Report on a Symposium on Air–Sea Interaction and Air Mass Modification over the Gulf of Mexico
7–9 January 1991, Galveston, Texas


1. Introduction

This symposium was held on 7–9 January 1991 in Galveston, Texas, and was sponsored by the Texas Institute of Oceanography (TIO), the Institute for Naval Oceanography (INO), the National Weather Service-Southern Region (NWS-SR), and the Cooperative Institute for Applied Meteorological Studies (CIAMS), Texas A&M University. A planning committee composed of representatives from these organizations selected topics and speakers, and planned the format of the symposium. All speakers were invited and a discussant was assigned to initiate a stimulating discussion of each paper. Forty-five minutes were allotted for the presentation and discussion of each paper.

2. Background

A Workshop on Atmospheric Forcing of Ocean Circulation (Scoggins and Mooers 1988), and a study called GUFMEX over the Gulf of Mexico in 1988 (Lewis et al. 1989), called attention to the importance of the Gulf of Mexico on the weather over much of the United States east of the Rocky Mountains, and the need to summarize what is known about air–sea interaction and air mass modification over the Gulf. This symposium provided a forum for operational and research meteorologists and oceanographers to present and discuss the state of knowledge of air–sea interaction and air mass modification over the Gulf, and to provide the basis for improved numerical models and weather forecasts particularly for the Gulf coast area. However, areas other than the Gulf were considered in some of the papers.

The symposium was divided into four sessions. They were: 1) Measurements; 2) Air Mass Modification; 3) Modeling, and; 4) Forecasting. It was recognized by the planning committee that overlap between the sessions was inevitable, but this breakdown seemed to best characterize the papers and the themes of the symposium.

3. Session summaries

a. Session 1. measurements. (James R. Scoggins, CIAMS, chair)

The first paper "Analysis of Gulf of Mexico return flow in the cool season using satellite imagery," was authored by Robert Rabin, NSSL, Lynn A. McMurdie, University of Washington, and Christopher M. Hayden and Gary S. Wade, University of Wisconsin. They investigated spatial and temporal changes of atmospheric water vapor and surface wind speed during periods following intrusions of polar air over the Gulf of Mexico. The investigations occurred during the Gulf of Mexico Experiment (GUFMEX) in February and March 1988 and during the winter of 1989–90. Microwave and infrared satellite measurements from the Special Sensor Microwave/Imager (SSM/I) instrument aboard the Defense Meteorological Satellite F8 and from the GOES VISSR Atmospheric Sounder (VAS) were used to augment the sparse coverage of rawinsonde sites and surface reports in the vicinity of the Gulf of Mexico.

The authors concluded: 1) microwave and infrared satellite data depict precipitable water and wind speed evolution associated with cold frontal passages and moisture return in the Gulf of Mexico. The data reveal features not evident in visible satellite imagery or in the rawinsonde network. 2) The rms difference between SSM/I, VAS, and rawinsonde estimates of precipitable water is within 3–4 mm. 3) Estimates of VAS-derived precipitable water have a slight high bias compared to SSM/I and rawinsonde. 4) Estimates of precipitable water in layers above and below 850 mb from VAS compare favorably to rawinsondes. However, the VAS underestimates the water content of the lower layer when the majority of the total moisture is confined below 850 mb. 5) Estimates of precipitable water from
SSM/I and VAS are complementary and can be used effectively in data sparse regions. 6) SSM/I and NGM 12-h forecast estimates of precipitable water reveal similar features. However, the NGM does not typically exhibit as much detail as the SSM/I. 7) SSM/I and NGM 12-h forecasts give comparable estimates of the atmospheric storage term in the water budget equation. Further studies are necessary to determine the applicability of satellite data to estimate other terms of the equation (i.e., flux divergence, evaporation).

