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An investigation of the heat budget of the Indian River lagoon, Florida, during winter months

Heat budget
Numerical model
Air-water exchange

Balance thermique
Modèle numérique
Échange air-eau

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ABSTRACT

Meteorological records and water temperature data from a 119-day period in the winter of 1979-1980 are used to develop and verify a numerical model of local air-water heat energy exchanges in the Indian River lagoon, on the Atlantic coast of South Florida. In terms of day-to-day variability, the most important processes are latent heat exchanges, net incoming solar radiation and sensible heat exchanges — in that order. Cold fronts moving through the study area alternate warm, moist maritime tropical air with relatively cool, dry continental polar air behind the front. As a result, the amount of heat stored in lagoonal waters is most highly correlated with the sensible and latent heat flux terms. Combining the individual heating and cooling processes, daily water temperatures can be simulated to a close approximation under a variety of meteorological conditions.

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RÉSUMÉ

Étude de la balance thermique de la lagune Indian River (Floride) pendant l'hiver.

Les données météorologiques et les températures de l'eau pendant une période de 119 jours durant l'hiver 1979-1980 sont utilisées pour développer et vérifier un modèle numérique d'échanges thermiques air-eau dans la lagune « Indian River », située sur la côte atlantique de la Floride du Sud. En terme de variabilité journalière, les processus les plus importants sont dans l'ordre : des échanges de chaleur latente, des apports net de radiation solaire et des échanges thermiques sensibles. Les fronts froids qui traversent la surface lagunaire font alterner des masses d'air marin tropical chaud et humide, et des masses d'air continentales refroidies, d'origine polaire. En conséquence, la quantité de chaleur emmagasinée dans les eaux lagunaires est très fortement corrélée avec les deux termes de l'échange thermique, sensible et latent. En combinant les deux processus qui controlent le réchauffement et le refroidissement, les températures journalières de l'eau peuvent être simulées avec une bonne approximation suivant des conditions météorologiques déterminées.

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INTRODUCTION

Heat budget studies in marine settings are generally conducted in open ocean waters, and are often restricted to defining annual cycles. Budyko (1956) and Malkus (1962) have presented heat budgets for entire ocean basins, using available climatological data in the form of routinely collected shipboard observations. More recently, Hastenrath (1976 ; 1980) and Hastenrath and Lamb (1980) have focused upon selected regions of the tropical oceans and described annual cycles using similar analytical techniques. Recent developments in satellite technology have provided data in regions where observations were sparse (Vonder Haar, Ellis, 1974 ; Flanders, Smith, 1975), but the emphasis has remained on the very low frequency variations. The large space and time scale studies provide a nice backdrop

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Harbor Branch Foundation, Inc. Contribution No. 329

for more highly focused work, and micrometeorological studies have contributed the empirical expressions necessary for quantifying local heat fluxes over any time scale. However, the methodology has only recently been applied to estuarine waters.

Estuaries are by nature highly responsive to air-water interactive processes. The relatively shallow waters of coastal bays and lagoons in particular result in a significant temporal variability which may exceed that of open ocean waters greatly, and which may fluctuate significantly about monthly or seasonal mean values. Thus results from open ocean heat budget studies cannot be extrapolated into intracoastal settings. Furthermore, the relative importance of the individual terms of the heat budget equation may be quite different in estuarine waters. Conductive heat exchanges between the water column and the underlying sediments may be substantial. On the other hand, advective fluxes may be small, except where fresh water enters the estuary, or at the mouth of the estuary where exchanges occur with the inner shelf. For the most part, air-estuary heat exchanges are limited to the local fluxes acting through the air-water and water-sediment interfaces.

The collection of ancillary hydrographic data in many biological and ecological studies has demonstrated clearly the gross features of the annual temperature cycle in estuaries, yet the processes which produce the day-to-day variations are themselves rarely characterized. Heath (1977) utilized weather data to estimate the heat budget of a small inlet on the south coast of North Island, New Zealand, during the austral autumn. Calculations were made for only one tidal cycle, however, and thus the temporal variability and relative importance of the terms over longer time periods could not be determined. Recently, Smith and Kierspe (1981) and Smith (1981) conducted studies during winter months to investigate local heat fluxes in lagoonal waters over time intervals in excess of two months. Results suggest that when cold fronts alternate maritime tropical and continental polar or continental arctic air masses, latent and sensible heat fluxes are the dominant processes producing the day-to-day variations in water temperature. Under summer conditions (Smith, 1982), the energy budget shifts significantly, and water temperature varies as a result of temporary imbalances between a more variable heating by insolation and a more quasi-steady cooling by the sum of the back radiation, evaporation and sensible heat loss terms.

