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Surface heat flux in the Gulf of Maine

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Abstract—The surface heat flux in the Gulf of Maine is estimated on a daily basis for the period 1979–1987 by combining air temperature, water temperature and wind speed data measured at a NOAA buoy in the central Gulf with insolation data from coastal stations and climatological parameters. The heat flux is compared with water column temperatures measured during the same period. The mean annual cycle of heat flux is similar to that reported by Bunker (1976) and to the rate of change in the heat content of the upper 100 m of the water column across the Gulf. The interannual variability in heat flux is dominated by the latent and sensible heat flux terms during winter and by insolation variability during summer. In the western Gulf the interannual variability in water temperature is significantly correlated with the heat flux variations. In the eastern Gulf, no relationship is found and the temperature variability is believed dominated by advective changes. Copyright © 1996 Elsevier Science Ltd

1. INTRODUCTION

The Gulf of Maine experiences a large seasonal change in temperature, particularly in the near-surface waters (Bigelow, 1927). This change in temperature is believed to be driven, primarily, by the atmospheric heat flux at the surface. In the winter, the water column cools and becomes denser—sufficiently dense on occasion to cause convection to at least 100–150 m depth (Brown and Beardsley, 1978; Mountain and Jessen, 1987). In the warm season, the heat flux warms the surface water and causes the development of thermal and density stratification.

The water temperature in the Gulf also experiences significant interannual variability (Davis, 1978; Holzwarth and Mountain, 1990; Mountain and Manning, 1994), which could be caused by interannual variability in the local atmospheric heat flux. Petrie and Drinkwater (1993), however, show that for the nearby Scotian Shelf, low frequency variability in temperature is greatest subsurface and appears to result from the influx of warmer, offshore water. The Gulf of Maine could represent a similar situation. The two major sources of water to the Gulf are the near surface inflow of cool, low salinity water from the Scotian Shelf from around Cape Sable (Smith, 1983) and the inflow of offshore Slope Water (SW) through Northeast Channel (Ramp *et al.*, 1985). Both inflows exhibit considerable seasonal variability and possibly interannual variability. Thus the eastern Gulf of Maine has a nearby source of warm, high salinity water at depth and of cooler, fresher water in the surface layer which could contribute to the local heat flux.

The purpose of this analysis is to calculate the surface heat flux in the Gulf of Maine and through comparison with hydrographic observations to address the following questions.

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1. Can the surface heat flux account for the large seasonal change in the heat content of the upper layers of the Gulf?
2. Can interannual variability in the heat flux account for interannual variability in observed water temperature?

2. DATA AND METHODS

The approach used in this analysis is to compare observed variability in water column temperature within the Gulf of Maine with simultaneous estimates of the surface heat flux. Bunker (1976) calculated monthly average heat flux values over the North Atlantic Ocean, including the Gulf of Maine region, from ship of opportunity observations. Isemer and Hasse (1987) revised the Bunker results, using more recent estimates of some of the exchange coefficients. While these results provide climatological values, an additional need for the present analysis is to calculate the surface heat flux for specific periods of time to compare with simultaneous water column temperature observations.

A budget technique was used to derive daily estimates of the surface heat flux using the relation:

$$Q_{\mathrm{n}} = Q_{\mathrm{i}} + Q_{\mathrm{lw}} + Q_{\mathrm{l}} + Q_{\mathrm{s}} \tag{1}$$

where Q_{n} is the net heat flux, Q_{i} the net insolation, Q_{lw} the net long-wave radiation, Q_{l} the latent heat flux, and Q_{s} sensible heat flux. The sign convention for all terms is such that positive values provide heat to the water column. The sensible and latent fluxes were computed using the bulk aerodynamic methods of Friehe and Schmitt (1976). To approximate reductions due to reflection, mean daily insolation values were reduced using 0.079 as an estimate of the mean annual albedo at 43° N (Payne, 1972). Values of upward, net long-wave radiation, calculated using the Efimova formula given in Simpson and Paulson (1979), were corrected for cloudiness by Reed's (1977) methods. Reed's cloud factor approximations were revised by replacing cloud amount in tenths, with the quotient of mean daily insolation to clear-sky insolation based on the Smithsonian formula (Seckel and Beaudry, 1973). These heat-flux quantities were calculated using values of insolation, air temperature, water temperature, humidity and wind speed.

Air temperature, water temperature and wind velocity observations were obtained from NOAA buoy 44005 for the period 1978–1990. Buoy 44005 is located in the central Gulf of Maine (see Fig. 1). The preprocessed hourly buoy data (Gilhousen, 1988) were further processed by removing values from a 10-h moving window that were beyond three standard deviations, linearly interpolating values for gaps of less than 6 h, and converting the wind data to a 10-m height. Humidity values were determined from monthly mean dew point temperatures from Bunker (1976) as reported by Joyce (1987).

Solar insolation data for eight stations were obtained from the Canadian Weather Service, the National Climatic Data Center, the Maine Department of Marine Resources and the Woods Hole Oceanographic Institution (Fig. 1). Most stations measured hourly insolation data for the primary period of interest (1978–1987), although only data from 1989 and 1990 were available for Boothbay Harbor, Maine. The data for Boston and Portland are modelled values (see NCDC, 1992). For the heat flux calculations presented here, the data series from Boston is used. The analyses were repeated using the insolation series from Portland and Halifax, with only small differences occurring in the correlation

