Empirical orthogonal analysis of Atlantic Ocean surface temperatures

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Summary

An empirical orthogonal function analysis has been performed on monthly mean sea surface temperature observations in the Atlantic Ocean between 70°N and 30°S for the years 1949–69. This method derives the most important ‘modes’ of variation, defined as those functions which explain the largest total variance in the data field. Such modes are calculated for two sets of temperature deviations in which the annual cycle is both included and excluded. For the seasonal case, only four functions explain more than 90% of the total variance, whereas in the nonseasonal case, ten functions explain less than 50% of the total. The most important seasonal mode indicates lower minimum temperatures in winter in the later years of study. The dominant nonseasonal function shows a cooling trend starting in early 1951. Nonseasonal functions of the tropical region alone suggest large variations, having a characteristic period of a few months.

1. Introduction

Because the oceans have relatively large heat capacities and slow motions, it has long been believed that they should exert considerable control on weather or climate for times of several weeks to a few years or longer. However, until recently, observational studies have been hampered by difficulties in interpreting the very large amount of data necessary to investigate oceanic space scales and ‘climatic’ time periods. Work by Craddock and Flood (1969), Kutzbach (1970), Kidson (1975) and others have illustrated the value of empirical orthogonal analysis in deriving a few functions which explain much of the variance of large fields of data such as surface air temperature and sea level pressure. Empirical orthogonal analyses of Pacific Ocean surface temperatures (Weare et al. 1976; Barnett and Davis 1975) have yielded several important results (Newell and Weare 1976; Davis 1976). This paper presents the results of a similar analysis of the sea surface temperatures (s.s.t.) of the Atlantic Ocean between 70°N and 30°S for the years 1949–69.

Empirical orthogonal function analysis enables fields of highly correlated data to be represented adequately by a small number of orthogonal functions and corresponding orthogonal time coefficients. Unlike most other orthogonal representations, such as the more familiar Fourier analysis, these functions do not require a predetermined form but, rather, depend upon interrelationships within the data being analysed. This property is especially important when investigating s.s.t., which does not have a known analytical form and which is subject to complex boundary conditions. Simply stated, the first of these functions is that linear combination of the original variables which, when used as a linear predictor of these variables, explains the greatest fraction of the total variance. Subsequent functions are required to account for the largest parts of the remaining variance (Lorenz 1956). Kutzbach (1967) and Davis (1976) give excellent discussions of the derivation of the functions and coefficients together with descriptions of the procedure necessary to calculate each. Craddock (1973) has attempted to define criteria which might be used to distinguish between those functions which are important components of the physical phenomena and those which are mainly due to measurement and sampling errors in the data. Although no precise cutoff seems possible, the most important functions, often referred to as the principal

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modes of variation of the field, may not only explain most of the total variance but their coefficients often portray relatively large-scale, low-frequency variations. Subsequent functions are often distinguished by much smaller spatial scales and time series of diminished amplitudes and higher frequencies, both of which are usually associated with "noise".

2. Data

The data used in this study are 1°-latitude-longitude grid monthly averages of s.s.t. observations covering the Atlantic between 70°N and 40°S. These were obtained from the British Meteorological Office for 80°N to 80°S for the years 1949–69 and from the United States National Climatic Center for 30°N to 30°S for 1911–72. In order to reduce the number of data points, the above averages were averaged again into a 5°-latitude by 5°-longitude grid. For the area and period in which the sources overlap, the mean temperature used in further calculations was that derived from the source having the greater number of observations in the 5° grid. This was necessary because the National Climatic Center data usually had far more observations contributing to the mean in the western Atlantic whereas the British data were generally much better in the eastern region. Fig. 1 illustrates for February and for August the regions which have at least one observation, and more than 20 observa-

Figure 1. Data quality of sea surface temperature measurements for the Atlantic Ocean in February and August. Clear regions have more than twenty observations per month in a 5° grid in at least ten of the twenty-one years studied. Single-hatched regions have at least one observation per month in at least ten of the years. Cross-hatched regions have observations in less than ten of the years.
tions, in a 5° square in a month in at least ten of the possible 21 years. The poorest data region is the mid South Atlantic. There is also relatively poor quality in the western region north of 30°N where only the British source could be used.

