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Cooling and heating due to latent and sensible heat over the Yucatan continental shelf

J. HERNANDEZ–TELLEZ[1], J. ALDECO[1], and D. A. SALAS de LEON[2]

[1]*Instituto Oceanográfico del Golfo, Depto. de Física, Secretaría de Marina. Antiguo Acuario, Col. Centro, 91700 Veracruz, Ver.*

[2] *Instituto de Ciencias del Mar y Limnol., Lab. de Ocean. Física, UNAM. Apdo. Postal 70-305, 04510 México, D. F.*

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RESUMEN

A partir de datos meteorológicos y de temperatura superficial del mar (SST), obtenidos sobre la plataforma continental de Yucatán, durante los cruceros oceanográficos PLAYUC (del 6 al 17 de enero de 1990) y YUCPLA (del 25 de mayo al 4 de junio de 1990), se calcularon las areas de enfriamiento y calentamiento producidas por el flujo de calor latente (Q_e) y sensible (Q_t). Los cálculos se realizaron usando las ecuaciones aerodinámicas de flujo turbulento.

Durante PLAYUC la línea de SST - Ta = 0 (temperatura del mar menos del aire) dividió el área de estudio en dos regiones (este y oeste). Esto fue causado por dos nortes moderados. En el lado oeste la diferencia SST-Ta varió entre 1 y 4°C; en el lado inferior esta diferencia varió entre -1 y -3°C. Los valores de Q_e y Q_t para la región de enfriamiento al oeste fueron desde 160 hasta 260 W/m^2 y desde 10 hasta 60 W/m^2, respectivamente. En el lado este el contraste diurno de Q_e fue observado en tres áreas pequeñas. Al norte de Cabo Catoche la bruma presente sobre la región de débil surgencia, disminuyó la cantidad de enfriamiento por Q_e desde 30 a menos de 10 W/m^2 y la cantidad de calentamiento por Q_t a valores de alrededor de -5 a -6 W/m^2. El valor promedio de Q_e y Q_t sobre la plataforma durante PLAYUC fue de 140.92 y 14.88 W/m^2, respectivamente.

Durante YUCPLA se observó la influencia de aire húmedo y cálido del este. Dos líneas de SST - Ta = 0 dividieron diagonalmente la región en dos porciones, una noroeste y otra sureste. Para la región noroeste la diferencia SST - Ta varió entre -1 y 0°C; para la sureste entre -4 y 0°C. Durante este segundo crucero el enfriamiento fue menos fuerte y con un débil contraste espacial. En la región NW se observaron dos intrusiones de Q_e, una hacia la costa y otra hacia el mar; en la región SE también se observó una lengua orientada de norte a sur. Similarmente a lo que ocurrió en PLAYUC, la región de surgencia y bruma promovió un calentamiento debido a condensación ($Q_e < 0$). En la región NW, mostrando las variaciones diurnas, tres áreas bien delineadas de calentamiento y enfriamiento fueron observadas. Para este crucero el valor promedio de Q_e y Q_t fue de 66.63 y 0.36 W/m^2, respectivamente.

ABSTRACT

From meteorological data and sea surface temperatures taken during the oceanographic cruises PLAYUC (January 6 to 17, 1990) and YUCPLA (May 25 to June 4, 1990), conducted over the Yucatan Continental Shelf, the cooling and heating areas produced by the fluxes of latent (Q_e) and sensible heat (Q_t) were determined. The computation was done using the bulk aerodynamic equations.

During PLAYUC, the line of SST - Ta = 0 (sea surface temperature minus air temperature) divided roughly the study area into two regions (east and west). This was caused by two moderated northers. At the west side the difference SST - Ta was between 1 and 4°C, and at the lower east side the difference was between -1 to -3°C. The values of Q_e and Q_t for the cooling area at the west were from 160 to 260 W/m^2 and from 10 to 60 W/m^2, respectively. At the east portion the diurnal contrast of Q_e was observed at three small areas. North of Cabo Catoche a fog was present over a weak upwelling area, reducing the cooling rate due to Q_e from 30 to below 10 W/m^2 and the heating due to Q_t to values around -5 to -6 W/m^2. The average values during PLAYUC for Q_e and Q_t over the shelf were 140.92 and 14.88 W/m^2, respectively.

