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Northeastern Gulf of Mexico Physical Oceanography Program: Eddy Monitoring and Remote Sensing

First Annual Report

MMS U.S. Department of the Interior
Minerals Management Service
Gulf of Mexico OCS Region

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Northeastern Gulf of Mexico Physical Oceanography Program: Eddy Monitoring and Remote Sensing

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Authors

Frank E. Muller-Karger
Fred Vukovich
Robert Leben
Bisman Nababan
Doug Myhre

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by
University of South Florida
Department of Marine Science
140 Seventh Avenue South
St. Petersburg, Florida 33701

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NORTHEASTERN GULF OF MEXICO PHYSICAL OCEANOGRAPHY PROGRAM: EDDY MONITORING AND REMOTE SENSING

INTRODUCTION

To properly manage shelf resources, we need to better understand processes in the ocean and be able to assess oceanic variability over large space and time scales. In particular, it is critical to understand the motion of waters within a region to assess the potential consequences of possible spills derived from oceanic, shelf, and coastal mining industries. This Cooperative Agreement between the University of South Florida (USF) and the Minerals Management Service (MMS) was established to jointly assess the value of merged satellite data and specific oceanographic field data in determining the circulation and biological productivity of waters within the NE Gulf of Mexico. The effort centers around collecting, processing, and merging historical and concurrent Infrared, Radar-Altimetry, and Ocean Color satellite data as well as selected *in situ* information. We use various national and international sensors based upon availability of the data, honoring restrictions in the use and distribution of such data.

We have developed a set of software tools to generate products which represent merged satellite data and field measurements. Specifically, we incorporate drifting buoy trajectories obtained through collaboration with other MMS programs being carried out in the Gulf of Mexico. We interact with MMS-supported groups to interpret satellite and field data. Through this Cooperative Agreement, the various groups tasked by MMS to carry out environmental studies in the Northeastern Gulf of Mexico obtain the most effective synoptic and regional satellite coverage of the study area. In addition, we participate in a limited number of MMS-supported field campaigns, in an effort to validate the satellite data products.

OBJECTIVES AND HYPOTHESES

General Objectives

The primary goal of this work is to assess the utility of merging specific satellite and field data sets in quantifying the magnitude and variability of water movement in the Northeastern Gulf of Mexico. Specifically, we seek to document and to better understand the behavior of the Loop Current, eddies shed by the Loop Current, the circulation of waters over the shelf and along the coast of the NE Gulf of Mexico, and the interaction between offshore and shelf waters. We have developed a strategy to derive new products useful to MMS and other interested parties for monitoring the circulation of the region by combining several different data sets. With these, we expect to update historical statistics on major oceanographic features observed in the region. Our goal is to publish the results of these analysis in the peer-reviewed literature.

Specific Scientific Objectives

The scientific goals of the proposed remote sensing activity are to:

a) assess the utility of the data products to examine regional time and space variability in circulation of the northeastern Gulf of Mexico, including the continental shelf;
b) assess the utility of the data products to quantify the variability in the dispersal pattern of coastal materials including river discharge;
c) assess the utility of the data products to quantify the variability in sea surface temperature patterns; specifically, define the spatial extent of the Loop Current and associated eddies; upwelling phenomena associated with wind or the interaction of offshore currents with the continental shelf, and seasonal variation;
d) assess the utility of the data products to quantify the regional wind stress and determine whether there is spatial and temporal correlation between field and satellite-observed winds, and visible, altimetric, and infrared signals;

e) determine whether there is a relationship between sea level changes determined with satellite altimeters and atmospheric forcing, sea surface temperature, or pigment concentration;
f) determine whether there is a relationship between sea level changes determined with satellite altimeters and drifting buoy tracks;
g) integrate the results of the synoptic satellite data analyses with results of other MMS field programs to address environmental impact assessment along the US continental margin in this region.

In addition, we provide a satellite data feed to support the companion MMS Interagency Agreement between MMS and the US Geological Survey (Program Manager: Rick Stumpf), which is charged with distributing satellite data products.