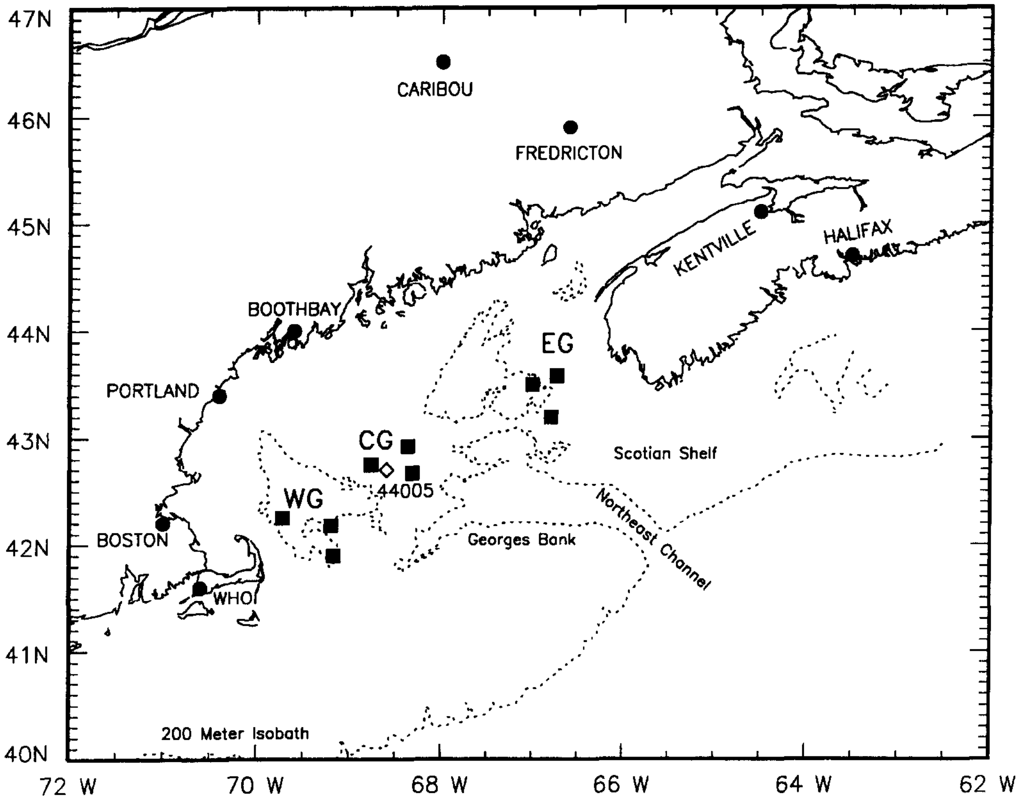

Fig. 1. The Gulf of Maine region, showing locations for the insolation time series (circles), for NOAA buoy 44005, and for the MARMAP hydrographic stations representing the western (WG), central (CG) and eastern (EG) Gulf of Maine (squares).

values calculated in the various analyses. None of the conclusions reached in the following analyses is dependent upon the insolation series used in the heat-flux calculations.

Daily average values were calculated for each term on the right of the heat flux equation above. Daily heat flux values were then calculated for all days having values for each term. Nearly complete records are available for 1979, 1983, 1984, 1985 and 1987, with intermittent data in the other years (Fig. 2). The heat flux values from the different years were averaged for each calendar day to derive daily means. These values were smoothed with a 31 (-15 to $+15$) day running mean to generate a characteristic annual cycle of the heat flux. A heat flux anomaly time series was derived by subtracting the smoothed daily mean heat flux values from the original daily heat flux.

Hydrographic data collected by the National Marine Fisheries Service MARMAP program are used to represent the water column conditions in the Gulf of Maine. The MARMAP program conducted 49 surveys of the U.S. northeast shelf, including the Gulf, between 1977 and 1987. Temperatures were measured by reversing thermometers at standard depths, except in the last year of the program when an electronic CTD profiler was used. Three groups of three stations each are used here to represent the western Gulf (WG), the central Gulf (CG) and the eastern Gulf (EG) (Fig. 1). The observations within each group were combined to derive the characteristic annual cycle of temperature at standard

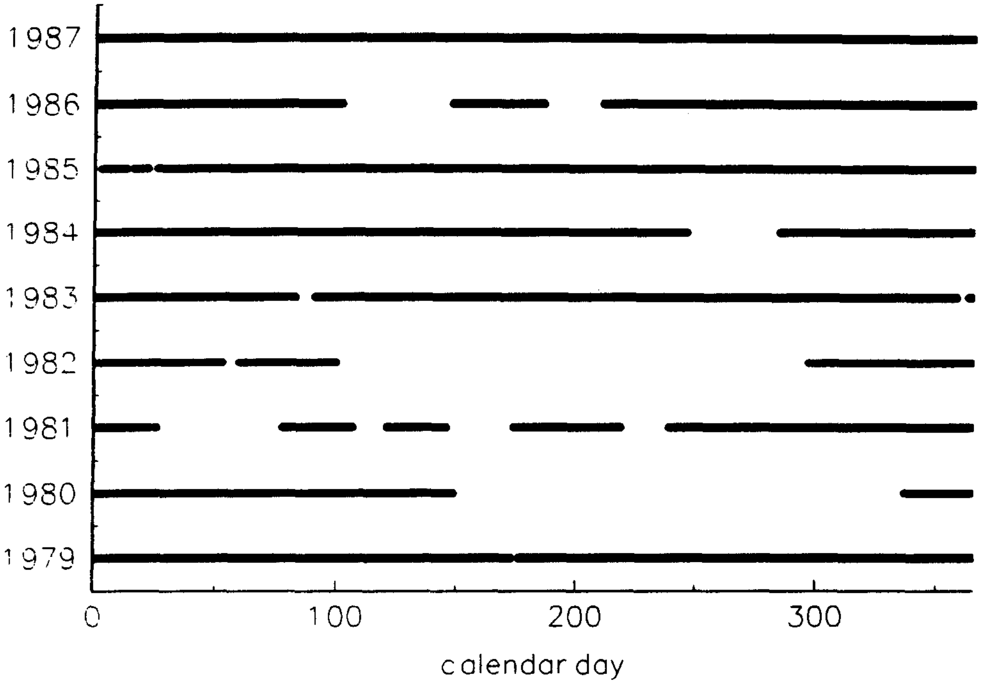

Fig. 2. Periods for which heat flux estimates were made.

