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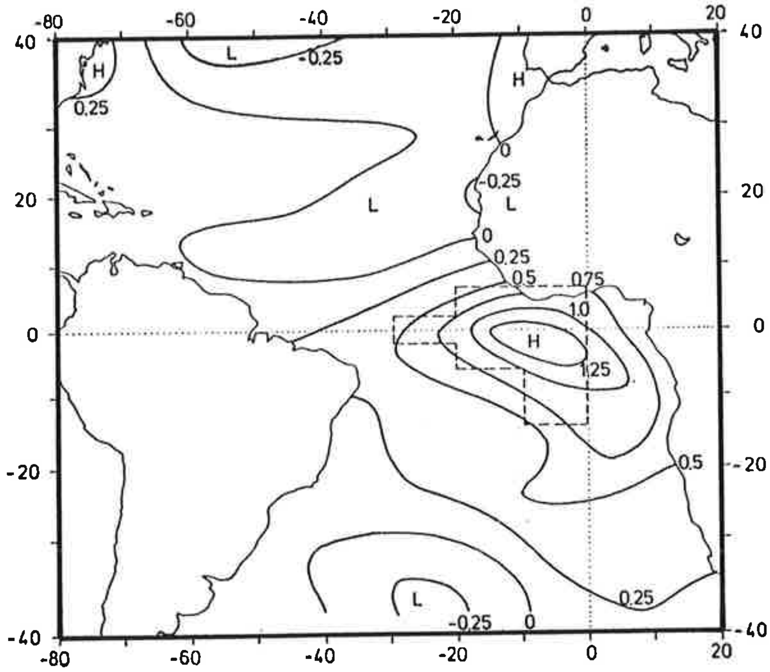

VARIATIONS IN TROPICAL ATLANTIC SEA SURFACE TEMPERATURES AND THEIR GLOBAL RELATIONSHIPS

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VARIATIONS IN TROPICAL ATLANTIC SEA SURFACE TEMPERATURES AND THEIR GLOBAL RELATIONSHIPS -- INTERIM REPORT

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ABSTRACT

The sea surface temperature (SST) in the tropical Atlantic (ATLO) exhibits fluctuations similar to those in the Pacific (ENSO), but of smaller amplitude and affecting a smaller area. Statistics of the ATLO index for three 30-year periods are presented. The annual variation of amplitude exhibits a consistent maximum in June-July, but the annual variation of persistence of anomalies is less consistent. Warm ATLO tends to follow warm ENSO and precede cold ENSO; these relationships are clearly marked and consistent with respect to ATLO in Dec-Feb, but weaker in other seasons and absent for ATLO in Jun-Aug.

To investigate teleconnections, we first subtract the Southern Oscillation signal from the data, then find correlations. ATLO warm SST anomalies are associated with low pressure over the tropical Atlantic and weak positive pressure anomalies over the Pacific, with appropriate wind anomalies, and also with higher cloudiness in parts of the tropical Atlantic.

Fields of correlation with the tendency of ATLO SST are also presented. These patterns differ between seasons. Warming sea in Dec-Feb and Sep-Nov is associated with weaker in situ easterly winds, and in Mar - May with weaker easterlies in the west Atlantic, and in JJA with warm sea (suggesting positive feedback).

It is concluded that ATLO and ENSO anomalies tend to influence each other, but the detailed mechanisms are very uncertain. Further analyses, and experiments with atmospheric and ocean dynamical models, are proposed to shed further light on the problem.

1. INTRODUCTION

There is evidence of a pattern of atmospheric and oceanic fluctuations centered in the equatorial Atlantic region, similar to the familiar El Nino / Southern Oscillation (ENSO) phenomenon centered in the equatorial Pacific. The purpose of this study is to document the statistical characteristics of this Atlantic phenomenon, and to determine its similarities to and differences from ENSO and its pattern of interaction with ENSO. This is done with the aid of empirical analyses using correlations and regressions. The results are interpreted in the form of a number of outline physical hypotheses. The present paper is an interim report -- plans for additional work to complete the study will be outlined in the final section.

In Section 2 we start by reviewing briefly some aspects of the behavior of ENSO, and we demonstrate evidence of an Atlantic phenomenon with broadly similar characteristics. An outline of the rest of the report is presented at the end of Section 2.

2. EQUATORIAL PACIFIC AND ATLANTIC PHENOMENA

2.1 ENSO

The El Nino - Southern Oscillation phenomenon (ENSO) is well known and has been studied from many aspects. Among its most important statistical characteristics are (Wright, 1985):

Persistence of anomalies in oceanic and atmospheric fields in several regions, mainly in the equatorial Pacific;

High amplitude of some of these anomalies;

Strong correlation between certain ocean and atmospheric anomalies;

A marked seasonal variation in all the above statistics;

Teleconnections between these anomalies and anomalies in other regions of the globe, some evident only in part of the year;

An irregular fluctuation of the anomalies with periods in the range 2 to 7 years.

The SST in the region 180°-90°W, 6°N-6°S is strongly correlated with many other features and has, with minor variations of defined region, been used frequently as an index of the state of the SO.

The Southern Oscillation is essentially a fluctuation of the coupled ocean-atmosphere system in the equatorial Pacific region. Its main characteristics conform with the hypothesis that there is positive feedback between the SST in the stated region and the overlying atmosphere, and that the feedback is strong during August - November and relatively weak during February - April (Wright, 1979). The teleconnections are generally regarded as global atmospheric responses to anomalous surface forcing by the equatorial Pacific SSTs (eg Horel and Wallace, 1981), and many of them have been simulated in atmospheric GCMs (eg Blackmon et al, 1983).

The causes of the fluctuations are less understood. Proposed explanations include: Quasi-deterministic processes involving heat storage and currents in the ocean (Cane and Zebiak, 1985); random atmospheric disturbances (Wright, 1979; Lau, 1985); and various systematic links involving the atmosphere over large regions of the globe (Nicholls, 1984; Barnett, 1984; Van Loon and Shea, 1985). It may be

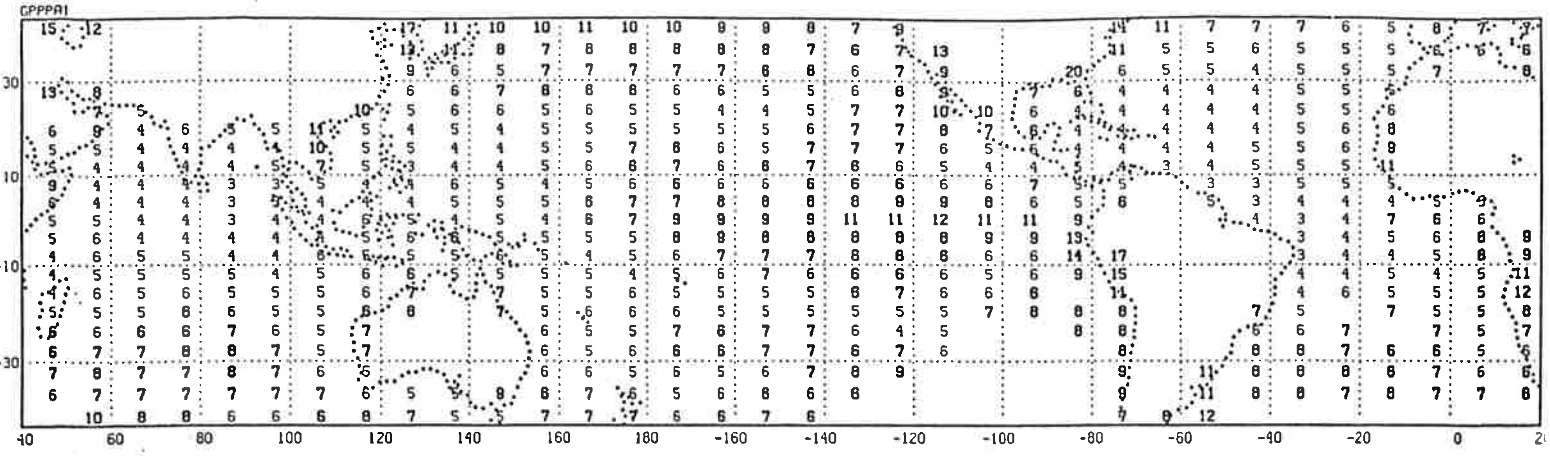


Figure 1: Standard deviation (tenths of deg C) of monthly anomalies of SST, all months 1950-1979, Values ≧ 0.60 deg C are in bold type.

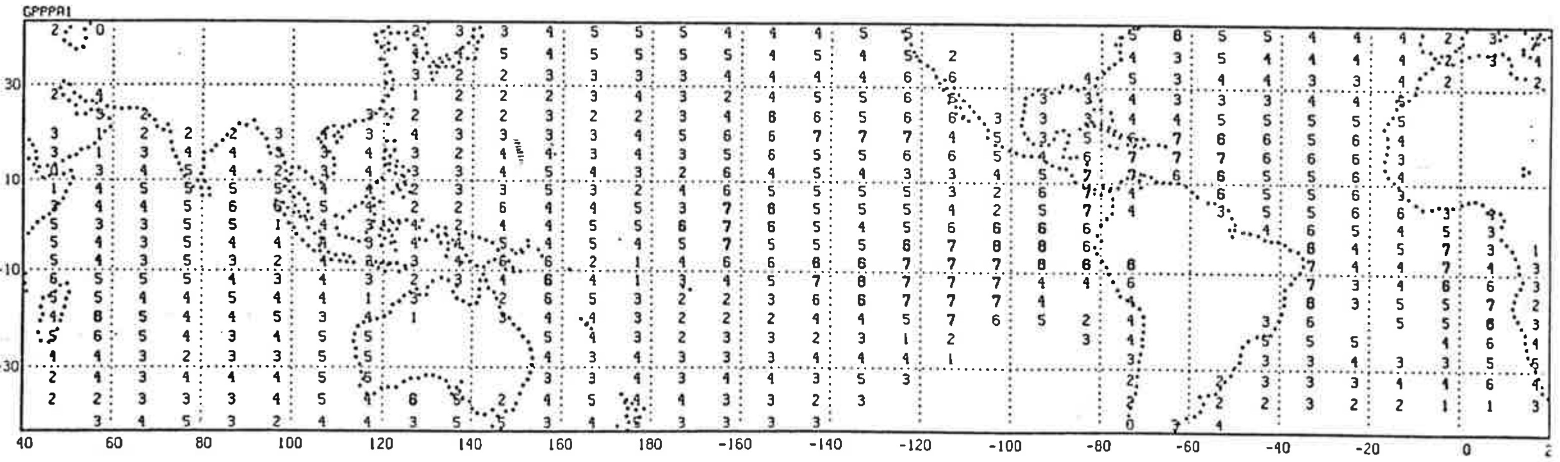


Figure 2: An estimate of the spatial coherence of SST anomalies, all months 1950-79. For each grid box, the mean correlation coefficient with the boxes to its west and east (10-degree interval) was found, then the mean with those to its north and south (4-degree interval). The value plotted is the product of the two quantities x 10. Values ≧ 0.60 are in bold type.

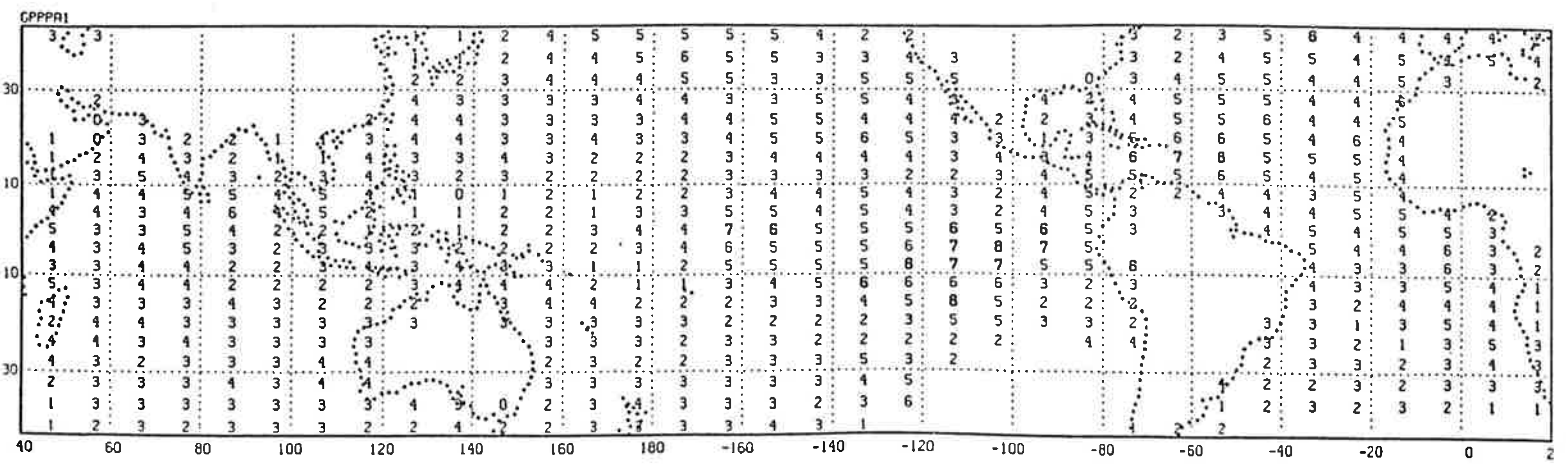


Figure 3: Autocorrelation x 10 at lag 2 months of monthly anomalies of SST, using all pairs Jan-Mar, Feb-Apr, ..., Oct-Dec in 1950-79, Values ≧ 0.60 are in bold type.

inferred that there could be several factors, in widely different regions, that can affect the SO. Some specific empirical relationships relevant to the present paper, described by Wright (1986), are: Warm equatorial Atlantic SST in DJF tends to be followed by cold equatorial Pacific; and a particular set of anomalies of the SST and several atmospheric fields in the southeast Pacific in DJF tends to favor changes in the SO.

That ENSO is a dominant mode of variation of the coupled ocean-atmosphere system is illustrated by maps of global SST statistics (Figs 1-3). These show that the equatorial east Pacific region is a strong local maximum of interannual variability (Fig 1), and a global maximum of spatial correlation (Fig 2) and of persistence (Fig 3).

2.2 Anomalies in the tropical Atlantic

A number of authors have pointed out similarities between the patterns of SST and atmospheric variables in the tropical Pacific and the tropical Atlantic, and have suggested that there is an Atlantic counterpart of El Nino (eg Weare, 1977; Servain et al, 1982; Hirst and Hastenrath, 1983). Figures 1-3 support this suggestion by indicating a maximum in all three statistics of SST in a region centered in the W Gulf of Guinea, although the values of all the statistics are much lower than those in the equatorial Pacific. A time series of SST anomalies in this area exhibits fluctuations with time scales of several years, and persistence of anomalies for several months (Weare 1977, his figure 11). Figure 4b confirms the existence of such fluctuations, and shows how they compare with the ENSO fluctuations (Fig 4a); although the average amplitude of the Atlantic fluctuations is much smaller, the amplitude and persistence of the most extreme 'events' are comparable with those of most El Nino events in the Pacific.

Atlantic SST anomalies have been convincingly related to rainfall anomalies in a number of adjacent areas (eg, NE Brazil by Markham and McLain (1977), the Sahel by Lamb (1978) and Folland et al (1986), and Angola by Hirst and Hastenrath (1983)), and there is strong evidence of the existence of a system of correlated variations in several fields (eg, Hastenrath 1984). Hastenrath indicated that the relationships between these fields are now well-documented and partially understood, but that the least understood aspect is how the SST anomalies develop and persist.

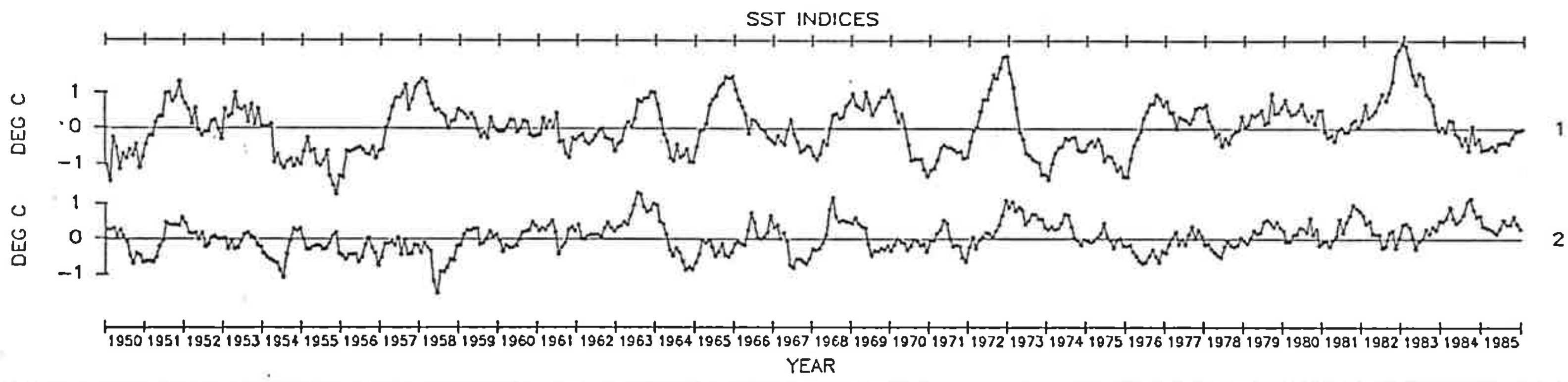


Figure 4: Monthly values of two SST indices, 1950-79.
a) Equatorial central and E Pacific (region 1 of Fig. 5)
b) Equatorial E Atlantic (region 8)

Wright (1986) examined relations between SSTs in the equatorial Pacific and the equatorial Atlantic. He noted lead-lag relations in both senses, suggesting an interaction between the two systems of anomalies.

Several recent papers (Nature, 1986) have discussed the period 1983-84 when an extreme event resembling an El-Nino event, but with smaller amplitude, occured in the tropical Atlantic.