During YUCPLA, influence of moist and warm air from the East was observed. Two lines of SST - Ta = 0 divided the study area diagonally in two portions, northwest and southeast. The difference SST - Ta for the northwest portion was from -1 to 0°C and for the southeast from -4 to 0°C. During this second cruise the cooling was less intense and with weaker spatial contrast. At the NW portion two intrusions of Q_e were observed, one toward the coast and another going offshore. At the SE portion a north-to-south tongue was observed. Similar to what was the case during PLAYUC, the upwelling and fog area promoted a heating due to condensation ($Q_e < 0$). At the NW portion three well delineated regions of heating and cooling were observed, showing the diurnal variations. The average values during this cruise for Q_e and Q_t were 66.63 and 0.36 W/m^2, respectively.

Introduction

Because the physical processes controlling the temperature of the shelf waters exhibit strong seasonal variations (Aldeco and Hernández–Téllez, 1989), and in recognition to their importance in understanding climatic variations, the thermal studies are currently receiving much attention; however, such studies have largely been confined to open ocean areas seaward of the continental shelves (Etter *et al.,* 1985).

The temperature differences at the air–sea boundary are mainly caused by: long wave radiation and the latent and sensible heat fluxes (Simpsom and Paulson, 1980). The first one and the evaporation are the causes of the cooling of the sea surface (depending on the air temperature and absolute humidity). The last one, the sensible heat, will cool or heat the sea surface depending on whether the adjacent air is colder or warmer than the sea.

The diurnal variation of temperature in the surface layer is due to the heating of the absorbed solar radiation. Normally the range is small because the entrainment is dominant over the molecular thermal diffusion (Deschamps and Frouin, 1984).

According to Bunker (1980) the latent heat flux increases directly with the SST, this is because the moisture content of the molecular layer air above the sea surface is increased; when cold water is found (i.e., an upwelling area) the mixing ratio in the molecular layer air is reduced causing a diminution in the latent heat flux.

Extensives studies have been done on the oceanic heat balance of the Gulf of Mexico and the Caribbean (Colón, 1963; Hastenrath, 1968; Nowlin and Parker, 1974; Etter, 1976 and 1983; Etter *et al.*, 1987; Hernández–Téllez and Aldeco, 1990a and 1990b). Etter *et al.* (1987) discussed the monthly means of net heat flux (sensible plus latent) previously obtained by Bunker, Budyko, Hastenrath and Lamb and Colón (in: Etter *et al.*, 1987). The main point of all these researchers has been that the maximum value of net heat flux is found during the late autumn, being higher in the Gulf than over the Caribbean Sea.

Nowlin and Parker (1974), dealing with the effects of one norther (cold and dry continental air) over the NW continental shelf of the Gulf of Mexico bring about the modifications of the sub-surface water masses and the large losses of oceanic heat.

Adem *et al.* (1991) using a thermodynamic model in the mixed layer (60 m thick), with and without heat advection by currents, simulated the SST on a monthly basis, showing explicitly that the heat transport by currents is important for the temperature of the mixed layer (SST) in the Gulf. Their spatial and temporal scale is greater than ours.

Bunker (1976) dealing with the surface energy flux over the Atlantic Ocean, postulates that the water flowing around the Yucatan Peninsula encounters moderately moist and warm air, then gaining more heat in summer than is lost in winter, and also that the weak northers do not extract large amounts of heat. He further defines an "upwelling index" which represents the difference between the SST of the coastal water and that of the offshore adjacent water; his computations are made for the upwelling area located at 23°N and 88°W (north of Cabo Catoche; Figure 1).

