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TEMPERATURE AND BOWEN RATIO ESTIMATES OVER LAKE PONTCHARTRAIN, LOUISIANA

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Meteorological data are often sparse over water bodies, even for lakes of economic and recreational importance. This research employs a technique whereby readily available atmospheric observations can be used to evaluate the thermal and atmospheric energy budget characteristics of a water body, in lieu of difficult and expensive field observations. Lake Pontchartrain, Louisiana is used as the example, because little is known about the physical properties of this important water body and because a network of automated platforms that provide atmospheric data for the lake has recently become available. On a diurnal basis, Lake Pontchartrain demonstrates a summer sea breeze and the land-water temperature contrasts that would be expected adjacent to a large water body. Bowen ratios are estimated to be between 0.10 and 0.14 and are relatively consistent in the diurnal and seasonal cycles. *Key Words: atmospheric energy balance, climatology, Lake Pontchartrain.*

To attain a proper understanding of the physical, chemical, and biological processes of a lake ecosystem, an understanding of the atmospheric properties and surface energy balance is important. For instance, how might changes in turbidity and wave action affect the rate of energy used to heat the air from a given surface area (sensible heat flux, Q_h) and the rate of energy used to evaporate water from a given surface area (latent heat flux, Q_e)? Such information is important be-

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cause changes in energy input and output affect lacustrine ecosystems. Since the magnitudes of the various components of the surface energy balance depend on many factors, including the type of surface and its moisture, vegetation, and texture characteristics, geographic location, time of year, time of day, and weather (Arya 1988), it is desirable to have field measurements of the energy balance components for a given aquatic ecosystem.

One common form of the surface energy balance is:

$$Q^* = Q_h + Q_e + Q_g \qquad (1)$$

where Q^* represents net radiation and Q_g represents substrate heat flux. $Q^* > 0$ when directed toward the surface and the other terms are positive when directed away from the surface. Other components, such as the dissipation of mechanical energy of the wind by surface friction and the latent heat of fusion associated with the change of state of water, may be important locally but are generally neglected in the computation of the surface energy balance.

Unfortunately, measurements on the right side of Equation 1 are usually lacking, particularly over water bodies, because of logistical difficulties. Moreover, some components of the energy balance are especially difficult to measure in the field because several variables are required and often necessitate expensive equipment. Therefore, attempts have been made to devise equations to approximate components of the surface energy balance without using the equipment and data that are required by conventional field techniques (Roll 1965).

The Bowen Ratio

A starting point for approximating the energy balance is to examine only the ratio of Q_h to Q_e, termed the Bowen Ratio (β). Over a lake surface, anomalous low β values over a period of days or weeks imply that either evaporation is high and the lake level will decrease, or that the lake is fed from an input of water from other sources (perhaps introducing different salinity levels or pollution concentrations). β was originally used as a means of simplifying the equation to compute the mass of water evaporated from the surface, an extremely difficult quantity to measure directly in the field (Lewis 1995). Since its introduction, β has been useful as a means of quantifying the evapotranspiration in such landscapes as agricultural fields (Pieri and Fuchs 1990; Dugas *et al.* 1991; Grantz and Meinzer 1991) and midlatitude pine and broadleaf forests (Vogt and Jaeger 1990; Pitacco *et al.* 1992; Herbst 1995).

The conventional ("profile") approach to measuring β involves all of the complications of measuring Q_h and Q_e upon which β is based. These techniques are so-named because they involve equations that require measurement of several obscure mean atmospheric entities (*e.g,* horizontal wind flow (u), potential temperature (θ), and specific humidity (q)) at more than one vertical level in the surface boundary layer. Although these methods are relatively accurate, their major disadvantages are that they are extremely difficult and expensive to measure, particularly during storms and especially in a lacustrine environment. In other words, the required parameters cannot be obtained from standard meteorological observations. Furthermore, the use of the equations is especially tedious and inaccurate under non-neutral atmospheric conditions.

