Air Mass Modification over the Eastern Gulf of Mexico as a Function of Surface Wind Fields and Loop Current Position

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ABSTRACT

The effects of surface wind patterns and Loop Current position on surface distributions of latent and sensible heat fluxes in the eastern Gulf of Mexico are demonstrated. Mean monthly fields of these fluxes computed from data collected during February 1975 and February 1976 are computed. The wind fields of February 1975 and 1976 are decomposed into two different modes, a north-wind mode associated with winter outbreaks of dry cold continental air masses and a trade-wind mode associated with advection from the south of warm moist maritime air. The distributions of sensible and latent heat fluxes are different for each mode, with both heat fluxes considerably larger over the northern Gulf, in particular, during times of the northerlies. However, during these two months, trade-wind days are more numerous and the mean monthly flux patterns reflect this preponderance. A simple model of the effect of extreme Loop Current configurations and the associated sea surface temperature distributions on air parcels traversing the Gulf below the inversion layer is presented. Total changes in air parcel temperature and specific humidity are shown to depend on the configuration of the Loop Current. Parcels which traverse the Gulf and cross the U.S. coastline between Louisiana and Florida during the time of a deep northern Loop intrusion have 1.3°C higher temperatures and 1.0 g kg^{-1} greater specific humidities than parcels which cross the Gulf during a shallow Loop intrusion.

1. Introduction

Northward flow of air from the Gulf of Mexico supplies both latent and sensible heat to the continental United States. Results from studies of atmospheric fluxes of water vapor, latent heat and sensible heat show that the Gulf is a source of a portion of this energy. For instance, using a dataset collected during the winter of 1960 Hastenrath (1966) shows that water vapor is added to air parcels which traverse the Gulf. He attributes the increase in water vapor to an excess of evaporation over precipitation. Franceschini (1976), using a three year dataset, also finds an average winter divergence of latent heat flux over the Gulf, suggesting that the results of Hastenrath (1966) are representative of the norm rather than anomalies. Similarly, Henry and Thompson (1976) find that continental air masses that traverse the Gulf from north to south also experience an increase in latent and sensible heat.

As indicated by Franceschini (1954), Hastenrath (1966), and Henry and Thompson (1976), sensible and latent heat fluxes through the sea surface are one of several factors responsible for modifications of air masses traversing the Gulf. In turn, the distribution of sea surface temperature (SST) affects the intensity of these surface fluxes. In the eastern Gulf, surface ocean circulation strongly influences SST distribution (Maul, 1977, for instance). In particular, the Loop Current, the dominant circulation feature in the eastern Gulf, transports warmer tropical waters from the Yucatan Channel into the interior of the eastern Gulf and then out of the Straits of Florida. The position of this looplike feature varies seasonally and interannually (Molinari, 1980; Sturges and Evans, 1983, for instance). As will be shown, SST changes associated with the Loop can be as large as 3° to 4°C. Thus, interannual variability in the position of the Loop could be a cause of interannual variability in air mass modification.

The relation of the surface circulation, SST distribution and surface winds of the eastern Gulf of Mexico to variability in sensible and latent heat fluxes will be examined herein. The dominant role of the surface wind distribution in establishing surface latent and sensible heat distributions is demonstrated. Simple models showing the effect of different Loop Current configurations on the surface fluxes are then presented. These estimates show that the position of the Loop Current can influence the degree of modification of air parcels traversing the Gulf.

2. Data analysis

Sensible, Q_S, and latent, Q_E, heat fluxes can be computed from oceanic and atmospheric data using the following bulk aerodynamic formulas from Hastenrath and Lamb (1978),

$$Q_E = \rho C_D L (q_s - q_a) u, \quad (1)$$

$$Q_S = \rho C_D C_p (T_s - T_a) u \quad (2)$$

where

ρ density of air = 1.175 kg m^{-3},
C_D exchange coefficient
C_p the specific heat at constant pressure = 1.012 KJ kg^{-1} °C^{-1},
T_s sea-surface temperature (°C),
T_a air temperature (°C),
u wind speed (m s^{-1}),
L latent heat of vaporization = $(2484 - 2.39 \times T_s)$ KJ kg^{-1},
q_s saturation specific humidity (g kg^{-1}) at T_s is given by an expression from List (1949), and
q_a specific humidity (g kg^{-1}) at T_a.

