

A Simulation of the Circulation in the Gulf of Mexico

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Abstract

The monthly climatology of the surface wind stress and heat flux and the seasonal climatology of the hydrography of the Gulf of Mexico have been created. These data provide the surface forcing, lateral boundary conditions and initialization for a $\frac{1}{2}^\circ \times \frac{1}{2}^\circ$, 16-level, three-dimensional, time-dependent numerical model of the Gulf. An analytical second moment turbulence closure scheme embedded within the circulation model provides for surface-mixed layer dynamics. The computational code uses a split-mode time marching procedure to include a free surface at minimal sacrifice in computer cost compared to rigid lid models. A year's simulation was obtained utilizing a two-component wind model which satisfies both synoptic surface mixing and climatological general circulation requirements. Comparison of the three-dimensional model results with observational data indicates that the model can reproduce many aspects of the large-scale features of the circulation. The seasonal cycle of the mixed layer and thermocline compares well, but not perfectly, with climatology. An area-averaged, one-dimensional ($z-t$) model and a reduced-gravity, two-dimensional ($x-y-t$) model are used to interpret some of the full model results. The model results indicate that attention must be paid to details of initialization techniques in spite of the ocean's rapid geostrophic adjustment rates. Toward the end of the model year, a weak anticyclonic eddy is pinched off the Loop Current; probably finer resolution than that offered in this paper is required to increase the intensity of the eddy. Nevertheless, a variety of transient, smaller scale, baroclinic eddies are evident in the calculated circulation patterns. Deficiencies in both the atmo-

spheric and lateral boundary forcing data are identified which should lead to strategies for improved model simulations.

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Introduction

The Gulf of Mexico is a region of scientific interest due to its intense current systems and large temporal and spatial variability. Moreover, there have been few previous modelling efforts for the Gulf. Those models that do exist do not include thermodynamical processes. The work of Baer et al. (1968) using a four-level quasi-geostrophic model developed by Hamm and Lesser (1968) was the first attempt to produce Gulf circulation patterns. This model, after initialization with data, was used to forecast a four-week period. The results of the forecast showed much temporal variability and large upwelling and downwelling velocities (of the order of the horizontal velocities). While producing interesting results, the model considered only an intermediate region away from surface and bottom influences, and excluded all topographical effects. Paskausky and Reid (1972) developed a barotropic Gulf model that included topography and inertial effects on a β -plane. The results were of limited use since one of the terms in the governing equations (vortex stretching from topographic changes) was inadvertently omitted from the finite difference version. Wert and Reid (1972) constructed a two-layer quasi-geostrophic model that was able to simulate qualitatively the annual cycle of Loop Current intrusion. A barotropic model, a reduced gravity model and, additionally, a two-layer model were used by Hurlburt and Thompson (1980, 1982) to elucidate some of the dynamical processes governing the Loop Current and its attendant eddy shedding. Their investigation showed that temporal variations in the inflow at the Yucatan Straits were not required for realistic shedding cycles and provided useful results for interpreting the effects of resolution and horizontal viscosity.

This article aims to describe and test a numerical three-dimensional circulation model of the Gulf. Realism is stressed in the model presented here in that realistic coastline, bottom topography, atmospheric forcing and oceanic initialization are accommodated. The model includes a free surface, a second moment turbulence closure model which should produce good simulation of the ocean surface layer, and numerical procedures which appear to cope gracefully with large baroclinic and topographic variability. The following sections contain a discussion of the hydrographic and atmospheric surface flux climatologies, data which provide the model with surface forcing, lateral boundary conditions and initialization, and a description of the circulation

calculated by the model which is, whenever possible, compared with oceanographic observations. The model simulation was for a period of one year; it is initialized with climatological temperature and salinity distributions (February 15) and is driven by climatologically derived surface wind stress and heat flux.

Climatology of the Gulf of Mexico

Anticipating the need for model initialization, surface forcing, lateral boundary conditions and data with which to compare model calculations, a climatology of the Gulf of Mexico has been created.

Climatological wind stress, heat flux and effective salt surface flux were determined from data files TDF-11 maintained by the National Climatic Center (NCC); the files consist of over a million Gulf surface ship observations. The raw data were edited and converted with the aid of bulk aerodynamic and radiational exchange formulas to produce monthly estimates of the wind stress statistics, heat flux and mass flux on a 1° square grid. The transfer coefficients in the formulas vary with wind speed and stability in a manner similar to those of Bunker (1976). The stresses and fluxes were then placed on the finer resolution numerical grid by an objective interpolation technique (see appendix by H.J. Herring in Kantha et al., 1981).

