Elsevier Oceanography Series, 40

COUPLED OCEAN-ATMOSPHERE MODELS

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ELSEVIER
Amsterdam — Oxford — New York — Tokyo 1985

ELSEVIER SCIENCE PUBLISHERS B.V.
Molenwerf 1
P.O. Box 211, 1000 AE Amsterdam, The Netherlands

Distributors for the United States and Canada:

ELSEVIER SCIENCE PUBLISHING COMPANY INC.
52, Vanderbilt Avenue
New York, NY 10017, U.S.A.

Library of Congress Cataloging in Publication Data
Main entry under title:

Coupled ocean-atmosphere models.

(Elsevier oceanography series ; 40)
Papers presented at the 16th International Liège Colloquium on Ocean Hydrodynamics, held in 1984.
Includes bibliographies.
1. Ocean-atmosphere interaction--Mathematical models --Congresses. I. Nihoul, Jacques C. J. II. International Liège Colloquium on Ocean Hydrodynamics (16th : 1984) III. Series.
GC190.5.C68 1985 551.5 85-10294
ISBN 0-444-42486-5 (U.S.)

ISBN 0-444-42486-5 (Vol. 40)
ISBN 0-444-41623-4 (Series)

Printed in The Netherlands

CHAPTER 20

THE SIGNIFICANT TROPOSPHERIC MIDLATITUDINAL EL NIÑO RESPONSE PATTERNS OBSERVED IN JANUARY 1983 AND SIMULATED BY A GCM

HANS VON STORCH and HARALD A. KRUSE

ABSTRACT

(1) Does the mean January 1983 500-mb height field differ significantly from the January fields observed in non-El Niño Januaries?

yes: – Intense depression north of the anomaly;
- mid-latitudinal high at Greenwich; and
- intensified pattern with an irregularly distributed series of three maxima and minima.

(2) Does the ECMWF T21L15 GCM respond to an El Niño SST anomaly (similar to the winter 1982/83 SST anomaly) significantly?

yes: – Intense depression north of the anomaly; and
- three stably located mid-latitudinal highs at 90°W, 10°W and 70°E.

(3) Are the 1983 observed and the GCM generated response patterns coherent?

yes: – The two patterns are significantly correlated; and
- most of the synoptic scale details of the patterns coincide with respect to location and sign.

(4) Is it possible to simulate the response with sufficient accuracy by linearized models?

no: – GCM experiments with negative anomalies point to a nonlinear relation "SST anomaly–circulation anomaly";
- linear experiments show that the relation "tropospheric heating anomaly–circulation anomaly" is nonlinear; and
- the link "SST anomaly–heating anomaly" is nonlinear, because the release of latent heat by condensation of moisture anomalies generated by evaporation at the sea surface depends essentially nonlinear on the large-scale flow.

(5) Conclusion: El Niño-type SST anomalies up to +4 K generate a unique response pattern in the 500-mb north-hemispheric mid-latitudinal height field. Cold anomalies ("La Niña") yield a varying and less significant mid-latitudinal response.

1. INTRODUCTION

There is no doubt about the existence of an effect of an El Niño SST anomaly on the tropical circulation, and about the appearance of the response patterns of, say, air pressure and precipitation. This uniqueness 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 mid-latitudes 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 extra-tropical atmosphere. Many efforts have been made to find a mid-latitudinal 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 given by Shukla and Wallace, 1983.) A good part of this uncertainty is due to the use of inadequate statistical assessment methods which reduces unfortunately to a discussion of insignificant patterns.

Our central ingredients of statistical methods for a signal recognition in the presence of a large natural variability are multi-variate test procedures for the assessment of whole vectors of, say, grid-point values, and an a-priori reduction of the number of parameters used to characterize the signal patterns. In this paper, we shall apply these methods both to observed and numerically simulated pressure distributions.

We shall first show that the north-hemispheric atmospheric circulation in terms of the 500-mb height in the winter 1982/83 was exceptional, i.e. significantly different from the normal variety of atmospheric states. Then the hypothesis is tested that this exceptional deviation from the long-term average is caused by the anomalous sea-surface temperature in the Pacific (Fig. 1a); for that we shall use the results of a ten-year simulation with the T21L15 GCM of the ECMWF. We show that the model simulates a significant and stable response to an El Niño-type SST anomaly (Fig. 1b), and that this response is similar to the observed one of 1982/83. From this analysis we conclude that a unique mid-latitudinal response pattern to El Niño anomalies exists.