depths (0, 5, 10, 15, 20, 25, 30, 35, 50, 75, 100, 150 and 200 m). The annual cycles were determined by fitting harmonics (annual, semi-annual, third-annual) to the data, as described by Mountain and Holzwarth (1989). Temperature anomalies were determined by subtracting the annual cycle from the observed values. The rate of change in the heat content of the water column was determined from the difference in heat content on successive days, with the heat content calculated by vertically integrating the temperature from the surface to the depth of interest, using the annual temperature cycles.

In Section 3 the correlation length-scale for the insolation data is discussed. The mean, seasonal cycle of heat flux is presented in Section 4 and compared with the cycle in heat content of the water column. In Section 5, the interannual variability in heat flux is compared with the interannual variability in water temperature. A one-dimensional mixed layer model is used in Section 6 to account for the seasonal development of stratification and to re-examine the relationship between interannual variations in heat flux and water temperature during the stratified season.

3. CORRELATION LENGTH-SCALE OF SOLAR INSOLATION DATA

No time series of insolation measurements are available from within the Gulf of Maine. Only data from terrestrial sites are available to estimate the heat flux over the Gulf. How representative are coastal values likely to be of the central Gulf, 200–400 km away? Data from eight locations in the greater Gulf of Maine region were used to estimate the correlation length-scale for insolation data. Records are available from each of the eight sites only during 1989 and 1990, and only these years were used in this length-scale analysis.

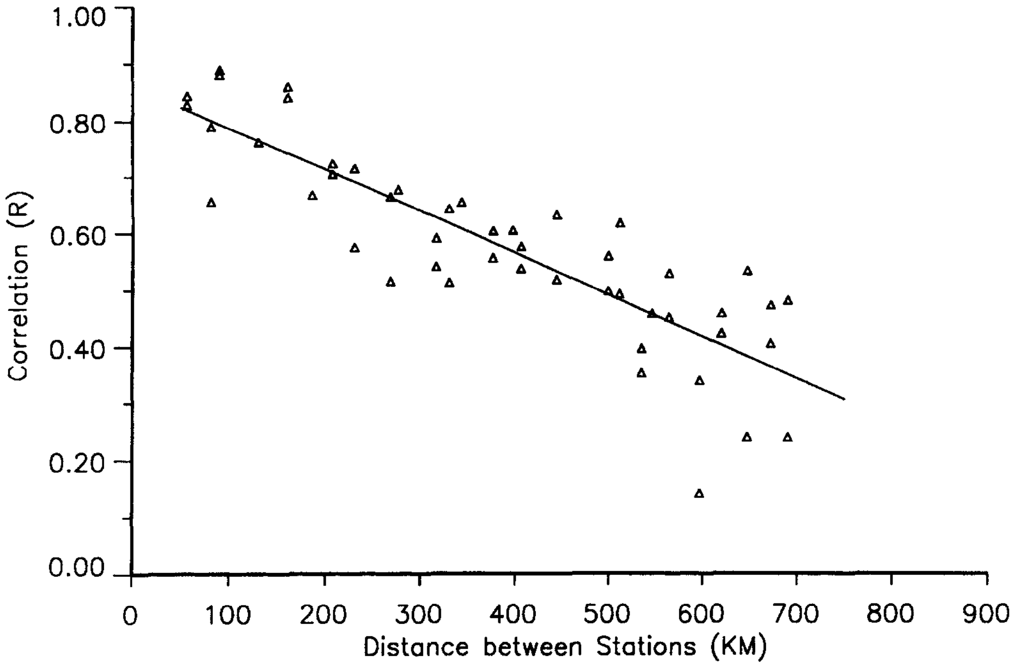

Fig. 3. Correlations between the residual insolation time series versus separation distance between the measurement locations indicated in Fig. 1.

The annual cycle of insolation for each site was determined using an harmonic analysis and subtracted from the original data. The resulting residual series were smoothed by a 3-day running mean to average over the passage of weather systems, and the associated cloud conditions, through the region. Correlations were calculated between each pair of stations using the smoothed, residual series. The correlations are plotted against the distance between the station locations in Fig. 3. There is an approximately linear decrease in correlation with increasing separation. At a separation of 200 km about half of the variance in one series can be explained by another.

The decrease in correlation with separation (Fig. 3) implies that the coastal records from Boston or Portland can adequately represent the western and, perhaps, central Gulf, but may not adequately represent insolation conditions in the eastern Gulf. Also the correlation between terrestrial series may not represent the correlation between the insolation received at a site on land and one on the ocean, the same distance apart, due to conditions associated with the ocean—e.g. increased frequency of fog. The insolation series from Boston is used in the heat flux calculations here. Without observations of insolation from the Gulf of Maine itself, the adequacy of the Boston data cannot be rigorously determined.

