Smith, N. P. (1989). An investigation of the heat energy budget of a coastal bay. *Contributions in Marine Science, 31*, 1-16.

Contributions in Marine Science. (1989) Vol. 31:1–16.

AN INVESTIGATION OF THE HEAT ENERGY BUDGET OF A COASTAL BAY

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ABSTRACT

Hourly surface weather observations from a 54-week period of time in 1973-74 are used to simulate local air-water heat energy fluxes for Corpus Christi Bay, Texas. Results show heat energy gains and losses, and the resulting simulated temperatures, varying over three distinct time scales. The annual cycle explains 82% of the variance of simulated bay temperatures. Approximately weekly variations in the storage term raise and lower water temperatures 1-2°C about the seasonal norm from May through August, and 3-4°C about the seasonal norm during the rest of the year. Diurnal variations are superimposed on both weekly and annual cycles. The mean amplitude of the diurnal cycle is 0.3°C. Seasonality appears in the magnitude and temporal variability of local heat fluxes. Evaporative cooling and solar heating are greatest during summer months. Day-to-day variations in daily mean net outgoing longwave radiation, sensible and latent heat fluxes and water-sediment conduction are significantly greater from September through April, when cold fronts move across the Texas Gulf coast. The relative importance of individual processes varies over the course of a year, but on average the energy budget of Corpus Christi Bay involves a near balance between solar heating and cooling by outgoing longwave radiation and latent heat flux.

INTRODUCTION

The physical processes responsible for energy gains and losses in any body of water are summarized by the well-known heat budget equation:

$$Qt = Qs + Qh + Qm + Qb + Qe + Qa.$$

The first three terms on the right hand side represent local heating by absorbed incoming solar radiation, sensible heat fluxes and conductive heat exchanges between the water column and underlying sediments, respectively. The next two terms represent local cooling by net outgoing longwave radiation and latent heat fluxes, respectively. The final term represents the warming or cooling associated with the importation or exportation of heat by currents. The storage term, Qt, in W/m^2, can be converted to temperature to simulate warming and cooling cycles.

Heat energy fluxes affecting estuaries, and the resulting temporal variability in water temperature, typically occur over three distinct time scales. A 24-

hour cycle in water temperature occurs as a direct response to variations in incoming solar radiation. Diurnal variations in solar heating force similar variations in air temperature, humidity, cloud cover and wind speed. Thus, the diurnal periodicity is fundamental to many warming and cooling processes. Quasi-periodic warming and cooling cycles over time scales of one to two weeks result from the passage of synoptic scale weather systems through the study area. The third time scale is the annual period, stemming from the sinusoidal variation of solar heating over the course of a year. To investigate the energy budget of a coastal bay over the full range of time scales, observations of meteorological variables must be closely spaced in time, yet records must extend through a full year to quantify seasonal variations.

The Texas coastal zone is well suited for investigating meteorological forcing on all time scales, and in a variety of forms. The climate is listed as "tropical semi-arid" by Critchfield (1974), yet it is anomalous enough to be included among the problem climates (Trewartha 1981). Anticyclonic flow in the middle troposphere over the southern Great Plains in summer months suppresses convection and advects relatively dry air into Texas and the lower Mississippi Valley. Thus, mid year rainfall amounts are reduced significantly in spite of ample moisture in the lower layers of the atmosphere. Characteristically low mean annual rainfall amounts call attention to the magnitude and temporal variability of latent heat fluxes in particular, because of the effect the associated evaporative water losses have on fresh water supplied to Texas coastal bays. Climatological data (U.S. Department of Commerce 1987) indicate a multi-annual scalar average wind speed of 19.3 km/h for the International Airport in Corpus Christi, and windy conditions serve to enhance both latent and sensible heat fluxes. Frontal passages during winter months produce rapid changes in wind speed and direction, air temperature, dew point and cloud cover over time scales on the order of one to two weeks. As a result of the low latitude setting, diurnal period solar heating in summer months is intense.

Corpus Christi Bay, lying along the northwestern rim of the Gulf of Mexico (Fig. 1), is an appropriate natural laboratory for investigating local heat energy fluxes. A weather station less than 1 km from the south shore of the bay, and about 10 km from the center of the bay, records routine weather data needed to quantify air-water heat energy fluxes. A large surface area to volume ratio, combined with a relatively small mean freshwater inflow, amplifies both the magnitude and the relative importance of local processes. The bay has a surface area of 381.75 km^2, a volume of $1.316 \times 10^9 \mathrm{m}^3$ and thus a mean depth of 3.45 m. The 29-year mean discharge for Nueces River, the primary tributary to Corpus Christi Bay, is 23.4 m^3/s (Diener 1975). Uncorrected for evaporation, this is equal to 56% of the volume of the bay per year. The accumulation of Gulf water in the bay through tidal exchanges is similarly slow. Smith (1985) has postulated a half-life for bay water of about four months due to tidal flushing. Because of the relatively slow rate at which bay water is renewed, advective heat fluxes play a secondary role to local processes in the heat budget.