There are other methods of estimating Q_h and Q_e, such as with lysimeters, remote sensing techniques, and eddy correlation (Arya 1988), but these rely on expensive instrumentation. Water balance techniques (*e.g.* Hsu *et al.* 1972; Vogt and Jaeger 1990) can also be used to estimate evaporation, which in turn can be used to approximate Q_e, but large errors can occur in midlatitude winters and springs under wet conditions.

For these reasons, a physically based estimate of β which circumvents the prerequisite approximation of Q_h and Q_e is beneficial. An approximation based on readily available climatological data for a given time of year and day over a given surface would be especially useful in providing estimates of the energy balance parameters.

Not only can calculations of β for various surfaces and times of day and year provide estimates of the relative roles of Q_h and Q_e, but β can be used in combination with field-measured Q_h to estimate the more cumbersome Q_e as simply Q_h / β, and evaporation rates can be derived from this quantity. Alternatively, and more precisely, β estimates can be used with the direct measurement of net incoming radiation (Q*) and measurement of the rate of temperature change in the diurnally "active" layer (to approximate heat flux between the lake and the surface beneath it, Q_g) to give a more precise calculation of evaporation rates using

$$Q_e = \frac{Q^* - Q_g}{1 + \beta} \tag{2}$$

and

$$E = \frac{Q_e}{L_v} \tag{3}$$

where E is the mass of water evaporated (in kg s^{-1} m^{-2}), and L_v represents the latent heat of vaporization (2.5008 X 10^6 J kg^{-1}).

Purpose

The purpose of this research is as follows: 1) to review Roll's (1965) method of estimating β using standard meteorological data for use over a marine environment; 2) to use a newly available meteorological data set to document the air and water temperature properties of Louisiana's Lake

Pontchartrain (1993-95); and 3) to use these Lake Pontchartrain data to approximate β diurnally and seasonally using Roll's (1965) technique.

This analysis will determine the effect of water and atmospheric circulation on β, and whether this value is similar to that of other water bodies. For example, a representative estimate of β over the northern hemisphere ocean is 0.12 (Lewis 1995), and for all oceans $\beta \approx 0.11$ (Oke 1987). However, it should be noted that β will vary depending on ocean subsurface current behavior and type of air advected over the surface. In a lake of the size of Lake Pontchartrain, however, the role of such circulation features, particularly currents, is not as great as in a larger, more unconfined water body.

Study Area

Lake Pontchartrain is a brackish estuary covering 1580 km^2 in southeastern Louisiana (Figure 1). Maximum depth is approximately 4.9 m. The 'lake' was formed as past deltas of the Mississippi River practically detached an inlet of the Gulf of Mexico from the remainder of the Gulf, creating the tenth-largest inland body of water in the conterminous United States. The lake has tremendous economic and recreational importance to the people of southern Louisiana, but until recently, there was only limited meteorological coverage of the lake.

In the early 1980s, the National Weather Service (NWS) installed automated stations to measure and record hourly observations for a variety of atmospheric and lacustrine variables at sites in and around the lake (Figure 1), primarily for real-time use during severe weather events. Archiving of the data began in October 1992 by the Southern Regional Climate Center and the data set represents the most comprehensive archived collection available for Lake Pontchartrain. However, no attempts have been initiated to use the data to provide a climatology of the area or to approximate more detailed energy balance parameters over the area.

