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A step towards long range weather prediction: The exceptional atmospheric circulation of January 1983 and its relation to El Niño

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Summary. One aim of teleconnection studies is the pursuit of a predicition of anomalous weather regimes several weeks or even months ahead. A widely investigated example is the connection of the atmospheric state and the warming of tropical East Pacific surface waters called an El Niño event. Indications to an effect of the tropical ocean warming on the remote midlatitudinal atmosphere have been found by several authors since this connection has been first hypothesized by Bjerknes in 1966 [4]. By a combination of statistical methods with extensive observational and model-simulated data we are now able to demonstrate that a clearly defined significant impact of tropical sea surface temperature anomalies on the atmosphere of the entire Northern hemisphere exists.

Ein Schritt in Richtung der Langfristwettervorhersage: Die Besonderheiten der atmosphärischen Zirkulation im Januar 1983 und ihre Beziehung zu einem El Niño-Ereignis

Zusammenfassung. Ein Ziel der Untersuchung von Telekonnexionen verfolgt die Vorhersage von anomalen Wetterereignissen Wochen oder gar Monate voraus. Besonders häufig wurde in diesem Zusammenhang die Beziehung zwischen dem Zustand der Atmosphäre und der Erwärmung des Oberflächenwassers im tropischen Ost-Pazifik, das sogenannte El Niño-Phänomen, untersucht. Anzeichen für eine Auswirkung dieser Erwärmung auf die Atmosphäre der mittleren Breiten wurden von mehreren Autoren belegt, seit Bjerknes 1966 [4] die Hypothese einer solchen Beziehung aufgestellt hatte. Durch die Kombination von statistischen Methoden mit einer Vielzahl von Beobachtungsdaten sowie numerischen Modellergebnissen kann jetzt gezeigt werden, daß ein deutlicher, statistisch signifikanter Einfluß der tropischen Meeresoberflächentemperaturen auf die gesamte Nordhemisphäre besteht.

1. Introduction

Tropical ocean surface temperatures show strong variations over periods of a few years. Particular attention has been given to the periods of increased sea surface temperature (SST) in the east-equatorial Pacific known as El Niño events (cf. reviews [19, 6]). The warming starts generally in a narrow region off the coast of Peru around Christmas and spreads westward until the entire equatorial Pacific east of the dateline has become warmer by several degrees.

The most striking impact of this phenomenon is the resulting decrease of fish population in the (normally cold upwelling) waters off Peru and a longitudinal shift of drought and rain zones along the equator [2, 22]. In addition to these effects in the tropical zone, it has been hypothesized by Bjerknes [4] that the disturbances in the tropical atmosphere also cause changes in the atmospheric circulation in the midlatitudes, thereby influencing weather regimes not only in North America but also over the Atlantic and Eurasia.

The existence of an effect of an El Niño SST anomaly on the tropical circulation in terms of, say, air pressure and precipitation is well established [31]. This is due to the fact that the signals are relatively strong as compared with the weak natural variability of the tropical atmosphere.

In contrast, the remote effect on the midlatitudes cannot be expected to be as large, and to detect a signal is much more difficult in the presence of the enormous natural variability of the extratropical atmosphere. Many efforts have been made to find a midlatitudinal reaction in the observations as well as in numerical simulations, but the particular appearance of the response patterns remained uncertain since it varied from experiment to experiment. (A good review is [23].) Much of this uncertainty is due to the use of inadequate statistical assessment methods to distinguish between genuine response patterns and spurious noise.

In this paper, we demonstrate the existence of a well defined significant effect of an El Niño SST anomaly on the midlatitudinal atmospheric circulation. For this, we apply multivariate statistical tools both to observed and model-simulated data of the Northern hemisphere.

The central ingredients of our statistical methods for a signal detection in the presence of large natural variability are multivariate test procedures for the assessment of whole vectors of, say, gridpoint values, and an a priori reduction of the number of parameters used to characterize the signal patterns. The mathematics are described in detail by [26].

A remarkably strong El Niño event occurred in 1982/83 (described by a series of papers [28, 15, 21, 7]). Its peak in winter 1982/83 with maximum anomalies up to 4K (Fig. 1) was accompanied by a number of extraordinary events in midlatitudes: "greatest negative 700 mbar seasonal mean height anomaly yet observed in the Northern hemisphere, which occurred in the north-east Pacific", "record-breaking extratropical jet winds in the east Pacific, where winds were up to 35—40 m/s greater than normal" and "extraordinary positive surface temperature anomalies over central latitudes of most of North America and Eurasia; and excessive precipitation and flooding in various regions of the world, with droughts in others" (cited from [21]).

