equal or longer than 43. Solid bar: QSP; stippled bar: TP.
random experiments have more cycles in the 6–25-day range than the real circulation data have. Consequently, the length of a “QSP–TP” cycle in the random series is shorter (around 16 days). This indicates that when considering more complex persistence characteristics of the hemispheric circulation, it cannot be precisely represented by a simple red-noise process. Apparently the atmosphere has more “memory” than that.

As far as the definition of QSPs and TPs goes, there is nothing to ensure temporal independence between consecutive QSPs. Adjacent QSPs, especially those that are part of short QSP–TP cycles, could show some time dependence as a manifestation of circulation regimes returning after some temporary interruption. However, a subsequent study of the dimensionality of the circulation phase space has required that consecutive hemispheric QSPs be temporally independent. A careful statistical study was performed on the winter half of the dataset. The distances between 290 consecutive QSPs showed some, though not highly significant (not at the 1% level), indication of temporal dependence (see the Appendix of Toth 1991a). It is interesting to note that it is not the short QSPs that contribute most to time dependence, as one would first assume. It is clear from the foregoing that the partitioning method is capable of separating different circulation regimes in time even if they are short lived. Apparently this could not have been achieved with a partitioning method based on purely low-frequency variations.

It should also be mentioned that in a subsequent paper (Toth 1991b) we classified the most frequently and least frequently occurring QSPs, based on their similarity, into preferred and unpreferred circulation types. The duration of QSPs in various preferred circulation types are clearly different, attesting that the partitioning method indeed separates real circulation regimes in the time domain.

b. Statistical tests

The objective of the three statistical tests applied in this section for partitioning results of hemispheric data

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**Fig. 7.** Frequency distribution of the length of QSP–TP cycles in the circulation data series with PSS limit value 1.11 and in generated red-noise process with 0.3, 0.79, and 0.9 autocorrelation values. For further details, see text.
Table 1. Results of a statistical test checking the validity of the null hypothesis that the average DGH distance between the first and last days of each time period is not different for QSPs and TPs. The right column shows the highest significance level at which the null hypothesis can be rejected. An asterisk stands for significance level exceeding 0.01. For further details, see text.

<table>
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<th>Length of period (days)</th>
<th>Average lag distance for</th>
<th>Number of cases</th>
<th>Value of ( u ) statistics</th>
<th>Significance level (%)</th>
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</table>

was to determine whether these results are, in a statistical sense, significantly different from random partitioning. The first test devised is based on the DGH distances between the hemispheric circulation on the first and last day of each QSP and TP. If the partitioning is effective, this distance should be considerably smaller for QSPs than for TPs with the same duration due to the slower rate of change in the large scales over QSPs. Consequently, the null hypothesis is that the differences between the circulation on the first and last day of QSPs and TPs with the same duration are not different. To boost the sample size and increase the reliability of the test, all the distances for durations 5–8 days and 9 days longer were collected into two bins. Then a simple statistical test, for determining whether the two samples' expected value are the same, was applied. The results with different two PSS limit values are shown in Table 1. As for experiments with limit value 1.11, the 5–8-day lag distances for QSPs and TPs are statistically different at the 5% and 10% level for the whole dataset and for the winter half-year (1 October–30 April), respectively. No significant difference was found in summer (1 April–31 October) or for longer periods in any season. However, when using a more stringent persistence criterion (with a limit value of 1.068), all the results, except for longer than 8-day summer periods, are significantly different. Since in the majority of the cases the partitioning with the two different limit values identifies the same cycles (see the previous subsection), the core of the QSPs (even for the longer than 8-day periods with limit value 1.11) and TPs are significantly different in their persistence characteristics. However, it can be also noted that the average difference between QSP and TP lags, listed in Table 1, are usually moderate in an absolute sense.