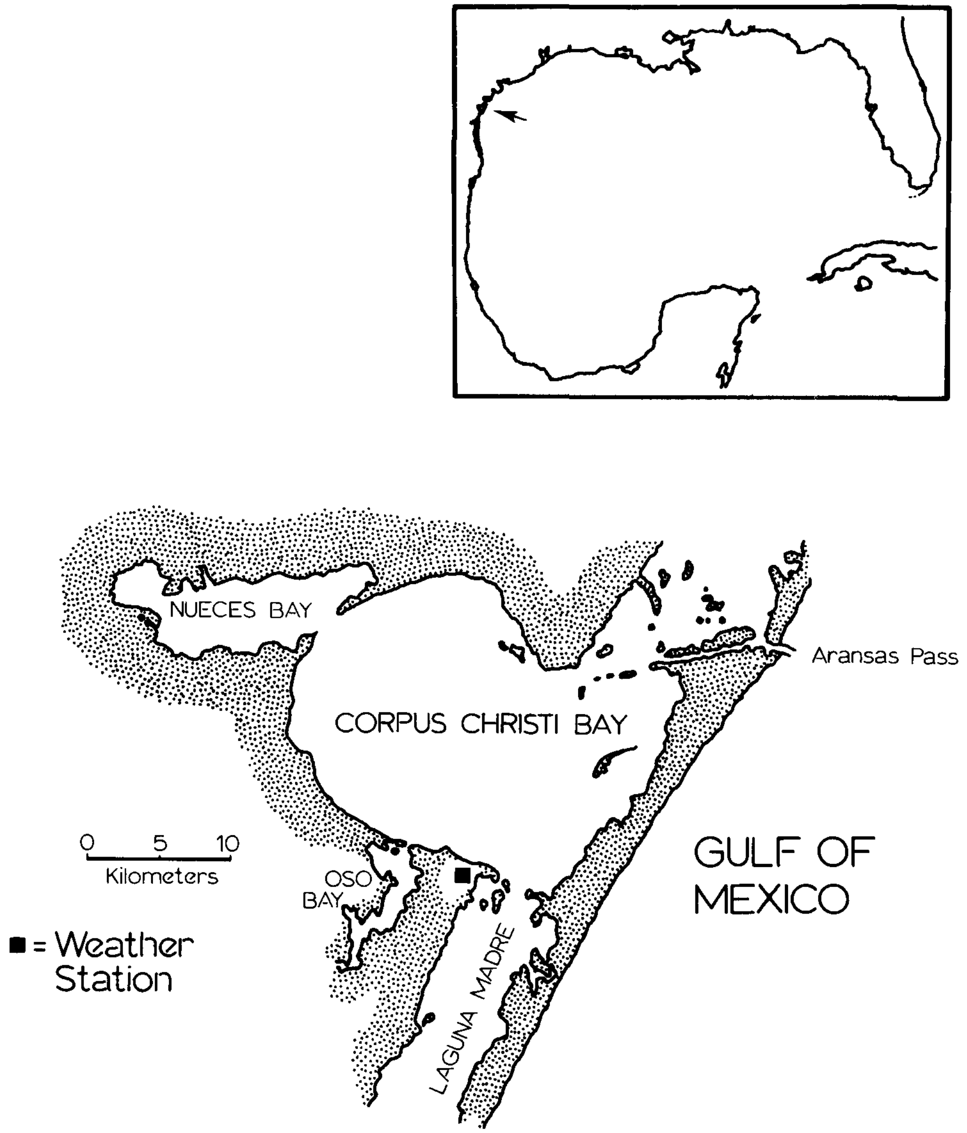

FIG. 1. Corpus Christi Bay, Texas, and the weather station on the southern shore. Insert map shows the study area in the northwestern Gulf of Mexico.

This paper presents results of a study designed to determine which physical processes control the heat budget of the bay, and the dominant time scales of each. Results indicate that the heat budget of Corpus Christi Bay is largely a balance between solar heating and cooling by evaporation and net outgoing longwave radiation. Sensible heat flux can be significant in the short term, but it is small over annual time scales. Water-sediment conduction plays a relatively minor role throughout the year. The seasonal time scale dominates the temporal variability of water temperature; quasi-periodic, low-frequency variations in warming and cooling processes become more important in winter months, when cold fronts move through the study area. In this physical setting, the diurnal cycle is a minor perturbation superimposed on seasonal and biweekly temperature changes.

METHODS

The Data

Hourly observations were recorded at the weather station from 0000 CST, December 15, 1973, through 2300 CST, December 31, 1974. Air temperature and dew point from 2 m above a land surface were entered to the nearest degree Fahrenheit (0.6°C). Total and opaque cloud cover were estimated to the nearest tenth. Air pressure was recorded to the nearest tenth of a millibar. Wind direction was recorded to the nearest ten degrees, and wind speed was averaged visually and estimated to the nearest knot (1.9 km/hr). Climatological data (U.S. Department of Commerce 1963) from the Corpus Christi International Airport indicate that the multi-annual mean monthly wind vector has an onshore-directed cross-shelf component throughout the year; 70% of the hourly observations recorded during the present study at the weather station on the south shore of the bay were directed normal to the Texas coast (shoreward). Thus, weather data at this coastal station reflect maritime conditions for the most part.

During an 18-month period of time in 1973-75, an investigation of plankton and benthos provided monthly hydrographic data from 14 stations throughout the bay (Holland, Maciolek, Kalke, Mullins and Oppenheimer 1975). Water temperatures were recorded to the nearest 0.1°C at near-surface, mid-depth and near-bottom levels. Field data were used to calculate the mean temperature of the bay for each month, as described in the following section. The availability of field data significantly influenced the choice of 1974 as a suitable year for the energy budget study.

Methods of Analysis

The computer program developed to simulate air-water and water-sediment heat exchanges was an eclectic compilation of results of many previous studies which focused upon individual heat flux processes. Simulations were made over hourly time steps. Results of any given hour's calculation of water temperature provide the input value needed for calculating the outgoing longwave radiation, the sensible heat flux, the saturation vapor pressure needed for the latent heat flux, and the water-sediment conduction during the following hour. Simulations began on December 15 to initialize the model with observed water temperatures.