The monthly means for each of the 289 grids were calculated for the entire 21 years. Data for grids having deviations from the long-term monthly mean greater than 5 K were rejected. This criterion eliminated less than 0.2% of the data, primarily in the region south of 30°S. For grids which did not have data in a particular month, but had at least two neighbours with data, values were interpolated by adding to their long-term means the average of the deviations from the respective means of the reporting neighbours. Uninterpolated areas were set to the long-term mean of the month. Revised monthly means were then calculated and are illustrated in Fig. 2 for four sample months. Differences between

Figure 2. Monthly mean s.s.t. (°C) derived from the entire twenty-one years (1949–69) for February, May, August and November. Analyses of the 5°-grid data used for this study.

original and revised means were up to 0.4 K in the sparse-data regions of the South Atlantic.

Figure 3(a) indicates the variance pattern over the Atlantic computed from the 252 months of deviations from the long-term annual mean, which is taken as the arithmetic mean of the long-term monthly means. Since these deviations are primarily due to seasonal fluctuations, the variance is greatest in extra-tropical regions, especially near the Gulf Stream and the Falkland Current. Local variance maxima also appear in the upwelling areas west of the Sahara and off Angola. The nonseasonal variance pattern, calculated from deviations computed from the long-term monthly means, is illustrated in Fig. 3(b). Although the numerical values are much smaller, the pattern is quite similar to that of the seasonal variance except for the addition of a local maximum in mid Atlantic at about 30°N.
Figure 3. Variances ($K^2$) of deviations from the s.s.t. long-term means (e.g. Fig. 2) for 1949–69. (A) deviations computed from the single annual mean, (B) deviations computed from monthly means.

3. RESULTS

Empirical orthogonal functions were calculated which included and excluded the seasonal cycle. The seasonal functions are based on deviations from the single annual mean. The nonseasonal functions were computed from deviations from the monthly means themselves. The region south of 30°S was not included in any of the computations because of inadequate data in that region. The cumulative percentage of the total seasonal variance explained by the first ten seasonal empirical orthogonal functions is indicated in Table 1. The percentages of the nonseasonal variance explained by the nonseasonal functions also

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<td>84·6</td>
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<td>37·2</td>
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<td>TNS</td>
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<td>43·8</td>
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Figure 4. Empirical orthogonal function S1, explaining 84.6% of the s.s.t. seasonal variance (Fig. 3(a)) and its corresponding time coefficients. Vertical lines in the time series correspond to January of the respective years, starting in January 1949 and ending in December 1969.

appear in Table 1. The values for the seasonal case are similar to those explained by seasonal empirical functions of Pacific s.s.t. (Weare et al. 1976) and hemispheric surface air temperature and sea level pressure (Kidson 1975). The first nonseasonal function explains only about half as much as the corresponding Pacific s.s.t. function. This suggests that more functions are probably necessary to describe the Atlantic adequately, than to describe the Pacific.

Figs. 4 to 10 display analyses of the spatial patterns and plots of the time coefficients of the most important seasonal and nonseasonal empirical functions, designated S1, S2, . . . and NS1, NS2, . . ., respectively. The contribution of a function to the temperature deviation from the given mean for a specified area and time is the product of the value of the function for that area and the value of the function’s time coefficient for the month in question. Therefore, two regions vary in phase with a proportionality factor equal to the ratio of the values of the function for the regions and with approximately the variance explained by the function.

S1 (Fig. 4), explaining 84.6% of the total seasonal variance, identifies the principal mode of seasonal variation. As would be expected, the high latitudes in general undergo the greatest variation, especially near the region where the Gulf Stream and Labrador current merge. There is, however, a local maximum in the tropics off Angola which has a sign opposite to that near the Gulf Stream, indicating that the two regions are quite strongly out of phase. Although the time series is clearly a very stable quasi-sinusoidal function, it does seem to indicate a decrease in northern hemisphere winter temperatures. The Gulf Stream region, for example, has a winter minimum about 1.5 K lower in 1969 than in 1949. Summer temperatures do not seem to have undergone any systematic change. The latter conclusion is in conflict with that of Perry (1974) who, using North Atlantic weather ship data, found the season of maximum change to be summer.

