# A Possible Explanation of the Observed Persistence of Monthly Mean Circulation Anomalies

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## ABSTRACT

The level of month-to-month persistence of anomalies in the monthly mean atmospheric circulation was determined from a 29-year data set of Northern Hemisphere analyses of 500 mb height, surface pressure and 500–1000 mb thickness. A well-defined annual march is found, with greatest persistence from January to February and from July to August. The minima occur in spring and fall. Expressed in a linear correlation coefficient the largest persistence amounts to no more than 0.3.

A qualitative explanation for the double peak in the annual march was sought in linear theory. The response of a stationary linear atmospheric model to the forcing of an anomalous heat source depends on the properties of the basic state around which the model is linearized. Model runs were made with climatological mean basic states corresponding to all 12 calendar months. In all runs the forcing was kept the same. As climatology changes least from January to February and from July to August, the model response to the constant forcing then is almost 100% persistent. The persistence is low from April to May and from October to November because in these months the basic state changes rather drastically.

Although the maxima in persistence on the monthly time scale in the observed circulation are indeed found in summer and winter, the level of persistence is far below 100%. This can be interpreted as observational evidence of the very large forcing of the time-mean atmosphere by high-frequency transient eddies. The forcing associated with long-lived anomalies in external factors (oceans, snow, etc.) seems to control only a small part of the observed anomalies in the atmospheric circulation.

## 1. Introduction

The persistence of weather and circulation parameters is interesting for several reasons. First of all if the persistence is known to be large at a certain place in a certain season for a certain atmospheric quantity, then an inexpensive method to make a useful forecast is available. Therefore a good empirical knowledge of correlations at various lags and of the occurrence of spells may help the forecaster. Persistence is also interesting for its own sake. The degree of persistence at various time scales, its variation with season and locality, and the difference in persistence of different atmospheric quantities calls for an explanation. The level of persistence tells us something about the memory that the atmosphere exhibits in the weather element under consideration.

In this paper we raise the question why the atmosphere shows some, but not much, persistence at long time scales, such as the monthly time scale. The frictional and radiational damping time scales of the atmosphere are on the order of 10 days. Therefore the intrinsic memory of the atmosphere is certainly not enough to explain much of the observed month-to-month correlation in the atmosphere. For example, Wright (1979) reports that monthly mean rainfall in the central Pacific has a month-to-month linear correlation coefficient of ~0.8. This positive correlation, or persistence of rainfall anomalies, decreases only very slightly with increasing time lag. It is likely that in such cases external factors, such as the oceans, force atmospheric anomalies to exist longer than they would do otherwise.

Some aspects must be emphasized:

1) We are concerned with the persistence of circulation *anomalies.* An anomaly is defined as a deviation from the normal appropriate for the time of the year. One can also say that the anomalies are the unseasonal components of the circulation. Anomalies in the circulation are considered to be a response to anomalous forcing.

2) We consider the *monthly* time scale, which is large compared to that of the dominant eddies but small compared to the time scale of variability of the upper layers of the oceans.

3) We do not investigate here the reason why in an *individual case* atmospheric anomalies are long-lived, for example why a blocking high persists to be at a certain place during a whole season. Throughout this paper, persistence is meant in a statistical sense; it will be used to indicate that the sign of the anomaly of a circulation parameter has an above-normal chance to be repeated in the next month.

4) Persistence of circulation anomalies, the topic of this paper, must be distinguished from persistence of near-surface weather elements such as the monthly mean temperature at 1.5 m above the surface. For

example, van den Dool and Nap (1981) found that month-to-month correlations of monthly mean temperature are large (~0.45) over the North Sea and decrease very rapidly over land with increasing distance to the coast, down to a value of 0.15 typically in the eastern parts of the Netherlands. It is thought to be impossible that such large spatial gradients are caused by properties of the large-scale atmospheric circulation; rather we should think of local inertia effects due to the presence of the North Sea.