The above suggests the existence of an 'Atlantic phenomenon' corresponding to ENSO for the Pacific. We will refer to this phenomenon as the 'Atlantic Oscillation' (ATLO). [Footnote: No connection is implied with the North Atlantic Oscillation (NAO) which, as defined by Walker and Bliss (1932) and studied more recently by Van Loon and Rogers (1978) involves only atmospheric pressure and temperature fields north of 30N.]

2.3 Outline of report

In the rest of this report we will document the main statistical characteristics of ATLO. In particular, we will address the following questions: How does the phenomenon compare with ENSO? What are the main factors that cause ATLO SST anomalies to develop and persist; in particular, do they involve positive feedback, and/or forcing from outside the region?

We define ATLO as: The variations of SST anomalies in the east equatorial Atlantic, together with all phenomena that are associated with those variations. We examine ATLO along lines similar to those used by the author in studies of the SO (Wright, 1977, 1985), as follows. We start by determining an SST index of ATLO. We then note the areas of best spatial correlation in the SST field, how the field is correlated with atmospheric fields in the region, and the patterns of teleconnections with global SST and atmospheric fields, in each case making comparisons with the corresponding characteristics in the Pacific. We attempt to assess cause-and-effect relationships; in particular, we try to elucidate whether positive feedback plays a part in the development of ATLO, and whether the anomalies are forced by the SO or other phenomena. To this end, we also calculate correlations between fields and the TENDENCY of ATLO SST.

We also attempt to document the relationships between ATLO and ENSO, in particular the interesting lead-lag relationships in both senses that appear to exist. These lead not only to further enlightenment about causes of ATLO, but also to an infererce about a possible contributory cause of ENSO.

Finally, we set up some plausible outline physical hypotheses that would account for the observed relationships, and we propose some possible means of verifying them with the aid of currently-available GCMs.

3. DATA AND GENERAL METHOD

The main data set used was the trimmed (fully quality-controlled) version of the Comprehensive Ocean-Atmosphere Data Set (COADS) (Fletcher et al, 1983) This was converted to anomalies in 4° latitude by 10° longitude boxes using the procedure described by Wright et al (1985). Fields used were SST, pressure, zonal and meridional components of wind and cloudiness for 1950-79, a period in which the data are probably homogeneous. The earlier period 1870-1949, for which data are much more sparse and certainly inhomogeneous in some of the fields, was used to compile a few selected indices. We use as an index of ENSO the mean SST anomaly in the region 1 shown in Fig 5. This is almost identical to the region used for an index by Wright (1984), and for periods before 1950 we use that index. We define a similar index for ATLO (Sec 4).

The main part of the work involves correlations and regressions between a monthly index and the monthly global fields. For many of these analyses, months were grouped into seasonal groupings, eg March, April and May, and analyses carried out with this set of months, ie three from each year. It must be emphasized that all our analyses, except where stated otherwise, used monthly means and not seasonal means; when we refer to seasons, we imply simply that the analysis was limited to the months of the given season.

Many correlation and regression studies have been done on the ENSO phenomenon, and the resulting patterns of association may with confidence be attributed to ENSO. However, when similar studies are done using the ATLO index, one finds that some of the observed patterns are simply reflections of the more dominant SO. Therefore, we decided to repeat some of our analyses with the SO signal removed from the fields. This was done as follows, taking the pressure field as example:

First, for the group of months December, January and February, the pressure field was regressed on the simultaneous monthly value of the ENSO SST

SST INDEX REGIONS

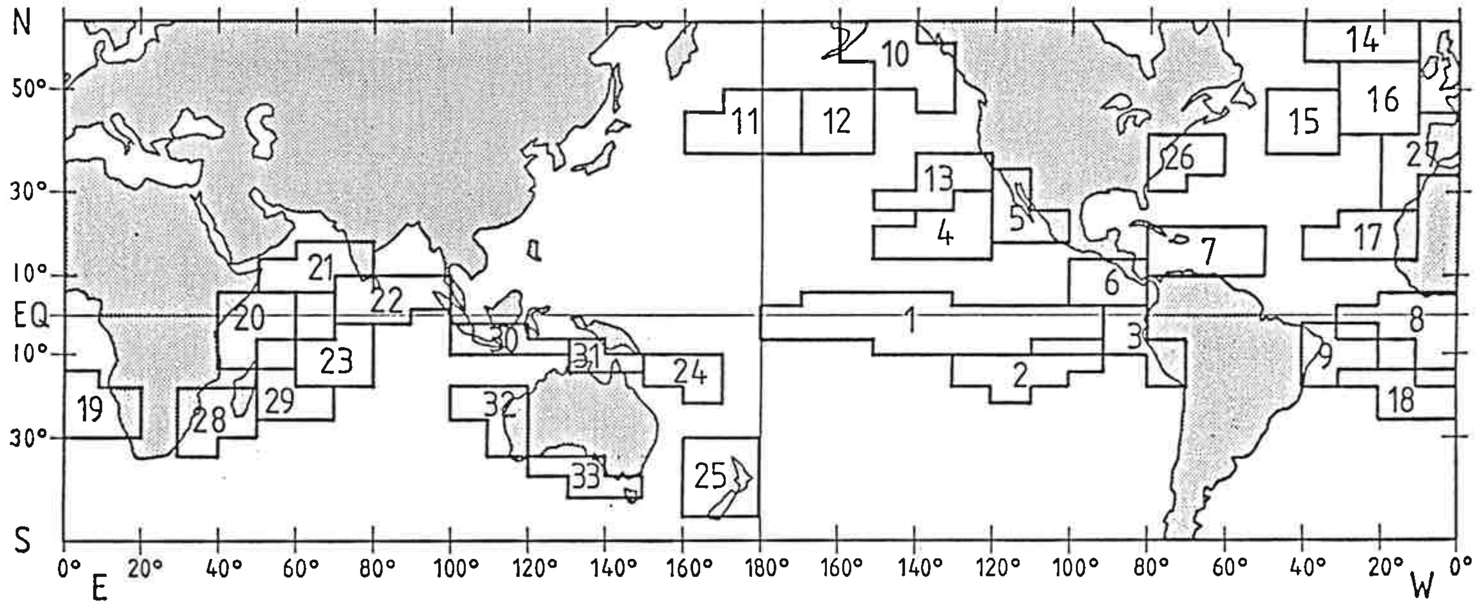


Figure 5: The 33 regions of relatively high variability, spatial correlation and autocorrelation of SST.

index. Then, for each individual month in this set, the product: Regression coeft × ENSO index was subtracted from the field to obtain the 'de-regressed field'. Then, the whole procedure was repeated for each other group of months (March, April, May; etc). Finally, a de-regressed ATLO index was calculated from the de-regressed SST fields.

In Section 8 we relate global fields to the TENDENCY of the ATLO index. The tendency T of the index A is defined as:

$$T_n = A_{n+1} - A_{n-1}$$

where n is the month number 1, 2, ... 12, 1, 2...

4. DEFINITION OF INDEX

The first analysis requirement is for an index that represents a large proportion of the variance of the tropical Atlantic SST, and involves a spatially coherent region. Figures 1-3, which show maxima of the three statistics in the Gulf of Guinea region, imply that this is an appropriate thing to seek.

The relevant region was identified during a preliminary study in which the global COADS SST was analysed to identify many such regions. That analysis will now be described briefly, because some of the results have implications for the way in which the Atlantic phenomenon will be viewed.

From preliminary versions of Figs 1 to 3, local maxima of the three statistics were identified. Some were eliminated as being close to greater maxima, or in areas of unreliable data. For each remaining maximum, a time series was produced and correlated with the time series for neighbouring 4°×10° boxes. Those boxes with high correlations then defined a region over which the mean anomaly was calculated. This provisional index was again correlated with all neighbouring boxes, the correlation being repeated for each month group seperately. From the results, modifications were made to the regions such that every included box had both a high correlation overall, and also a moderate correlation in all 4 month groups. Also, boxes eligible for more than one region were allocated to one only.

The final set of 33 indices was classified according to the magnitude of its statistics, especially of the 2-month autocorrelation both overall and in each month. As a result, three classes were identified (Fig 5):

Class 1 (regions 1-9) had high 2-month autocorrelation in nearly all months.

Class 2 (regions 10-25) had high or moderate 2-month autocorrelation (≧ 0.5) in most months.

Class 3 (regions 26-33) had an overall 2-month autocorrelation of about 0.4 to 0.5.

The equatorial Pacific region is unique in having strong correlations over large distances, demanding to be combined as a single index covering a much larger area than any of the others. The resulting region is nearly the same as that used by Wright (1984), and not very different from the 'Nino-3' region used by the Climate Analysis Center.

TABLE 1. Statistics of the 9 class 1 indices.

Nr.		nr boxes	st dev deg C	2-mo autocor			cors with index	
				max	mean	min	nr. 1	nr. 8
1	Eq E. Pacific	26	.73	,96	,84	,61	1,00	,20
2	SE Pacific	8	,49	,91	,81	,65	,70	,09
3	Peru coast	6	1,10	,88	,67	,07	,67	,05
4	E of Hawaii	9	,52	,84	,74	,57	,30	-,07
5	Baja Calif.	6	,70	,81	,68	,60	,56	-,03
6	Costa Rica	6	,45	,89	,76	,61	,81	,13
7	Caribbean	9	,31	,88	,77	,60	,41	,07
8	Eq E Atlantic	9	,42	,84	,72	,56	,20	1,00
9	NE Brazil	6	,31	,79	,69	,49	,06	,42

Table 1 presents the main statistics of the Class 1 indices. Since the equatorial Pacific index has the second largest amplitude as well as being much the largest spatially, it dominates the global picture, and several other indices are correlated with it strongly (indices 2,3 and 6) or weakly (4,5 and 7). Most of those have smaller amplitude and much smaller area. All, however, have high persistence, which may be partly due to their strong link with the equatorial E Pacific index. The Peru Coast index has much the highest amplitude, a fact that explains why this region has received prominence in El Nino studies; nevertheless, it is of much smaller spatial extent and less persistent than the main Pacific index, and is far from perfectly correlated with it.

Two of the indices (8,9) are negligibly correlated with the east Pacific index overall. These are, however, moderately correlated with each other. Their amplitudes and persistences are comparable with the weaker ones in the east Pacific 'family'. The 'leader' of the pair in terms of all characteristics is the equatorial east Atlantic. This region may thus reasonably be regarded as the most important region for SST anomalies that is also largely independent of the ENSO system. Index 8 therefore proves suitable for our purposes, and the above analysis provides a background for its role in the global climate system.

LAG	1	2	3	4	5	6	7	8	9	10	11	12
JAN	94	84	54	30	11	2	−11	−3	−2	−5	−5	−9
FEB	87	61	46	27	14	3	7	7	8	8	2	−4
MAR	74	61	47	32	25	32	32	30	31	23	16	7
APR	81	74	61	56	59	57	55	53	51	43	36	9
MAY	89	77	75	77	76	79	77	70	60	49	18	−11
JUN	88	85	83	84	87	86	81	69	58	21	−2	−10
JUL	95	90	90	93	91	87	79	67	29	2	−5	−15
AUG	91	92	94	93	89	83	69	33	1	−7	−16	−29
SEP	95	95	93	90	83	70	29	0	−12	−23	−36	−25
OCT	97	96	94	86	76	42	15	0	−8	−21	−12	−10
NOV	97	95	86	72	34	5	−9	−17	−27	−19	−16	−22
DEC	96	89	76	39	11	−4	−16	−26	−17	−13	−19	−19

LAG	1	2	3	4	5	6	7	8	9	10	11	12
JAN	85	78	69	48	24	20	13	1	3	−1	−10	−3
FEB	89	85	59	27	17	12	−2	−1	−1	0	6	2
MAR	91	71	43	28	25	9	3	0	−8	0	−8	−1
APR	82	55	37	36	26	23	21	10	19	12	11	0
MAY	85	62	56	46	47	40	28	38	25	10	4	9
JUN	84	74	60	60	57	48	49	38	17	5	−5	−20
JUL	89	73	66	62	57	59	52	40	27	14	−6	−9
AUG	89	77	76	65	65	52	41	25	4	−11	−13	−16
SEP	89	85	72	73	58	49	35	21	8	2	5	−15
OCT	95	82	80	58	46	34	22	3	3	9	−1	0
NOV	88	83	63	51	38	19	−7	−4	0	−10	−9	−15
DEC	93	77	66	57	28	0	1	3	−4	−3	−6	−18

Figure 6: Autocorrelations x 100 stratified by month of the ENSO and ATLO indices, 1950-79, left: ENSO SST index; right: ATLO SST index. Isopleths are drawn for correlations of 0.8, 0.6, 0.4 and 0.2.

LAG	1	2	3	4	5	6	7	8	9	10	11	12
JAN	79	63	49	37	31	−9	−1	−11	−28	−12	−2	0
FEB	78	69	55	55	5	15	−4	−21	−1	15	25	30
MAR	69	52	45	−6	25	8	2	23	29	32	29	19
APR	54	38	9	19	−8	−18	−19	−6	22	15	3	−3
MAY	63	41	52	32	3	19	25	45	36	25	27	29
JUN	39	71	36	18	36	43	44	52	33	23	33	12
JUL	56	59	1	13	30	36	44	50	13	34	20	−2
AUG	71	50	55	70	67	59	48	27	28	11	−15	−16
SEP	52	65	72	73	64	59	30	13	15	−19	−11	−20
OCT	81	64	53	47	24	36	−2	−4	−9	−43	−40	−50
NOV	82	75	72	55	60	13	17	−17	−20	−29	−30	−25
DEC	75	69	71	60	30	20	−11	−7	−30	−25	−14	−8

LAG	1	2	3	4	5	6	7	8	9	10	11	12
JAN	75	71	38	27	−7	18	9	30	33	36	37	36
FEB	68	41	26	11	29	20	24	38	23	20	8	−7
MAR	67	54	29	54	37	60	56	31	12	4	−4	−8
APR	83	64	75	69	74	54	31	−9	−20	−4	0	−11
MAY	82	82	77	72	55	43	16	6	20	14	1	−8
JUN	76	79	65	59	35	19	2	20	4	−16	−33	−28
JUL	86	81	56	29	18	4	12	16	−12	−20	−15	3
AUG	74	54	24	26	11	17	26	3	−7	2	12	8
SEP	76	49	27	19	26	28	−10	−11	−8	2	0	3
OCT	68	48	23	36	14	−11	−1	1	−2	2	−3	23
NOV	50	27	52	6	−8	−1	0	−14	−7	−16	12	11
DEC	82	73	55	37	27	2	21	18	27	33	31	15

Figure 7: As Fig. 6 but for 1920-49. Isopleths are slightly smoothed.

LAG	1	2	3	4	5	6	7	8	9	10	11	12
JAN	88	75	67	66	43	27	4	10	−1	−2	1	14
FEB	71	65	62	40	34	15	17	11	14	11	19	14
MAR	75	68	55	37	23	28	21	21	17	25	15	24
APR	70	63	53	39	33	28	32	24	30	39	14	13
MAY	76	46	41	59	42	40	47	49	43	36	37	15
JUN	70	66	76	61	61	68	70	68	42	36	33	8
JUL	81	79	68	71	66	63	67	47	40	49	21	−3
AUG	81	82	81	83	78	77	58	41	51	23	20	0
SEP	83	88	87	81	79	68	53	51	27	11	−4	1
OCT	90	92	90	85	71	56	60	37	22	6	16	0
NOV	89	91	84	80	53	59	39	12	0	9	−1	1
DEC	94	87	71	64	55	33	21	4	6	−5	0	−7

LAG	1	2	3	4	5	6	7	8	9	10	11	12
JAN	70	75	58	41	25	39	23	11	15	8	−12	−19
FEB	64	64	38	36	47	26	35	38	24	6	7	11
MAR	74	54	45	54	37	28	39	13	−6	−19	−10	−20
APR	64	47	48	45	45	47	26	22	2	−1	−2	2
MAY	57	66	41	47	38	24	18	16	5	7	−2	7
JUN	72	63	46	44	24	19	20	26	−12	−4	0	0
JUL	65	54	62	36	14	22	16	10	4	8	9	3
AUG	64	65	45	27	13	16	5	10	15	23	0	2
SEP	66	70	54	34	35	24	20	21	25	18	10	14
OCT	50	33	32	43	28	36	19	12	9	16	42	17
NOV	61	47	33	38	14	9	22	11	3	−1	−7	−4
DEC	54	36	49	40	29	22	23	20	4	12	−19	−29

Figure 8: As Fig. 6 but for 1870-1919. Isopleths are slightly smoothed.