The area-averaged wind stresses shown in Figure 1a indicate that while the zonal stress is easterly, weak winter "northers" and summer southerlies are present. The net heat flux of the Gulf shown in Figure 1b (where a positive value implies a net warming of the ocean) shows that the basin loses more heat to the atmosphere during the winter than it gains in the summer time with an annual mean of -48 Wm^{-2} . Annual rates determined by Hastenrath and Lamb (1978), Bunker (1976) as recomputed by Etter (1975, 1983) are somewhat lower, -27 , -21 and -8 Wm^{-2} , respectively. The contribution of the latent heat flux is greater than in the previous estimates and accounts for most of the differences (a reduction of the mass transfer coefficient for evaporation by 25% produces a nearly null, net annual heat flux). The reason for this is not yet clear; it should be noted that all of these heat flux estimates are based on substantially the same data base. The total uncertainty in these calculations was estimated by Hastenrath (1980) to be in the order of $20-30 \text{ Wm}^{-2}$.

The mass budget for the Gulf is shown in Figure

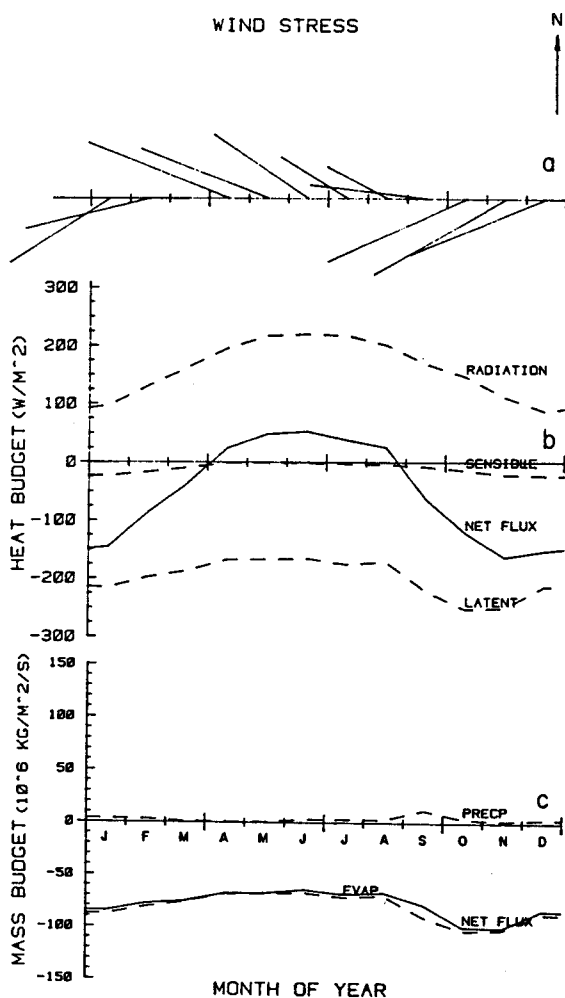


Fig. 1. The annual cycle of Gulf averaged wind stress (a), heat budget (b), and mass budget (c) derived from climatological, atmospheric surface data. Direction of arrow at top right indicates North; its magnitude represents a wind stress of $0.2 \text{ dynes cm}^{-2}$.

1c. The observations of precipitation are much too low. The net mass flux, $-78 \times 10^{-6} \text{ kg m}^{-2} \text{ s}^{-1}$ or equivalently $\sim 250 \text{ cm yr}^{-1}$, is much larger than the estimates of Franceshini (1961), Jacobs (1951), Maul (1979) and Etter (1975). The disparity in these precipitation estimates is not yet understood and further investigation is required. Monthly net heat flux and mean wind stress distributions were calculated from the data and used as boundary conditions for the model; data for every third month is shown in Figures 2 and 3. (Distributions for all months are available from the authors.) These quantities exhibit considerable horizontal structure as well as seasonal variability.

