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Effects of Cold Air Outbreaks on Evaporation and Heat Loss from Three Regions in the Gulf of Mexico

S. A. Hsu

Simultaneous hourly measurements of atmospheric pressure; wind speed; and air, sea-surface, and dew-point temperatures from three regions in the Gulf of Mexico in 1996 are incorporated in the analysis of sensible and latent heat fluxes and the evaporation rate from the Gulf to the atmosphere. The three regions included in the study are the deep western Gulf, the northern Gulf continental shelf break near De Soto Canyon, and the northern Gulf nearshore environment at Grand Isle, LA. After the case study of a severe cold air outbreak is presented, monthly variations of evaporation and heat fluxes are investigated. It is found that on an annual basis the sensible heat flux is nearly the same between the nearshore and the shelf break regions. For the latent heat flux, the northern shelf break and deep western Gulf are nearly equal and are higher than the northern nearshore region. Also, the evaporation rate and the rainfall amount are approximately in balance in the northern Gulf nearshore environment.

Cold fronts and the cold air outbreaks that follow the fronts are the meteorological forcing agents affecting many air–sea interaction mechanisms, including evaporation and heat loss from the Gulf of Mexico to the atmosphere (e.g., Henry, 1979; Huh et al., 1984; Mortimer et al., 1988; Konrad, 1996). This study examines the spatial and temporal variability of these processes on the event scale and seasonal scale.

On 18 Dec. 1996, a cold front entered the northern Gulf. On the next day (Fig. 1), while this front proceeded toward south Florida, the freezing line (0 C) associated with this strong cold air outbreak moved over the northern Gulf coast where it lingered for 3 d. Due to the tight pressure gradient behind the front (Fig. 1), northerly winds reached 10 to 15 m/sec over the northern Gulf.

From 18–20 Dec. 1996, simultaneous hourly measurements at three locations in the Gulf (Fig. 2) were made available from the National Data Buoy Center (NDBC, Stennis Space Center, MS). These data included atmospheric pressure; wind speed and direction; and air, sea, and dew-point temperatures. This cold air outbreak episode provided a good opportunity to estimate both latent and sensible heat fluxes as well as evaporation from the Gulf to the atmosphere. A further purpose of this study is to extend these estimates to monthly averages for 1996.

METHODS

At the air–sea interface under unstable conditions, when the sea is warmer than the air, the sensible heat flux, H_s, is defined as (Smith, 1980:eq. 4)

$$H_s = \rho C_p C_T (T_{sea} - T_{air}) U_{10} \qquad (1)$$

where ρ is the air density and C_p is the specific heat capacity at constant pressure, T_{sea} is the seawater "bucket" temperature in the wave-mixed layer, T_{air} is the mean air temperature at the 10-m reference height, C_T is the sensible heat flux coefficient, and U_{10} is wind speed at the 10-m reference height.

The latent heat flux, H_l, is defined as (Roll, 1965)

$$H_l = L_T E = L_T C_E \rho \, (q_{sea} - q_{air}) U_{10} \qquad (2)$$

where L_T is the latent heat of vaporization, E is the evaporation rate, C_E is the latent heat coefficient, and q_{sea} and q_{air} are the specific humidities for the sea and air, respectively.

At the sea surface, the specific humidity, q_{sea}, is related to the saturation vapor pressure, e_{sea}, through (Hsu, 1988:20–21)

$$q_{sea} = 0.62 \, (e_{sea}/P) \qquad (3)$$

where

$$e_{sea} = 6.1078 \times 10^{[7.5\, T_{sea}/(237.3 + T_{sea})]} \qquad (4)$$

and P is the atmospheric pressure.

Similarly,

$$q_{air} = 0.62 (e_{air}/P) \qquad (5)$$

where

$$e_{air} = 6.1078 \times 10^{[7.5\, T_{dew}/(237.3 + T_{dew})]} \qquad (6)$$

and T_{dew} is the dew-point temperature in degrees C.