PROPOSED RESEARCH

This MMS-USF Cooperative Agreement seeks to:

a) collect and process selected satellite time series data; specifically, generate:
AVHRR Sea Surface Temperature distribution fields,
TOPEX and ERS-1 Radar Altimetry Sea Surface Height fields, and
SeaWiFS ocean color-derived pigment concentrations if available;

b) Merge satellite data products. This includes generating the following products:
- Merged Sea surface height fields from TOPEX/ERS-1 data and Sea Surface Temperature fields from the AVHRR sensor on the NOAA Polar Orbiters;
- Merged Sea surface height fields from TOPEX/ERS-1 data and Ocean Color Pigment Products from SeaWiFS, based on availability and honoring specific data distribution restrictions (see below);
- Sea Surface Temperature fields from the AVHRR and Ocean Color Pigment Products from SeaWiFS, based on availability and honoring specific data distribution restrictions (see below);

c) Merge satellite and field data products from companion operational projects sponsored by the MMS, specifically concurrent buoy track, hydrographic, and wind velocity data. This includes merging Sea surface height fields from TOPEX/ERS-1 and sea-surface drifting buoy trajectories obtained through collaborative efforts with companion operational MMS programs. Merged products will depend on the availability of the ancillary data.

METHODS

Satellite Data Compilation

SeaWiFS and Other Satellite Ocean Color Data

The University of South Florida (USF) is a NASA-designated repository for the global CZCS data. These holdings include the 1 km data collected between 5S and 45N along the eastern American continental margin between 1978 and 1986. We have processed the 4-km data to various product formats. Specifically under this activity, we have produced a series of monthly pigment concentration means for the Gulf of Mexico and concerted it to 'gif' format for ease in analysis and distribution.

With the HRPT antenna installed in St. Petersburg, FL, we started collecting SeaWiFS data in September 1997, when this new sensor became operational. We have operated this antenna to collect AVHRR data since late 1993.

Pigment concentrations from the CZCS data have been estimated following Gordon et al. (1983a, 1983b). For SeaWiFS, we follow the systemic algorithms developed by McClain et al. (1995), with atmospheric correction based on Gordon and Wang (1994), and bio-optical products based on Carder et al. (1991) and Aiken et al. (1995). In general, procedures and quality control criteria will be followed as described in Muller-Karger et al. (1989). These algorithms are not finalized yet, due to issues with the calibration of the SeaWiFS, and the fact that the SeaWiFS pigment algorithms have not been finalized nor peer-reviewed to date. Therefore, these pigment products require reprocessing. To date, we have reprocessed the SeaWiFS pigment products twice, and we are preparing for a third reprocessing in July, 1998, to account for errors found in the SeaWiFS calibration. To date, approximately 100 useful SeaWiFS images are available over the NEGOM region.

All data used in this study are mapped to a spatially congruent Cylindrical Equidistant projection to permit data overlays. Adjustments to the algorithms will be considered based on the field data and will be implemented by incorporating the data directly into the bio-optical database of Kendall Carder at USF and SEABASS at the Goddard Space Flight Center. We routinely generate several products from each SeaWiFS pass, including a 1-km GOM-wide product and a 512-512 pixel, 1-km resolution map covering the NEGOM and west Florida shelf regions. Each of these products includes all the SeaWiFS Level 2 bands (water leaving radiances, chlorophyll and pigment concentration, diffuse attenuation coefficient at 490 nm, and atmospheric correction parameters). These maps are spatially congruent with similar products generated from the AVHRR data.

Advanced Very High Resolution Radiometer (AVHRR)

We have collected high resolution AVHRR data of the NE Gulf of Mexico at USF St. Petersburg since late 1993. Since the beginning of this Cooperative Agreement, we have generated a regional product covering the NEGOM, and to date, approximately 2,400 images are available over the NEGOM region. The digital sea surface temperature products from the antenna are routinely delivered up to 8 times per day in real time. The AVHRR imagery is processed and mapped to Cylindrical Equidistant projection grids. We routinely generate several products from each AVHRR pass, including a 1-km GOM-wide product and a 512-512 pixel, 1-km resolution map covering the NEGOM and west Florida shelf regions. These maps are spatially congruent with similar products generated from the SeaWiFS data.

We use the Multichannel Sea Surface Temperature (MCSST) products using the split window techniques (Walton, 1988; Strong and McClain, 1984; McClain et al., 1983) and up-to-date NOAA calibration coefficients. We preprocess the data for clouds and land following techniques similar to those described by Wick et al. (1992). Overview SST images, covering approximately 2,000x2,000 km within any one satellite pass, are archived for historical reference and used to examine the relationship between regional SST, *in situ* temperature observations, and weather patterns. The nominal accuracy of AVHRR SST retrievals should be in the range of ±0.3K to ±1.0 K (Brown et al., 1985; Minnett, 1991). However, decreased accuracies are usually expected within tropical regions where the atmosphere is humid. Since few *in situ* series within the region of interest have been developed or incorporated into the MCSST algorithm, MCSST values are suspect. We expect that the MMS time series measurements and field programs will help assess the accuracy of these products.