The next paper, "Analysis of surface fluxes in the marine atmospheric boundary layer in the vicinity of rapidly intensifying cyclones," was presented by Gennarino H. Crescenti and Robert A. Weller, Woods Hole Oceanographic Institute. These authors computed surface fluxes of heat, moisture, radiation, and momentum from meteorological and oceanographic data taken at a mooring with a surface buoy during the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA), 1 December 1988 to 28 February 1989. The Severe Environment Surface Mooring (SESMOOR) was developed in order to make long-term meteorological and near surface oceanographic measurements in areas where harsh environmental conditions prevail. SESMOOR was deployed on 17 October 1988 in 2984 m of water on the eastern edge of the ERICA storm region. The mooring was located about 300 km southeast of Nova Scotia and slightly north of the Gulf Stream. SESMOOR was recovered after 141 days at sea on 7 March 1989. During ERICA, eight Intensive Observation Periods (IOP) were initiated to study rapidly intensifying cyclones. Three of these periods were examined using SESMOOR data including one case when a storm passed within 100 km of the buoy.

Conclusions reached in this study were: 1) SESMOOR demonstrated the capability of obtaining reliable and high quality meteorological and near surface oceanographic measurements in an area where harsh environmental conditions prevail. The only major failures were that of the 20- and 50-m current meters. These failures were attributed to commercial fishing lines which tangled the VMCM propellers. 2) The three case studies showed that surface heat flux was generally quite large during the cold air outbreaks preceding and following the storms. However, the heat lost by the ocean over the course of each storm was at least an order of magnitude smaller than the total heat content of the upper 20-m ocean layer. 3) An examination of the momentum transfer at the air–sea interface showed that the upper 20-m ocean layer was forced by the atmospheric wind.

Robert M. Aune, University of Wisconsin, presented the last paper in this session, "Impact of VAS precipitable water retrievals on a numerical simulation of return flow in the Gulf of Mexico." He examined the impact of assimilating precipitable water retrievals from the VISSR Atmospheric Sounder (VAS) on a numerical simulation of a return flow event in the Gulf of Mexico. Two case studies during GUFMEX of numerical forecasts with and without the VAS precipitable water data were compared to determine what impact the data have on the predicted 3-dimensional return flow moisture field. His conclusions were: 1) VAS precipitable water retrievals impacted the analysis of moisture in the Gulf of Mexico. This should improve the prediction of vertical stability in return flow air. 2) It may be necessary to use 4-dimensional visualizations of model simulations to identify the numerous air mass modification processes that have an impact on the return flow.

b. Session 2. air mass modification (Robert C. Willems, INO, chair)

The first paper in this session, "Synoptic analysis of the GUFMEX return flow event of 10–12 March 1988," was presented by Robert T. Merrill, University of Wisconsin. Merrill presented a rapid return flow case from 10–12 March 1988 using GUFMEX data. The complexity of the synoptic meteorology in the Western Gulf of Mexico was stressed with the possibility of five distinct air masses over Texas and the adjacent coastal waters during the late winter and spring. Although the analysis of return flow often times tends to be simplified, the relative roles of the diabatic and advective processes in airmass transformation revealed distinct dominating processes during different phases of return flow. On 10 March, NOAA P-3 flights into the developing western Gulf of Mexico return flow indicated three distinct vertically stacked air masses below 3 km: an incompletely modified polar air mass at the surface, above it a thin moist layer possibly of tropical origin and, finally, a continental tropical air mass, likely originating from the Mexican plateau which was found to play a key role in return flow. Modifications of this layered air mass were dependent on the moisture above the PBL, the initial theta of the PBL, and large scale divergence from above. The flight on 11 March revealed that despite strong southerly wind flow, maritime tropical air near the surface in the Bay of Campeche did not advance poleward.

Using observations from aircraft, rawinsonde, and satellite, the synoptic analysis of 12 March revealed that the low-level jet which developed into Texas earlier in the return flow cycle had shifted eastward into Louisiana. In the cool return flow, the capping inversion on top of the moist low-level air was part of the return flow. The very shallow southerly return flow over the extreme upper Texas coast and west Louisiana area was bounded by dry adiabatic continental
tropical air to the west and continental polar air to the east. Cross sections showed the return flow expanding both in areal coverage and depth over time. A perturbation in the low clouds also hinted at the existence of a gravity wave. Merrill concluded that: 1) advection dominates maritime tropical return air, 2) air mass transformation dominates "cool return" flow, and 3) return flow can occur independently at the surface and aloft.

