An Objective Approach to Breaks in the Weather

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ABSTRACT

An objective approach to breaks in the weather is presented. A simple mathematical procedure is described that makes it possible to detect changes in a time series. The method is based on a comparison of a typical change, prescribed *a priori*, with an interval of a local record of daily temperature, for instance. A break quality is defined as the ratio of the amplitude of the change (computed by a least-squares method) to the corresponding rms difference between the typical and observed change. In this way for each day a break quality may be computed. The real breaks are found by requiring that the break quality have a maximum value with respect to time. Since the break quality is a dimensionless quantity, different weather elements may be compared immediately.

Results are given of a break analysis of daily values of temperature, sunshine and precipitation as observed at De Bilt during the period 1949–74. Daily mean temperature shows the highest break qualities while precipitation hardly shows clear breaks. The correlation between break qualities of different weather elements appears to be small.

The method was also applied to the geopotential height field over the North Atlantic Ocean. The existence of the preferred region of blocking over the northeastern part of the Atlantic is seen very clearly by means of the break analysis.

Finally, some remarks are made concerning the construction of a statistical significance test and some further possibilities of the break analysis are indicated.

1. Introduction

A great deal of the public interest in weather seems to be devoted to *changes* in its character, in particular when these changes take place rapidly. Of course, this is quite natural since changes draw more attention than persistence. A break in the weather that has not been predicted is remembered quite a long time, whereas a series of perfect forecasts during a period of persistent weather does not impress the public. One may argue that a verification method designed *to reflect the public's judgement of the forecasts* should account for the occurrence or non-occurrence of sudden changes. Such a method requires a definition of the "weather break".

Another point that requires investigation of breaks in the weather is the need for some kind of climatology of sudden changes. Questions like "Do periods exist in which drastic changes in temperature occur more frequently?" are heard in agriculture and other fields. Most climatological descriptions give mean values and standard deviations but do not provide information about the occurrence of rapid transitions from one type of weather to another. Probably this is a consequence of the difficulties which arise if one tries to construct a simple objective definition of a break in the weather. Ideas about this subject vary widely among meteorologists and we realize that the approach to be presented in this paper will satisfy only a part of them.

According to the *Glossary of Meteorology* a break is defined as "A sudden change in the weather; usually applied to the end of an extended period of unusually hot, cold, wet or dry weather." In this paper, we will try to translate this statement into a quantitative one, i.e., a so-called break quality will be defined which is obtained by a simple mathematical procedure.

Reports of investigations concerning weather breaks are very sparse. An example of a paper that touches the subject is the detailed study of the occurrence of wet and dry spells in Sweden carried out by Eriksson (1965). Most studies, however, are case studies and do not provide a basis for the present purpose.

A few guidelines were used in the construction of the weather break definition. First, the existence of *two* time scales should be reflected. An important break has to be a transition from one period with persistence to another. The time scales are fixed by the length of these periods and the speed with which the transition occurs. Second, the break should get a higher quality if it is smoother; for example, a break

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from dry to wet weather should get a lower quality if showers occurred during the dry period.

We note that the weather break definition given by the *Glossary of Meteorology* does not imply the appearance of a period with persistent weather after the change. In this study we require that such a period be present, but this is not crucial to the method that will be discussed.

Although the method of analyzing time series presented in this paper was developed to determine breaks in the weather, it may be used to detect sudden changes in *any* time series. Two applications will be discussed—a weather break climatology for De Bilt (The Netherlands) based on surface weather data of the period 1949–74 and an analysis of the 500 mb geopotential height field over the northern Atlantic and western Europe covering the same period. The latter demonstrates the well-known existence of the preferred region of blocking over the northeastern Atlantic from a different point of view.

A disadvantage of the method is the fact that a statistical significance test (e.g., a comparison of two break climatologies) cannot be constructed with existing tests. The alternative is to generate time series with an appropriate stochastic model. This will be discussed shortly.

Finally, an experiment was carried out in which the transition speed was varied. Although the results are very interesting in themselves, the intention of this experiment is simply to show an example of other applications that are possible with the kind of analysis to be discussed in the following section.

2. The method of detecting breaks

The basic idea is to fit a prescribed typical change to a series of observations (temperature, sunshine, etc.). The fitting procedure then should provide a quantity that enables us to decide whether a break occurred or not.