First we show that the north-hemispheric circulation in winter 1982/83 was indeed exceptional, i.e. significantly different from the normal variety of atmospheric states. Then the hypothesis is tested that this exceptional devia-

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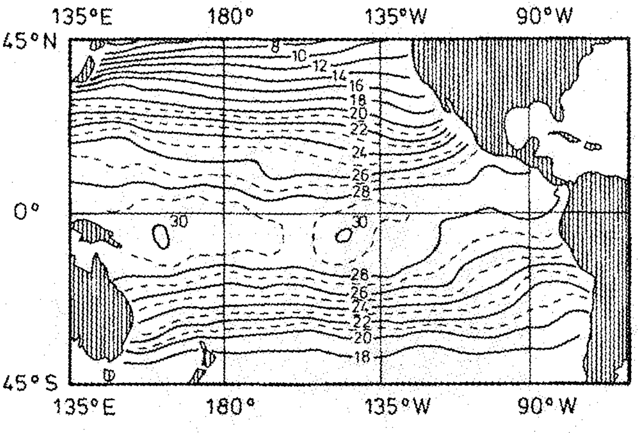


Fig. 1a. Isolines of the sea surface temperatur (SST, in °C) in the Pacific as observed in the El Niño January 1983. The tropical Pacific waters are still coldest in the east.

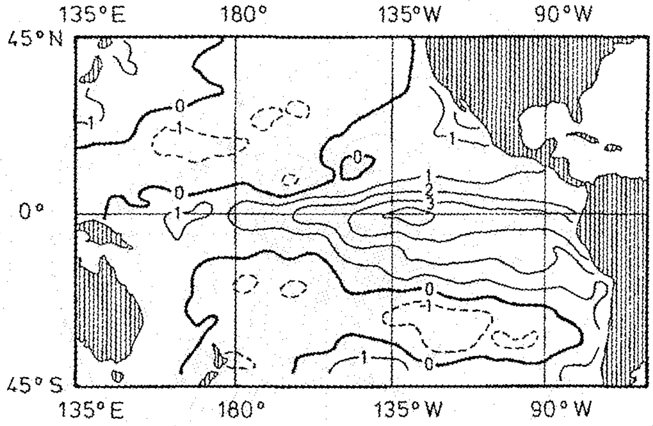


Fig. 1b. The anomalous warming of the eastern tropical Pacific (shaded areas) during the El Niño event becomes clearly visible after the subtraction of the climatological January average. The figures give the temperature deviation from the normal °C. (Fig. 1a, b from [1]).

tion from the long term average is caused by the anomalous sea surface temperature in the Pacific; for this we shall use the results of a simulation with a general circulation model of the global atmosphere [9]. We show that the model simulates a significant and stable response to an El Niño type SST anomaly, and that this response is similar to the one observed in 1982/83. This analysis shows a clearly defined midlatitudinal response to El Niño anomalies.

The meteorological parameter investigated is the winter average of the height of the 500 mbar pressure surface, since it is a quantity analysed pretty reliably over an extended period. Due to the sparsity of Southern hemisphere observations, we shall restrict the analysis to the Northern hemisphere.

If it is possible to prove that there is a deterministic link between tropical ocean temperatures and the remote midlatitudinal circulation of the atmosphere, this offers a promising tool for the prediction of the probably prevailing weather regimes one season or so in advance. Furthermore, if one manages to predict the SST anomalies themselves, the forecast period could be extended even further. This requires a knowledge of the causes of the SST anomaly (which in turn is expected in the tropical atmospheric circulation) whereas we shall restrict ourselves here to the impacts on the tropospheric circulation.

2. The need for a statistical assessment

To detect the specific peculiarities of the January 1983 state one has to accept that the considered quantity "January mean height field" is a random variable: it varies considerably from year to year even without such drastic impacts as an El Niño sea surface temperature anomaly. To illustrate this basic problem, Fig. 2 shows 6 different January anomalies, i.e. the deviations of 6 individual Januaries from a long term average (1967—83; see Fig. 3). The 1983 state is included, the other 5 cases are selected at random.

By visual inspection, all one can see is that these maps differ considerably from each other with respect to many details, e.g., the number of relative extrema as well as their location and amplitudes. How can one decide what the "normal variability" of such patterns is, and what is the criterion for an "unusual" pattern? This problem is solved if one notes that each of these patterns is only a graphical representation of a number of gridpoint values, which may be regarded as the components of a vector in a high-dimensional space. Equally well, the patterns may be represented by a vector of the amplitudes of a spectral, e.g., Fourier expansion. Hence, the problem is reduced to the task of determining the mean length and direction of a high-dimensional vector, together with the region around this vector which contains most of the individual vectors. An "unusual" pattern is then recognized as a vector which lies outside this region of normal variability.

Thus, we can distinguish between deviations which are "normal" in the sense of interannual variability generated by the atmosphere's internal dynamics ("climatological noise") and deviations caused by external events ("signals"), here: by an El Niño SST anomaly. If our random variable were univariate, i.e. if we would consider a single gridpoint or a particular spectral expansion coefficient, then the signal had to be at least about twice as large as the noise to be identified as significant with 95 % confidence.