Hernández–Téllez and Aldeco (1990a) computed the latent and sensible heat flux at a point north of Puerto Progreso, Yuc. (22°11'N and 89°41'W), describing the variations of two time series from different seasons. In the first period (March, 1988) the arriving of two moderated northers (separated by three days) were followed by surface cooling. This loss of heat was also observed in the parameterized heat storage of the water column (Aldeco and Hernández–Téllez, 1989). During the second period (May-June, 1988), between the 12 and 15 hours, the flux of moist and warm air was observed showing surface warming and heat storage of the water column. Hernández–Téllez and Aldeco (1990b) computed the heat balance and indicate that the water mass that is flowing toward their study point loss heat due to the entrainment with the upwelled waters from the area north of Cabo Catoche.

The Yucatan Continental Shelf is oceanographically interesting because: a) it is influenced by the waters of the Gulf of Campeche (south Gulf of Mexico) as well as by the Yucatan and Loop Currents; b) the effects on the circulation by the atmospheric forcing over such shallow area with a steep continental slope and; c) the upwellings that occurs over the area influence the biological and chemical processes of the region (González, 1975; López–Veneroni *et al.*, 1984; Espinoza, 1989; García, 1976; Ruíz–Rentería, 1979; Flores–Téllez and Villa–Aguilar, 1984).

Besides, it is economically important due to the fisheries that take place in the area.

The aim of the present study is to quantify and determine the surface cooling and heating areas generated by the exchange of latent and sensible heat over the Yucatan Continental Shelf during two cruises carried out in January and May of 1990.

Study area

The study zone is located on the Yucatan Continental Shelf, between the latitudes 21°30' and 24°N and the longitude 86°30' and 91°W . The area presents peculiar details due to its reefs, shoals, general shallowness and the steep slope at the easter border. Figure 1 shows the section lines, oceanographic stations numbers and respective cruise dates.

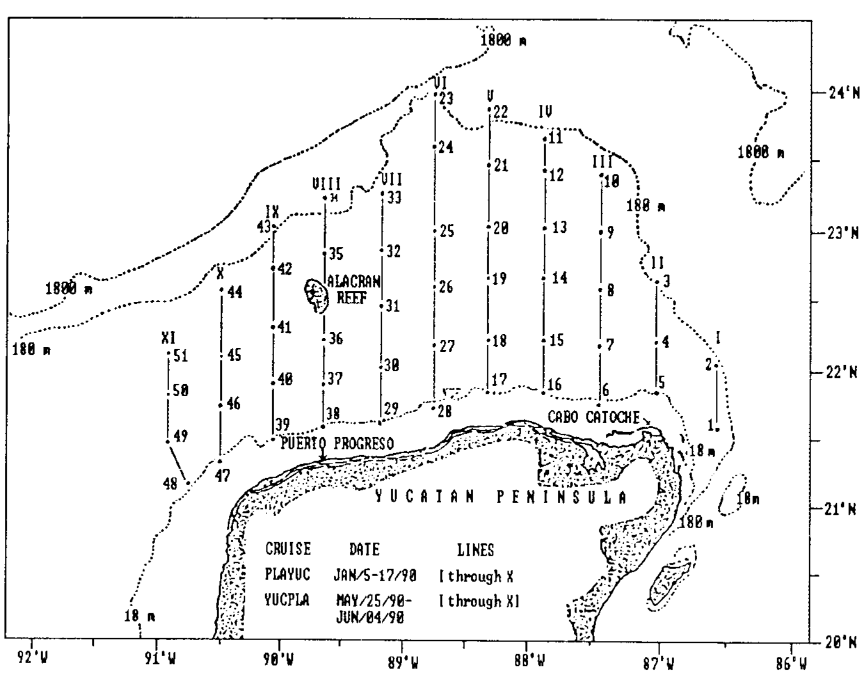

Fig. 1. Study area and lines of oceanographic stations for the PLAYUC and YUCPLA cruises.

Methodology

The two oceanographic cruises, PLAYUC and YUCPLA, were conducted on board the R/V *Justo Sierra*. The PLAYUC cruise took place from January 6th through 17th, and the YUCPLA cruise from May 25th through June 4th , both in 1990. During these cruises, meteorological and oceanographical parameters òn predetermined stations were taken.