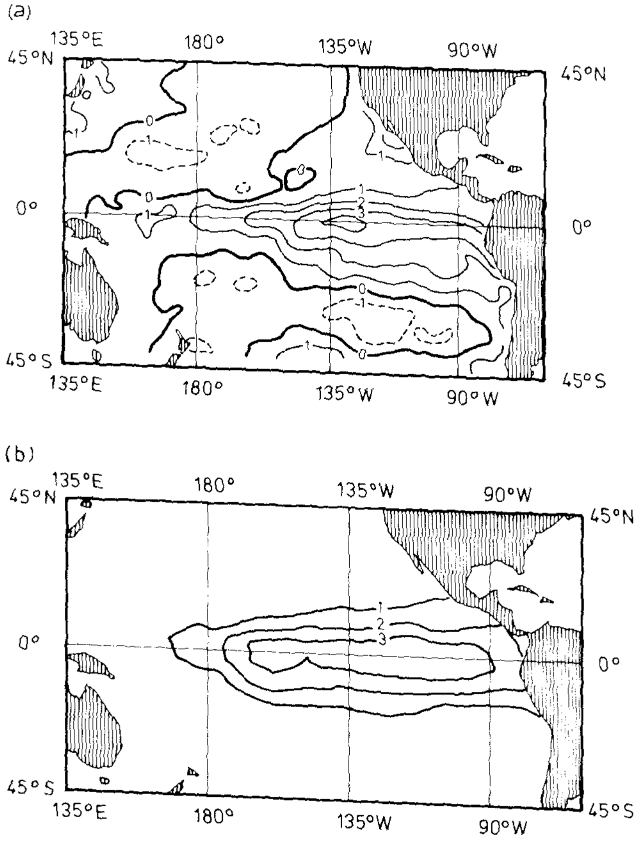

Fig. 1. SST anomaly in the Pacific: (a) Observed in winter 1982/83 (average December–February; from Arkin et al., 1983); contour interval: 1 K; (b) used in the ECMWF simulation [Twice standard Rasmusson/Carpenter anomaly, from Cubasch (1983)]; contour interval: 1 K.

2. STATISTICAL ASSESSMENT TOOLS

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. By eye, all one can see is that such fields differ considerably from each other with respect to the number of relative extrema as well as their location, width, 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 grid-point 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 length and direction of a high-dimensional mean 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 inter-annual variability generated by the atmosphere's internal dynamics ("climatological noise") and deviations caused by external events ("signals"), here: by an El Niño SST anomaly. 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 grid-point values or spectral expansion coefficients. In particular, the correlation of more or less distant grid points must be considered as well as the probability to obtain just by chance a positive test result at a fraction of grid points if the same test procedure is applied to a set of many grid points (for illustration see, for example, Von Storch, 1982; Livezey and Chen, 1983).

Therefore, one has to use a multivariate procedure. At present, basically two kinds are available: the parametric chi-square or the Hotelling test assuming normally distributed data (Hasselman, 1979a; Von Storch and Roeckner, 1983; Hannoschöck, 1984), and the nonparametric approach using permutation techniques and combinatorial arguments (Preisendorfer and Barnett, 1983; Von Storch and Roeckner, 1983). In this paper, we shall apply both the chi-square and the permutation procedure.

Multivariate tests are likely to fail to detect an existing signal if too many (noisy) parameters (e.g., grid-point values or spectral expansion coefficients) are used to describe the circulation pattern (Hasselmann, 1979b). 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 spatial interest.

(b) Spectral expansion into a short series of either fast converging empirical orthogonal functions (EOFs) or spherical surface harmonics (SSHs), 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 it is at that point not yet clear whether the reduction if 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 be specified a-priori, i.e. independent of the analysis result (Hasselmann, 1979a). The selection criterion for the optimal model from such a hierarchy is a matter of choice, and influences the statistical confidence measure as well (Barnett et al., 1981). 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. JANUARY 1983 – EXTRAORDINARY WITH RESPECT TO ITS PREDECESSORS

To detect and assess the particulars of the January 1983 mean of the north-hemispheric 500-mb height field (Fig. 2) we tested by means of a chi-square statistic whether it is distinguishable from its predecessors (Von Storch, 1984). Data are available for the Januaries 1967–83. 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 January correctly as "climatological".

The data compression was done in two steps: The first consists of a meridional averaging from 30° to 60°N and the second of an expansion of the resulting zonal structure in five EOFs. Thus, the considered quantity is the vector of the first five EOF coefficients of the zonally distributed 30°–60°N average of the mean January 500-mb height. The choice of the averaging interval and of the cutoff number is due to our focus on the mid-latitudes and a blend of experience, free will, and personal inertia.

