Seasonal Variability of the Export of River Discharged Freshwater in the Northern Gulf of Mexico

S. L. Morey[1], J. J. O'Brien[1], W. W. Schroeder[2], and J. Zavala-Hidalgo[1]

[1] Center for Ocean – Atmospheric Prediction Studies
Florida State University
Tallahassee, FL 32306-2840
morey@coaps.fsu.edu
obrien@coaps.fsu.edu
zavala@coaps.fsu.edu

[2]Marine Science Program
The University of Alabama
Dauphin Island Sea Lab
101 Bienville Blvd.
Dauphin Is., AL 36528
wschroeder@disl.org

***Abstract*-Numerical simulations of the Gulf of Mexico (GoM) using the Navy Coastal Ocean Model (NCOM) predict a seasonal signal of surface salinity throughout the northern Gulf. The model variability of salinity and currents is compared to historical hydrographic data and to transport inferred from drifting buoys. Model experiments are used to examine the roles of mesoscale eddy activity and the seasonal variability of wind forcing and river discharge in connection with the upper ocean salinity field. It is shown that the annual cycle of the local winds greatly influences the fate of the freshwater discharged by the local rivers, primarily the Mississippi river. Model results and drifter data show that the low salinity water is directed westward over the broad Louisiana – Texas (LATEX) shelf in the fall and winter where it remains trapped to the coast. This water is transported southward as a coastally attached current and often offshore by jets associated with eddy pairs along the western continental margin. In the spring and summer, the low salinity water of the northern Gulf spreads over deeper water to the east of the Mississippi Delta where it is influenced by the offshore circulation. Mesoscale eddies associated with the Loop Current (LC) can then entrain the low salinity water and transport it great distances from its origin[1].**

I. INTRODUCTION

The circulation in the GoM is dominated by the energetic LC and its associated eddies. Large anticyclones pinch off from the LC at irregular intervals and drift generally westward where they decay against the continental margin. Associated with the LC and the large anticyclones are a wealth of smaller cyclonic and anticyclonic eddies interacting in a seemingly chaotic manner. These features have vertical scales from several hundred to 1000 m and thus remain offshore of the continental shelf break.

Wind patterns over the northern GoM are typified by light southeasterly winds during the summer, with frequent cold fronts shifting the mean winds to northeasterly and northerly during the fall and winter. The influence of the seasonality of the winds on the GoM circulation is small compared to the energetic LC-induced circulation, but can be important near the coast.

Coastal regions of the GoM exhibit large temporal variability in salinity, which in turn has a large influence on the coastal ocean stratification. Filaments and lenses of low salinity water have been observed throughout the Gulf. The source of this low salinity water is freshwater discharged from large rivers to the Gulf, primarily from the Mississippi River. The Mississippi River has an annual mean discharge of over 13,000 m^3/s (as measured by the U. S. Geological Survey gauging station 7374000) with the neighboring Atchafalaya River discharging at about one-half the rate. The annual cycle of the Mississippi River discharge has a maximum in April of over 22,000 m^3/s and a minimum in September of just over 6,300 m^3/s. A unique feature of the Mississippi River is that the discharge locations are located at the end of a delta extending to very near the edge of the continental shelf. Thus, if the river plume is directed toward the east, it will extend over deep water, whereas it will flow over the wide Louisiana-Texas (LATEX) shelf should it be directed westward.

This paper presents some preliminary work using model data, real and simulated drifting buoys, and historical hydrographic data. The existence of an annual cycle of surface salinity in the northern GoM, and of an annual cycle of wind-driven currents in the northern GoM are demonstrated. The role of seasonal variability of the wind-driven advection of the low salinity water eastward in the spring and summer and westward in the fall and winter are investigated as a mechanism for exporting low salinity water near the coast across the shelf break to the open ocean. It is shown that the annual cycle of river discharge is not a controlling factor for the seasonal variability of the surface salinity far from the discharge location.

II. THE MODEL

The NCOM is a three-dimensional primitive equation hydrostatic ocean model developed at the Navy Research Laboratory [1]. The model's hybrid sigma (terrain following) and z (geopotential) level vertical coordinate is useful for simulating upper ocean processes in domains encompassing both deep ocean basins and very shallow shelves. The NCOM is set up to simulate the entire GoM and Caribbean north of Honduras (15.55°N) to 80.6°W with 1/20° between like variables on the C-grid, 20 sigma levels above 100 m and 20 z-levels below 100 m to a

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maximum depth of 4000 m. The model is forced by discharge from 30 rivers, transport through the open boundary (with monthly climatology temperature and salinity) yielding a mean transport through the Yucatan Strait of approximately 30 Sv ($10^6 m^3 s^{-1}$), and monthly climatology surface heat and momentum flux. A surface salinity flux has the effect of uniformly evaporating an amount of water at a rate equal to the sum of the annual average discharge rates of the 30 rivers. Experiments are run with monthly varying river discharge, and with constant river discharge rates.