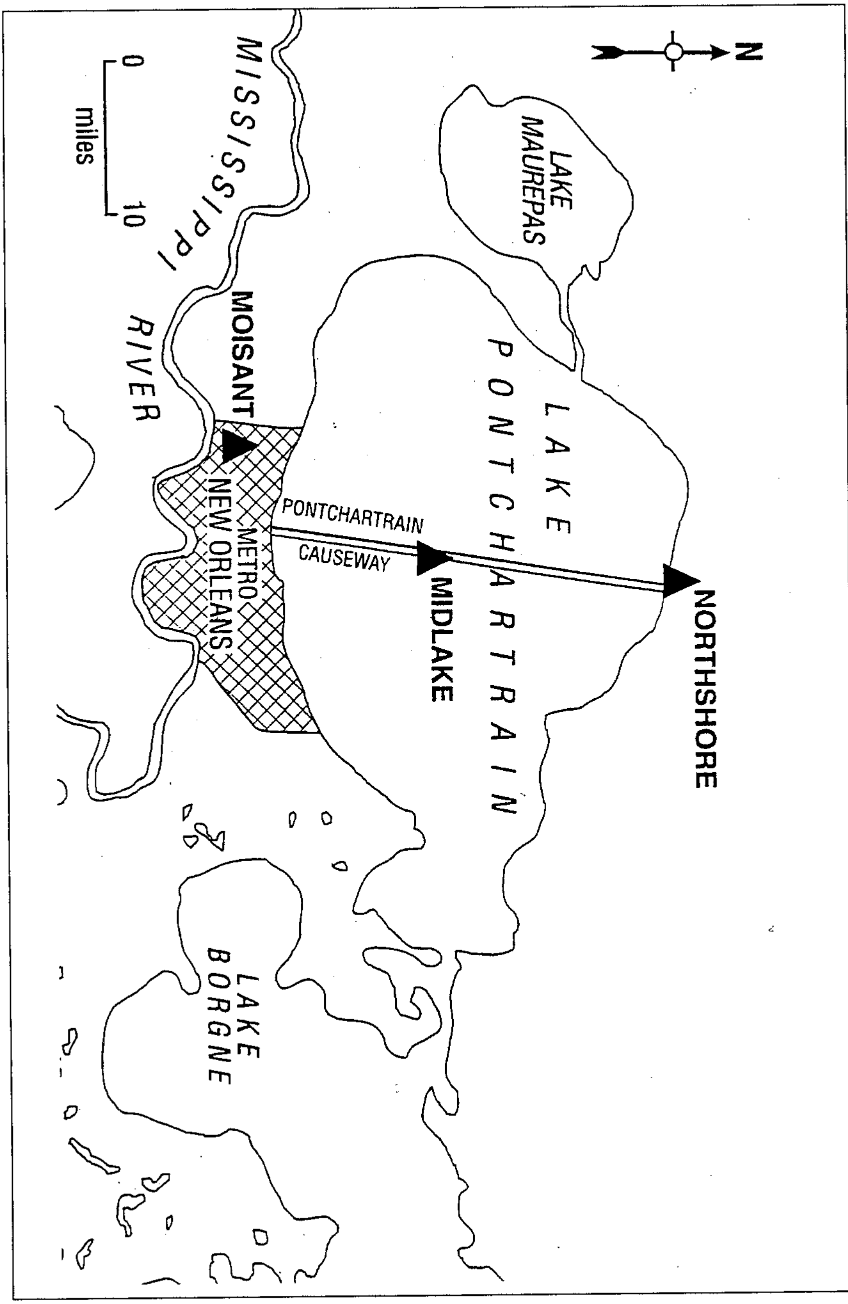

Figure 1. The study area.

Methods And Data

A substitute for the field measurements of Q_h and Q_e can be derived based on well-known "bulk" equations (Hsu 1988:112):

$$Q_h = \rho\, C_p\, C_h\, u_{10}\, (\theta_{sea} - \theta_{air}) \qquad (4)$$

and

$$Q_e = \rho\, L_v\, C_e\, u_{10}\, (q_{sea} - q_{air}) \qquad (5)$$

where ρ represents atmospheric density, C_p is the specific heat at constant pressure (1004 J kg^{-1} K^{-1}), C_h and C_e represent turbulent transfer coefficients for sensible and latent heat respectively, and u_{10} is the horizontal wind speed at the 10 m level. This method is advantageous over the direct measurement methods because of ease of application. Required atmospheric variables are often available from routine NWS observations. However, although u_{10} data are available for Lake Pontchartrain, they are susceptible to error resulting from the presence of the nearby Causeway Bridge and its associated traffic. Thus, it is convenient that for the computation of only the ratio of Q_h/Q_e (β), measurement of u_{10} is not required.