The air temperature was taken with a hand psycrometer, on the windward side of the ship at 10 m above the sea surface. The sea surface temperature was taken over the side with a bucket thermometer and at the water intake located on the bow stem two meters below the ship's flotation line. The humidity values were determined by means of the wet and dry bulb temperatures. The air velocity was obtained from the ship's anemometer, at 15 meters above the sea surface.

As a first measure of the energy exchange between the sea and the atmosphere the temperature differences (SST–Ta) were computed. The cooling and heating areas were computed, using the aerodynamic equations for turbulent flow.

The equation for the latent heat of vaporization according to Gill (1982) is:

$$Q_e = \delta_a CeW(q_s - q_a)L_v$$

The equations for the sensible heat flux according to Friehe and Schmitt (1976) are:

$$\begin{array}{ll} Q_t = \delta_a Cp(0.0026 + 0.00086W\Delta T) & W\Delta T < 0 \\ Q_t = \delta_a Cp(0.0020 + 0.00097W\Delta T) & 0 < W\Delta T < 25 \\ Q_t = \delta_a Cp(0.000146W\Delta T) & W\Delta T > 0 \end{array}$$

where:

–Q_e and Q_t are given in W/m^2

–δ_a is the air density (kg/m^3)

–Cp is the specific heat at constant pressure (J/Kg^{o}K)

–W is the wind velocity (m/s)

–q_s and q_a are the specific saturation humidity at the sea level and of the air at 10 m above (Kg/Kg)

–L_v is the latent heat of vaporization (J/Kg)

–Ce is the aerodynamic coefficient of latent heat transference and is a function of W and ΔT ($\Delta T = Ta - SST$; the difference between the air and sea surface temperatures in ^{o}C).

The δ_a, Cp, q_s and q_a were computed according to Blanc (1985).

Results and discussions

From the PLAYUC and YUCPLA cruises the water temperature down to the 30m depth, indicated the presence of an upwelling area to the north of Cabo Catoche. Fog was observed there. During PLAYUC this upwelling process was however not fully active, the isotherms are bent but do not break at the surface; as was the case during YUCPLA.

Figures 2 through 4 show the presence of concentric areas (cores) and tongues with higher or lower values of the difference SST–Ta, the flux of latent heat (Q_e) and the flux of sensible heat

(Q_t). The figures also show with dots the oceanographic stations taken at nigth (between 18 and 06 hrs), and with squares those performed during the day (between 06 and 18 hrs).

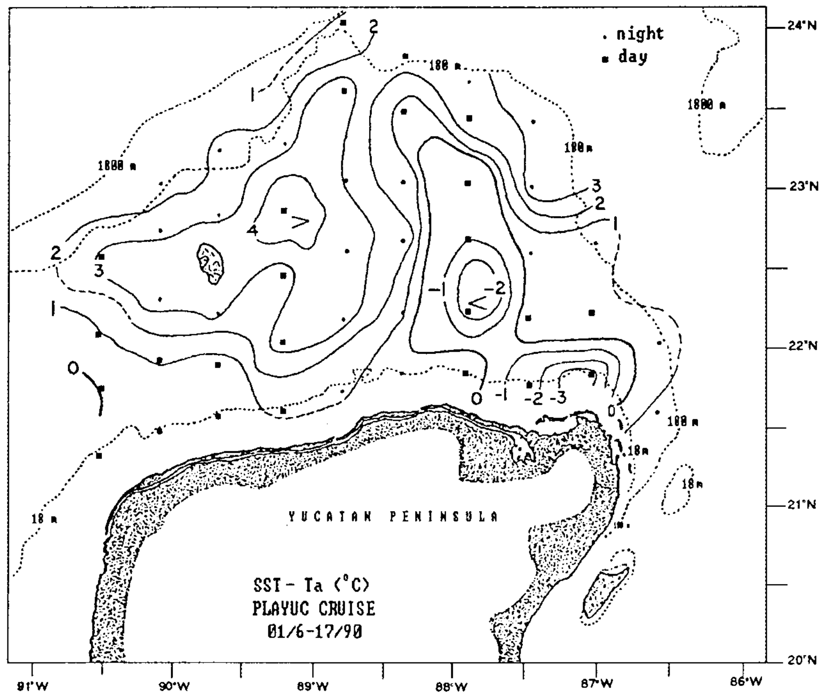

Fig. 2a. Temperature difference ($SST - Ta$) horizontal distribution for the PLAYUC cruise.