The result of the statistical test is that the mean January 1983 state is different from the normal with high significance (95% confidence) whereas the 1982 case is not. The latter alludes to the fairness of the procedure and a sufficient estimation of the statistical parameters by the data set 1967–81.

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 grid space and check whether there are longitudes with unusually large deviations from the "normal". For that purpose, we plot the meridional mean 500-mb height as a function of longitude together with the point-wise 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, which are not supported by the multi-variate statistical test performed in the five-dimensional subspace.

This 95% band of the control set is plotted in Fig. 3 together with the curves of the Januaries 1982 and 1983. While the insignificant 1982 curve lies mostly within that 95% band, we can see that the 1983 curve leaves it at two locations: there is an anomalous negative deviation of about 170 m north of the anomaly in the interval 130°–160°W ("Feature 1") and a positive deviation of about 100 m at about Greenwich ("Feature 2").

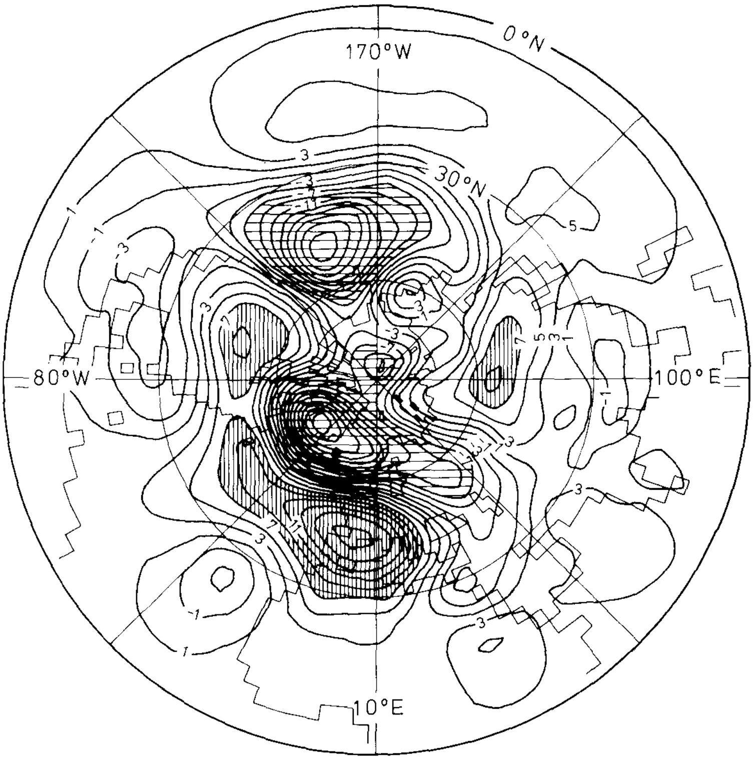

Fig. 2. Observed response pattern used as "guess pattern": Difference of the 500-mb height fields of Januaries 1967–82 average minus the El Niño January 1983. Contour interval: 20 m.

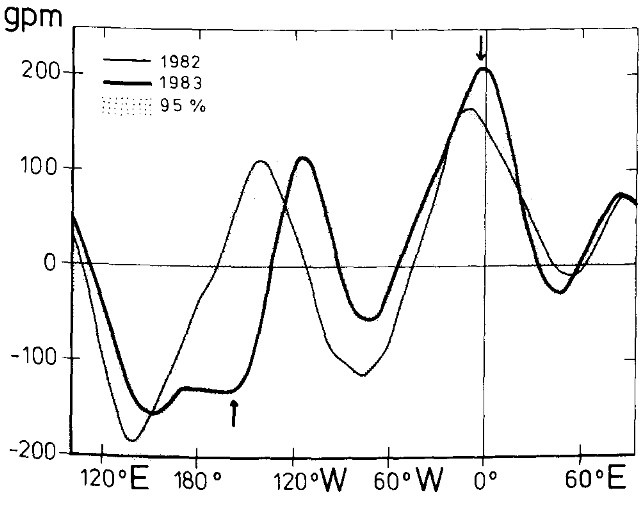

Fig. 3. Observed January circulation: 30°–60° N average of the mean 500-mb height of January 1983 (thick line) and of January 1982 (thin line). The univariately defined "95% band" of 1967–81 is stippled (from Von Storch, 1984).

