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Spatial and Temporal Scales of Temperature Variability in the Bay of Fundy

by

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INTRODUCTION

Low returns of Atlantic salmon to the rivers of the inner Bay of Fundy during the later half of 1980s have lead to an unprecedented closure of all harvesting of these stocks in 1991. In February of 1992 the Canadian Department of Fisheries and Oceans held a one day workshop at Halifax to review the possible causes of the low returns and determine prospective research strategies. At that workshop we presented information on environmental conditions in the Bay of Fundy. The workshop was particularly interested as to whether there had been any significant changes in the temperature regime during the period of the decline of the salmon stocks. The present paper provides a summary of our analysis and results.

STUDY AREA, DATASETS AND STATISTICAL METHODS

The Bay of Fundy is surrounded by New Brunswick and Nova Scotia and borders the Gulf of Maine (Fig. 1). From Grand Manan Island to Cape Chignecto the Bay is approximately 150 km long and varies in width from 75 km at Grand Manan to slightly less than 50 km at Cape Chignecto. At the mouth there is a topographical depression known as Grand Manan Basin. The maximum depth decreases gradually from 220 m in this depression to approximately 40 m near Cape Chignecto. This Cape separates a series of narrow embayments, the largest being Chignecto Bay to the north and Minas Basin to the south.

Resonance near the semi-diurnal tidal frequency for the Gulf of Maine-Bay of Fundy system results in high tidal elevations and strong tidal currents (Garrett 1972) with the tides in the upper Bay of Fundy being reputed to be the highest in the world. The strong tidal currents cause intense mixing through bottom-generated turbulence. This produces vertically well-mixed conditions throughout most of the Bay (Garrett et al. 1978) although horizontal along-bay gradients in temperature and salinity do persist (Holloway 1981).

Long-term temperature records have been collected in the Bay of Fundy by the St. Andrews Biological Station at two sites. Twice daily measurements of sea surface temperature have been taken at the St. Andrews wharf since 1921. Data were originally measured with thermometers but in the past few years an internally recording thermograph has been used. The Biological Station has also monitored temperature and salinity conditions at Prince 5 Station (Fig. 1) near the entrance to the Bay of Fundy since 1924. Measurements were taken approximately once per month at standard depths down to the bottom (90 m) using reversing thermometers and water bottles. Since 1991, however, a conductivity-temperature-depth (CTD) profiler has been used. To determine how representative these measurements are of conditions in the inner Bay of Fundy, we obtained approximately monthly sea surface temperature (SST) data on a 41 point equally-spaced grid (20 by 20 km) for the period 1980 to 1990 (Fig. 2). The temperatures were based upon IR thermal imagery from the NOAA polar-orbiting satellites and were obtained from the Atmospheric Environment Service in Ottawa.

Monthly temperature anomalies were determined for the St. Andrews and Prince 5 stations by subtracting the monthly means determined over the period 1951-80. The means have been published by Trites and Drinkwater (1984) and Drinkwater (1987), respectively. For the satellite-derived SST data, seasonal cycles were determined at each grid point using harmonic analysis. The temperature data for all the years were combined and fitted to sine and cosine functions with frequencies corresponding to the annual and semi-annual periods following the procedure outline in Smith (1983). The anomalies were then calculated by subtracting the seasonal cycles from the raw temperature data. The spatial structure of the temperature anomalies were explored using correlation analysis.

RESULTS

Satellite SST Data

Before examining the long-term temperature trends at St. Andrews and Prince 5 we shall explore the spatial variability in the satellite-derived SST data. Because of the intense vertical mixing, the SSTs should reflect changes throughout the water column. We shall return to this point in the discussion of the Prince 5 data.

The annual means from the grided data show a range from just above 8°C near the mouth of the Bay to just below 7°C in Chignecto Bay and east of Saint John on the New Brunswick side (Fig. 3). The slightly colder mean temperatures on the New Brunswick side in the inner half of the Bay coincide with a region of upwelling identified by Lauzier (1967) from bottom drifter releases and recoveries.

The seasonal cycles in temperature at grid point (GP) 9 in Minas Basin and GP16 at the mouth of Passamaquoddy Bay are shown in Fig. 4. Note the temperature range in Minas Basin was a factor of 2 larger than that in Passamaquoddy Bay. The spatial structure of the amplitude reveals a generally increase from 4-5°C at the mouth to 9-10°C at the head in the narrow embayments (Fig. 5). There is a distinct asymmetry across the Bay with lower amplitudes on the southern side. This pattern reflects the mean circulation which is inward along the Nova Scotian coast and outward along the New Brunswick coast (Bumpus and Lauzier 1965). The waters with lower amplitude seasonal cycles near the mouth are therefore advected inwards on the southern side of the Bay while the waters from the inner reaches of the Bay are advected out along the New Brunswick side producing the higher amplitude seasonal cycles there. The phases in the seasonal cycles represent the time of maximum temperature and range from late August in the shallow waters of Chignecto Bay, Minas Basin, and off southwestern Nova Scotia to mid-September in the region off Grand Manan Island. Throughout most of the Bay of Fundy the phases were similar, varing between the 1st and 10th of September but with a tendency for an earlier maximum along the New Brunswick shore.

The seasonal cycles were subtracted from the temperature records to obtain anomalies. These show significant high-frequency variability superimposed upon a low-frequency trend (Fig. 6). The later consisted of maximum temperatures in the early half of the decade (1982-84) and a decline through the later half. Correlation analysis between anomalies at the 41 grid points was carried out. The correlations relative to the center of the Bay (GP20) and the Passamaquoddy region (GP16) are displayed in Fig. 7. The former shows a gradual decrease away from the center to values near 0.6 at both the mouth and the head of the Bay. There is some asymmetry with correlations tending to be higher on the Nova Scotian side than on the New Brunswick side. The correlations relative to GP16, however, indicate a local minimum towards the center of the Bay. The correlations relative to both grid points were then plotted as a function of horizontal distance (Fig. 8). They show a slightly more rapid fall off in correlation with distance when using GP20 as a reference station. An e-folding distance based on variance translates to the distance at which the correlation coefficient is reduced to about 0.6. For the SST data this distance is roughly 180 km which corresponds to the approximate length of the Bay. This suggests that the data at Prince 5 and St. Andrews should be reasonably representative of most of the Bay of Fundy.

Prince 5

At Prince 5 the 25-month running mean temperatures at the surface and near bottom (90 m) are similar but there is a tendency towards greater high frequency variance at the surface (Fig. 9). We partitioned the monthly means into low pass (the 25-month running means) and high pass components (the monthly means minus the low pass component). The variance of the high pass was $0.79[^{\circ}C]^2$ at the surface compared to $0.61[^{\circ}C]^2$ at 90 m. The correlation between the high pass signals at the two depths was only 0.2. The low pass signals, on the other hand, were strongly correlated (r=0.8, p=0.01) and the variance at 90 m ($0.39[^{\circ}C]^2$) exceeded that at the surface ($0.28[^{\circ}C]^2$). Both of these features were also found in an analysis of temperature variability in Emerald Basin on the Scotian Shelf (Petrie et al. 1991) although there was less of a difference in the low pass variance with depth at Prince 5. This smaller difference is most likely explained by the greater mixing due to the high tides in the Bay of Fundy. The larger variance at depth suggests that the signal is not driven by local heating and cooling through the net surface heat fluxes but rather by oceanic advection (Petrie et al. 1991).

These results indicate that, for at least low frequencies, i.e. interannual periods and longer, the SST data in the Bay of Fundy do reflect changes throughout the water column.

At Prince 5 temperatures during the last two decades have generally been above their long-term (1951-80) normals (Fig. 9). From approximately 1970 to 1985 surface temperatures increased slowly before beginning to decrease. Near-bottom the maximum occurred in the mid to late 1970s and temperatures have gradually decreased since then. In the last three years, temperatures at both levels have been near normal.