In order to formalize this idea we define a change M by

$$M_i = af_i, \quad \text{where} \quad f_i = \frac{\arctan(\beta i)}{\arctan(\beta n)}. \tag{1}$$

The function f is called the transition function and a the amplitude of the change. Both M and f are discrete functions of the independent variable i which is an integer and runs from $-n$ to n. Note that $f_n = 1$, $f_{-n} = -1$, and that the central point of the change is at $i = 0$. The speed of the change is determined by β. Fig. 1 shows some transition functions for different values of β. If $\beta = 0.01$ we have a trend, $\beta = 0.5$ gives a slow change, and for $\beta = 2$ we may speak of a break. The two time scales mentioned in the Introduction are determined by β and n.

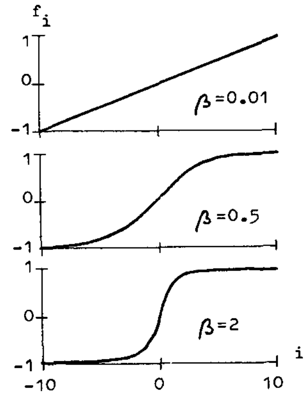

FIG. 1. Three transition functions with $n = 10$: a trend ($\beta = 0.01$), a slow change ($\beta = 0.5$) and a break ($\beta = 2$).

Next, we consider a time series of some weather element, e.g., daily temperature. From this series we choose an interval with $2n + 1$ elements and from each value we subtract the mean value over the interval and denote the resulting series by E_i. A measure of the difference between M and E may be expressed by the quantity

$$h(a) = \frac{1}{2n+1} \sum_{i=-n}^{n} (E_i - af_i)^2. \tag{2}$$

When $h(a)$ is a minimum, the change M fits best to the series E_i in a rms sense, so the amplitude a^* of the change is found by requiring

$$\left.\frac{dh(a)}{da}\right|_{a=a^*} = 0. \tag{3}$$

Differentiating (2) with respect to a and applying (3) yields the normal equation

$$\sum_{i=-n}^{n} (E_i - a^*f_i) = 0, \tag{4}$$

from which the amplitude a^* is easily computed for given β. Substitution of a^* into (2) gives the corresponding value of $h(a^*)$.

The following step is to account for the noise in E with respect to M. Fig. 2 shows two series of

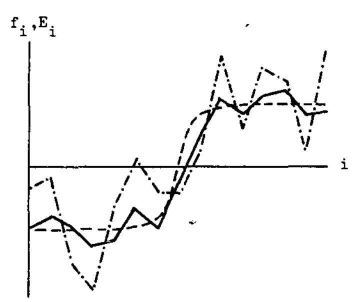

FIG. 2. Two examples of a break: one with large γ (solid line) and one with small γ (dot-dashed line). The transition function is indicated by the dashed line.

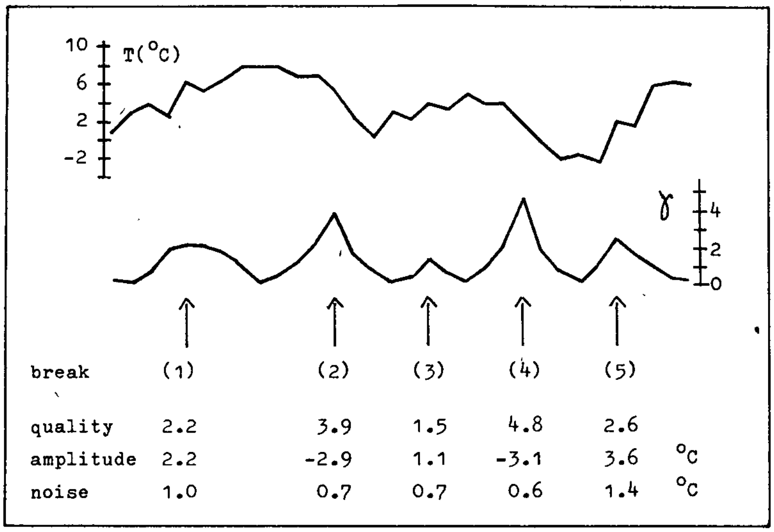

FIG. 3. An example of the output of the break analysis. The upper curve shows a record of daily temperatures; the lower curve gives the computed break qualities. The real breaks are indicated by arrows. At the bottom of the figure, the corresponding values of γ (quality), a^* (amplitude) and $h(a^*)$ (noise) are given.