John M. Lewis, and Charlie Crisp, NSSL, were authors of the next paper, "Return flow in the Gulf of Mexico: A taxonomical study." Transient synoptic circulation patterns during the cool season that occur over the Gulf of Mexico and adjacent coastal plains cause an alternating sequence of offshore and onshore flow. Return flow typically refers to the return of modified air to the continent once it has penetrated the Gulf of Mexico and swung back around. The authors pointed out the lack of history of return flow studies in the English language literature although, in China, there are extensive studies especially with the "Yellow Sea High." They stressed that return flow was a complex combination of midlatitude and tropical meteorology. Air masses entering the Gulf of Mexico were classified according to H. C. Willet's classical work on North American Air Mass Analysis, i.e., air masses were classified into three categories: 1) maritime polar, 2) continental polar, or 3) a mixture of different maritime polar and continental polar. Maritime polar usually breaks off from the north Pacific high while continental polar originates in the Siberian high.

Lewis et al. studied a 12-year history of return flow during which 134 events were recorded. Preliminary statistics summarize that: 1) an average of six events occur in February and six events in March, giving an average of five days per cycle; 2) duration of offshore flow depends on air mass type and is approximately 24-30 h for mP, 60 h for cP, and 40 h for a mixed air mass; and 3) the duration of return flow is about 43-48 h for each type of air mass.

By examining the several cases of GUFMEX, they concluded that: 1) trajectories of boundary layer air are very sensitive to the speed and duration of the high pressure center; 2) transformation of air masses depends strongly on the trajectory relative to the loop current and warm waters of the Gulf; and 3) modifications studied with the aid of upper-air measurements from the USCG ship Salvia on 21–28 February 1988 indicated that the modification of the air mass was significantly different, as expected, on the outward-bound portion of the trajectory (unstable air) and the portion over progressively colder water when the boundary layer becomes unstable.

S. A. Hsu, LSU, presented the next paper, "Effects of air–sea interaction on frontal overrunning characteristics along the central Gulf coast." Hsu investigated the effects of air–sea interaction on frontal overrunning, both synoptically and climatologically, along the U.S. Gulf coast and northern Gulf of Mexico. He analyzed the temperature fields along the central Gulf region over land, shelf water, and deep Gulf water. From these, he found that from May through September, a barotropic zone prevails along the Gulf. However, following cold air outbreaks from October through April, baroclinicity between the shelf water and deep water is increased as the shelf waters become colder. A temperature difference of 7°C can exist between shelf and deep water while only 0.5°C exists between the land and shelf water. Therefore, during the winter, the east-west orientation of the continental shelf break becomes more important than the physical coastline because fronts tend to stall and become stationary along this baroclinic zone rather than at the coast, resulting in overrunning. Cyclogenesis over the Gulf was associated with frontal overrunning. The difference in temperature was enough to set up a vorticity field and thus cyclogenesis. Unstable or convective conditions prevail in the Gulf especially in the winter. The most convective regions were found to be over the continental shelf break region, while the most stable region in the Gulf was in the west Louisiana and upper-Texas shelf waters.

Hsu presented some useful nomograms showing the frequency of overrunning in the Gulf coast versus sea surface temperature and vorticity. Using a 29-year database at New Orleans, the frequency of frontal overrunning was explained by computing the slope of the front for each month using a kinematic equation. From November through March, the slopes were shallower than 1/1000 with frequency of overrunning over 20% per month. A significantly high correlation of 0.95 from linear regression was found between monthly frequency of frontal overrunning at New Orleans and the difference in air temperature between the deep Gulf (buoy 42001) and New Orleans. A high correlation coefficient of 0.86 was also found between vorticity over the Louisiana/Texas shelf using LCH and the frequency of frontal overrunning.