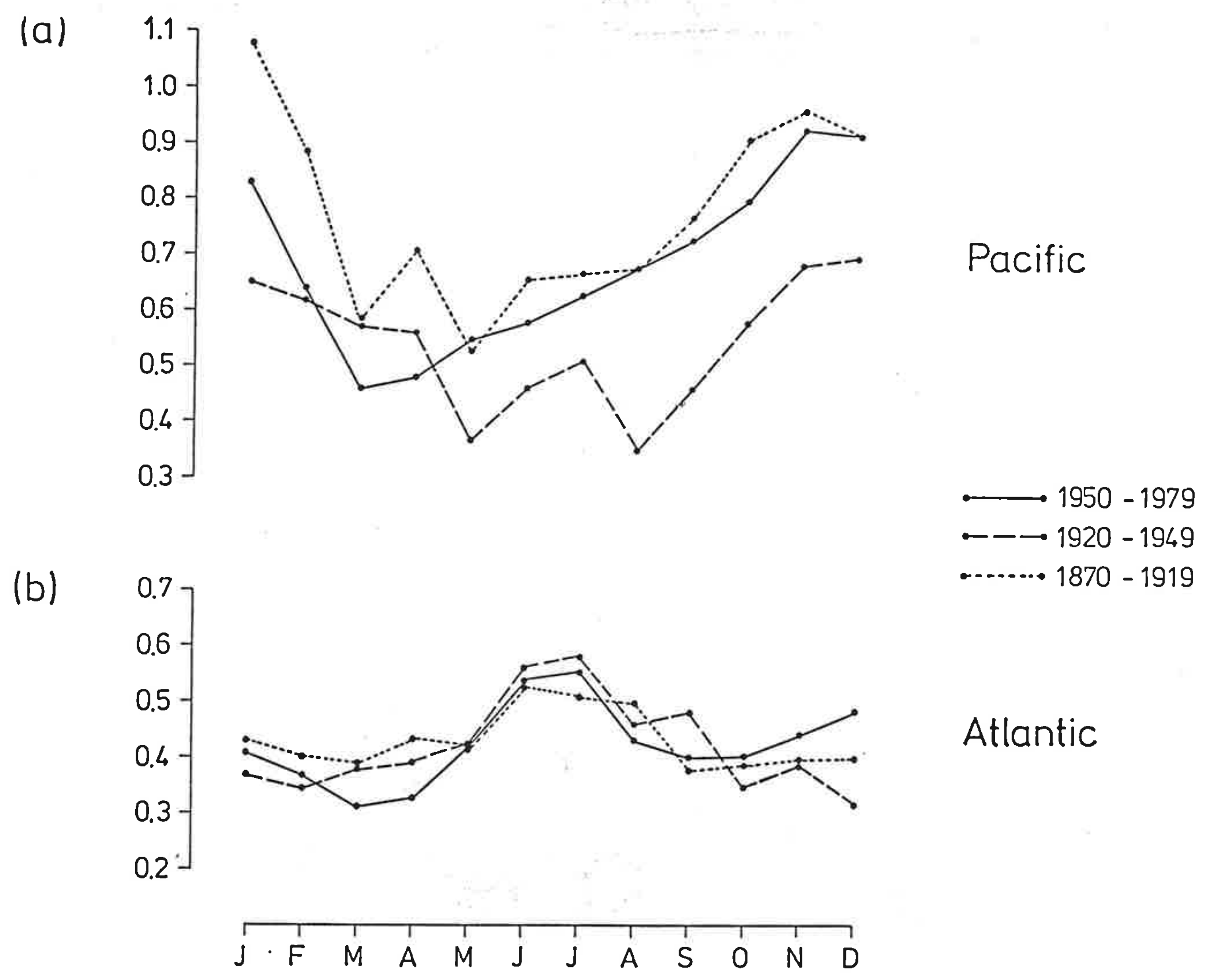


Figure 9: Standard deviation (deg C) of the ENSO and ATLO indices for each month during three periods.
a) ENSO index
b) ATLO index

5. BEHAVIOR OF ATLANTIC INDEX AND COMPARISONS WITH PACIFIC

5.1 Spatial coherence

From Table 1, we see that the Atlantic index has high spatial coherence over an area of about 1/3 of the size of the Pacific index, and its variance is just over 1/3 of that of the Pacific index.

5.2 Time series

From the graphs of the time series of the two indices (Fig 4), we see that the Atlantic index exhibits marked persistent spells, but not as consistently or with as high amplitude as the Pacific.

5.3 Autocorrelations

Fig 6 shows the autocorrelations of the two indices, stratified by month. The Pacific diagram, based on a preliminary data set, has been previously presented (Wright, 1985). The Pacific index shows a marked annual cycle of autocorrelation, with a maximum in March-April. The Atlantic index shows a rather less pronounced annual cycle, with a rather less marked minimum in April-May, and with the general level of autocorrelations much lower than in the highly correlated part of the Pacific pattern.

To assess the consistency of these patterns over a longer period, we present the same results for two earlier periods (Fig 7-8). The numbers of observations on which the data are based were much lower than in the recent period especially for the Pacific, and this is reflected in the greater noise level of the correlations. The Pacific pattern was similar in all three periods, although less clearly defined in 1920-49 (Fig 7a). The Atlantic patterns, however, differed substantially between the three periods.

5.4 Interannual Variability

The interannual variability of the Pacific index during 1950-79, as measured by the standard deviation for each month separately, had a marked annual cycle, with a minimum in March-April (Fig 9a, full line). In 1870-1919 a similar pattern occurred (dotted line), but in 1920-49 the annual behavior of this statistic was somewhat different (dashed). In the Atlantic (Fig 9b) there was also a marked seasonal pattern, with a peak of variability in June-July that was notably consistent between the three periods, and a rather flat minimum extending over the rest of the year. There was a secondary maximum in December clearly evident in the most recent period, but not in the previous periods.

5.5 Relation between the two indices

In 1950-79 the monthly values of the Pacific and Atlantic indices were correlated 0.20. Correlations for the Pacific index leading up to three months were almost the same, indicating that the Pacific index tends to lead the Atlantic by some two months. The simultaneous correlation between monthly values varied with season, from 0.43 in the group of months December, January and February to 0.06 in March, April and May.

Correlations between seasonal mean values of the indices are presented in Fig 10. The full lines, for 1950-79, support the evidence above. For all seasons together (fig 10a), the simultaneous correlation varied between the three periods of years, but a feature common to all the periods was a slight tendency to positive correlations when ENSO leads, and negative when ATLO leads. This implies that warm ENSO tends to be followed by warm ATLO, which in turn tends to be followed by cold ENSO, the latter being more consistent. Fig 10b-e shows that these characteristics varied substantially between seasons. They were clearly marked in DJF in all periods, weakly marked in MAM, absent in JJA, and evident but not consistent in SON. The most consistent result is that warm ATLO in DJF, and to a weaker extent in MAM and SON, tends to be followed by cold ENSO. These relationships for 1950-79 were noted by Wright (1986), and it is encouraging that many of them are supported by data for other periods.

5.6 Evidence relating to feedback

The temporal behavior of the Pacific index is consistent with the hypothesis that it is involved in positive feedback with the atmosphere, with the feedback varying with season (Wright, 1979). The relevant characteristics are: High autocorrelations of both the SST and an atmospheric index; high correlations between them; and a synchronous annual cycle in autocorrelations, standard deviations and correlation. For ATLO, the persistence throughout the year suggests that positive feedback may be operating, and during the periods May to July and October to December, when persistences are moderately high and the variability increases, the evidence is more compelling. Further elucidation

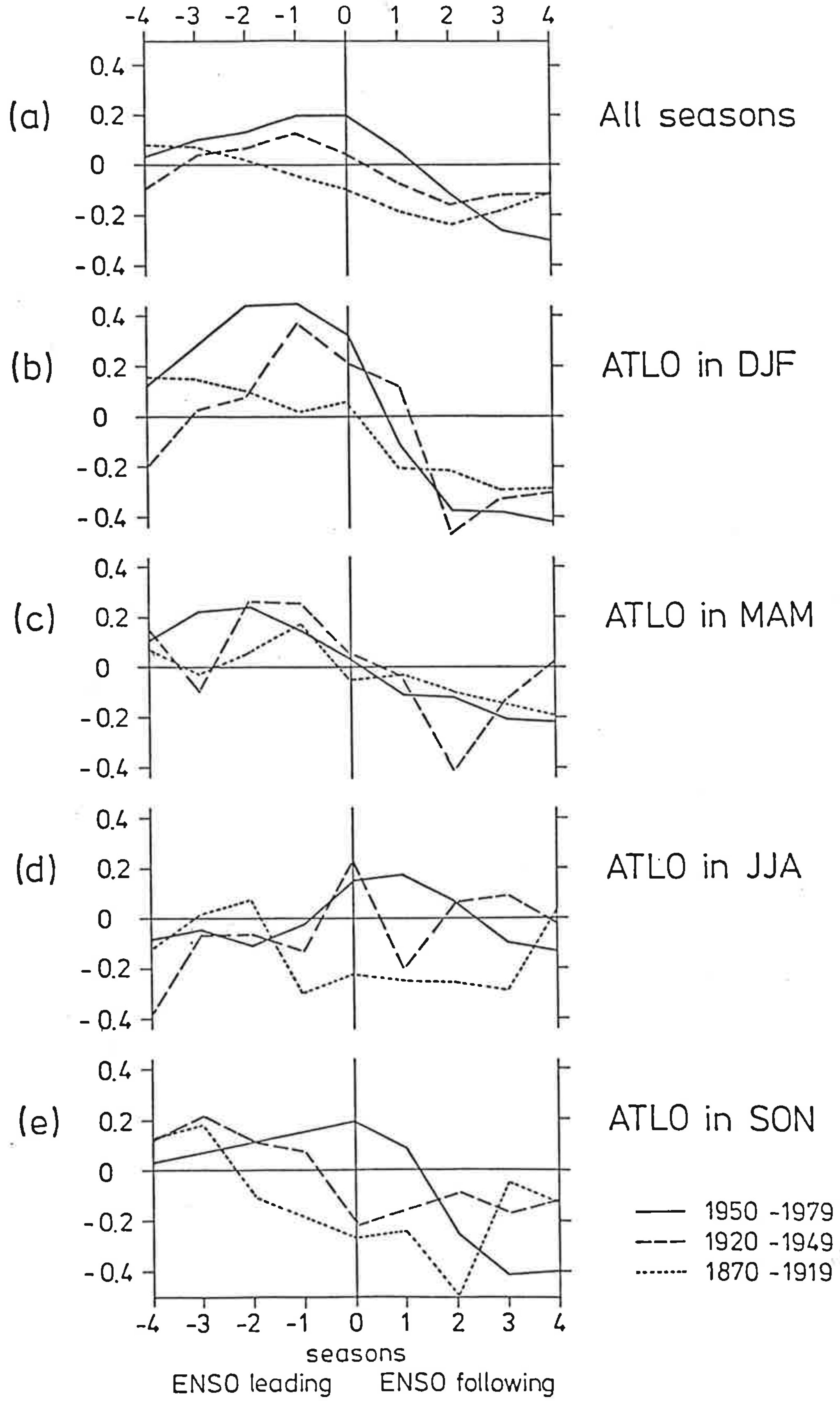


Figure 10: Correlation between ENSO and ATLO seasonal mean indices for lags from 0 to 4 seasons each way.

requires evidence that another physical feature exhibits complementary behavior.

6.SPATIAL PATTERN OF SST ANOMALIES

6.1 The general picture

Fig. 11 shows the result of regressing the SST in each square on the ATLO index. The center of the anomaly is in the W Gulf of Guinea, as expected from the definition of the index. In addition, a region of moderate anomalies extends well to the SE, and there is also an extension W to the Brazil coast. The 'center of action' is south of the Equator, and there is a sharp cutoff to the north where the anomaly becomes negligible.

This pattern is similar to the dominant pattern of tropical SST variation identified by Weare (1977) in a Principal Component Analysis. However, it differs from the patterns found by Lough (1986) who performed a Principal Component Analysis on normalised departures. It has resemblances to patterns found by Hastenrath (1984) and others to be related to rainfall in the Sahel or in N E Brazil. However, most of those patterns include a pronounced anomaly with opposite sign in the northern tropics, whereas ours does not. Our subsequent results, therefore, are somewhat different from those of previous studies. In particular, our results do not reproduce the pattern identified by Moura and Shukla (1981) and used as forcing in a GCM experiment.

6.2 Seasonal variations

Next, we look at how the spatial pattern changes with season. For this purpose we relate the SST field in the months from April to the following March, grouped in 3's, to an annual index which was defined as the mean index July-January. This set of months was chosen on the basis of Fig. 6b, which suggests that the index is relatively highly autocorrelated then. The following regression maps (Fig. 12) may be regarded as 'weighted composites' in which every year is used,weighted according to its annual index. They may be viewed as showing the 'typical evolution' of Atlantic SST anomalies.

In every season, the region of greatest amplitude is nearly the same, the W Gulf of Guinea, centered 2°S, 10°W. This is only partly due to the definition of the key region, since the April-June data are independent and January-March largely

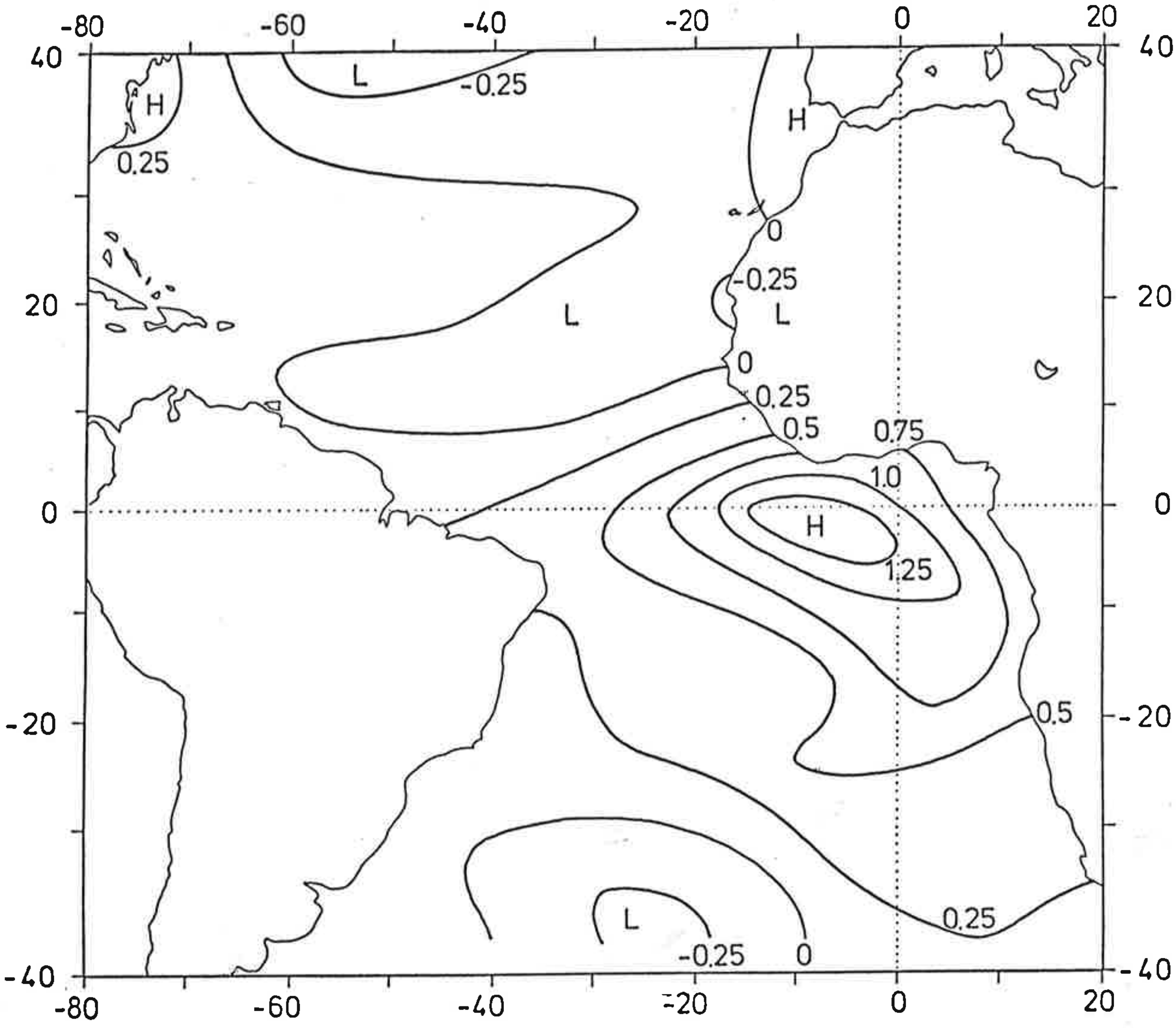


Figure 11: Regressions of monthly SST anomaly on the monthly ATLO index, all months 1950-79 (deg C).