Since we are dealing with heat loss from the

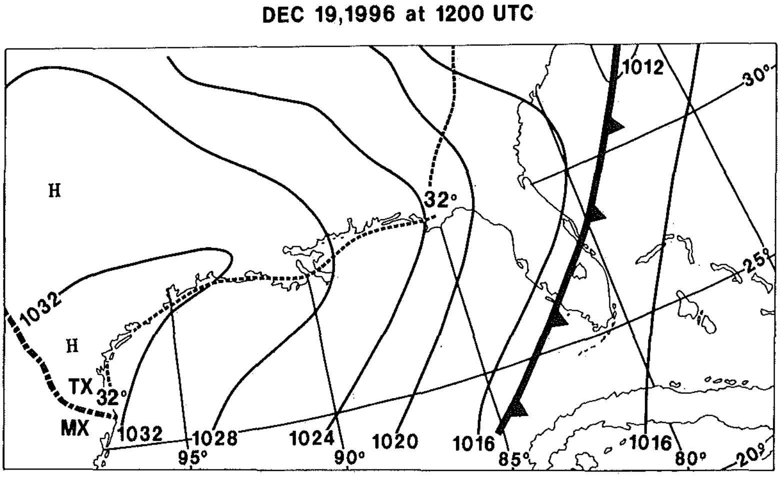

Fig. 1. A simplified weather map for 19 Dec. 1996 at 6 a.m. CST (or 1200 UTC). Note the freezing line (0 C) along the northern Gulf coast. The unit of atmospheric pressure is millibar.

sea to the air (i.e., when $T_{sea} > T_{air}$), the following values are used in our computations: $C_T = 1.13 \times 10^{-3}$ (Large and Pond, 1982); $C_E = 1.12 \times 10^{-3}$ (Smith et al., 1994); $\rho = 1.2$ kg/m^3; $C_p = 1{,}004$ J/kg; and $L_T = 2.5 \times 10^6$ J/kg (Hsu, 1988:239). Note that a latent heat flux of 1 W/m^2 is equivalent to an evaporation rate of 3.56×10^{-3} cm/d (Colon, 1963).

Hourly measurements of P, U, T_{sea}, T_{air}, and T_{dew} are available in 1996 from the NDBC. Therefore, estimates of H_s, H_l, and E may be made from the equations listed above. Because only buoy 42002 had a wind sensor located at 10 m, U_{10} values for the other stations were computed according to Hsu (1988:202, table 8.5)

RESULTS

Results of the heat loss from sensible and latent fluxes, $H_s + H_l$, estimated for the three regions in the Gulf for our case study (Fig. 2) are plotted in Figure 3. It can be seen that $H_s + H_l$ from the shelf break region, as represented by buoy station 42040, is similar in magnitude to that for the deep Gulf represented by buoy 42002. On the other hand, the magnitude of $H_s + H_l$ from the nearshore environment, as