The possible influence on the atmospheric circulation of anomalous external factors, such as sea surface temperature (SST), ice and snow cover, and soil moisture content has been discussed by many authors (see, e.g., Namias, 1965). But the forcing by these anomalous external factors may not be the most important part of the net forcing experienced by the monthly mean atmosphere. If external factors were so important as many long-range weather forecasters hope they are, then how can we understand why the time–mean atmosphere is so highly variable, while the anomalies in the external factors themselves are quasi-constant (as far as we know). There are two possible explanations for this apparent inconsistency. The first is that the atmospheric response to an absolutely persistent forcing is not the same in different months. The second is that there could be a great deal of internal forcing, probably due to large-scale transient eddies, which is at best weakly correlated to abnormal external conditions; as a result, the net forcing varies considerably even though external factors remain nearly the same.

In this paper we will compare the level of persistence throughout the year as revealed by the real atmosphere with that of an idealized stationary model of the atmosphere. In Section 2 we describe the month-to-month persistence of the response of this stationary model in a situation of perfectly persistent anomalous forcing. There are variations in response in spite of the non-varying forcing. As a result of the annual cycle in the basic state we find a well-defined annual course in the persistence. In Section 3 we describe the results of a diagnostic study to find the level and annual variation of persistence. We used observations of the real atmosphere over the last 30 years. This period appeared to be sufficient to find a reliable annual course of the persistence in monthly mean flow patterns over the Northern Hemisphere north of 20°N. The results are compared and discussed in Section 4.

## 2. Persistence in a model

In this section we describe the changes of a stationary model atmosphere in successive periods of the year while keeping the forcing fixed. The model that we use here is described by Opsteegh and van den Dool (1980). For the present discussion it suffices to recall that it is a stationary, two-layer, linearized primitive equation model on the Northern Hemisphere. The value of the friction and diffusion coefficients are chosen sufficiently large to suppress the amplitude of resonant waves. In this model the transient eddies are not represented. The equations are linearized with respect to a basic state that consists of a latitude- and height-dependent zonal flow ($U_n$) and latitude-dependent temperature ($T_n$) and static stability ($\sigma_n$) fields. The model computes anomalies in wind, temperature and pressure that arise from anomalous forcing. Because the magnitude and position of the atmospheric anomalies depend on $U_n$, $T_n$ and $\sigma_n$, the response in two successive months is not the same even though we do not change the forcing.

The model can be considered a January model by inserting the observed climatological values of $U_n$, $T_n$ and $\sigma_n$. Via the choice of these climatological ingredients the model becomes month- or season-dependent. The climatological data are averages over the years 1968–73.

In Opsteegh and van den Dool (1980), maps have already been presented demonstrating that the response to a given fixed forcing is, indeed, season-dependent. Here, we investigate in more detail the changes (or the absence of changes) from month to month. For one fixed heat source twelve runs were made. The set of twelve experiments was performed for a heat source at two different latitudes, so a total of 24 model runs was made. In all cases the size of the heated area (degrees of latitude and longitude) and the magnitude of the heating were the same. The size of the heated area is ~23° of latitude and 34° of longitude. In the center of the area the heating is $+10^{-5}$ K s$^{-1}$, which decreases according to a parabolic profile to zero at the corners. The center of the heat source is placed at two latitudes, 13.7°N and 41°N. Because the basic state is independent of longitude, only the latitude of the heat source matters.

We will investigate the similarity of the temperature response (or 400–800 mb thickness) in successive months. The degree of persistence is expressed here as a pattern correlation coefficient:

$$\rho(T^i, T^{i+1}) = \frac{W^{-1}\sum_n w_n T_n^i T_n^{i+1} - W^{-2}(\sum_n w_n T_n^i)(\sum_n w_n T_n^{i+1})}{[(W^{-1}\sum_n w_n T_n^i T_n^i - W^{-2}(\sum_n w_n T_n^i)^2)(W^{-1}\sum_n w_n T_n^{i+1} T_n^{i+1} - W^{-2}(\sum_n w_n T_n^{i+1})^2)]^{1/2}}, \tag{1}$$

where $T$ is the temperature averaged over the 400–800 mb layer, $i$ the number of the month, $n$ an index indicating a grid-point, $W = \sum_n w_n$, and $w_n$ the weight factor for the area represented by the gridpoint. The coefficient is computed for the entire Northern Hemisphere.

In Fig. 1 the pattern correlation coefficients are plotted as a function of the pair of months involved, i.e., the time of the year. From top to bottom we present graphs for the fixed heat source at middle and low latitudes. In general, the correlation from month to month is very high except for some periods in spring and autumn when it is lower. As far as the time of the year of the extremes is concerned the two graphs are surprisingly consistent.