The last paper in this session, "A study of cold air modification over the Gulf of Mexico using in situ data and mixed layer modeling," was authored by Quingfu Liu and J. M. Schneider, University of Oklahoma. Cold air outbreaks into the warmer Gulf of Mexico are subjected to air modification from heating and turbulence, resulting in a mixed marine boundary layer. Although many properties tend to be distributed vertically homogeneous in the mixed marine boundary layer, the depth and properties of the mixed layer will continuously change with time. Liu and Schneider used an integrated (or slab) model to predict this time
dependence as a function of initial and boundary conditions. Aircraft data and CLASS observations from the GUFMEX experiment were used to assess applicability of this simple 1D modeling to flows over the Gulf of Mexico. The integrated (slab) mixed-layer models developed earlier by other authors apply only to an unstable situation without deep convection. This mixed-layer model includes four physical mechanisms in a cloud-free marine boundary layer: entrainment, surface fluxes, wind shear, and subsidence. In Liu and Schneider’s model, the diabatic heating term is neglected in the equations since its magnitude is smaller than the turbulent effect. Therefore, the mixed layer as presented was controlled by surface characteristics and upper-boundary conditions. The numerical results indicated good agreement between the predictions and measurements of marine boundary height, and the potential temperature and specific humidity in the mixed layer. The sensitivity analysis showed that the mixed-layer height is sensitive to sea surface temperature; however, the other mean characteristics in the mixed layer were relatively insensitive to the input parameter. The slab models were found to be adequate for practical prediction of the mean characteristics of the marine boundary layer during cold air outbreaks over the Gulf of Mexico.

c. Session 3. modeling (William Evans, TIO, chair) Wendall A. Nuss, NPS, presented the first paper “Marine boundary layer and surface frontogenesis in numerical simulation of an ocean cyclone.” The analysis of numerical model simulations of GALE IOP 9 revealed a significant interaction of boundary layer and baroclinic processes in the warm frontal region of an oceanic cyclone. The interaction of baroclinic processes and air–sea interaction processes were important for establishing the surface frontogenesis in this ocean cyclone. Although the contributions by the air–sea interaction processes were relatively small at any instant in the simulation, their feedback on the baroclinic structure and processes was important. The generality is being tested in other cases.

Nuss drew the following conclusions from this case study: 1) early in the cyclogenesis surface heating maximizes over the Gulf Stream to establish a gradient of surface heating that contributes to intensifying the surface thermal gradient along the Gulf Stream. This direct contribution to surface frontogenesis decreases as the cyclone intensifies and moves northeastward across the Gulf Stream due to an increase in low-level warm advection. The importance of this surface heating process for other cyclones apparently depends upon the degree of low-level warm advection relative to the surface heating magnitude. 2) Vertical motion along the surface warm front is forced by both baroclinic processes and the curl of the surface stress (frictional convergence). Initially the curl of the surface stress contribution is secondary to the baroclinic processes but becomes dominant as the shear in the geostrophic wind across the front increases. Differential momentum mixing due to boundary layer stability differences across the front help to concentrate this frictional convergence which is largely established by the distribution of surface geostrophic winds. 3) Thermal wind turning within the baroclinic zone established along the Gulf Stream by the surface heating gradient was important for producing the surface wind distribution that yields frontogenesis in this region. Winds above the boundary layer are rotated into a confluent flow by thermal wind effects in the boundary layer and friction acts to enhance this surface convergence. Once the baroclinic zone is established by the heating, the associated boundary layer thermal wind turning maintains substantial frictional convergence for the duration of the cyclogenesis even after the front has propagated north of the Gulf Stream.

The second paper in this session, “A study of air-mass modification over the Gulf of Mexico using a cloud ensemble model,” was by S. T. Soong, University of California-Davis and John Lewis, NSSL. This paper analyzes two cases of return flow during GUFMEX. A cloud ensemble model was used to investigate the modification of the low-level air mass by heat and moisture fluxes from the warm sea surface, and the effect of vertical velocity and horizontal advection of temperature and moisture on the stability of the return flow and the possibility of storm formation. The model includes microphysical processes with cloud, rain, ice, snow, and graupel, and a turbulence scheme based on turbulent kinetic energy. Two cases of the cold air outbreak and return flow during GUFMEX were considered. In one case, the return flow produced only shallow convection over the coast. In the other, it produced storms and heavy precipitation. In both cases, the underlying sea surface temperatures were similar but the stabilities of the resulting return flows were quite different. The major differences between the two cases lie in the difference in large scale vertical velocity and the horizontal advection of temperature.