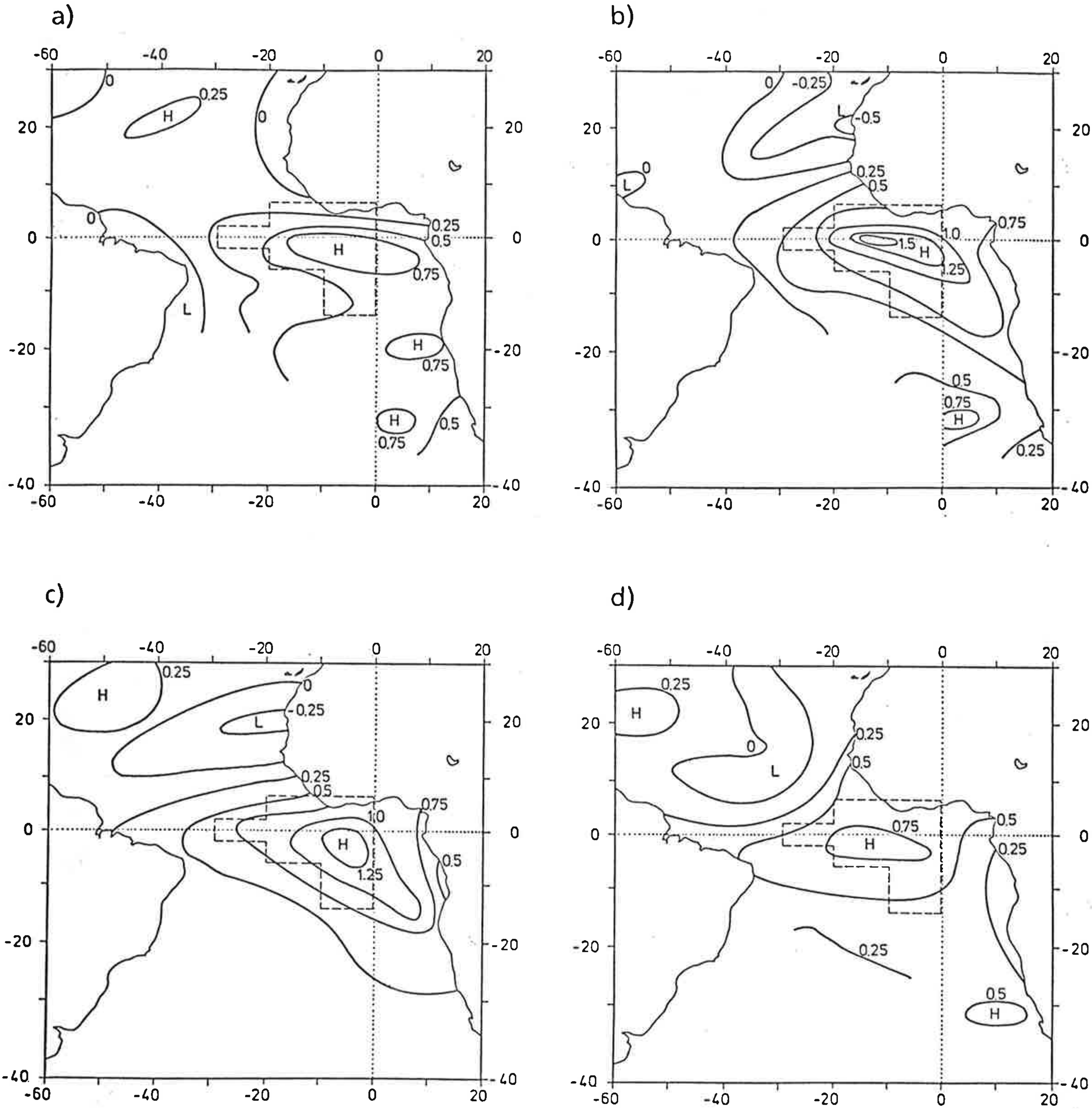
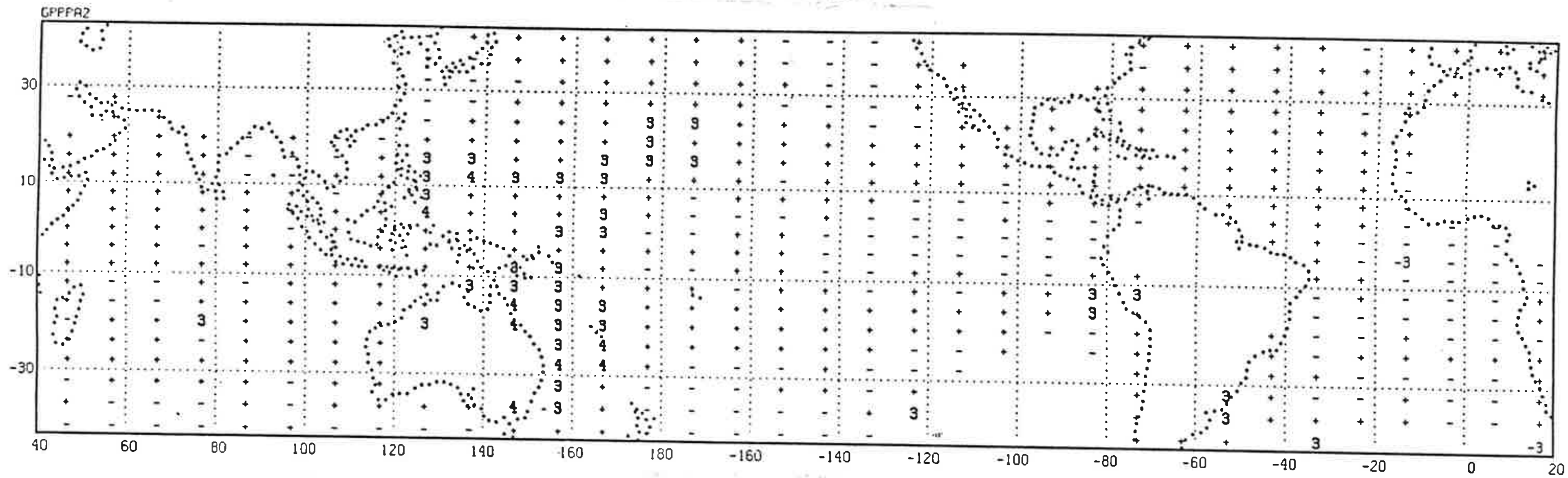


Figure 12: Regressions of monthly SST anomaly in months shown on the ATLO annual index (mean over July-January). a) Apr, May and June prior to period of annual index; b) July, Aug & Sep; c) Oct, Nov & Dec; d) Jan, Feb and Mar following period of annual index.

independent of the data used for the index. This implies that a dominant characteristic of the SST variability is a quasi-stationary fluctuation in amplitude.

The early season shows a strong extension of the affected region towards the south, and very weak anomalies in the north and west; by contrast, the third and fourth seasons show a lobe extending to the coast of Brazil. This sequence indicates a pattern of propagation of anomalies from the SE Atlantic to the key area and subsequently westward to Brazil. The propagation is in the direction of the surface currents. This pattern of behavior may be identified in the analysis of Markham and Mclain (1977), and implies that a component of the tropical Atlantic SST variation involves propagation of anomalies.

a) D, J, F



b) M, A, M

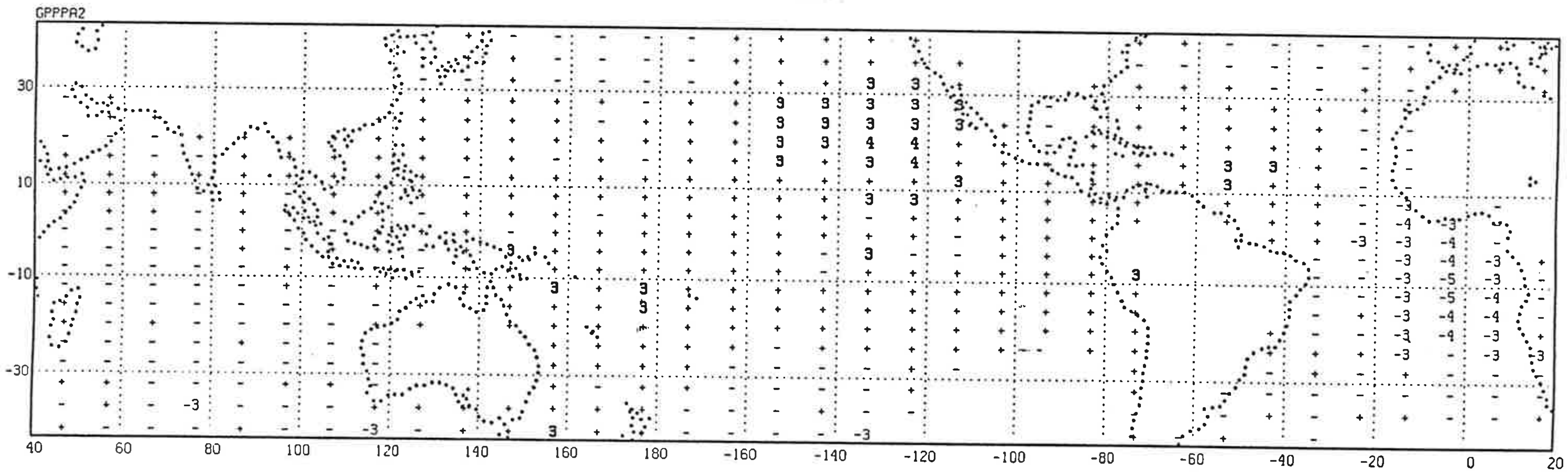


Figure 13: Correlation x 10 between pressure and ATLO SST index for 2 month groups, 1950-79. Correlations within the range ± 0.25 inclusive are shown by sign only. Except in data-sparse areas, a value of ± 0.26 is significant at the 98% level if considered in isolation. a) Dec, Jan & Feb; b) Mar, Apr & May.

7. RELATIONS OF GLOBAL FIELDS TO ATLANTIC SST INDEX

7.1 Introduction

We now examine simultaneous relationships between the ATLO SST index and atmospheric fields. Many of these relationships are apparent in the results of previous authors who have examined anomalies of several variables in relation to rainfalls in specific regions (Hastenrath, 1984).

7.2 Pressure

Fig 13 shows the correlation patterns for two of the month groups for pressure related to the ATLO SST index, using the original data set.

In a widespread region centered on the ATLO area, there is a negative pressure anomaly in all seasons. In JJA (not shown) it is strong, but in DJF it is very weak. In other regions, the only teleconnections clear enough to be of interest are: In DJF and SON, parts of the W Pacific have a positive correlation; in MAM, the area between California and Hawaii is positive; and in all seasons, the area over and east of the Caribbean is weakly positive.

First consider the local correlations. The observed patterns conform with theory, as follows. Warm sea favors warming of the lower troposphere, thence instability, increased convection and latent heating of the upper atmosphere, therefore a decrease in density throughout the troposphere and therefore a fall in surface pressure. This is accompanied by convergence, which implies appropriate wind anomalies in neighboring areas. Further support is given by the evidence that SST anomalies in the Pacific are associated with similar anomalies, and by evidence (not presented here) that anomalies in many of the other SST regions referred to in Sec 4 are also accompanied by pressure anomalies (warm sea by low pressure).

Therefore, what is surprising is not the existence of a local signal in the pressure field, but the lack of it in DJF. But we may note that, in DJF, ATLO exhibits the largest correlation with the SO (warm Atlantic is associated with warm Pacific, Fig 10b), and that warm Pacific then is associated with high pressure in the tropical Atlantic (eg Wright et al, 1985). Perhaps the effects of the two SST anomalies on the Atlantic pressure field are tending to cancel out.

This question can be resolved using the pressure data with the SO signal regressed out. Fig. 14 shows the correlations for all 4 month groups using this de-

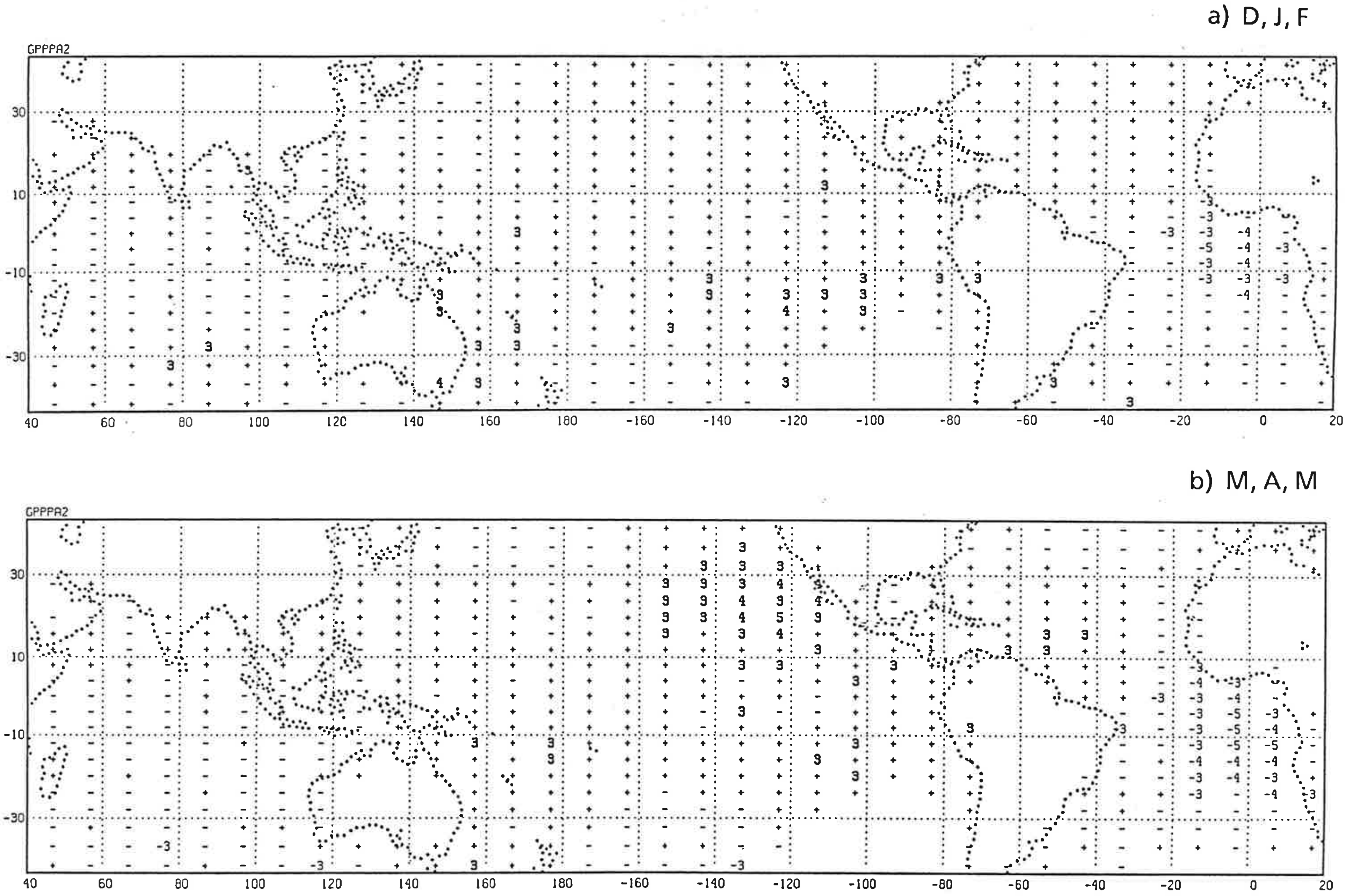
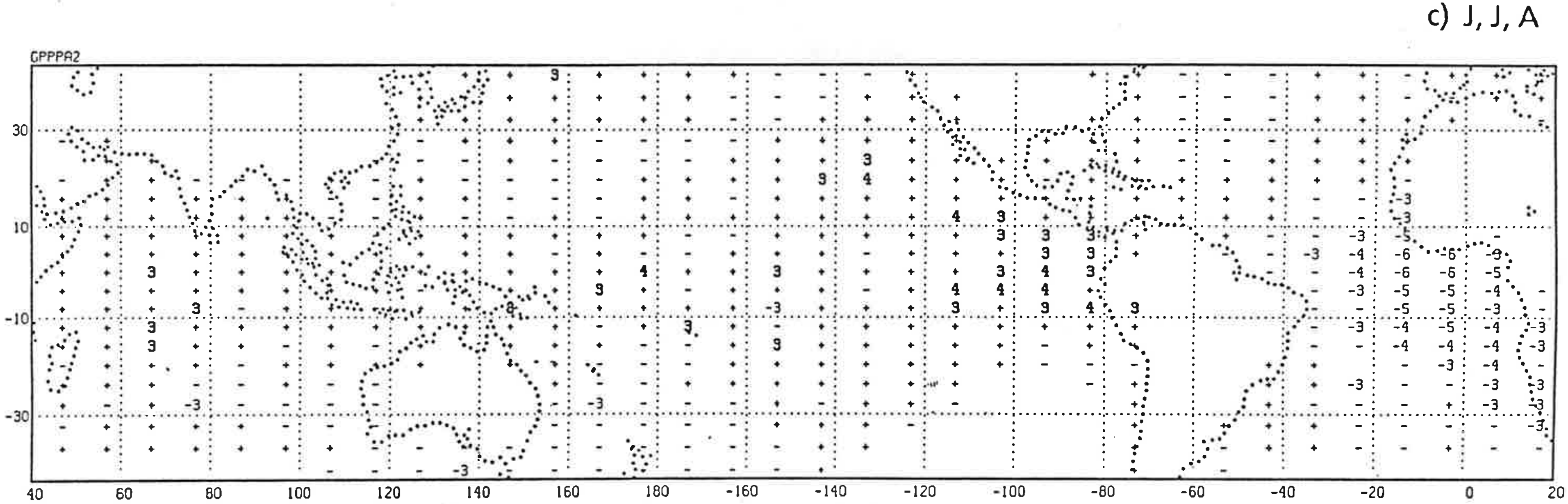


Figure 14: As Fig. 13 but using the de-regressed pressure data and de-regressed ATLO index.



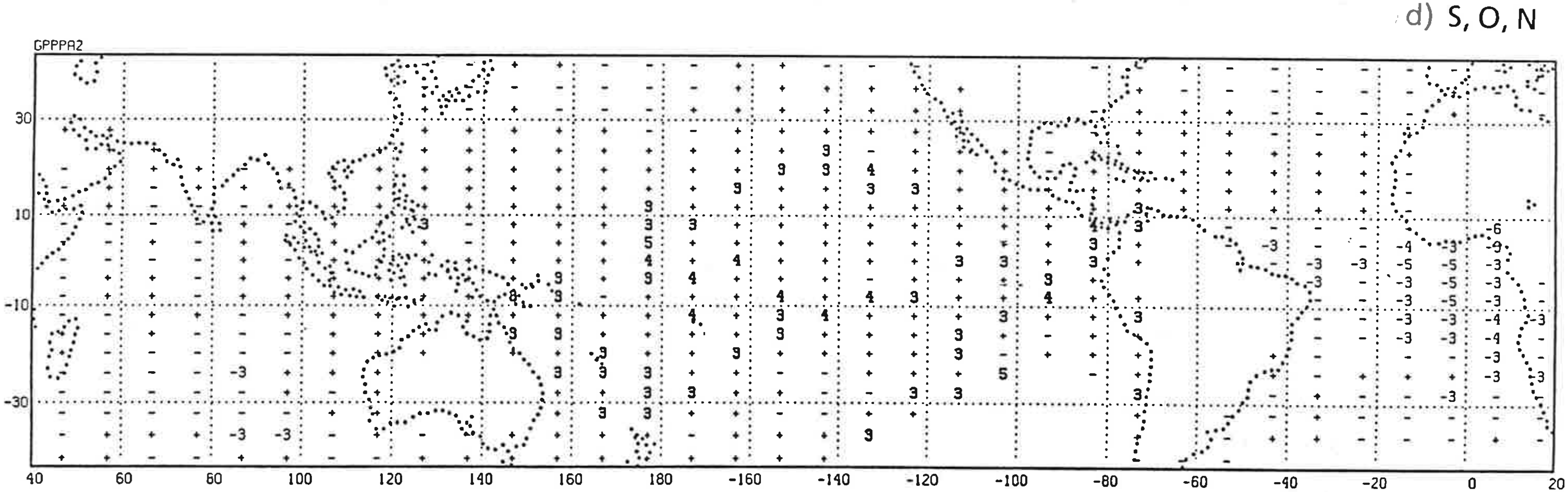


Figure 14: As Fig. 13 but using the de-regressed pressure data and de-regressed ATLO index.

regressed set. Over the Atlantic the negative correlations in the 3 seasons MAM, JJA and SON are similar to those of the original set and slightly stronger. But now, in DJF a pattern similar to and only slightly weaker than those of the other seasons appears. These results support the suggestion that warm equatorial Atlantic tends at all times to cause low pressure over itself, but that, in DJF, the addition of the correlated SO effect tends to cancel out the pressure anomaly.