The MMS buoys may also help assess the problem of the skin vs. bulk temperature difference for ocean environments. Operational MCSST products are based on algorithms derived from empirical comparisons between drifting buoys and satellite infrared measurements (Walton, 1988; Strong and McClain, 1984; McClain et al, 1983). These buoys drift, for the most part, in deep ocean environments. However, radiometers sense radiation emitted from the upper few micrometers of the ocean only (Grassl, 1976). This "skin" is the top of the millimeter-thin molecular boundary layer that transports heat from a turbulent ocean below to a turbulent atmosphere above (Wick et al., 1992). There can be considerable differences between the skin temperature and the bulk temperature of sea water (Schluessel et al, 1987; Schluessel et al, 1990), and mass flux by evaporation and radiative cooling, i.e. processes that act strongly on daily and seasonal scales, lead to considerable differences (Maul, 1985, page 186). This effect therefore may mask variability in the depth dimension.

As part of our daily operations we generate Level-1b format data from each AVHRR pass and transfer each of these to the USGS (R. Stumpf) via network-ftp. We have also provided Dr. Stumpf with a link to our world wide web pages for him to serve as an additional entry point to our products. However, these links are not yet developed within the USGS. Therefore we provide access to our research products to MMS PM's via our password-protected world wide web sites.

Scatterometer (ERS-1, ERS-2)

The European Space Agency has two operational Earth Remote Sensing satellites (ERS-1 and ERS-2). ERS-1 was launched in July 1991, and ERS-2 in April 1995. Each has an Active Microwave Instrument (AMI) on board which provides both SAR and Wind (scatterometer) modes. ESA operates the AMI in Wind mode to provide, whenever possible, near-global coverage over a period of one week. Here we propose to examine the time series of AMI Wind products generated since the launch of the ERS-1 spacecraft, and continue studying the regional variability in winds as determined from ERS and NSCAT. We routinely receive the ERS scatterometer products from both the NASA JPL PO DAAC and from the French Centre ERS d'Archivage et de Traitement (CERSAT) at IFREMER, the French Ocean Research Institute. We will request NSCAT products from the NASA JPL PO DAAC and NOAA NESDIS.

We intend to develop this component of this Cooperative Agreement over the next 2 years, as the MMS meteorological initiative for the NS Gulf of Mexico develops. This new agreement will permit comparisons with the satellite data.

Altimeter (TOPEX, ERS-1, ERS-2)

The Ocean Topography Experiment (TOPEX/Poseidon) is a cooperative project between the United States and France to develop and operate an advanced satellite system dedicated to observing the Earth's oceans. The mission provides global sea level measurements with an unprecedented accuracy. The data from TOPEX/Poseidon is used to determine global ocean circulation and to understand how the oceans interact with the atmosphere.

The First and Second European Remote-Sensing Satellites (ERS-1 and ERS-2) were developed by the European Space Agency as a family of multi-disciplinary Earth Observation Satellites. They orbit the Earth approximately every 100 minutes and in 35 days have covered nearly every corner of the globe at least once. Both satellites are still in good health

At the University of Colorado, when possible, TOPEX altimeter data has been blended with the European Space Agency's ERS altimeter data to produce the most accurate maps of sea surface topography in the Gulf of Mexico to date. Every three days updated maps of the sea surface topography in the Gulf of Mexico are created, and products are interpolated to generate a daily rendition of the sea surface dynamic height. Sea surface height anomalies are estimated by referencing the corrected sea surface height relative to an accurate mean sea surface. Maps produced using data referenced in this manner show only circulation anomalies. The sea surface height deflection caused by mean currents such as the Loop Current are absent from these maps. An estimate of the total sea surface height is made by adding the mean circulation calculated using a numerical ocean model of the Gulf of Mexico.

Maps of sea surface height anomalies and sea surface topography are provided by the Colorado Center for Astrodynamics Research (CCAR) to the University of South Florida (USF) for blending with AVHRR and ocean color imagery and in situ data. Altimetry-derived maps based on historical data collected from T/P and ERS 1&2 and will benefit from tandem altimetric coverage of the region. T/P data are available from October 1992 to the present. ERS 1/2 data suitable for oceanographic studies are available from April 1992 to the present. No ERS data is available during January through April 1994, because the ERS 1 satellite was in a 3-day repeat orbit for ice mapping. Near-real-time altimetry from T/P and ERS 2 are also provided to USF. Tandem coverage is expected from T/P and ERS 2 through the end of the century.