We performed a second univariate analysis, as to whether some of the EOFs exhibit extremely large coefficients in 1983. The result (Fig. 4) is an extraordinarily large coefficient of a particular EOF, the pattern of which shows three maxima and three minima ("Feature 3"). The location of these extrema are about 140°E, 80°W and 5°W–25°E (positive) and 175°–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 EOFs, 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 1 comes from an intense negative anomaly of −200 m in the Gulf of Alaska, Feature 2 from a positive deviation of + 160 m centered at Andorra. Also, Feature 3 can be identified pretty well with the distribution of respective extrema in January 1983. The huge depression centered at Greenland with a minimum of −220 m could not be 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.

Thus, we have found that the January 1983 mean circulation differs significantly from the preceding January patterns, which finds its visible expression in the exceptional Features 1–3. However, no causal relation between these findings and the El Niño SST anomaly was proven up to now.

However, the connection of a "positive east Pacific SST anomaly" and the occurrence of Feature 1 was established with statistical confidence by the correlation of respective long time series (Chiu et al., 1981). A hint that Feature 3 is linked to El Niño is the fact that just that EOF which has the largest coefficient in 1983 takes up its second largest coefficient in January 1973, when a more canonical El Niño event (i.e., with half the amplitude of 1983) took place. GCM simulation experiments with an El Niño SST anomaly (Shukla and Wallace, 1983; Blackmon et al., 1983; cf. Fig. 5) gave as a common property the intense depression north of the anomaly (Feature 1) but otherwise no

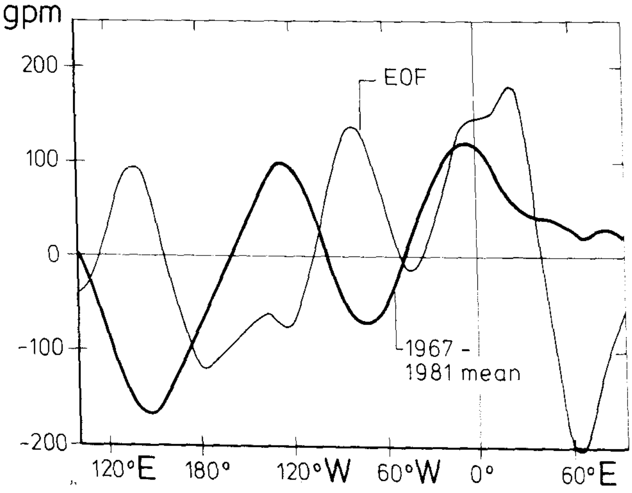

Fig. 4. EOF of the 30°–60°N average of quasistationary 500-mb disturbances which coefficient was found to be extraordinary large in January 1983 (thin line) and the 1967–81 January mean (solid line; from Von Storch, 1984).