Now consider the teleconnections (correlations at greater distances). In the de-regressed data, the feature in the W Pacific has largely disappeared, suggesting that it is essentially a characteristic of the SO and not a response to ATLO. The other features are little changed. There is a tendency in all seasons for most of the tropical and subtropical Pacific to exhibit positive pressure anomalies when the equatorial Atlantic is warm. The Indian Ocean anomaly, on the other hand, changes sign with season.

It is well known that ENSO SST warm anomalies are associated, not only with negative pressure anomalies in the Pacific sector, but also with a large area of positive pressure anomalies over the Indian Ocean sector, the two forming the familiar SO pressure 'see-saw'. Many authors have presented a map of this pattern (eg Berlage 1957). Fig. 15 presents a new version based on the trimmed COADS monthly mean data, with the SST index as the reference index. The pattern is very familiar, but the improved data coverage in the Pacific reveals that the 'centre of action', or at least, the centre of correlation, of the Pacific arm lies near the Equator and not, as often believed, near Tahiti, although correlations are generally greater in absolute magnitude in the Southern Hemisphere than in the Northern. Note the two lobes of positive anomalies extending symmetrically eastward in the N and S subtropical W Pacific.

The equivalent of Fig. 15, but using the ATLO index as reference and based on the de-regressed data, is shown in Fig. 16. The negative pressure anomaly over the Atlantic is similar in shape to that over the Pacific in Fig. 15. In addition, there is a large though weak positive correlation covering nearly all the Pacific, which could be regarded as corresponding to the Indian Ocean anomaly in Fig. 15. There is even a suggestion of two lobes to the east in the subtropical NW and SW Atlantic. The pattern but is thus remarkably similar to the characteristic SO pattern but displaced some 140° to the east. We may thus regard Fig. 16 as a display of the atmospheric component of ATLO. It will be very interesting to explore further its similarities to and differences from the Southern Oscillation.

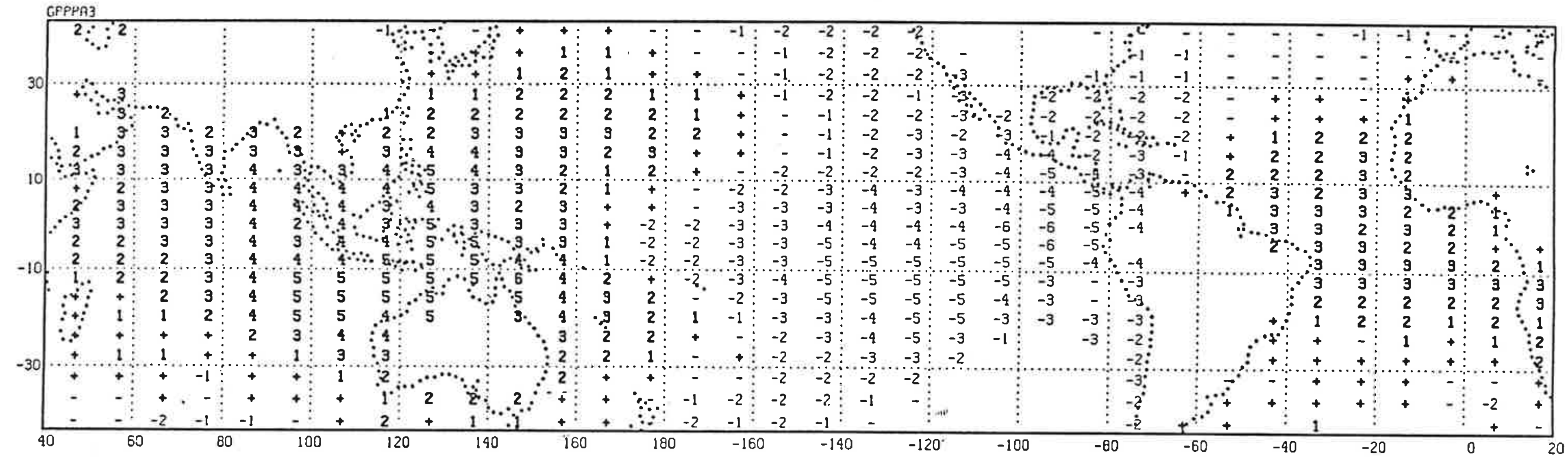


Figure 15: Correlation x 10 between monthly pressure and ENSO SST index, all months 1950-79.

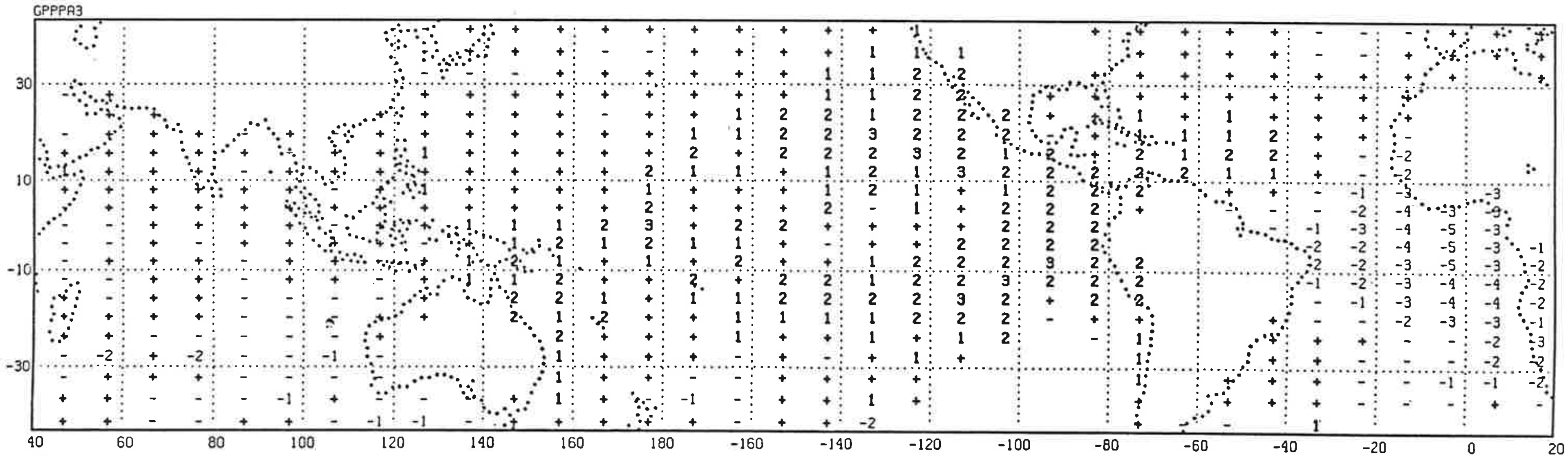


Figure 16: Correlation x 10 between monthly de-regressed pressure and de-regressed ATLO SST index, all months 1950-79.

7.3 Winds

The pressure anomaly over the Atlantic associated with ENSO in DJF is rather uniform over a large area (Wright et al, 1985, their Fig. 20), implying that the wind anomalies there associated with ENSO are weak. As a result the wind anomaly patterns over the tropical Atlantic for ATLO, unlike the pressure patterns, differ little between the original and the de-regressed data sets. The latter (Figs. 17, 18) are in all seasons marginally stronger.

The main features associated with warm equatorial E Atlantic are: Increased westerlies in the W tropical Atlantic; increased northerlies to the N and southerlies to the S, both across the whole Atlantic; and a weak tendency to easterlies in the east tropical Atlantic. These features are present in all seasons, except that the zonal wind anomalies are very weak in SON. They conform with the corresponding pressure anomalies, and they also resemble the wind anomalies over the Pacific that accompany ENSO anomalies. The fact that they are present in DJF in the original set, in which the pressure anomaly does not agree with them, supports our inference that the pressure anomaly associated with ATLO in DJF is really quite strong but is masked by the influence of ENSO.

In the Pacific a number of areas of spatially consistent anomalies appear, but they are different in different seasons. In the SE tropical Pacific, weaker westerlies and stronger southerlies in DJF both imply that the Trades are stronger when ATLO is warm. In the N tropical Pacific in MAM, a pattern of anomalous northerlies, easterlies and southerlies as one moves west conforms neatly to the anomalously high pressure noted between California and Hawaii. In other seasons and regions no strong signals are evident.

7.4 Cloudiness

The cloudiness correlation patterns for full (not shown) and de-regressed (Fig. 19) data are nearly identical. The strongest feature is a region of high cloudiness in the west tropical Atlantic in MAM. This reflects the correlation of Atlantic SST with rainfall in NE Brazil noted by numerous authors. The same feature is present more weakly, and in slightly different areas, int the other season. A region of low cloudiness is apparent in the E Atlantic in 3 seasons, in varying positions. The regions of stronger trades noted above in the E Pacific in DJF and MAM both tend to be also regions of higher cloudiness. In the regions not shown in Fig. 19, no significant anomalies were evident.

7.5 Summary

Warm SST in the equatorial E Atlantic is associated with the following simultaneous atmospheric anomalies (and cold SST with the opposite anomalies):

1) Low pressure in the area of the SST anomaly, with winds converging on that area from N, S and W (except very weak in SON), and weakly from E.
2) High cloudiness in the W tropical Atlantic (though weak and of small extent in SON, DJF).
3) A weak tendency for high pressure over most of the Pacific in all seasons.
4) Low cloudiness in part of the tropical E Atlantic, varying in position with season, and including the region of SST anomaly in SON, DJF.
5) In the SE tropical Pacific in DJF, high pressure, increased trades and a weak tendency to greater cloudiness.
6) In the NE tropical Pacific in MAM, high pressure and associated wind anomalies on its E, S and W flanks.

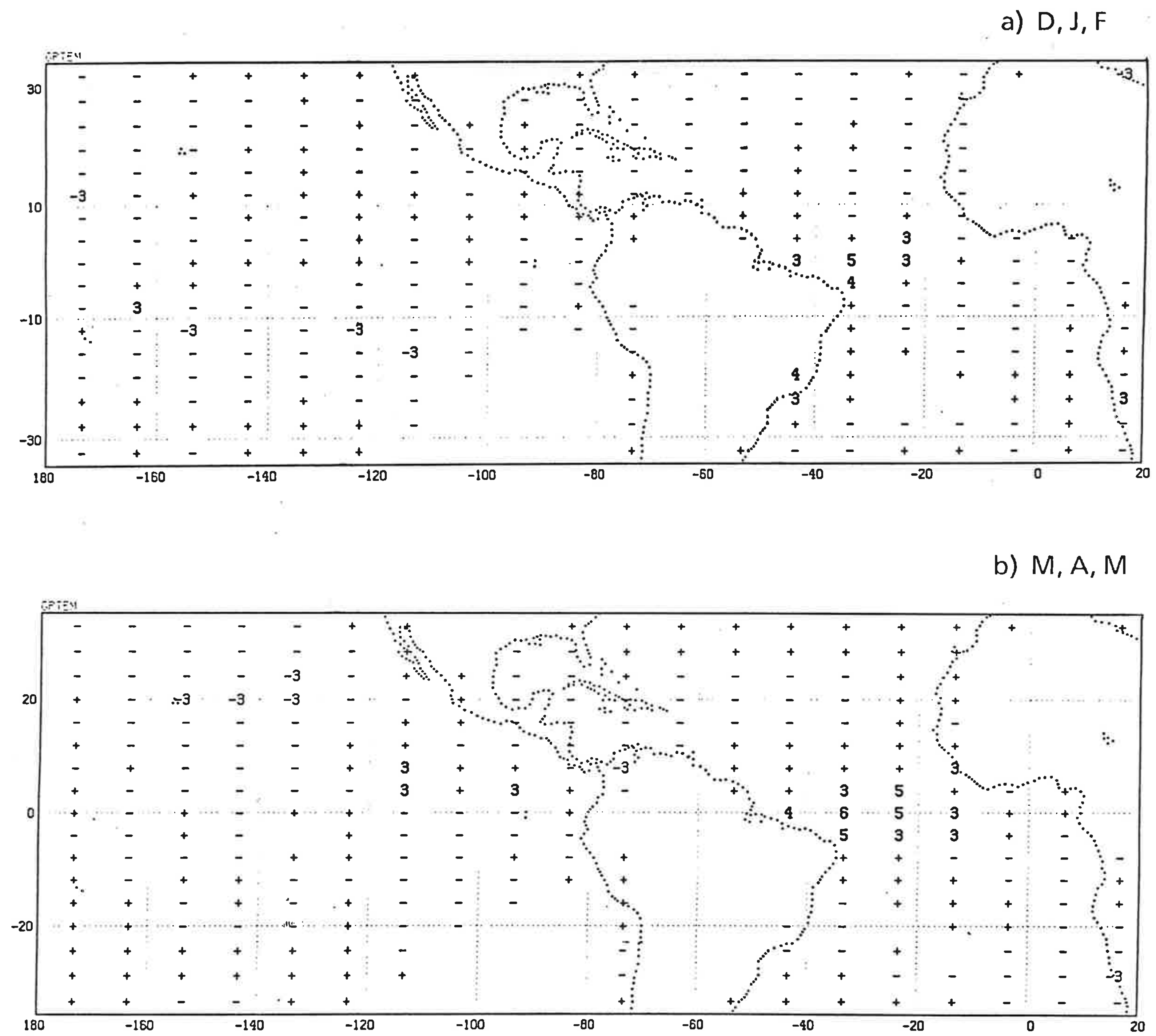


Figure 17: As Fig. 13 but using the de-regressed zonal component of wind and the de-regressed ATLO index.

c) J, J, A

d) S, O, N

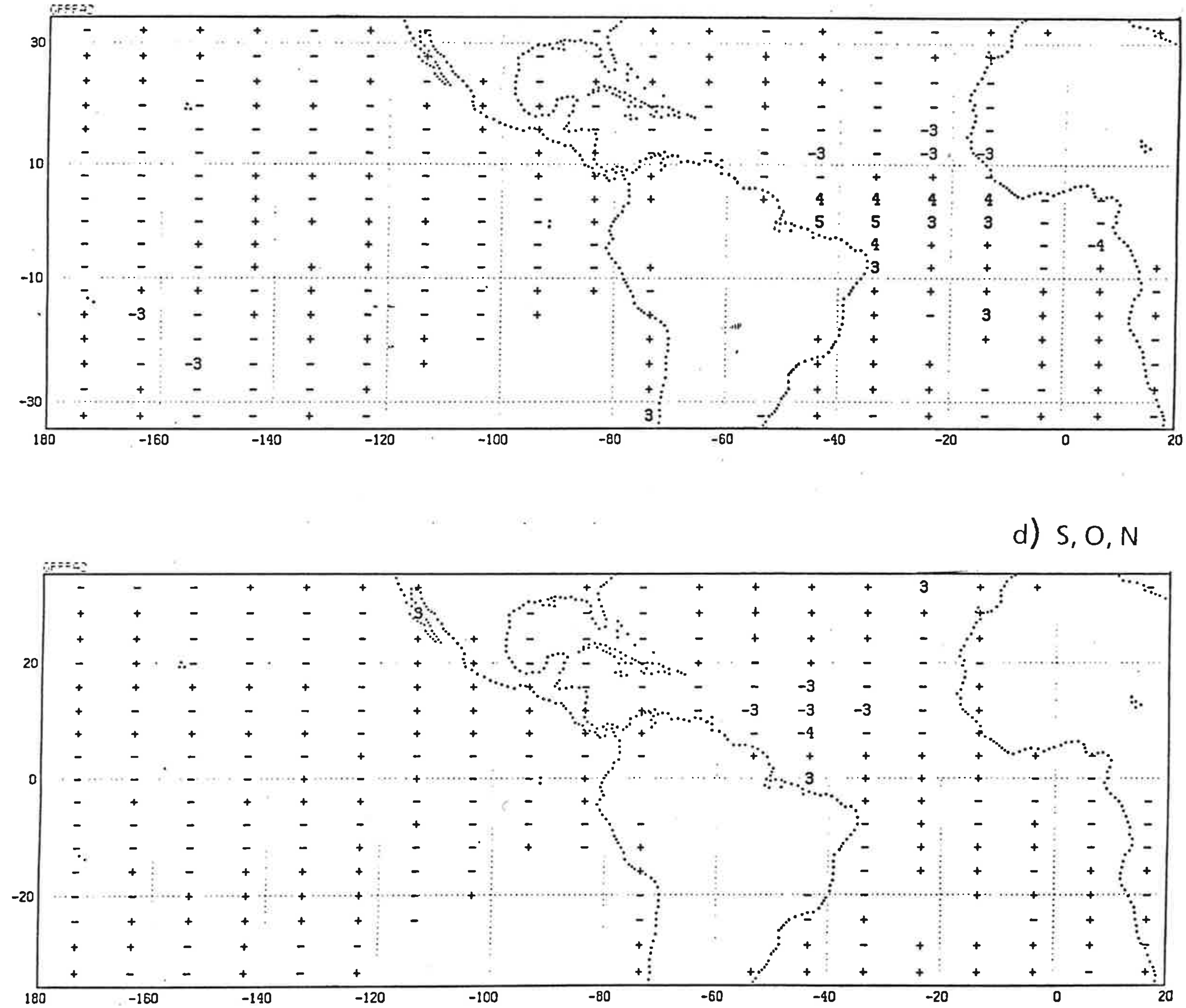
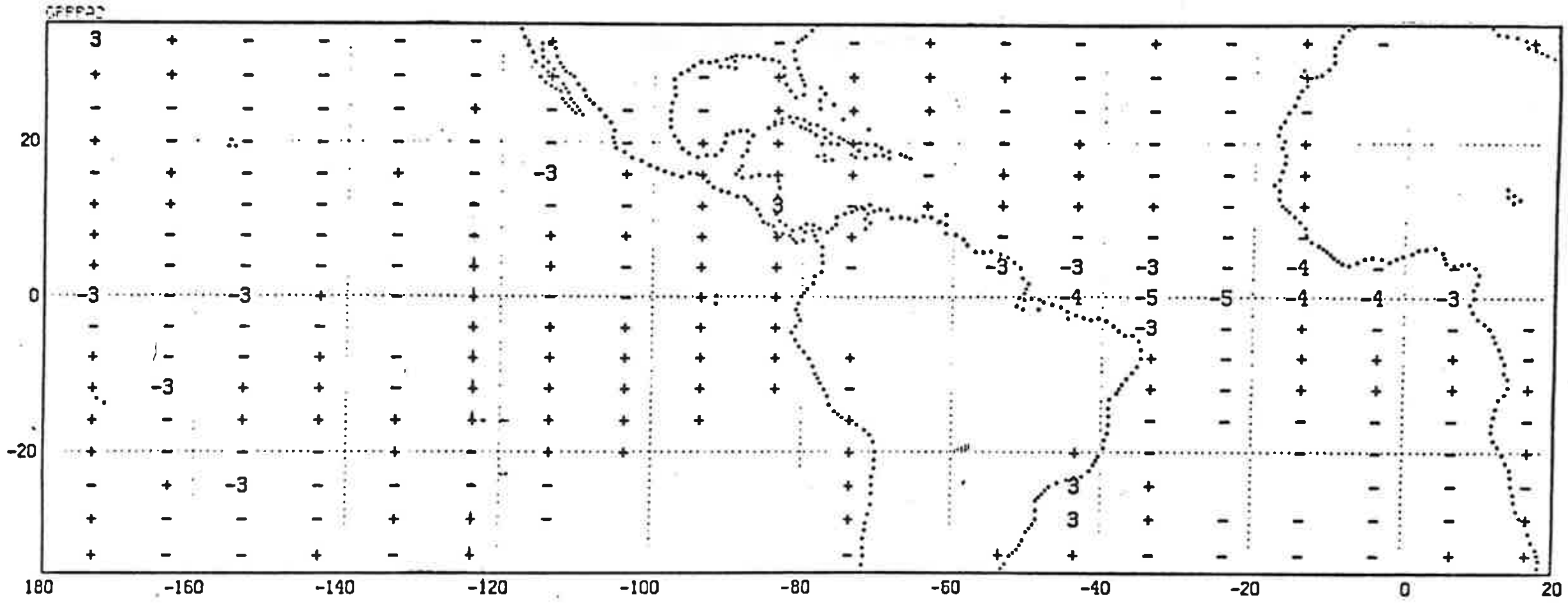