weather elements having the same a^* but differing highly in character. According to the remarks made in the Introduction, the "quiet" series represents a finer break than the "wild" one. We may account for this difference by defining the break quality γ by

$$\gamma = |a^*|/\sqrt{h(a^*)}. \tag{5}$$

This break quality has some convenient properties. First, it is a *dimensionless* quantity which makes it possible to compare changes in different weather elements *without any scaling*. Second, it accounts for the seasonal cycle of the variance confined in time scales shorter than n. Consequently, it is also possible to compare breaks in different seasons without scaling. Theoretically, γ goes to infinity if the noise approaches zero. In practice, however, this is not a serious drawback. For most time series $h(a^*)$ has a lower boundary, i.e., background noise is always present. Except for very low values of n (say $n < 3$), the correlation between break quality and break amplitude is high. Breaks with large quality and small amplitude appeared to occur so rarely that they do not distort the picture.

For any interval with length $2n + 1$ from the time series considered the break quality may be computed. We denote it by γ_j, where j is the element of the time series that coincides with the central point of the break ($i = 0$). The real breaks in the time series are found by the requirement

$$\gamma_{j-1} < \gamma_j > \gamma_{j+1}, \tag{6}$$

which merely states that γ should reach a relative maximum with respect to time.

Throughout the previous discussion we have assumed that β is fixed *a priori*. One could ask whether it makes sense to minimize h with respect to both a and β. However, in that case difficulties arise since there might be more than one solution to the minimizing problem. Although this does not necessarily imply that the solutions are useless, in this first survey it was decided to simplify the problem by keeping β fixed.

At this point, one could ask whether the analysis technique just presented has advantages over such methods as Fourier analysis or computation of running means. Using a function of the arctan-type to fit observations appeared to be preferred by those who work in practical meteorology. Essentially, the method is a comparison of two mean values scaled with some standard deviation and formulated in a way that provides some flexibility.

It is important to realize that weather breaks are a very special case of weather variability. Knowledge of this variability by means of a power spectrum does not give full insight into the break characteristics of a time series. Adding the quadrature spectrum should give this because the spectra together contain all information, but it is obvious that the break characteristics we are investigating are hidden. This justifies the present method which aims at applicability rather than mathematical elegance.

3. An example

In order to give some insight into the behavior of the break quality, we provide an example in Fig. 3. The upper curve shows a series of observed daily temperatures T_j; the lower curve gives the values of γ_j computed with a transition function with parameters $n = 4$ and $\beta = .2$. We see that maximum values of γ (denoted by arrows) are related to the principal changes in temperature. The two "fine" breaks (2) and (4) have high break qualities. The fact that γ shows rather sharp peakes at these significant breaks justifies the use of the break quality as defined by (5).

The corresponding values of a^* (note that the temperature change is given by $2a^*$) and of $h(a^*)$ are given at the bottom of the figure. The effect of dividing the amplitude by the noise with respect to M is clearly seen for break (5). Although it has the *largest* amplitude, the break quality is *less* than that of breaks (2) and (4).

This example already suggests a way by which a definition of the weather break may be constructed. A possibility would be to require $\gamma > \gamma_{\rm crit}$, or $\gamma > \gamma_{\rm crit}$ and $a^* > a^*_{\rm crit}$. The critical values $\gamma_{\rm crit}$ and $a^*_{\rm crit}$ may be chosen in accordance with the particular application. It seems desirable to base the final definition of a weather break on a quantity in which break qualities of *more than one* weather element are incorporated. This will be discussed in Section 4.

4. Application I: A break climatology for De Bilt

We now present a break climatology at De Bilt (The Netherlands) to show an application of the procedure proposed in the foregoing sections.

We consider a transition function with $n = 4$ and $\beta = 2$. These values were thought to be suitable for De Bilt but they are arbitrary, of course. For the period 1949–74 all breaks were computed for T_x (maximum temperature), T_n (minimum temperature), T_d (daily temperature, i.e., the mean value of T_x and T_n), S (relative duration of sunshine), R (precipitation) and ϕ (geopotential height of the 500 mb level obtained from spatial analyses). Table 1 shows a cumulative frequency distribution of γ for various weather elements, arranged in accordance to the number of high-quality breaks. Most high-quality breaks are found for ϕ, whereas R hardly shows any. Daily temperature performs better than maximum and minimum temperature and sunshine comes between temperature and rainfall. It is not surprising that T_d and ϕ show more high-quality breaks. This is partly due to the fact that T_d is a mean quantity and ϕ was derived from spatial analyses. Such operations reduce the noise with respect to M.