Incoming solar radiation, or insolation, was estimated using the solar constant suggested by Willson, Duncan and Geist (1980). Cloud-top reflection was quantified using values for tropical conditions and at the same latitude (Smith 1985). An atmospheric transparency of 0.75 was assumed and used both for atmospheric extinction (Miller 1981), and for entering tables of surface reflectivity (Payne 1972). Insolation calculations assumed that cloud cover was distributed uniformly from horizon to horizon. Net outgoing longwave radiation was calculated from the Stefan-Boltzmann equation, with corrections for the insulating effects of cloud cover (Reed 1976) and near-surface vapor pressure (Kondratyev 1969).

Sensible and latent heat fluxes were calculated with bulk aerodynamic formulas, as suggested by Priestley and Taylor (1972). In both expressions, wind speed recorded at the bayside weather station was increased (Hsu 1986) to approximate over-water conditions. Latent heat fluxes were determined from the specific humidity gradient (Hsu 1978), assuming that the atmosphere at the air-water interface was saturated and equal to the temperature of the water. The gradient was defined by assuming that the weather station vapor pressure, recorded 2 m above the land surface, represented over-water conditions 10 m above the bay surface.

The flux of heat through the water-sediment interface was calculated for muddy-sand sediments, using a conductivity suggested by Geiger (1965) and a thermal diffusivity value from List (1963). Twelve, 50-cm thick sub-bottom layers were initialized with a temperature profile that assumed an exponentially-damped sinusoidal warming and cooling in the overlying medium (Sellers 1965).

In practice, the 14 hydrographic stations were sampled over a 2-3 day period. Low-frequency warming and cooling during that time prohibited a simple weighted averaging of all available temperatures to obtain mean values for the bay. A preliminary, though relatively minor correction was made to bring all bay segment temperatures together to the same point in time. Low-frequency temporal variability was estimated from a preliminary simulation which used weather data to quantify warming and cooling rates. These temperature changes were applied to individual stations to forecast or hindcast temperatures to midnight on the 15th day of each month. Time-corrected water temperatures were then combined into a single, spatially-integrated value by gridding the bay with a resolution of 1 km by 1 km (0.5 km by 0.5 km where bathymetric features were significant). Water depths at grid intersection points were estimated by interpolating linearly between nearby soundings on navigational chart C&GS 523. Volumes of surface, mid-depth and bottom layers within each segment were calculated using the Interactive Surface Modeling graphics software of Dynamic Graphics, Inc. The volume of each layer, divided by the total volume of the bay, provided the weighting factor for the associated temperature measurement. Weighted temperatures were then summed to obtain the single, bay-wide mean value needed for initializing calculations and quantifying residual fluxes not accounted for by local processes.

The advection term was not calculated directly in this study. It could only be approximated in a very crude way by the heat energy required to force a match, at monthly intervals, between bay-averaged observed temperatures and temperatures simulated by the model. This residual, however, contains all of the errors in the calculation of the five local heat energy fluxes. Thus, while it may be dominated by the advection term, it will be referred to as the residual heat flux.

RESULTS

The Seasonal Cycle

A good introduction to the results of the calculations is provided by summing hourly heat energy gains and losses, and plotting the accumulation, in kW-h/m^2, as a function of time. This form of presentation compresses both axes, and transient features and minor perturbations are suppressed. It is well suited for showing the longer period, seasonal fluctuations, however. Results are presented in Figure 2 in composite form.

Energy gains associated with incoming solar radiation are shown at the top of the plot. The curve rises relatively slowly early in the year; the mid-year accumulation is slightly faster, as a result of higher zenith angles and/or lower cloud cover amounts during daylight hours. A plot of total opaque sky cover (not shown), filtered to damp diurnal and shorter period variability, indicates that cloud cover is somewhat lower from late May to the latter part of October, but the decrease is not great. The increase in solar heating therefore seems to be primarily a result of higher zenith angles.

Cumulative energy losses due to net outgoing longwave radiation, shown in the second plot, are very nearly constant with time. The slight decrease in