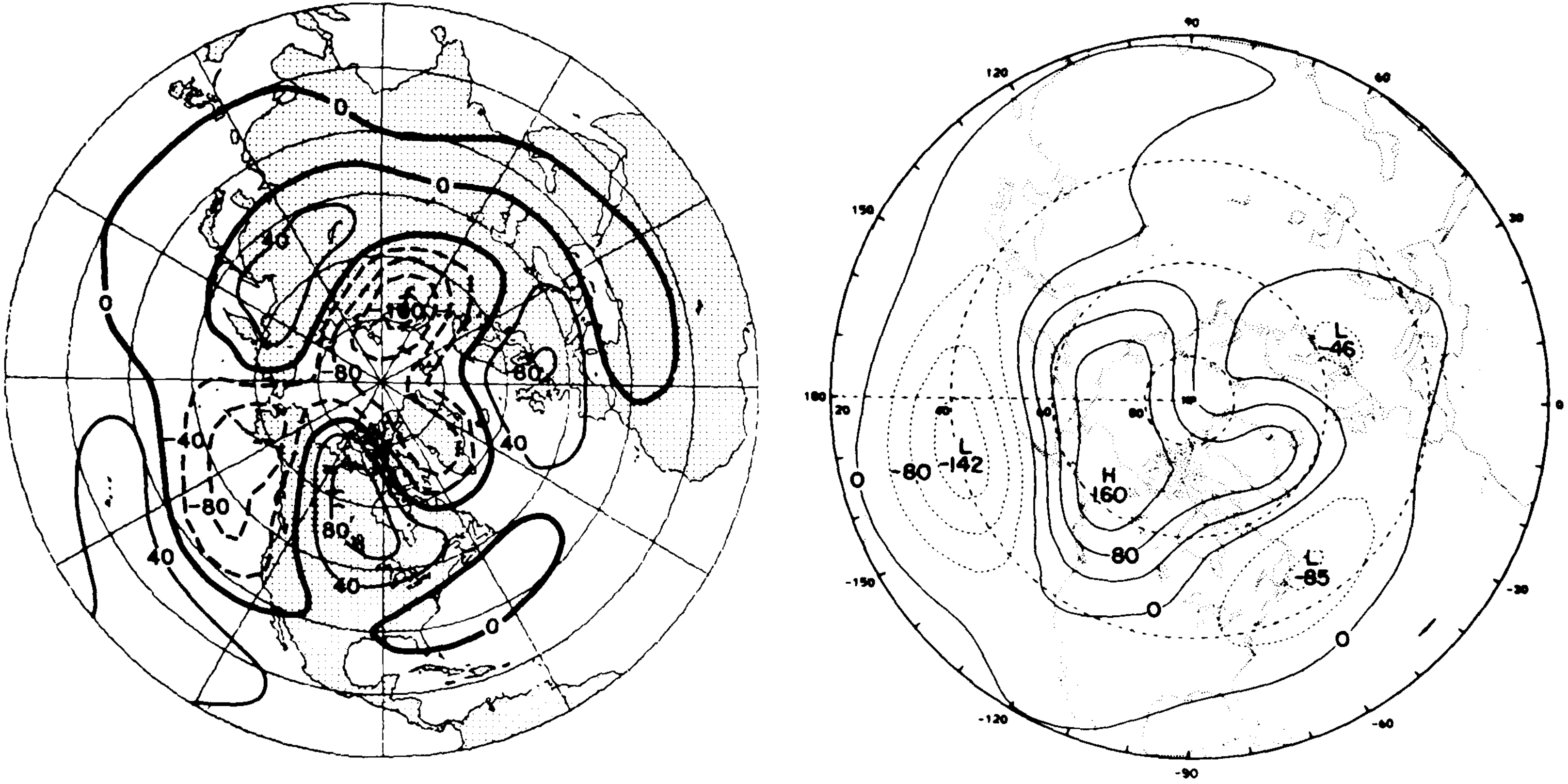

Fig. 5. Simulated response to El Niño SST anomalies given by Shukla and Wallace (1983; left) and Blackmon et al. (1983; right).

congruent remote responses. However, one of the model circulations exhibits Features 2 and 3 as well.

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 the T21L15 GCM performed at the European Centre for Medium Range Weather Forecast (ECMWF; Cubasch, 1983). These experiments consisted in the simulation of a total of nine winter seasons with a climatological SST distribution and of three winter seasons with a superimposed SST anomaly essentially equal to the January 1983 El Niño SST anomaly.

4. SIGNIFICANT EL NIÑO RESPONSE SIMULATION WITH THE ECMWF GCM

We investigated the ECMWF 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 done by a spectral expansion into a series of spherical surface harmonics (SSHs). A hierarchy of a few, large-scale SSHs, expected to represent the global character of the response, was established. A triangular truncation at total wavenumber seven was performed. Each member of this hierarchy was tested by a chi-square statistic. As the final significant response we selected that member of the hierarchy with maximum skill at the fixed significance level of 95% (Barnett et al., 1981).

These three tests resulted in a significant response in all three cases, which are displayed in Fig. 6. The selected members of the hierarchy differ with respect to the spectral resolution: the patterns of cases (*b*) and (*c*) consist of a superposition of 30 SSHs and are hard to distinguish from the respective untruncated patterns; pattern (*a*) shows up 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, insofar as the sequence of mid- and high-latitudinal relative 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 a "wave train" (e.g., Hoskins and Karoly, 1981), we may say 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. Again we found that the difference of the mean "control" and the mean "anomaly" state is highly significant (99%).

To analyze the differences, we return as in Section 2 back to the grid-point space and plot the 95% bands of the control ensemble and the three curves simulated by the anomaly experiments (Fig. 7). Since we are interested in the differences, we subtracted the mean state of all 12 experiments mentioned so far and of three further experiments with a cold anomaly, which will be discussed in Section 6. Thus, in Fig. 7 the details of the climatological patterns as e.g. the Pacific and East-American troughs are missing.

As can be deduced from Fig. 7, the pattern entitled Feature 1 in Section 3 is found in all three experiments. At two locations this pattern has an exceptional amplitude of 60 and 85 m, respectively, the third curve has at that longitude a maximal deviation at the lower bound of the normal, namely about 20 m.