Figure 17: As Fig. 13 but using the de-regressed zonal component of wind and the de-regressed ATLO index.

a) D, J, F



b) M, A, M

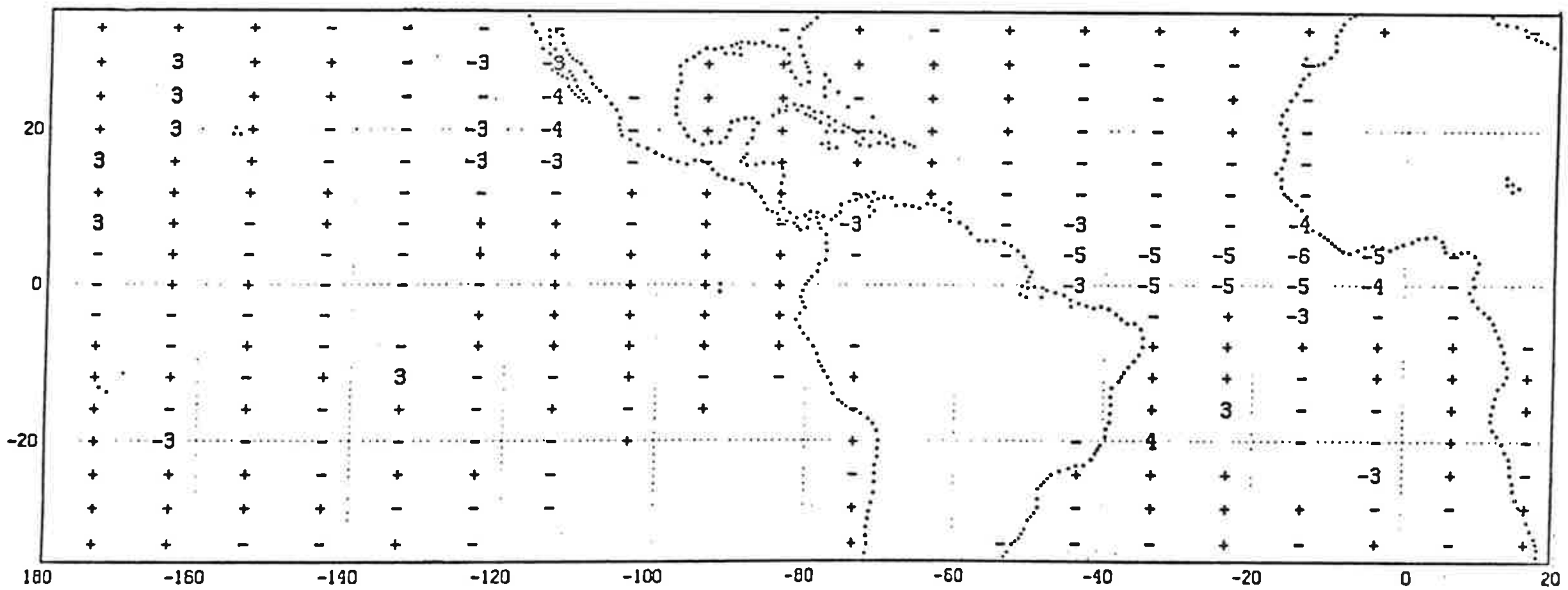


Figure 18: As Fig. 13 but using the de-regressed meridional component of wind and the de-regressed ATLO index.

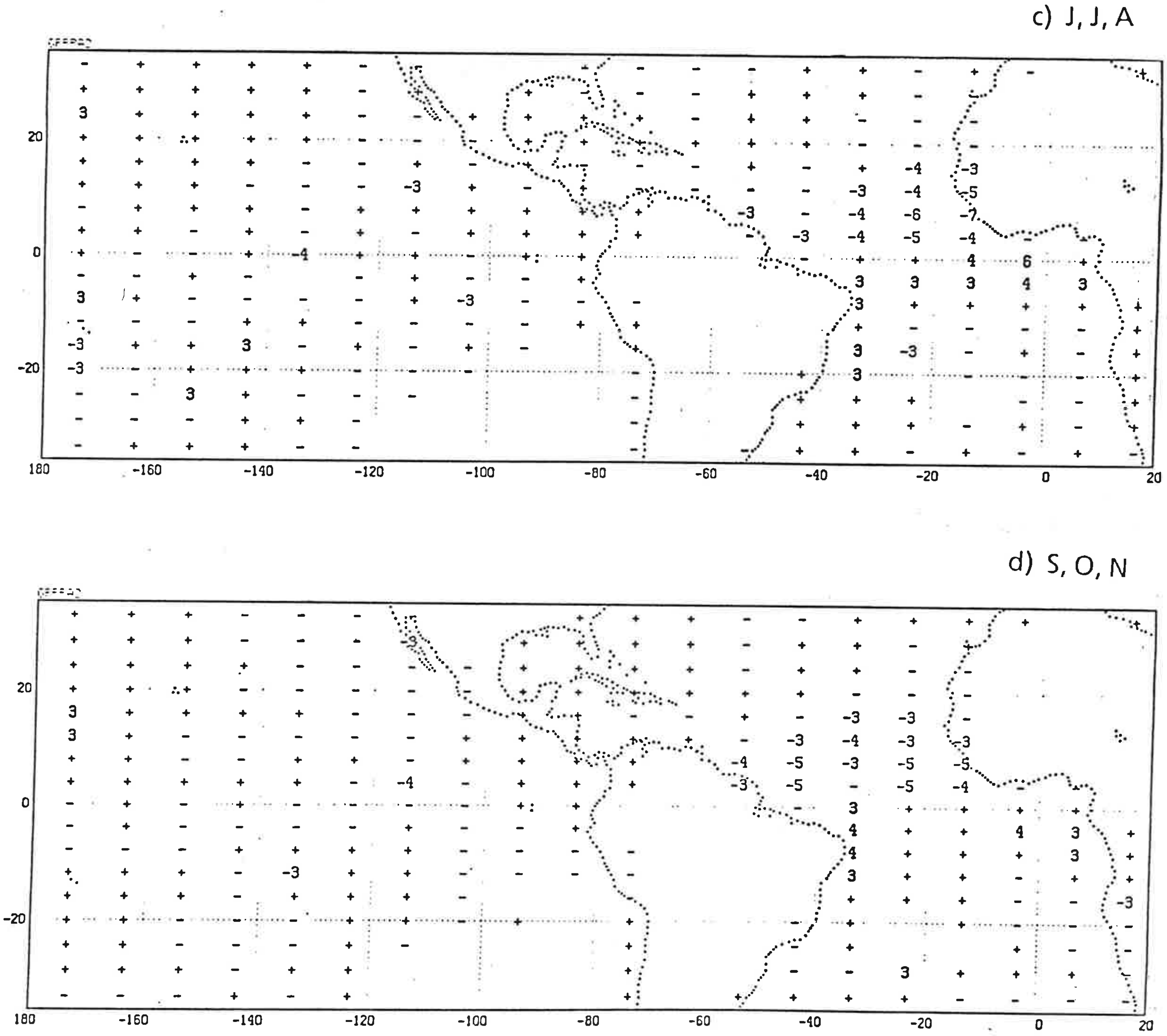


Figure 18: As Fig. 13 but using the de-regressed meridional component of wind and the de-regressed ATLO index.

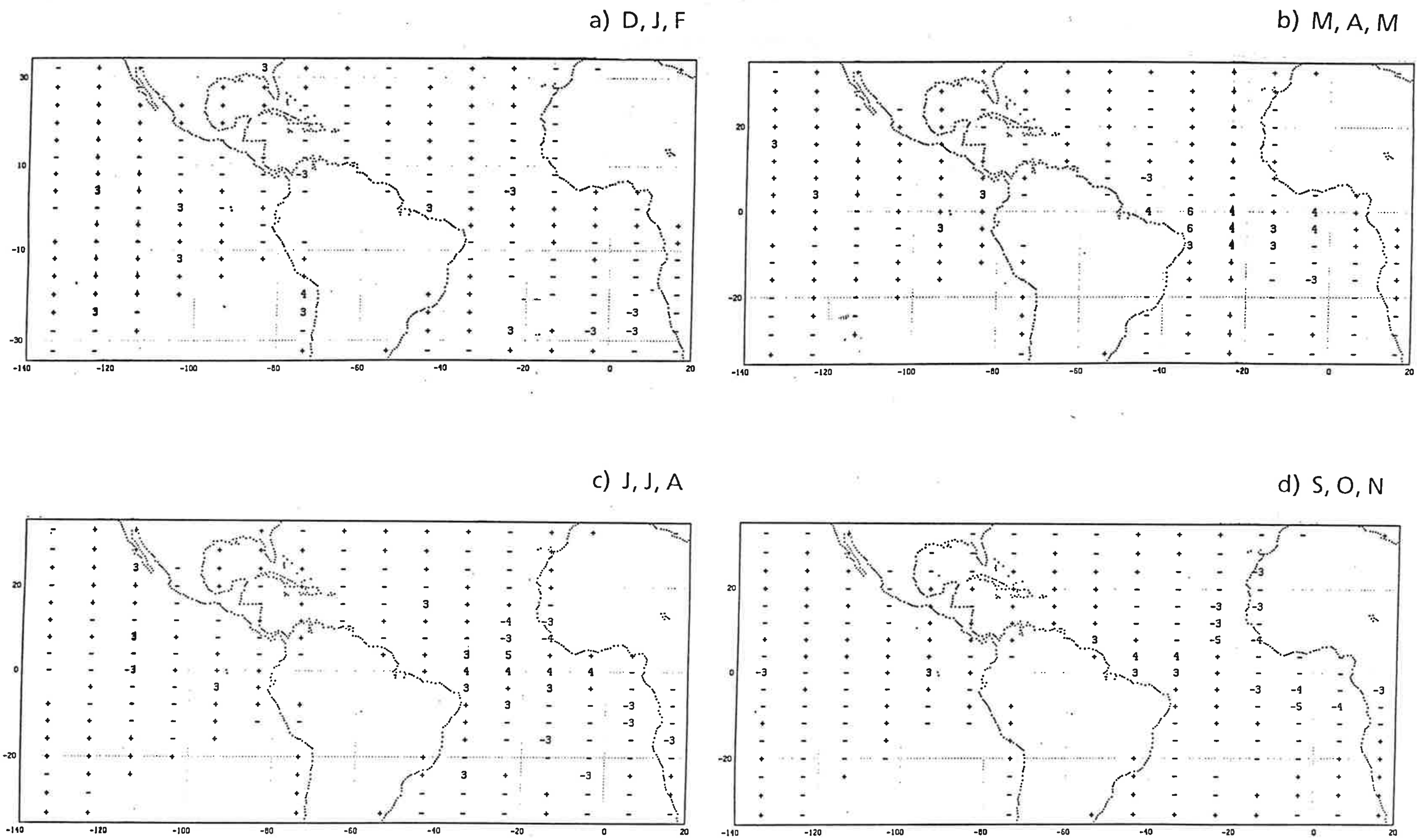


Figure 19: As Fig. 13 but using the de-regressed cloudiness and the de-regressed ATLO index, Atlantic and east Pacific sectors only.

8. RELATIONS OF GLOBAL FIELDS WITH TENDENCY OF ATLANTIC SST INDEX

8.1 Introduction

Correlations between the tendency of the ATLO index and fields of SST, pressure, wind components and cloudiness were found for each group of months. A selection of the maps is presented (Figs. 20-23). We interpret the results on the hypothesis that the observed anomalies tend to cause changes in the ATLO SST. Relationships were distinctly different in each season.

8.2 In DJF

(Fig. 20). The following anomalous features are associated with a trend to warmer Atlantic SST (and their opposites with a trend to colder):

Cold SST in and to north and west of the ATLO area.

Warm SST to SE of the ATLO area.

Some fairly coherent SST anomalies in several other regions.

High pressure over the ATLO region and low to the SE, both very weak.

Low pressure over the whole of the tropical central and east Pacific.

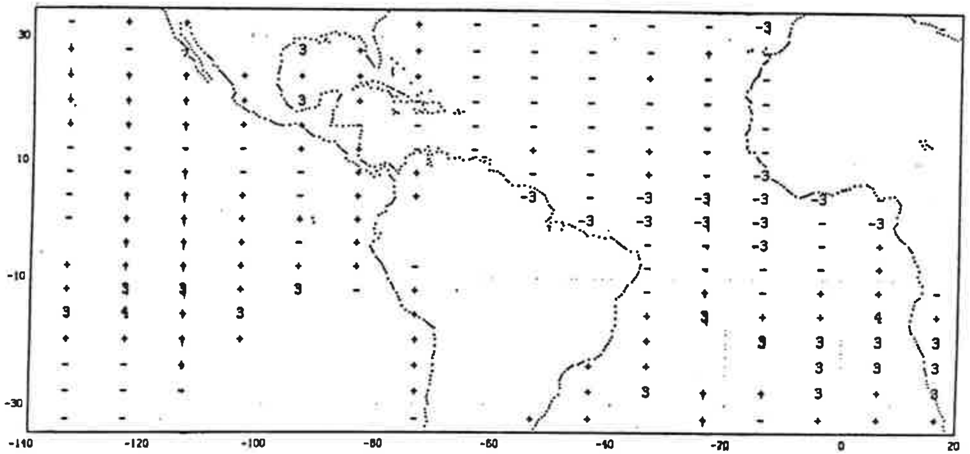
Weaker easterlies over the ATLO region (a strong relationship).

Weaker southerlies in the SE Pacific.

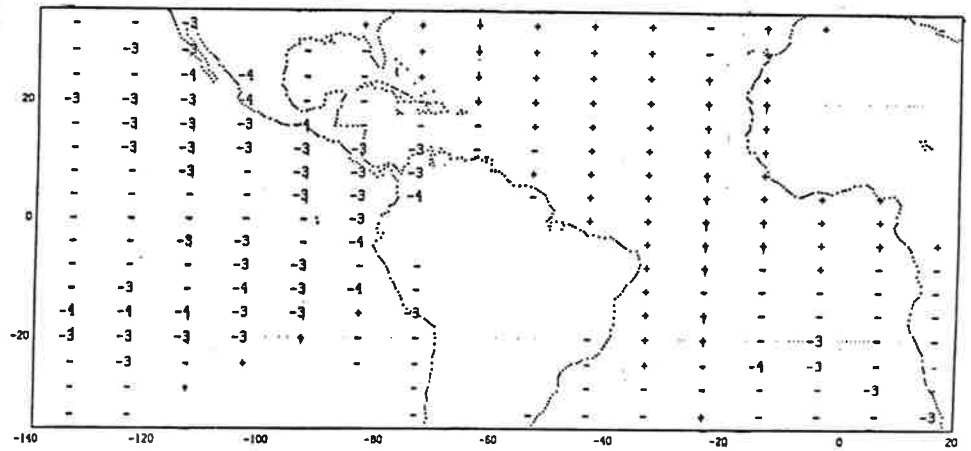
These results suggest that a major cause of warming Atlantic in DJF involves a weakening of the easterlies directly over the anomaly. This seems physically reasonable; weaker easterlies would be expected to favor weakened upwelling, and also weaker advection of the relatively cold air from the southeast, as is believed to be the case in the east Pacific. A second cause appears to involve advection of anomalies from the southeast; if the sea to the southeast is warmer, the winds that have blown over it are warmer when they reach the equator.

