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R.J. Haarsma

ABSTRACT

A number of model simulations of the changes in observed monthly mean sea surface temperature anomaly (SSTA) patterns for the North-Pacific and North-Atlantic oceans have been performed with a simple model for the mixed layer of the oceans. Of all possible important processes we have considered only advection of the climatological mean temperature field by anomalous winddriven currents and the effect of small eddies which is represented as a diffusion term.

In periods when persistence of the anomalies is high, the model produces little skill over persistence. The skill is mainly due to the diffusion term. However in an individual case of strong windforcing when persistence is low and new anomalies are formed, the model performance is much better than persistence. The performance of the model indicates that to a large extent SSTA patterns are formed in periods of strong windforcing and are slowly moving back to normal in subsequent periods of relatively low surface wind forcing.

Introduction

In many recent research papers the existence of (lag) correlations between sea surface temperature (SST) anomalies and anomalies in the atmospheric circulation has been convincingly shown. Examples are the studies by Davis (1976, 1978), who showed that sea level pressure (SLP) anomalies in fall and winter are statistically correlated with both SLP anomalies and SST anomalies 2 to 3 months earlier.

It is less clear to what extent and in what order the ocean and the atmosphere influence each other. Nevertheless the results of both statistical studies (Namias (1976), Ratcliffe and Murray (1970) Davis (1976, 1978) and model simulations (Rowntree 1976, Julian and Chervin 1978) suggest that SST anomalies have a certain, although small, influence on the long term averaged atmospheric circulation. Prediction of SST anomalies therefore seems meaningful to the problem of long range weather prediction.

The first attempts to predict large-scale SST anomaly patterns by dynamical methods are from Namias (1965), Arthur (1966), Jacob (1967), Adem (1970) and Namias (1972). All these models are two dimensional mixed layer models in which vertical fluxes are neglected. They are based on the equation for the conservation of heat:

$$\frac{\partial \hat{T}}{\partial t} = - \underset{(a)}{\hat{\vec{v}}.\nabla T_N} - \underset{(b)}{\vec{v}_N \cdot \nabla \hat{T}} - \underset{(c)}{\hat{\vec{v}} \cdot \nabla \hat{T}} + \underset{(d)}{K_H.\nabla^2 \hat{T}} + \underset{(e)}{\hat{Q}} \qquad (1.1)$$

$\hat{T}$ is the SST anomaly, $\hat{\vec{v}}$ the surface current anomaly, T_N and $\vec{v}_N$ the long-term mean temperature and current, $\hat{Q}$ the anomalous heating, K_H the horizontal eddy viscosity and ∇ the horizontal nabla operator. In these models the local time-rate of change of $\hat{T}$ is thus balanced by advection of normal SST by anomalous currents (a), advection of SST anomalies by normal currents (b), advection of SST anomalies by anomalous currents (c), horizontal diffusion as a crude parameterization of subgridscale processes (d) and anomalous heating (e).

Namias (1965) simulated the observed changes of the SST anomaly pattern in the pacific ocean during 1962-1963 using only term (a) in equation (1.1).

For $\hat{\vec{v}}$ he used the Ekman current calculated from the monthly mean anomalous windstress, which was obtained from the anomalous geostrophic wind, observed during the forecast period. He found an average pattern correlation coefficient between the observed and simulated anomaly pattern of 0.54. Jacob (1967) extended the work of Namias by including also term (b) and (c), but his results did not show a dramatic improvement over those of Namias. Nevertheless Namias (1972) demonstrated that term (b) was important in the formation of the SST anomaly pattern in the Pacific ocean during the winter of 1971-1972. The importance of the last two terms in equation (1.1) has been stressed by Adem (1970, 1975). He showed that for both the Atlantic and Pacific ocean when only horizontal diffusion is considered the sign of the simulated anomaly change is correct in 65% of the gridpoints, averaged over 6 years. In contrast the investigation of a few months suggest that the scores for either term (a) or (b) are about 58 percent, while the score of the model when all terms are included is about 66 percent.

More recently dynamic ocean circulation models of the Pacific ocean such as those of Haney (1978, 1980) and Huang (1978) have increased our knowledge of the formation of SST anomaly patterns. The model of Haney (1978) is a 10-level primitive equation model of a baroclinic ocean in a closed rectangular basin with a grid distance of approximately 2°. Salinity is neglected, whereas the heat fluxes at the surface have climatological values. The model is driven by monthly mean anomalous windforcing. He used the model for a case study of the winter 1976-1977 when enormous changes took place in the North Pacific ocean. After an integration of 122 days starting from 15 September 1976, the pattern correlation coefficient (PCC) between the observed and simulated SST anomaly pattern was 0.80, while in the run with climatological windforcing, the pcc was 0.26. For this period the persistence was low with a pcc of 0.12. Therefore the conclusion is that advection of SST anomalies by anomalous winddriven and anomalous geostrophic surface currents are the dominating processes in the development of SST anomalies. In a later study Haney (1980) also included anomalous heatfluxes to the atmosphere. For the same period the pcc increased from 0.80 to 0.88, demonstrating the importance of anomalous heating. The results of Huang (1978) with a similar model point in the same direction. Moreover he finds that the upwelling term $w' \frac{\partial T_N}{\partial Z}$ may be important, especially at lower latitudes. Locally it accounts for about 15% of the computed rate of change of the anomalous temperature.

In this paper we will develop a simple 2-dimensional mixed layer model based on equation (1.1). The main problem to be solved seems to be that, based on studies for different periods, authors arrived at highly conflicting conclusions as far as the importance of certain processes in explaining their skill is concerned. Our goal is to test such a model for many situations and not just for a single case. We have studied the importance of the individual terms in all situations. Our main finding is that in most cases persistence of the anomaly is very high and the diffusion term is dominant. However in individual cases of strong windforcing new anomalies are formed rapidly, which is reasonably described by the advection terms of the model. In those cases the skill is much better than persistence.

The model

Because the variability of the deeper parts of the ocean is much smaller than the variability of the mixed layer, we shall only take into account the coupling of the atmosphere with the mixed layer.

Our assumptions about the structure of the mixed layer are:

a. The mixed layer depth D is constant.
The high frequency variations of D are mainly caused by the day-to-day variations in the windstress at the surface. These daily fluctuations are outside the scope of long-range weather prediction. The only variation of D that we allow for is a prescribed annual cycle. D is generally small in summer and large in winter. We account for this by chosing a constant D for each month without horizontal variation.

b. The temperature and horizontal velocity in the mixed layer are independent of depth.
This implies that we assume that heat and horizontal momentum are thoroughly mixed in the layer.

c. There is no heat exchange at the bottom of the layer.