SST at St. Andrews

The monthly mean variations at St. Andrews are less than those at Prince 5 (Fig. 10). This is to be expected since the former are well resolved temporally (averages from twice daily measurements) whereas the Prince 5 are single point observations. The pattern of the filtered SST anomalies, however, is generally similar (Fig. 10). The St. Andrews anomalies in recent years show a decline from the early 1980s to 1989 followed by an increase through into 1991. In contrast to Prince 5 the St. Andrews temperature anomalies appear to be below normal through most of this period.

Autocorrelation of the monthly mean SSTs at St. Andrews shows that within 2 months the correlation has fallen to below 0.5 (Fig. 11). A more rapid decrease is observed at Prince 5 in both the surface and near bottom waters. This is likely due to the single point measurements at Prince 5 whereas the St. Andrews are true monthly averages.

The difference in the filtered SST anomalies (Prince 5 minus

St. Andrews) showed a significant jump in 1985 and have remained high (average since 1984 of 0.8°C with St. Andrews being cooler, Fig. 12). Indeed, the temperature differences since this event have exceeded all previous values. The correlation between the filtered sea surface temperature data at St. Andrews and Prince 5 was 0.91 for the years 1926-1984 but falls to 0.81 if the data from 1985 on is added. The timing of the large temperature difference corresponds to the reconstruction of the wharf at St. Andrews. The new wharf may have altered flushing or mixing rates or flow patterns such that temperatures are now colder on average. We plan to explore this further in future.

The motivation for our work was the inner Bay of Fundy salmon stocks which have fallen to record low returns. Could this have been a response to environmental change? Certainly it does not appear to be related to temperature. Our data suggest that in the late 1980s when the stocks were decreasing, temperatures were also decreasing but still were near their long term historical means. Previous analysis has shown that salmon returns generally increased with decreasing temperatures (P. Amiro, DFO, Halifax Lab, personal communication), therefore, the slightly cooler temperatures should not have contributed to the decline in the salmon stocks.

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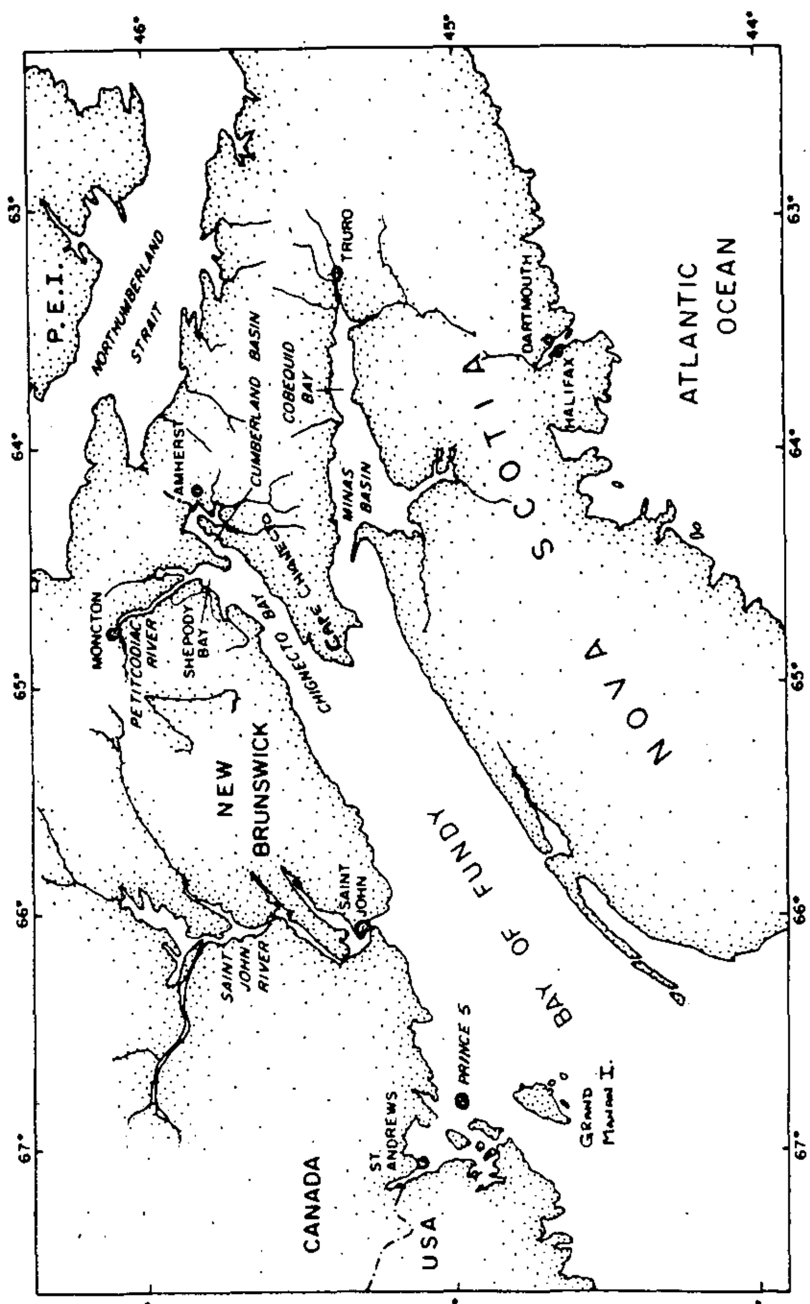


Fig. 1. Map of the Bay of Fundy.

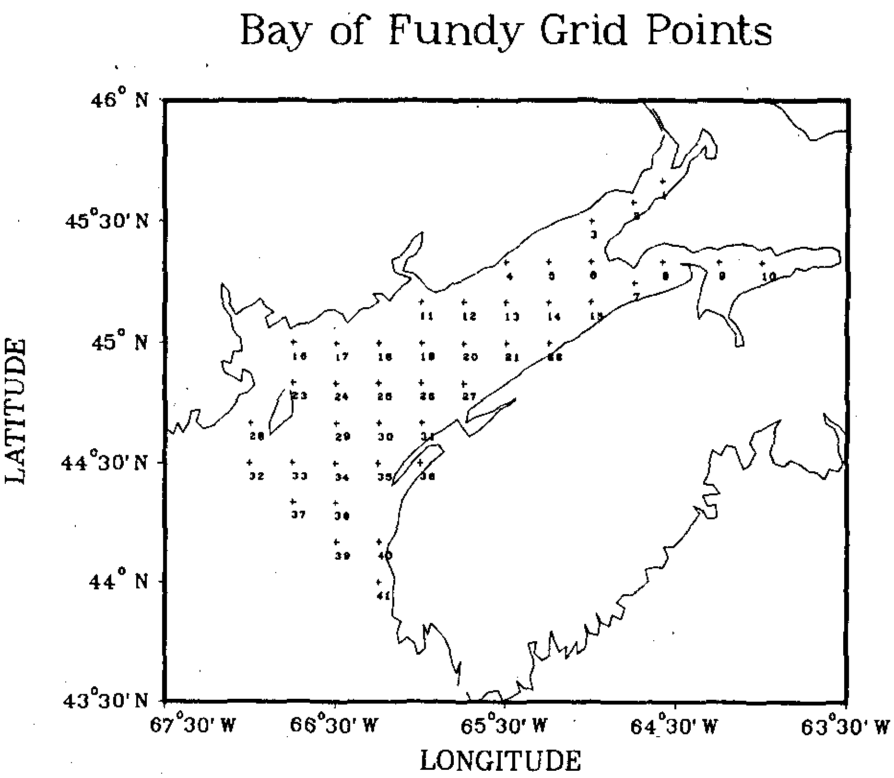


Fig. 2. The grid locations for sea surface temperatures determined from satellite imagery.