If air temperature (T_{air}) is taken instead of θ, which does not imply any appreciable error at low levels (Hsu 1992), and we assume that for unstable and near-neutral conditions over water bodies (*i.e.* $T_{air} \leq$), $C_h \approx C_e$ (*i.e.*, 1.13 x 10^{-3} *vs.* 1.15 x 10^{-3}, see Hsu 1988:113), combining Equations 4 and 5 gives

$$\beta \approx \frac{C_p\, (T_{sea} - T_{air})}{L_v\, (q_{sea} - q_{air})} \qquad (6)$$

The latter assumption is legitimate because C_h and C_e vary with roughness (which is a function of wave height and wind speed) and stability *in the same way* under near-neutral and unstable conditions. Moreover, since

$$q = \frac{0.62\,e}{p} \qquad (7)$$

where *e* represents vapor pressure and *p* is sea level atmospheric pressure, Equation 6 becomes

$$\beta \approx \frac{0.66\,(T_{sea} - T_{air})}{(e_{sea} - e_{air})} \qquad (8)$$

This is a form of Roll's (1965) Equation 5.10, where

$$e_{sea} = 6.1078 \times 10^{((7.5\,Tsea) / (237.3 + Tsea)} \qquad (9)$$

and

$$e_{air} = 6.1078 \times 10^{((7.5\,Td) / (237.3 + Td))} \qquad (10)$$

where temperature is in °C, pressure is in millibars, and T_d is dew point temperature (Hsu 1988:20-21). In this way, β can be approximated using only air, water, and dew point temperatures.

T_{air} data are used for three sites located adjacent to the Causeway Bridge (Figure 1): at the north shore, near the middle of the lake nine miles from the south shore, and approximately two miles inland from the south shore at New Orleans International Airport ("Moisant"). T_{sea} observations are collected at the former two sites. This allows for the identification of any local-scale temperature features such as an urban heat island signal, land/sea breeze thermal modification, and "continentality" effects produced by the "inland" site.

The "Midlake" site is used to represent Lake Pontchartrain in the energy balance analysis. Since T_d is not available at Midlake, the value at "Northshore" is used. However, to ensure that T_d is representative of the atmosphere over the lake, only the hours of unstable or near-neutral atmospheric conditions during which the wind direction at Midlake is between 140° and 230° are used in the energy balance analysis. For these hours, T_d at Northshore is assumed to be equal to that at Midlake. In addition, T_{air} and T_{sea} at Midlake are used in the calculation of β. Analyses of β are done by season and by time of day to identify fluctuations in the diurnal or intra-annual cycles.

Results and Discussion

Air Temperature

The diurnal march of T_{air} at the three sites is shown for January and February in Figure 2, and for July and August in Figure 3. Daily January/February minimum temperatures average 9-11°C, while afternoon highs range from 14° to 16°C. Figure 2 shows evidence that Lake Pontchartrain does indeed serve to moderate temperatures, as Midlake has the smallest daily temperature range. Furthermore, the "inland" site at Moisant warms far more than the other sites in the afternoon. Apparently, the northerly winds, which are relatively common in winter, collect sufficient moisture to prevent minimum temperatures at Moisant from falling as low as those at Northshore, despite its "inland" site.

Figure 3 reveals some interesting summer patterns. Morning low temperatures average 25-28°C, and mean afternoon highs are 30-32°C. As in winter, the summer diurnal temperature regime at Moisant shows some features of continentality compared to the other sites. Midlake demonstrates questionable values in summer mid-afternoon hours, possibly resulting from instrument exposure problems due to the proximity of the concrete bridge. This may be causing an overly conservative estimate of the number of unstable days, and may reduce estimated β by reducing Q_h under such conditions. However, since T_{air} is required for the estimation of β over the middle of the lake and Midlake provides the only such data, the data are used. However, caution should be exercised in interpreting results.