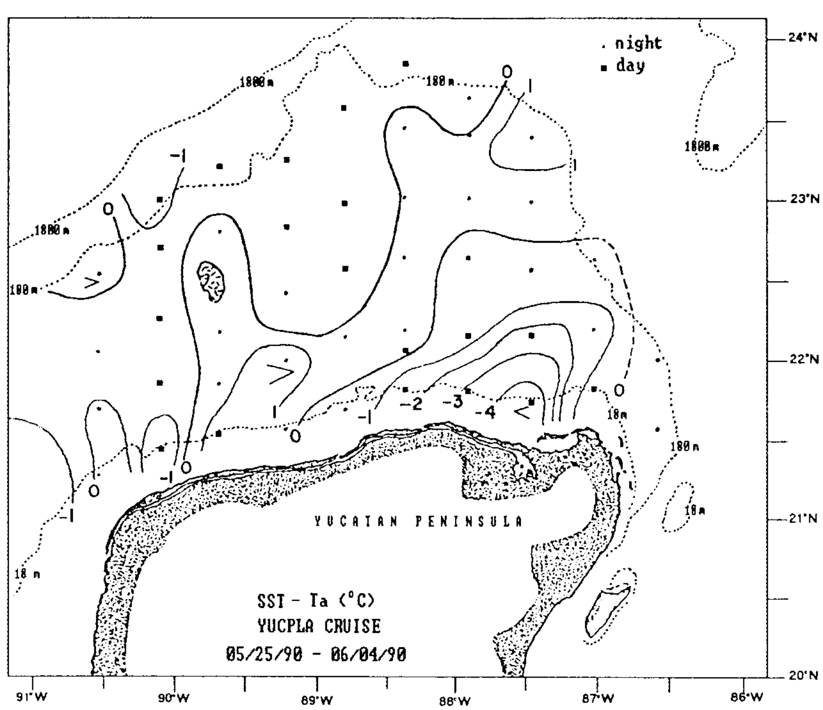

Fig. 2b. Temperature difference ($SST - Ta$) horizontal distribution for the YUCPLA cruise.

Table 1 shows mean fluxes of latent heat (Q_e), sensible heat (Q_t), and the net flux defined as $Q_e + Q_t$. For each cruise the average for all oceanographic stations is shown, giving positives or negatives values and the net flux. If Q_e is positive the flux is from the sea toward the atmosphere, cooling the sea due to heat loss. A negative value of Q_e means heat transfer by condensation (this process transfers energy in the form of sensible heat). The sensible heat flux toward or from the sea (heating or cooling) depends on the air temperature adjacent to the sea surface, positive for cooling and negative for heating.

Table 1.- Latent (Qe) and Sensible (Qt) heat fluxes summary, in W/m², for the PLAYUC and YUCPLA cruises.

PLAYUC CRUISE 01/6-17/90				YUCPLA CRUISE 05/25/90-06/04/90			
FLUXES (W/m²)	STATIONS 47	AVERAGE (POS OR NEG)	TOTAL AVERAGE	FLUXES (W/m²)	STATIONS 51	AVERAGE (POS OR NEG)	TOTAL AVERAGE
Qe	47 POS 0 NEG	140.92	140.92	Qe	47 POS 4 NEG	72.79 -5.76	66.63
Qt	44 POS 3 NEG	15.70 -4.95	14.88	Qt	31 POS 20 NEG	4.06 -5.14	0.36
Qe + Qt			155.70	Qe + Qt			66.99

During PLAYUC two cold fronts (northers) with moderate wind, arrived from the NW. During YUCPLA warm and moist wind from the east was frequently detected

On both cruises the study area was divided by the line of $SST - Ta = 0$ (equal sea surface and air temperatures). During PLAYUC this line separated a west and northeast part from a south east part (Figure 2a). During YUCPLA there were two parallel lines of $SST - Ta = 0$, extending from Puerto Progreso toward the 23°30'N and 87°30'W, that separated the NW portion from the SE portion (Figure 2b).