S2 (Fig. 5), explaining 3.1% of the variance, has a time series with a less regular sinusoidal pattern having maxima in early spring and minima in late autumn. The spatial
pattern appears to be dominated by the upwelling areas off the Sahara and south of the equator. Surface easterlies tend to be a maximum in these regions in the spring of the respective hemisphere (Newell et al. 1972). These periods are just those which S2 indicates are periods of cooler water in the upwelling and adjacent regions, as would be the case if these s.s.t. anomalies were controlled largely by upwelling (Wooster et al. 1976).

The time series of S3 (Fig. 6) is dominated by a quasi-semiannual oscillation which has maxima in February–March and July–August, and minima in May and October–November. The spatial pattern is dominated by a centre in the western North Atlantic with a relatively

Figure 5. S2, explaining 3.1% of the seasonal variance as in Fig. 4.

Figure 6. S3, explaining 2.2% of the seasonal variance as in Fig. 4.
flat field nearly everywhere else. This pattern is quite similar to an empirical orthogonal function of Pacific s.s.t. except that the Pacific function explains slightly more variance and has a spatial pattern centred more in mid ocean (Weare et al.). Although other seasonal functions may be physically significant, space considerations preclude their presentation.

NS1 (Fig. 7) is the nonseasonal function which explains the largest fraction of the total nonseasonal variance. It is clearly dominated spatially by the region along the northern part of the Gulf Stream and the western region of the North Atlantic current. A comparison of S1 and NS1 would seem to indicate that the mode of greatest seasonal variation is quite closely related to that of the largest nonseasonal variation. The time series of this function shows a distinct, nearly linear downward trend from early in 1951 to late in 1965 of about 1 K per year. This is preceded by a dramatic increase in late 1950.

![Empirical orthogonal function NS1](image)

**Figure 7.** Empirical orthogonal function NS1, explaining 9.1% of the s.s.t. nonseasonal variance (Fig. 3b)) and its corresponding time coefficients. Vertical lines in the time series correspond to January of the respective years starting in January 1949 and ending in December 1969.

NS2 (Fig. 8) appears to be a good measure of a condition that seems often to arise in the North Atlantic: the area near the United States coast warms while the area just to the east cools, or vice versa. There also appears to be significant variation in the tropical region in this mode. The time series indicates dramatic changes during 1951, 1957-58, 1958-59, and 1967-68. Inspection of the deviation maps (not shown) for the individual months during the latter two periods verifies that there were large reversals of anomaly centres in the western and central North Atlantic.

NS3 and NS4 (Figs. 9 and 10) have much more complex spatial patterns than those of the previous function. No further discussion of these or less important functions will be made.

Because of the interest in the El Nino phenomenon in the Pacific (dramatic s.s.t. rises in the eastern tropical region) an empirical orthogonal analysis was made of tropical Atlantic data between 30°N and 30°S. The percentage of the total tropical nonseasonal variance explained by the first ten functions is indicated in Table 1 in the row designated TNS. Somewhat surprisingly, these ten explain only 52.2% of the variance, perhaps indi-
Figure 8. NS2, explaining 7.4% of the nonseasonal variance as in Fig. 7.

Figure 9. NS3, explaining 5.6% of the nonseasonal variance as in Fig. 7.

cating the poor quality of the data or that the tropical region is as complex as the ocean at large.

In the first tropical function, TNS1 (Fig. 11), which explains 11.9% of the variance, the variations are in phase over nearly the whole region. The greatest changes occur in the eastern region which corresponds well to the El Nino region in the Pacific. The time series indicates some very sharp changes in temperature with a characteristic time scale of 2–6 months. However, during 1963 there is a substantial warming lasting about 12 months which is the most intense and sustained anomaly during the 21 years of record. Since TNS1 has
positive values over most of the region analysed, comparison was made between this time series and that of the average deviation from the monthly means for the whole tropical Atlantic. The correlation coefficient is -0.92 so that TNS1 explains about 83\% of the variance of deviations from the tropical mean.

The second most important tropical function, TNS2 (Fig. 12), indicates a pattern in which the eastern region south of the equator varies out of phase with the remainder of the tropical Atlantic. It is strongest in the region where the equatorial current and countercurrent
merge, and in the region at the southern edge of the southern hemisphere subtropical gyre. The time series suggests a large increase in temperature in the southwestern Atlantic during 1958, which has been confirmed from individual anomaly maps for the year (not shown).