4. ANNUAL CYCLES OF HEAT FLUX AND OF WATER COLUMN HEAT CONTENT

The mean annual cycle of each term of the heat flux budget [equation (1)] was calculated using data from Buoy 44005 and Boston insolation data (Fig. 4). In the winter the latent and sensible terms are the major contributors to the net heat flux. In summer, the net heat flux is

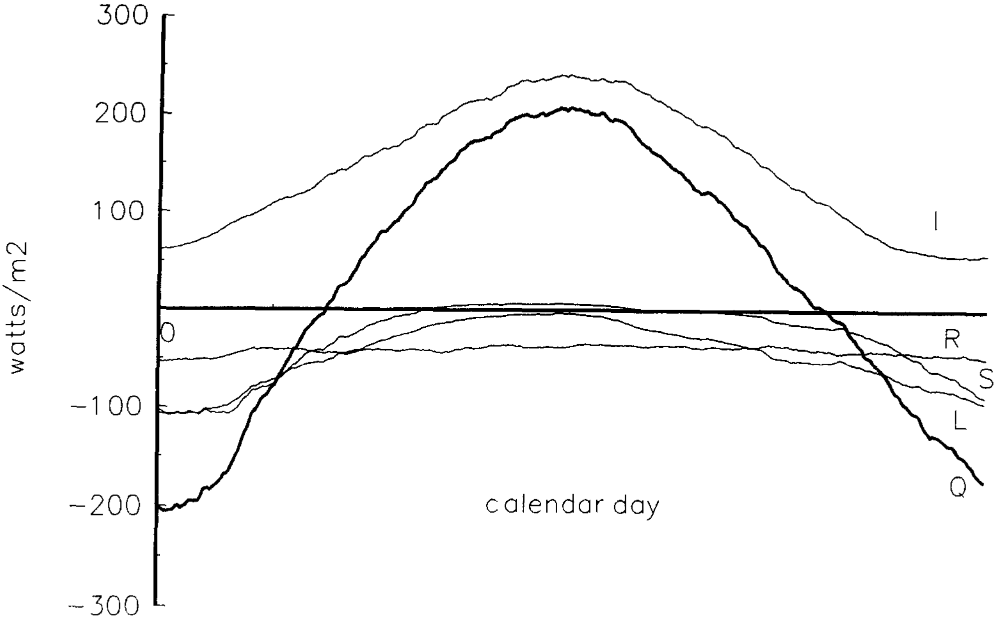

Fig. 4. Mean annual cycle of each component in the heat budget: I—insolation, R—long wave, S—sensible, L—latent, Q—net heat flux. The means were calculated for each calendar day, and smoothed by a 31 (−15 to +15) day running average.

determined almost entirely by the insolation term. During the first half of the year the annual cycle of net heat flux is intermittant between the monthly mean heat flux values of Bunker (1976) and the Bunker values as corrected by Isemer and Hasse (1987) for the location 42°N 69°W (Fig. 5). During the second half of the year the annual cycle of heat flux calculated has a positive bias relative to both the Bunker (1976) and Isemer and Hasse (1987) values. The rates of change in heat content for the upper 100 m of the western (WG) and central (CG) Gulf follow closely the heat flux values of Bunker (1976) (Fig. 5). The change in heat content over the upper 100 m in the eastern Gulf (EG) exhibits a somewhat larger amplitude cycle than the other parts of the Gulf or any of the heat flux cycles in Fig. 5. However, calculating the change in heat content over the upper 60 m in the eastern Gulf results in a curve similar to those for the WG, CG and the Bunker (1976) values in Fig. 5.

5. INTERANNUAL VARIABILITY IN HEAT FLUX AND IN WATER TEMPERATURE

Anomaly series for each term in the heat budget were determined by subtracting the mean annual cycle (Fig. 4) from the original observations. The standard deviation of the anomalies for each term was calculated in two week intervals (Fig. 6). The interannual variability in the net heat flux is largest in winter. The latent and sensible heat flux terms make the largest contribution to this winter time variability. In summer, the insolation term is the major contributor to the variability in heat flux.

Comparison of the interannual variability in heat flux and water temperature was done separately for the winter season (calendar days 300–120), when the upper 100 m of the water column is generally well-mixed, and for the summer season (calendar days 120–300), when

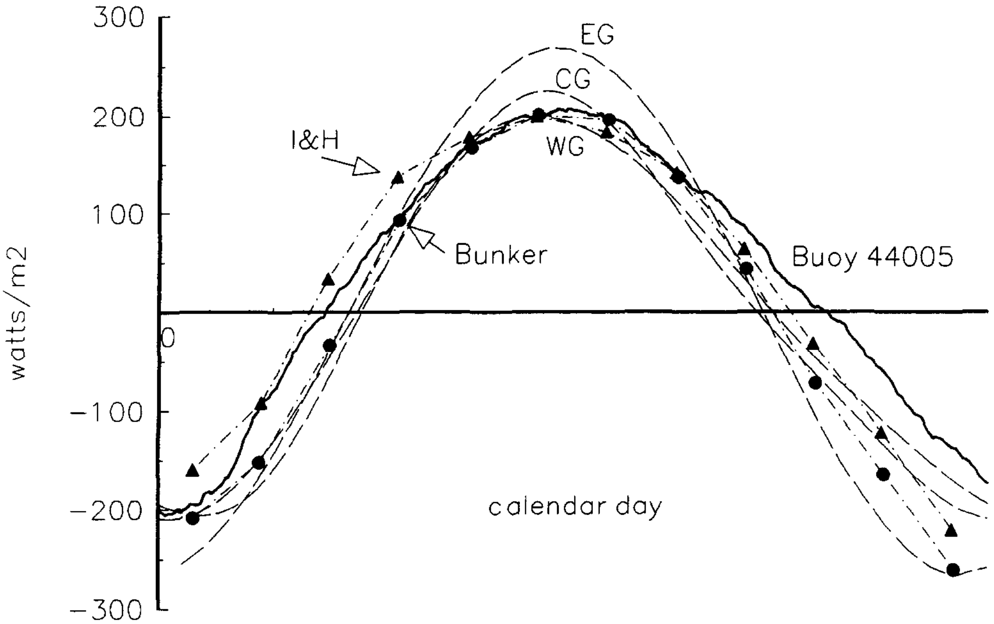

Fig. 5. Annual cycle of net heat flux calculated here using Buoy 44005 (—), the monthly mean heat flux values from Bunker (1976) (● – ●) and from Isemer and Hasse (1987) (▲ – ▲), and the rate of change in heat content of the upper 100 m of the water column in the western (WG), central (CG) and eastern (EG) Gulf of Maine (- -).