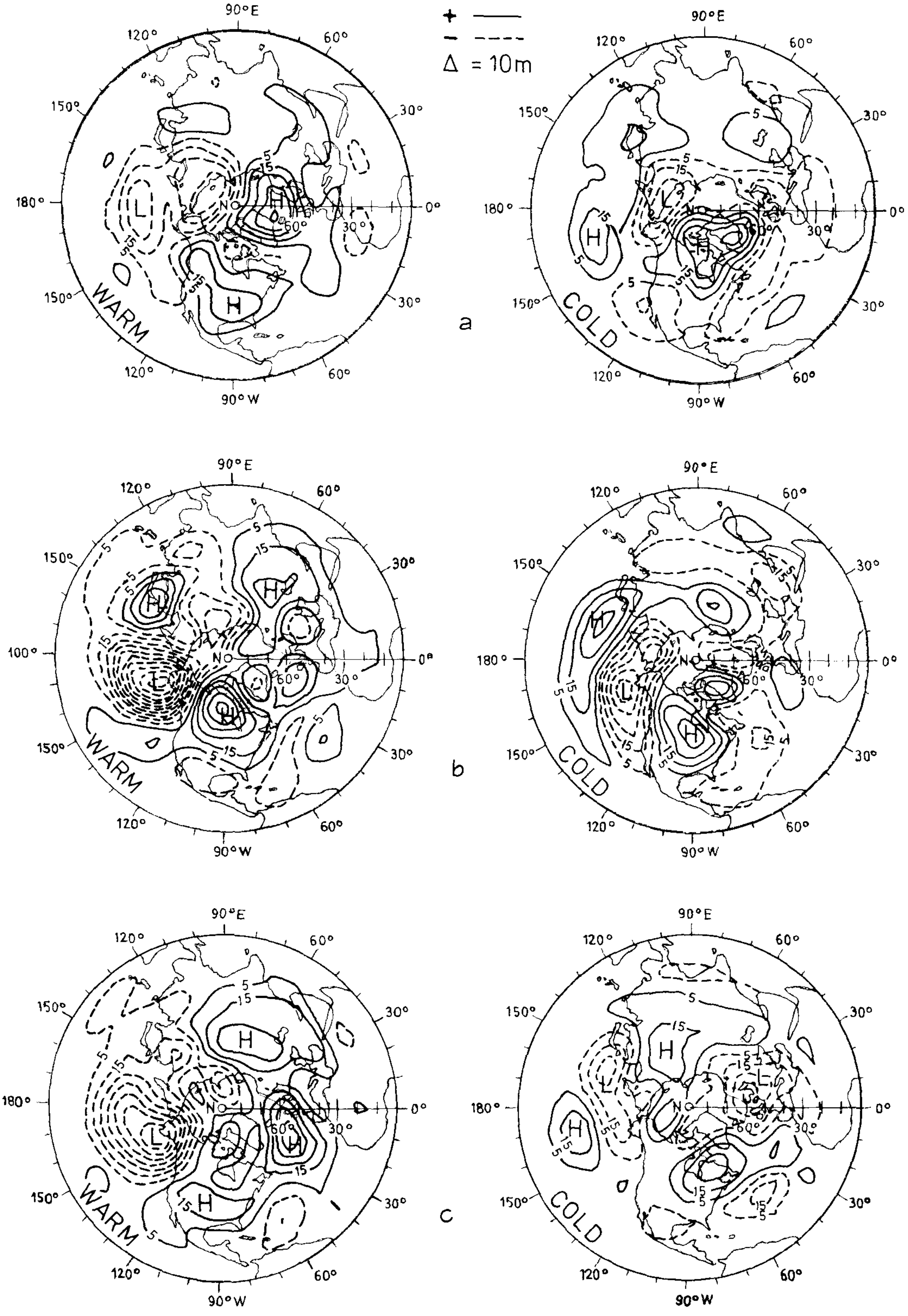

Fig. 6. Significant north-hemispheric response of the ECMWF GCM to a prescribed positive (left column) and negative (right column) El Niño SST anomaly. The negative anomaly experiment is discussed in Section 6. Contour interval: 10 m.