Previous studies in offshore waters off Florida's Atlantic coast (Hastenrath, 1976) have indicated a seasonal cycle in the magnitude of energy fluxes acting across the air-water interface. This is supported by lagoonal studies. But work carried out in the Indian River lagoon, focusing upon shorter time scales, has documented a seasonal shift in the variability about the monthly means as well. Day-to-day variations in any given heat flux process are less in summer months, as a result of more stable meteorological conditions.

The study reported in this paper is a continuation of the work designed to investigate the magnitude and relative importance of local heat flux processes in lagoonal waters using regionally representative meteorological data. The data presented are from the winter of 1979-1980 and show a dominance of sensible and latent heat fluxes at a time of year when cold fronts are alternating distinctly different air masses in the study area.

THE OBSERVATIONS

Meteorological variables and estuarine water temperatures were recorded over a 119-day period of time from 20 December, 1979, through 16 April, 1980. The study site in the Indian River lagoon (27°32.1'N, 80°21.0'W) was approximately 50 m offshore and directly north of a jetty which had a blocking effect upon both tidal motions and the wind-driven circulation (Fig. 1). The study area was a seagrass flat, containing beds of *Halodule wrightii* and *Syringodium filiforme*. Water depths in the area were generally 100-150 cm. Locally, the dominant M_2 tidal constituent amplitude was 10 cm ; nontidal processes varied water levels by an additional ±10 cm. The Atlantic Intracoastal Waterway borders the study area to the east. The long-channel tidal excursion in the Waterway locally is 4.7 km. The study area is approximately 12 km from the Fort Pierce Inlet, and it is felt that advective tidal exchanges with the Atlantic Ocean do not bring water this far into the lagoon against the net freshwater outflow.

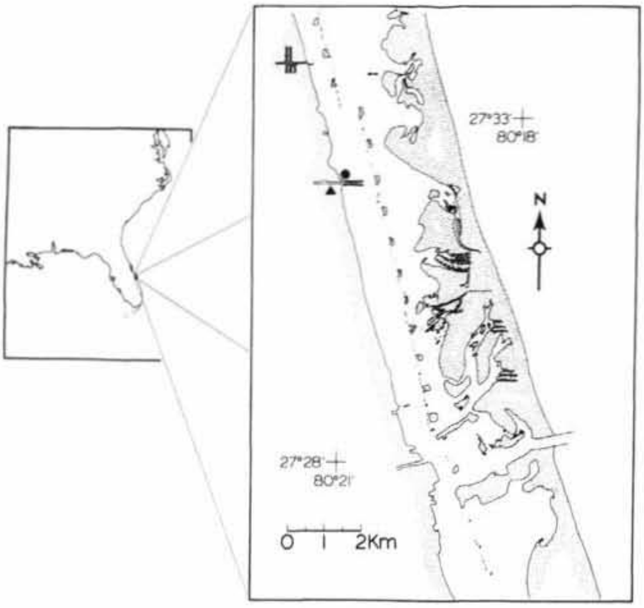

Figure 1

Study site in the Indian River (solid circle) and weather station (solid triangle) used for hydrographic and meteorological measurements, December 20, 1979, through April 16, 1980.

Weather data were recorded at a Climatronics Corporation weather station about 200 m from the study site. Daily accumulations of insolation were obtained with a pyranometer having a spectral response between 0.35 micron and 1.15 microns, a peak sensitivity at 0.85 micron and an accuracy of ±5 %, according to the manufacturer. The relative humidity sensor utilized hygroscopic crystals to drive a strain gage. Humidity values are accurate to within 2 % according to the manufacturer ; data were calibrated against measurements made with a sling psychrometer throughout the study. Hourly air temperatures were recorded to the nearest 0.6 °C and calibrated against the dry bulb reading of the psychrometer. The sensor was a precision thermilinear probe with an accuracy of ±0.6 °C. Wind speed was sensed with a three-cup anemometer, coupled to a light chopper which converted the speed of rotation to a frequency proportional to wind speed. The accuracy was ±1 cm/sec. according to the manufacturer, however hourly values were estimated from an analog record and digitized to the nearest 45 cm/sec. (1 mile/h). This procedure suppressed considerable gustiness at times. High frequency variations were damped further by taking 24-hour averages. All calculations involved 24-hour averages or accumulations.