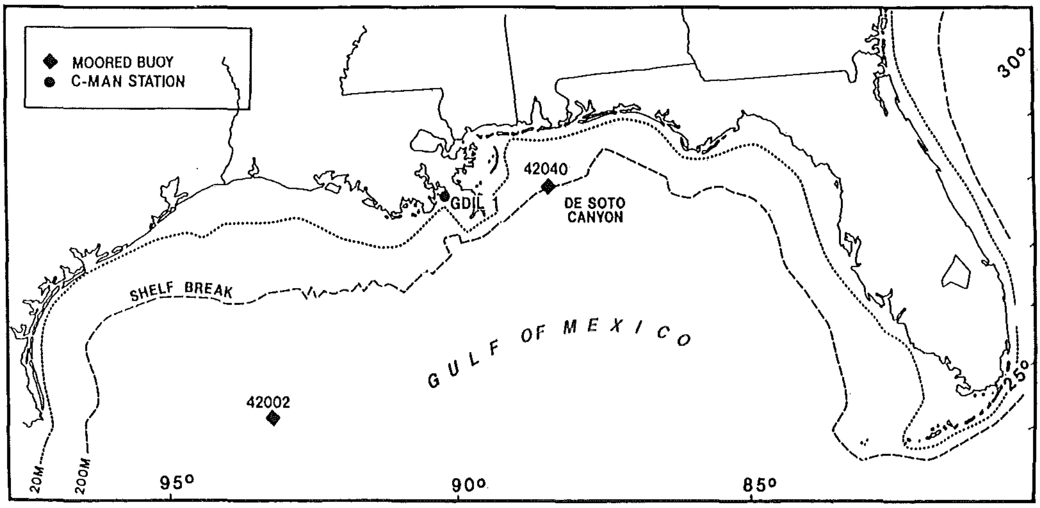

Fig. 2. Stations with simultaneous air, sea, and dew-point temperatures along with P and U measurements used in this study.

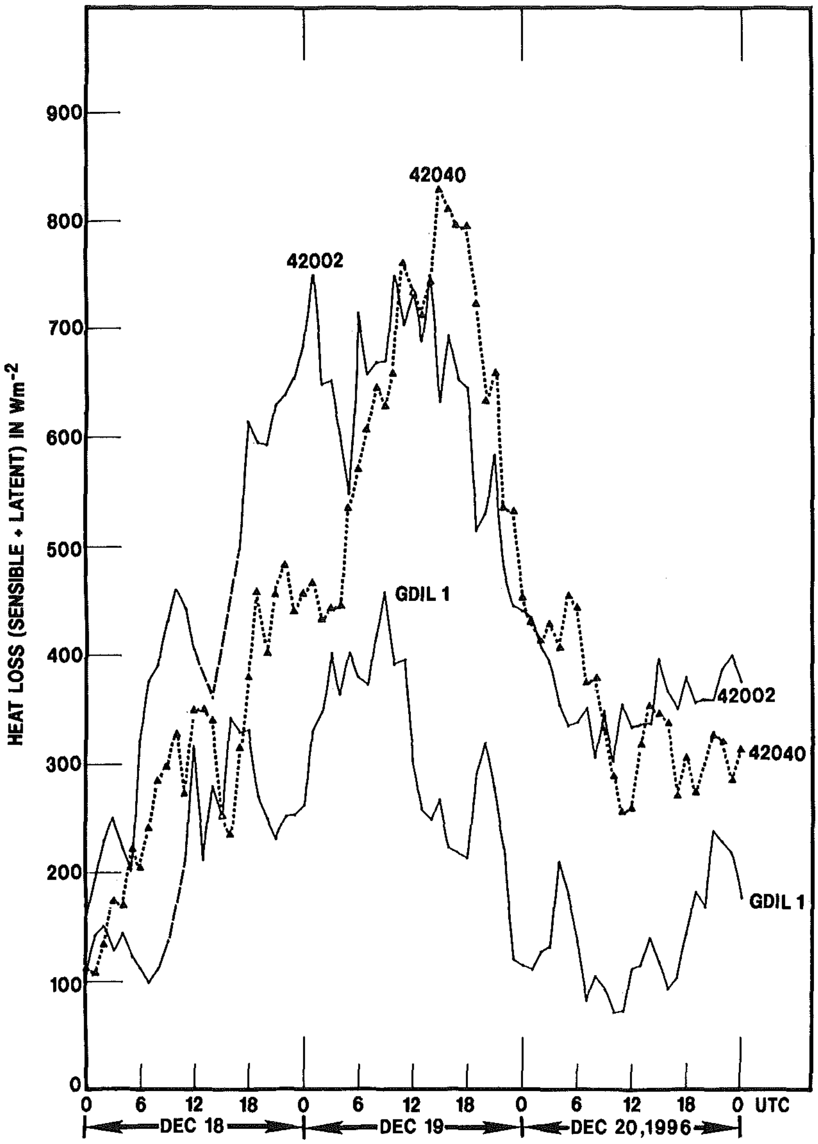

Fig. 3. The time series of heat loss ($H_s + H_l$) during the cold air outbreak from 18–20 Dec. 1996 over the northern Gulf of Mexico.