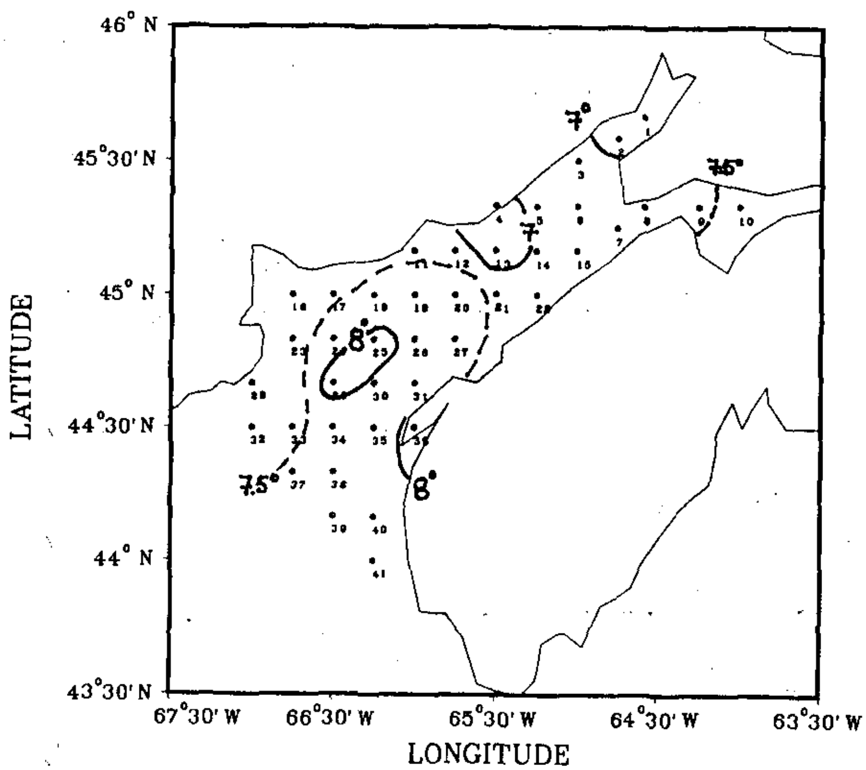
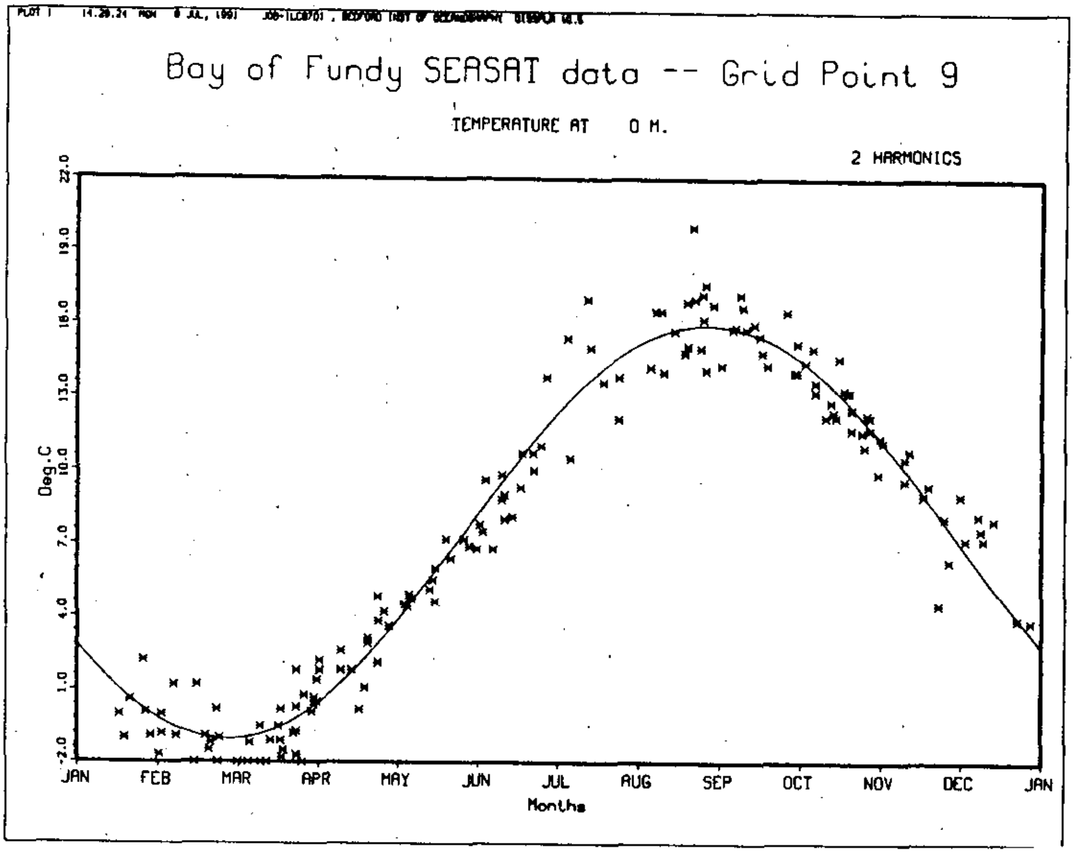


Fig. 3. The annual mean sea surface temperatures.



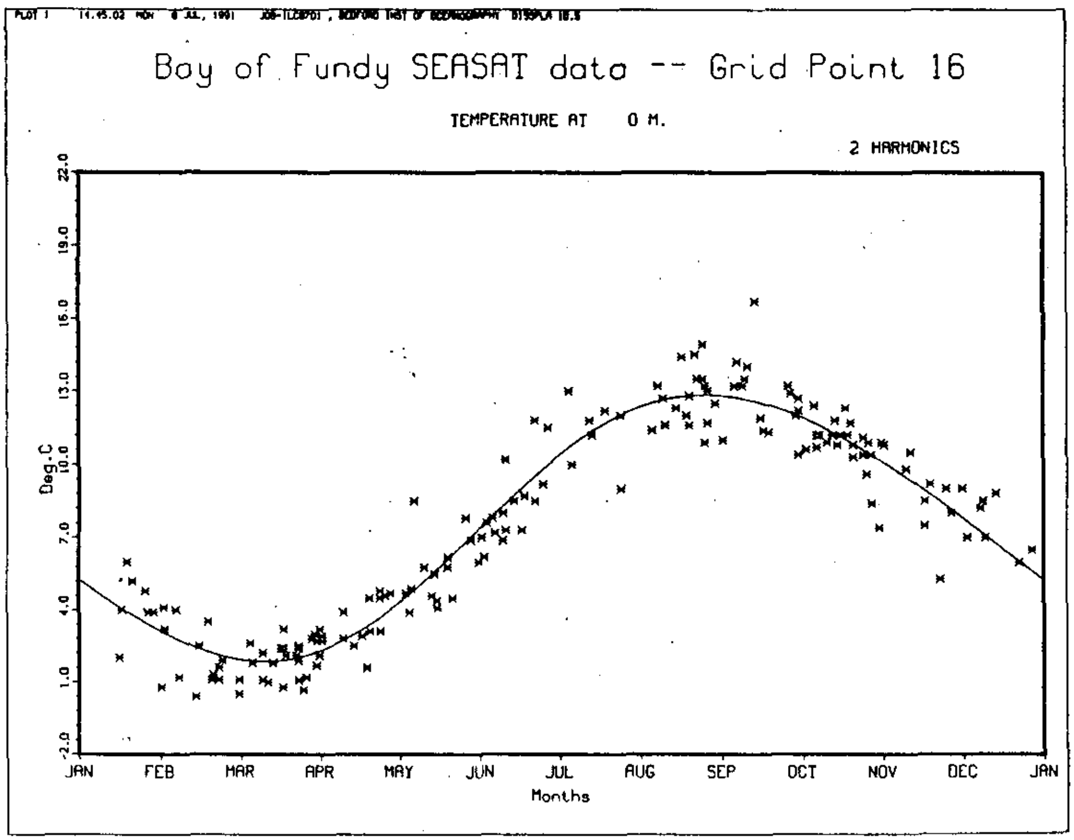
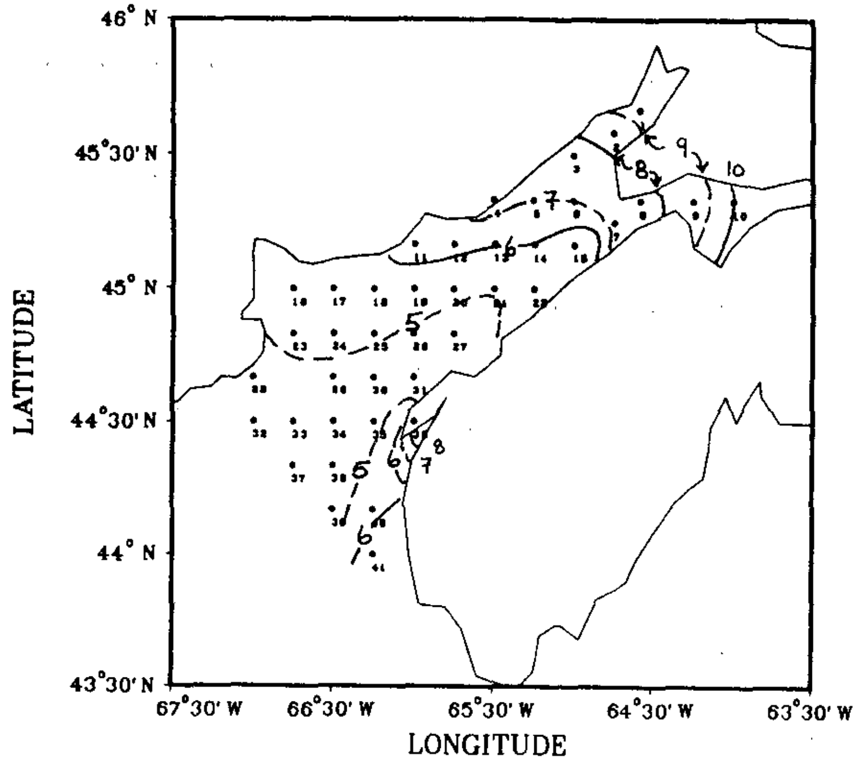