In fact, the univariate approach was first used to assess the reliability of the analyses of the response to SST anomalies: more or less sophisticated univariate statistical tests were applied simultaneously at a large number of gridpoints. However, it is known from statistical theory that a set of simultaneous univariate tests cannot give a decision with known risk for the multivariate problem, i.e. if the variable is a random vector made up of a number of gridpoint values or spectral expansion coefficients. In particular, the correlation of more or less distant gridpoints must be considered as well as the probability to obtain just by chance a positive test result at a fraction of gridpoints if the same test proce-

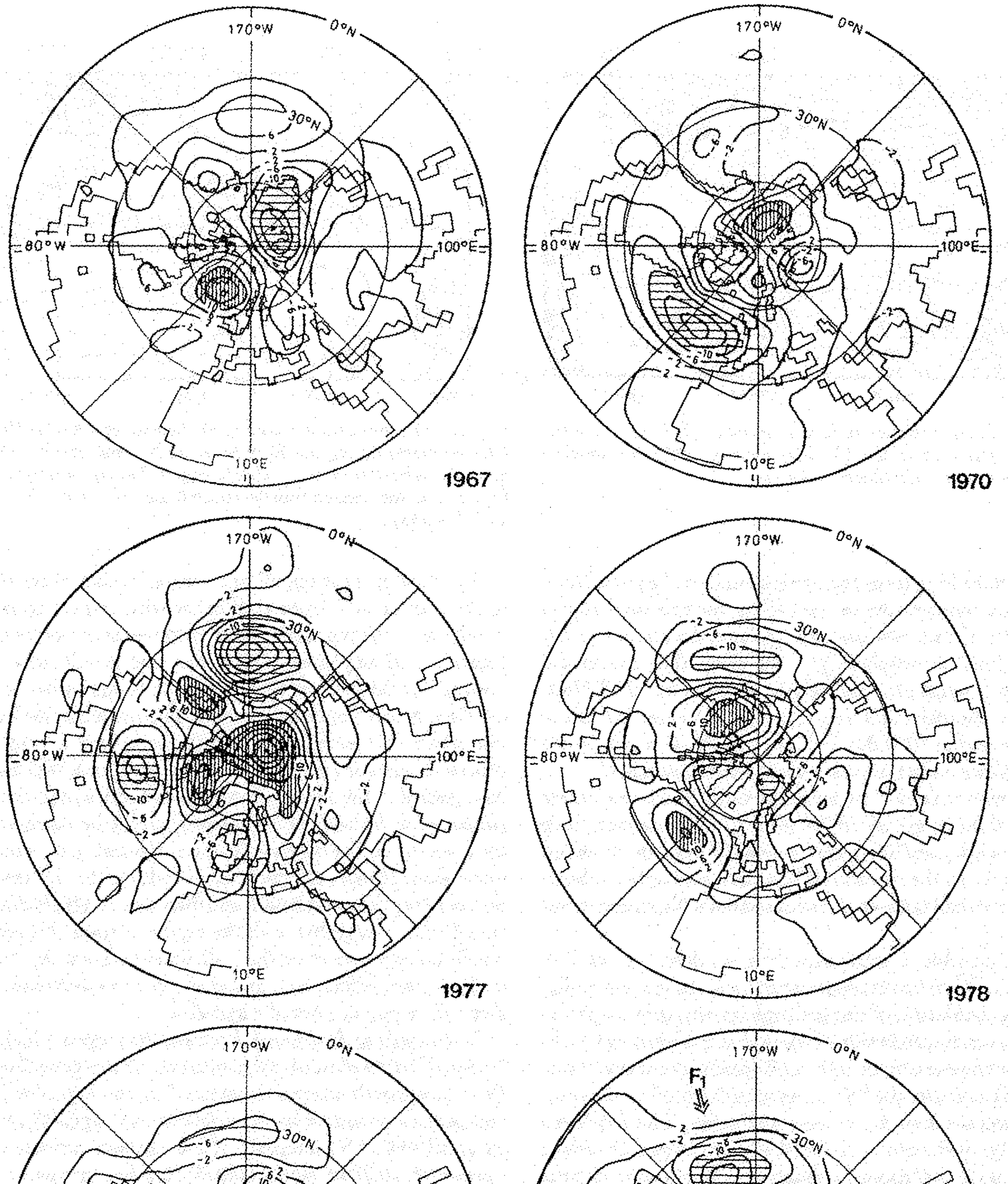


Fig. 2. The large variability of monthly averaged atmospheric circulation features is illustrated by this randomly selected collection of north-hemispheric maps. Shown are the isolines of the deviation from the long-term average (Fig. 3) of the height of the 500 mbar surface for January averages of different years. The right bottom panel shows the circulation of the El Niño January 1983. The exceptionally deep low (Feature F1) over the midlatitude Pacific and the unusual high over (Feature F2) Western Europe are marked. The exceptionality of these features is not concluded from this figure but can only be revealed by the test procedures decribed in the text.