With these basic assumptions the equation for the local time-rate of change of the monthly mean SST anomaly becomes the already mentioned equation for the conservation of heat:

$$\frac{\partial \hat{T}}{\partial t} = - \hat{\vec{v}} \cdot \nabla T_N - \vec{v}_N \cdot \nabla \hat{T} - \hat{\vec{v}} \cdot \nabla \hat{T} + K_H \nabla^2 \hat{T} + \hat{Q} \qquad (1.1)$$

The anomalous currents are divided in an ageostrophic winddriven part $\hat{\vec{v}}_W$ and a geostrophic part $\hat{\vec{v}}_g$.

$$\hat{\vec{v}} = \hat{\vec{v}}_W + \hat{\vec{v}}_g \qquad (2.1)$$

Anomalous winddriven current

The total mass transport $\vec{S}$ in the Ekman layer caused by the windstress $\vec{\tau}$ is given by:

$$\vec{S} = \rho \int_o^{D_E} \vec{v} dz = \frac{\vec{\tau} \times \vec{k}}{f} \qquad (2.2)$$

where ρ is the density, $D_E = (\frac{2K_V}{f})^{\frac{1}{2}}$ the depth of the Ekman layer, $\vec{k}$ the unit vector in the z-direction and f the coriolis parameter.
From the total mass transport the vertically averaged horizontal velocity in the Ekman layer is easily computed with $\vec{v} = \vec{S} / (D_E \cdot \rho)$

Because of our assumption of thorough mixing in the mixed layer, we assume that the windgenerated horizontal momentum is uniformly mixed down to the bottom of the mixed layer.
This implies that we replace D_E by D in the equation for the horizontal velocity:

$$\hat{\vec{V}}_W = \frac{\vec{\tau}}{\rho f D} \times \vec{k} \qquad (2.3)$$

One of the main shortcomings in the theory of the Ekman currents, is that the detailed structure of the velocity pattern is highly dependent on the value of the vertical eddy viscosity K_V, which is an uncertain and variable parameter. The total mass transport (2.2) however is independent of the value of K_V. The anomalous windstress $\vec{\tau}$ is computed using the bulk formula:

$$\hat{\vec{\tau}} = \vec{\tau} - \vec{\tau}_N = C_D \rho \{ \| \vec{U}_{10} \| \cdot \vec{U}_{10} - \| \vec{U}_{N_{10}} \| \cdot \vec{U}_{N_{10}} \} \qquad (2.4)$$

$\vec{U}_{10}$ is the wind at 10 meter height above the surface, for which we have taken 80% of the geostrophic wind, veered with 15 degrees. C_D is the dimensionless drag coefficient, with a value of 2.10^{-3}.

Anomalous geostrophic current

If we neglect density changes other than those caused by temperature differences, we can calculate the geostrophic currents from the thermal wind relation:

$$\vec{V}_g = - \frac{H_o \, g \, \alpha}{f} \vec{k} \times \nabla T \qquad (2.5)$$

Here is H_o the level of no motion, α the thermal expansion coefficient and g the gravity acceleration.

Under the assumption that the normal currents are in geostrophic balance and have the same level of no motion as the anomalous geostrophic currents, it follows that the contribution of $\vec{V}_g \cdot \nabla T_N$ is cancelled by the contribution of $\vec{V}_{Ng} \cdot \nabla \hat{T}$.

Therefore we shall only use winddriven currents in equation (1.1).

Anomalous heating and horizontal diffusion

We shall assume that atmospheric air temperatures have climatological values. Under climatological conditions an SST anomaly induces an anomalous heatflux, which tends to damp the ocean anomaly. Horizontal diffusion has a similar effect on the evolution of a SST anomaly pattern. The effect of both processes is a back to normal tendency of the SST anomalies. Because the horizontal eddy viscosity and the induced anomalous heatflux are both uncertain parameters, we will only include horizontal diffusion with an appropriate value for K_H, which also accounts for the effect of anomalous heating.

As result of the foregoing discussion equation (1.1) simplifies to:

$$\frac{\partial \hat{T}}{\partial t} = - \hat{\vec{V}}_W \cdot \nabla T_N + K_H \nabla^2 \hat{T} \qquad (2.6)$$

The term $\hat{\vec{V}} \cdot \nabla \hat{T}$ has been dropped here, because its contribution turned out to be negligible.

Numerical solution

Integration of equation (2.6) gives:

$$\hat{T}(t_2) = \hat{T}(t_1) + \int_{t_1}^{t_2} [- \hat{\vec{V}}_W \cdot \nabla T_N + K_H \nabla^2 \hat{T}]dt \qquad (2.7)$$

Obviously the second term on the right hand side of (2.7) gives the extra contribution over persistence. For the calculation of the advection term we make use of the upstream differencing scheme. The diffusion is calculated with spatial central differences and forward time differencing. This system is stable if $\Delta t < \frac{\Delta x}{v}$.

The calculations have been performed on a grid of 25°N-70°N and 150°E-10°E, that is the northern part of the Atlantic and Pacific ocean. The grid distance is $\Delta\phi = \Delta\lambda = 2.5°$, and the time step is 1.5 day. The data of the normal SST and monthly mean SST anomalies were kindly provided by the U.K. Meteorological Office, on a grid of 5° x 5°. The intermediate points were computed by interpolating. The normal SST distribution is based on the period 1901-1960 for the Atlantic and 1931-1960 for the Pacific ocean. We choose the mixed layer depth D to be 100 m for the period October-March and 25m for April-September. The horizontal eddy viscosity K_H is 3.10^4 m^2/s (Adem, 1965).

Results

In order to test the model we did simulation experiments for the year 1978. Starting from an observed monthly mean SSTA pattern centred at the first of a month (say January) we used the mean anomalous winddriven current for January in order to advect T_N. Including also diffusion the integration predicts the monthly mean SST anomaly pattern centred at the first of February.

The computed velocities of the winddriven currents are of the order of 1 cm/s, giving rise to SST anomalies of about 0.5 K after 1 month. The observed anomaly changes are of the same order.

The depth of the mixed layer D is uncertain and therefore the amplitude of the predicted changes. In view of this uncertainty a useful method to test the model is to look at the pattern correlations between the observed and predicted changes in the anomalies (tendency correlations), because in our

persistence. The level of persistence is expressed by the pattern correlation between the actual SST anomaly pattern and the SST anomaly pattern of the foregoing month. These coefficients are also displayed in fig. 1. As expected persistence is rather high in general, with a pcc of 0.71 averaged over a year for both oceans combined. The main improvement over persistence is due to diffusion, which represents the back to normal tendency. For the diffusion term, the tendency pcc averaged over a year for both oceans together is 0.39. The contribution of the advection term varies considerably throughout the year. In some months there is a notable improvement over persistence, while in other months the contribution is negative. The pcc averaged over a year is 0.12. There appears to be a kind of anti-phase between the pcc of the persistence and the pcc of the tendency due to the advection term, which means that the tendency pcc is low when the persistence is high and vice versa. This indicates that whenever important changes in the SST anomaly pattern occur, they are partially predicted by the model.
The increase in the tendency pcc in months with low persistence can be seen both for the Atlantic and the Pacific.

The results have also been analysed by counting the percentage of points for which the sign of the anomaly changes have been predicted correctly. As the predictions for the Atlantic and Pacific did not show significant differences, the remaining figures only show the results for both oceans combined. The percentages are shown in fig. 2.The general picture is about the same as for the tendency pcc; the domination of the diffusion term, but in some months a notable contribution from the advection term. The scores averaged over a year are 58 and 66 for the advection and diffusion term respectively.