represented by C-MAN station GDIL1, is approximately one-half that of the deep Gulf value. Note that the large magnitude of $H_s + H_l$ around 800 W/m^2 is comparable to that obtained by Murty (1976:fig. 14) from the East China Sea under severe weather outbreak conditions. Based on Figure 3, the average heat loss during the peak day of 19 Dec. 1996 at buoy 42002 was approximately 643 W/m^2. Since the monthly average heat flux ($H_s + H_l$) for Dec. 1996 at this station was 202 W/m^2, the contribution of this single day of our cold air outbreak case was 643/(202 × 31 d) ≈ 10%. Similar results (7.5%) were derived for station GDIL1. During the winter season, the passage of two or three cold fronts a month of multiple days duration is not uncommon. Thus, the magnitude of influence of these seasonal weather systems is clearly implied.

Simultaneous hourly measurements of T_{air}, T_{sea}, T_{dew}, P, and U made by the NDBC from our three Gulf regions during 1996 were employed to extend our estimates over the year. Our results are summarized in Figure 4 and Tables 1–3 for sensible and latent heat fluxes and evaporation rates, respectively. The coef-

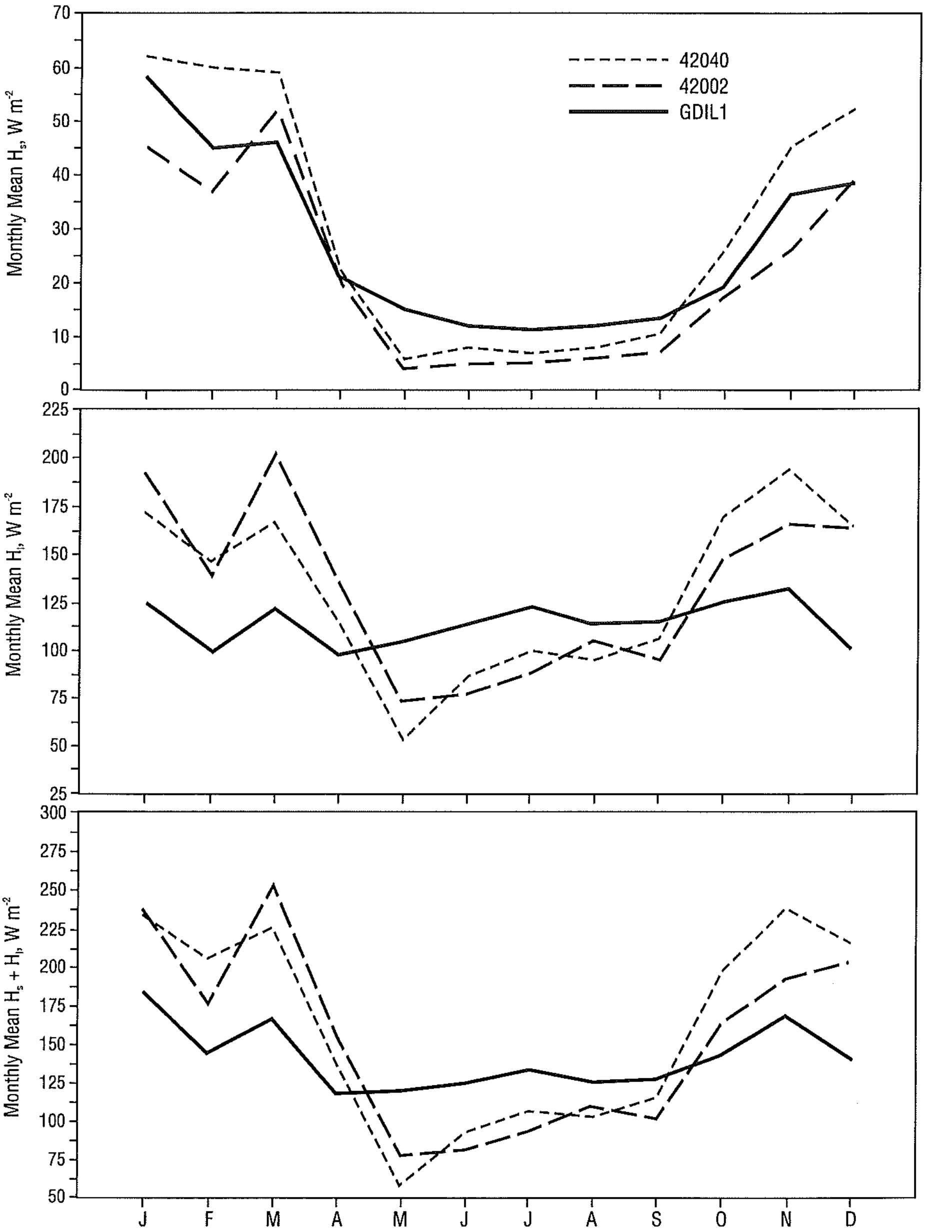

Fig. 4. Monthly distribution of 1996 mean sensible, latent, and total heat fluxes (top, middle, and bottom panels, respectively) based on Tables 1 and 2.

ficient of variation (COV), defined as the ratio of the standard deviation to the mean (Spiegel, 1961:73), is presented since it is useful in comparing distributions where units are different, such as heat flux in W/m^2 and evaporation in cm/d.