To complement the atmospheric forcing data, the complete set of Gulf temperature and salinity data files maintained by the National Oceanographic Data Center (NODC) were processed. The edited raw data were averaged on a 1° square grid at the standard NODC depth levels. This new data set includes all the data which were archived prior to 1979 and consists of over half a million temperature and salinity observations. The number of observations is about 50% higher than that used by Behringer et al. (1977). Despite this, the quantity of data is still insufficient for forming meaningful monthly Gulf-wide distributions. Seasonally varying distributions are therefore constructed in the upper 1000 m while annual mean values are used between 1000 m and 1500 m; below 1500 m area-averaged, annual mean values are used. This final data set, after being spread onto the model grid points via the objective interpolation technique, is fitted to the vertical levels in the model by linear interpolation. The model uses the data from the first season, averaged January–February–March conditions, and is therefore initialized on February 15. Other seasonal distributions are available against which model simulations can be compared to provide a form of model verification. Figures 4 and 5 show the seasonal temperature and salinity distributions at four levels in the model. Analogous distributions exist at all 15 model levels.

The effect of averaging and interpolating the historical data files is to produce representative but considerably smooth temperature and salinity fields. The thermal manifestation of the Loop Current (Fig. 4) is smoothed considerably when compared to synoptic maps, as is upwelling along the northern and western coasts of Yucatan.

The Circulation Model

The ocean circulation model developed for use in this study is intended to represent ocean physics as realistically as possible. The model is three-dimensional, incorporating a turbulence closure submodel to provide a firm basis for the parameterization of the vertical mixing processes. A complete description of the governing equations and the numerical techniques can be found in Blumberg and Mellor (1983, 1985). For the reader's convenience a brief discussion of the principles and assumptions is presented here.

Two simplifying approximations are used: (i) it is assumed that the weight of the fluid identically balances the pressure (hydrostatic assumption), and (ii) density differences are neglected unless the

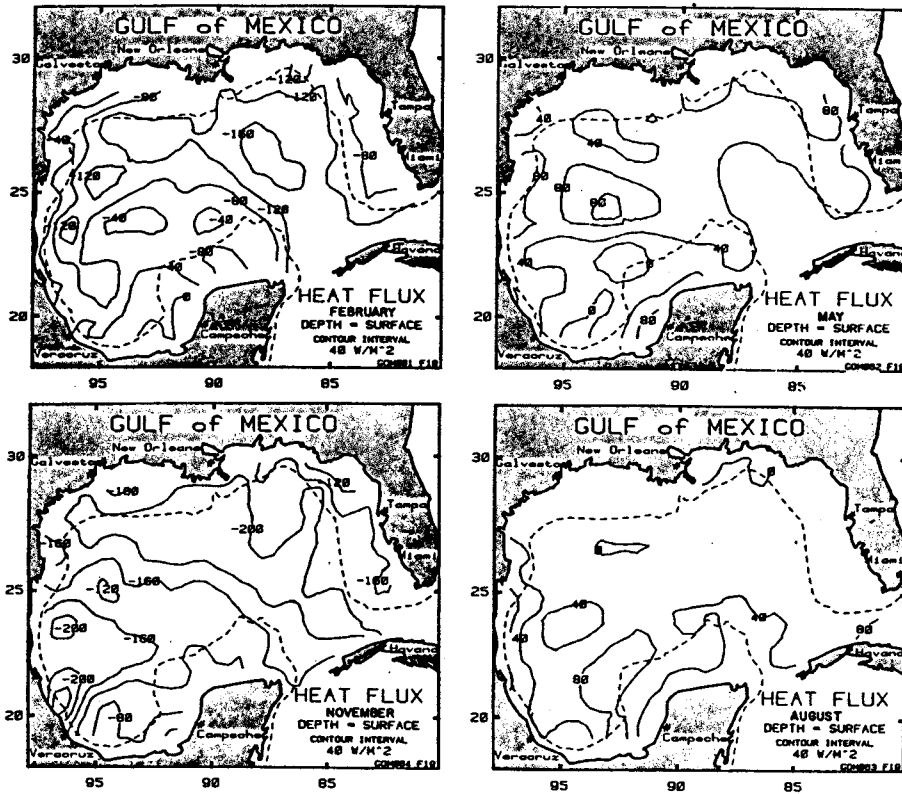


Fig. 2. Monthly mean, observed heat fluxes for February, May, August and November. The time sequence is clockwise.