Fast delivery TOPEX and ERS 2 geophysical data records (GDRs) are routinely combined to produce the best possible nowcast of the circulation in the Gulf of Mexico. TOPEX interim GDRs are available from JPL via the Naval Oceanographic Office(NAVO) within 8 hours and NOAA provides RGDRs from ERS 2 within 24 hours of overflight. An updated 'hindcast' is generated once the model is validated with various field data. The along-track data from both satellites are filtered to remove orbit and pathlength corrections errors after referencing the data to the Ohio State University mean sea surface (OSUMSS95). The planned update interval for interpolated maps is every three days. Raw data and along-track format data is provided as soon as processed. An interactive Web form allows the user to interactively plot selected formats or download the raw data. However, we have direct access via on-line ftp to the gridded daily fields.

Field Program

We have teamed up with Texas A&M University (MMS PM Worth Nowlin) to collect specific field data on oceanographic cruises to the NEGOM. These cruises provide an extensive, high quality hydrography and chemical oceanographic background against which we collect detailed phytoplankton pigment and bio-optical observations. This will serve to characterize regional waters and to validate the regional SeaWiFS products that are processed systematically under this activity.

Validation of SeaWiFS products is a multi-step process. First, the sensor must provide top-of-the-atmosphere radiances that are consistent with the sum of path radiances (including skylight reflectances) and water-leaving radiances diffusely transmitted through the atmosphere. The process of atmospheric correction must be robust enough that turbid-water reflectances in the infrared are not falsely interpreted as aerosol scattering. To help this step, measure the reflectance spectrum of the ocean. We also measure relevant constituents in the water, and their optical properties. We are preparing now to correctly identify water-column path radiance and attenuation, and to properly interpret bottom reflectance (if any), to derive accurate products. We will conduct a series of comparisons between the field data and the various satellite data products. At this stage, we will also assess which algorithm elements require seasonal or regional tuning.

We seek to complement the field measurements done for the TAMU Cooperative Agreement with spectral water-leaving radiance (Lw), downwelling irradiance (Ed), diffuse attenuation coefficient (K), and PAR (Kpar) measurements at CARIACO. Remote Sensing Reflectance (Rrs) is computed using both above-water and in-water instrumentation.

The bio-optical and radiometric measurements and the satellite product validation effort follow the SeaWiFS protocols (Ocean Optics Protocol for SeaWiFS Validation, SeaWiFS Tech. Report Series). Instruments are calibrated at the manufacturer's laboratories at least twice per year at facilities that use standards and protocols traceable to the National Institute of Standards and Technology (NIST).

The procedures used to interpret data from submersible optical instrumentation (SeaWiFS protocols) are currently limited and produce spurious results near the surface. This leads to erroneous estimates of optical quantities such as Rrs and PAR. The limitations are most severe in Case II waters (waters which are highly affected by suspended particles, dissolved organic matter and terrigenous particles from rivers). The NEGOM may experience Case II situations both during peak upwelling around the DeSoto Canyon as well as during peak river discharge seasons during the spring freshet or when the Mississippi or Mobile River plumes affect the region. The river plumes are clearly a Case II situation (Gilbes et al., 1996).

There are two schools of thought regarding estimates of Remote Sensing Reflectance (Rrs): one uses profiling instruments such as the Biospherical 2040 Multichannel Environmental Radiometer (MER), and a smaller group that advocates use of above-water spectral instrumentation such as the Photo-Research PR650 or other spectrometers for measuring the color of water. Above-surface instruments could be an effective way to validate SeaWiFS or conduct rapid environmental assessment from other platforms such as aircraft or ships. Further, many above-water instruments such as the PR650 are hyperspectral, as opposed to the 13 channel MER 2040-class radiometers. Hyperspectral data may be useful to infer the composition of optical constituents, if it were possible to reconcile the submersible and above-water measurements.

Surprisingly, there have been very few systematic comparisons of the oceanic reflectance measured by these two types of instruments. While procedures to process radiance/irradiance profile data remain crude, we are just beginning to understand the observations made from above-water instruments.