Table 1 shows that on an annual basis both nearshore water (GDIL1) and shelf break (42040) regions exhibit slightly higher sensible heat flux, H_s, compared to the deep Gulf (42002). The maximum H_s occurred in Jan. for both GDIL1 and 42040, and the minimum occurred in July for GDIL1 and in May for 42040. Maximum H_s for the deep western Gulf (42002) occurred in March and the minimum in May. The largest COV occurred in the deep western Gulf and the smallest at the nearshore region. The monthly distribution of latent heat flux, H_l, is assembled in Table 2. It is surprising to see that, on an annual basis, H_l in the shelf

TABLE 1. Monthly variations of the sensible heat flux for 1996 from the three regions in the Gulf as shown in Figure 2.

Month	H_s (W/m²)		
	GDIL1	42040	42002
Jan.	58	62	45
Feb.	45	60	37
March	46	59	52
April	21	22	20
May	15	6	4
June	12	8	5
July	11	7	5
Aug.	12	8	6
Sept.	13	10	7
Oct.	19	26	17
Nov.	36	45	26
Dec.	38	52	39
Annual mean	27	30	22
SD	16	23	18
COV[a]	59%	77%	82%

[a] COV, coefficient of variation (= SD/mean).

TABLE 2. Monthly variations of the latent heat flux for 1996 from the three regions in the Gulf as shown in Figure 2.

Month	H_l (W/m²)		
	GDIL1	42040	42002
Jan.	125	172	193
Feb.	99	146	140
March	121	166	201
April	97	115	136
May	104	52	73
June	113	86	76
July	122	99	88
Aug.	113	94	103
Sept.	114	105	94
Oct.	124	169	146
Nov.	131	193	164
Dec.	99	163	163
Annual mean	114	130	131
SD	12	44	44
COV	11%	34%	34%

break region (130 W/m²) was nearly equivalent to that in the deep western Gulf (131 W/m²). It is also intriguing to find that the standard deviation of H_l (= 44 W/m²) and the COV (= 44%) for both shelf break and deep Gulf regions are the same.