What determines the times of the year of the extremes in Fig. 1? Obviously, when $U_n$, $T_n$ and $\sigma_n$, together defining the basic state, do not change, $\rho(T^i, T^{i+1}) = 1$. To give an example, Fig. 2 displays the climatological annual variation (from top to bottom) in the temperature difference between 30 and 60°N at 800 mb, the value of the zonally averaged zonal wind in the jet at 400 mb, and the latitude of the zero-wind line at 400 mb. The sensitivity of the model to changes in the basic state is rather complex; the solution strongly depends on the strength of the zonal wind, the latitude of the zero wind line ($\approx$30°N), and for lower values of $U_n$ also on $\partial T_n/\partial y$ and $\sigma_n$. Of course, in Fig. 1 all these factors have been taken into account; the model weighs the importance of changes in the basic state. Apparently, January–February and July–August are the times of the year with the smallest relevant changes in the basic state, whereas April and November are characterized by crucial changes in the climatology of the atmosphere.

We conclude that imperfect persistence in the atmosphere does not imply that external factors do not control the circulation. That is, in our numerical experiment we have an atmosphere completely controlled by perfectly known external forces, which has, nevertheless, variability in time. It may very well be that some of the temporal variability of the real atmosphere has the same origin.

The consistency of the two graphs in Fig. 1 indicates that our conclusions are not too sensitive to the choice of the forcing. We feel that any other heat source at 600 mb, arbitrary in shape and intensity, would have produced a variation of persistence throughout the year similar to that in Fig. 1.

## 3. Persistence in the monthly mean atmosphere circulation

In the Introduction we posed the question of how we can understand why a near-constant external "control" results in a highly variable time-mean atmosphere; but how variable is the atmosphere?

Our data base consists of daily maps of the 500 mb height and surface pressure provided by the German Meteorological Service at Offenbach (FRG). These maps, available on tape from 1 January 1949 to 31 July 1977, are represented by values in a 5° × 10° latitude–longitude grid that covers most of the area north of 20°N. Unfortunately, the data coverage is not completely homogeneous in time, and especially at low latitudes, and over the Pacific we have to skip many gridpoints in the following calculations.

We first made monthly (calendar months) mean patterns from January 1949, February 1949, . . . , to July 1977. For each calendar month straightforward computations of normals can be made by averaging over 29 (28) individual maps. As the next step, anomaly maps were prepared by subtracting the

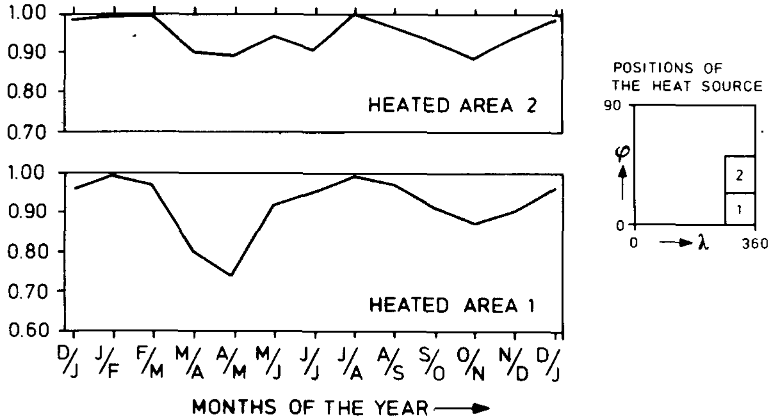

FIG. 1. Month-to-month pattern correlation coefficients of the temperature (400–800 mb thickness) response of a stationary Northern Hemisphere atmospheric model. The forcing is the same in all months and consists of a heat source which is situated at middle (2) and low (1) latitudes, respectively.