One way to test how the actually predicted SST anomalies correspond to the observed SST anomalies, is to compute the pcc between the predicted SST anomaly pattern and the observed anomaly pattern. This is displayed in fig. 3 as a function of time. The results show only a small improvement over persistence. This seems to be contradictory to the results of the tendency pcc where the diffusion term showed a notable contribution. However horizontal diffusion does not really changes the structure of the anomaly pattern, it mainly flattens out, therefore it makes no contribution to the pcc between the predicted SST anomaly pattern and the observed anomaly pattern. As a consequence the small improvement over persistence in fig.3 is almost completely due to the advection term, which is indeed a small effect averaged over a year.

On the other hand the r.m.s. error of the predicted SST anomaly pattern shows a marked improvement over persistence due to the effect of the diffusion term. Fig. 4 shows the r.m.s. error normalised by the r.m.s. error of climatology. A value of 1.0 indicates a prediction with an r.m.s. error equal to that of climatology. Here the improvement over persistence stands out more clearly, which is mainly due to the diffusion term. The results of the model for 1978, averaged over a year are given in Table 1, from which we can see that the r.m.s. error decreases by about 20 percent.

Discussion and conclusion

The small skill of this model comes mainly from the diffusion term. This seems to be contradictory to the results of other studies such as for instance those of Haney (1978) and Huang (1978), who found that advection of normal temperature by anomalous currents is the most important process in changing the SST anomaly pattern. However those studies are case studies, which are selected at the criterium of major changes in the SST anomaly pattern. Namias (1975), who also asserted the importance of the advection term, investigated a longer period. He found an average pcc between the observed and simulated SST anomaly pattern of 0.54 for the pacific ocean. If we compare this with the average pcc of persistence for the Pacific ocean in this paper (0.60), then the question arises whether his model performed much better than sole persistence. The pcc that he obtained starting from a climatological SST pattern (0.26), also points in that direction. Adem's (1978, 1975) results come close to ours. He also found that diffusion and heating are the important processes while on the average the advection term shows minor improvement over persistence.

Returning to the study of Haney (1978), we remind that he considered the winter of 1976-1977, for the North Pacific ocean, and simulated a period of 4 months from September to January. In this period, especially in January, there was a large SLP anomaly over the Pacific ocean, with a maximum of -20 mb. In the period that we have chosen the situation over the Pacific in January 1978, with a minimum of -15 mb more or less resembles Haney's case.

Fig. 5 shows the anomalous sea level pressure pattern over the Pacific ocean for January 1978. The pattern is dominated by a large negative anomaly covering almost the entire Pacific Ocean.

The main feature of the SST anomaly distribution at the beginning of January, shown in fig. 6, is a cold anomaly at $30^{o}N$ with a minimum value of $-1.25^{o}C$. At the end of the month the anomaly has become colder and shifted northward, meanwhile extending its area to the east (fig. 7a). For the same month we performed a simulation experiment, including only the advection term. The simulated SST anomaly pattern at the end of the month (fig. 7b) corresponds to a great extend with the observed anomaly pattern. It also displays the cooling, northward shift and extension to the east of the cold anomaly. If we compare the observed and predicted changes in the anomaly pattern during January 1978 (fig. 8a and 8b) we see that in this month with strong anomalous windforcing, the advection term alone predicts the large scale changes of the anomaly pattern rather well, but is unable to predict the smaller scale changes. From table 2 which displays the results of the simulation for January 1978, we see that in this month the advection term alone has a tendency pcc of 0.49, thereby dominating the effect of the diffusion term. In agreement with the ideas of Haney (1978) the results show that for this particular month of strong anomalous windforcing the advection term is the most important term for creating SST anomalies.

The following picture of the general long term behaviour of large-scale SST anomalies now emerges.

During relatively short periods of strong anomalous atmospheric forcing, SST anomalies are created. In the following months these are then slowly damped, until new strong anomalous forcing is able to generate new SST anomalies.

Our conclusion is that advection of normal SST by anomalous winddriven currents is the main mechanism in generating SST anomalies, but averaged over a year the main skill comes from the horizontal diffusion.

Figure captions

Fig. 1. Verification of the results of some forecasting schemes for both oceans. Solid line: pattern correlation between measured SSTA and the SSTA of the foregoing month (Persistence). Dashed and dot-dashed line: Pattern correlation of the measured change of the SSTA and the simulated changes of the SSTA (Tendencies).

A: advection of normal SST by anomalous winddriven currents.

D: Horizontal diffusion.

Fig. 1a) Atlantic Ocean.

Fig. 1b) Pacific Ocean.

Fig. 1c) Atlantic and Pacific Ocean combined.

Fig. 2. Percentage of points for which the sign of the anomaly change has been simulated correctly. Advection: A (dashes); diffusion: D (dashed-dotted). (Atlantic and Pacific Ocean combined).

Fig. 3. Pattern correlations (Atlantic and Pacific Ocean combined):

P: persistence

P + A + D: Persistence + advection + diffusion.

Fig. 4. r.m.s. error of SSTA simulations normalized by the r.m.s. of the observed SSTA. (Atlantic and Pacific Ocean combined).

Fig. 5. Monthly mean SLP anomaly pattern January 19678. Isobar distance: 3 mb.

Fig. 6. observed SSTA pattern at the beginning of January 1978.

Fig. 7 (a) observed SSTA pattern at the end of January 1978.

(b) simulated SSTA pattern at the end of January 1978, including only persistence and advection.

Fig. 8. (a) Observed SSTA changes during January 1978.

(b) Simulated SST changes for January 1978, including only persistance and advection.

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Table 1

	Pattern correlation Tendency	Pattern correlation	r.m.s. error normalised	Sign correctly predicted (percentage)
P	-	0.71	0.57	-
A	0.12	0.71	0.57	58
D	0.39	0.72	0.50	66
A + D	0.40	0.73	0.48	68

Table 1: Results of the S.S.T.A. simulation averaged over 1978. P = persistence; A = advection of normal temperature by anomalous currents; D = horizontal diffusion.

Table 2

	Pattern correlation Tendency	Pattern correlation	r.m.s. error normalised	Sign correctly predicted (percentage)
P	-	0.46	0.51	-
A	0.49	0.63	0.43	80
D	0.39	0.49	0.44	63
A + D	0.71	0.67	0.35	82

Table 2: Results of the S.S.T.A. simulation for the North Pacific, January 1978.