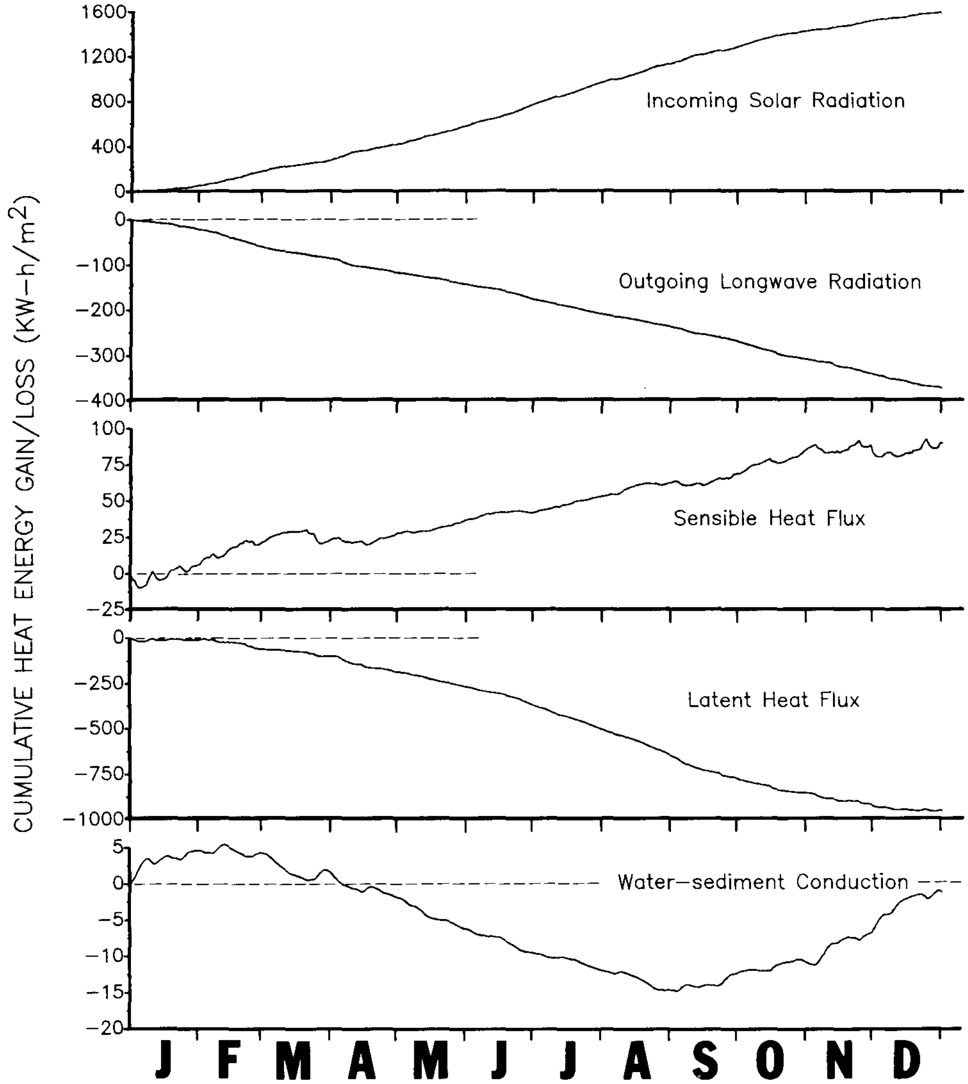

FIG. 2. Composite of cumulative heat energy gains and losses calculated for local processes, January 1 - December 31, 1974.

cloud cover noted above would, by itself, permit greater radiative energy losses, and thus increase the slope of the curve. Combined with higher water temperatures, radiative cooling in summer months should be considerably greater. However, vapor pressures from June through August averaged 26.2 mb—twice the mean value calculated for December, January and February, and 28% greater than the annual mean. Increased moisture in the lower atmosphere tends to insulate the bay, and the net radiative loss is decreased. In this case, the vapor pressure correction very nearly cancels the increase which would occur in response to water temperature and cloud cover effects combined.

Sensible heat flux, in the third plot, is shown on an expanded scale. This process serves as a heat source on average, however transient periods of heat loss are indicated, especially early and late in the year when cold fronts bring relatively cool continental air masses to the Texas Gulf coast.

The latent heat flux exhibits a seasonality in the sense that the curve becomes steepest in mid year. Relatively slight heat energy losses are indicated early and late in the year. Evaporative cooling is a function of wind speed and the specific humidity gradient. Low-pass filtered plots of these two variables (not shown) suggest that higher midsummer evaporation is due more to an increase in the specific humidity gradient than to higher wind speeds. The specific humidity gradient exhibits a distinct seasonal variation, while seasonally averaged wind speeds vary only slightly. During June-August, over-water wind speeds averaged 24.2 km/hr—only 0.4 km/hr above the average for the year, and within 1.5 km/hr of other seasonal means.

The plot at the bottom of Figure 2 shows the heat flux into the water column through the water-sediment interface. Calculations used assumed values for sediment conductivity and thermal diffusivity. Thus, while the temporal variability indicated in the plot is probably valid, the magnitude of the fluctuations is open to question until thermal properties of bay sediments can be verified. Over the longest time scales, this process should show no net heat flux. Over shorter periods, however, a net warming or cooling may be indicated. Significant changes are expected in spring and autumn seasons, but a more subtle net warming or cooling may occur even over annual time scales, if, for example, a relatively mild winter follows a relatively intense winter, or vice versa. In this study, calculations indicate a very nearly balanced condition. The cumulative heat flux through the water-sediment interface was only -1.2 kW-h/m^2, which is 2-3 orders of magnitude smaller than any of the other terms. Equally significant is the result that the cumulative heat energy per unit area remained small throughout the year. Results therefore suggest that water-sediment conduction is the least significant term contributing to the heat budget of Corpus Christi Bay.

Table 1 summarizes the above results by providing both seasonal and annual mean values. The decision to subdivide the year into four seasons was guided by the curves presented in Figure 2, however these definitions are somewhat arbitrary. Seasonal mean insolation values show the expected summer maximum. A well-defined seasonal cycle is also apparent in the latent heat flux averages, with mid year minimum values offsetting the effects of absorbed insolation. It is noteworthy that the mean summer evaporative heat energy loss is over four times greater than that calculated for the winter season.

Little seasonal variation is apparent in either the net longwave radiation or sensible heat flux. Both the sensible heat flux and water-sediment conduction remain relatively small in magnitude throughout the year. Mid year negative values calculated for water-sediment conduction are consistent with the significant thermal lag of sediment temperatures, as noted above. Residual heat fluxes are consistently negative, and no seasonal pattern is apparent. As noted earlier, and as discussed in the following section, it is likely that this term is influenced significantly by errors from the five local heat flux terms, even though it may be dominated by advective heat fluxes.

Small values for the storage term suggest a nearly balanced condition in winter and summer seasons. However, pronounced energy gains and losses are calculated for spring and autumn, respectively. A harmonic analysis of hourly storage values (Panofsky and Brier 1963) indicated that the amplitude of the annual cycle was only 22.9 W/m^2, and that it explained less than 1% of the variance in the time series. The annual mean calculated for the storage term is very nearly zero. Annual mean values for the five other terms indicate that the heat budget of the bay can be characterized generally as solar heating balanced by evaporative and radiative cooling.