III. MODEL RESULTS

Seasonal variability in the surface salinity (actually, depth-averaged salinity in the topmost grid cell) spatial pattern is easily recognizable in animations of the model solution. The model is forced by monthly climatology fluxes, yet there is significant interannual variability due to the aperiodic LC eddy shedding and the associated highly nonlinear eddy field. Nevertheless, certain features are characteristic of different seasons.

Occasionally, jets of low salinity water can be seen flowing offshore of the continental shelf across the shelf break to deep water. These features seem more evident east of the Mississippi Delta in the spring and summer, and off the Texas and northern Mexican shelf in the fall and winter (Fig. 1). Also evident in the model snapshots are the spreading of the low salinity water to the east of the Mississippi Delta in the summer and the confinement to the coast on the LATEX and northern Mexican shelf in the winter. Similar features can be seen in satellite thermal images in the winter, as the coastal low salinity water is much cooler than the offshore water (Fig. 2).

Monthly climatology of the model surface salinity shows a similar east-west pattern on the shelf in the northern Gulf, as well as the effect of the seasonal preference for cross-shelf transport of low salinity water in the eastern and western GoM in the summer and winter, respectively (Fig. 3) [2]. Monthly climatology near surface (10 m) salinity from the 1998 World Ocean Atlas (WOA98) [3] validates that the annual signal of salinity seen in the model does indeed occur (Fig. 4). Away from the river discharge locations, the model annual cycle of surface salinity agrees with the WOA98 values in the experiments with monthly varying river discharge, and with time constant river discharge. This indicates that the seasonal variability of river discharge is not the controlling mechanism for the annual cycle seen in the upper ocean salinity field in the GoM.

IV. DRIFTER STUDIES

The annual cycle of river discharge has been ruled out as a mechanism for controlling the seasonal variability of the upper ocean salinity field in the GoM. The seasonal variability of currents in the northern GoM is now examined to explore the possibility of a seasonal signal of advection of low salinity water. Drifting buoy data from

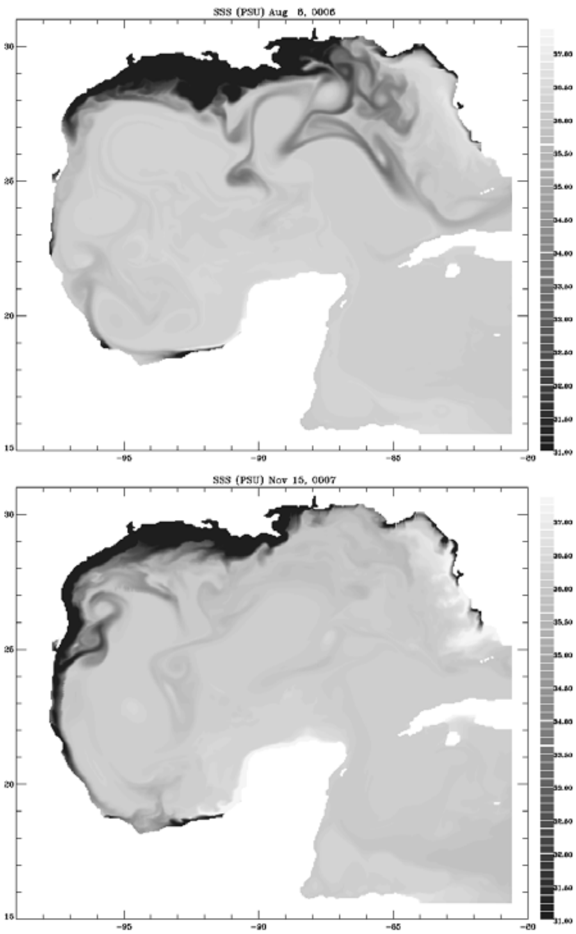

Fig. 1. Salinity of the topmost grid cell from the NCOM simulation. Top: August snapshot showing filaments of freshwater in the eastern GoM. Bottom: November snapshot showing low salinity water along the western boundary and jets flowing eastward from the shelf.