At the study site, an Environmental Devices Corporation Type 109 temperature recorder was maintained to provide a data base against which temperature changes simulated by a computer model could be compared and verified. Bihourly average bottom temperatures were digitized by the manufacturer to the nearest 0.1 °C with an accuracy of ±0.2 °C, according to instrument specifications. It is noteworthy that this accuracy corresponds to energy fluxes of $\pm 11\ W/m^2$, and it is within this range that the calculations described in the next section can be verified.

NUMERICAL SIMULATIONS

The numerical model utilized in this study was developed from the heat budget equation:

$$Q_t = (Q_s + Q_v + Q_m) - (Q_b + Q_h + Q_e),$$

where Q_t is the storage term, Q_s is the net insolation term, Q_v is the advective heat gain, Q_m is the conductive heat exchange with the underlying sediments, Q_b is the net longwave radiative energy loss and Q_h and Q_e are the sensible and latent heat fluxes.

Reflectivity of insolation at the air-lagoon interface was incorporated into the calculations using results of Payne (1972). Net longwave radiation was estimated from the Stefan-Boltzmann equation, with corrections for counter radiation from the atmosphere (Swinbank, 1963) and from cloud cover (Reed, 1976).

Conductive exchanges with the underlying sediments were modeled with 12 layers, each having a thickness of 50 cm, and a thermal diffusivity of 0.021 cm^2/sec. The initial temperature profile was given by

$$T(z,t) = \overline{T} + A \exp(-Z\gamma) \cos(\omega t - z\gamma),$$

where $\overline{T}$ is the mean annual water temperature (24 °C from historical data), A is the amplitude of the annual temperature curve (7 °C from historical data), and z is the depth below the water-sediment interface. γ is given by $\sqrt{(\omega/2\alpha)}$, where α is the thermal diffusivity and ω is $2\pi/365$ days. t is the time, in days, that has elapsed since the summer solstice. The sediment temperature profile on the starting day, t_o, was corrected in the upper 3 m by interpolating linearly to the observed water temperature on that date. Thereafter, all conductive heat exchanges were calculated from the expression

$$Q_b = -\lambda \Delta T / \Delta z,$$

where conductivity, λ, was taken to be 0.011 cal/cm/sec./°C.

Sensible and latent heat fluxes were calculated with bulk aerodynamic type formulas, as suggested by Priestley and Taylor (1972). The sensible heat flux is directly related to the water-air temperature difference, and the latent heat flux is directly related to the vapor pressure deficit. Air in direct contact with the surface of the lagoon was assumed saturated and at the temperature of the water. The actual vapor pressure of the atmosphere over the lagoon was estimated from relative humidity measurements made at the weather station. Evaporation into air brought to the surface of the lagoon was calculated by comparing the vapor pressure of the overlying atmosphere with the saturation value at the air-water interface, and making corrections for wind speed and stability.

The 200 m distance separating the study site from the weather station required a somewhat different and more general form for the eddy exchange (Austausch) coefficients. My choice incorporated both wind speed, V, and stability, θ, as components of the product $A_o A(V) A(\theta)$. The wind speed effect was given by $A(V) = 1 + pV^q$, which is of a form similar to that used by Penman (1948). The stability effect was given by $A(\theta) = 1 + S\theta^r$, where $\theta = (T_w - T_a)/T_o$. When $r = 3$, the stability effect produces results similar to those found by Deardorff (1968) in non neutral conditions. T_o was chosen to be large enough such that it was always greater than the absolute value of $(T_w - T_a)$. Thus the term $[1 + (T_w - T_a)/T_o]$ by itself could effectively suppress or double sensible and latent heat fluxes under stable and unstable conditions, respectively.

The empirical coefficients p and S were introduced as proportionality factors to translate variations in meteorological conditions into variations in energy fluxes. These coefficients also incorporate differences in wind speed and stability, respectively, that might have existed between the weather station and the study site. The coefficients q and r are introduced to allow for nonlinear relationships between meteorological conditions at the weather station and energy fluxes at the study site.