the column is thermally stratified. The temperature conditions are expected to reflect the accumulated heat flux over some preceding period. For the winter period, temperature anomalies were correlated with the average heat flux anomaly over the previous 90 days, while for the summer an averaging period of 30 days was used. The averaging period was chosen to maximize the correlation. The temperature anomalies were determined for both the surface and for the upper 100 m of the water column. The correlations between temperature and heat flux anomalies in winter are listed in Table 1, and for summer, in Table 2. Due to the averaging period of the heat flux anomaly data, not all of the points used in the correlation are fully independent. For determining the signficance level, the degrees of freedom were reduced to reflect the number of points for which no overlap occured in the averaging period.

Table 1. *Winter temperature anomalies vs heat flux anomalies*

	Western Gulf		Central Gulf		Eastern Gulf	
	pts	*R*	pts	*R*	pts	*R*
Surface	15	0.44	9	0.29	8	−0.28
0–100 m	15	0.68*	9	0.66	8	−0.19

R is the correlation coefficient and pts is the number of points used in the correlations.

*Correlations significant at the 0.05 level. Significance determined with degrees-of-freedom reduced to reflect data points with no overlap in their averaging periods.

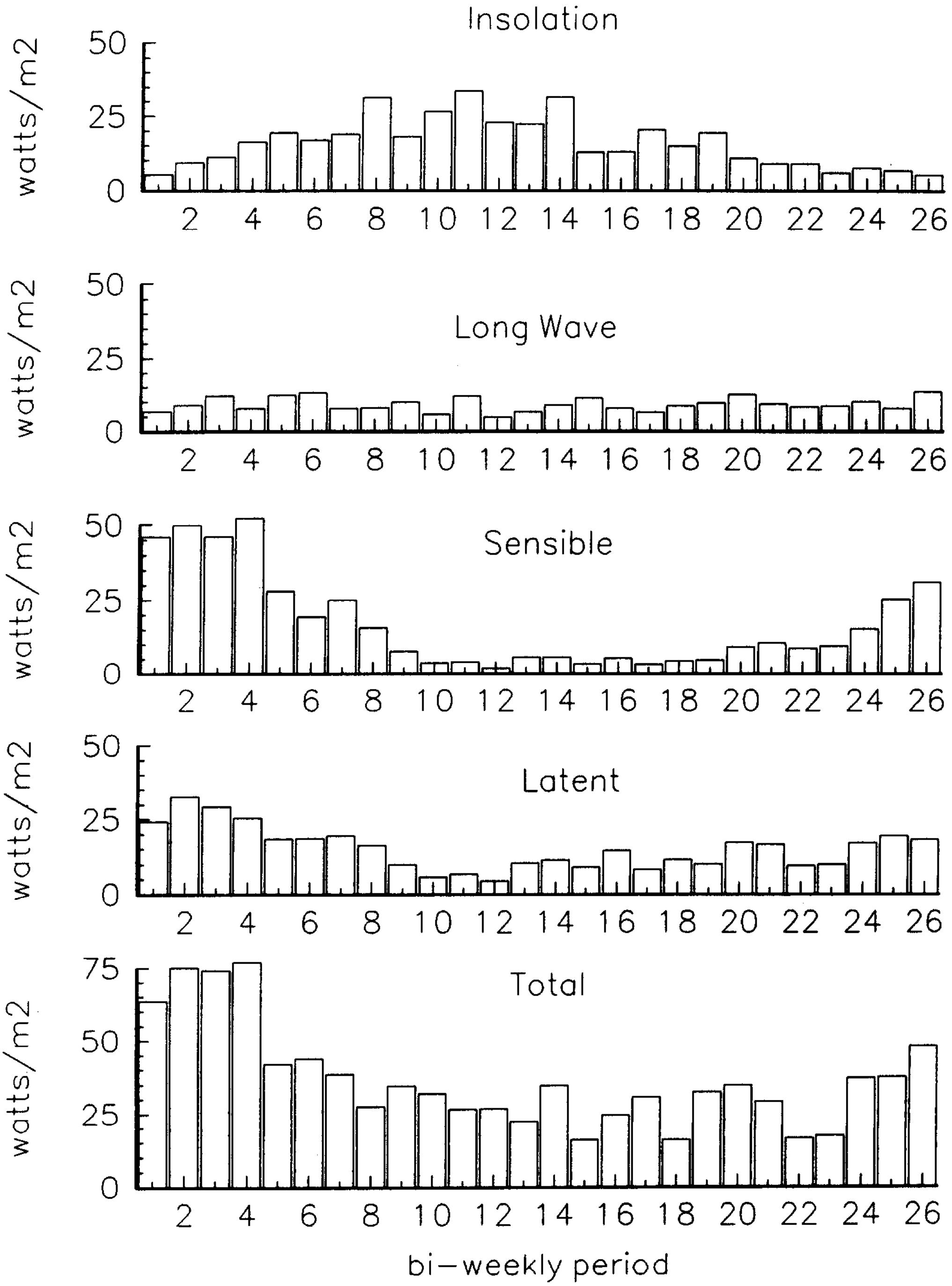

Fig. 6. Standard deviation of the interannual variability in each term of the heat budget, calculated in two week intervals.