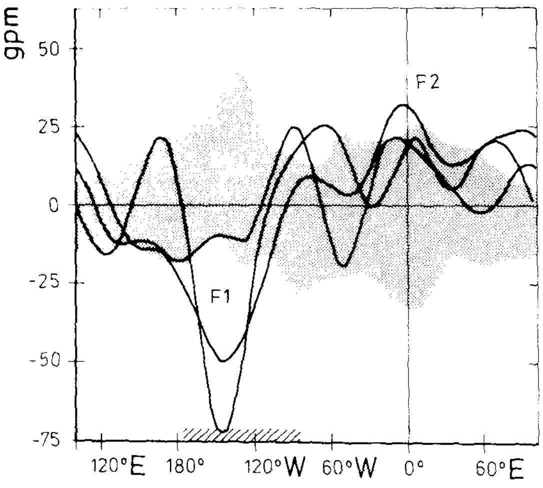

Fig. 7. The simulated SST anomaly response: 95% band of the 30°–60°N average of the mean 500-mb height built up of nine control experiments (stippled), and the corresponding states from three anomaly experiments (thin lines). Compare Features 1 and 2 with Fig. 6.

Furthermore, three maxima with stable location (namely about 90°W, 10°W and 70°E) are simulated, which are often found outside the 95% tube. The 10°W maximum coincides reasonably well with Feature 2 and the distribution of maxima and minima resembles Feature 3.

5. THE COINCIDENCE OF THE SIMULATED AND OBSERVED RESPONSE PATTERNS

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 that, 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. 2). We project the nine simulated "control fields" and the three "anomaly fields" onto this "observed response"; this procedure yields a total of 12 numbers, the scalar products, namely nine "controls" and three "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%.

This means that the simulated (significant) response pattern is correlated with the (significant) observed one. A side-by-side comparison of the observed (Fig. 2) and the simulated response (Fig. 8) shows that both fields are really very similar in structure. Besides Features 1–3, the North-American and Central Siberian ridges and the East-European and Greenland/North-Atlantic troughs are common properties. The difference in the amplitude values results from the under-estimated spatial variance of the GCM and the longer averaging period (three months) for the simulated patterns.

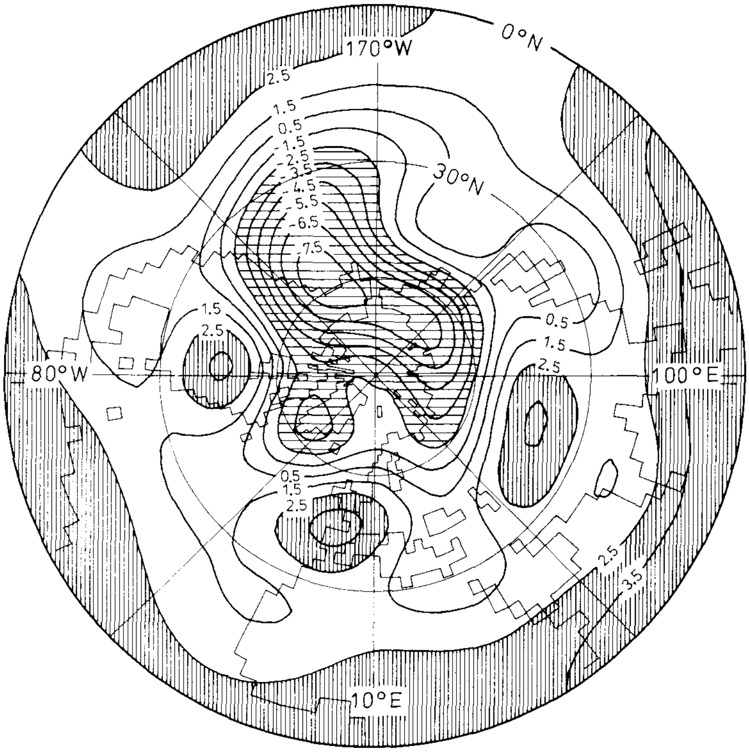

Fig. 8. Mean simulated response pattern: Average of anomaly runs minus average of control runs. Contour interval: 10 m.

6. DISCUSSION: THE LINEARITY HYPOTHESIS

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 three further GCM simulations with an SST anomaly distributed as the one studied above but with reversed sign (Cubasch, 1983). Following a proposal of Philander we denote such an anomaly as a "La Niña" event. A linear relationship would imply similar response shapes and amplitudes both for the warm El Niño and cold La Niña SST anomaly, but opposite sign.

In Section 4, we found a stably located negative center near the date line as the most pronounced response to the positive El Niño SST anomaly. At the same location, La Niña induces apparently a positive center, with half the amplitude. From this "principal center", wave trains emanate with wavelengths shorter than those in the warm anomaly experiments. However, the wave trains are not stable but vary with respect to strength and path. In fact, the application of the chi-square test sketched in Section 4 yields for La Niña significance levels of about 84% in two cases and below 50% in one case, whereas El Niño gave in all three cases responses significant at levels of more than 95%.