With submersible instrumentation, it is commonly assumed that unreliable data exist from the surface to some predetermined depth (e.g. 0-15 m). Data collected near the bottom are also considered suspect. Some advocate discarding these data, which however, may be useful data. Others use all data, including those distorted by environmental conditions such as waves, sun glint, and bottom reflection. A major limitation in making shipboard measurements has been the lack of time to perform even a minimum quality check to assure data reliability, prior to leaving the sample site. The NEGOM cruises offer the unique opportunity to sample various types of waters to address these issues. This permits the testing of hypotheses regarding the quality of the emergent light field as seen from satellites, which observe the ocean at different times of the day, or from varying azimuths, elevations, and at varying scan angles.

In collaboration with TAMU, we have established a routine for collecting an extensive suite of hydrographic and biological data during NEGOM cruises. We collect the following:

Above-water spectral remote-sensing reflectance (Rrs, 380-700 nm) is measured using a calibrated, hand-held radiometer (8 nm resolution), using protocols refined by K. Carder and H. Hochman (USF). These include definitions for view angles and sky-radiance corrections. We will modify these according to the recommendations of the SeaWiFS SIRREX held at NIST in July 1996 (Co-Investigator H. Hochman participated in these meetings). This equipment is currently available at no cost to this study. The basic algorithm for Rrs, using two instruments (one to measure radiance, the other irradiance) is:

$Rrs(0+,\lambda) = L_w(\lambda)/Ed(\lambda)$, where:

$Ed(\lambda)$ = Incident Spectral Irradiance (Use of Cos Collector)
$L_w(\lambda) = L_t(\lambda,\theta) - r(\lambda,\theta)L_{sky}(\lambda,\theta)$, where:
$L_t(\lambda,\theta)$ = Total measured surface radiance
$r(\lambda,\theta)$ = Fresnel water reflectance
$L_{sky}(\lambda,\theta)$ = Direct Sky Radiance
$Ed(\lambda)$ = Incident Spectral Irradiance (Use of Cos Collector)

Alternatively, we use a single instrument with a radiance head and estimate downwelling irradiance by measuring a calibrated grey lambertian Spectralon™ plate. In this case, we correct Rrs for 750nm=0, and the radiometer does not need to be calibrated exactly:

$Rrs`(0+,\lambda) = L_w(\lambda)/Eg(\lambda)$, where:

$Eg(\lambda) = \pi L_g(\lambda)/r_g(\lambda)$ = Plaque Spectral Irradiance
$\pi = 3.1416$
$L_g(\lambda)$ = Plaque radiance
$r_g(\lambda)$ = Plaque reflectance

The data from the profiling instrument are treated somewhat different. An ASCII file will be created which includes calibrated Ed(λ,z), Lu(λ,z), and deck solar+sky irradiance values, Es(λ), for all scans, at a minimum of 13 wavelengths (412, 443, 455, 475, 490, 510, 532, 560, 589, 625, 671, 683, and 700 nm). The lnEd(λ,z) values are examined to determine which near-surface data should be discarded and at what depth subsequent processing should begin. This depth, which can range from 1-5m will be used to define the depth at which to begin depth bins. Causes for discarded data include out-of-water measurements, wave effects, poor instrument orientation, noise, etc.

The modified ASCII file is transferred to a Unix workstation for further processing. Using a packing routine, the starting pack depth is interactively entered based on the step outlined above. The routine examines all data, eliminating spikes and dropouts, and interpolates over missing data/depths. The data are examined for outliers (+/-3σ of a 7-point bin). Bad data are replaced by interpolated values. For "clear" water conditions, the data are binned into 1 meter intervals, centered on the half-meter. When we use a MER-2040, the Ed(λ,z) values are offset to account for the 0.7 meter difference in location between the Ed(λ,z) sensor and the pressure sensor. Ed(λ,z) and Lu(λ,z) are then extrapolated to the surface using a log least-squares fit. This provides Ed(λ,0-) and Lu(λ,0-) just below the surface. In the case of "turbid" water, binning may not be applicable and extrapolation is done with raw data.

Ed(λ,0-) and Lu(λ,0-) are then normalized to the deck cell Es(λ), which measures the incident spectral radiance from the sun and sky, following the procedure of Smith and Baker (The Analysis of Ocean Optical Data, SPIE Vol. 489 1984 and SeaWiFS Technical Report #26). Using the Gordon & Ding model (L & O, 1992), Lu(λ,0-) is corrected for instrument shadow using *in situ* absorption coefficients and the sun angle as determined from an irradiance model based on the Gregg and Carder (1990) model, which we have coded in IDL. The relationships discussed in Kirk (1983) and Austin (1980), allow estimates of water-leaving radiance Lw just above the surface from subsurface Lu. We then compute the remote sensing reflectance Rrs(λ,0+). KEd(λ,z), KLu(λ,z), and Kpar are derived with a sliding regression window to obtain the slope of the least squares fit of the log-transformed normalized vertical profiles of attenuation coefficients (Smith and Baker, 1984, 1986).