The next paper, “Airmass modification during GUFMEX as forecast with a mesoscale model and an airmass transformation boundary layer model” was authored by Stephen D. Burk and William T. Thompson, NOARL. These authors examined airmass transformation processes that occurred during GALE IOP-2 and GUFMEX. They used a 1D model with high vertical resolution within the boundary layer, and a 3-D mesoscale model which is a version of the Navy’s operational regional model with a nested high-resolu-
tion boundary layer capability. The mesoscale model was used to analyze the GALE IOP-2 data off the Carolina coast. They found that the warming, deepening, and destabilization of the boundary layer as the air crossed the shelf and moved out beyond the Gulf Stream was well captured by the model. This conclusion was based on comparisons between model forecasts and observations made by GALE aircraft, raobs, and surface reports including buoys.

Both the 1D and 3D models were used in the GUFMEX part of the study to examine three aspects of airmass modification. These aspects were: 1) the thermodynamic structure of the air mass that had circulated out over the Gulf and returned; 2) the extent to which the models accurately characterize the thermodynamic transformations which occur along the Texas-Louisiana coast when the return flow is re-established; and 3) the insight provided by the models relative to differential advection and boundary layer processes which can produce severe weather. The authors concluded: 1) strong surface fluxes substantially alter the cold, dry air initially pushing southward from the continent out over the warm Loop current; 2) the extent to which the models accurately characterize the thermodynamic transformations which occur along the Texas-Louisiana coast when the return flow is re-established; and 3) the insight provided by the models relative to differential advection and boundary layer processes which can produce severe weather. The authors concluded: 1) strong surface fluxes substantially alter the cold, dry air initially pushing southward from the continent out over the warm Loop current; 2) The thermodynamic structure of the air in the return flow along the Texas coast was complex. This return flow contained at various levels air that had circulated out over the Gulf and returned, subtropical air from the vicinity of the Yucatan, and dry air from the mountainous regions of Mexico.

“Ocean-atmospheres in the Tropics (A review of recent theories and models),” was presented by George Philander, Princeton University. Philander considered several coupled ocean-atmosphere models as a means for examining the Southern Oscillation. He noted that some models successfully simulate a Southern Oscillation while others do not, and that those that fail are too ambitious—they attempt to reproduce not only interannual variability but the time-mean state of both the ocean and atmosphere as well. Models in which the mean states are specified, so that they are anomaly models, are generally more successful. On the basis of model results, Philander discussed the relevance of models for reproducing observed phenomena.

The last paper in this session "Numerical simulation of airmass modification over the Gulf of Mexico," was presented by Jocelyn Mailhot, Recherche En Préservation Numerique, Quebec. Mailhot used the Canadian regional finite-element model to simulate a return flow event over the Gulf of Mexico for 9–11 March 1988 during GUFMEX. He concentrated on the rapid modification of the cold air mass by the underlying warm ocean as the air moved out over the water. His investigation focused on air–sea fluxes and the vertical destabilization of the air mass. Through comparisons between model results and observed data, Mailhot reached the following conclusions: 1) a realistic numerical simulation of the air mass transformation can be obtained; 2) a strong interplay between large-scale subsidence occurring behind the cold front and destabilization of the cold airmass takes place near the sea surface; 3) above the PBL, advective processes play a central role in the modification of the air mass and in the maintenance of a strong capping inversion; and 4) within the PBL itself, the dominant mechanisms are surface heat flux, evaporation from the sea surface, and vigorous vertical mixing.

d. Session 4. forecasting (Stephen Rinard, NWS-SR, chair)

The first paper in this session, “Some aspects of forecasting severe thunderstorms during the cool-season return flow episodes,” was presented by Steven Weiss, NSSFC. National Meteorological Center operational model performance was evaluated during the synoptic evolution of three cool-season return flow episodes. The Aviation (AVN) model provided the best overall 48-h forecasts of anticyclone movement and intensity, as well as the development of return flow over the Gulf of Mexico. Although the LFM predictions contained large systematic errors, it was noted that forecaster knowledge of these biases can be used to improve the resultant forecast. It was also shown that the performance of operational severe weather outlooks issued by NSSFC during GUFMEX were correlated with the antecedent conditions of low-level moisture and airmass stability present along the Gulf coast prior to the issuance of the outlooks. The accuracy of the NGM lifted index predictions was also found to influence the skill of the outlooks. Implications concerning lack of data over the Gulf vs. improper model physics in resolving forecast errors were discussed.