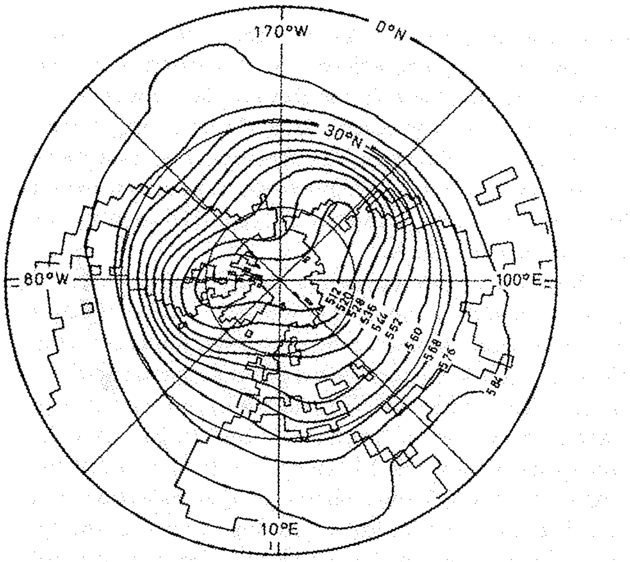


Fig. 3. The hemispheric map of isolines of the height at the 500 mbar level in the long-term average (January of 1967 through 1983). The figures give the height in gpdm.

dure is applied to a set of many gridpoints (for illustration cf. e.g. [17, 24]).

Therefore, one has to use a multivariate procedure. At present basically two kinds are available: the parametric χ^2 or the Hotelling test assuming normally distributed data [10, 12], and the non-parametric approach using permutation techniques and combinatorical arguments [20, 26]. In this paper, we shall apply both the χ^2 and the permutation procedure. (A nice review of the present state of the art is given by [16]).

Multivariate tests are likely to fail to detect an existing signal if too many (noisy) parameters (e.g. gridpoint values or spectral expansion coefficients) are used to describe the circulation pattern [11, 12]. Thus, an a priori reduction of the number of parameters is necessary. Possible methods to compress the data are:

a) averaging with respect to spatial coordinates over limited areas of special interest;
b) spectral expansion into a short series of either fast converging empirical orthogonal functions (eof's) or spherical surface harmonics (ssh's), which represent certain spatial scales;
c) projection onto a set of "guess patterns" that are presumed to build up the signal: these guess patterns may be derived from dynamical considerations, from independently performed numerical simulations, or from independent observations.

It is possible that the appropriate number of parameters, or degrees of freedom, cannot be specified explicitly before the analysis has been done, since at that point it is not yet clear whether the reduction is sufficiently radical to ensure a significant result. In such cases, a whole hierarchy of compressions has to be considered, and for the statistical assessment of the result it is essential that the sequence within the hierarchy is specified a priori, i.e. independent of the analysis result [11]. The selection criterion for the optimal model from such a hierarchy is a matter of choice, and also influences the statistical confidence measure [3]. One possible choice is to select the resolution with the highest significance level, i.e. with maximum likelihood. We prefer another criterion, namely we select at a fixed significance level the version with maximum skill, i.e. the best approximation to the fully resolved pattern.

3. Was January 1983 exceptional with respect to its predecessors?

To detect and assess the particulars of the January 1983 mean of the north-hemispheric 500 mbar height field we tested by means of a χ^2 statistic whether is statistically distinguishable from its predecessors [25]. Data are available for the Januaries 1967 through 83. The necessary statistical parameters (expectation vector and covariance matrix) describing the "normal" climate are estimated from the Januaries 1967—81. In fact, in this period two other El Niño periods are included, but the SST anomaly amplitudes were clearly smaller in 1973 and 1977. We excluded the 1982 January for a check as to whether the test procedure will classify this year correctly as "climatological".

The data compression is performed in two steps: The first consists of a meridional averaging from 30°N to 60°N and the second of an expansion of the resulting zonal structure in five empirical orthogonal functions (eof's). Thus, the quantity considered is the vector of the first 5 eof coefficients of the zonally distributed 30—60°N average of the mean January 500 mbar height. The choice of the averaging interval and of the cutoff number is governed by our focus on the midlatitudes and a subjective compromise between resolution and statistical significance.

The result of the statistical test is that the mean 1983 January state is different from the normal with high significance (95 % confidence) whereas the 1982 case is not (as expected).

In order to find those features which might have caused the classification of the 1983 field as "not climatological" we return to the high-dimensional longitudinal gridspace and check whether there are longitudes with unusually large deviations from the "normal". For that purpose, we plot the meridional mean 500 mbar height as a function of longitude together with the pointwise defined confidence interval which contains roughly 95 % of all values of the control ensemble (1967—81). It must be kept in mind that this univariate (a posteriori) analysis yields arguments of plausibility and that more details are shown than are warranted by the rigorous 5-dimensional significance test.

This 95 % band of the control set is shown in Fig. 4 together with the curves for the Januaries 1982 and 1983. While the insignificant 1982-curve lies mostly within the 95 %-region, we can see that the 1983-curve leaves it at two locations: there is an anomalous negative deviation of about 170 gpm north of the SST anomaly in the interval 130—160°W ("Feature F1") and a positive deviation of about 100 m at about Greenwich ("Feature F2").