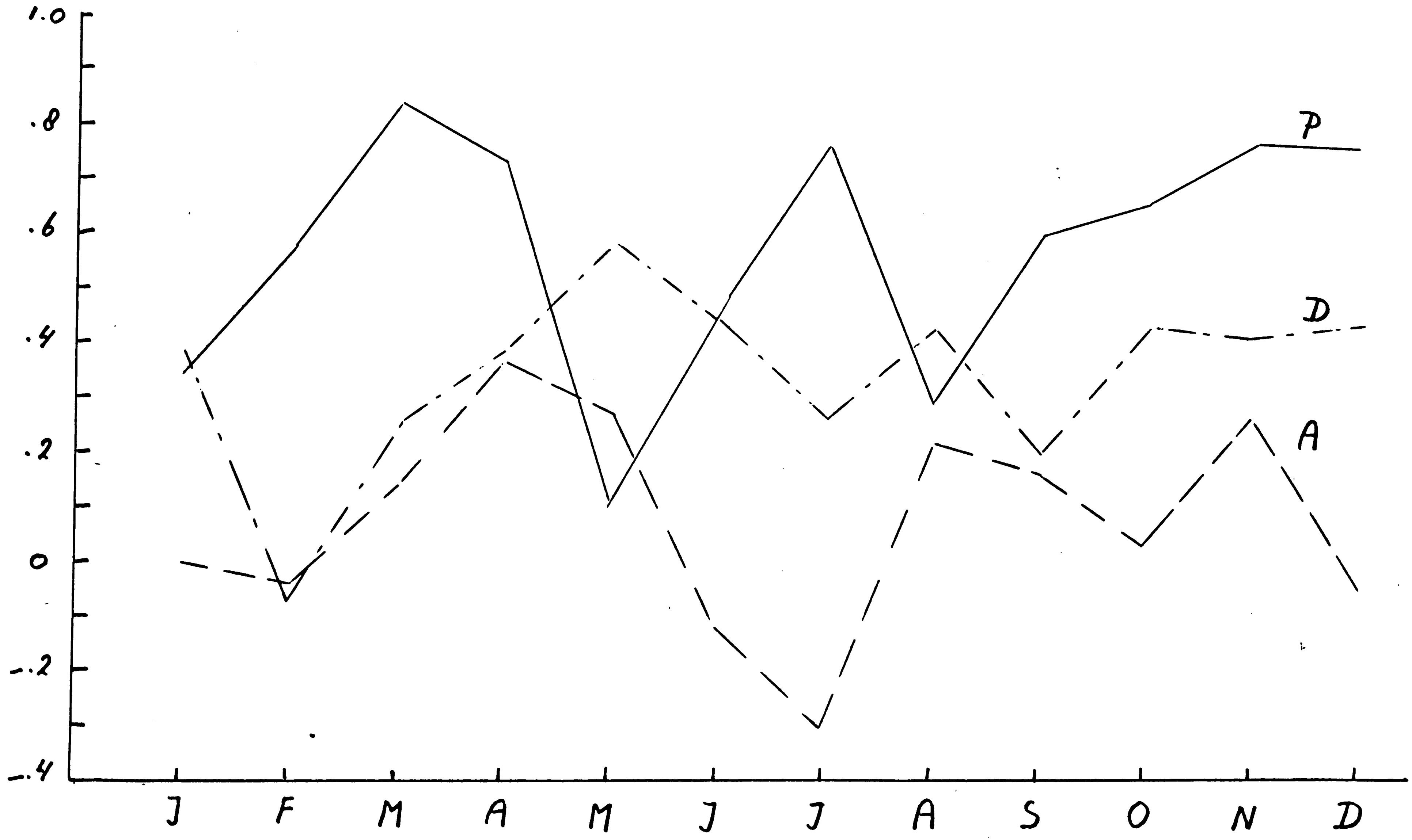

Fig. 1a.

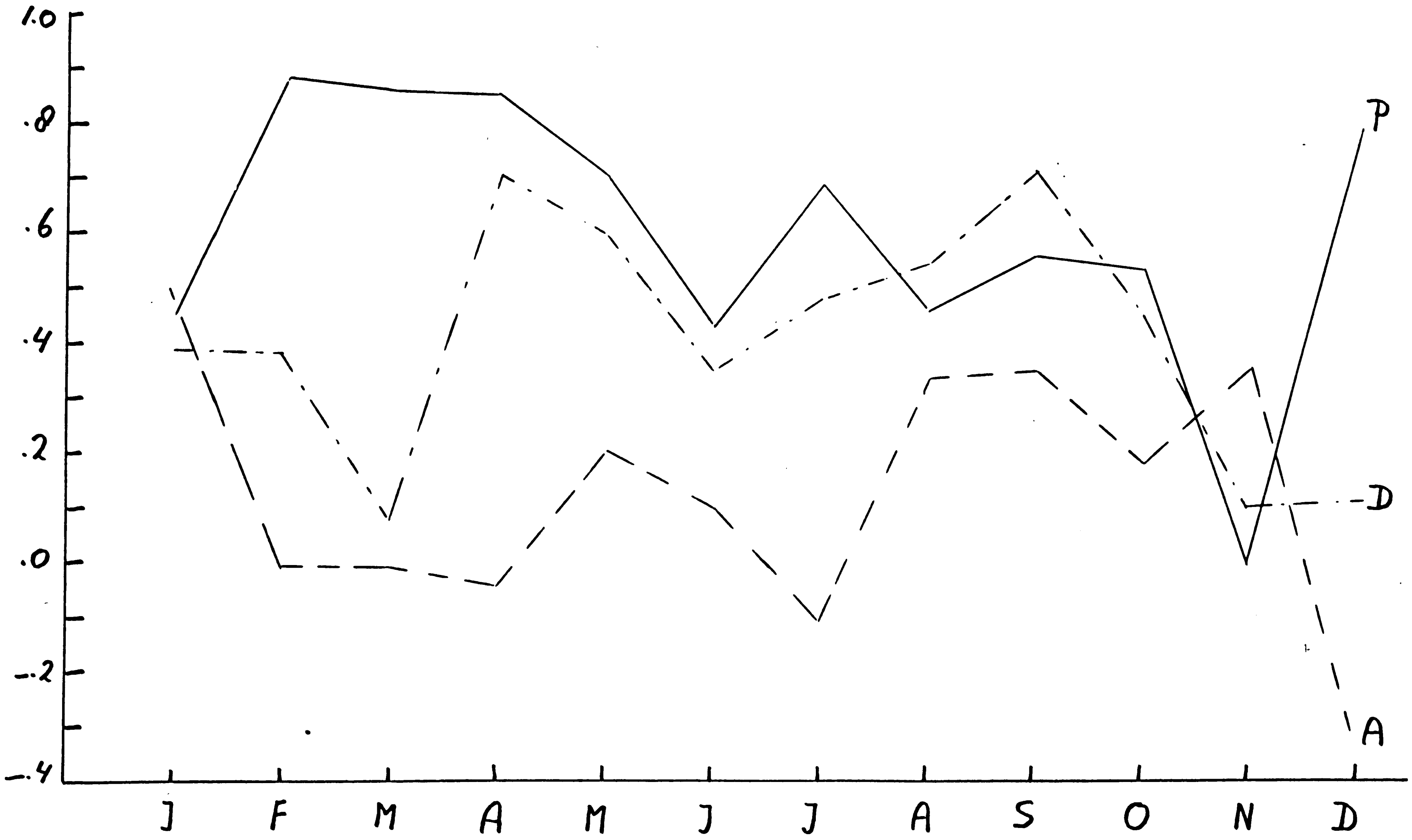

Fig. 1 b.