Fig. 4. The harmonic fit to the seasonal cycle for grid points 9 in Minas Basin and 16 at the mouth of Passamaquoddy Bay.

AMPLITUDE (°C)



PHASE (DAY OF THE YEAR)

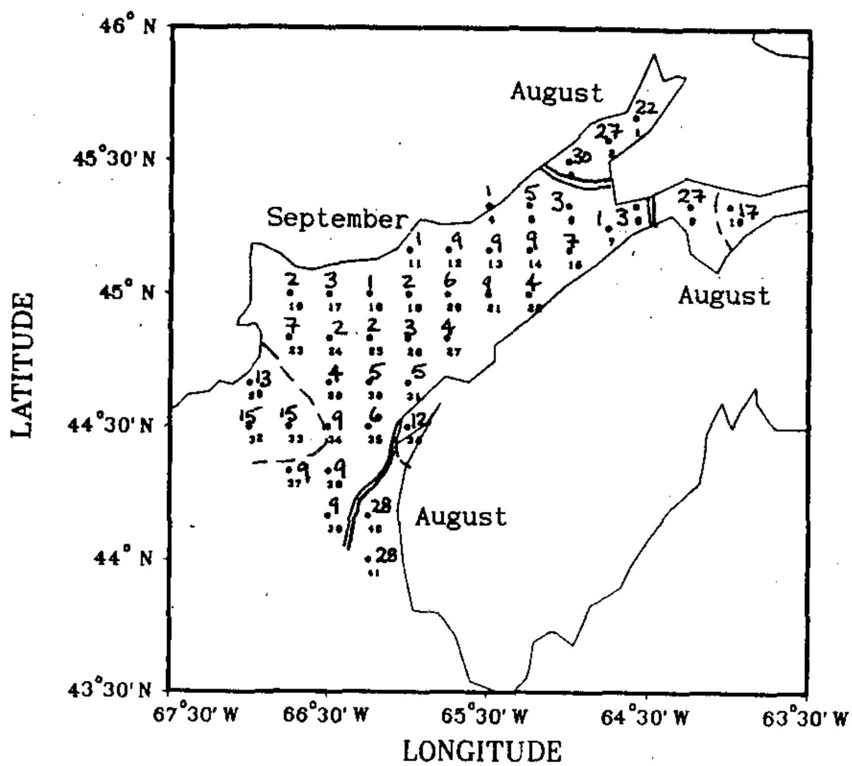
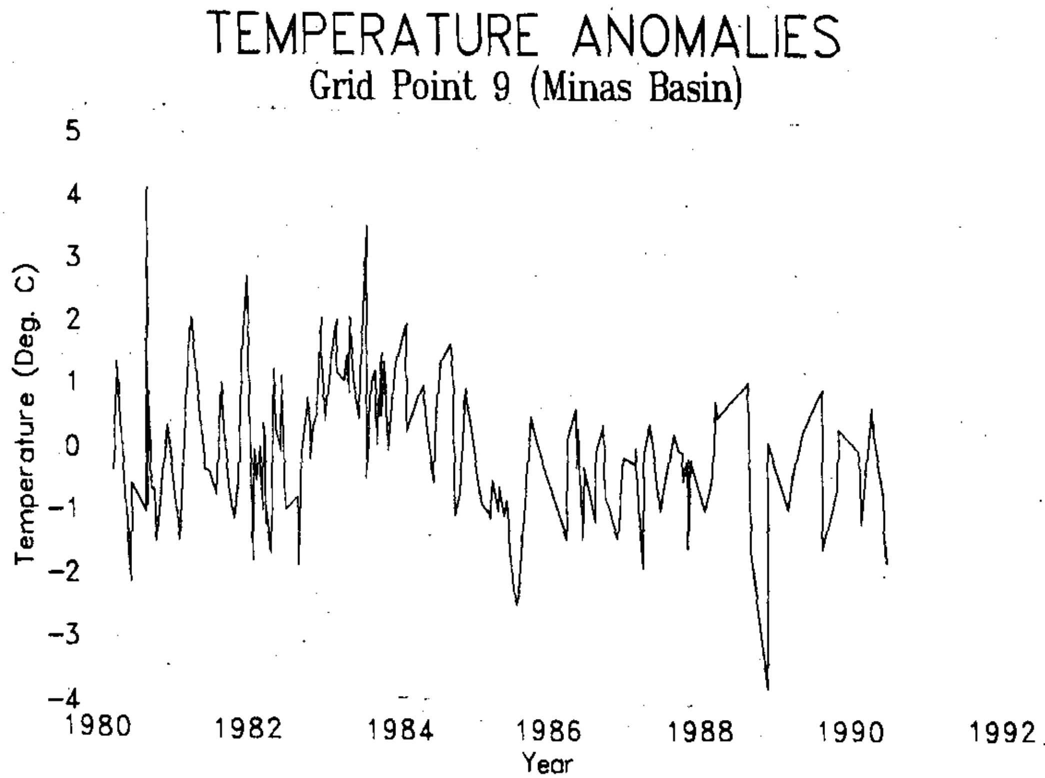


Fig. 5. The spatial variations in the amplitude and phase of the seasonal cycles of sea surface temperature.