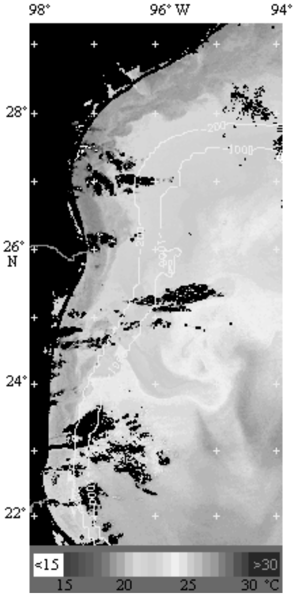

Fig. 2. Sea surface temperature from NOAA-AVHRR on 3/21/97. A cold filament extends southeastward from the shelf at 25°N. Image produced by Agustin Fernandez of UNAM, Instituto de Geografia. Lab. de Observacion de la Tierra.

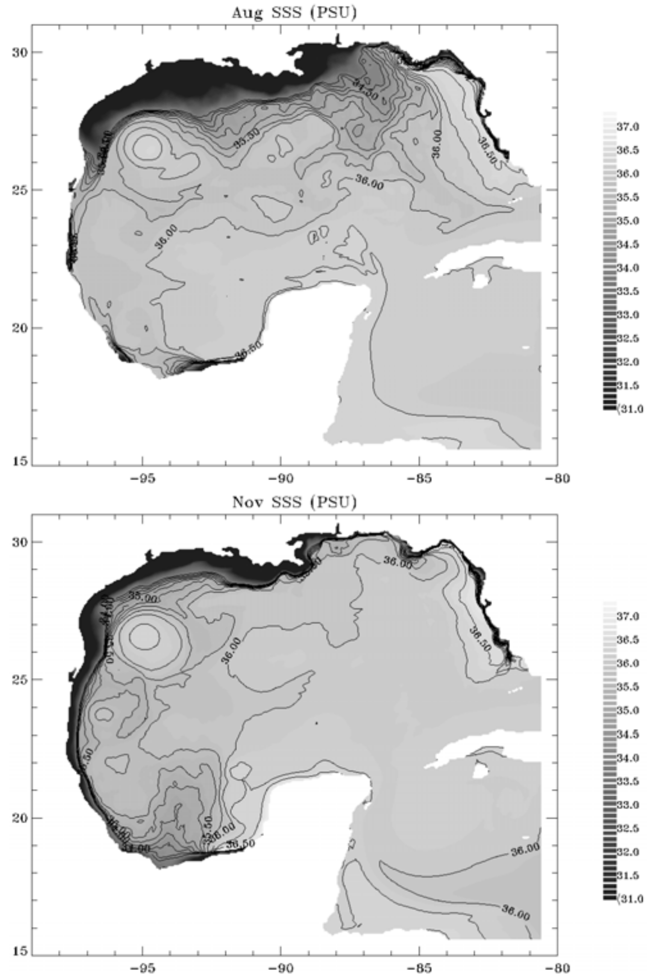

Fig. 3. Monthly mean salinity of the topmost grid cell from the NCOM simulation. Top: August. Bottom: November.

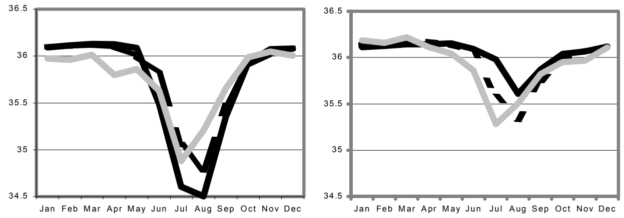

Fig. 4. Monthly climatology surface salinity from 1°x1° boxes centered at 86.5°W, 28.5°N (left) and 85.5°W, 26.5°N (right) from the WOA98 10 m level (gray), NCOM with steady river discharge (dashed), and NCOM with monthly climatology river discharge (black).

the SCULP 1, SCULP 2, and LATEX projects (provided by Walter Johnson, Minerals Management Service) are analyzed to find evidence of such variability in the transport in the northern Gulf.