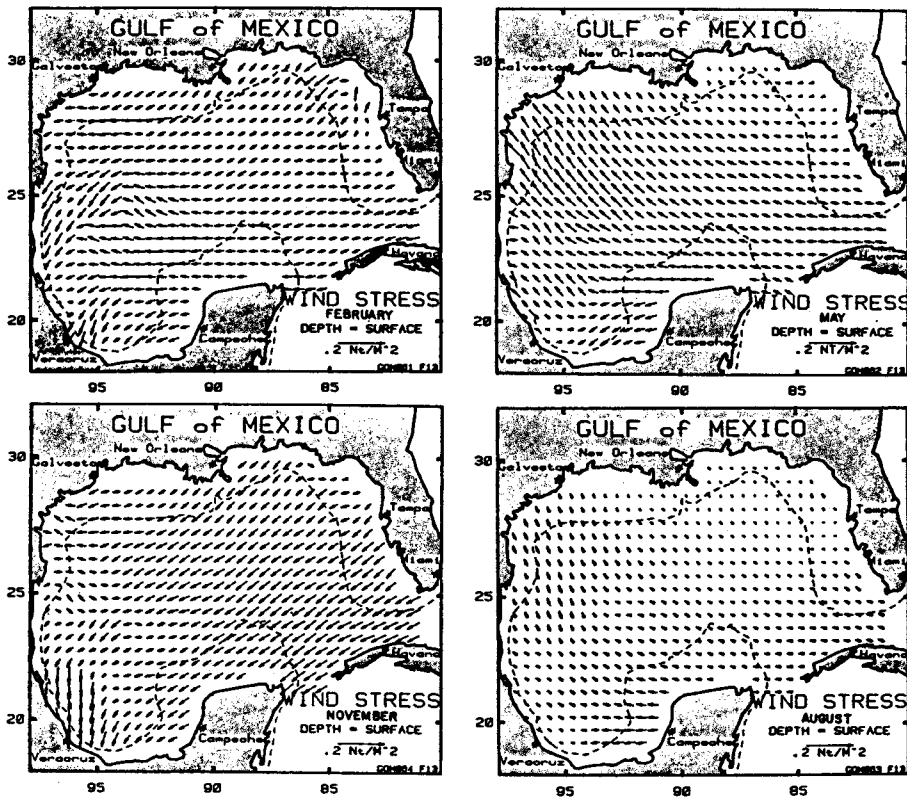


Fig. 3. Monthly mean, observed wind stress vectors for February, May, August and November. The time sequence is clockwise.

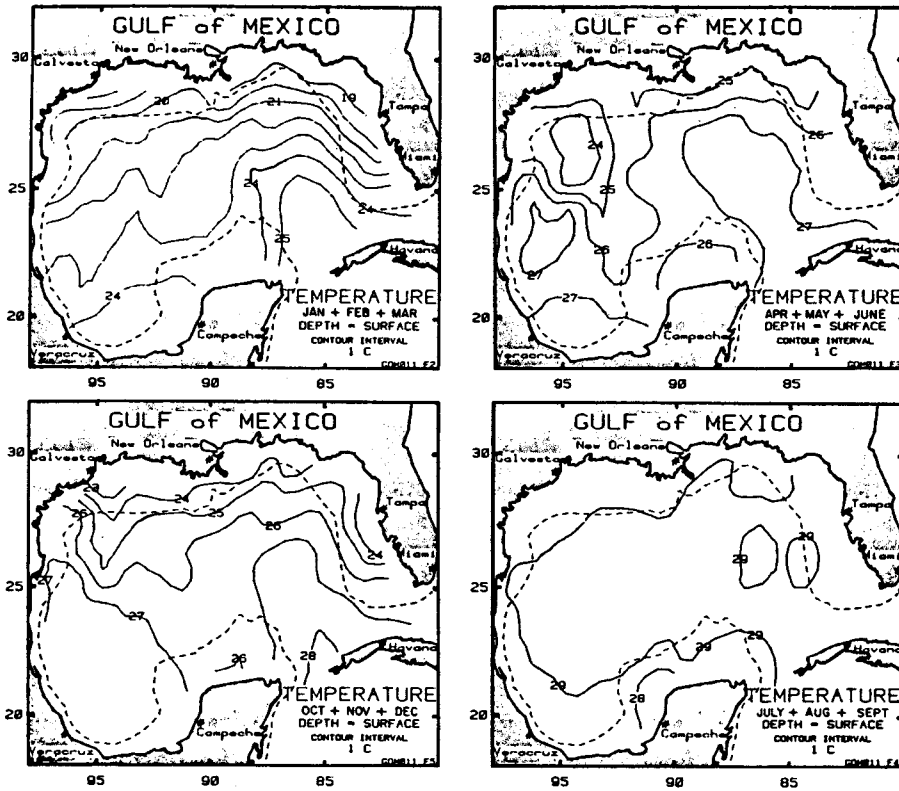


Fig. 4a. Seasonally averaged, observed climatological temperature distributions at the surface. The time sequence is clockwise.