Thus, we conclude that the remote response of the 500-mb height field to the equatorial SST anomaly on the whole is nonlinear. A possible exception might be the subtropical center at the date line, which alludes to the possibility of a regional linearity.

The beauty of linear relationships gives the motivation to search for linear subsystems in the chain that leads from the ocean surface temperature anomaly to the global atmospheric response. The first link is the influence of the SST anomaly on the various diabatic heating processes, and the second link is the effect of these sources on the global atmospheric circulation.

Whereas diabatic heating anomalies due to sensible and radiative heat flux anomalies may be regarded as more or less linear in the SST anomaly, the latent heating is the essentially non-linear part of the game, even in simple parameterizations. From a simple two-layer model (Webster, 1981) the latent heat release has been estimated to be of the same order of magnitude as the sensible heat input, if the SST anomaly is placed in the tropics. Thus, the non-linear part of the heating processes plays an important part.

The second step to be considered is the dependence of the flow field on the heat sources. Here the question is whether the anomaly variables are small enough to allow for a linearization of the advective processes. To that end, the response of a GCM to a mid-latitudinal Pacific SST anomaly was compared to the response of a relatively simple linearized model to the forcing by the total heating induced by the SST anomaly as computed by the GCM (Hannoschöck, 1984). *It turned out that only a very small* fraction of the GCM response can be explained by a model with the linearized advection (Fig. 9).

Unfortunately, we cannot repeat Hannoschöck's study with our El Niño anomaly, because the heating anomaly generated by the ECMWF GCM is not available. Therefore,

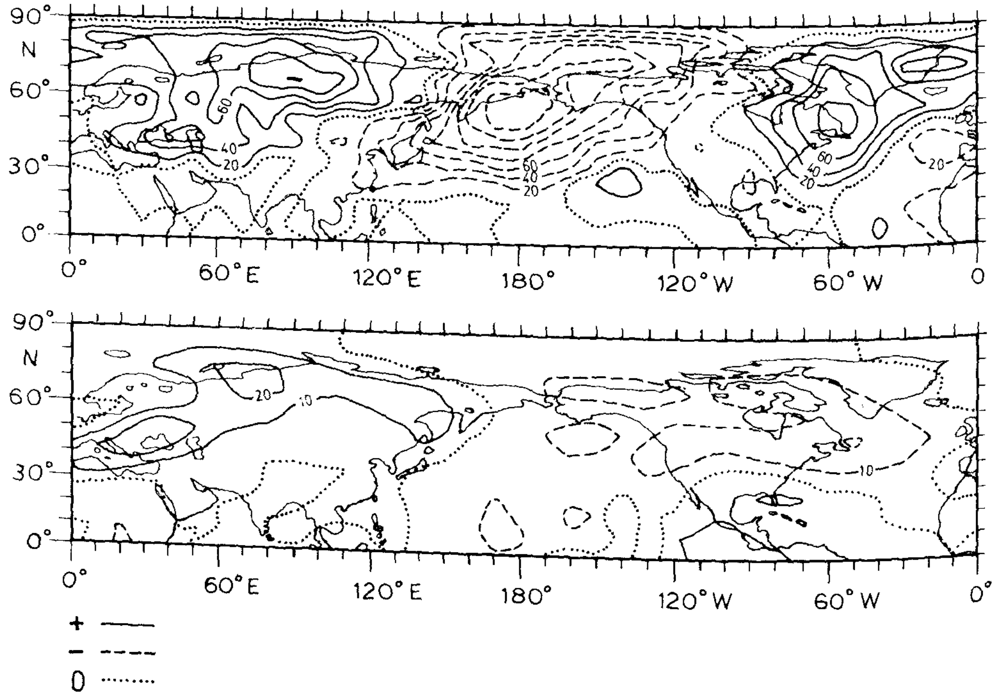

Fig. 9. Response to a mid-latitudinal SST anomaly of a GCM (top) and of a linearized model (bottom; from Hannoschöck, 1984).

we have to speculate whether Hannoschöck's result may be transferred to tropical conditions. However, even if the regional response to the tropical heating anomaly would be linear, this response would in turn induce mid-latitudinal heating anomalies, again causing non-linear reactions.

To summarize, the tropical SST anomaly produces a latent heating contribution that is an essentially non-linear function of the flow field, at least in the tropics. Furthermore, the global flow field depends non-linearly on these sources due to advection, at least in the mid-latitudes.

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