Annual values of total heat flux for all three locations were found to be comparable (~ 150 W/m²). On the other hand, greater variation is seen at the shelf break and deep western Gulf stations, particularly for the winter season H_l contribution, as shown in Figure 4. This is an indication of the more rapid response of the shallow nearshore waters, compared to the shelf break and deep Gulf where the enormous heat capacity of the Gulf is prominent. Since the difference in total heat flux between the shelf break (buoy 42040) and the deep western Gulf (buoy 42002) is smaller than that between the shelf break and near shore (GDIL1), it is inferred that the baroclinicity is larger between the shelf break and nearshore waters. This suggests that the more favorable region for fronto- and cyclogenesis in the Gulf is along the shelf break, as suspected by Hsu (1992).

Monthly evaporation rates from the Gulf to the atmosphere are synthesized in Table 3. Since evaporation is related to latent heat flux through Equation 2 with the latent heat of vaporization as a constant, the results of evaporation given in Table 3 are similar to those of latent heat flux in Table 2. It can be seen that the evaporation rate along the shelf break is nearly the same as that from the deep western Gulf. It is interesting to note that, on a yearly basis, from the nearshore water where E = 0.40 cm/d, to the shelf break where E = 0.46 cm/d, to the deep western Gulf where E = 0.47 cm/d, the mean E for the three regions as a whole is 0.44 cm/d. Furthermore, the largest monthly variation of E occurred along the shelf break (42040) with a maximum of 0.69 cm/d in Nov. and a minimum of only 0.19 cm/d in May. The smallest variation in monthly E

TABLE 3. Monthly variations of the evaporation rate for 1996 from the three regions in the Gulf as shown in Figure 2.

Month	E (cm/d)		
	GDIL1	42040	42002
Jan.	0.45	0.61	0.69
Feb.	0.35	0.52	0.50
March	0.43	0.59	0.72
April	0.35	0.41	0.48
May	0.37	0.19	0.26
June	0.40	0.31	0.27
July	0.43	0.35	0.31
Aug.	0.40	0.33	0.37
Sept.	0.41	0.37	0.33
Oct.	0.44	0.60	0.52
Nov.	0.47	0.69	0.58
Dec.	0.35	0.58	0.58
Annual mean	0.40	0.46	0.47
SD	0.04	0.16	0.16
COV	10%	35%	34%

values occurred in the nearshore water region at GDIL1, where E = 0.40 cm/d or 146 cm/yr. According to Monthly Climatic Data for the World (U.S. National Climatic Data Center, 1996), the total rainfall in New Orleans, LA, in 1996 was approximately 135 cm. Since the difference between the estimated evaporation and measured rainfall is only 7.5%, we conclude that the evaporation and rainfall in this northern Gulf nearshore environment are approximately in balance.

CONCLUSIONS

The vigorous equatorward movement of cold polar air associated with cold air outbreaks affects the Gulf of Mexico in many ways. This paper deals with the sensible (H_s) and latent (H_l) heat flux and evaporation losses from the Gulf to the atmosphere. A case study of a single cold air outbreak is provided. During this event, it was found that the sensible and latent heat loss from the continental shelf break area was nearly the same as that from the deep western Gulf, while heat loss from the nearshore environment was only half as much.

Simultaneous hourly measurements of air, sea, and dew-point temperatures, along with atmospheric pressure and wind speed, from three regions in the Gulf in 1996 further indicate that, on a yearly basis, the nearshore and shelf break regions have similar values of H_s. The northern shelf break and deep western Gulf have nearly equal values of H_l, which are higher than those for the northern nearshore region. This implies greater baroclinicity between the shelf break and near shore and, thus, a more conducive location for fronto- and cyclogenesis. An estimation of evaporation shows that that rainfall and evaporation rate in the northern Gulf nearshore environment are nearly in balance.

The presence or absence of loop current intrusions in the northeastern Gulf and loop current rings in the northwestern Gulf may bias estimates for a single year. Statistical analysis should be performed using time series of decadal scales or longer. However, since humidity measurements in the Gulf only became available in 1996, this study presents a beginning view, which can be refined as more data are obtained.

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