Table 2. Summer temperature anomalies vs heat flux anomalies

	Western Gulf		Central Gulf		Eastern Gulf	
	pts	*R*	pts	*R*	pts	*R*
Surface	15	0.30	15	−0.20	7	−0.07
0–100 m	15	0.30	12	0.24	7	−0.61

R is the correlation coefficient and pts is the number of points used in the correlations.

Table 3. Summer surface temperature anomalies vs model surface temperature anomalies

Western Gulf		Central Gulf		Eastern Gulf	
pts	*R*	pts	*R*	pts	*R*
10	0.64*	8	0.32	7	0.11

R is the correlation coefficient and pts is the number of points used in the correlations.

*Correlations significant at the 0.05 level. Significance determined with degrees-of-freedom reduced to reflect data points with no overlap in their averaging periods.

During winter the temperature anomalies for the upper 100 m in the WG are significantly correlated (at the 0.05 level) with the heat flux anomalies. The winter surface temperature anomalies are not correlated with the heat flux anomalies. During the summer period none of the temperature anomalies is significantly correlated with the heat flux anomalies, although a large (nearly significant) negative correlation is found for the EG.

6. SEASONAL STRATIFICATION

The summer period is characterized by the development of thermal and density stratification in the upper layers of the Gulf of Maine. The thermal stratification represents an uneven distribution through the water column of the heat entering at the surface. In seeking a relationship between the observed water temperature anomalies and the heat flux anomalies, the stratification process should be taken into account. To do this, the simple, one dimensional model of James (1977) was used. The model physics are described in the Appendix. Driven by an imposed surface heat flux and surface winds, the model calculates the water column temperature profile through time. Mixing within the model is determined by a gradient Richardson number formulation of a depth dependent vertical eddy coefficient.

The model was run with the heat flux and wind speed series from individual years and for the annual mean heat flux and wind series. The results for the mean series were subtracted from the results for the individual years to obtain model derived temperature anomaly series. The calculations were done for years 1979, 1983, 1984, 1985 and 1987, since they had nearly complete heat flux series. Because the model surface value can be sensitive to day-to-day variations in the wind, the model anomalies were calculated for the upper 20 m (the upper 5 depth bins in the model). The model derived temperature anomalies were compared to the MARMAP surface temperature anomalies for each of the three regions of the Gulf (Table 3). For the WG the correlation between the observed and modeled anomalies is significant at the 0.05 level. For the CG the observed vs model anomaly correlation is higher than for the heat flux (Table 2), but still does not approach the 0.05 significance level. For the EG no relation is found between the observed and model anomalies. By taking stratification into account, a significant relationship can be found between atmospheric forcing and surface temperature anomalies in the WG during summer.

7. DISCUSSION AND CONCLUSIONS

No error or confidence limits have been placed on the heat flux values calculated here. The lack of direct measurements of insolation and humidity over the Gulf make estimating errors an uncertain process. Friehe and Schmitt (1976) and Simpson and Paulson (1979) report uncertainties of 10–20 W m^{-2} in the determination of the sensible, latent and long wave flux terms. The standard deviations for the different terms (Fig. 6) indicate true daily variability about the mean cycle, plus error, and provide an upper bound on the uncertainty. Still, without actual insolation and humidity measurements, important aspects of the heat flux problem cannot be considered—e.g. the occurrence of fog over marine waters and the correlation of air temperature and humidity, such as when cold, dry air moves off the land in winter. The correlations of interannual variability in heat flux and in water temperature (Tables 1–3) rely on relative changes in heat flux, not on actual values. Also, the correlations are based on values averaged for 30 or 90 days, so that uncertainty in individual estimates has little influence the degree of correlation. The comparison of the mean annual cycle of heat flux and the rate of change in water column heat content (Fig. 5) does require direct comparison of actual values. Without error estimates, the significance of the difference between the calculated heat flux and change in heat content during fall cannot be determined. Comparison with the Bunker values, however, suggests that the mean cycle calculated here may have a positive bias in the fall, whose cause has not been identified.

The calculated surface heat flux can account for the characteristic seasonal change in the heat content of the upper 100 m of the water column in the western and central Gulf of Maine and upper 65 m in the eastern Gulf—although with some uncertainty in the fall. The eastern Gulf remains stratified in the upper layers even in winter due to the input of low salinity surface water from the Scotian Shelf (Smith, 1983; Mountain and Manning, 1994), while the western Gulf becomes well mixed to at least 100 m depth (Mountain and Manning, 1994). A shallower depth of influence for surface heat flux in the eastern Gulf than to the west is consistant with the observed patterns in density structure.

The interannual variations in local heat flux appear to exert a decreasing influence, from west to east across the Gulf, on the local interannual variations in water temperature. In the western Gulf the water temperature variations are significantly correlated with variation in the calculated surface heat flux, while in the eastern Gulf they are not. The central Gulf is intermediate between the western and eastern Gulf, exhibiting a degree of correlation between surface heat flux and water temperature approaching that observed in the western Gulf, but not signficant at the 0.05 level. This west to east pattern of influence matches the atmospheric circulation in which the continental air over the New England states moves first over the western Gulf of Maine with both the characteristic northwest winds of winter and southwest winds of summer. Still, the results presented here are based on estimates of the heat flux and on relatively few comparisons with water column temperatures. Direct measurements of surface heat flux, from different locations within the Gulf, in conjunction with oceanographic observations, will be needed to confirm the patterns suggested here.

The lack of correlation between variations in water temperature and heat flux in the eastern Gulf is believed due to the temperature variations there being more heavily influenced by advective processes—i.e. input of cold Scotian Shelf Water around Cape Sable (Smith, 1983) and warm Slope Water through Northeast Channel (Ramp *et al.*, 1985). This advective vs local source of variability is similar to the situation described for the Scotian Shelf by Petrie and Drinkwater (1993). No physical or circulation related explanation has been found for the large negative correlation between summer water temperature in the eastern Gulf and heat flux in Table 2.