The anomalies over the Pacific are more of a puzzle. They may be related to the SO, but the SST anomaly pattern (Fig. 20a) suggests that the feature involves only a small part of the SO area. These patterns are approximately the opposite of the corresponding patterns for simultaneous correlations, suggesting that they may involve a negative feedback relationship,but this does not help to explain how they influence the Atlantic SST.

a) D, J, F



b) D, J, F



c) D, J, F

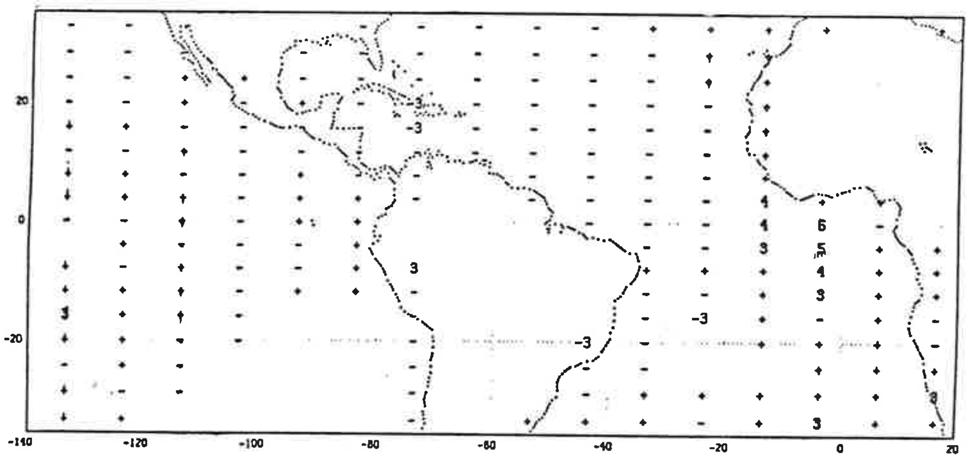


Figure 20: Correlation x 10 between various fields and tendency of ATLO index for month group Dec, Jan & Feb.
a) SST; b) Pressure; c) Zonal component.

8.3 In MAM

(Fig. 21). The following anomalies were associated with a tren..
Atlantic:

Warm SST in and to SE of the ATLO area.

Some fairly coherent SST anomalies in other oceans.

Low pressure over and to SE of the ATLO area.

Weaker easterlies over the whole tropical Atlantic, but especially near the Equator in the west Atlantic.

Stronger northerlies just north of the Equator in the Atlantic.

More cloud near the Equator across the Atlantic, but less cloud in the SE tropical Atlantic.

Many of these correlations are the opposite of those for DJF. Moreover the pressure, wind and cloudiness patterns are very similar and of the same sign to those described in Section 7. This suggests that warm sea → atmospheric anomalies → warming sea, that is, a positive feedback. It remains possible that only one of the features, or even some other factor, is actually involved in the feedback, but the result provides good support for the evidence in Section 5 of suspected positive feedback in that season.

There appears to be again a contribution from advection of anomalies from the southeast.

Servain et al. (1982), analysing data for all months, noted a relationship between the east equatorial Atlantic SST and westerlies in the west Atlantic. They hypothesised that the increased westerlies cause warming locally, and then the warming propagates eastwards via a Kelvin wave in about two months. Katz (1987) has suggested that decreased westerlies near 40°W would result in increased downwelling which would propagate east via a Kelvin wave to 0°W in about 20 days. Our results are consistent with these suggested mechanisms, but only in this season; there is no evidence in the present results of a similar relationship in the other seasons.

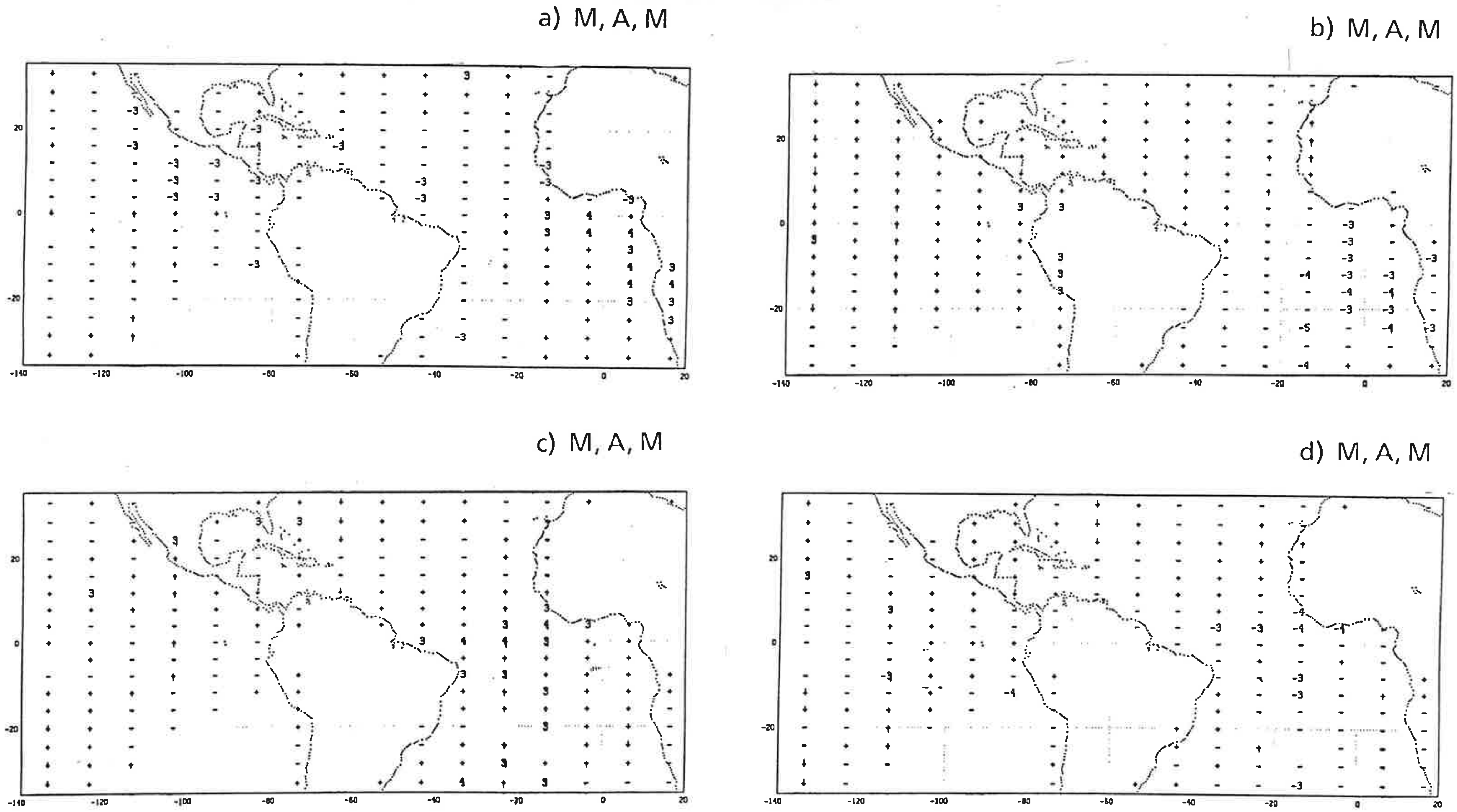


Figure 21: As Fig. 20 but for month group Mar, Apr & May.
a) SST; b) Pressure; c) Zonal component; d) Meridional component; e) Cloudiness.

8.4 In JJA

(Fig. 22). There is no significant signal in any of the fields. There is a weak tendency to high pressure over the tropical Atlantic accompanying warming sea. Since warm sea appears to cause low pressure in this, as in the other seasons (Sec 8), then any feedback with pressure must be negative. Thus there is little indication of what factors cause SST changes during this season.

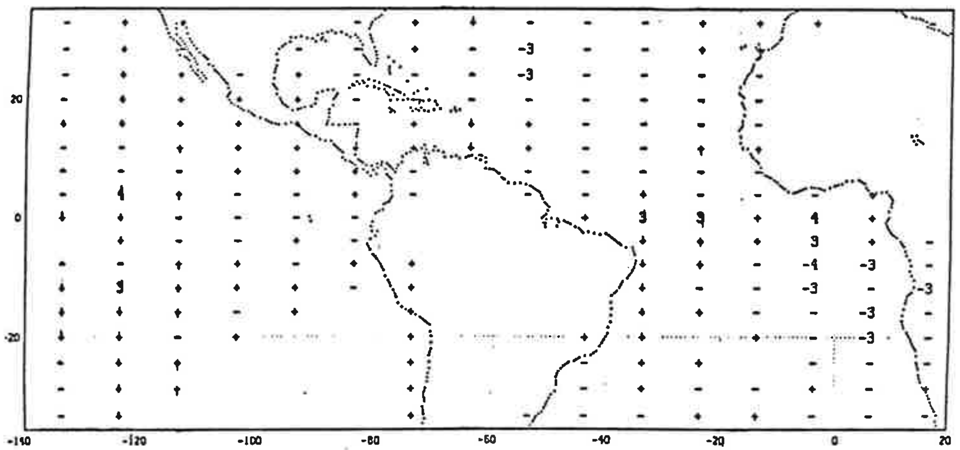
8.5 In SON

(Fig. 23). In the SST field there is no appreciable signal in the Atlantic, but a pattern of SST anomaly in the other oceans closely resembling the pattern associated with low index SO stands out clearly as being associated with warming Atlantic. Of particular interest is a coherent area of warm sea in the west Indian Ocean, south of the Equator. In pressure there is no appreciable signal in the Atlantic, but some intriguing spatially coherent patterns elsewhere, namely high pressure in the Australasia area and low pressure in the Arabian Sea area. These are not very similar to the characteristic SO pattern.

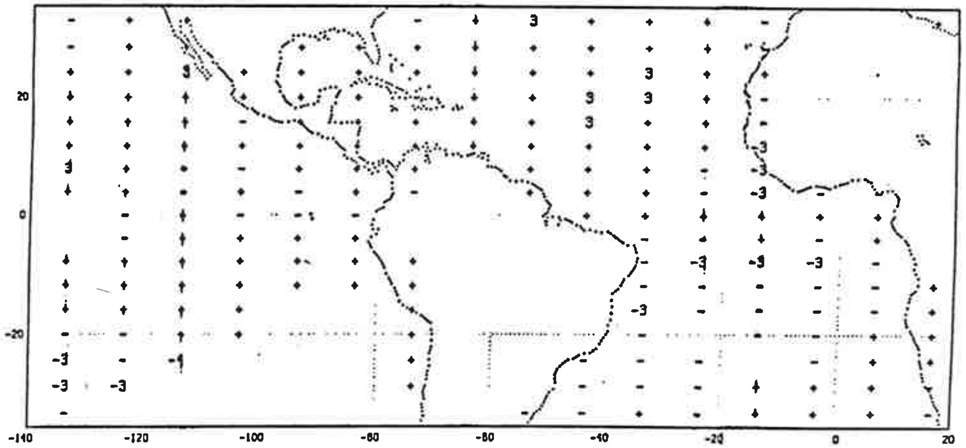
In the zonal component of wind, there is a weak tendency for increased westerlies over the ATLO region, and there are anomalies near the Equator in the west Pacific and the Malaysia sector consistent with a state of low SO index. In the meridional component, there is a slight tendency for convergence over the ATLO region. In cloudiness there are no strong signals.

These results suggest that in SON the local winds have some influence on the changes of Atlantic SST. There also appears to be some influence from the Southern Oscillation, supporting the evidence in Sec. 5.5, and in addition some influence from the western Indian Ocean region.

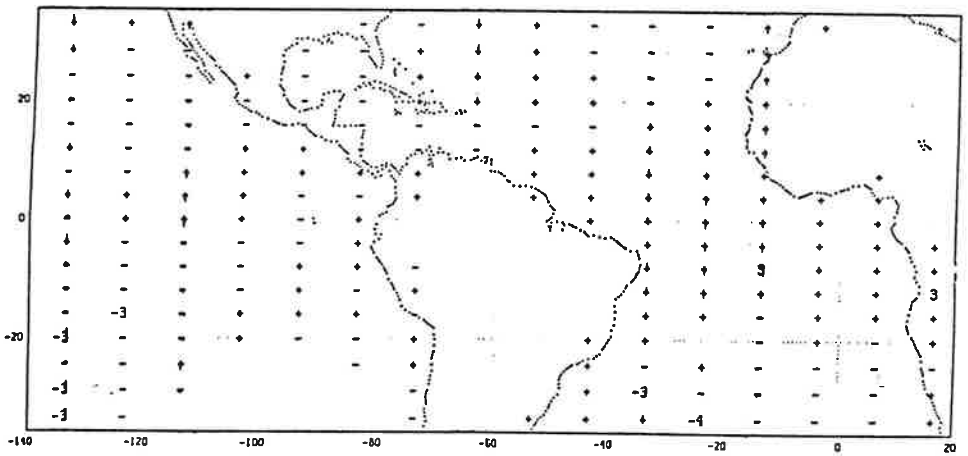
21 e) M, A, M



22 a) J, J, A



22 b) J, J, A



22 c) J, J, A

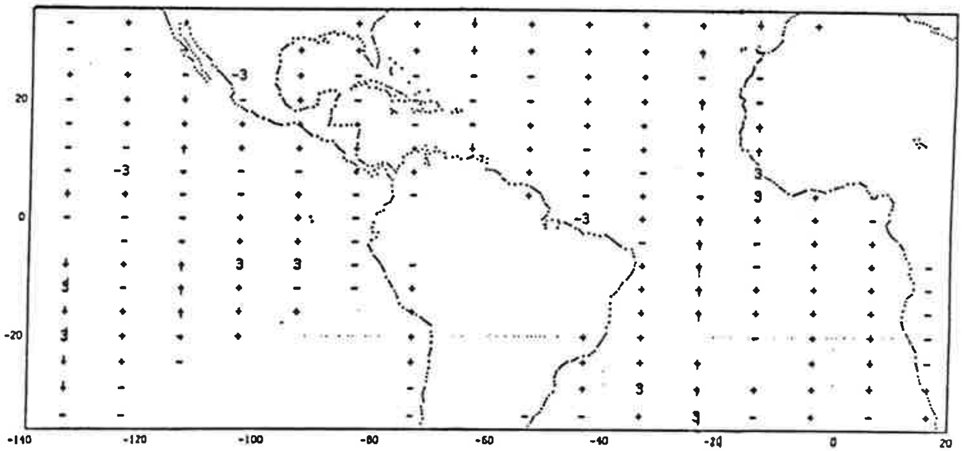


Figure 22: As Fig. 20 but for month group Jun, Jul & Aug.

a) SST

b) Pressure

c) Zonal

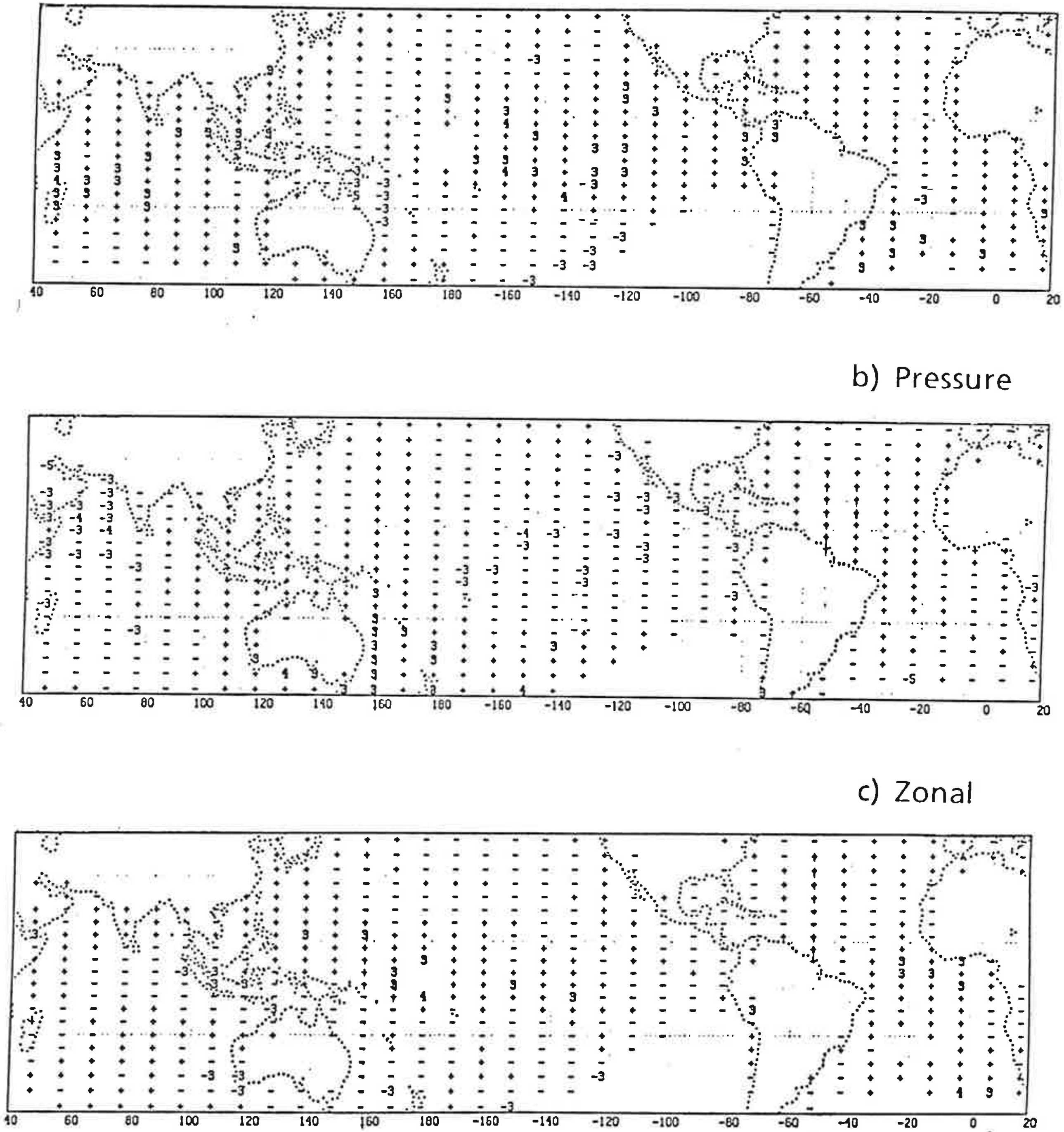


Figure 23: As Fig. 21 but for month group Sep, Oct & Nov.

9. SUMMARY OF THE BEHAVIOR OF THE ATLANTIC OSCILLATION

The Atlantic Oscillation (ATLO) comprises a temporal pattern of fluctuations of the SST in the equatorial east Atlantic, in an area centred in the west Gulf of Guinea and biased towards the Southern Hemisphere. SST anomalies in this region are spatially coherent and exhibit persistence throughout the year but weakest about April. There is a weak tendency for anomalies to propagate from SE to W through the region.