The other two statistical tests we performed are more global in nature and consider large-scale characteristics of QSPs. Here we examined the distribution of time-average QSPs in the circulation phase space through Monte Carlo tests. Using the distribution of QSP and TP durations found in the circulation data and presented in Fig. 6, 100 partitionings were performed allocating QSPs and alternating TPs randomly to the data series. Then the time-average circulation was determined for all QSPs and TPs by averaging the randomly allocated, consecutive daily circulation patterns. The null hypothesis again is that partitioning with limit value 1.11 is not different from a random partitioning. If the null hypothesis is true, it means that the method will tend to combine consecutive days into the same QSPs randomly, with relatively large day-to-day (or 2-day) lags between them. Let us consider now distances in one particular direction in the phase space, the circulation patterns' distance from the climate mean on the consecutive QSP days. In random partitionings daily circulation patterns that are far away from each

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3 In this standard error test it was assumed that the distribution of QSP and TP lag distances is normal and the standard deviation of the two distributions, \( s_1 \) and \( s_2 \), is known (i.e., that their estimate from the samples has only negligible error). With these assumptions, 

\[
\begin{align*}
\sigma &= m_1 - m_2 \\
&= \left( \frac{\sum s_i}{n_1} + \frac{\sum s_j}{n_2} \right)^{1/2},
\end{align*}
\]

where \( m_1 \) and \( m_2 \) are the estimated means and \( n_1 \) and \( n_2 \) are the sizes of the two samples, respectively, and \( \sigma \) has a standardized normal distribution (e.g., see Bury 1975).

4 These partitionings can be thought of as 100 special permutations. The data series of daily circulation patterns were originally partitioned into \( n \) QSPs and \( n \) alternating TPs, as described in the previous section. A random partitioning was achieved by 1) randomly selecting a QSP (without repetition). If its duration is \( m \) days, then the first/following \( m \) days in the circulation data series will be designated as a QSP. In step 2), a TP is selected from the original series randomly (without repetition) and if its duration is \( m \) days, then that many days, following the previous QSP, will be assigned as a TP. The iterative process continues with step 1 until all the QSPs and TPs are selected from the original series, and hence, the random partitioning is finished.
other and consequently have very different (large and small) distances from the climate mean are often combined into the same QSPs. The time-mean circulation patterns of such random QSPs will often have a distance from the climate mean that is close to the average distance of daily circulation patterns from the climate mean. In other words, all the time-average QSPs will be situated roughly at an average distance (not close or far) from the climate mean (test 2). It also follows, as the QSPs are within a narrow branch in the phase space, that the average distance among QSPs will also be small (test 3). But if the opposite of the null hypothesis is true, namely, that our method separates persistent episodes, then the days grouped together into QSPs would be closer than average to each other. As a consequence, the mean circulation of these real QSPs would have different average distances from the climate mean (some QSPs being close, some far away from the mean). Therefore, the average distance of all QSPs from the climate mean will be larger than in a random case. This is because if we average two sets of mean-square (DGH-type) distances of randomly assigned or real QSPs from the climate mean, the set with a greater variability of distances (real QSPs including close to the climate and far from the climate average patterns) will always have a higher average mean-square–type distance (supposed, as it is in our case, that the average of absolute, i.e., not squared, distances for the two sets are identical). And it also follows that for such well-separated QSPs, the average distance among the periods would be larger than that for randomly chosen QSPs.

The preceding tests were performed on the first three partly overlapping winters (1 October–30 April) and summers (1 April–31 October) of our data series. Comparing the average distance of real QSPs from the climate mean to that of 100 randomly generated QSP sets, test 2 shows that it is highly unlikely that the real QSPs are a result of a random partitioning. The average distance from the climate (ADC), both in winter (64.41) and in summer (70.13), is above the range of the 100 randomly generated average value (64.35 and 70.11, respectively). The same is true for the average distance among (ADA) wintertime QSPs (93.05 vs 92.43, test 3). However, this test was negative for summertime QSPs, indicating no difference from a random partitioning in this respect.