Quasi-periodic, Low-frequency Cycles

Figure 3 uses 24-hour average energy gains and losses to highlight the low-frequency response to meteorological forcing. In this paper, the term "low-frequency" is used to refer to time scales on the order of 5-10 days. The curve for the insolation term combines light and dark conditions in the 24-hour averages. While this is not a good representation of either daytime or nighttime conditions, it is a necessary step before one can compare this term with other processes sharing the same fundamental periodicity. In this format, the seasonal variation is relatively subtle. The dominant feature of the plot is the day-to-day variability associated with changes in cloud cover as synoptic scale weather systems move through the study area. Fluctuations over these shorter time scales in summer months are about 85% of those in spring and autumn, but a seasonality in the variability of 24-hour average insolation is a minor feature.

Diurnally averaged net outgoing longwave radiative losses are shown in the second plot of the composite. There is some indication of greater day-to-day variability during months when frontal passages alternate continental and maritime air masses and produce low-frequency variations in cloud cover. Summer months show less variability, and radiative losses are more consistently at lower (less negative) levels. This demonstrates the insulating effect of water vapor in the lower layers of the atmosphere.

Low-frequency sensible heat fluxes are distinctly greater in magnitude during winter, spring and fall months, when maritime and continental air masses alternately blanket the Texas coastal zone. The relatively rapid rise and fall of air temperature, combined with slower changes in bay water temperature, reverse the sign of the air-water temperature difference over time scales on the order of a week. In summer, when both air and water temperatures are high, the sensible heat flux term decreases in both magnitude and variability. The standard deviation of the 24-hour averages during June-August is only 21% of the value calculated for December-February.

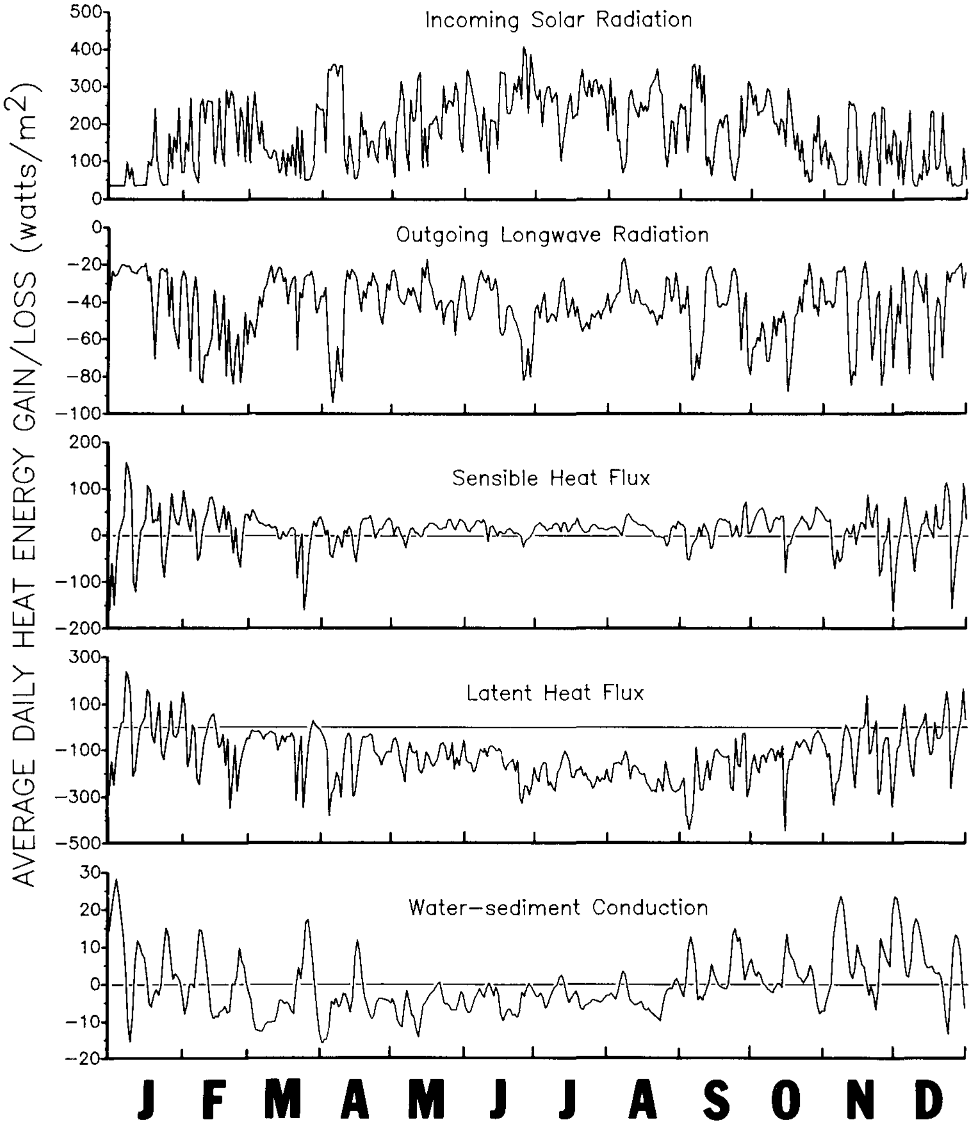

FIG. 3. Composite of 24-hour average heat energy gains and losses calculated for local processes, January 1 - December 31, 1974.

The latent heat flux also responds to alternating air masses, insofar as there is a corresponding variation in vapor pressure. The curve shows considerable variability early and again late in the year; relatively little is indicated during May-August. The standard deviation of daily mean latent heat flux values during June-August is 48% of the value calculated for December-February. In the case of evaporation, however, mid year is a time of maximum heat energy loss, if not maximum day-to-day variability. The maximum in evaporative heat energy loss occurs primarily in response to seasonal changes in the specific humidity gradient. As noted above, seasonal variations in wind speed were minimal.