A major shortcoming in applying these formulas is the uncertainty in selecting the exchange coefficients. The coefficients are different for latent and sensible heat and also vary as functions of the stability of the air column (higher for unstable conditions, lower for stable conditions) and wind speed (increase with wind speed). For instance, Bunker (1976) quotes values of latent heat exchange coefficients ranging from 1×10^{-3} to 1.6×10^{-3} and sensible heat exchange coefficients ranging from 0.9×10^{-3} to 1.5×10^{-3} at the moderate wind speeds typically observed over the eastern Gulf. Blanc (1985) summarizes these difficulties by noting that "There is no single, universally accepted bulk transfer coefficient scheme." Because of this lack of "universality," for simplicity it is assumed that the exchange coefficients for heat and water vapor are equal and the tabulated (as a function of wind speed and stability) coefficients for water vapor given by Bunker are used. Blanc also summarizes variations in estimates of surface fluxes as a function of exchange coefficients. For unstable conditions, Bunker's coefficients are typically higher than coefficients proposed by other investigators. However, these differences are not considered significant in view of the computations performed here.

The baroclinic nature of the Loop Current is such that the horizontal distribution of temperature within the main thermocline is correlated with the dynamic topography of the sea surface (Ichiye, 1962; Nowlin and Hubertz, 1972) and thus surface geostrophic currents. For instance, large gradients in temperature at 150 m are approximately coincident with the axis of the Loop Current. The 15°C isotherm at 150 m is typically found within these gradients and is used to define the axis of the Loop Current. Subsurface temperature profiles obtained from ship-of-opportunity and research vessel cruises were used to generate 15°C topographies for February 1975 and February 1976. The 150 m contours from these topographies are given in Fig. 1. These contours indicate that during February 1975 the axis of the Loop Current was found far north in the Gulf, a "deep" Loop intrusion and during February 1976 the axis was further south, a "shallow" Loop intrusion.

Surface meteorological and oceanographic observations were obtained from the ship-of-opportunity files of the National Climate Center, Asheville, for February 1975 and February 1976. The merchant ship-of-opportunity data provide considerably more spatial coverage than available from the research vessel data used to construct the 20°C topographies. The following

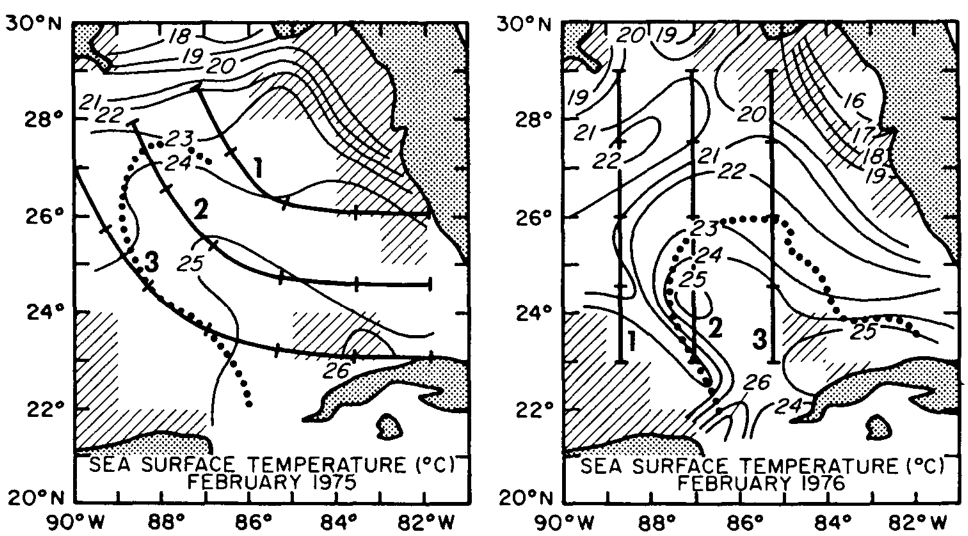

FIG. 1. Sea surface temperature (°C) distributions derived from merchant ship-of-opportunity data collected during February 1975 and 1976. The data were averaged onto a 1° × 1° grid and subjectively contoured. Quadrangles with less than four daily values are shaded. Heavy dashed lines represent the position of the axis of the Loop Current as given by the 150 m contour of the 15°C isothermal surface. Parallel solid lines on the left panel represent trajectories of trade-wind regime air parcels and on the right panel north-wind parcels along which surface fluxes are computed. The trajectories have different lengths in the trade-wind case.