4. DISCUSSION

Much of the usefulness and physical significance of the patterns and time series shown depends upon their stability to minor changes in the data used in the computations. Although extensive tests of this have not been made, there is some evidence that the principal features of each of the analyses shown are quite stable. For instance, the seasonal functions for the area north of the equator were calculated using only the British data for 1953–69. The three most important functions have spatial patterns very similar to those of S1, S2 and S3, the largest differences being those for S3. The time series are also very similar in the three cases except that the semiannual oscillation in S3 is not so regular in the case in which no gross data error eliminations or missing data interpolations were used. Nonseasonal functions for the area from 70ºN to 40ºS, rather than to 30ºS as illustrated in the preceding figures, were also calculated. The patterns of these functions were very similar to those illustrated except that there appeared to be spurious results south of 30ºS due to the poor data quality. No corresponding time series were computed for functions which included the most southerly region. In both cases, however, the conclusion is that the first three or four functions, at least, are indicative of the variability of the ‘present day’ ocean.

As previously mentioned, the variance explained by the first few nonseasonal functions is much less than is explained by similar functions for the Pacific Ocean north of 20ºS (Weare et al.). This may be because the narrower Atlantic basin is indeed more complex in so far as current and surface-mixing changes are concerned. It also may be because the size of the analysis grid for the Pacific was twice that for the Atlantic. This would result in de-emphasizing to some extent the smaller-scale features, especially near the Kuroshio, relative to similar features in the Atlantic.
A comparison of the present results with those for the Pacific reveals some interesting differences between the two most important nonseasonal functions. Whereas the variability in the Atlantic is dominated by changes near the Gulf Stream, that in the Pacific is dominated by the area near the coast of Peru and along the equator. In fact, the spatial pattern of the most important nonseasonal function in the Pacific closely resembles the Atlantic TNS1 in the tropical region. A comparison of time series of these two functions reveals other important differences. While that of TNS1 appears to have a characteristic period of a few months, that of the Pacific function has a period of a year or more. Also, if one correlates these two series (smoothing the Atlantic function with a six-month filter), it is found that they have a correlation coefficient of 0.33. This suggests that while there may be some 'teleconnection' between these two ocean basins, it seems quite weak at best.

There has been a great deal of study of possible air-sea interaction on these time and space scales. Much of this work has been concerned with the possibility of using the more slowly varying s.s.t. as a predictor of atmospheric mean quantities. In this regard, Ratcliffe (1971) has classified nonseasonal s.s.t. variations from 1877 to 1970 into eight major spatial types. The most important has a variability centered just east of the 0°C contour near the Gulf Stream in NS1; Ratcliffe and Murray (1970) suggest that cooler water in this region is associated with blocked atmospheric patterns over western and northern Europe during the next month. Ratcliffe (1973) has identified May as the critical month for an anomaly persisting through the summer. Unfortunately, at present, the predictive skill using such relations is small. No attempt has been made so far to test whether one or more of the nonseasonal functions would improve the skill, although Davis (1976) has recently shown that their use is likely to do so.

The time series coefficient of TNS1 was also calculated for the period 1911–1972. Only data obtained from the National Climatic Center were used. This is illustrated in Fig. 13 in which results for the war years of 1914–21 and 1940–47 have been excluded because of inadequate data during those periods. Qualitatively, the whole period resembles the 1949–69 period in that there are variations of amplitude of as much as 10 K, and in that the characteristic time of these changes is a few months. The temperature changes during 1963–64, however, appears to be the most dramatic since 1911. Perhaps more significantly, there is a steady upward trend from 1911 through the early 1960s. This trend was calculated for each of the periods 1911–14, 1921–39, and 1948–72 and was found to be 0.036, 0.014, and 0.004 K/month, respectively. This is reflected in the fact that the difference between the means of the latest and the earliest periods is about 5 K, which would imply an
increase in the average tropical sea temperatures of 0.5–1.0 K. However, Kirk and Gordon (1952) and Saur (1963) seem to indicate that the ‘bucket’ method of taking measurements during the earlier period gives temperatures in the tropics which are about 0.4 K lower than by the ‘intake’ method used more recently. Therefore, the actual tropical mean temperature difference between 1972 and 1911 is likely to be about 0.1–0.6 K.

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REFERENCES