During PLAYUC (early winter), the values of $\Delta T(SST - Ta)$ were from 1 to 4°C at the west side, and between 1 and 3°C at the northeast ($SST > Ta$) portion. At the southeast area, the upwelling area, the values of $SST - Ta$ were from -1 to -3°C ($SST < Ta$; Figure 2a). The loss of heat due to Q_e at the west side lay between 160 and 260 W/m^2 (Figure 3a), and by Q_t the range was from 10 to 60 W/m^2 (Figure 4a). At the east, the diurnal contrast was evident in three small areas (Figure 3a) with Q_e values from 120 to 200 W/m^2 in the morning, from 100 to 40 W/m^2 before noon and between 100 and 120 W/m^2 at night. At the upwelling–fog area a diminution of the heat loss due to Q_e from 30 to less than 10 W/m^2 was caused by warm and moist air; consequently a gain of heat by Q_t from -5 to -6 W/m^2 occurred (Figure 4a). On the other hand, Table 1 shows that almost all the Q_e and Q_t values at the stations were positive (except 3 values at the upwelling area).

Adem *et al.* (1992) made the simulation of the annual cycle of the SST, Q_t and Q_e fluxes, the radiation balance and of the rate of oceanic heat storage; but only show their results for January and July. Comparing the January average latent heat flux (Q_e) value computed with the isolines simulated over the Yucatan Shelf, it is seen that the former mean value is lower (140.92 against 200 W/m^2); however, without considering the upwelling areas, the values computed here are in agreement with those simulated (values around 200 W/m^2). The same is for the average sensible heat flux (Q_t), the value computed here is lower (14.88 against 25 W/m^2).

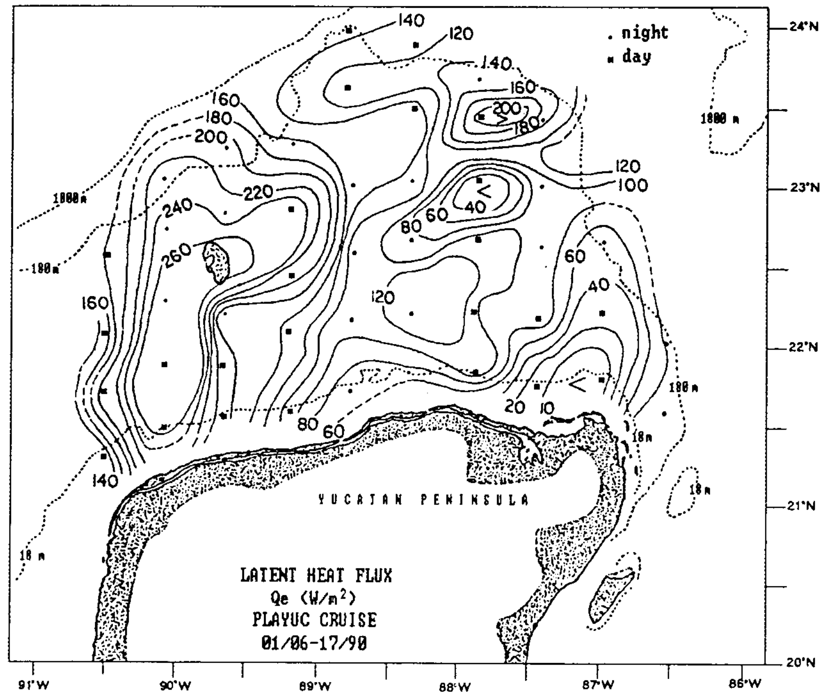

Fig. 3a. Latent heat flux horizontal distribution for the PLAYUC cruise.