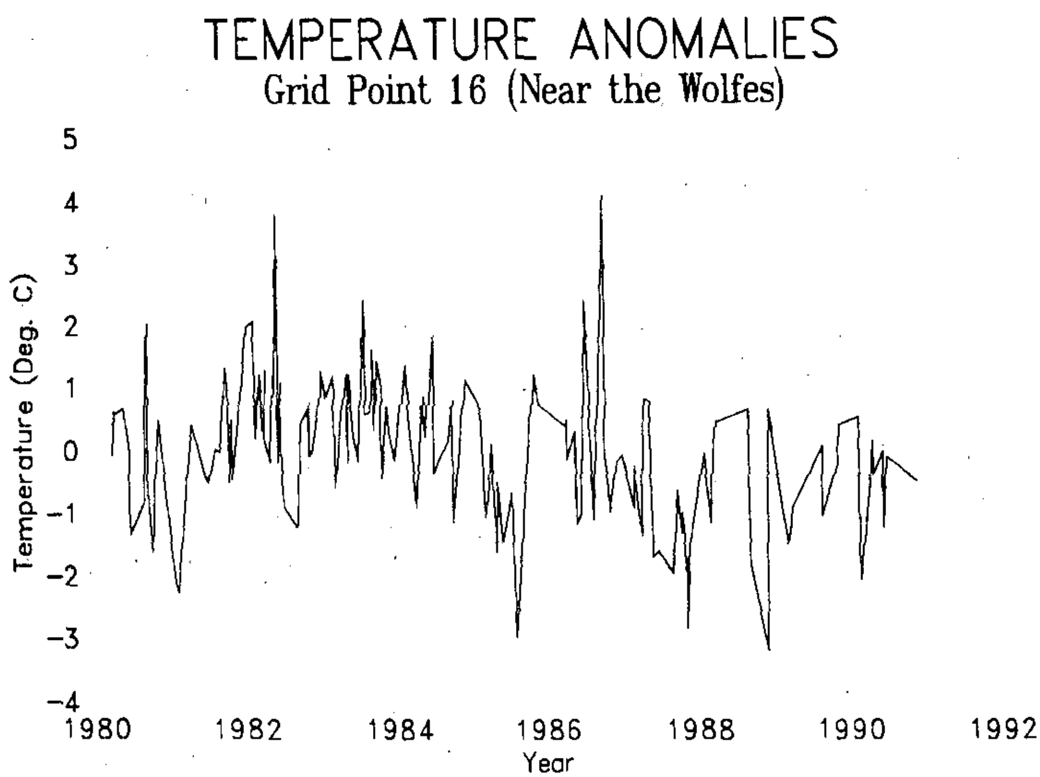


Fig. 6. The sea surface temperature anomalies at grid points 9 and 16.

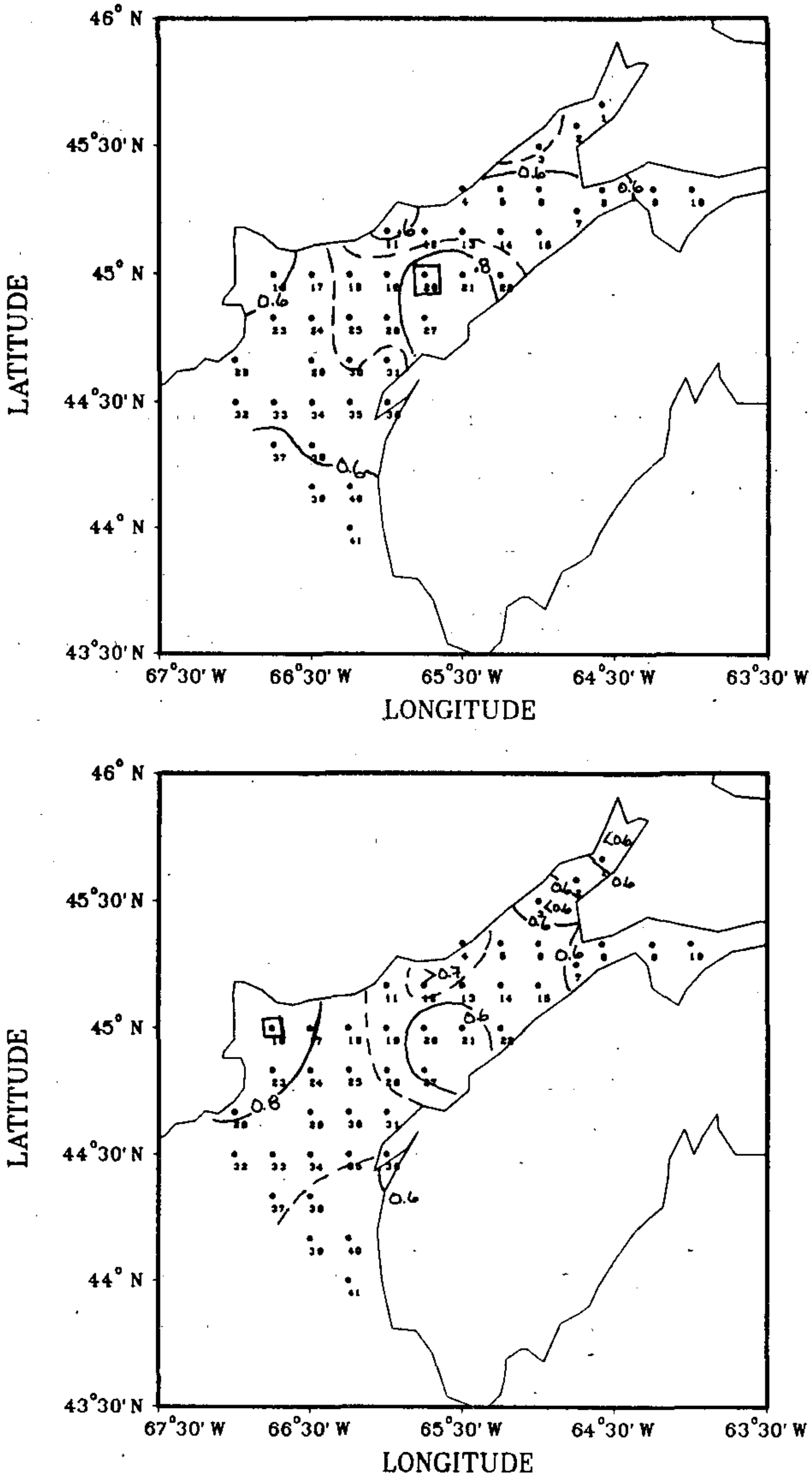


Fig. 7. The correlation between sea surface temperature anomalies on the grid using grid point 20 (top) and 16 (bottom) as the reference.