Weiss concluded the following: 1) the LFM moves anticyclones eastward too rapidly and lowers central pressure too much, averaging 5 mb too low at the 48-h forecast. In contrast, the AVN and NGM showed little in the way of systematic directional errors and only a small underforecast bias in central pressure. The AVN displayed the best overall skill in anticyclone forecasting. 2) The prediction of surface pressure along the Gulf coast showed similar results. The AVN and NGM exhibited a small underforecast bias, with the mean AVN error of -0.4 mb being the smallest. The LFM substantially underforecast surface pressure along the coast averaging nearly 8 mb too low at 48 h. 3) The AVN and NGM both had good success in predicting the onset and areal extent of return flow. The LFM
overforecast the occurrence of return flow, predicted the onset 24–36 h too soon and opened the Gulf too quickly from west-to-east. 4) The skill of the initial second-day severe outlooks during GUFMEX correlated well with antecedent conditions of low-level moisture and airmass stability present along the coast prior to the issuance of the outlooks. A moist, unstable air mass was already present before good outlooks were issued, whereas a relatively dry stable air mass was noted before false alarm outlooks were issued. 5) NGM 48-h forecasts of lifted index used as input to the false alarm outlooks were excessively unstable, averaging 8°C too low over the lower Mississippi valley region. For the good outlook cases the grid-averaged error was one-half the error of the false alarm outlooks, with much smaller errors near the Gulf coast.

Next, Ken Davidson, NPS, presented the paper, “Forecasting boundary layer phenomena in coastal regions.” Davidson reported that atmospheric layer properties and processes in Gulf and coastal regions have special characteristics that are important in forecasting evolving mesoscale as well as synoptic-scale circulations. The coastal regime has a unique drag coefficient, and wind-wave coupling is a factor in forcing. Davidson also indicated that low inversion and sea surface temperature (SST) gradients present unique coastal wind conditions. Finally, many of the phenomena are mesoscale in nature.

The last paper in this session was entitled, “Operational model performance in return flow episodes during the cool season,” by Paul Janish and Steven Lyons, C1AMS. Janish presented the paper and showed that the NGM 48-h forecasts of moisture are in serious error following the cold air outbreak over the Gulf. The model appears to advect the moisture gradient over the Gulf rather than modify the air mass as is observed. NGM analysis and observations indicate that much of the NGM forecast error is due to model physics and not due to poor or inadequate model initialization (at least for the forecasts diagnosed in this study).

Janish reported that the character of the return flow shows a definite relationship to the height of the observed inversion and the low-level jet (LLJ). The LLJ is maximum near the 850-mb level, is associated with strong and ageostrophic southerly flow, and is highly correlated with the amount of lee mountain troughing east of the Rockies. He indicated also that prior to the setup of return flow, a trough is observed to develop in the lee of the Rockies and is most pronounced at 850 mb. The development of this wave can be observed 36-48 h prior to the onset of the return flow in some cases, and is always present in cases of strong return flows.

NGM 48-h forecasts do not resolve or properly predict the observed temperature inversion in the 800–850-mb layer during the return flow. This results in a misinterpretation of the vertical moisture content of the air, the depth of the moist layer, and the character of the low-level jet.

4. Future plans

A summary of each paper presented at the symposium and tentative conclusions reached by the authors are presented here in order to get important results to the scientific community as quickly as possible. The sponsors, planning committee, and authors agreed that each paper would be submitted for publication in an appropriate AMS journal. Our plans are to request that the editor of the journal considered most appropriate reserve a special issue for these papers. The conclusions presented herein must be considered tentative until the papers appear in the journal.

References