Water-sediment conduction is shown at the bottom of the plot, again on an expanded scale. The relatively high specific heat of both water and sediment suppresses high frequency fluctuations at all times of year, but a relatively large day-to-day variability appears early and late in the year—an indirect effect of frontal passages. Mid year fluxes are slightly negative, reflecting the temporal lag of sediment temperature, and thus the cooling effect of sediments on a water column which is at its annual maximum temperature.

The Diurnal Cycle

Mean diurnal cycles exhibited by the five local heat flux processes were investigated by combining the 365 values calculated for a given hour. For example, all latent heat flux values calculated for 0100 CST were grouped and averaged. This was repeated for all other hours within the diurnal cycle, and for each of the other processes. The resulting mean diurnal cycles are shown in Figure 4. The insolation term has the most exaggerated diurnal variation.

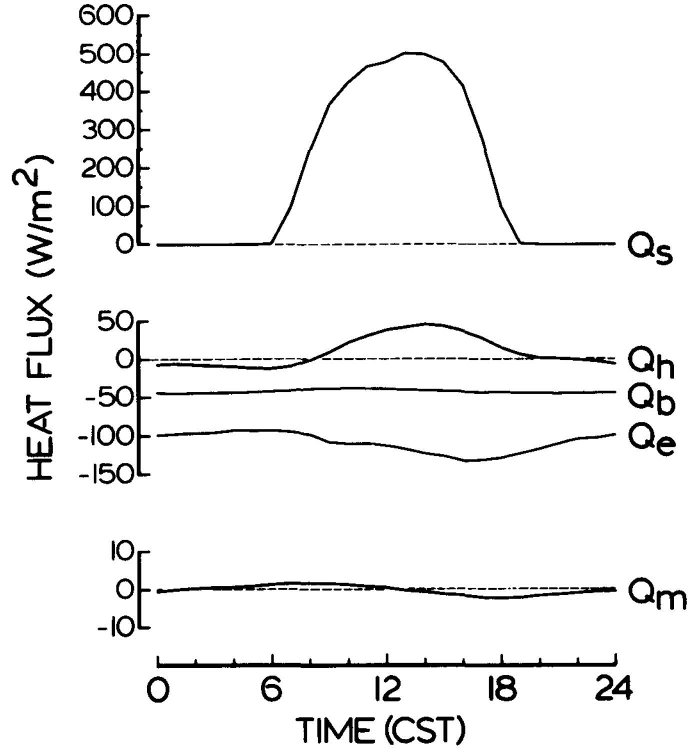

FIG. 4. Average diurnal cycle of heat energy gains and losses for local processes. Averages are calculated from the 365 24-hour periods simulated from January 1 - December 31, 1974. Symbols at right correspond to those introduced in Equation 1.

Although over the course of a year times of sunrise and sunset each vary by an hour and forty-five minutes at this latitude, essentially all of the heating by insolation occurs between 0600 and 1900 CST.

By comparison, other processes—especially water-sediment conduction and net outgoing longwave radiation—remain relatively stable throughout the course of an average day. The sensible heat flux term changes sign, becoming positive during daylight hours, because air temperatures rise and fall more than water temperatures do. The net effect is relatively small, though. The curve representing the mean latent heat flux is roughly the mirror image of the sensible heat flux curve. Values remain negative throughout an average day, and greatest heat energy losses are indicated during late afternoon hours.

Temperature Simulations

The net effect of local heat energy fluxes discussed above, plus advective gains and losses, is an increase or decrease in the storage of heat energy in the bay. This can be expressed in units of W-h/m^2, calories or, perhaps more meaningfully, in terms of the temperature of the bay—spatially averaged, as discussed in the preceding section. Figure 5 is a plot of simulated bay temperatures for 1974. Calculations were initialized with field data collected

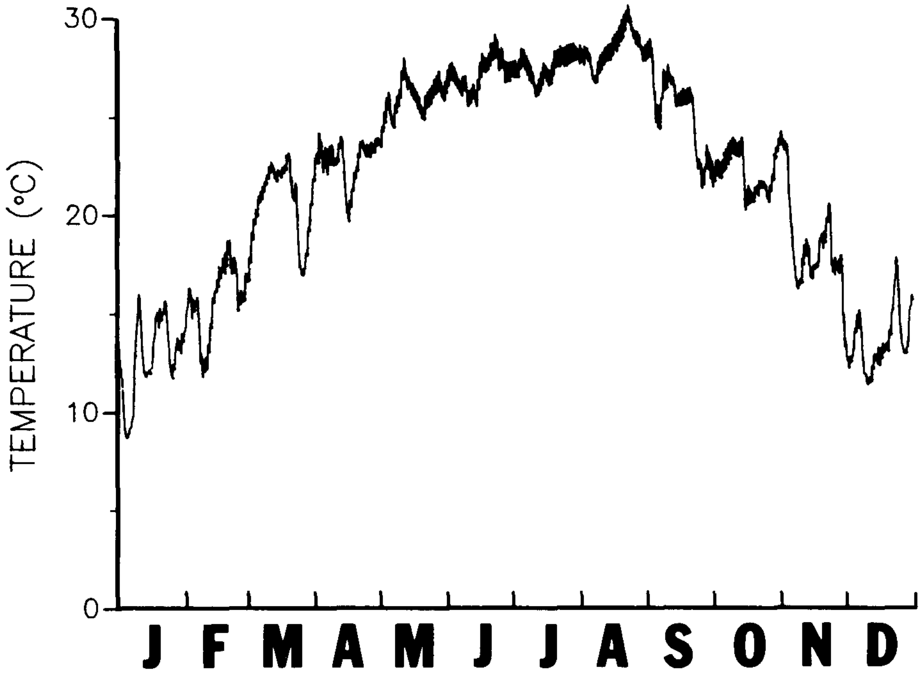

FIG. 5. Simulated hourly water temperatures for Corpus Christi Bay, January 1 - December 31, 1974.

in mid December, 1973, although the plot begins on January 1, 1974. The plot continues through the end of the year even though calculations can be verified only through mid December, 1974.