We will base our bio-optical algorithm development effort on the work of Gordon et al. (1988) and Carder et al. (SeaWiFS Tech. Report in prep.; Carder et al., 1991). At chlorophyll *a* concentrations <1 mg m^{-3}, the semi-analytical relationships will be adjusted for regional discrepancies. We have implemented these models using the interactive data visualization environment IDL, linked to the atmospheric model of Gregg and Carder (1990).

Comparison of In-water and Above-water Measurements

Product validation using data collected concurrently with calibrated in-water and above-water instrumentation will constitute an important part of this study. Instruments used include the hyperspectral Photo Research Spectrascan PR650 for above-water measurements, and a MER-class submersible instrument (e.g. Biospherical Instruments MER2048/2041). We pay particular attention to details such as time of data collection relative to sky and water conditions, placement of equipment to avoid shadowing and interference, etc. Many investigators, including ourselves, have found a mismatch in products between the above-water and the profiling instruments.

Offset

Many underwater optical instruments have irradiance, radiance, and pressure sensors separated by some vertical distance. Corrections for possible errors in both time and vertical space that may be introduced by this design are now addressed in SeaWiFS Technical Report Vol. #25, Section 6.1.4 K-Analysis. Still, many users do not correct for the distance effect; some do not consider the offset in their processing, while others accommodate the distance offset, but ignore the time differential introduced by correcting for depth alone. A time differential may be important because the separate optical heads may sample different light regimes, for example wave-focusing/facet effects. Some argue that not correcting for the vertical offset counters the effects of the time offset, or that correcting the offset aliases the irradiance signal. For whatever reason, while individual K values (upwelling or downwelling) may not be affected, the Rrs value could be affected by the offset. This can lead to major errors in turbid waters. To complicate matters, binning the data (or not) may also affect the results due to the offset. We will analyze this problem with the NEGOM data.

Normalization

Normalizing the subsurface data using the deck cell irradiance measurements is recommended according to the SeaWiFS protocols, to correct for the presence of clouds. Some investigators do not normalize, because they collect sufficient profiles to choose those free from perturbations. In most instances, however, only a limited number of profiles is collected on standard cruises, due to time constraints. Some investigators have questioned the validity of normalizing because of corrections needed to account for the difference in the light field as viewed by a surface reference versus an underwater profiler. These differences are brought about by the focusing effect of the water, the weighting difference that the radiation might experience as it passes through the water, and the immersion coefficient which does not have a cosine response. This study will examine these variables to determine if the resultant error levels are within tolerance for product validation. Tests will be conducted under varying sky and water conditions and the products will be analyzed in conjunction with ancillary data to determine the best procedures to characterize optical properties.

Atmospheric Correction

In the assessment of atmospheric effects, of particular interest is the accurate estimation of L_a. To obtain a first order estimate of atmospheric effects, we will apply the algorithms implemented by the various instrument teams for each SIMBIOS-related instrument (e.g. Fukushima, Gordon, et al., unpubl., for ADEOS-OCTS; Gordon and Wang, 1994, for SeaWiFS and MODIS). In the NEGOM, over the continental margin, several different aerosol types may be present. Proper correction of products from SeaWiFS may require independent assessment of the contribution of the water reflectance to the apparent reflectance of aerosols. This problem is probably most severe closer to deltas and in river plumes, or during the rainy season due to sediments washed off adjacent coasts, or due to bottom reflection.

The University of South Florida has a full complement of satellite data processing tools. Having installed the Miami dsp software used for processing CZCS and AVHRR data, the SEADAS software and the Interactive Data Language (IDL from RSI, Inc.). We have developed a comprehensive set of IDL tools to post-process, extract, visualize, and examine CZCS, AVHRR, and ERS vector wind data from the CERSAT products.

We plan to manipulate the congruent, remapped satellite data products to examine gradients in property fields and potential cross-correlations, and address the objectives listed above.