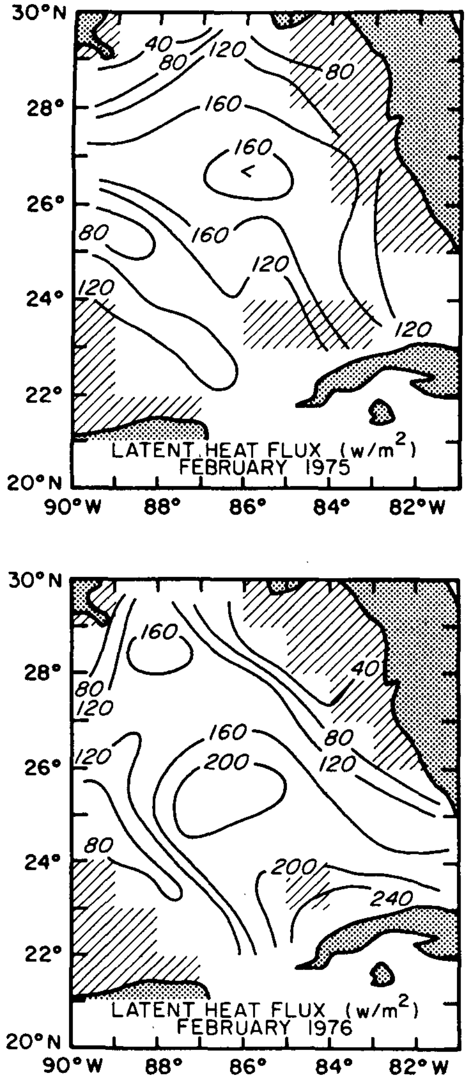

FIG. 2. Mean monthly latent heat flux (W m^{-2}) distributions for February 1975 and February 1976. Shaded regions represent quadrangles with less than four daily values of at least one parameter needed to compute the mean monthly latent heat flux [see Eqs. (1) and (2)].

procedure was used to generate the data necessary to estimate latent and sensible heat fluxes. Average daily values of the required variables were first generated on a 1° × 1° grid. The daily values were then averaged to obtain mean monthly estimates. For instance, mean monthly SST distributions for February 1975 and 1976 are also shown in Fig. 1. The dramatic difference in SST between shallow and deep intrusions is apparent.

Sensible and latent heat fluxes were then computed from Eqs. (1) and (2) using the mean monthly SST and meteorological parameters as input. The resulting fields are shown in Figs. 2 and 3. Although the SST patterns are different, atmospheric variables, such as wind speed and air temperature, also vary and it is difficult to isolate Loop induced effects.

3. Surface wind effects on surface fluxes

The mean monthly surface wind pattern over the eastern Gulf of Mexico during a typical February is comprised of distinctly different wind regimes at the sea surface. For instance, cold fronts frequently cross the Gulf in the winter. These "northers" bring cold dry air over the Gulf in their wake as described in DiMego et al. (1976), for instance. During other times, the trade winds extend over the Gulf and advect relatively warm, moist air from the southeast to the continental United States. The specific properties of the air masses associated with these features are obviously a function of their past history. In addition, cold fronts frequently become stationary over the Gulf or cyclogenesis occurs. During these times, winds vary spatially over the Gulf with no basinwide wind pattern prevailing.