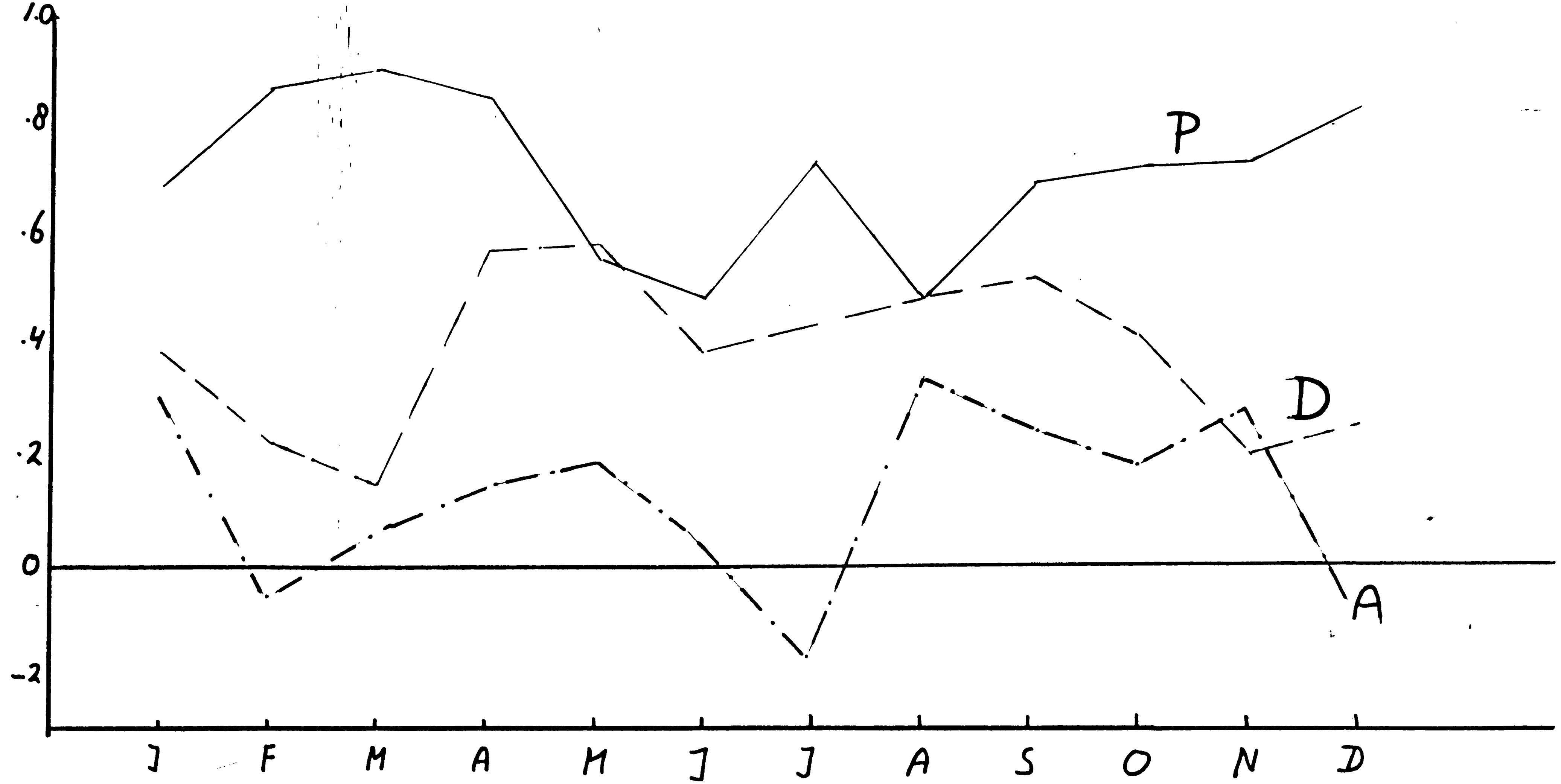

Fig. 1c.

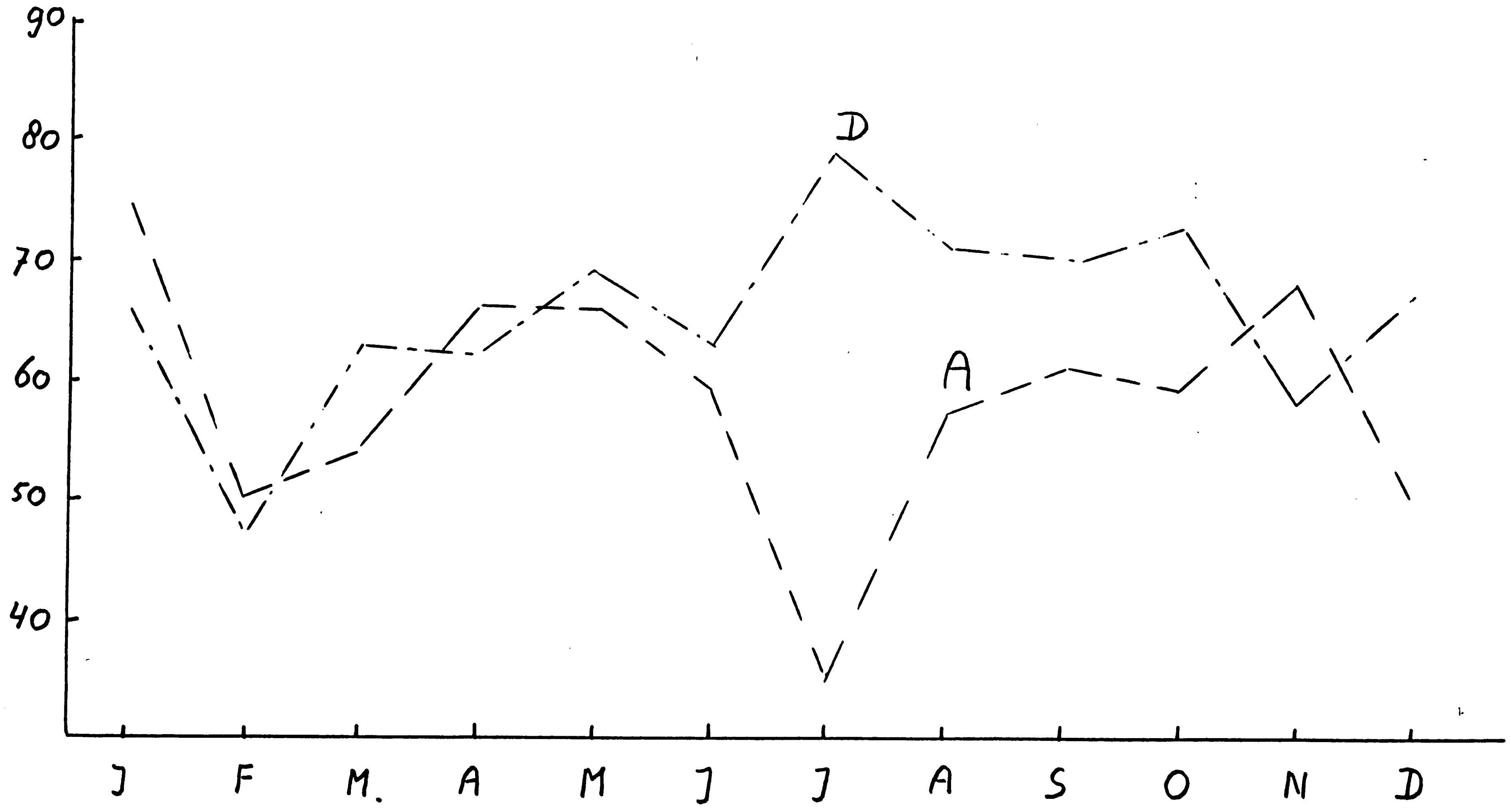

Fig. 2.