FIRST-YEAR RESULTS

For the period covered under this study, we have collected approximately 2,400 AVHRR images (since April 1997), and about 150 SeaWiFS images (since September 1997, the date of first SeaWiFS data) over the Northeastern Gulf of Mexico. The historical CZCS data, obtained from the NASA Goddard Space Flight Center, were processed at USF to pigment products representing the concentrations of phytoplankton, and then averaged to derive a series of 92 monthly mean pigment concentration means. We have also computed monthly mean sea surface temperatures for the Gulf of Mexico for the period 1996-1998, and merged the corresponding average sea surface dynamic height with each of the SST monthly means, in the form of overlayed contours. The AVHRR data were remapped to cover only the NEGOM region.

Under the subcontract headed by Dr. Fred M. Vukovich of Science Applications International Corporation (SAIC), both Walter Johnson (MMS) and Peter Niiler (Scripps) were contacted to provide available bouy data for the Big Bend region of Florida. These data cover the period February, 1996 through May, 1997. Buoys were deployed every two weeks or 24 deployments in the Big Bend region over the period above. A total of about 335 drifters were used in the experiment.

We developed a set of software tools for purposes of overlaying drifting buoy tracks over the satellite-derived SST and altimeter maps covering the NEGOM. Our initial analysis included combining all drifter data according to launch data and plotting this on a map of the Big Bend/NEGOM region. We further mapped and overlayed monthly-mean velocity vectors derived from the drifter tracks on top of these SST/altimeter fused fields. From this study, the AVHRR images that have low SST and low dynamic sea level indicate a cyclonic circulation whereas the high SST and high dynamic sea level indicate anticyclonic circulation. Such features are particularly pronounced along the Loop Current.

The mean drifter tracks representing January, February, and March included data from drifters deployed both in 1996 and 1997. This leads to ambiguities in the directions of the vectors when compared with the AVHRR and altimeterd data over which we overlayed these. Nevertheless, the following general patterns can be inferred form the combined data sets:

In January-March, flow immediately to the east of the Mississippi delta seems to be erratic or turbulent, with vectors in adjacent 25-km cells having either northward or southward components. However, flow in the eastern portion of the NEGOM and over the west Florida shelf is distinctly and strongly (> 10 cm/s) southward. Waters here are much colder (>5^{0}C) than Loop Current waters. The Loop Current was extended about half-way north into the GOM from the Yucatan Channel, and a cyclonic eddy sat between the northern extension of the Loop Current and the NEGOM shelf. In April 1996, drifter vectors over the shelf reversed, showing a slow (< 10 cm/s) drift to the north. However, along the shelf break of the West Florida shelf proper, current vectors remained strongly southward. The cyclone north of the LC drifted somewhat to the West in May but drifted back East over the summer. By August, currents over the shelf aligned themselves to flow northward at speeds exceeding 10 cm/s. In September, currents over the shelf were to the south again (~10 cm/s), and an eddy was shed from the Loop Current. The southward flow over the shelf intensified in October. In November, while southward flow was observed over the shelf, northward flow was observed along the shelf break. In December 1996, southward flow prevailed over the West Florida shelf.

The USF AVHRR files for that period have been and continue to be examined to determine events (e.g. eddies, wind forcing, etc.) which could have an influence on that oceanographic region and that could help place the drifter track data in the appropriate context.

CONCLUSIONS

Traditionally, it is known that the AVHRR data provides substantial information on circulation patterns during the winter (October-May), when temperature gradients are strong. However, during summer (June-September), AVHRR data for the most part shows uniform sea surface temperature patterns over the NEGOM. We confirmed that the AVHRR provides information on the position of the Loop Current during summers after images are contrast-stretched. Also, significant upwelling events can be seen during summer along the periphery of the NEGOM, specifically in coasts of the Big Bend region and in the region off Pinellas and Manatee Counties (near the mouth of Tampa Bay). The historical ocean color data obtained from the CZCS shows that the pigment concentration patterns are an effective tool for tracing small scale as well as large scale circulation patterns in the GOM. These patterns are very clearly outlined during summer months, and therefore the combination of AVHRR and CZCS/SeaWiFS is very robust for outlining the position of the Loop Current, eddies, and various instability waves visible along fronts in the region. Upon merging the AVHRR sea surface temperature data with the altimeter fields, we found extremely good correlation between warm areas and elevated dynamic heights, and cool areas and low dynamic heights. Most individual drifter tracks were very close to the shore (<50 km) where there is usually uniform temperature and pigment concentration as derived using the standard NASA algorithms, and where the altimeter data are questionable. However, farther offshore, both the individual drifter tracks and the monthly-mean velocities derived from these drifters help in interpreting the direction of flow within specific features observed in the images. Features in the images seem to be stable enough so that over the period of several weeks to a month, there is correspondence between what can be observed in the ephemeral drifter tracks and the time-averaged satellite data.