The ship-of-opportunity data used to generate Figs. 2 and 3 were restructured and averages were taken ac-

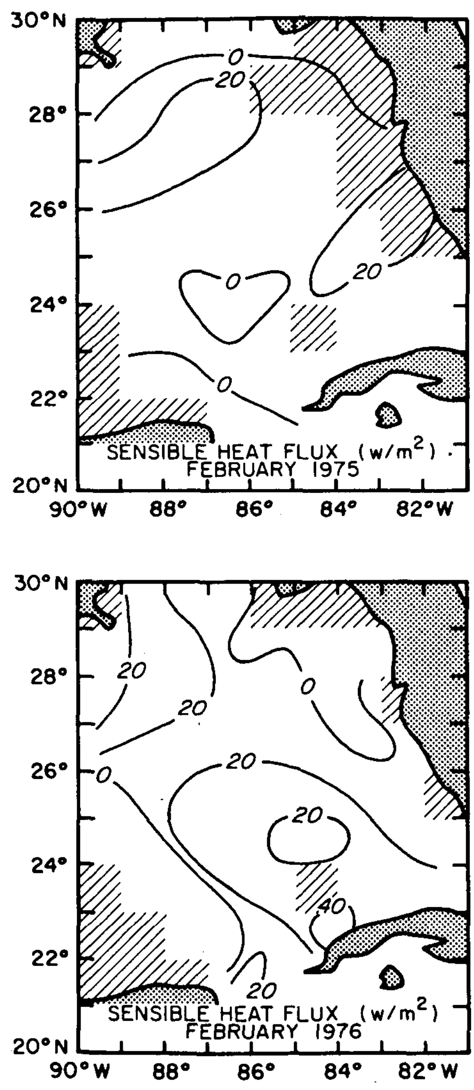

FIG. 3. As in Fig. 2 except for sensible heat flux.

cording to the surface wind field at the time of observation. The wind field was estimated from the pressure maps in the NOAA Environmental Satellite Data and Information Service Daily Weather Maps, Weekly Series. The resulting latent heat fluxes for both cases of northers and Trades are given in Fig. 4; the corresponding sensible heat fluxes are given in Fig. 5.

In the northern Gulf, in both Februaries, the latent heat fluxes during northerly winds are some two times larger than under trade wind conditions (Fig. 4). In February 1975, fluxes during norther conditions increase from minima near the coast to maxima in the central Gulf, decreasing again to the south. The data are inadequate during 1976 to describe the coastal conditions; farther south the fluxes are similar to the 1975 case. Nowlin and Parker (1974) show similar patterns in the western Gulf both before and after the passage of a cold front. Before the passage, they show latent heat fluxes ranging from 50 W m^{-2} at the coast to 250 W m^{-2} some 275 km offshore. After the passage, fluxes range from 100 W m^{-2} at the coast to 600 W m^{-2} offshore. These values are larger than those given in Fig. 4 as the Nowlin and Parker values are not averaged. The increase in fluxes offshore is related to smaller differences in air-sea temperature differences (which in part control latent heat fluxes) near the coast which increase as warmer water is encountered by the air masses offshore. Farther south, as the air masses gain moisture due to surface fluxes, latent heat fluxes decrease. In the trade wind case, equilibrium is reached