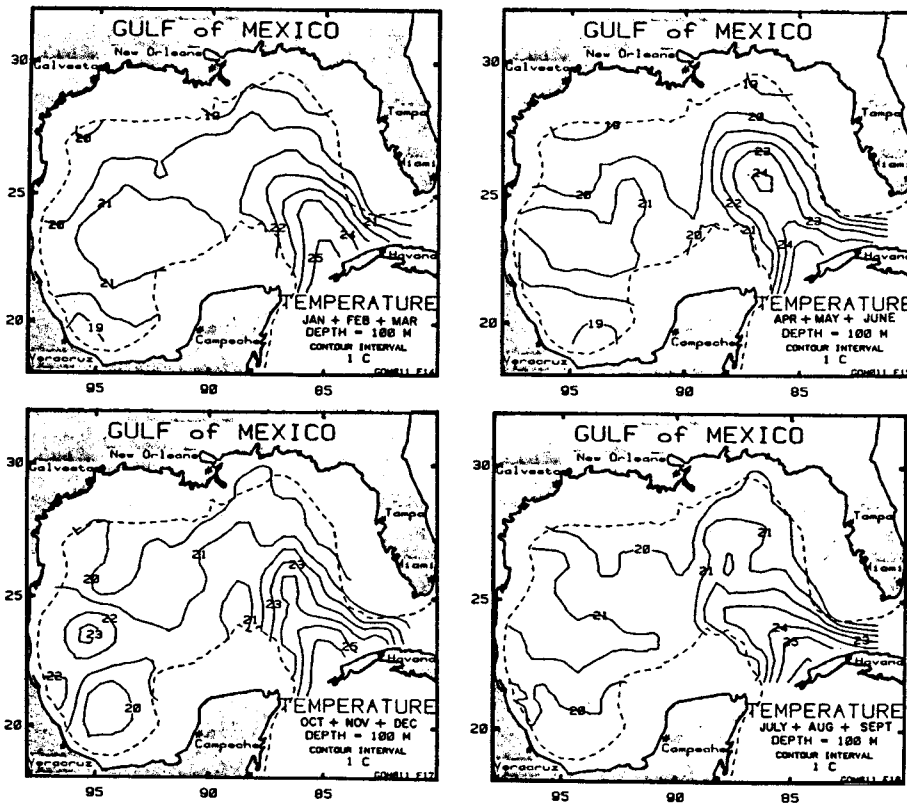


Fig. 4b. Same as Fig. 4a except for the 100-m depth.