We note that a relation exists between the total number of breaks and the number of high-quality breaks: if the former is smaller, the latter is larger. Since the total number of breaks in T_d is 1850 and the length of the series is 9496 days, a break in temperature occurs at intervals of about 5 days. Each 45 days a high-quality break ($\gamma > 3$) may be expected.

Fig. 4 shows the seasonal cycle in the frequency of occurrence of breaks in T_d. The solid line gives the number of breaks with $\gamma > 2.5$ for each month. Most of these breaks occur in winter and spring; March shows a pronounced maximum. In summer the number of breaks reaches a minimum value and during fall it gradually increases. Inspection of weather maps corresponding to the high-quality breaks brought to light that such breaks often occur during the development or breakup of meridional circulation types (large-scale circulation patterns with a strong southerly or northerly wind component). Fig. 4 illustrates this point. It shows the frequency with which meridional circulation types occur over western Europe (dashed line), and the number of high-quality breaks in T_d. Clearly, some relation is present.

In order to construct a weather break definition in which changes in more than one weather element are incorporated, correlation coefficients between series of break qualities of different weather elements were computed with various time lags. Although these coefficients reached significant maximum values for time lag 0 or 1, they never exceeded 0.08. This means that breaks in the various weather elements do not coincide. It also means that a combined break quality of the kind $\gamma^p(T_d)\cdot\gamma^q(S)\cdot\gamma^r(R)$, where p, q and r are constants, does not make sense because it would be a strongly smoothed quantity. The alternative is to define a

TABLE 1. Frequency distribution of γ for various weather elements observed at De Bilt (see text for explanation of symbols).

Weather element	N(all γ)	$N(\gamma > 2)$	$N(\gamma > 3)$	$N(\gamma > 4)$	$N(\gamma > 5)$
ϕ	1784	706	336	164	74
T_d	1850	483	177	79	35
T_x	1877	431	143	51	26
T_n	1995	312	94	32	10
S	2251	153	44	15	8
R	2217	39	6	2	1

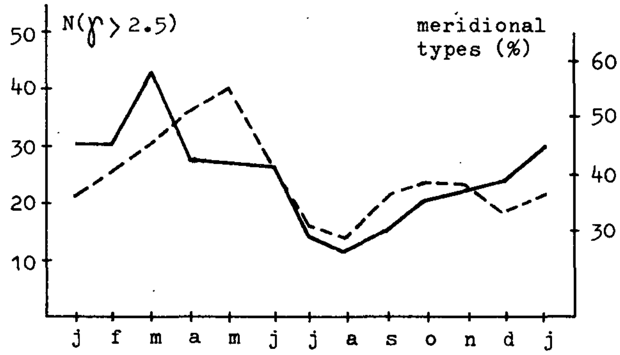

FIG. 4. The seasonal cycle of the number of fine breaks in T_d (solid line) and the occurrence of meridional circulation types over western Europe [dashed line (from Hess and Brezowsky, 1969)].