With regard to the above characteristics, ATLO resembles ENSO, except that all the characteristics are weaker. In other respects, its characteristics are different. ATLO, being weaker than ENSO, is somewhat dominated by it; in particular, the ATLO pressure anomaly pattern over the Atlantic in DJF and those over the Pacific in all seasons are clearly discernible only after the ENSO signal has been removed from the data.

The patterns associated with changes in ATLO appear to be different in different seasons. In MAM it seems that the same atmospheric anomaly pattern that is simultanously associated with an ATLO SST anomaly is also correlated with the *changes* in that SST, resulting in a tendency for amplification of anomalies then. In other seasons this pattern of behavior appears to be absent. Features associated with SST warming in those seasons seem to include: Weaker easterly winds over the ATLO region; SST anomalies SE of the ATLO region; and anomalies related to ENSO.

10. SYNTHESIS

In this preliminary study we have noted a number of relationships relevant to the causes of Atlantic SST changes, and to the interaction of equatorial Atlantic and Pacific SSTs. We may interpret the results in the form of a number of outline hypotheses:

H1: Anomalies in ENSO involve anomalies in the atmospheric conditions over the Atlantic. These atmospheric anomalies act to favor Atlantic SST anomalies of the same sign as those prevailing in the Pacific. The sequence is evident only during approximately September-February.

H2: Anomalies in ATLO involve pressure anomalies over the Pacific. These are of the form: Warm Atlantic SST → High pressure over the whole tropical Pacific. However, the details differ between seasons. In DJF, the detailed anomaly pattern involves stronger SE trade winds in the SE Pacific, which act to favor a cooling of the equatorial Pacific SST. Although the pattern seems weak, its persistence for 3 months could be sufficient to achieve the observed effect on Pacific SSTs.

H3: During the months March-June approximately, ATLO involves particularly strong relationships between the SST and atmospheric variables. Also, anomalies tend to amplify. This suggests that a positive feedback relationship is an important component of the mechanism in that season. In the other seasons, there is little evidence of positive feedback. Certain atmospheric anomalies seem to favor changes in SST, but the cause of those atmospheric anomalies is uncertain.

H4: Most SST changes in the ATLO region are locally generated rather than advected. However, there appears to be a component of advection from the SE, and also anomalies tend to propagate from the ATLO region westwards.

11. PROPOSED FURTHER WORK

11.1 Correlations

To complete the documentation of the role of ATLO in global and regional climatic fluctuations, it is proposed to document correlations between ATLO indices and regional rainfalls, with particular reference to the Atlantic sector. Correlations will also be calculated with pressure and 500 mb heights over the Northern Hemisphere Atlantic and neighboring sectors.

11.2 Relevant to Hypothesis H1.

ENSO is known to cause certain atmospheric anomalies over the Atlantic. Warm Pacific is associated with higher pressure in September-February and rather higher cloudiness and stronger easterlies in September-November over the Atlantic (Wright et al, 1985); however, there is no evidence that these changes would cause the Atlantic to become warmer. Warm Pacific is also associated with higher temperatures throughout the tropical upper troposphere, including over the Atlantic (Horel and Wallace, 1981); and it seems possible that these could act to increase Atlantic SST by means of changes in radiation balance or intensity of convection. This may be tested by further data analysis. A test using surface air temperature is not likely to be definitive because that quantity is physically constrained to be highly correlated with SST. We shall rather test the hypothesis by finding correlations with upper tropospheric heights. If a relationship is apparent, one might be able to test it quantitatively by using the relevant atmospheric anomaly to force a model of the Atlantic ocean circulation.

11.3 Relevant to Hypothesis H2.

The influences proposed in H2, if real, seem very weak and may be dependent on the detailed spatial pattern of anomalies. One might employ a good atmospheric GCM, forcing it with equatorial Atlantic SST anomalies, and investigate the pattern of atmospheric anomaly it produces over the Pacific. But to prove the hypothesis, the model must be sufficiently realistic to demonstrate different responses in different seasons. One might also impose the hypothesised Pacific atmospheric anomalies on an ocean GCM, to investigate whether they would indeed lead to a cooling of the equatorial Pacific SST.

11.4 Relevant to Hypothesis H3.

Further analysis of selected atmospheric variables needs to be made, to discover in more detail the patterns of correlation, persistence and variability. This may help to clarify the questions of cause and effect.

11.5 Relevant to hypothesis H4.

A model of the Atlantic Ocean circulation could be employed to investigate the propagation of anomalies by means of oceanic processes. However, the observed propagation may be mainly via the wind rather than by movement of water; to test this would require a more complex model.

12. ACKNOWLEDGEMENTS

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APPENDIX

Table A1 presents monthly values of the ATLO SST index for 1854-1985, and Table A2 the annual means. The data sources and treatments were as follows.

1) Data for 1854-1979 were obtained from COADS (Sec 3), and homogenised using the corrections for global mean SSTs proposed by Jones et al (1986). Specifically, the following values were added to the data; 1854-89, +0.08 deg C; 1890-1902, a linear trend from +0.10 to +0.46; 1903-40, +0.49; 1941, +0.34; 1942-45, -0.10.

2) Data for 1980-85 were obtained from a magnetic tape of gridded values supplied by R Reynolds of the Climate Analysis Center. These data were also available for 1970-79. Following a regression of the COADS indices on the Reynolds indices for each of the regions in Figure 5, for the period 1970-79, it was decided to sutract 0.25 deg C from the Reynolds data to make it homogeneous with COADS. These corrected values are presented.

If the series presented in Tables A1 and A2 contain no further inhomogeneities, we may infer that the ATLO region was persistently cold during 1854-1908, and relatively warm during 1920-40 and 1979-85. These long-term fluctuations were of similar amplitude to the year-to-year variations. Further, according to these data, the warmest year was 1963-4, the third warmest 1984-5. The coldest year in the last 80 was 1958-9, but before 1910 there were many years colder than that.

Table A1. ATLO SST index for 1854-1985, deg C*100. M = missing value.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1854	M	M	M	M	-86	-35	-42	-36	-48	-88	-1	-92
1855	-49	-92	-114	-73	-79	-83	-39	-51	-17	-54	-116	-34
1856	-119	-15	-32	-72	-77	-35	-43	-1	11	-10	-74	-28
1857	-54	-83	-47	-77	-133	-61	-70	-71	-29	-89	-83	-114
1858	-88	-102	-77	-82	-83	-84	-85	-27	30	4	63	-19
1859	-39	33	7	22	22	1	-100	-67	-72	-70	-32	28
1860	-1	-58	-79	-78	-22	-40	-61	-21	-67	-65	-6	16
1861	-50	-105	-94	-137	-72	-58	-59	-86	-38	-18	-63	3
1862	-75	-60	1	-47	-22	12	6	1	-35	-10	-32	-54
1863	-122	9	8	-9	-25	-21	-149	-77	-71	-82	-59	-84
1864	-132	-153	-36	-88	-56	-44	-9	-96	-68	-81	-22	-50
1865	-47	-24	-91	-23	-56	-58	12	19	28	-1	-8	-15
1866	13	29	-44	-46	-20	-3	-21	-20	6	-11	-33	-94
1867	-58	-68	-40	-27	-51	-54	-82	-12	-74	-26	-87	-33
1868	-105	-61	-14	-50	-45	-60	-34	-138	-11	-80	-17	-19
1869	-75	-73	-68	-34	-117	-82	-85	-43	8	-46	-55	-81
1870	-37	-20	-62	-54	-24	-95	-41	-31	-38	-49	-47	-56
1871	-104	-65	-17	-62	-46	9	-37	-98	-29	-25	-67	8
1872	-30	6	-71	-36	-53	-52	-12	-24	-16	-7	-29	-33
1873	20	24	27	47	-34	-78	-11	-40	-18	-10	18	-70
1874	-94	-83	-80	-138	-64	-84	-70	-88	-27	-70	-21	-72
1875	42	47	17	-51	7	-5	61	-27	-23	-24	29	25
1876	-22	-23	17	-58	-44	-38	21	-38	-109	6	-128	-148
1877	-144	-39	-82	-59	-65	-59	-69	-1	35	2	-2	17
1878	-42	-34	-37	-19	-40	-28	-50	-20	-34	33	-36	-81
1879	-121	-32	-115	-71	-101	-8	-85	-44	-60	-32	-9	-32
1880	-20	-5	-69	-90	-126	-153	-121	-159	-95	-75	-75	-121
1881	-49	8	-48	-28	-46	-65	17	-55	-52	-49	-74	-55
1882	-34	-74	-57	-60	-130	-123	-107	-17	-124	-99	-43	-48
1883	-103	-109	-77	-69	-61	-50	-76	-12	-34	-68	-50	-37
1884	-71	-40	-56	-39	-37	-7	-52	-123	-77	-80	-141	-84
1885	-70	-60	-85	-46	-81	-78	7	27	-7	24	-13	12
1886	25	-1	17	64	-17	28	30	25	12	-25	-3	11
1887	-39	-43	-49	-66	-38	-120	-73	-123	-60	-66	-25	-71
1888	-95	-119	-93	-108	-96	-121	-102	-67	-79	-88	-57	-43
1889	-32	-26	-5	-4	-1	-1	13	-4	-9	12	20	1
1890	43	-6	-32	-68	-62	-107	-97	-76	-54	-75	-98	-48
1891	-86	-48	-73	-50	-76	-121	-105	-90	-70	-5	-33	-30
1892	-47	-39	-33	-57	-158	-138	-152	-86	-41	-83	-47	6
1893	-96	-46	-85	-94	-78	-73	14	2	13	-34	-12	-51
1894	-33	0	-47	-76	-129	-12	-67	-9	-32	-14	-42	-23
1895	-38	25	-42	-12	-95	-68	-64	-46	-29	-18	-34	-9
1896	-33	2	-27	-1	6	-107	-73	-68	-21	-16	-22	35
1897	20	-26	33	43	13	-23	-21	-9	14	18	-5	-26
1898	-78	-13	-68	-26	-37	-83	-61	-76	6	-46	11	41
1899	0	-3	19	-6	10	26	10	23	-42	-7	-45	-54
1900	-33	-46	-85	-78	-61	-40	-15	-29	26	13	56	54
1901	35	2	-1	62	7	-5	23	28	-18	2	-20	5
1902	-19	-13	-45	-11	-11	-29	-52	-63	-53	-95	-91	19
1903	-24	-16	-47	-80	-81	-58	-30	-48	-54	-31	-42	-52
1904	-45	-76	-89	-92	-59	-96	-97	-127	-102	-114	-82	-68
1905	-66	-67	-58	-43	-30	-93	-56	-116	-69	-44	-31	20
1906	-11	4	8	-18	-90	-110	-62	-69	-53	-79	-58	-61
1907	-50	-64	-15	-43	-26	-23	-36	-4	-21	-40	-19	-32
1908	-62	-70	-55	-93	-111	-118	-72	-57	-30	-32	-47	-18
1909	-62	-74	-49	-42	-8	15	18	63	4	24	15	31
1910	22	32	9	-8	30	68	66	25	38	-16	-17	-13

1911	-62	-58	-92	-74	-66	-59	-65	-91	-64	-58	-31	20
1912	28	36	28	18	-7	20	-30	-9	-12	-8	-3	20
1913	25	17	3	-1	22	58	27	26	-1	-35	-9	-23
1914	6	-18	-34	-34	-45	-70	-91	-22	-49	-2	-17	-26
1915	-26	-10	-15	26	-90	15	-13	-84	-55	28	-44	-26
1916	13	9	13	-3	-10	-18	30	26	10	42	7	M
1917	-23	11	M	M	101	M	M	2	-2	146	M	-58
1918	-19	M	M	-44	M	M	M	-70	M	-54	79	M
1919	30	34	-39	M	-135	7	-44	22	-47	-26	13	-75
1920	-22	-9	-27	-31	-9	-38	-9	29	-2	22	-7	68
1921	3	15	23	44	68	91	98	77	52	37	15	-5
1922	-27	-40	18	-51	-45	-47	-45	-15	-20	-15	-33	-2
1923	3	-21	-32	-45	-20	-12	-34	-47	-27	2	31	88
1924	76	56	41	57	26	-6	43	34	7	3	-24	-31
1925	-21	-33	-13	8	64	75	72	64	-10	-18	0	22
1926	19	60	49	57	24	52	54	35	57	52	22	11
1927	-5	3	0	-7	-30	2	41	10	17	45	43	49
1928	16	24	0	-27	-6	-27	36	-13	-12	4	11	9
1929	15	9	-12	-2	-26	-55	-16	-38	-58	-42	7	-30
1930	-60	-42	-77	-60	-62	-5	-11	-14	-1	0	-10	3
1931	-4	22	33	-11	-14	5	-24	-16	-17	4	-32	-1
1932	-30	-34	-94	-55	-80	-59	-109	1	-69	-25	-17	24
1933	31	0	34	30	12	23	14	15	-4	42	5	29
1934	10	24	11	22	51	92	143	133	100	76	54	76
1935	53	40	26	-7	6	48	21	10	-2	51	52	61
1936	34	6	-18	-19	-17	-92	-86	-60	-29	-10	19	11
1937	47	16	42	44	72	49	49	47	75	46	75	58
1938	50	43	31	10	-6	-24	17	50	9	29	25	27
1939	5	10	2	19	28	81	84	74	39	-23	-64	M
1940	44	-15	31	36	3	-24	65	41	79	15	-45	18
1941	22	14	66	M	-3	-43	67	31	39	38	-5	41
1942	-11	-67	-12	-28	-51	-26	-29	-54	47	15	31	-47
1943	-56	-35	-58	-76	M	-4	-69	-46	-66	7	-71	-33
1944	M	M	M	-2	M	M	16	-30	M	-71	M	M
1945	23	12	M	M	M	M	M	M	-59	M	M	22
1946	69	50	6	-104	-100	-130	-75	-79	-64	-41	-33	29
1947	13	-32	3	-18	24	39	35	43	38	25	52	22
1948	-2	7	-18	-43	-54	-63	-43	-29	-39	-28	-46	3
1949	-6	25	14	41	15	38	72	47	57	35	9	7
1950	26	25	30	7	25	8	-8	-48	-69	-42	-47	-65
1951	-62	-63	-64	-52	-21	-6	46	39	38	39	37	60
1952	44	16	14	17	-2	16	-23	-14	3	8	0	0
1953	1	-28	-3	-29	-25	-7	11	17	8	2	-16	-24
1954	-42	-52	-58	-63	-68	-87	-108	-44	-6	28	22	29
1955	0	-29	-30	-22	-19	-20	-30	-27	-12	9	18	-42
1956	-48	-57	-45	-45	-44	-64	-52	-16	2	-27	-40	-74
1957	-52	-13	-14	-10	-18	3	-46	-2	-45	-43	-17	-20
1958	-39	-11	-25	-34	-119	-152	-93	-93	-82	-59	-61	-21
1959	-18	10	24	23	27	29	-15	-12	-1	21	5	10
1960	-5	-35	-19	-26	-25	-19	-2	19	21	24	47	36
1961	23	31	25	38	50	19	-44	-24	-12	26	32	23
1962	39	2	-1	9	12	12	11	5	31	45	31	21
1963	32	36	48	40	68	97	131	127	91	76	82	101
1964	97	49	42	11	-31	-48	-27	-39	-64	-87	-81	-86
1965	-67	-46	-3	-13	-4	-24	-49	-38	-14	-47	-51	-39
1966	-14	-9	-14	-18	24	75	46	3	0	5	18	66
1967	32	39	1	17	-7	-74	-81	-59	-58	-64	-71	-56
1968	-29	-33	-28	-12	10	83	118	63	48	54	49	47
1969	43	60	43	34	31	-15	-47	-34	-37	-28	-31	-21
1970	-34	-17	-1	-10	-12	-31	-21	-2	-8	-19	-14	-36

1971	-5	-6	15	25	53	43	1	-23	-18	-22	-54	-64
1972	-24	4	-28	-4	5	18	14	4	22	39	67	110
1973	90	106	80	90	82	40	51	70	69	56	56	32
1974	26	35	26	29	44	70	67	34	2	-6	-17	-2
1975	-6	-11	-5	3	15	43	8	-5	-27	-4	1	-20
1976	-22	-19	-37	-50	-63	-70	-65	-49	-31	-51	-65	-34
1977	-41	-15	1	19	-16	-1	-16	12	35	1	24	8
1978	-16	-15	-29	-39	-48	-52	-22	-8	-19	-23	-18	2
1979	-6	-13	2	24	14	19	48	54	46	35	48	32
1980	24	-8	-7	10	14	32	30	19	59	12	29	-18
1981	-9	-6	-22	-4	8	57	18	48	68	98	87	80
1982	68	44	50	15	13	13	-26	-20	19	24	-26	4
1983	41	44	33	5	-28	-6	0	28	15	35	26	50
1984	50	61	91	60	45	53	70	107	116	84	63	67
1985	36	32	29	23	15	30	55	41	41	65	44	29

Table A2. Annual mean values of ATLO SST index for April of given year to March of next, threshold = 8 months.

	+ 0	1	2	3	4	5	6	7	8	9
1850	M	M	M	M	-62	-59	-43	-83	-24	-34
1860	-49	-55	-24	-75	-56	-9	-34	-52	-56	-55
1870	-52	-37	-16	-38	-44	-3	-67	-26	-45	-45
1880	-92	-48	-87	-52	-71	-9	-1	-79	-69	3
1890	-74	-58	-82	-33	-38	-36	-20	-13	-21	-21
1900	-3	1	-39	-57	-86	-38	-61	-36	-64	15
1910	-3	-33	3	1	-34	-17	7	M	M	-31
1920	5	36	-27	9	4	34	30	18	-1	-37
1930	-9	-22	-27	18	72	22	-15	53	13	27
1940	24	7	-24	-45	M	M	-51	21	-26	33
1950	-36	21	-2	-18	-30	-25	-37	-23	-58	2
1960	13	12	24	83	-47	-26	24	-45	51	-17
1970	-12	-9	46	53	17	-5	-44	0	-20	27
1980	12	52	11	27	63	38	M	M	M	M

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