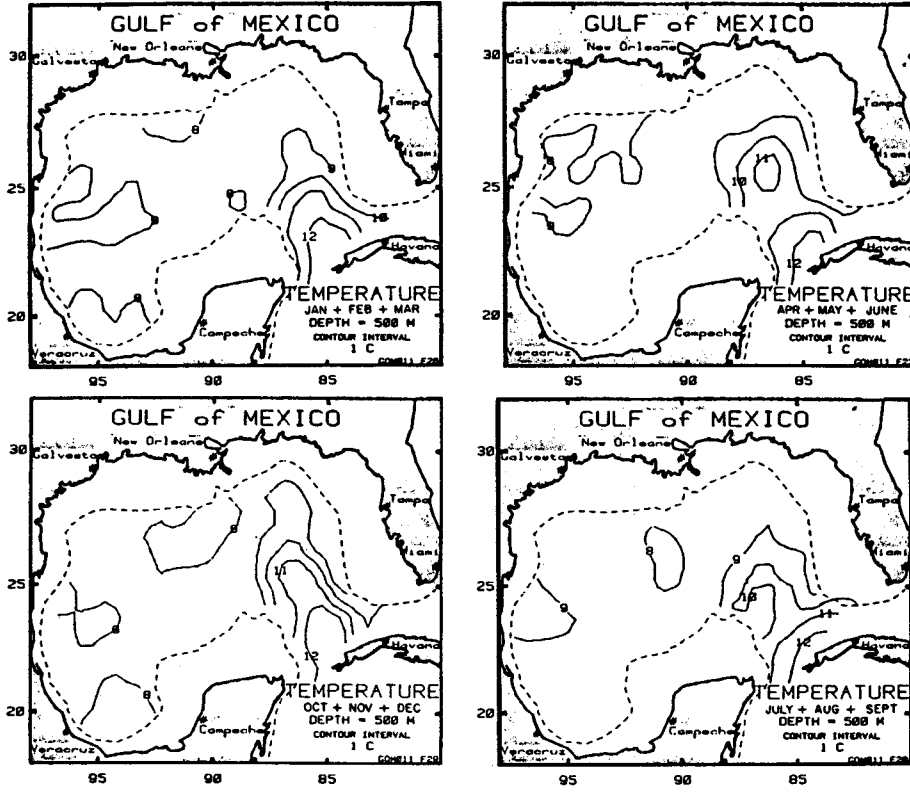


Fig. 4c. Same as Fig. 4a except for the 500-m depth.

differences are multiplied by gravity (Boussinesq approximation). Consider a system of orthogonal Cartesian coordinates with x increasing eastward, y increasing northward and z increasing vertically upwards. The ensemble mean velocities are U , V , W . The free surface is located at $z = \eta(x, y, t)$ and the bottom is at $z = -H(x, y)$.

The continuity equation is

$$\partial U / \partial x + \partial V / \partial y + \partial W / \partial z = 0. \quad (1)$$

The Reynolds momentum equations in conservative form are

$$\begin{aligned} \partial U / \partial t + \partial U^2 / \partial x + \partial UV / \partial y + \partial UW / \partial z - fV \\ = -(1/\rho_0) \partial P / \partial x + \partial / \partial z (K_M \partial U / \partial z) + F_x, \end{aligned} \quad (2)$$

$$\begin{aligned} \partial V / \partial t + \partial UV / \partial x + \partial V^2 / \partial y + \partial VW / \partial z + fU \\ = -(1/\rho_0) \partial P / \partial y + \partial / \partial z (K_M \partial V / \partial z) + F_y, \end{aligned} \quad (3)$$

$$-\rho g = \partial P / \partial z, \quad (4)$$

with ρ_0 , the reference density; ρ , the in situ density; g , the acceleration due to gravity; and P , the pressure.

A latitudinal variation of the Coriolis parameter, f , is introduced by use of the β plane approximation as

$$f = f_0 + \beta y. \quad (5)$$

For the Gulf of Mexico, $f_0 = 6.147 \times 10^{-5} \text{ s}^{-1}$ and $\beta = 2.070 \times 10^{-11} \text{ m}^{-1} \text{ s}^{-1}$ appropriate to a latitude of 25°N .

The pressure at a depth z can be obtained by integrating the vertical component of the equation of motion, equation (4), from z to the free surface, η , and is

$$P(x, y, z, t) = P_{\text{atm}} + g \rho_0 \eta + g \int_z^0 \rho(x, y, z', t) dz'. \quad (6)$$

Henceforth, the atmospheric pressure, P_{atm} is assumed constant.

The equations for the mean of any scalar, Θ_i , may be written

$$\begin{aligned} \partial \Theta_i / \partial t + \partial U \Theta_i / \partial x + \partial V \Theta_i / \partial y + \partial W \Theta_i / \partial z \\ = + \partial / \partial z (K_H \partial \Theta_i / \partial z) + F_{\Theta_i}, \end{aligned} \quad (7)$$

where Θ_i may represent mean potential temperature, Θ , or salinity, S .