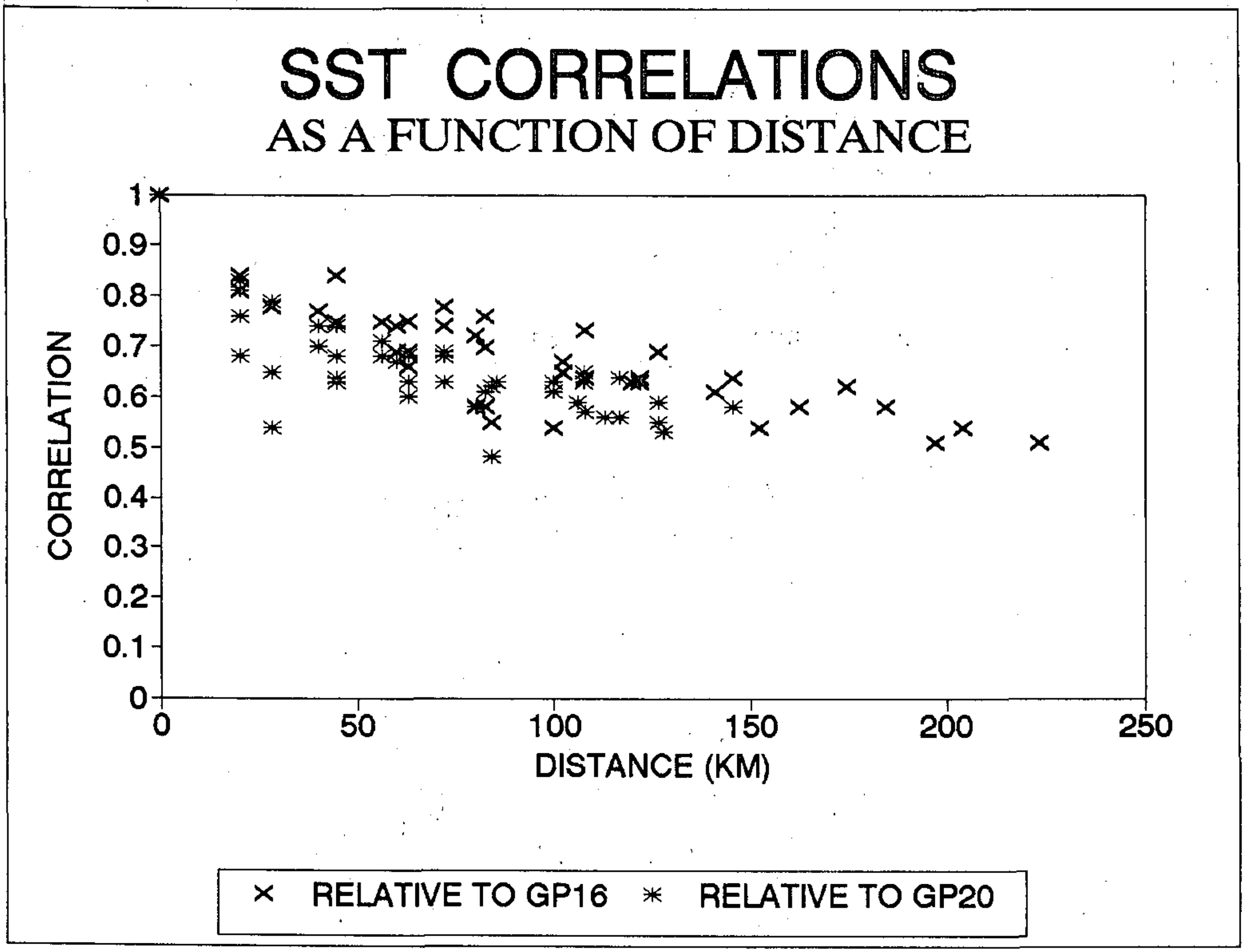
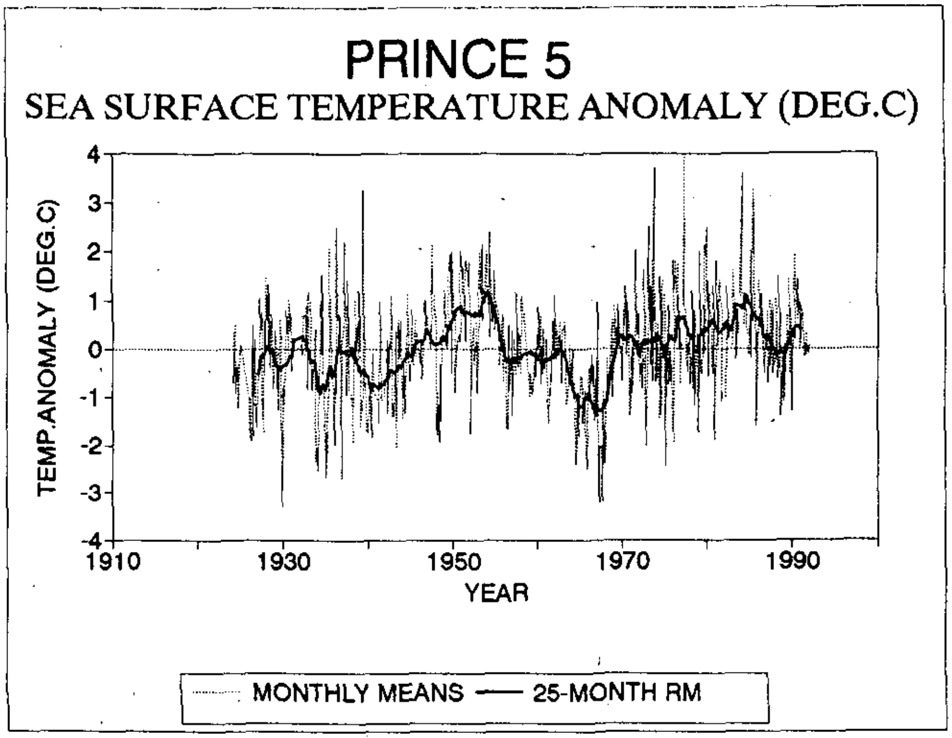


Fig. 8. The sea surface temperature correlations as a function of separation distance between the grid points.



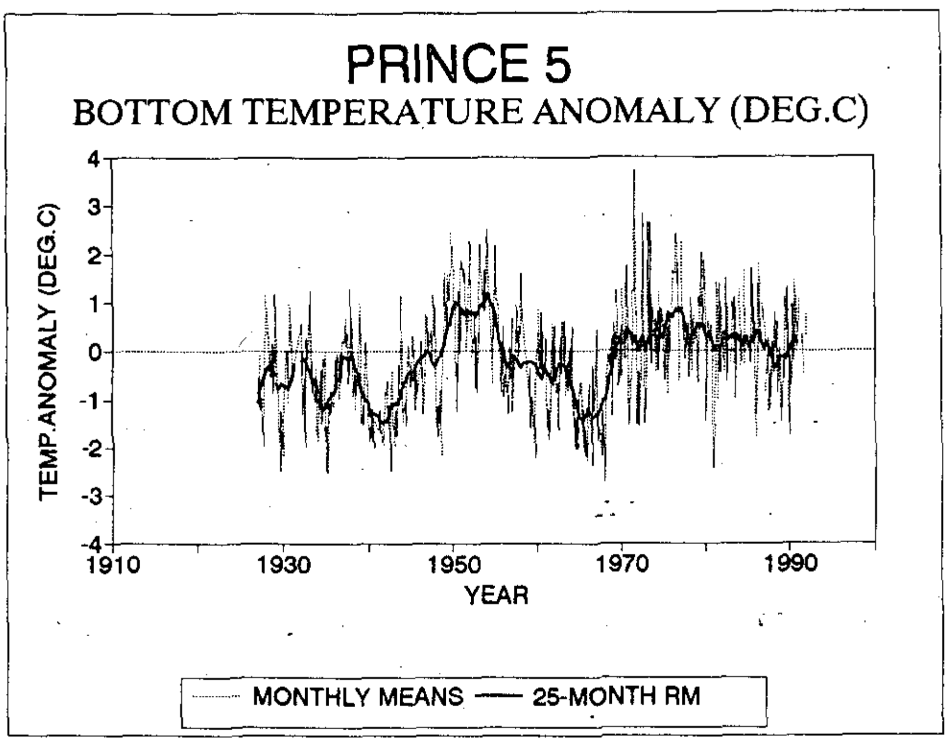


Fig. 9. The monthly means and the 25-month running mean of the temperature anomalies at the sea surface and near bottom at Prince 5.