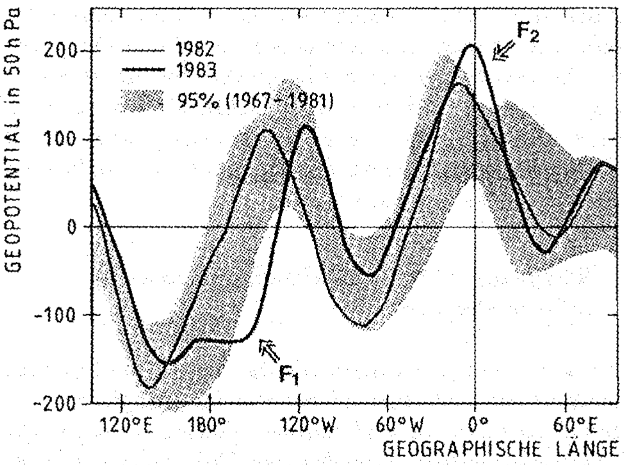


Fig. 4. The observed January mean circulation expressed by the 30°—60°N average of the 500 mbar height as function of longitude. The thin line represents the 1982 case which is not found to be exceptional by the statistical test. This curve lies entirely within the range of values which are — at a given longitude — observed in 95 % of all cases (stippled area). The heavy line shows the exceptional 1983 case which by the statistical test in the low-dimensional parameter space was found to be significantly different from the normal. In the high resolution representation on the longitude grid, the strongest deviations from the normal appear as a low near the dateline (Feature F1) and as a high near Greenwich (Feature F2).

We performed a second univariate analysis to test whether some of the eof's exhibit extremely large coefficients in 1983. The result (not shown here) is an extraordinarily large coefficient of a particular eof, the pattern of which shows three maxima and three minima ("Feature F3"). The locations of these extrema are about 140°E, 80°W and 5°W—25°W (positive) and 175°W—120°W, 40°W and 65°E (negative). Note that these extrema are those of this particular eof. Since the signal is built up by several eof's, the distribution of extrema of the signal may differ from that of this eof.

These three features can be recognized in the hemispheric representation of Fig. 2. Feature F1 comes from an intense negative anomaly of -200 gpm in the Gulf of Alaska, Feature F2 from a positive deviation of + 160 gpm centered at Andorra. Also, Feature F3 can be related fairly well with the distribution of respective extrema in January 1983. The huge depression centered at Greenland with a minimum of -220 gpm was not found by our objective procedure, because in the course of the meridional averaging we excluded the northern latitudes, where the bulk of this pattern is located.

In summary, we have found that the 1983 January mean circulation differs significantly from the preceding January patterns, which finds its visible expression in the exceptional Features F1 through F3. However, no causal realation between these findings and the El Niño SST anomaly has yet been demonstrated.

However, the connection of a "positive East Pacific SST anomaly" and the occurrence of Feature F1 was established with statistical confidence by correlations between long time series [8]. A hint that Feature F3 is linked to El Niño is the fact that just that eof which has the largest coefficient in 1983 adopts its second largest coefficient in January 1973, when a more canonical El Niño event (i.e., with half the amplitude of 1983) took place. Another indication of a causal relation between east-equatorial warming of the upper ocean and Features F1 and F2 is provided by the study of the second largest observed El Niño event more than a hundred years ago, in 1877/78. Kiladis and Diaz [14] recently published the January 1878 mean surface pressure distribution covering North America, the North Atlantic and parts of Eurasia: Feature F2 was clearly present, and enhanced westerlies at the western US coast pointed to an enhanced or eastward shifted Aleutan Low.