Values for A_o, p, S, q, and r were determined from repetitive simulations over all possible 14-day periods, until the standard deviation of the errors of the simulated temperatures (the differences between simulated and observed values) was minimized. The empirical coefficients were adjusted individually in the sensible and latent heat flux terms, and there was no assumption that the transport of sensible heat and moisture proceeded at the same rate. The final expression was

$$A = 0.30(1 + 0.84\ V^{0.75})\ \{1 + 0.03[(T_w - T_a)/10]^3\},$$

for the sensible heat flux, and

$$A = 0.31(1 + 0.03\ V^{1.50})\ \{1 + 0.06[(T_w - T_a)/9]^3\},$$

for the latent heat flux. The general form of the eddy exchange coefficient has been used in studies of other lagoons (Smith, 1981) and in the Indian River lagoon during mid winter months (Smith, Kierspe, 1981) and mid summer months (Smith, 1982). There appears to be distinct similarities in the empirical coefficients from one study to the next, but the exact values must be considered both site-specific and study-specific, and therefore they must be redetermined for each application of the model.

Advective heat transport could be estimated only as a residual in the calculations. Results are not presented due to uncertainty surrounding this term. In comparing observed and simulated water temperature variations, it became apparent that the study site responded to gains and losses of energy as if the local water depth were 215 cm. With this value, simulated temperatures approximated those observed most closely. The water depth at the point where the temperature recorder was installed to verify the calculations was actually on the order of 105 cm during the 119-day study period. This greater effective depth may indicate that there is a transient exchange of heat between the water column and the uppermost few tens of centimeters of the sediment — a conductive exchange not modeled adequately by an isothermal layer 50 cm thick. Indeed, unpublished data from the study area have revealed strong vertical temperature gradients of as much as 2.2°C per 10 cm in the upper 40 cm during winter months.

Alternately, the greater effective depth may indicate that the local wind-driven circulation was exchanging water between the study site and the surrounding area, where the depth does in fact exceed 200 cm. If this is the case, then by using an effective depth a portion of the advective heat flux term — that associated with the local wind drift — was distributed implicitly through the other, local heat flux terms. At the same time, however, these terms were made more regionally representative by utilizing a depth more representative of the surrounding area. The advective heat flux that could not be incorporated into the model, then, was that which produced a net import or export of heat into or out of the study area, respectively, rather than a local mixing within the study area. This is not a completely satisfying way to treat the advective heat flux term, since it is impossible to define a distance within which there is a local mixing, and beyond which the effect is a net import or export of heat. But the common alternative of defining advective heat flux as the residual unaccounted for by the calculations is not appealing either. That approach ignores the fact that residuals contain errors that are inherent in empirical relationships, and that should in fact be associated with the other, local heat flux terms.

RESULTS

The results of the computer simulation are shown in analog form in Figure 2, which is a composite of the day-to-day energy fluxes associated with the five local heat exchanges operating through the air-water and water-sediment interfaces. At the top of the plot, the insolation term shows energy gains generally between 100 and 400 W/m^2, depending upon the average cloud cover for a given day. Back radiation is plotted on the same scale and appears relatively constant at between 60 and 80 W/m^2 when computed from the 24-hour average weather conditions. Mean values of net insolation and net longwave radiation indicate a net radiation balance for the study period of + 162 W/m^2.

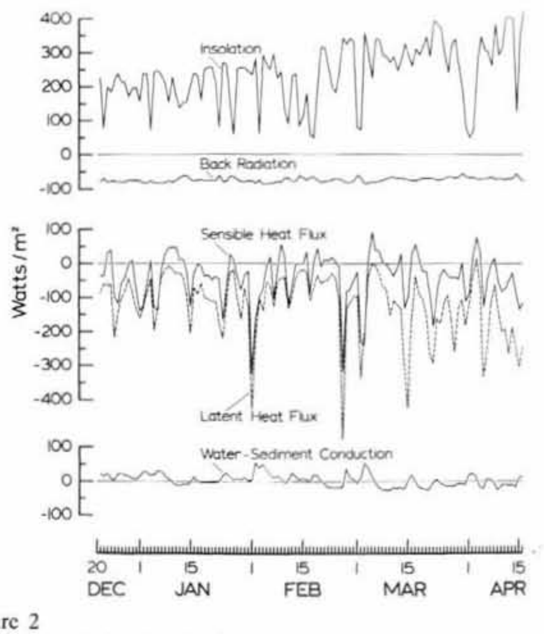

Figure 2

Composite of the five local energy exchange processes, in W/m², simulated for the study site from December 20, 1979, through April 16, 1980.