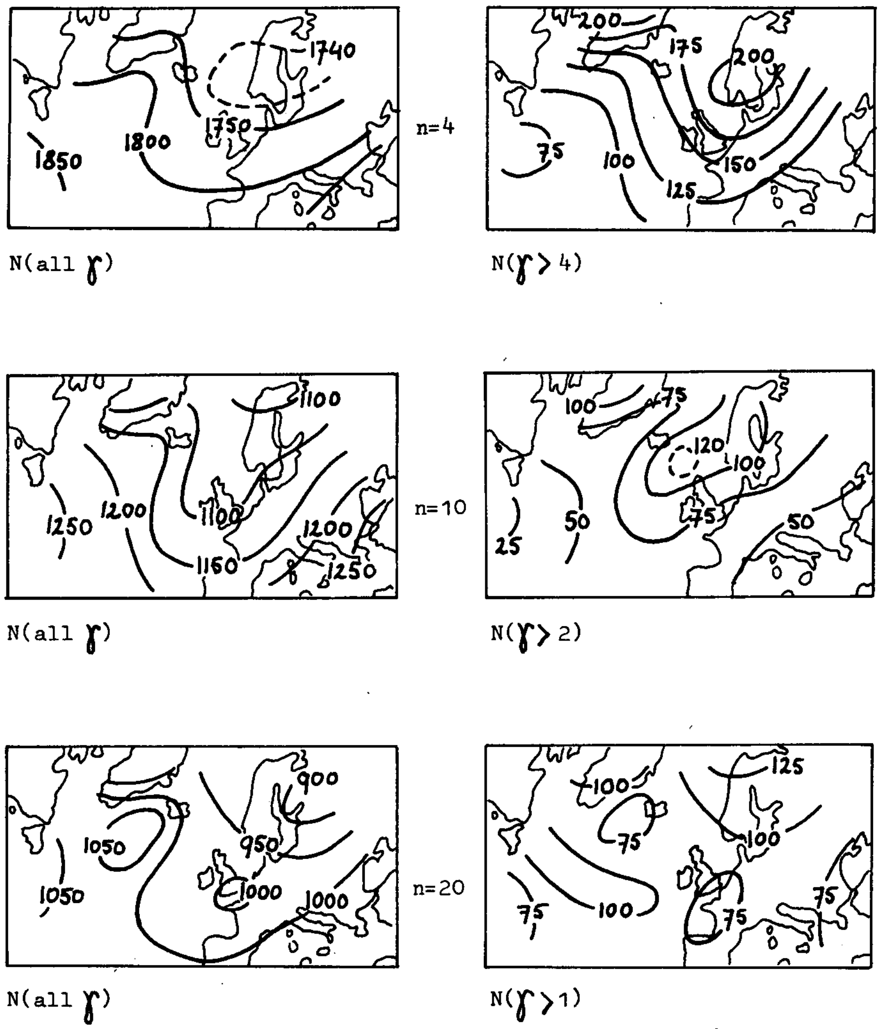

FIG. 5. Break climatology of the 500 mb geopotential height field over the North Atlantic Ocean and western Europe. The total number of breaks is shown in the left part of the figure, the fraction of fine breaks in the right part. Computations were made for three values of n (4, 10 and 20) while β was kept at 2. Period: 1949–74.

weather break by the requirement that a high-quality break occurs in at least one weather element. It should be stressed that these conclusions apply to De Bilt. It is quite possible that other locations would show a much higher correlation between breaks in different weather elements.

5. Application II: An analysis of the 500 mb geopotential height field

So far we have considered time series at one location. It is also interesting to investigate the spatial variability of the occurrence of breaks. Since it was immediately available, the geopotential height of the 500 mb level over the northern Atlantic was analyzed. At 18 grid points covering the area bounded by latitudes 40 and 70°N and longitudes 50°W and 30°E, a break climatology was computed over the period 1949–74. Each time series consisted of ϕ values at 1200 GMT and the seasonal cycle was carefully removed. This was done because transition functions with a large value of n (up to 20) were used and it seemed undesirable for the seasonal cycle to affect the break quality (in this analysis, anyway). The material used was originally prepared at the German Weather Service, Offenbach.

Three transition functions were used: $n = 4$, 10, 20 and $\beta = 2$. Fig. 5 presents the results. For each value of n the total number of breaks and the number of breaks with γ larger than a certain value are shown. First, we note that *the total number of breaks and the mean break quality decrease if n increases*. Consequently, for larger values of n

lower values of γ were used to define the high quality breaks shown in the right-hand part of Fig. 5. For $n = 4$, most high-quality breaks occur over southern Scandinavia, while on the left part of the map (from now on referred to as Newfoundland region) a minimum is present. If n is set at 10, the Newfoundland minimum appears again but the region of most high-quality breaks shifts to the west: it occurs between Iceland and Scotland. With $n = 20$ we are dealing with quite a large time scale and we see that the pattern becomes more chaotic.

The interpretation of these results is not difficult. Inspection of 500 mb topographies revealed that high-quality breaks in ϕ generally occur when a blocking circulation starts to develop or breaks down (mostly to a circulation type with a strong zonal flow). Without doubt, the preferred region of baroclinic wave excitation near Newfoundland is associated with a small number of high-quality breaks. The large number of these breaks over the northeastern Atlantic reflects the fact that in that region blocking occurs frequently. Of course, this is a well-known feature which has been revealed by a number of diagnostic studies (e.g., Sawyer 1970). Nevertheless, it is interesting to see that the blocking region appears very sharply by means of a break analysis.