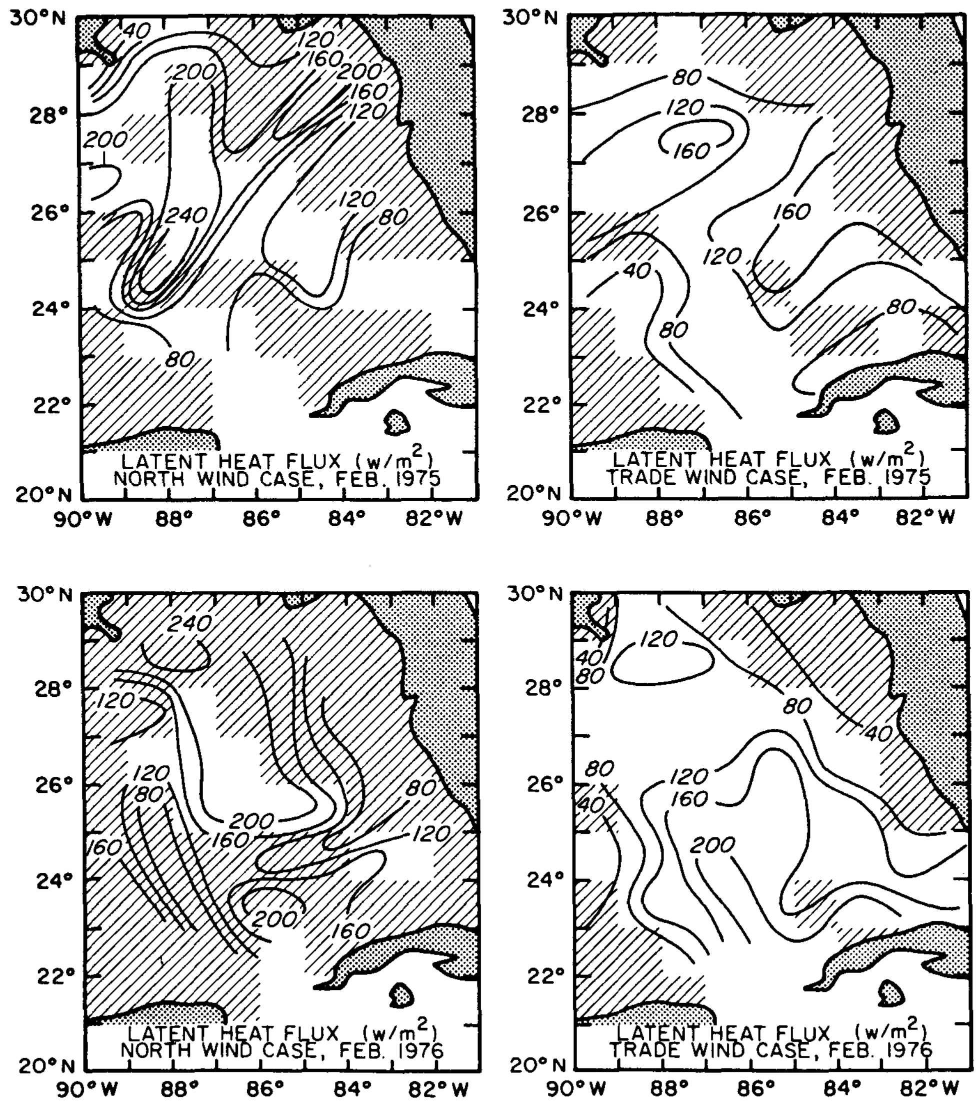

FIG. 4. Latent heat flux distributions computed from those days during February 1975 and 1976 during which north winds are dominant (left panels) and during which trade-winds are dominant (right panels). Shaded regions represent quadrangles with less than four daily values of at least one parameter needed to compute the mean monthly latent heat flux [see Eqs. (1) and (2)].