The summer afternoon temperature curve at Northshore is flat for several hours, suggesting that an afternoon sea breeze may be advecting enough moist air onshore to suppress maximum temperatures. Such a pattern is not found at Moisant, either because the site is too far inland to be affected by such a local-scale circulation or because the synoptic-scale southerly winds that commonly occur over the region are not ad-

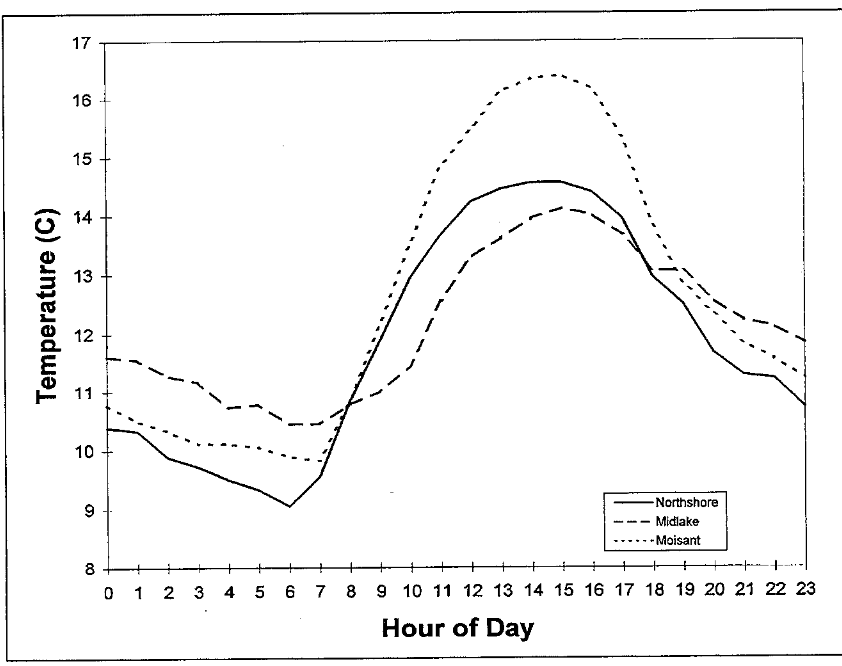

Figure 2. Average January-February air temperature by hour: Northshore, Midlake, Moisant, as reported by automated sensors.

vecting lake moisture over Moisant. This phenomenon should be investigated further in future research.

Water Temperature

Average T_{sea} values are shown by hour for the January/ February period in Figure 4 and for July/August in Figure 5. Comparison of these with Figures 2 and 3 shows that, as expected, there is a short time lag between T_{air} and T_{sea} curves, with T_{air} showing much greater extremes. Not surprisingly, Midlake shows a much smaller diurnal T_{sea} range than Northshore in Figures 4 and 5, and is cooler than Northshore in summer. More surprising, however, is the tendency for Midlake to be cooler than Northshore in winter. Furthermore, the results suggest that T_{sea} at