The satellite tracked buoys were deployed at various locations on the LATEX shelf and the Mississippi-Alabama-Florida (MAF) shelf. For this experiment, the buoy position data are not studied based on deployment positions and times, but are instead grouped together for this study. Subsets of buoys are selected based on their existence within a defined region during a particular time of year. The first time a buoy is found to have a location within the prescribed region and time of year is taken as its new "deployment" position and time. Its subsequent trajectory is tracked for the time period under consideration. This allows better exploration of seasonal variability without being constrained to the buoys' actual deployment times and locations. Four experiments are conducted to include summer and winter seasons on both the MAF and LATEX shelves. The selection regions are:

MAF Shelf: 89°W to 86.5°W within the 200 m isobath
LATEX Shelf: 95°W to 91°W within the 200 m isobath.

Buoys existing with these defined region during June - July of any year are considered as "deployed" during the summer. Buoys existing in the regions during November – December are considered as part of the winter deployments. The buoys are tracked through the end of August for the summer experiments, and through the end of January for the winter experiments.

The buoy trajectories are followed and the net number of buoys exiting a larger defined region across various line segments are counted. For the LATEX shelf, this test region is divided as: along 27.5°N from the coastline eastward to 96°W (the 200 m isobath), along 27.5°N from 96°W to 90°W, and along 90°W from the coastline southward to 27.5°N. For the MAF shelf, the test region is divided as: along 89.5°W from the coastline southward to 28°N, along 28°N from 89.5°W to 85.5°W, and along 85.5°W from the coastline southward to 28°N (Fig. 5).

To compare the model solution to the observed data, the drifting buoy experiments are simulated in the model surface velocity field. 150 simulated drifting buoys are deployed 10 at a time at two day intervals for 60 days at random locations within the deployment regions, and deployment months, as defined above. The buoys are tracked as they are advected for the prescribed time interval, and are counted as they pass through the different segments of the test regions.

A striking example of the seasonal variability of the export of LATEX shelf water is seen along the western boundary of the domain. During the winter months, the vast majority of the buoys leaving the test region exit southward very close to the coastline. These buoys are trapped in a southward flowing coastally attached wintertime current. This current has been shown to be relatively fresh [4]. The Lagrangian approach used here supports that this water attains its properties on the LATEX shelf where it is influenced by the Atchafalaya and Mississippi Rivers. A secondary export pathway southward across the LATEX shelf break in the winter is suggested. No buoys pass eastward out of the test domain during the winter. During the summer, most of the buoys remain within the LATEX shelf region. There is little export of the shelf water at this time of year, although there is some evidence of a weak transport eastward out of the region.

Over the MAF shelf in the winter, a large number of drifting buoys are observed to exit the test region westward, past the Mississippi Delta, and onto the LATEX