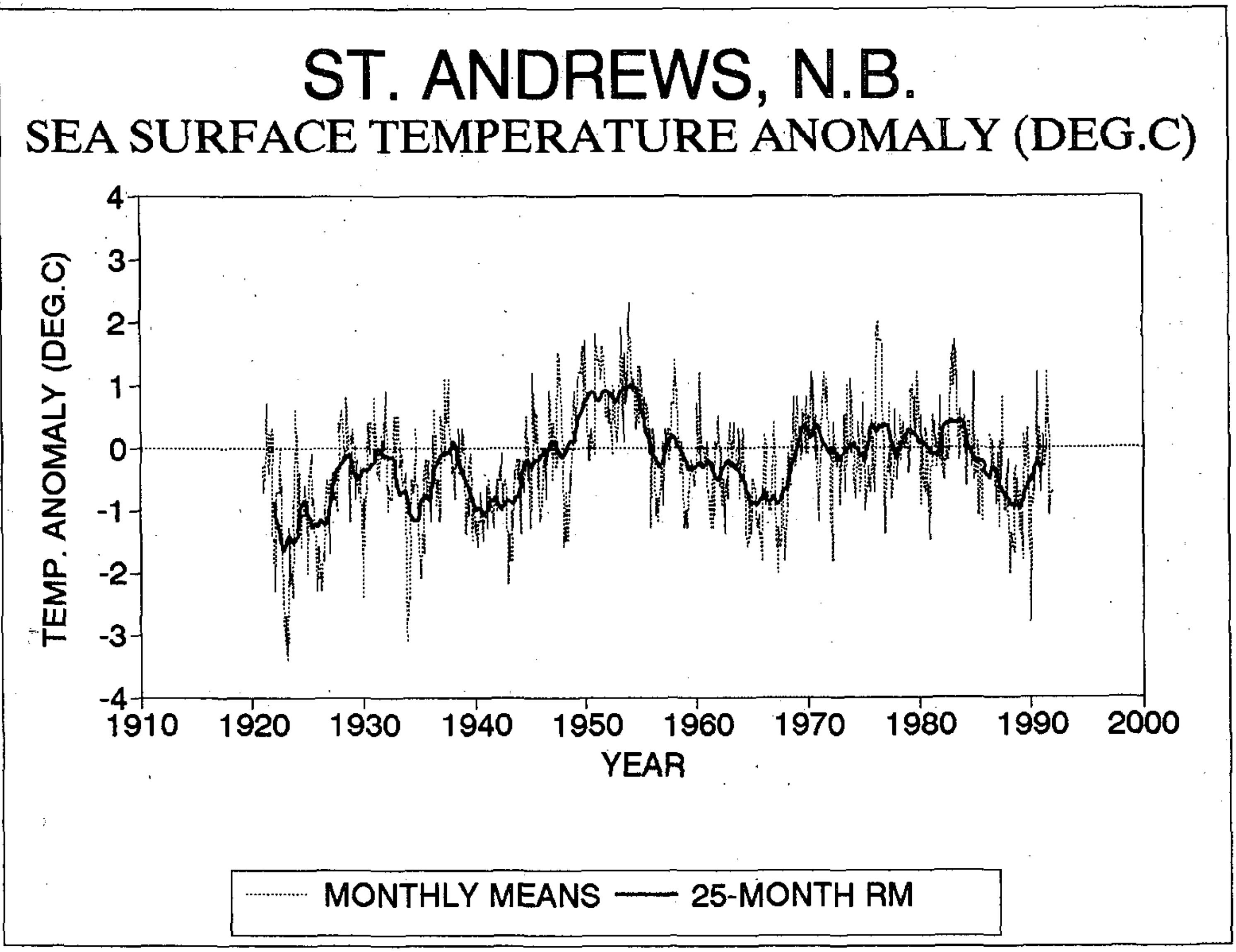


Fig. 10. The monthly means and the 25-month running mean of the sea surface temperature anomalies at St. Andrews.

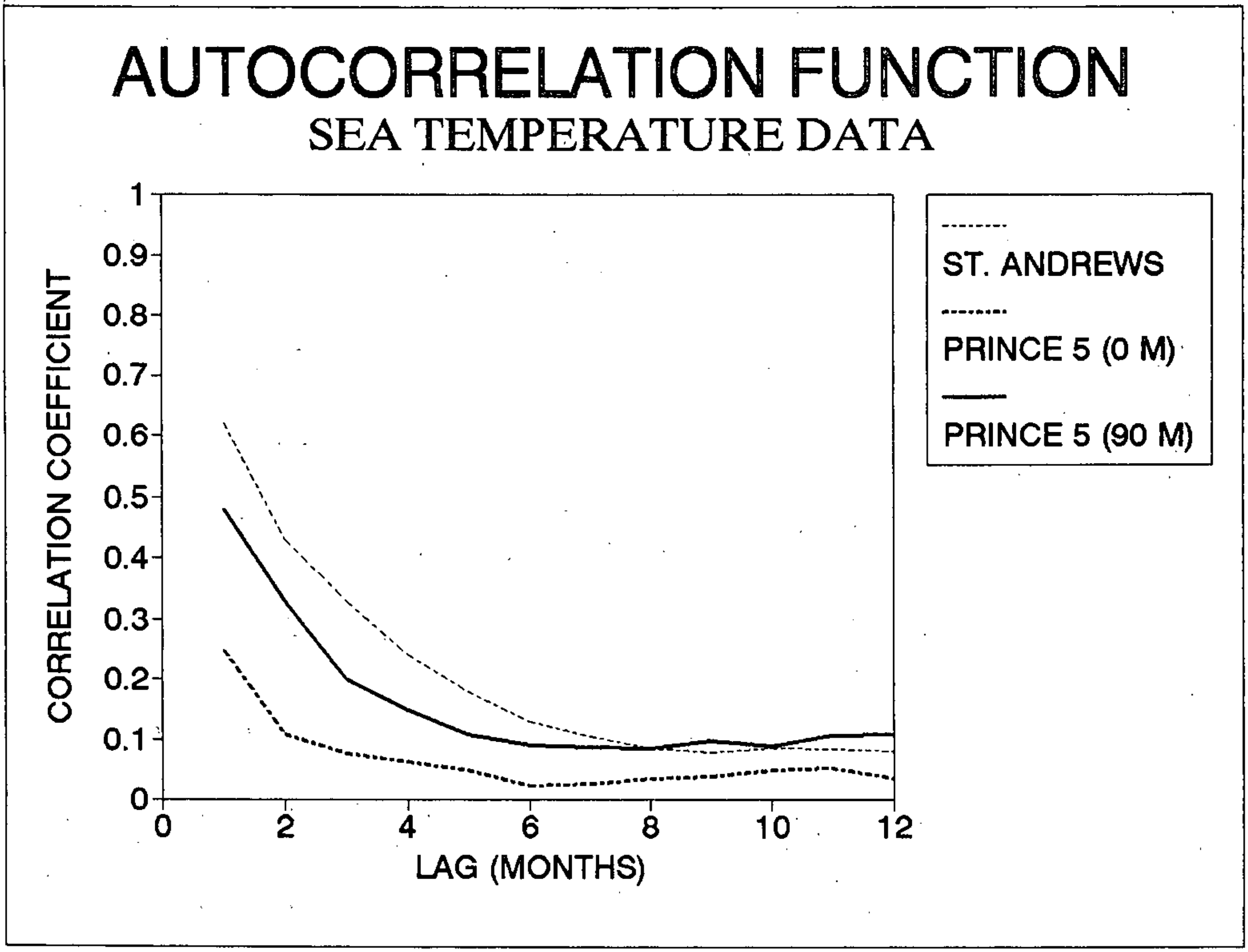
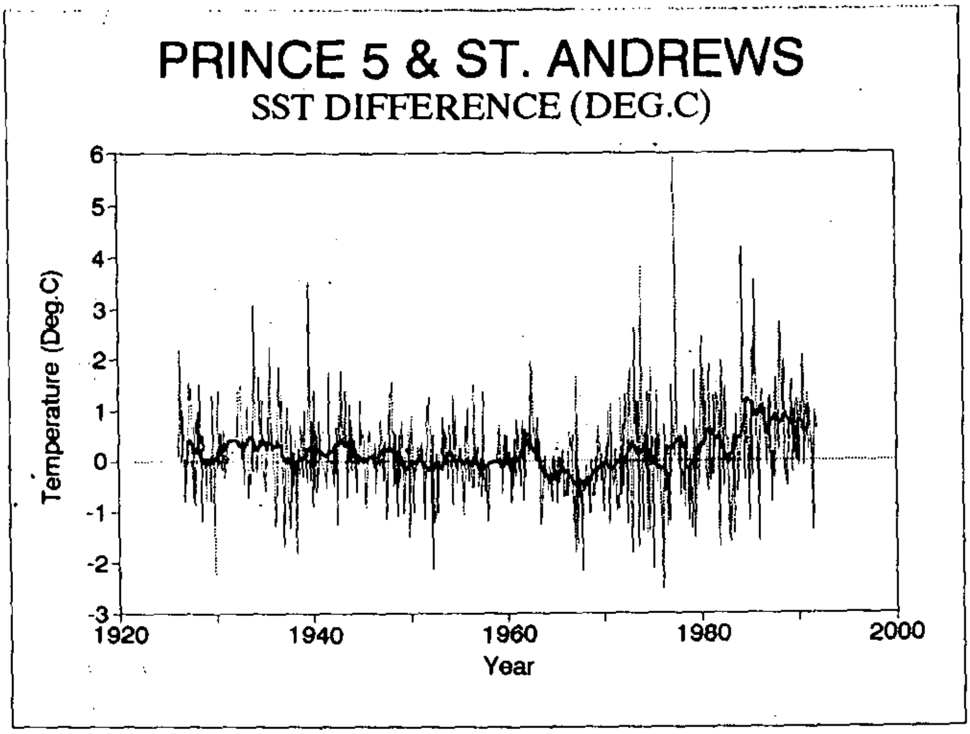


Fig. 11. The autocorrelation as a function of lag for St. Andrews sea surface temperatures and Prince 5 temperatures near surface and bottom.