In passing, we can note that comparing ADC and ADA for the real wintertime QSPs gives another way of testing whether the circulation patterns are distributed as a multivariate normal distribution in the phase space, in a phase–average sense. If this is the case, the ratio of ADA and ADC, as in the univariate case, should be around \( \sqrt{2} \). The actual value for 33 winters is 1.4127, which is, according to Monte Carlo experiments, indistinguishable (at any applicable significance level) from values expected from a multinormal sample. This is, after the evidence presented in section 3c, a second circumstantial indication that the gross statistical characteristics of wintertime circulation patterns can be reproduced by a multivariate normal distribution. We note here that the ratio of ADA and ADC for summertime QSPs is considerably different (1.1154), suggesting that these circulation patterns come from a quite different statistical distribution.

### c. Regional applications

Considering the uncertainties about the regional versus hemispheric characteristics of the circulation, the application of the partitioning method to regional data series may be as useful as the hemispheric application. In this section results are reported about a slightly different version of the partitioning method than that described in section 3. In these experiments, the NH was divided into three complementary sectors by longitudes 60°W, 180°, and 60°E. The 4-day lag circulation change series were computed for the three sectors separately. Though no statistical tests were performed, the partitioning results for the three sectors and for the whole hemisphere did not show any major difference. The average length of the QSP–TP cycle in these experiments was 17.9 days for the entire hemisphere and for Asia, 17.4 for America, and 16.8 for the European sector. We also performed the same experiments with height data at a few selected grid points. The average length of QSP–TP cycles for these experiments did not differ too much from each other but they were roughly 20% less than regional or hemispheric results (around 14.9 days). Using the same method, red-noise processes generated with different autocorrelations gave results in the same 14–15-day range. These results confirm and generalize our finding in section 4a. Although the gridpoint height series can be modeled with a simple red-noise process very well, the regional and hemispheric circulation data series, evidently due to the physical interactions, have a more complex structure exhibiting more persistence than expected from a red-noise process.

Given that the results for the three regions and also for the hemisphere are statistically very close to one another, an interesting question arises. Beyond the statistical similarity, do the individual changes in the regions or on the hemisphere also tend to occur at the same time? To answer this question, we compared the 1-day, 2-day, etc., change data series for the different regions to each other. The correlation coefficients for the 1-day lag distances (which are very similar to results with longer lags except those correlation coefficients are generally smaller) are presented in Table 2. Note that since this method, whose special characteristics are not detailed here, created some "fake" QSP–TP cycles, the average length of QSP–TP cycles was roughly 10% less than that with the method discussed in the previous sections. However, the regional studies were performed with this less effective version. Although we know that the average cycle length in these experiments deviates from the most probable values, the intercomparison of these regional experiments does not suffer in any way from this shortcoming.
Table 2. Correlation coefficients between 1-day lag DGH distance series measured on different parts of the hemisphere. Am: 180°–
60°W; Eu: 60°W–60°E; As: 60°E–180°; Hem: the whole extratropical NH. See text for further details.

<table>
<thead>
<tr>
<th></th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hem–Am</td>
<td>0.787</td>
</tr>
<tr>
<td>Hem–Eu</td>
<td>0.729</td>
</tr>
<tr>
<td>Hem–As</td>
<td>0.723</td>
</tr>
<tr>
<td>Am–Eu</td>
<td>0.279</td>
</tr>
<tr>
<td>Am–As</td>
<td>0.321</td>
</tr>
<tr>
<td>Eu–As</td>
<td>0.221</td>
</tr>
<tr>
<td>Am–(Eu + As)</td>
<td>0.390</td>
</tr>
<tr>
<td>Hem–(Eu + As)</td>
<td>0.944</td>
</tr>
</tbody>
</table>

that when computing the coefficient values for Table 2, no information on the direction of changes was considered; only the magnitude of changes, as measured by DGH, was detected. Hence, opposite changes in two regions, such as development of a ridge in one region and a trough in another, if aligned in time, could contribute to a high correlation, too. It is interesting to see in Table 2 that in general, there is not too much relationship between changes in any two sectors of the hemisphere. Only 5%–10% of the variability in one sector can be explained by synchronous changes in another sector. The correlation between changes in one sector and in the rest of the hemisphere is not considerably higher either. This is an indication that the greater part of the changes over the hemisphere is regional in nature (see the examples in section 4a). Changes in any of the sectors and changes on the whole hemisphere are connected much better; the explained variance here is more than 50%, reaching 60% for the east Pacific–American sector. Also, changes over two-thirds of the hemisphere and over the whole hemisphere are very well correlated, with an explained variance close to 90%. These explained variance values are close to what one can expect from the region-to-region correlation values. Those correlations, though low, are far from being zero. Hence, the changes over the different regions are not completely decoupled. In this respect one may say that a smaller part of the processes involve larger areas than any of the three regions; in some cases, the processes may be hemispheric in nature. Another parallel interpretation is that if a major change takes place on a part of the hemisphere, that will have a great effect on the hemispheric picture, too.