Simulated temperatures indicate net gains and losses of heat energy occurring over three distinct time scales. The dominant time scale is the annual cycle. A harmonic analysis of simulated temperatures (Panofsky and Brier 1958) indicates an annual temperature range of 14.5°C, centered about a mean value of 21.7°C. The annual cycle explains 82% of the variance in the curve. The annual curve has a somewhat flattened crest: temperatures remain between 28-30°C from the latter part of May into early September. Superimposed on the annual cycle are quasi-periodic, low-frequency fluctuations occurring over time scales on the order of a week. This component arises in response to synoptic scale weather systems—especially cold fronts moving through the study area. In late autumn, winter and early spring months, water temperatures may increase or decrease 2-4°C about the seasonal norm. This is about twice the variability calculated for summer months.

The diurnal temperature cycle is a relatively minor perturbation superimposed on both annual and low-frequency fluctuations. Harmonic analysis of the data used to plot Figure 5 indicates that the amplitude of the diurnal variation averages 0.3°C. Harmonic analysis of each of the 365 24-hour periods provided harmonic constants (amplitudes and phase angles) of the diurnal cycle (Panofsky and Brier 1958). The time series used for this purpose was a high-pass filtered version of Figure 5. Simulated temperatures were smoothed using a low-pass Lanczos filter with a half-power point at 37 hours, and high-frequency variations were extracted by subtracting the low-frequency output of the filtering operation from the original time series. Phase angles (not shown) indicate that maximum temperatures in the diurnal cycle are tightly clustered within a two-hour interval between 1600 and 1800 CST. Amplitudes are distributed between 0.0 and 0.5°C. Figure 6 is a plot of the amplitude of the diurnal cycle over the course of the year. Seasonality is poorly defined, although there is a suggestion of somewhat higher values in mid year. Presumably, the amplitude could be related at statistically significant levels to any of several meteorological variables—notably cloud cover—but the characteristically low amplitudes found in the Corpus Christi Bay study did not encourage a closer investigation of this feature.

DISCUSSION

Results of the Corpus Christi Bay study indicate a direct relationship between the importance of air-water heat energy exchanges and the time scale over which they occur. The annual temperature range is several times that of the low-frequency temperature range; the diurnal rise and fall in water temperature is insignificant for many practical purposes. Energy budget studies tend to be site-specific, however, and in another setting, where water is shallower, the diurnal variation could assume greater prominence. Smith

(1977, 1983) has shown mean diurnal temperature ranges as high as 3-4°C in two coastal lagoons where water depths are on the order of 1 m. Presumably the annual cycle would not vary significantly as a function of water depth in estuarine studies, because the long time scales would allow water temperatures to remain in thermal equilibrium with the warming and cooling processes.

In view of the dominance of the annual variation in water temperature (Fig. 5), the small amplitude of the annual periodicity in the hourly storage values was surprising. The explanation requires a distinction between causes and effects. This result of the Corpus Christi Bay study demonstrates that the cumulative effect of even a slight variation in the storage term can be large indeed, if the time scale over which it persists is sufficiently long. In this case, because of the annual time scale, a slight imbalance that explains only 1% of the variance in the storage term results in a gradual heating and cooling that explains over 80% of the variance in the temperature plot.

The analog plots (Fig. 3) show that seasonal variability should be thought of in terms of both seasonal mean fluxes and the low-frequency variability about the mean. Day-to-day variations in the 24-hour averages of most of the processes considered are distinctly greater from late autumn through early spring. One would expect greater day-to-day variability in winter, when cold fronts move through the study area. Summer months, in contrast bring relatively quiescent weather conditions and a corresponding decrease in

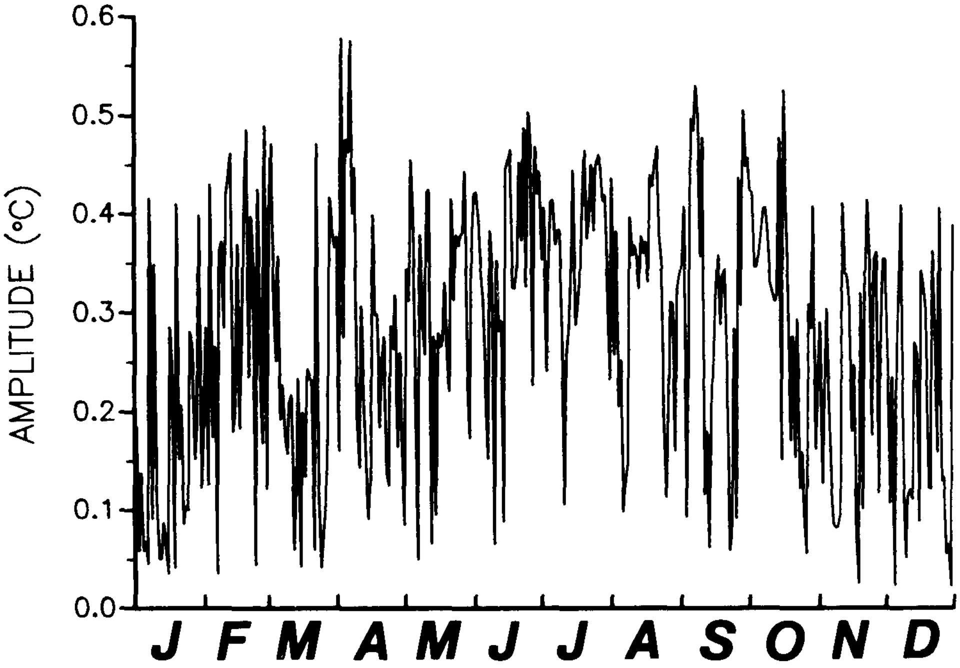

FIG. 6. Amplitudes of 24-hour period simulated water temperature variations as a function of time, January 1 - December 31, 1974.

temporal variability as relatively steady-state conditions are maintained. If processes contributing to the storage term exhibit a seasonality of this type, it follows that the same pattern should appear in simulated bay temperatures.