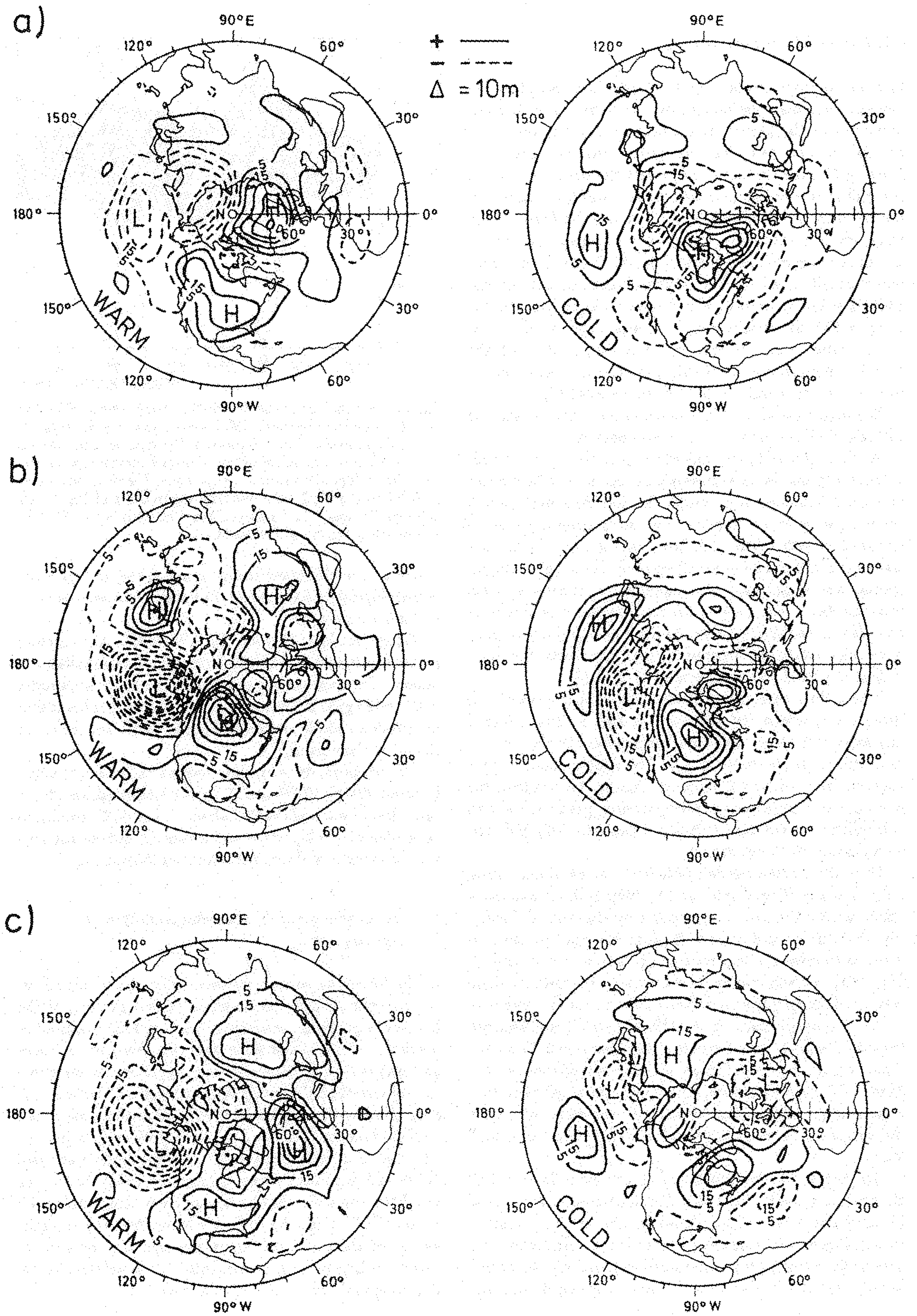
Simulation experiments with an El Niño SST anomaly as a lower boundary condition [6, 23] gave as a common property the intense depression north of the anomaly (Feature F1) but otherwise no congruent remote responses. However, one of the model circulations exhibits Features F2 and F3 as well [23].

4. Demonstration of a relation between the El Niño temperature anomaly and the observed midlatitudinal tropospheric anomalies

We hypothesize that the particulars of the mean January 1983 tropospheric circulation are related to the El Niño event. To test this hypothesis, we utilize the result of a numerical experiment with a General Circulation Model (GCM) performed at the European Centre for Medium Range Weather Forecast (ECMWF) [9]. These experiments consisted in the simulation of a total of 9 winter seasons with a climatological SST distribution and of 3 winter seasons with a superimposed SST anomaly essentially equal to the January 1983 El Niño SST anomaly.

Fig. 5. left panels: The significant response of the north-hemispheric 500 mbar height to an El Niño warming of the tropical East Pacific as simulated for three different initial conditions with the General Circulation Model (GCM) of the European Centre, ECMWF [9]. These patterns are superpositions of a small number of spherical harmonic modes. The test procedure assessed each pattern individually as significant with 5 % error probability. Note that the gross features are similar to each other in all three cases, and resemble the observed structure in 1983 (cf. Fig. 2, bottom right). The contour interval is 10 gpm.

Fig. 5. right panels: The corresponding maps for the same initial conditions and same sea surface temperature anomaly structure and amplitude, but with the sign of the temperature anomaly reversed (see Section 5). In all three cases, a Pacific high is generated, but the global structure differs from case to case. The patterns of case (a) and (b) are significant with 16 % error probability, whereas case (c) is "significant with 50 % error probability", i.e. insignificant. The contour interval is 10 gpm. See Section 5.



a)
b)
c)
+
−
Δ = 10m
90° E
90° W
120°
150°
180°
60°
30°
0°
N
H
L
5
15
WARM
COLD

4.1. *The model generated response*

General circulation models (GCM's) of the atmosphere are aimed to simulate mathematically the hydro- and thermodynamics of the global atmosphere in as many details as possible in view of limited computer resources. Presently existing GCM's simulate pretty well the basic features of the global atmospheric circulation (i.e. wind, pressure and temperature distribution), as for instance the Hadley cell, trade winds, location and intensity of the tropospheric jet-stream, cyclogenesis and blocking highs. On the other hand, many details need further improvement. In case of the ECMWF GCM used in this study, a closer look to the January 500 mbar height statistic revealed a too weak north-south temperature difference, an eastward shift of the North American stationary ridge, and too strong a damping of the stationary and transient disturbances [27].

We investigated the GCM's response to the prescribed El Niño SST anomaly with two approaches.

As first approach, we studied the complete north-hemispheric response in three anomaly experiments which differ by their initial conditions only. The data compression was carried out by a spectral expansion into a series of spherical surface harmonics (ssh's). A hierarchy of a few, large scale ssh's expected to represent the global character of the response was established. A triangular truncation at total wavenumber 7 was performed. Each member of this hierarchy was tested by χ^2 statistic. As the final significant response we selected that member of the hierarchy with maximum skill at the fixed significance level of 95 % [3].