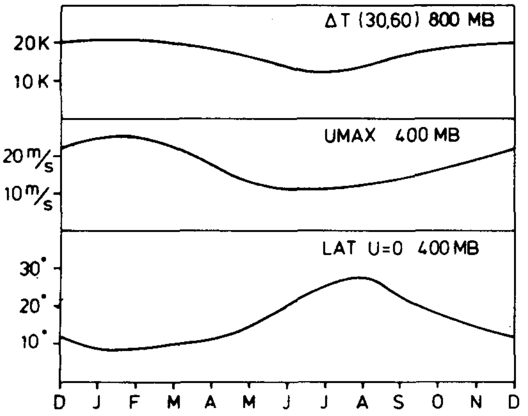

FIG. 2. From top to bottom, the climatological annual course of 1) the zonally averaged temperature difference between 30 and 60°N at 800 mb, 2) the value of the zonally averaged west-east wind in the jet at 400 mb, and 3) the latitude where the transition from easterlies to westerlies takes place. The data are for the years 1968–73 and were provided by Oort.

individual monthly mean from its normal value. We are now in the position of computing a pattern correlation coefficient[1] between anomaly maps of any pair of adjacent months. For the pair January/February, for example, we calculated 29 coefficients for the years 1949–77. Of course the correlation differs widely from year to year and it seems wise to average them over all 29 cases. The result is a climatological value of the correlation coefficient of the atmospheric circulation in adjacent months.

The procedure described above has been applied to the thickness patterns, but for completeness we also give the numbers for the 500 mb height and surface pressure. The results are shown in Fig. 3 and, more extensively, are given in Table 1. From Fig. 3 it becomes evident that there is a small, generally positive month-to-month anomaly correlation in the observed monthly mean atmosphere. On the average, the value of the correlation coefficient amounts to 0.20 for the thickness pattern, and 0.14 and 0.13 for the 500 mb height and surface pressure, respectively. These values differ significantly from zero. The standard deviation of an individual estimate of $\rho$, say $s(\rho)$, seems to be typically 0.25 (for 500 mb height, surface pressure and thickness as well); see Table 1. If $\rho$ is averaged over all 29 years ($\bar{\rho}$) and all 12 months (this yields $\bar{\bar{\rho}}$) then $s(\bar{\bar{\rho}})$ is given by $0.25/(MN)^{1/2}$, where $M$ is the number of independent years (close to 29, say 25) and $N$ is the number of independent months, say 6. Therefore, $s(\bar{\bar{\rho}})$ seems to be at most 0.023. So the average values of 0.13, 0.14 and 0.20 in Table 1 are all highly significant.

Fig. 3 is based on data for the period 1949–77. Namias (1952) used 700 mb heights covering a smaller area, North America and parts of the oceans, for the early period 1932–50. Although for many purposes this set of 700 mb data is out of date, it should be noted that Namias' results are essentially similar to Fig. 3.

Although the values in Fig. 3 are much lower than those in Fig. 1, we note that a similar annual variation is found. Persistence in the observed circulation, although low, reaches maximum values in summer and winter shortly after the solstices, whereas the minima are found in spring and autumn.

## 4. Discussion and conclusions

In this paper we try to explain persistence in the atmospheric circulation at long time scales from persistence in external parameters. From the similarity of Figs. 1 and 3 we conclude that the annual variation in the persistence of the large-scale atmospheric circulation can be reproduced remarkably well with a stationary model in which atmospheric anomalies are considered to be a linear response to the forcing of a constant heat source. Persistence is largest if the basic state of the model (and real) atmosphere changes least—January to February and July to August. Persistence is smallest if the basic state of the model (and real) atmosphere changes most—April to May and October to November.

We may also conclude that just as in the model, part of the anomalies in the real atmosphere are controlled by near-constant forcing. However, we cannot prove at this stage that this near-constant forcing of the real atmosphere is necessarily related to external factors, such as the oceans, but this is more likely to be true than a near-constant forcing related to large-scale transient eddies.

For a correct appreciation of the conclusions, some aspects of the comparison of the model runs with observations must be stressed.

1) In the model runs we assumed that the anomalous forcing does not change at all from one month to the next. However, in reality the persistence of anomalous external factors may be less than 100% and could even show an annual march.

2) In the model runs the basic state is, unlike reality, independent of longitude, nor does it contain meridional and vertical motion. Nevertheless we feel that even the most realistic basic state (i.e., very detailed) changes least, shortly after the solstices.

3) In the model runs the basic state, together with the forcing, determines the response, and unlike reality, there is no feedback of this response on the basic state. As long as the anomalies are small, this omission of the feedback is not serious.

The explanation for persistence in the atmosphere at long time-scales given here relies completely on linear theory. This theory implies that for a given fixed forcing there is only one atmospheric solution.