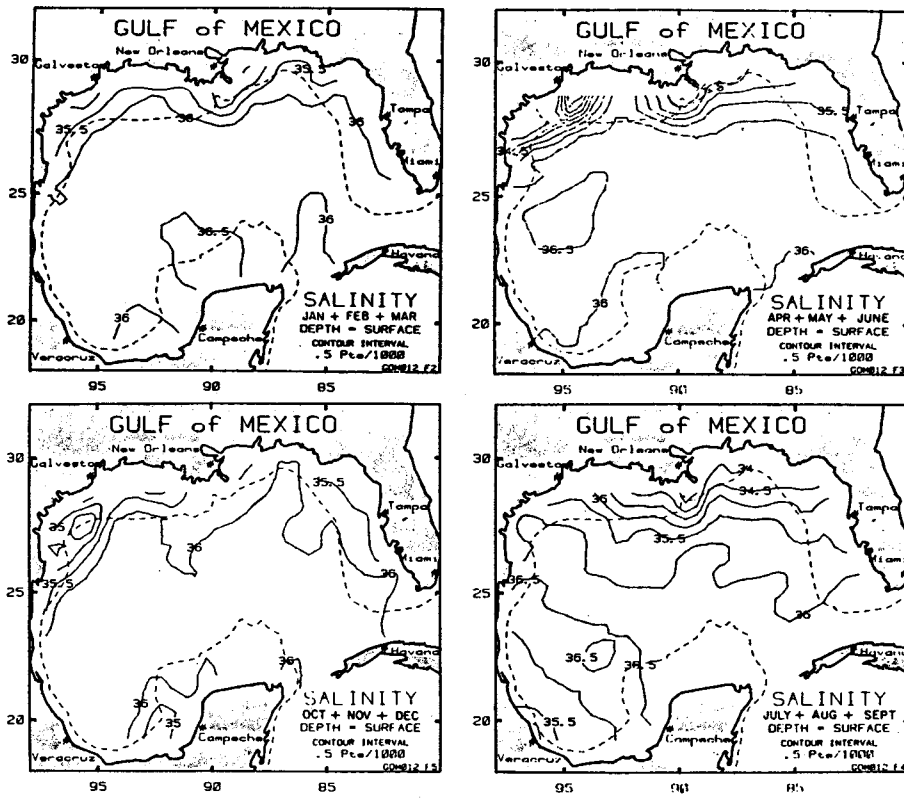


Fig. 5a. Seasonally averaged, observed climatological salinity distributions at the surface. The time sequence is clockwise.

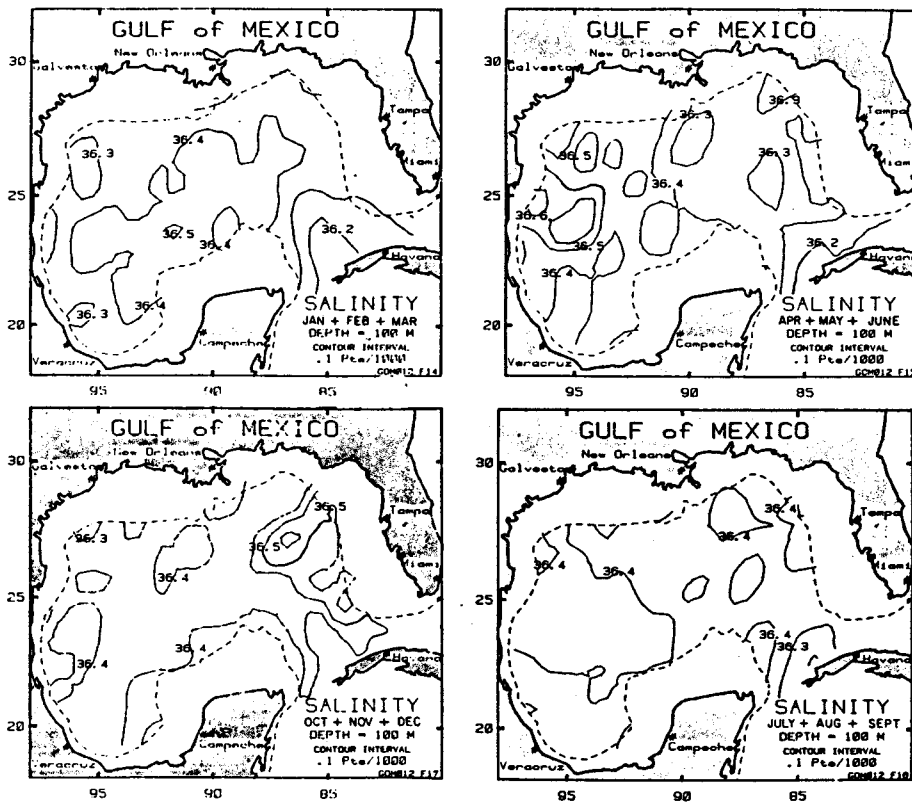


Fig. 5b. Same as Fig. 5a except for the 100-m depth.