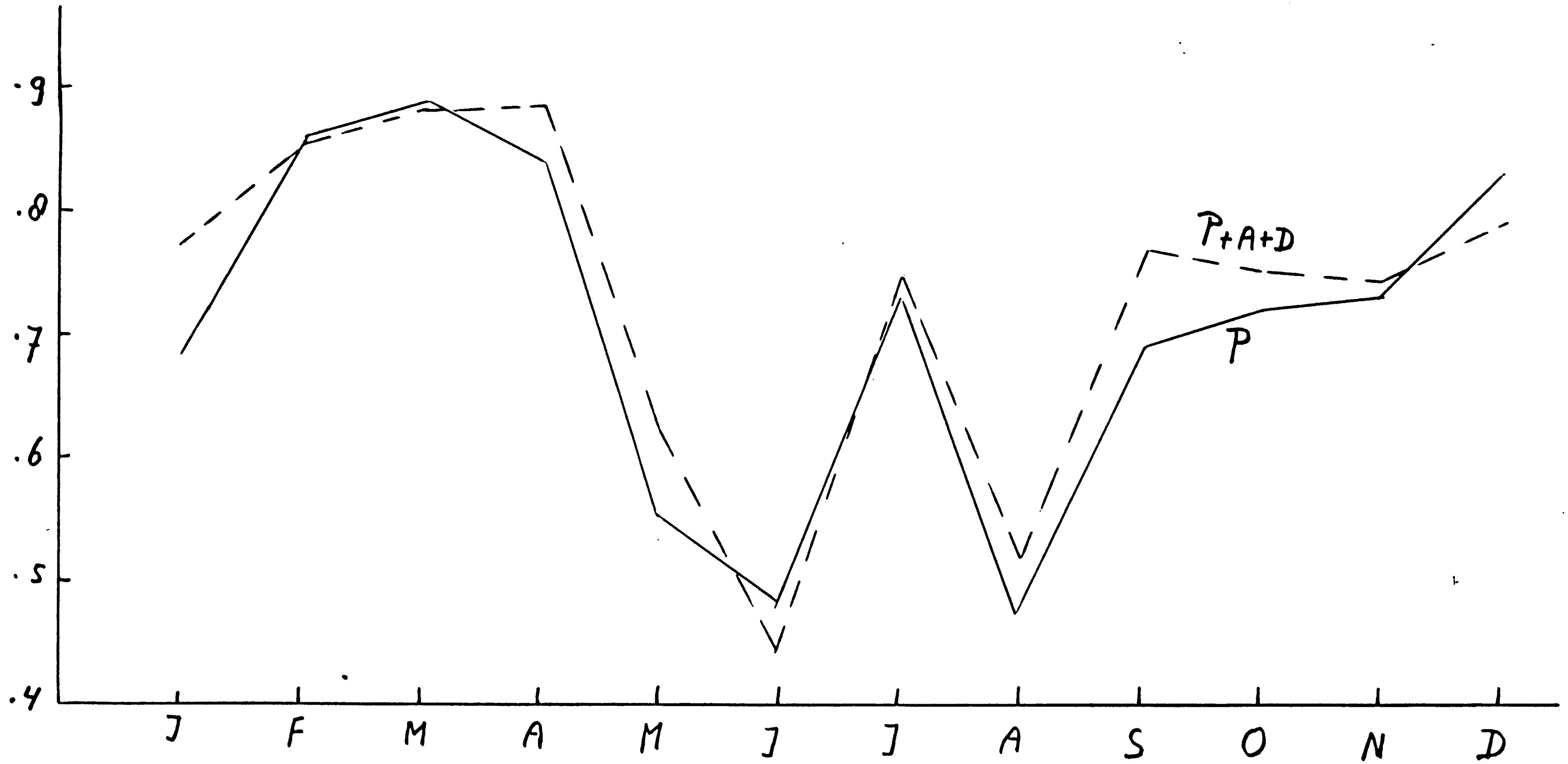

Fig. 3

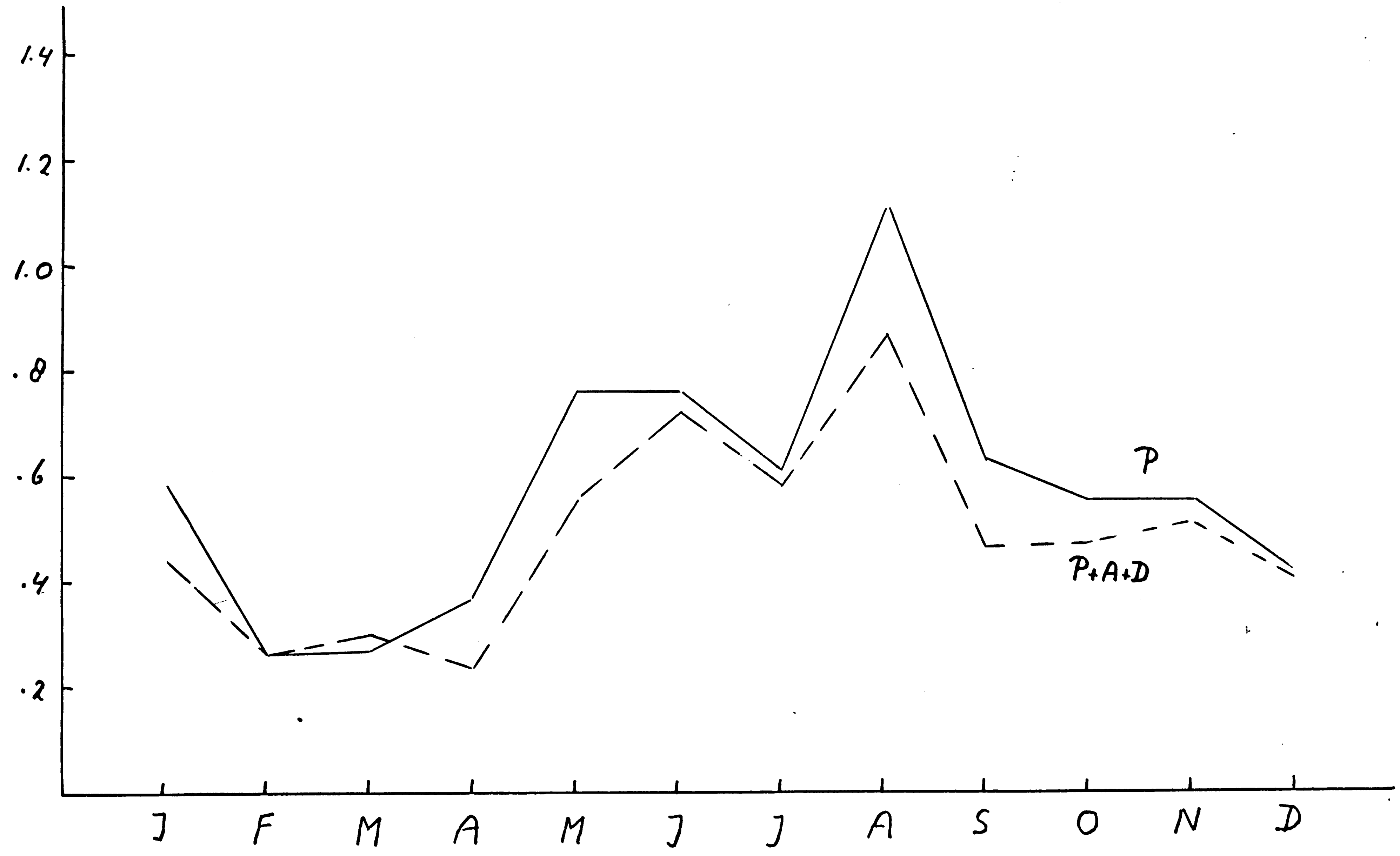

Fig. 4

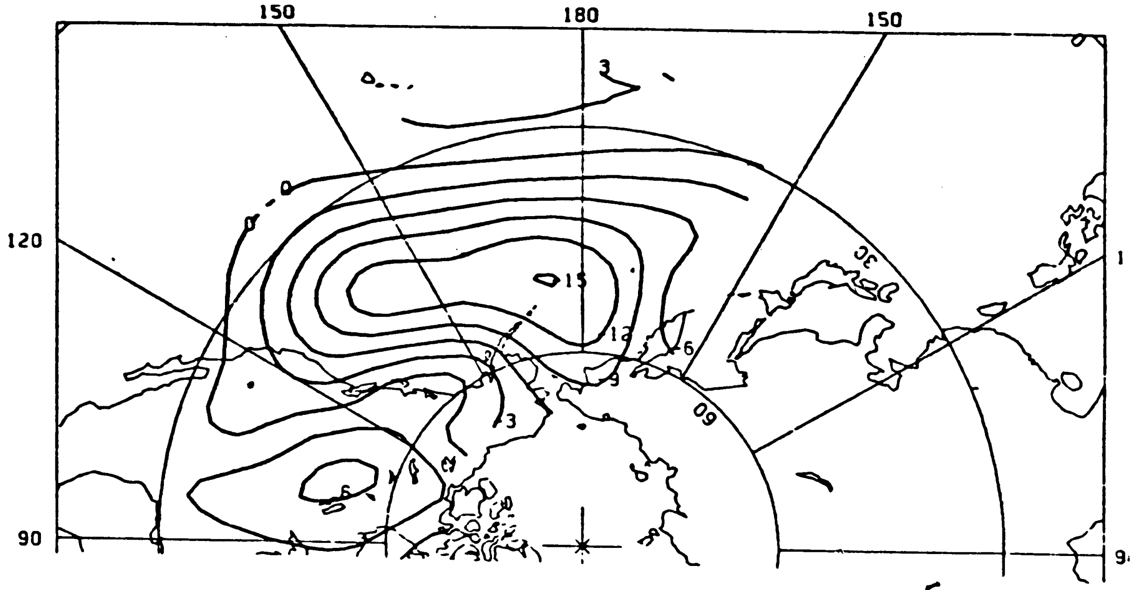