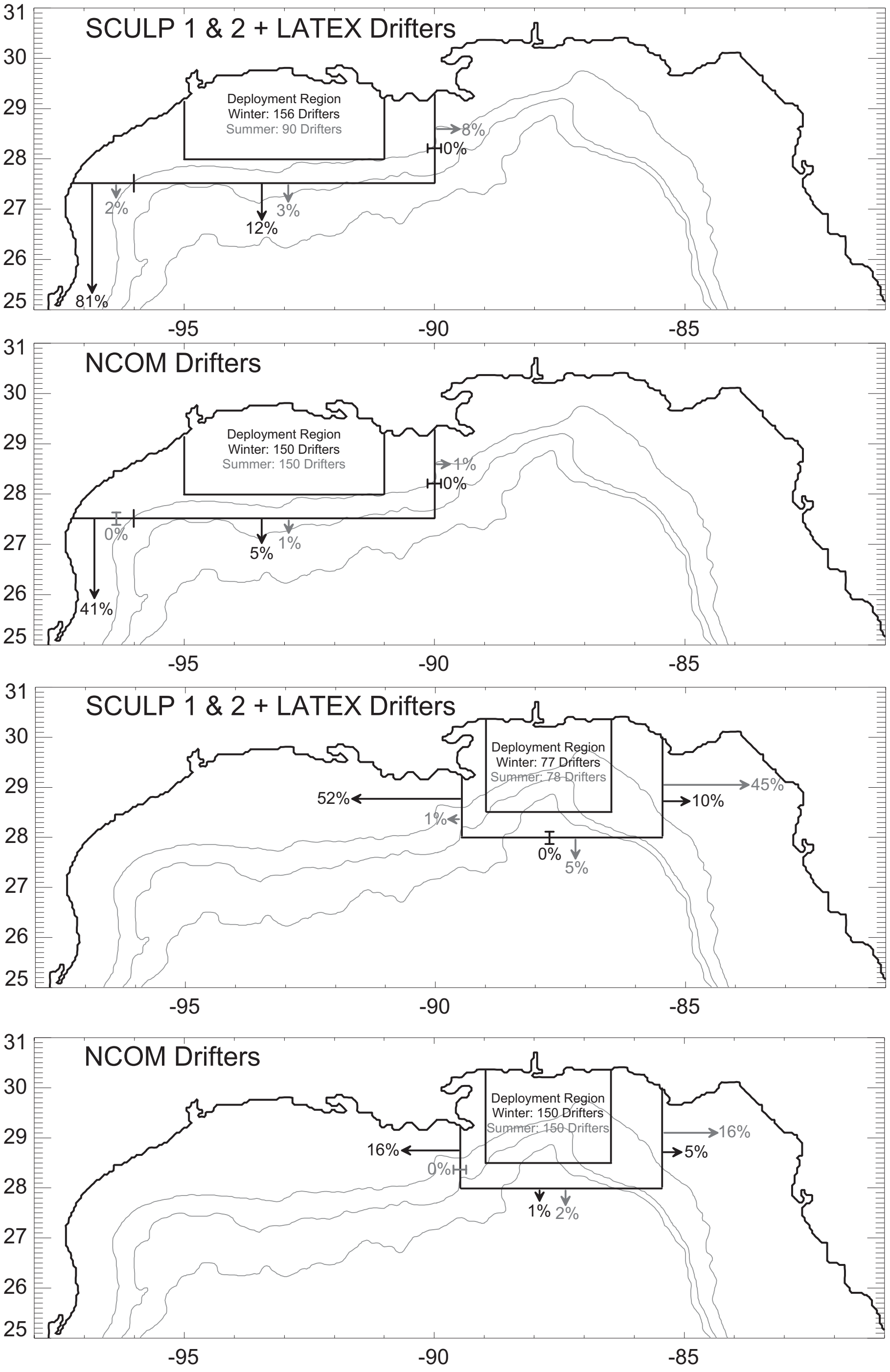

Fig. 5. Schematic of results from the real and simulated drifting buoy experiments. The 200 m, 1000 m and 2000 m isobaths are plotted. The inner boxes on the shelf show the deployment regions (the deployment regions only consist of the shelf within the 200 m isobath). The larger boxes show the test domains. The arrows (black for winter, gray for summer) show the percentages of deployed buoys exiting the test domain through the indicated line segments.

shelf. During the summer there is nearly no westward transport out of the test region, yet there is clear evidence of eastward transport. Since the major contributor of freshwater in the region, the Mississippi River, is located to the west of the deployment region, it is reasonable to expect that the water near the MAF shelf is more saline during the winter and freshened in the summer as a result of eastward advection of the freshwater discharged by the river.

The real and simulated drifting buoy experiments qualitatively agree, suggesting that the model can be used to explain the variability of the advection of low salinity water westward and eastward in the northern Gulf.

V. DISCUSSION AND SUMMARY

The model results and analysis of observational data show a clear annual signal in the upper ocean salinity field throughout the northern GoM. A seasonal transition from eastward to westward transport of the low salinity water from the spring and summer seasons to the fall and winter seasons has also been demonstrated. The model experiments with constant and climatological river discharge give similar results, indicating that the variability in river discharge does not control the seasonal variability of salinity in the region, away from the fresh water sources. This can be explained by the fact that the ocean has a "memory" of the freshwater input over a region. If the export of the freshwater is not rapid, the low salinity water can accumulate in a region over a period of months effectively reducing the variability caused by varying river discharge rates.

The model can give insight as to the cause of the seasonal reversal of transport in the northern GoM. The only seasonally-varying forcing functions in the model are river discharge rates (in only one experiment), surface wind stress, and surface heat flux. The reversing current near the coast can be wind driven or density driven. A density driven current, however, would flow in the direction with less dense water to the right. Thus, a density driven westward/southward current on the LATEX shelf and along the Mexican coastline during the winter could be explained by a reduction of the density along the coast. However, the coastal waters are actually cooling faster than the offshore waters at this time of year, so the seasonal variability of heat flux is not the cause. Additionally, the current forms in both experiments with and without seasonally varying freshwater input, and the formation of the coastally attached current occurs just following the climatological minimum of river discharge in the northern GoM. Thus, seasonal variability of freshwater input along the coast is not responsible. This leaves a climatological shift in wind direction over the northern GoM from southeasterly in the spring and summer to northeasterly in the fall and winter as the mechanism responsible for the seasonally reversing transport.

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