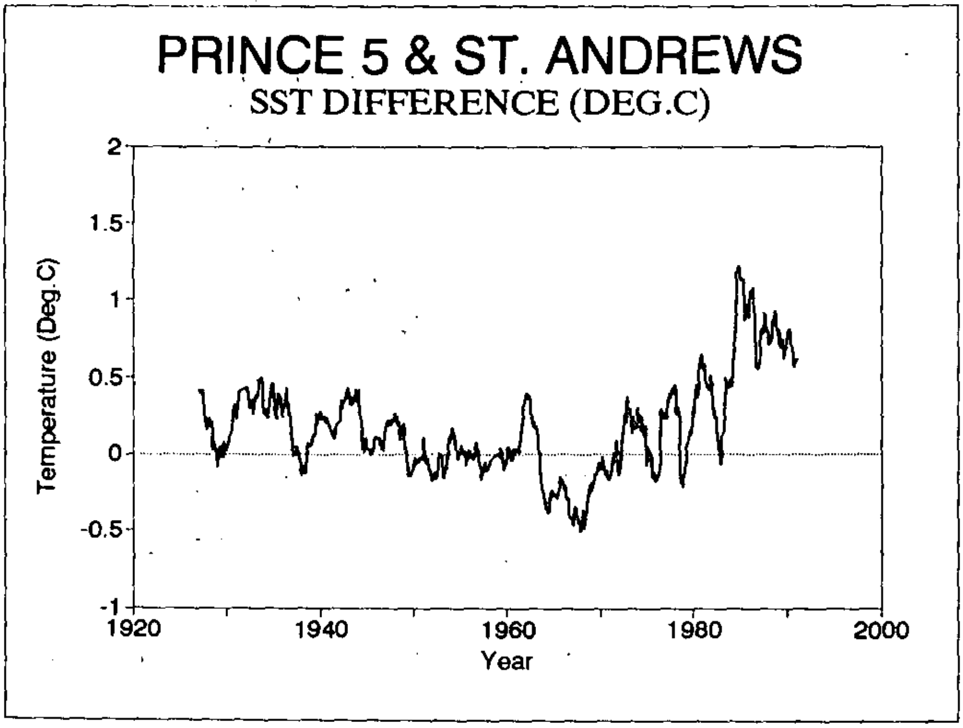
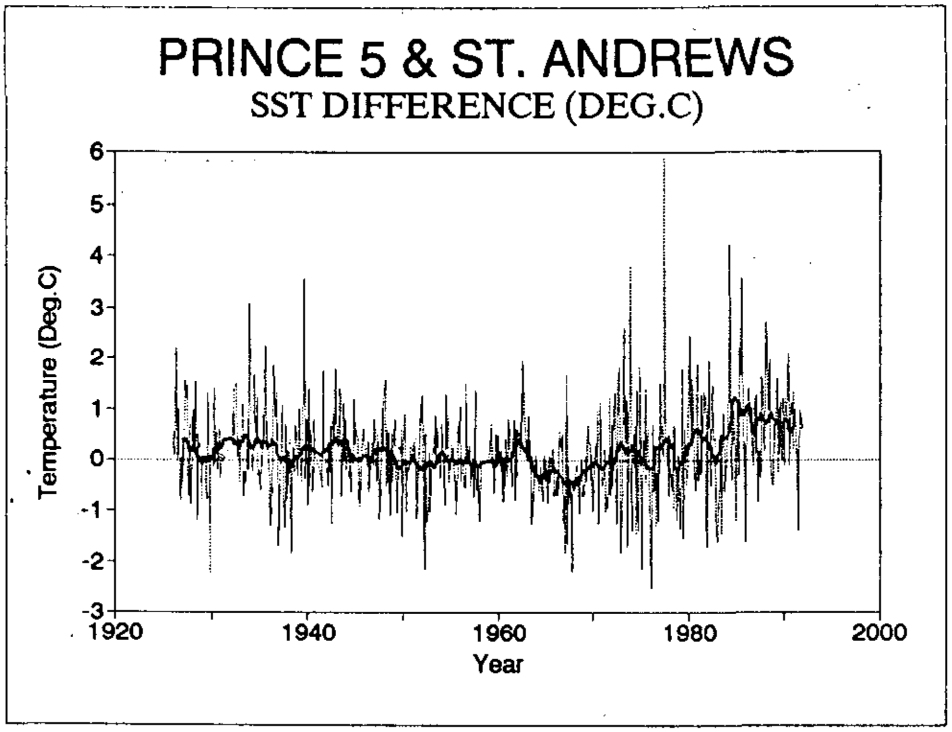
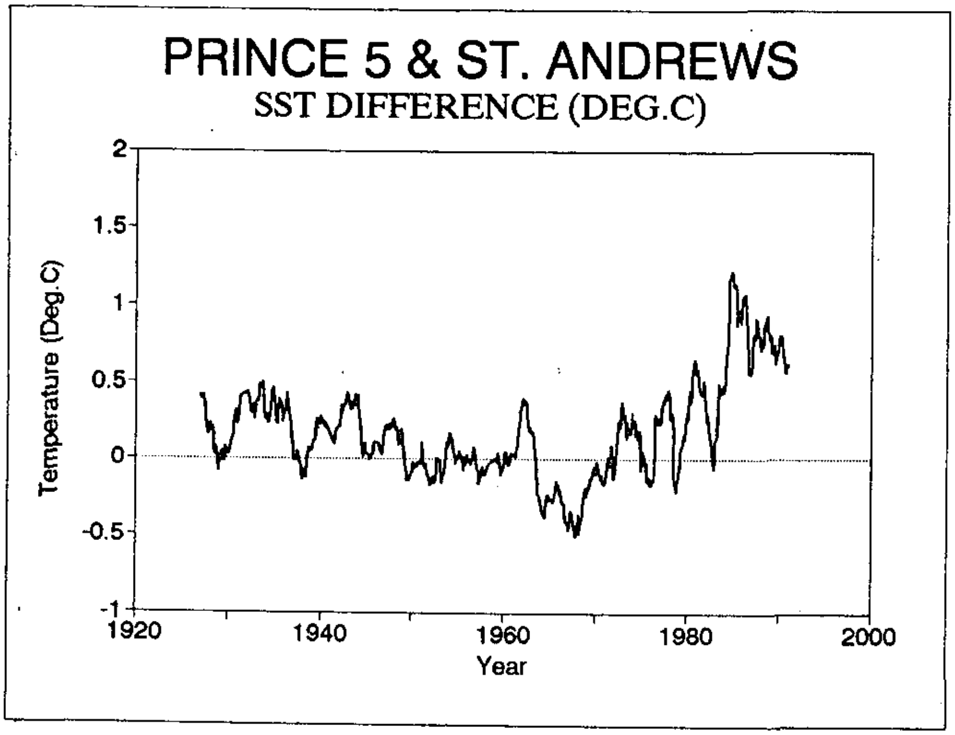


Fig. 12. The monthly means and 25-month running mean of the difference between Prince 5 and St. Andrews sea surface temperature anomalies (top). The lower panel shows the 25-month running mean replotted on a reduced scale.





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