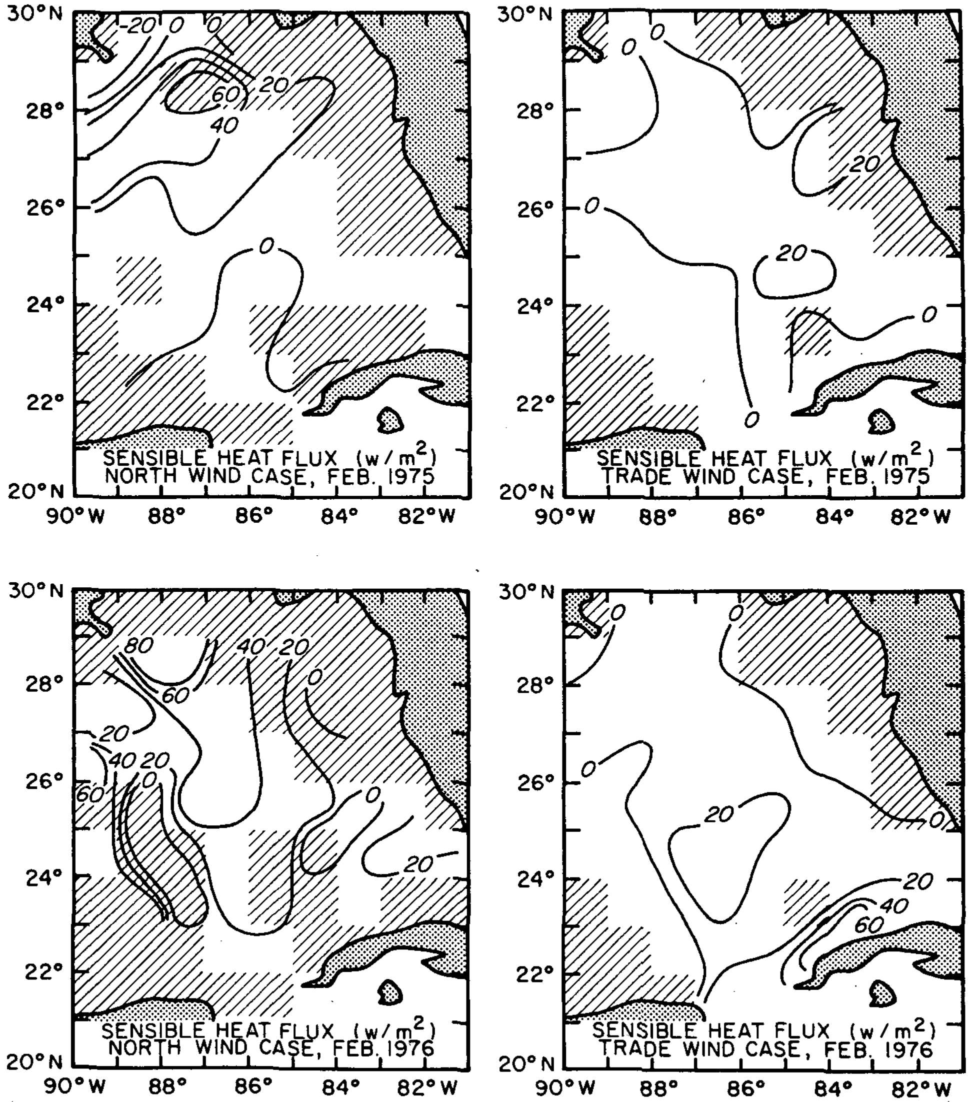

FIG. 5. As in Fig. 4 except for sensible heat flux.

as air parcels move north, causing the decrease in latent heat fluxes observed (Fig. 4).

In the central Gulf, sensible heat fluxes during northerlies are considerably larger than during trades (Fig. 5). During trade wind regimes, sensible heat fluxes can be into the ocean over areas of the Gulf. Sensible heat flux distributions given by Nowlin and Parker (1974) are similar to the 1975 northerly cases, with values increasing offshore. During 1976, data are insufficient to determine sensible heat fluxes in the extreme northern Gulf.

4. Sea-surface temperature effects on surface fluxes

The effect of different Loop Current positions, and the corresponding SST fields, on modifying air parcels which traverse the Gulf are estimated using a simple Lagrangian trajectory model. A model is required as it is not possible to isolate SST-induced modifications from other factors, such as surface wind fields, with the present dataset. In the model, air parcels are assumed to be advected along the trajectories given in Fig. 1. These trajectories represent modifications of trade wind trajectories given by Franceschini (1954) and north-wind trajectories given by Henry and Thompson (1976).

Total changes in the specific humidity and temperature of air parcels which cross the Gulf along the trajectories in Fig. 1 can be determined through numerical integration of the following Lagrangian equations,

$$\frac{dq_a(l)}{dl} = \alpha[q_s(l) - q_a(l)], \tag{3}$$

$$\frac{dT_a(l)}{dl} = \alpha[T_s(l) - T_a(l)] \tag{4}$$

TABLE 1. The final temperatures (°C) and specific humidities (g kg^{-1}) of air parcels crossing the Gulf of Mexico along the trajectories given in Fig. 1. The temperatures/specific humidities are given as functions of trajectories; months (1975 ≡ February 1975, a deep Loop intrusion, and 1976 ≡ February 1976, a shallow Loop intrusion); and initial temperatures, T_0, and specific humidities, q_0, of the air parcels.