These three tests resulted in a significant response in all three cases, which are displayed in Fig. 5. The selected members of the hierarchy differ with respect to the spectral resolution: the patterns of case (b) and (c) consist of a superposition of 30 ssh's and are hardly dinstinguishable from the respective untruncated patterns; pattern (a) shows some differences in the longitudinal sector 0—140°E due to a truncation to 18 ssh modes.

In all three cases, the response patterns are similar, in so far as the sequence of mid- and highlatitudinal extrema is stable within the 270° sector covering the central Pacific, North America, and parts of Eurasia. If we adopt the convention to term the sequence of extrema as "wave trains" (e.g., [13]), we may conclude that these wave trains emanate westward starting from a negative center near the date line.

As second approach we used the data compression from Section 2, namely an eof expansion of the 30—60°N meridional average. As test we chose the generalized randomized Mann-Whitney procedure, which is based on permutation arguments [27]. Again we found a highly significant result, i.e. difference of the mean "control" and the mean "anomaly" state.

To analyse the differences, we return as in Section 2 to the gridspace and plot the 95 %-bands of the control ensemble and the 3 curves simulated by the anomaly experiments (Fig. 6). Since we are interested in the differences, we subtracted initially the mean state of all 12 mentioned experiments and of 3 further experiments with a cold anomaly,

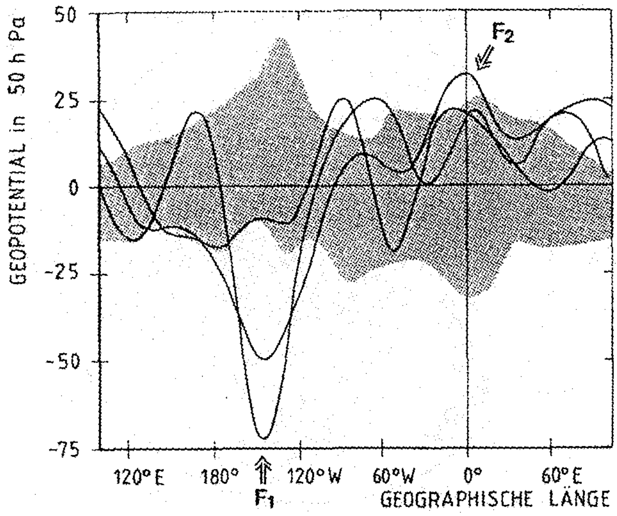


Fig. 6. The response in the 30—60°N average of the 500 mbar height as simulated by the GCM. Different from Fig. 4, the deviation from the model climate is plotted. The stippled band contains 95 % of all simulated values obtained from 9 control experiments with climatological sea surface temperature. The three curves correspond to the 3 El Niño anomaly experiments of Fig. 5, left column. Compare the Features F1 and F2 with Fig. 4. The observed deviations are well reproduced.

which will be discussed in Section 5. Thus, in Fig. 6 the climatological patterns as e.g. the Pacific and East American troughs are missing.

As can be deduced from Fig. 6, the Pacific low pressure pattern entitled Feature F1 in Section 3 is found in all experiments. This pattern has exceptional anomaly amplitudes of 60 and 85 gpm at two locations, the third curve has at that longitude an amplitude about 20 gpm which is at the lower bound of the normal.

Furthermore, three maxima with stable locations (namely about 90°W, 10°W and 70°E) are simulated, which are often found outside the 95 %-band. The 10°W-maximum coincides reasonably well with Feature F2, and the distribution of maxima and minima resembles Feature F3.

4.2. *The coincidence of the simulated and observed response pattern*

In the foregoing section we found that the simulated response exhibits prominent details similar to those of the observed circulation anomaly of January 1983 discussed in Section 3. Now we shall ensure the similarity of these patterns as a whole in an objective way. For this, we define the "observed SST anomaly response pattern" as the difference of the normal Januaries (1967—82) average minus the El Niño January 1983 (see Fig. 7). We project the 9 simulated "control fields" and the 3 "anomaly fields" onto this "observed response"; this procedure yields totally 12 numbers, the scalar products, namely 9 "controls" and 3 "anomalies". With the ordinary Mann-Whitney statistic, we tested the one-sided alternative that the "anomalies" tend to be larger than the "controls". We found this alternative acceptable with a risk smaller than 5 %.