The decrease in the heat flux–temperature correlation from west to east across the Gulf could be influenced by the use of insolation data from Boston in the heat flux calculations. The correlation length-scale of the insolation data (Section 3) is about 200 km, which would extend from Boston only to the central Gulf. To test this possibility, the analyses were repeated using the insolation data from Halifax, N.S. The results were essentially the same—significant correlations for the western Gulf, a lack of correlation for the eastern Gulf, and intermediate values in the central Gulf.

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APPENDIX—STRATIFICATION MODEL

During the spring and summer the surface heat flux causes the development of seasonal thermal and density stratification, such that the incoming heat is concentrated in the near surface layer. To compare interannual anomalies of heat flux with anomalies of water temperature, the development of stratification needs to be considered. To do this, the one-dimensional mixed layer model of James (1977) is used. In the model the distribution of heat is determined by:

$$\partial T/\partial t = -\partial(N_z)/\partial z$$

where $N_z = w'T'$ which is parameterized as

$$N_z = -A_v\ \partial T/\partial z$$

and the eddy diffusivity A_v is assumed to be dependent upon the gradient Richardson number:

$$A_v = A_0(1 + \sigma Ri)^{-p}$$

$$Ri = -(g/\rho_0)(\partial\rho/\partial z)/(\partial U/\partial z)^2$$

A_0 is the eddy diffusivity in the absence of stratification. It is determined by the sum of wind and tidal components which are functions of the wind speed and tidal current speed, respectively.

The boundary conditions are

$$\mathrm{surface}(z = 0) : N_z = -Q/\rho C_p\ (Q = \text{surface heat flux})$$

$$\mathrm{bottom}(z = -h) : N_z = 0\ (\text{no heat through the bottom})$$

The vertical current shear is determined by:

$$\partial U/\mathrm{d}z = -w/z$$

where w^* is the surface friction velocity, such that a log profile is assumed for the current. This implies:

$$(\partial U/\partial z)^2 = (\rho_a/\rho)c_a W^2/(kz)^2$$

where W is the wind speed, k is von Karmon's constant, c_a is the wind stress drag coefficient, and ρ_a and ρ are the air and water densities, respectively. The model allows for a tidal current and mixing by shear from the bottom boundary layer associated with the tidal current. In this exercise the model is applied to the upper 100 m of the Gulf of Maine water column, and no tidal current or bottom boundary layer is included.

Given an initial temperature profile, equation (A1) is solved for a 100 m water column in 4 m bins with a time step of 0.01 day, using the finite difference scheme given by James, with a correction each time step to insure heat conservation.

To select values for the two free parameters, σ and p, in the gradient Richardson number expression, the model was run for a range of parameter values using the mean heat flux series (in Fig. 5) and the results were compared to temperature profiles derived from the MARMAP annual temperature cycles at standard depths for the central Gulf. The model was run from calendar day 80, when the water column is well-mixed over the upper 100 m, to day 240. The standard deviation of the difference between the model output and the MARMAP data each 40 days at

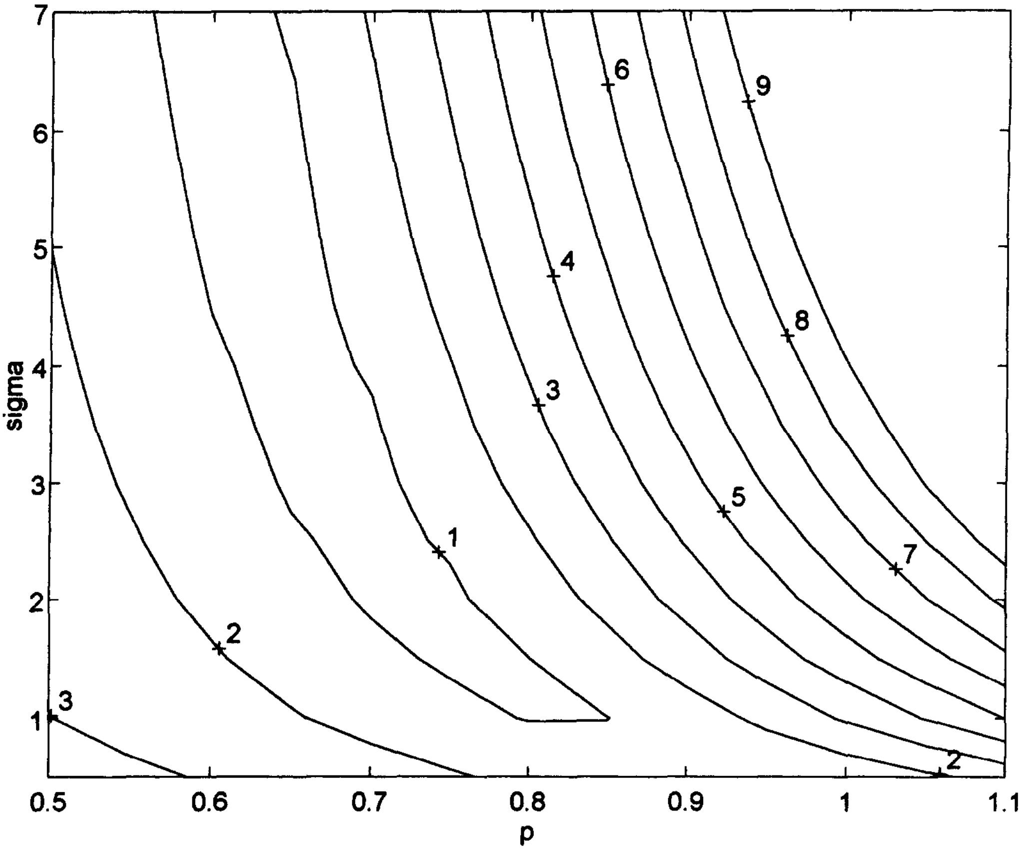

Fig. A1. Standard deviation (°C) of the difference between the stratification model and the MARMAP annual cycles of temperature for a range of values for the σ and p parameters in the gradient Richardson Number expression in the model.