Fig. 5

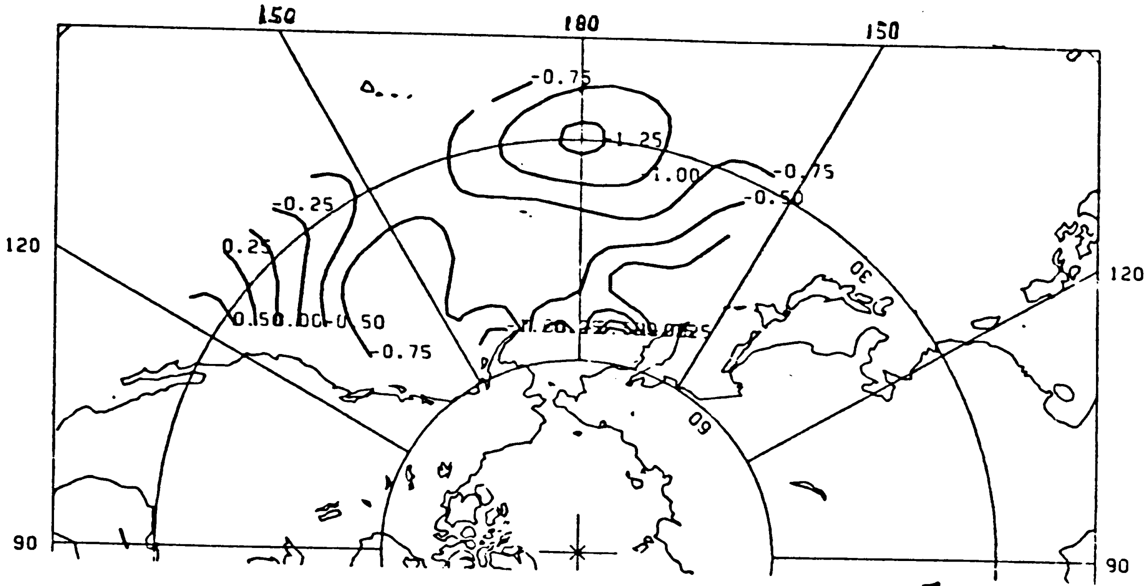

Fig. 6

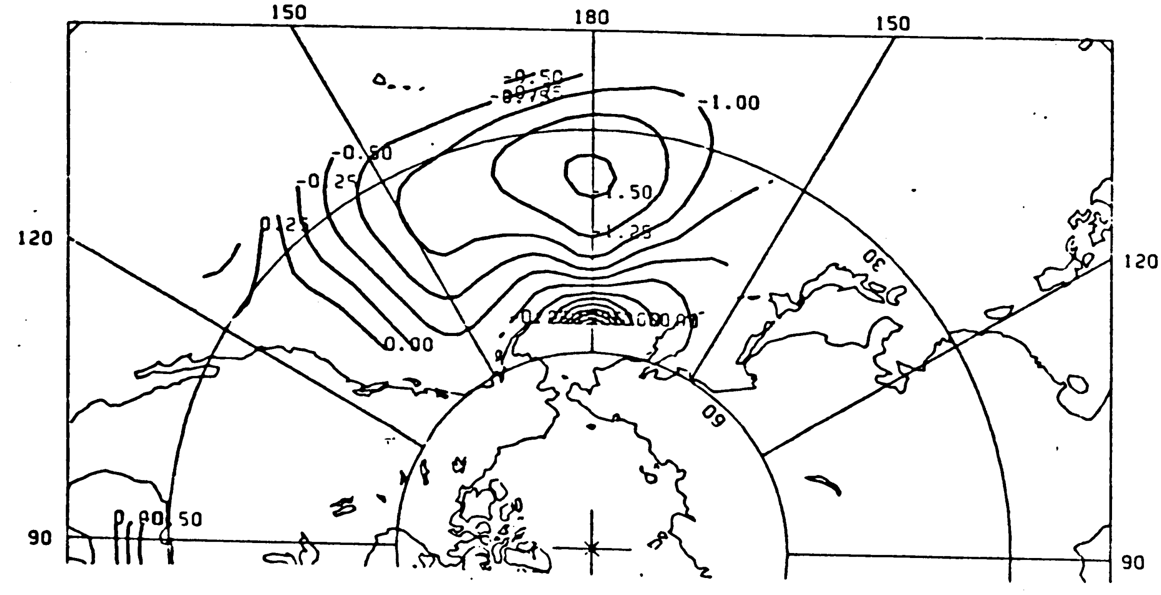

Fig. 7a