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[1] The use of the pattern correlation coefficient in an observational study like this has the advantage that it is not sensitive to the presence of long-term spatially uniform trends in the data set. A temporal correlation coefficient determined from gridpoint values suffers seriously from such trends.

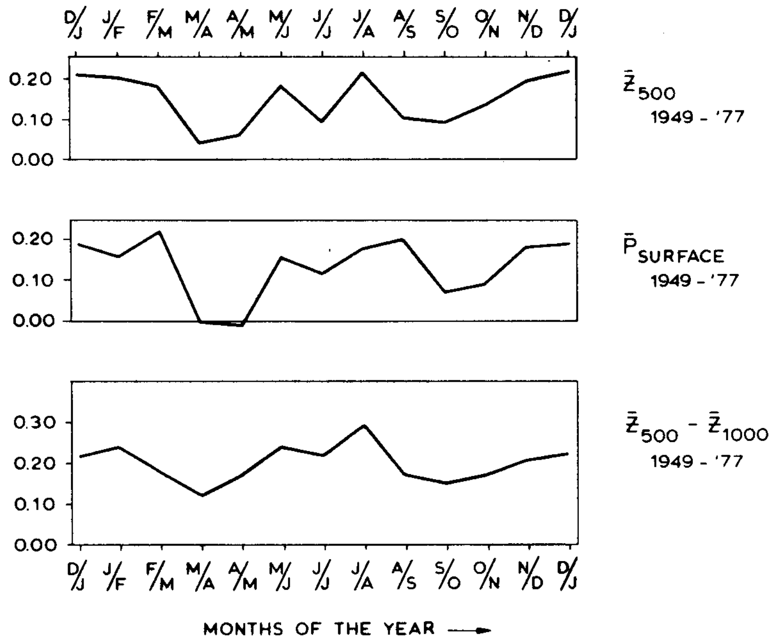

FIG. 3. Month-to-month pattern correlation coefficients of anomalies in observed monthly mean fields of 500 mb height, surface pressure and 500–1000 mb thickness. The observations, analyzed at Offenbach, cover most of the area north of 20°N. The graphs represent averages over 29 (28) individual estimates for the years 1949–77 (76). Further information can be found in Table 1.

If there were more solutions (because of the nonlinearity of the problem) then it would be too simple to state that the atmosphere is partially persistent because the forcing remains quasi-constant. Starting from Charney and Devore (1979), many authors have shown that in increasingly more realistic models multiple equilibria are possible. Nevertheless, it is unknown as yet whether high and low index atmo-

TABLE 1. The month-to-month correlation (%) of anomaly patterns in 1) 500 mb height, 2) surface pressure and 3) thickness. J/F denotes January to February, etc. The correlation is determined for the area north of 20°N. The four rows per item contain the average over 1949–77, the highest and lowest values in the 1949–77 period, and the standard deviation. Finally the number of years is given per pair of months.

| | J/F | F/M | M/A | A/M | M/J | J/J | J/A | A/S | S/O | O/N | N/D | D/J | Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 1) $Z_{500}$ | | | | | | | |
| $\bar{\rho}$ | 20 | 18 | 4 | 6 | 18 | 9 | 21 | 10 | 9 | 13 | 19 | 21 | 14 |
| max | 72 | 53 | 55 | 35 | 64 | 57 | 54 | 45 | 42 | 74 | 57 | 66 | |
| min | −53 | −14 | −39 | −32 | −20 | −17 | −12 | −29 | −42 | −57 | −42 | −56 | |
| $s(\rho)$ | 28 | 20 | 24 | 17 | 20 | 17 | 19 | 20 | 21 | 27 | 24 | 29 | |
| | | | | | | 2) $p_{\text{surface}}$ | | | | | | | |
| $\bar{\rho}$ | 16 | 22 | 0 | −1 | 16 | 12 | 18 | 20 | 7 | 9 | 18 | 19 | 13 |
| max | 62 | 54 | 53 | 49 | 57 | 42 | 63 | 57 | 35 | 43 | 57 | 80 | |
| min | −42 | −25 | −47 | −48 | −40 | −17 | −38 | −21 | −33 | −48 | −38 | −48 | |
| $s(\rho)$ | 29 | 21 | 25 | 20 | 24 | 17 | 25 | 17 | 21 | 21 | 25 | 29 | |
| | | | | | | 3) $Z_{500} - Z_{1000}$ | | | | | | | |
| $\bar{\rho}$ | 24 | 18 | 12 | 17 | 24 | 22 | 30 | 17 | 15 | 17 | 21 | 22 | 20 |
| max | 66 | 55 | 58 | 51 | 60 | 62 | 56 | 50 | 42 | 53 | 67 | 60 | |
| min | −39 | −29 | −23 | −10 | −1 | −10 | −4 | −17 | −25 | −57 | −33 | −31 | |
| $s(\rho)$ | 27 | 22 | 21 | 15 | 17 | 17 | 16 | 18 | 19 | 25 | 25 | 22 | |
| | | | | | | Number of years | | | | | | | |
| | 29 | 29 | 29 | 29 | 29 | 29 | 28 | 28 | 28 | 28 | 28 | 28 | |