The sensible and latent heat fluxes are plotted together on the same vertical scale in the center of the figure to emphasize their strong correlation. Both processes depend upon the characteristics of the air mass overlying the lagoon. Sensible heat fluxes (solid line) show a preference for negative values, indicating an energy loss from the lagoon. Isolated positive values are found throughout the record, however. A statistical analysis of the sensible heat flux data indicates a standard deviation of 71 W/m² about a mean value of −41 W/m². There is some suggestion of a quasi-periodic variation in the sensible heat flux term. Maxima occur roughly every 6-8 days, corresponding with the movement of frontal passages through the study area. The difference in the moisture content in air masses ahead of and behind a front has a similar effect on the latent heat flux term. The day-to-day variation follows that of the sensible heat flux term closely, though values are more consistently negative. Over the 119 days of the study, the latent heat energy loss averaged −121 W/m², with a standard deviation about the average of 94 W/m². On only one occasion does the model suggest that the lagoon was warmed by a condensation of water vapor at the air-water interface.

At the bottom of the figure is the plot of the energy fluxes across the water-sediment interface. This term has a mean value of 3 W/m², and may be characterized as being relatively slight in its day-to-day variation. The standard deviation is 18 W/m², exceeding only the back radiation term in this regard. There is some suggestion of a slight preference for positive values at the start of the record, and negative values at the end. Sediment temperature lags behind that of the overlying lagoonal water, and the sediments are relatively warm in early winter and relatively cool in spring months.

The elementary statistics computed from the time series of the local heat flux terms are summarized in the Table. Some of the mean and standard deviation values have been referred to above. In addition, multiple linear regression correlation coefficients have been calculated to determine both the interrelationships of the individual terms, and the correlation between the energy flux terms and the storage term. This latter relationship in particular can be interpreted in a cause-and-effect sense to infer the processes most responsible for the day-to-day heating and cooling of lagoonal waters in winter months. Thus, of particular interest are the correlation coefficients along the top line, opposite the storage term, Q_t.

Two terms appear to play a particularly important role in the heat budget of the lagoon. Specifically, the latent and sensible heat flux terms are correlated with the storage term at a level in excess of 0.80. The humidity and temperature of the overlying air mass vary considerably in winter months, when frontal passages occur over time intervals on the order of six to eight days. When a frontal passage replaces relatively warm, moist maritime tropical air with relatively cool, dry continental arctic or continental polar air, both sensible and latent heat energy losses increase. Furthermore, the Table quantifies what is implicit in Figure 2 : the sensible and latent heat flux terms are highly correlated with each other. The multiple linear regression correlation coefficient is + 0.818.

Neither of the two radiative terms is significantly correlated with the storage term. Some additional combinations of terms are related in a statistically significant way — for example the net longwave radiation and water-sediment conduction terms — but the physical interpretation of this is not readily apparent.

Although the analog plot of the individual terms shows that the dominant activity occurs on a day-to-day basis, it is nevertheless of interest to compare the averages computed for the entire 119-day study to characterize the heat budget of the lagoon for winter conditions. The data available from this study suggest that heating by net insolation and, to a much lesser extent, water-sediment conduction is balanced on the average by a cooling due to net longwave radiation, evaporation and sensible heat loss. The resultant effect of both the heating and cooling terms is a slight increase in the storage term, but the large standard deviation about the mean shows clearly that a balance in the heat exchange processes was an exceptional situation.

The only way to verify the calculation of the individual heat flux terms is to convert them to the corresponding heating or cooling that would occur in the lagoon, and then compare the simulated temperatures with those actually observed. Heat fluxes, in W/m², are converted to heating or cooling, in °C/day, by dividing by the product of the density, the

Table

Statistical properties of local heat flux terms computed for the Indian River lagoon, 20 December 1979 through 16 April 1980. Mean and standard deviation are in Watts/m² ; correlation coefficients less than 0.233 are not significant at the 99 % confidence level.