For Corpus Christi Bay, the relative importance of individual heat flux processes can be quantified by comparing annual and seasonal means listed in Table 1. For example, the sensible heat flux provides only 5% of the total annual heating. Conversely, the latent heat flux term contributes 57% of the total heat energy loss. The relative importance can change significantly from one season to the next, however. Latent heat energy losses, for example, increase from 30% of the total in winter to 67% of the total in summer. Similar calculations are not available for other estuaries, but one would expect considerable differences to appear. Not only would meteorological forcing vary considerably from one study site to the next, but the role of advection would be much greater in estuaries with larger tidal amplitudes and freer connection with the sea.

The importance of the latent heat flux term in controlling the heat budget of Corpus Christi Bay is accentuated by the semi-arid nature of the climate along the central Gulf coast of Texas. Evaporative water losses are more significant in view of the approximately 75 cm of annual rainfall for the region (Texas Water Development Board 1960). The annual average latent heat flux of -109 W/m^2 corresponds to an annual cumulative water loss of approximately 138 cm. Alternately, if surface evaporation is calculated using vapor pressure deficits (see Penman 1948, de Bruin 1978), a still higher value results. This latter approach was incorporated into a follow-up simulation, and an annual water loss of 265 cm resulted. Aside from the uncertainty revealed by these alternate means of estimating just one of the heat budget terms, calculations suggest that the annual water loss by evaporation constitutes a significant fraction of the effective depth of the bay—40 to 77%. Regardless of the exact

TABLE 1

Seasonal and annual heat budgets for Corpus Christi Bay, Texas. Heat energy fluxes are in W/m^2. Winter averages are calculated from simulations for December, January and February; spring represents March-May conditions; summer is defined as June-August; and autumn is September-November.

	Winter	Spring	Summer	Autumn	Annual
Incoming Solar Radiation, Qs	+118.9	+179.4	+250.6	+173.6	+181.0
Net Outgoing Longwave Radiation, Qb	-41.9	-37.8	-42.8	-47.4	-42.5
Sensible Heat Flux, Qh	+13.5	+7.1	+11.6	+8.9	+10.2
Latent Heat Flux, Qe	-39.9	-93.1	-173.8	-127.3	-108.8
Water-sediment Conduction, Qm	+4.4	-6.0	-3.8	+3.8	-0.1
Advection, Qa	-49.4	-32.2	-38.5	-38.6	-39.6
Storage, Qt	+6.0	+18.7	+3.6	-27.3	+0.3

value, in view of the relatively small amount of annual rainfall, freshwater inflow is crucial for maintaining brackish water conditions.

Another possible source of error in using routine weather data to quantify latent heat energy fluxes was the choice of 10 m for the denominator of the specific humidity gradient term. Although the moisture content of the atmosphere was sampled 2 m above the ground, that same value is probably inappropriate as the denominator of the gradient term. At a height of 2 m above the bay surface, the humidity may be significantly higher. If so, the measured, over-land value should be applied to a higher level over water. Field measurements are not available to suggest what that level might be. A value of 10 m was used in the calculations, but if this is incorrect by even 2-3 m the resulting calculations would contain errors which would be absorbed by the advection term.

The availability of monthly *in situ* data made it possible to correct the heat storage in the bay over sub-seasonal time scales. It was felt that in this way the Corpus Christi Bay study would provide some insight into at least seasonal variations in advective heat fluxes. However, calculations indicate a positive residual only during the period from August 15 to September 15. During the autumn transition season, one might expect that temperature differences between the Gulf and the bay would be greatest, because the bay would cool faster by virtue of its shallower depth. Autumn cooling does begin in late August (Fig. 5), but the fact that seasonal residuals remain negative throughout the year (Table 1) calls into question the ability of the model to single out and describe advective heat fluxes accurately by calculating them in this way. The negative residual for the year as a whole suggests that on average bay waters remain warmer than Gulf waters. This is possible, but the question cannot be resolved with the available data base. It is noteworthy in this regard that the mean bay temperature of 21.7°C simulated for 1974 is similar to the mean inner shelf temperature of 22.0°C, calculated from surface measurements made 14 km offshore during 1976-77 (Smith 1980). Also, it is important to keep in mind that advective heat fluxes can occur between Corpus Christi Bay and any or all of the other bays and lagoons to which it is connected on its landward sides (Fig. 1). Thus, the magnitude and relative importance of the advective heat fluxes remains open to question and unresolved by the Corpus Christi Bay study. It is clear, however, that an investigation of the heat energy balance for the bay is incomplete without some way to account for the residual, once local heat fluxes have been quantified and summed.

ACKNOWLEDGMENTS

Weather data used in this study were obtained form the National Climatic Center, Asheville, North Carolina. Programming assistance was provided by Paul Mikkelsen; Patrick Pitts plotted the data appearing in Figures 2, 3, 5 and 6. Special thanks to George Ward and Bill Wiseman for their objective and helpful comments as reviewers.
Harbor Branch Oceanographic Institution, Contribution No. 738

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