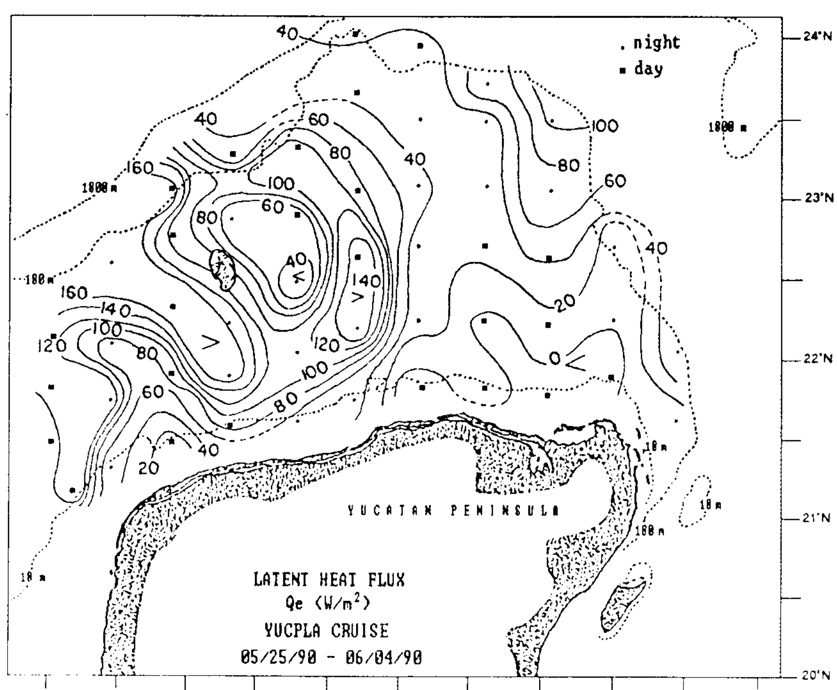

Fig. 3b. Latent heat flux horizontal distribution for the YUCPLA cruise.

During YUCPLA (late spring), to the NW portion and to the SE portion values of $SST - Ta$ from -1 to 0 and from -4 to 0°C, respectively, were observed; the contrast being greatest at the upwelling area as can be seen on Figure 2b. This figure also shows that, between the two lines of $SST = Ta$ almost all the oceanographic stations were taken at night. Figure 3b shows, to the left of the upper diagonal a conspicuous decrease in the heat loss due to Q_e compared with the west side of PLAYUC (Figure 3a). Also, above the upper diagonal, two tongues of Q_e were observed at the west side of the Alacran Reef, one toward the coast and another going offshore.

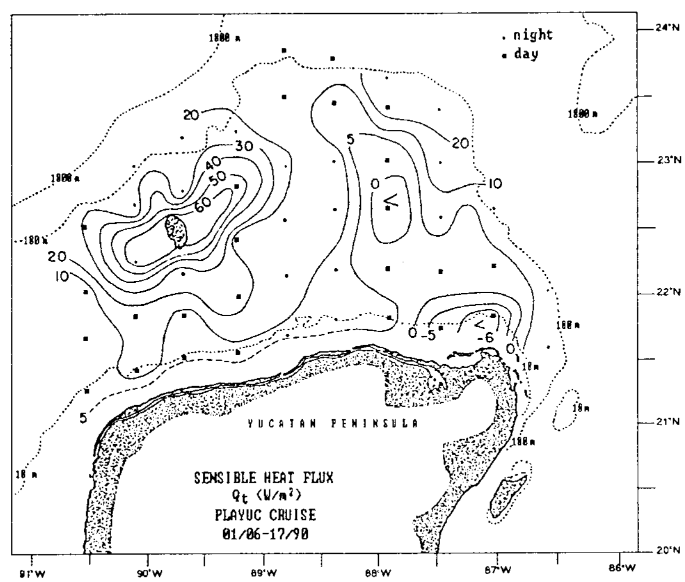

Fig. 4a. Sensible heat flux horizontal distribution for the PLAYUC cruise.