5. Conclusions and discussion

In the previous sections a relatively simple method has been proposed to identify and separate quasi-stationary periods (QSPs) and transition periods (TPs) in circulation data series. The speed with which the atmosphere changes over a 2-day-long period in the phase space is measured and if 1) it drops below a certain limit value 2) for at least 5 consecutive days those days are designated as a QSP. All other days are considered part of TPs. The method is based on two assumptions, namely, that 1) large-scale circulation regime changes are relatively fast (compared to the regime's lifetime) and project heavily on the instantaneous phase-space speed (PSS) of the atmosphere and 2) transient activity is either unchanged or enhanced during transition periods. Though there is an increasing amount of supportive evidence for both assumptions, the application of the method itself is considered as a test of the validity of these assumptions. The main findings of this study follow.

1) QSP–TP partitioning results on a hemispheric basis show that the persistence characteristics of the atmosphere have a cyclical behavior. The average length of a QSP–TP cycle is about 20 days. The change of the PSS limit value within a certain range increases the cycle length only moderately (up to 23 days), while within the same range the ratio of QSP and TP length changes dramatically from 0.73 to 4.42 (see Fig. 4).

These results are, of course, sensitive to the 5-day minimum duration requirement for QSPs. However, the small change in the average cycle length and the remarkable change in the ratio of QSP and TP length is strong evidence that the method is not particularly sensitive to the choice of PSS limit value. This advantage of the method is clearly manifested in the fact that the identified number of QSPs and their average circulation pattern do not change considerably when the PSS limit value is changed in the foregoing range. Hence, the emphasis in this paper is on QSP–TP cycles and not isolated QSP events. Another observation from Figs. 6 and 7 is that if we choose to represent the intraseasonal changes of the circulation by fixed-length periods, the length of this period should be somewhere between 10 and 20 days. In this context, the choice of 15-day averages by Maryon and Storey (1985) seems reasonable. Using more than 20 days will often merge different regimes. However, a fixed-length system will always artificially mix some separate regimes while making unnecessary separations at other times.

2) Four statistical tests devised and performed on hemispheric partitioning indicate that, generally, the QSPs previously identified cannot be the results of a random partitioning (where QSPs and TPs would be assigned by chance, see Table 1), and can well represent the large-scale, low-frequency behavior of the atmosphere.

This, along with arguments presented in the previous point, strongly suggests that the assumption about the regimelike behavior of the atmosphere, discussed in section 3b, is at least partially true, especially in winter. If the large-scale regimes did not change rapidly during unchanged or increased transient activity, our method would not give any result other than random partitioning. Also, the positive results of the test on hemi-
spheric data suggest that at least part of the circulation processes are hemispheric in nature.

3) Partitioning the circulation series in three complementary sectors of the hemisphere gives statistically very similar QSP–TP results to the hemispheric application. However, changes in the three sectors are usually not aligned in time; only 5%–10% of the variance in one sector is explained by synchronous changes in another region (see Table 2). Nevertheless, temporal changes in one (two) sectors of the hemisphere account for 50%–60% (90%) of the variance over the whole hemisphere.

The explained variance values of course reflect average conditions over a long period of time. They indicate that the greater part of the time changes over the hemisphere are regional in character. However, a portion of the time changes over the whole (or most of the) hemisphere seem to occur simultaneously. The regional versus hemispheric nature of the circulation apparently needs more attention in future studies. We also note that it is changes in the east Pacific–American sector that have the highest correlation either with changes in other sectors or over the whole hemisphere. This is not surprising in view of teleconnection or rotated principal-component studies. This is just the region where the strongest patterns can be found (see, for example, the Pacific/North American patterns in Wallace and Gutzler 1981 or Barnston and Livezey 1987).