each standard depth level was calculated for each set of parameter values. Plotting the standard deviation as a function of the parameter values (Fig. A1) shows a minimum region with standard deviation of less than 1°C. Larger deviations to the lower left (lower values of both parameters) result from the water column developing less stratification than in the MARMAP observations, while those to the upper right result from too much stratification and the heat being trapped at the surface. For the model runs in the present analyses the values $\sigma = 6.0$ and $p = 0.6$ were selected. Using these values, the model results are compared with the MARMAP profiles through an annual cycle in 40 day intervals in Fig. A2 for the heating (day 80–240) and cooling (day 280–40) periods of the year. The model is able to represent the development of seasonal thermal stratification quite well and the fall/winter breakdown of the stratification somewhat less well.

The model is used to generate temperature anomaly series for the stratified season of a particular year by subtracting the model results driven by the mean annual heat flux from the results driven by the heat flux for that particular year. The selection of the σ and p values was done to optimize the comparison of the mean model results and the mean observed temperature conditions, not the correlation of the model and observed temperature anomaly series (Table 3).

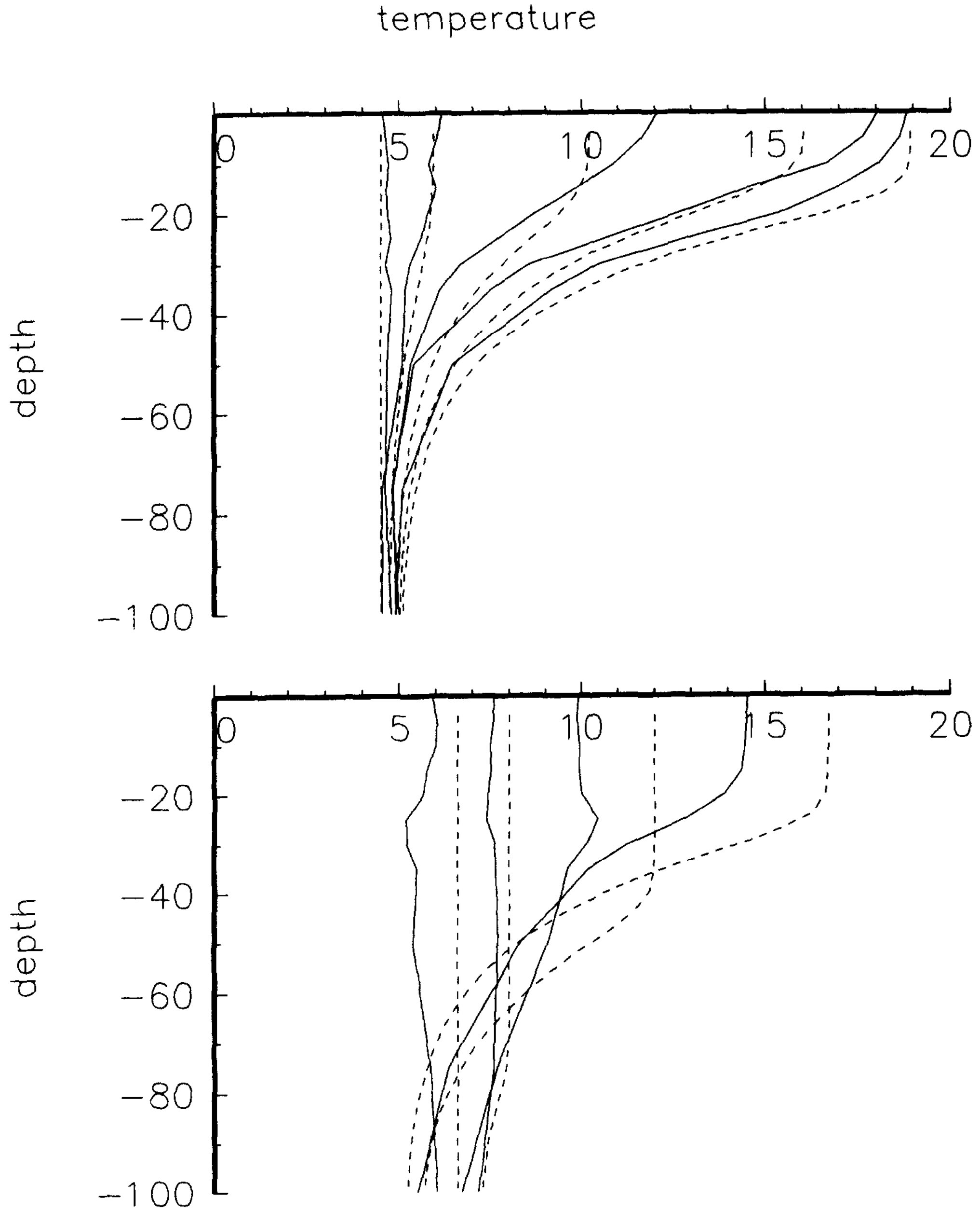

Fig. A2. Comparison of temperature profiles from the stratification model (- - -) and from the MARMAP annual temperature cycles (———), every 40 days during the warming period (days 80–240, top) and cooling period (days 280–40, bottom).