spheric circulations should be regarded as multiple equilibria rather than different solutions to different forcings.

In the Introduction we emphasized the distinction between the persistent presence of a pressure anomaly during a particular season and the statistical notion of persistence used in this paper. Blocking highs and cutoff lows appear in all seasons and may occasionally be long-lived even though the month-to-month correlations, according to Fig. 3, are known to be low in that time of the year. It could have been possible, of course, that blocked circulation types appear mainly in January/February and July/August; in that case, Fig. 3 just shows the net effect of many individual cases of long-lived weather systems. However, if we rely on the statistics collected by Rex (1950), blocks both in the Atlantic–European and Pacific sectors appear with a single maximum of occurrence in April. Surprisingly, this is one of the periods in which monthly mean pressure anomalies persist least. Also the level of month-to-month persistence cannot be understood from day-to-day persistence. To quantify this point we assume a first-order Markov process $Y_{j+1} = \rho Y_j + \epsilon_j$, where $Y_j$ is the value of some variable at day $j$, $\rho$ the autocorrelation coefficient at lag 1 day (whatever the cause of that autocorrelation may be) and $\epsilon$ a random number. One can derive, after some manipulations, the autocorrelation coefficient of 30-day mean values at lag 30 days:

$$\rho_{30} = \frac{\rho(1 - \rho^{30})^2}{30(1 - \rho^2) - 2\rho(1 - \rho^{30})}. \tag{2}$$

According to Lorenz (1973), a representative Northern Hemisphere value of the lag 1 day autocorrelation for tropospheric pressure surface heights is 0.75, resulting in a month-to-month value of ~0.07. In Fig. 3 we find values significantly higher than that, indicating that this effect does not explain the observed month-to-month persistence.

We believe that the present results have several implications in the context of long-range predictability of the time-mean circulation. First of all, we note that the level at which atmospheric anomalies are persistent in our model atmosphere is very different from that in the real atmosphere. The maxima in Figs. 1 and 3 are ~1.0 versus 0.3. We attribute this large difference mainly to the anomalous internal forcing by large-scale eddies. It is not unlikely that the eddy forcing varies at random in time on these large time scales. If we add a large random component to the constant forcing in the experiment described in Section 2, then the effect would be to lower the correlations in Fig. 1, but nothing would happen to the annual course. This naturally leads to the conclusion that the eddy forcing of the monthly mean flow must be very large. Assuming the most pessimistic view none of the eddy forcing is known beforehand, and therefore, the difference between Figs. 1 and 3 indicates that monthly means are unpredictable to a very large extent. In terms of explained variance, about 10% ($0.3^2$) is associated with external forcing and is therefore potentially predictable; this leaves 90% of the variance to be interpreted as noise associated with high-frequency transient eddies. Also, the results of Madden (1976) and Manabe and Hahn (1981) indicate that the potentially predictable part of the interannual variance of monthly means of circulation parameters in the midlatitude is on the order of 10%.

A second implication of our results concerns the notorious low skill of long-range forecasts in spring and autumn. In a verification of 10 years of forecasts of monthly mean quantities in northwestern Europe according to seven methods, Nap *et al.* (1981) have found that the skill is restricted mainly to those months in which nature offers us persistence as a gift. Therefore it is hopeful that we have presented evidence here that a lack of persistence is not necessarily identical to a lack of predictability. It seems that the skill of circulation predictions in autumn and spring can be improved by taking into account the changes in the basic state, via a model.

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