4) Using the partitioning method with height data series from different single grid points, the QSP–TP cycle length decreases roughly 20% as compared to hemispheric experiments. This cycle length is in the range expected from randomly generated red-noise process.

Although the persistence properties of single-gridpoint height series could be well represented by a single autoregressive model, this is not true for larger-scale circulation. Such data have higher persistence than the random data, probably due to spatial interdependence.

5) Two additional statistical tests were performed to see whether the circulation patterns in phase space are distributed multinormally in a phase-average sense. The first test considered the local density characteristics of the phase space as a function of distance from the mean (Fig. 3), while the second test compared the average distance of QSPs from the climate mean (ADC) to the average distance of QSPs from each other (ADA). The tests found no statistically significant discrepancy from phase-average multinormality, thus confirming the results of an earlier investigation (Toth 1991d).

It is necessary to stress again that phase-average multinormality, where density is considered only as a function of distance from the mean, leaves open the possibility that the distribution of circulation patterns is not multinormal in a full sense, when the density is considered in all directions of the phase space. Based on earlier studies (for example, see Cheng and Wallace 1992 and references therein), one may think that the phase space of the atmosphere does not comply with full multinormality. This was found to be true in a separate study (Toth 1991b), despite the demonstrated phase-average multinormality. This is because local density maximum areas in one direction of the phase space are balanced by local density minimum areas in other directions, thus ensuring phase-average multinormality.

The physical significance of phase-average multinormality is that in any finite sample, the distance between neighboring realizations (circulation patterns) is strongly dependent on the distance from the overall mean. This is the primary and most important attribute of distributions characterized by phase-average multinormality, and any local density maxima or minima are embedded in this gross feature and are of only secondary importance. Although earlier studies have neglected the phase-average multinormality of the circulation phase space, there is a wide range of areas where it is important and hence ought to be considered, such as studies of persistence (see Fig. 2), classification of circulation patterns, dimension estimates of the atmosphere, model verification, and analog forecasting (Toth 1991a,b,d).

In conclusion, we argue that the presented method provides a viable alternative way to describe large-scale circulation changes through QSPs. As to the comparison of the results presented here to those from other studies of persistence (e.g., Horel 1985), we stress that we did not follow these studies in establishing any arbitrarily stringent criterion for quasi stationarity. Instead, we let the atmospheric data objectively reveal its QSP–TP cycles by changing the PSS limit value in our method within a certain range. Consequently, our QSPs are, on average, less persistent than, for example, Horel’s cases (but virtually insensitive to the choice of the limit value in identifying QSPs). It was not our aim to determine the most persistent cases but rather separate the relatively persistent periods from the surrounding, relatively quickly changing, periods. Hence, some of our QSPs are more persistent than others, but as a set they offer an effective way of time-average representation of circulation changes, definitely more effective than the widely used fixed-length time averages based on calendar dates. However, as is clear from the discussion of the method’s weak points in section 4a, we do not think the technique based only on a simple measure of phase-space speed (2-day lag distances) is the optimal way of partitioning. Probably a careful combination of information from the large and small scales and from the high- and lower-frequency band would give a better solution. Also, special consideration is needed for the appropriate handling of regional ver-
sus hemispheric processes. Perhaps a generalization of the present method, considering persistence not only as a function of time but also as a function of the three spatial dimensions, would give a more appropriate description of quasi stationarity in the atmosphere.

However, we should not expect much improvement from such refinements of our techniques. This is because the persistence characteristics of the circulation itself, though fluctuating significantly, rarely change dramatically on the time scales (∼5–60 days) concerned here. This somewhat pessimistic conclusion is also well documented by the analysis of large-scale quasi-stationary patterns of Vautard (1990, see his Fig. 4) or the circulation regimes of Cheng and Wallace (1992, see their Fig. 15).

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