	Trade-wind case				North-wind case		
Trajectory February	1 1975/1976	2 1975/1976	3 1975/1976		1 1975/1976	2 1975/1976	3 1975/1976
				q_0			
12.5	16.1/15.0	15.4/14.8	14.7/14.0	8	12.4/11.5	12.6/12.1	12.9/12.1
15.0	17.4/16.3	17.0/16.1	16.4/15.3	9	12.9/12.0	13.1/12.6	13.4/12.6
17.5	18.5/17.2	18.2/17.2	17.7/16.6	10	13.7/13.4	13.9/13.2	14.0/13.6
				T_0			
23.0	23.8/22.7	23.6/22.8	23.2/22.2	0.0	10.5/9.7	10.7/10.2	11.0/10.3
25.0	24.7/23.5	24.6/23.7	24.3/23.1	7.5	14.6/13.8	14.8/14.3	15.1/14.3
27.0	25.4/24.2	25.5/24.5	25.3/24.1	15.0	18.9/18.7	19.1/18.4	19.1/18.8

where l is distance along the trajectory, $\alpha = C_D/h$, and h is the thickness of the air column below the inversion layer. This thickness is taken as 1000 m for the north-wind case (Henry and Thompson, 1976) and 1750 m for the trade-wind case (Franceschini, 1954). The integration of (3) and (4) is performed at 1.5 degrees of latitude (167 km) intervals (the tick-marks on the trajectories given in Fig. 1) which represents the distance traversed by an air parcel traveling at about 8 m s^{-1} for six hours.

Sea surface temperature values are taken from the mean monthly distributions of SST given in Fig. 1. Saturation specific humidities, q_s, were computed from these SSTs.

Franceschini (1954) gives temperature changes for trade-wind trajectories ranging from 0 to −2°C and specific humidity changes ranging from −0.3 to 1.4 g kg^{-1}. Henry and Thompson (1976) estimated temperature and specific humidity changes for two air parcels advected over the Gulf during winter north winds. The air temperature changes were 16° and 26°C and the humidity changes were 7.5 and 8.5 g kg^{-1}. The total temperature and humidity changes given in Table 1 for the trade-wind cases are similar to the earlier results; the north-wind cases are the same order of magnitude but somewhat less. These favorable comparisons lend some support to the simple model.

On the average, trade-wind air parcels which are advected over the deep intrusion (1975) are 1.3°C warmer and 1.0 g kg^{-1} more humid than those advected over the shallow intrusion. Similarly, north-wind air parcels advected over the deep intrusion are about 0.7°C warmer and 0.6 g kg^{-1} more humid than those advected over the shallow intrusion. These trade-wind and north-wind differences are similar although total air mass modification, independent of Loop position, is much larger for north-wind trajectories.

5. Discussion

The February 1975 and 1976 mean monthly latent and sensible heat flux distributions (Figs. 2 and 3) closely resemble, particularly in terms of the amplitude of the fluxes, the trade-wind distributions (Figs. 4 and 5) rather than the north-wind distributions, although the fluxes during the northerlies are significantly larger. However, days with trade-wind conditions are more prevalent than those with north-wind conditions (three times more days with trades during February 1975 and 1976), thus giving the mean monthly flux distributions the characteristic Trade-wind patterns.

Franceschini (1976) shows a correlation between water vapor transport into the continental United States from the central Texas coast to Tampa and precipitation in various coastal Gulf states. Linear correlations range from 0.40 to 0.75, suggestive of a relation between the two variables. The average water vapor transport across this boundary over a three-year period is 1.1×10^{11} g s^{-1}, with an annual signal of the same order. Winter transport values are typically one-half to two-thirds this value. Interannual variability of the order of 0.2×10^{11} g s^{-1} is also observed in the three wintertime minima in water vapor transport. The 0.6 g kg^{-1} change in specific humidity attributed to different Loop Current positions is equivalent to a water vapor transport of 0.05×10^{11} g s^{-1} for a section 1750 m high, and extending from 87° to 91.5°W (the coastal region crossed by the trajectories given in Fig. 1) and a wind speed of 8 m s^{-1}. This simple calculation suggests that large changes in Loop Current position can have an effect on the amount of water vapor transported into the United States.

Acknowledgments. The February 1976 subsurface oceanographic data were collected from the R/V *Virginia Key* and R/V *Westward.*

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