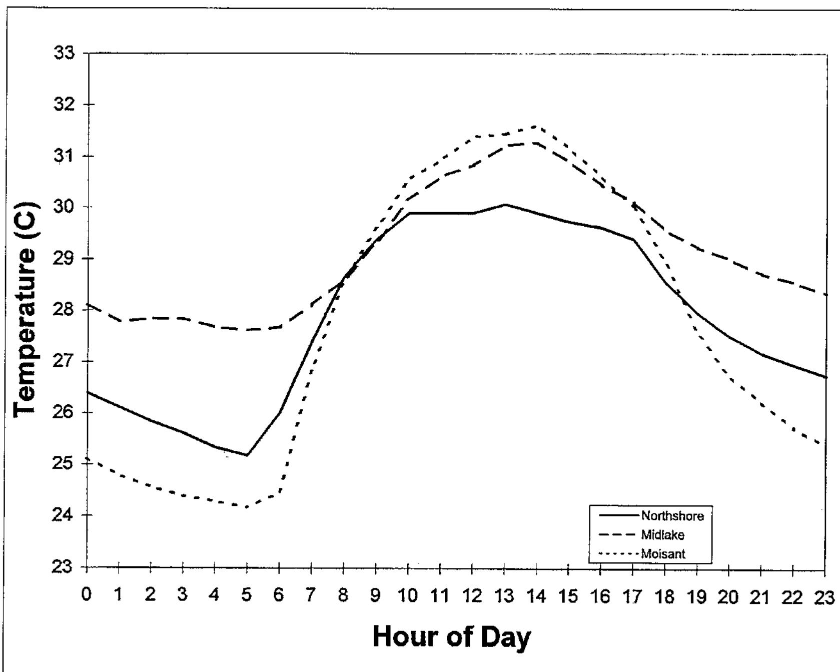

Figure 3. Average July-August air temperature by hour: Northshore, Midlake, Moisant, as reported by automated sensors.

Northshore averages nearly 32°C in summer, a value that seems too high, especially considering that the July-August T_{air} at Covington (11 miles north of Northshore) over the same period averages only 32.8°C. One possible explanation for this questionable water temperature is that the sensor may be extending above the water level during low tides at the shore. Another possibility is that the Northshore sensor is sufficiently near the lake bottom in very shallow water to be influenced by radiation incident upon it rather than "true" T_{sea}. As a result of this data problem, the energy balance is not computed at Northshore since this would require use of the spurious T_{sea} data. Furthermore, caution should be exercised in future uses of T_{sea} data from the Northshore site.

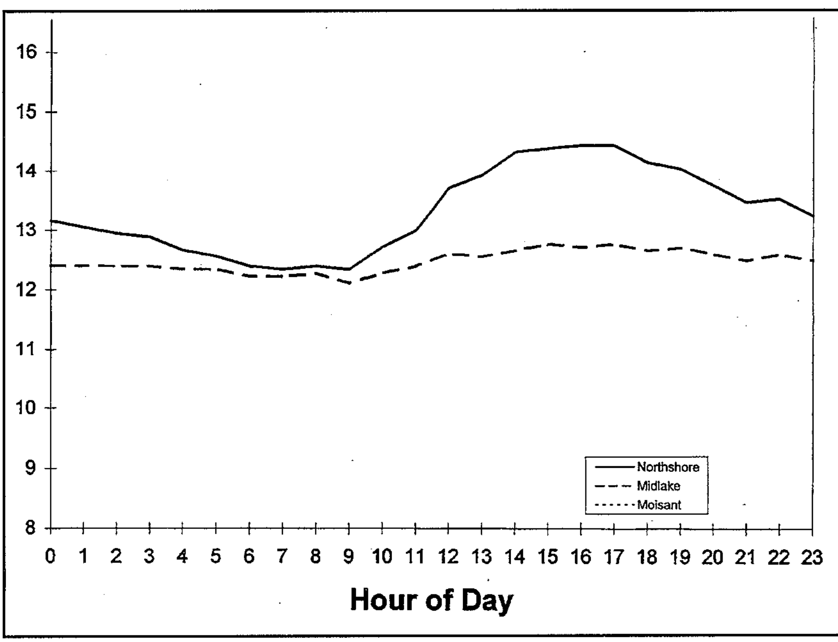

Figure 4. Average January-February water temperature by hour, as reported by automated sensors.

Bowen Ratio

During the 36-month period, wind direction at Midlake was between 140° and 230° in 5541 hourly observations, or 23.2% of the total available hours. Of these, 2415 hourly observations occurred during neutral or unstable conditions having available T_{air}, T_{sea}, and T_d. The mean value of β during these times was 0.10, with a standard deviation of 0.09. These values correspond well with those calculated for similar water bodies (*e.g.* Sverdrup 1951). The relatively high standard deviation may result from differences in the dew point depression, which affects Q_e. Attempts to derive estimates of β during times of high static stability were less successful, perhaps because the turbulent transfer coefficients for sensible and latent heat cannot be considered equal under such conditions, despite the fact that standard profile theory suggests that they should be equal.