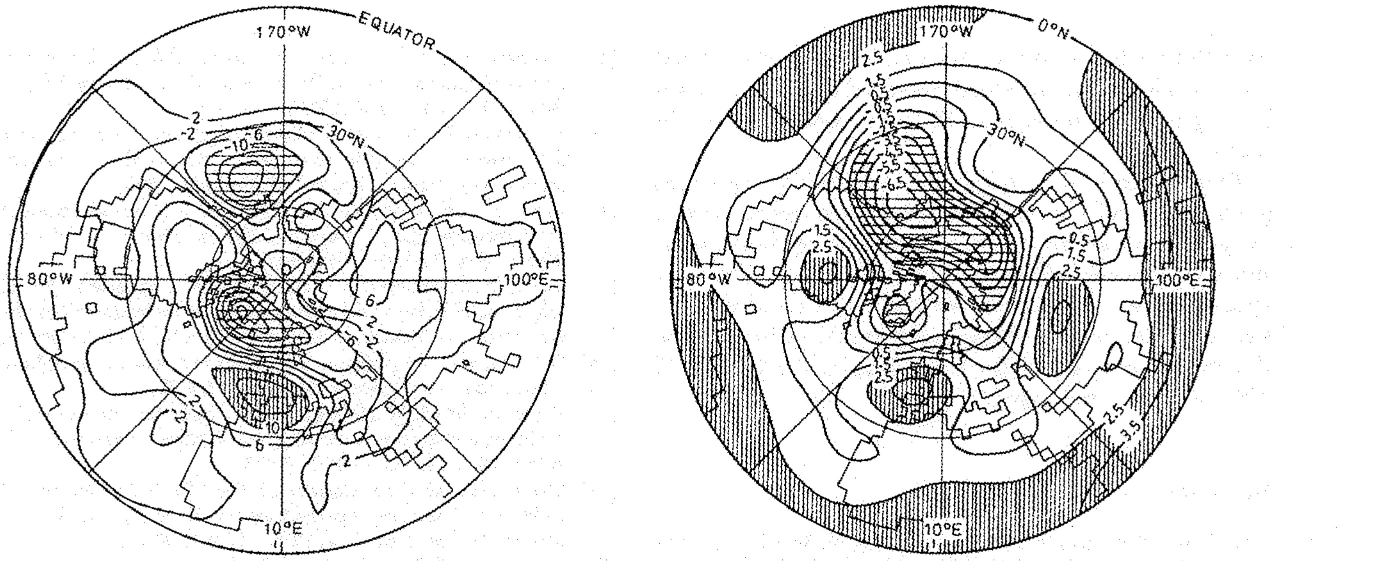


Fig. 7. In order to objectively compare the observed and simulated response patterns, an average "observed" and "simulated response" is defined:
a, "observed response" = "El Niño January 1983 mean" minus "average of 1967—82 January means";
b, "simulated response" = "average of 3 El Niño model winters" minus "average of 9 control model winters".
Contour interval is 10 gpm. This plot visualizes the result of the statistical test, that the structure (with no regard to the amplitudes) of the simulated and observed response is quite similar.

This means that the simulated (significant) response pattern is correlated with the (significant) observed one. A side-by-side comparison of the observed and the simulated response (Figs. 7a, b) shows that both fields are really very similar in structure. Besides the Features F1 through F3, the North American and Central Siberian ridges and the East European and Greenland/North Atlantic troughs are common properties. A factor of 3 difference in the amplitude can presumably be explained by the underestimated spatial variance of the GCM, the seasonal instead of a monthly averaging period, and the averaging over a 3-member ensemble instead of the single observed case.

A puzzling aspect is the fact that in a similar experiment performed with the NCAR Climate Community Model [5] and in composite maps [18] the flow anomaly over the North Atlantic is associated with weakened westerlies, which is in contrast to our findings. However, most GCM's indicate intensified westerlies (cf. [30]). This was also the case during the 2nd most intense El Niño event in the records, 1877/78 [14].

5. Would linear models do as well?

A linear relationship between the hemispheric response and the SST anomaly would facilitate the understanding of the involved mechanisms and simplify the prediction of seasonal averages of atmospheric states from ocean surface states. We tested the existence of such a linear relationship by evaluating a series of 3 further GCM simulations with a SST anomaly distributed as the one studied above but with reversed sign [9]. A linear relationship would imply similar response shapes and amplitudes both for the warm and cold SST anomaly, but opposite sign. However, the results are different.

In the preceding section, we found a stably located low pressure center near the date line as the most pronounced response to the warm El Niño SST anomaly. At the same location the cold anomaly induces apparently a high pressure center, with half the amplitude (cf. Fig. 5). From this "principal center", wave trains emanate with wavelengths shorter than those in the warm anomaly experiments. The wave trains are not stable but vary with respect to strenght and path. In fact, the application of χ^2 test sketched in Section 4 yields significance levels of about 84 % in two cases, and below 50 % in one case, whereas the response to the positive SST anomaly was found to be highly significant (> 95 % in all three cases).

6. Conclusion

We have demonstrated that it is possible to detect the significant effect of a tropical sea surface temperature anomaly on the midlatitudinal atmospheric circulation. To achieve a simulation of this connection, it is necessary to use nonlinear General Circulation Models of the presently available state of art.

Thus in principle it is possible to forecast monthly or seasonal means of the tropospheric circulation based on extraordinary sea surface temperature anomalies. It should be stressed that long range prediction does not imply prediction of the detailed weather of a particular day some weeks ahead. Instead, such forecasts concern only the preference for a prevailing weather regime. In our case, one could expect for example, an increased likelihood of high pressure over Western Europe during January. Basically, the forecast potentialities may be extended even further if it were possible to predict the onset of an El Niño event some months ahead.

One has to bear in mind that statistically significant predictions can be provided by the present method only if the predicted anomaly itself is sufficiently large to stand out above the natural variability of the atmosphere. Thus, the approach does not provide continuous extended range weather prediction but — promising enough — forecasts on the impact of exceptional events, such as the 1982/83 El Niño studied in this paper.

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