			Correlation coefficients				
	Mean [1]	SD	Q_m	Q_h	Q_e	Q_b	Q_s
Storage, Q_t	+ 3	156	+ 0.028	+ 0.865	+ 0.804	− 0.201	+ 0.162
Net insolation, Q_s	+ 236	88	− 0.176	− 0.144	− 0.333	− 0.360	
Net longwave radiation, Q_b	− 74	6	− 0.555	+ 0.065	− 0.131		
Latent heat flux, Q_e	− 121	94	+ 0.153	+ 0.818			
Sensible heat flux, Q_h	− 41	71	− 0.149				
Water-sediment conduction, Q_m	+ 3	18					

1. Positive and negative mean values indicate fluxes into and out of the water column, respectively.

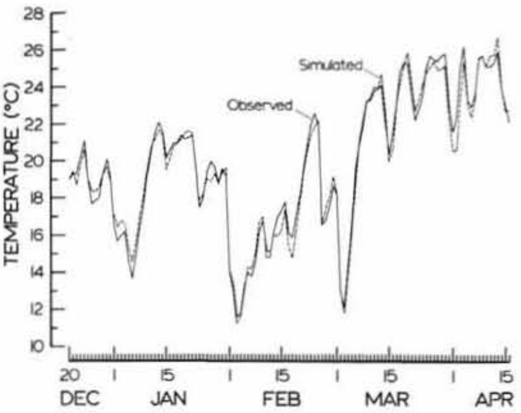

Figure 3

Observed (solid line) and simulated (broken line) water temperatures, in °C, for the study site from December 20, 1979, through April 16, 1980.

specific heat and the water depth. The results are shown in Figure 3. Some of the extrema are missed in the computations, but for the most part the fit is quite good. Simulated temperatures rarely deviate from observations by more than half a degree.

DISCUSSION

Results of this study suggest that the dominant local heat energy exchanges in the Indian River lagoon during winter months are those associated with the turbulent fluxes of sensible and latent heat through the lowest layers of the atmosphere over the lagoon. Day-by-day variations in the insolation term are substantial, but they are not as well correlated with the storage term. Clear to partly cloudy skies can exist both ahead of and behind a cold front, when the lagoon is warming and cooling, respectively. These results are consistent with those of an earlier study of the Indian River lagoon (Smith, Kierspe, 1981), and another of the Laguna Madre of Texas (Smith, 1981). During summer months, on the other hand, and in the absence of frontal passages, the energy budget in the Indian River lagoon is significantly different (Smith, 1982). Then, warming and cooling cycles arise as a temporary imbalance between a more variable heating by insolation and a more quasi-steady cooling by the net outgoing longwave radiation, evaporation and sensible heat flux terms. Both sensible and latent heat fluxes become relatively stable during summer months.

The energy balance of this coastal lagoon appears to be quite different from that of nearby waters in the open ocean. Hastenrath (1976) compiled shipboard observations to construct annual curves for Gulf Stream waters off the Atlantic coast of Florida. Aside from the advective and storage terms, which logically would differ considerably in unbounded open ocean waters, and which were computed as a residual, it is of interest to compare some of the local heat fluxes from the Atlantic Ocean and adjacent Indian River lagoon waters. Specifically, Hastenrath finds a sensible heat loss generally within the range of 10-20 W/m^2 during the period from December to April. This compares with approximately 40 W/m^2 found in this study, and suggests that continental polar or arctic air may be modified rapidly as it moves offshore. The latent heat flux loss in open ocean waters is decreasing during winter and spring months but averages just over 150 W/m^2. This is somewhat greater than the mean of 121 W/m^2 found in this study, however it may reflect year-to-year variability about the long-term mean. Finally, the radiation balance increases sharply between late winter and spring, but Hastenrath's mean of just over 80 W/m^2 is about half the 162 W/m^2 computed in this study.

The relatively close match of simulated and observed water temperatures (Fig. 3) suggests that the individual heat flux terms themselves are being modeled reasonably accurately. It is an encouraging result of this and earlier studies that energy budget calculations can be made with meteorological measurements made some distance from the study site itself. Apparently all that is required is a regionally representative data base, which is then adjusted empirically for spatial gradients that may exist between the sensors and the study site. This approach opens the door for similar studies which may involve several sites. One would need only enough water temperature data from each study site to calibrate the model to the desired degree of accuracy.

Acknowledgements

Mr. George H. Kierspe wrote the computer program used in simulating the local fluxes, and digitized the weather data used in the calculations. Cloud cover was recorded by the Federal Aviation Administration at the Municipal Airport in Vero Beach, Florida, and weather records were obtained from the National Climatic Center in Asheville, North Carolina.

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