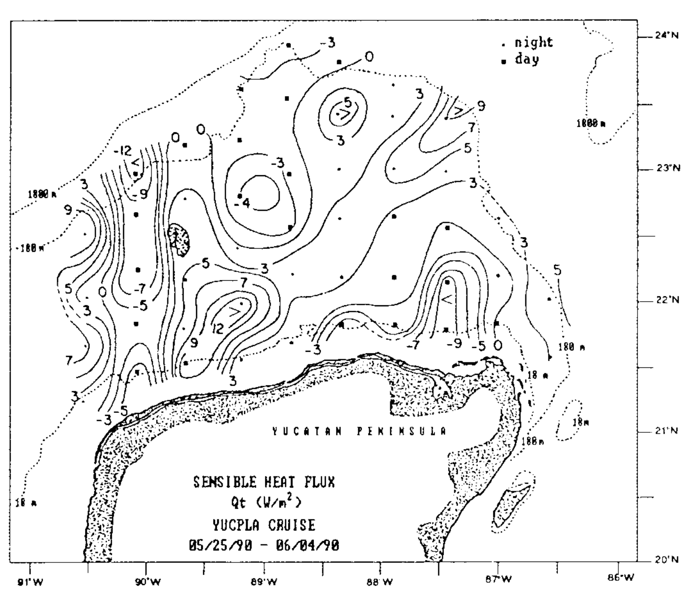

Fig. 4b. Sensible heat flux horizontal distribution for the YUCPLA cruise.

To the east of the Reef two areas, one from 100 to 40 W/m^2 (at dawn) and another from 120 to more than 140 W/m^2 (at dusk) were observed. Below the lower diagonal a tongue towards south was observed (Figure 3b). Similar to what was the case during PLAYUC, the upwelling area indicated a net gain of heat due to Q_t from -5 to more than -9 W/m^2 and a $Q_e < 0$ (Figures 4b and 3b). At three areas above the upper diagonal the solar effect was evident on the sensible heat flux, Q_t (Figure 4b). On the other hand, through the values of Q_e and Q_t (Table 1) the influence of upwelling and fog is evident. The great decrease of the positive values in relation to PLAYUC is also shown. Is further interesting to note that the net balance of Q_t over the area is close to zero during this cruise.

The comparison of the latent heat fluxes computed here with those simulated for July by Adem *et al.* (1992) shows that, without considering the influence of the upwelling areas, the values of the isolines of latent heat flux (Q_e) are in accordance with those simulated. The same is for the isolines of sensible heat flux (Q_t).

Conclusions

During PLAYUC the SST divided the study area into an east and west parts, and the line of $SST - Ta = 0$ is used as the limit between the two portions. On this occasion, two moderated northers affected mainly the west and northeast side of the area and caused the loss of oceanic heat in such a way that Q_e and Q_t were greater at these areas than at the southeast portion. The diurnal contrast of Q_e was particularly well depicted on three small areas over the east portion. At the area of weak upwelling and fog, warm and moist air was found to reduce the heat loss due to Q_e, and also a small gain of Q_t through the condensation heat was detected. The Q_e increases toward west from the upwelling area to reach it maximun in the western area, to the north and south of the Alacran Reef. Over the whole area, for this cruise the total average of Q_e was 140.92 W/m^2 and of Q_t was 14.88 W/m^2.

During YUCPLA warm and moist air was present over whole study area. Two parallel lines of $SST - Ta = 0$ divided diagonally the area and the value of $SST - Ta$ was less than zero over most of the area. The distribution of Q_e is caracterized by two tongues or pockets over the west portion, and one similar tongue over the E portion, wich may be caused by currents or eddies. From the upwelling area and toward the coast a net gain of Q_t and Q_e was observed. At the W portion the cooling and heating processes were evident. It is noteworthy that there is a decrease of the cooling during this period in relation to PLAYUC. The diurnal effects were also observed during this cruise. The total average of Q_e was 66.63 W/m^2 and of Q_t was 0.36 W/m^2, both values lower than those of PLAYUC.

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