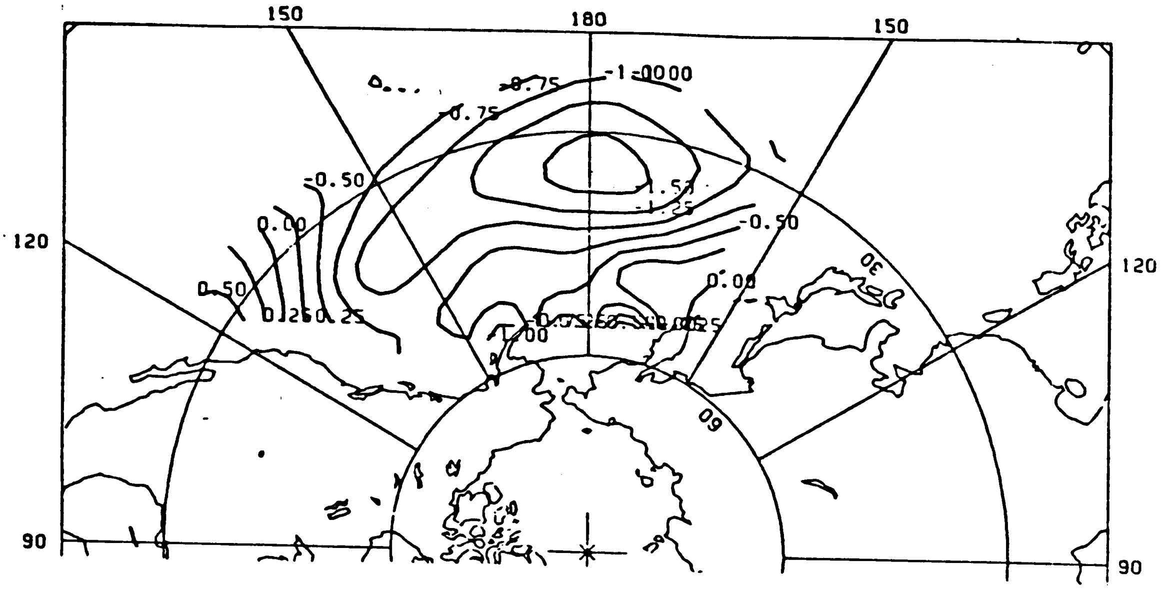

Fig. 7b

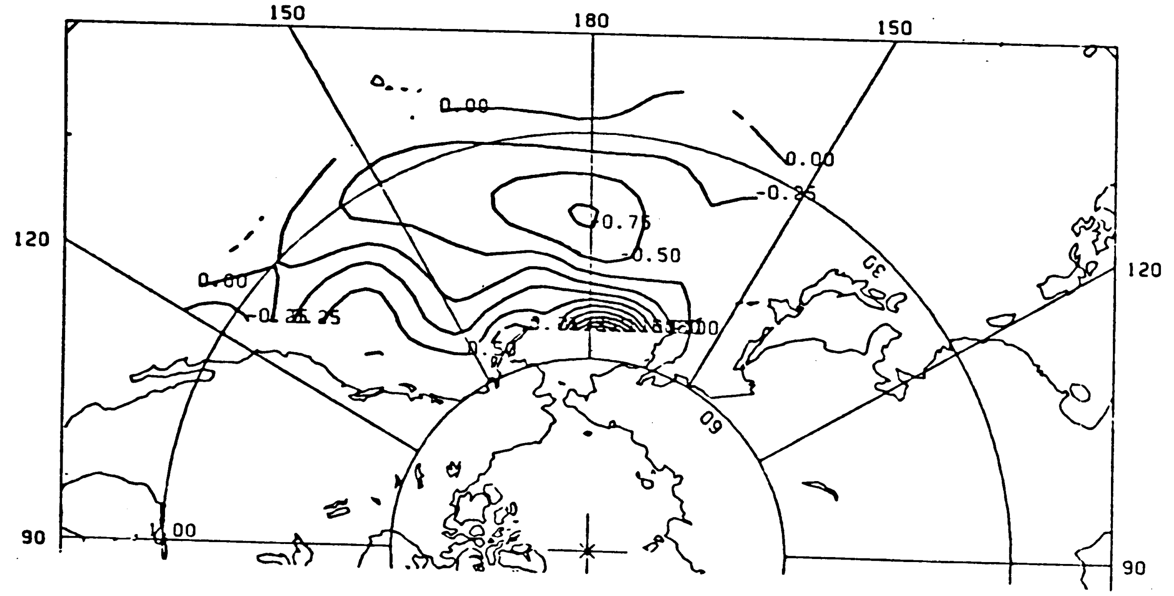

Fig. 8a

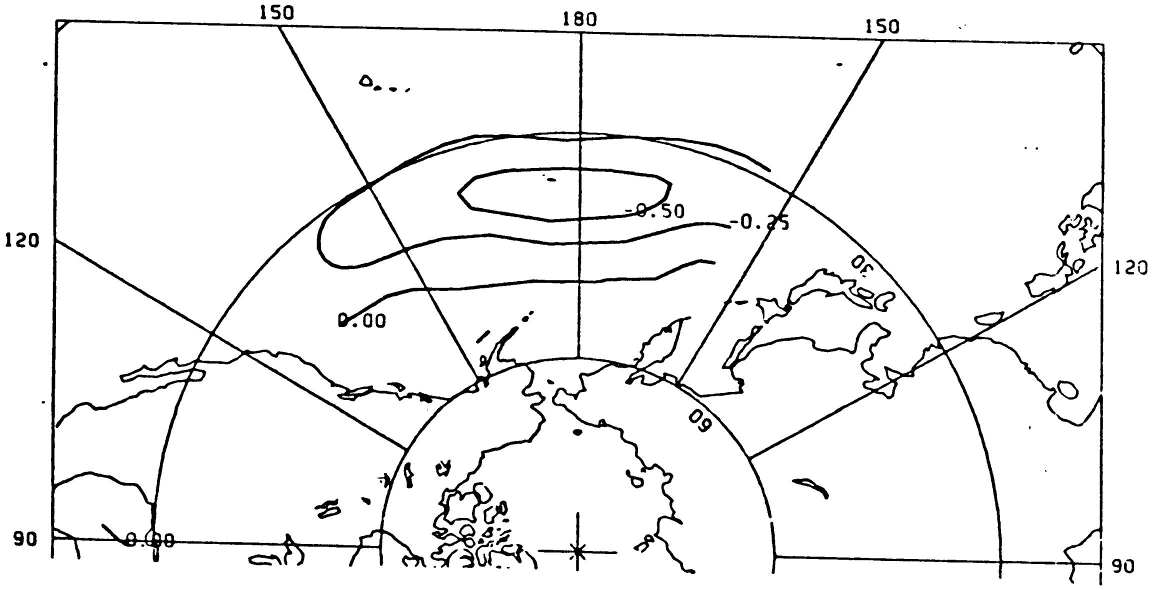

Fig. 8b