6. Testing statistical significance

Since different breaks are often partly based on the same elements of the time series, the break analysis is not very elegant from a mathematical point of view. In most practical applications, however, convenient mathematical properties are not needed. Only one question should be answered: How do we know whether two break climatologies differ significantly or not?

After some consideration it appeared to be very difficult to find a reliable measure of significance based on existing statistical tests. Therefore, it is necessary to generate many time series with an appropriate stochastic model and to compute the distributions of breaks in these series. From these we may compute the chance that, for a particular series, $N(\text{all } \gamma)$, $N(\gamma > 4)$, or whatever we want, differs more than a certain value from the mean. If we assume that the values of $N(\ldots)$ have a more or less normal distribution, it is convenient to compute the standard deviations of $N(\ldots)$. Once these are known, a common significancy test can be applied to compare, for instance, two observed break climatologies.

A stochastic model that seems to be suitable is a Markovian process of first order (frequently referred to as "red-noise model"), which is generated by

$$X_i = \rho_1 X_{i-1} + (1 - \rho_1^2)^{1/2}\epsilon_i. \qquad (7)$$

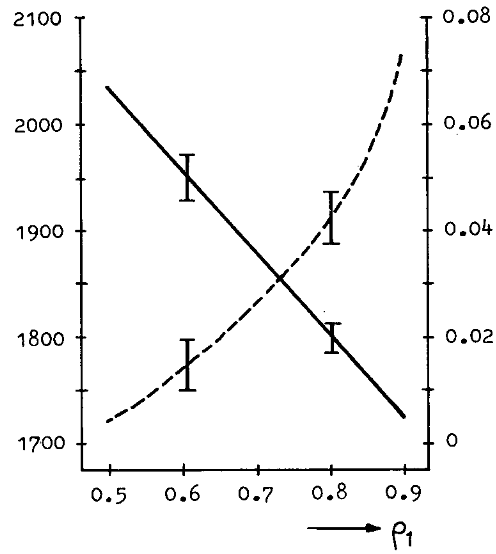

FIG. 6. Break climatology for a first-order Markovian model with lag 1 autocorrelation coefficient ρ_1. Transition function used: $n = 4$ and $\beta = 2$. The solid line gives the total number of breaks (left scale) and the dashed line the fraction of breaks with $\gamma > 4$ (right scale). Vertical bars indicate estimates of twice the standard deviation.

In (7), ρ_1 is the autocorrelation coefficient at lag 1 and ϵ_i is a number drawn at random from a distribution with zero mean and standard deviation 1. In the following, a normal distribution is used for ϵ, implying that X is also normally distributed. It is well known that time series of a large number of weather variables resemble such a Markovian model, at least with regard to the power spectrum.

Fig. 6 shows a break climatology for some Markovian models computed with the transition

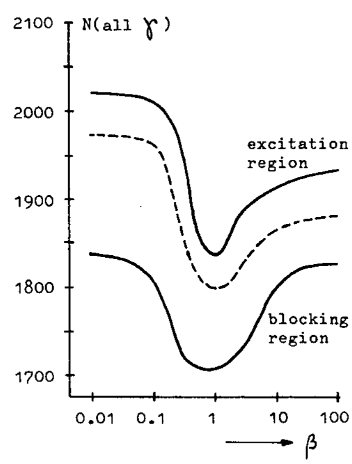

FIG. 7. Total number of breaks as a function of β for $n = 4$. The geopotential height field was investigated in two grid points: one in the baroclinic wave excitation region near Newfoundland and one in the preferred region of blocking over the Norwegian Sea. The dashed line corresponds to a Markovian process fitted to the ϕ series in the blocking region ($\rho_1 = 0.75$).

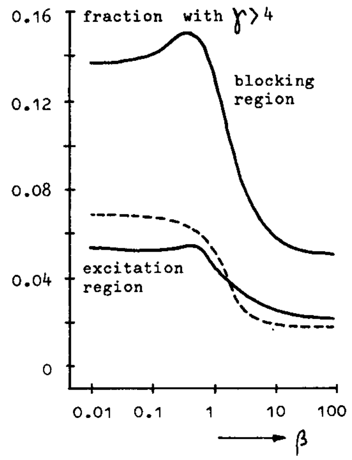

FIG. 8. As in Fig. 7 except for the fraction of breaks with $\gamma > 4$.

function $n = 4$, $\beta = 2$. The length of the generated series was equal to the observed series used earlier. The solid line gives the total number of breaks and the dashed line the fraction of these breaks with $\gamma > 4$. Apparently, $N(\text{all } \gamma)$ is smaller if ρ_1 is larger, i.e., if persistence is stronger. In contrast, the number of high-quality breaks increases rapidly with increasing ρ_1. Fig. 6 is based on 50 time series, 10 for each indicated value of ρ_1. The vertical bars show estimates of twice the standard deviation which may be used in a statistical significancy test.