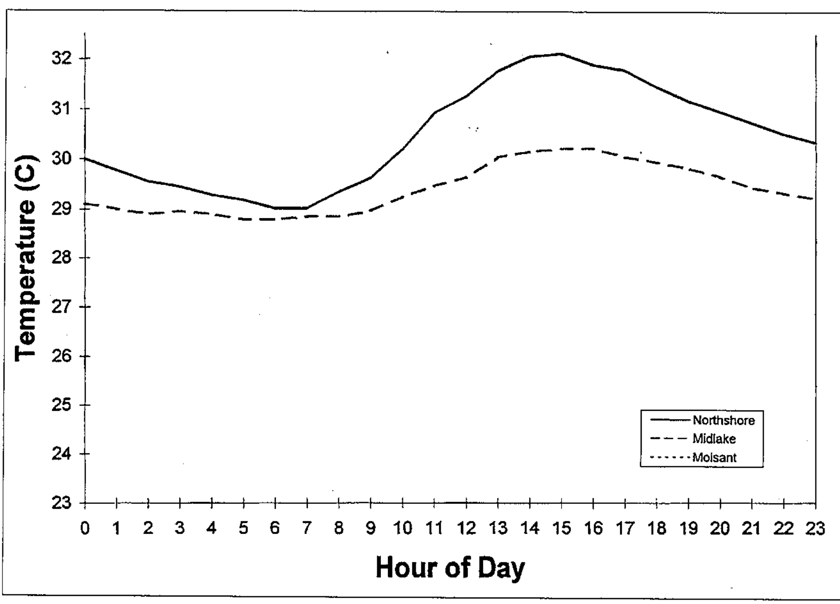

Figure 5. Average July-August water temperature by hour, as reported by automated sensors.

Seasonal analyses were conducted during hours when the atmosphere was not stable in order to determine whether the simplified equation is valid for all times of the year. Seasonal values are shown in Table 1. Results suggest that β remains remarkably consistent in the seasonal cycle with slightly greater values in winter, when potential evapotranspiration values are lowest.

In the diurnal cycle (Table 2), β is again consistently near 0.10, with similar standard deviations as before. Results show that during midday hours, it is relatively unusual that the atmosphere is cooler than the water, but when it is, sensible heating takes on a slightly greater role than during other times.

Table 1: β during unstable or neutral conditions by season.

Season	N	Mean β	Standard Deviation
Winter (D-J-F)	159	0.14	0.14
Spring (M-A-M)	668	0.11	0.11
Summer (J-J-A)	1122	0.10	0.07
Autumn (S-O-N)	881	0.10	0.08

Table 2: β during unstable or neutral conditions by time of day.

Observation Time (LST)	N	Mean β	Standard Deviation
2200 – 0300	1064	0.11	0.09
0400 – 0900	433	0.12	0.10
1000 – 1500	183	0.12	0.10
1600 – 2100	735	0.07	0.08

Conclusions

This study has used a newly available data set to describe the air and water temperature characteristics and Bowen Ratio (β) of Lake Pontchartrain. Although some exposure problems seem to exist with the sensors, the data are generally useful for environmental assessments of an important water body, about which little climatic information was previously available. Lake Pontchartrain seems to demonstrate some of the same local- to meso-scale atmospheric features that exist in other similar environments, such as the land/sea breeze phenomenon and the thermal modification of a large water body. Values of β are estimated to be between 0.10 and 0.14, and are remarkably consistent in the diurnal and seasonal cycles. Such information is useful to those requiring estimates of the energy balance in that the sensible or latent heat flux can be calculated using field methods, while the other turbulent flux can be derived based on the known flux and estimated β.

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