7. Other values of β

So far a value of 2 has been used for β, a rather arbitrary choice. The question rises how break climatologies change if β is changed. To state it more specifically: Does a value of β exist for which break qualities are highest? In the following we will deal with this question.

In order to avoid the difficulties mentioned in Section 2, β was specified *a priori* in each computation. For a wide range of values of β (from 0.01 to 100, i.e. for a transition function that changes from a straight line to a step function), two time series were analyzed: ϕ at a grid point in the baroclinic wave excitation region near Newfoundland and ϕ at a grid point in the preferred region of blocking in the northeastern Atlantic. Fig. 7 displays the total number of breaks in these series. For both series a marked dip in $N(\text{all } \gamma)$ is present for $\beta \approx 1$. This dip is sharper in the excitation region. The dashed line shows $N(\text{all } \gamma)$ computed by averaging over five series generated by the Markovian model with $\rho_1 = 0.75$. This value results from fitting the Markovian model to the time series of ϕ in the blocking region by setting ρ_1 equal to the quotient of the autocorrelation coefficients at lag 2 and 1. The dip is present again but the curve is much closer to that of the excitation region than to the blocking region. The difference between the Markovian curve and the blocking region curve is highly significant. The corresponding fractions of high-quality breaks are shown in Fig. 8. The difference between the blocking and excitation regions is striking. Still more interesting is the fact that, in the blocking region in particular, the fraction with $\gamma > 4$ shows a maximum for $\beta \approx 0.5$. This suggests that a preferred transition speed exists. This result becomes more important if we compare it to the curve corresponding to the Markovian model: *no maximum is present now*. Of course, the Markovian model could be chosen in such a way that it makes a better fit to the ϕ series with regard to the break climatology, but the maximum in $N(\gamma > 4)$ cannot be simulated. We conclude that the Markovian model fails to describe the ϕ time series with regard to the break properties, which does *not* necessarily imply that it also fails with regard to the power spectrum. Anyway, one should be careful with the use of a first-order Markovian model. Further investigation is required to see what kind of stochastic model performs best with regard to both the break properties *and* the power spectrum.

A similar investigation (but in less detail) was carried out for the T_d series. Again, a value of β between 0.5 and 1.0 appeared to be most suitable. However, the particular practical application should also have some influence on the final choice of β. If one is interested in rapid changes only, $\beta = 2$ seems to be a good choice.

8. Summary and concluding remarks

A mathematical procedure has been discussed that permits the objective detection of changes (sudden or not) in time series. Two parameters were used to specify the transition function that is fitted to observed series. These parameters define two time scales: the length of the persistent periods and the speed of the change. As output we obtain the break amplitude and the break quality. These quantities may be used to define breaks in the weather: they form a basis; the final definition depends on the specific location and the application. For De Bilt the correlation between breaks in different weather elements appeared to be small, so it did not make sense to construct a combined break quality. It is not clear how general this result is. Computations with time series observed at other locations should give the answer.

As an example of other applications, an analysis of the 500 mb geopotential height field over the Atlantic Ocean was carried out. The method appeared to give a clear picture of the preferred blocking region over Scandinavia and the Norwegian Sea. Although it takes a lot of computer time, it seems worthwhile to extend this analysis.

A few remarks were given concerning the way in which statistical significance tests may be arranged. Although we found that a first-order Markovian process behaves somewhat differently than the observed time series of ϕ, nevertheless, it may serve to provide a first estimate of standard deviations that may be expected. More sophisticated stochastic models can be found in numerous textbooks (e.g., Bhat, 1972). It would be interesting to see which one performs best with regard to the break properties of meteorological time series.

Finally, it should be noted that the method of detecting changes may be applied to any time series. Questions like "Do negative breaks occur more frequently then positive ones?" or "Is there any difference in preferred speed (β) between negative and positive changes?" may be answered by experiments along the lines discussed in this paper.

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