The combined AVHRR, altimeter, and drifter-derived monthly velocities indicate that there is a seasonal cycle in the flow over the west Florida shelf, with southward flow during the spring and northward flow during late summer. While some very strong currents were also observed in the northern and western part of the NEGOM, currents here in general were more erratic.

We are now preparing to work the ground-truth field data obtained during the cruises to help interpret the data closer to shore.

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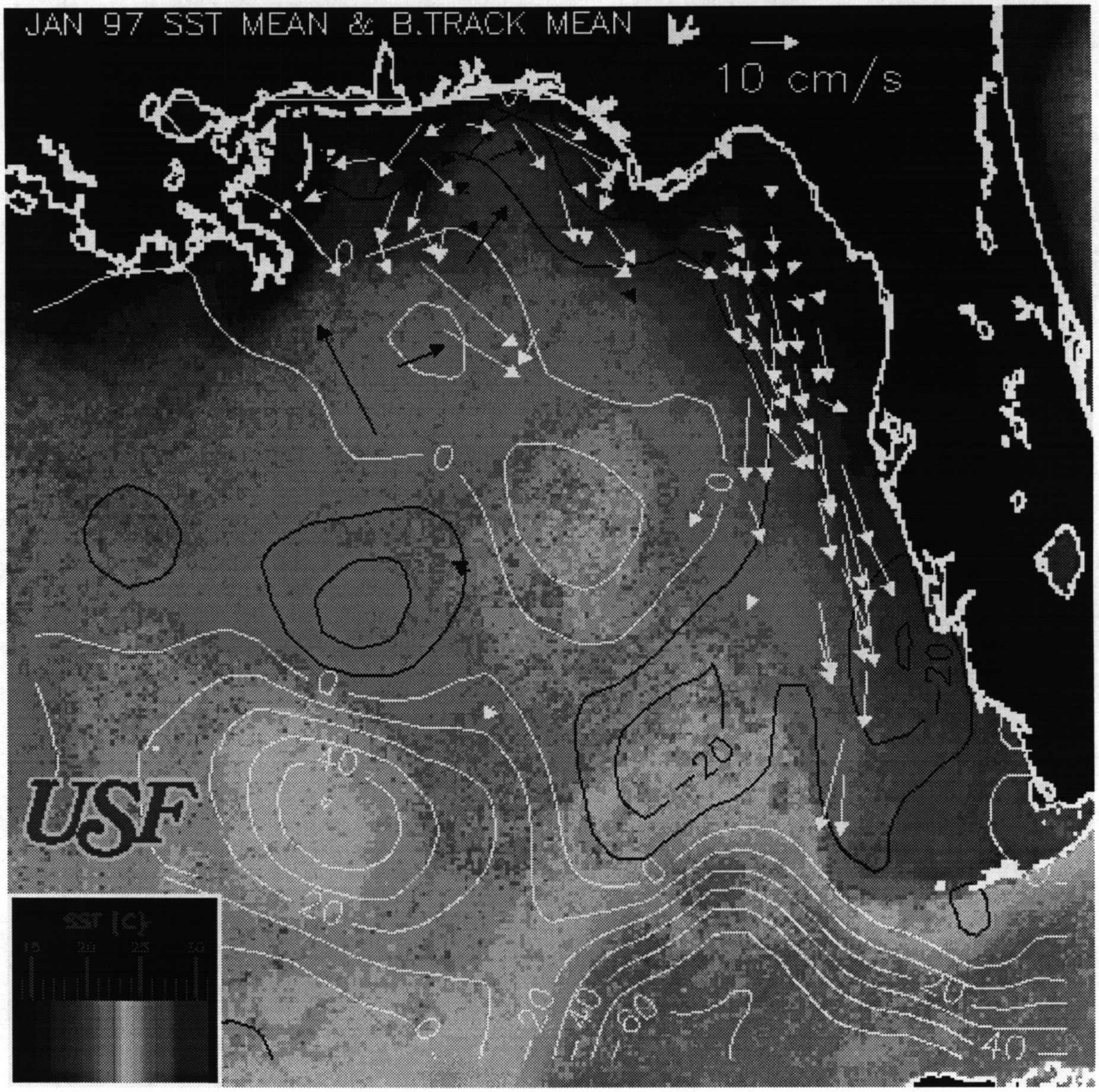


Figure 1. Dynamic Features: SST, Buoys and Altimetry (January 1996)

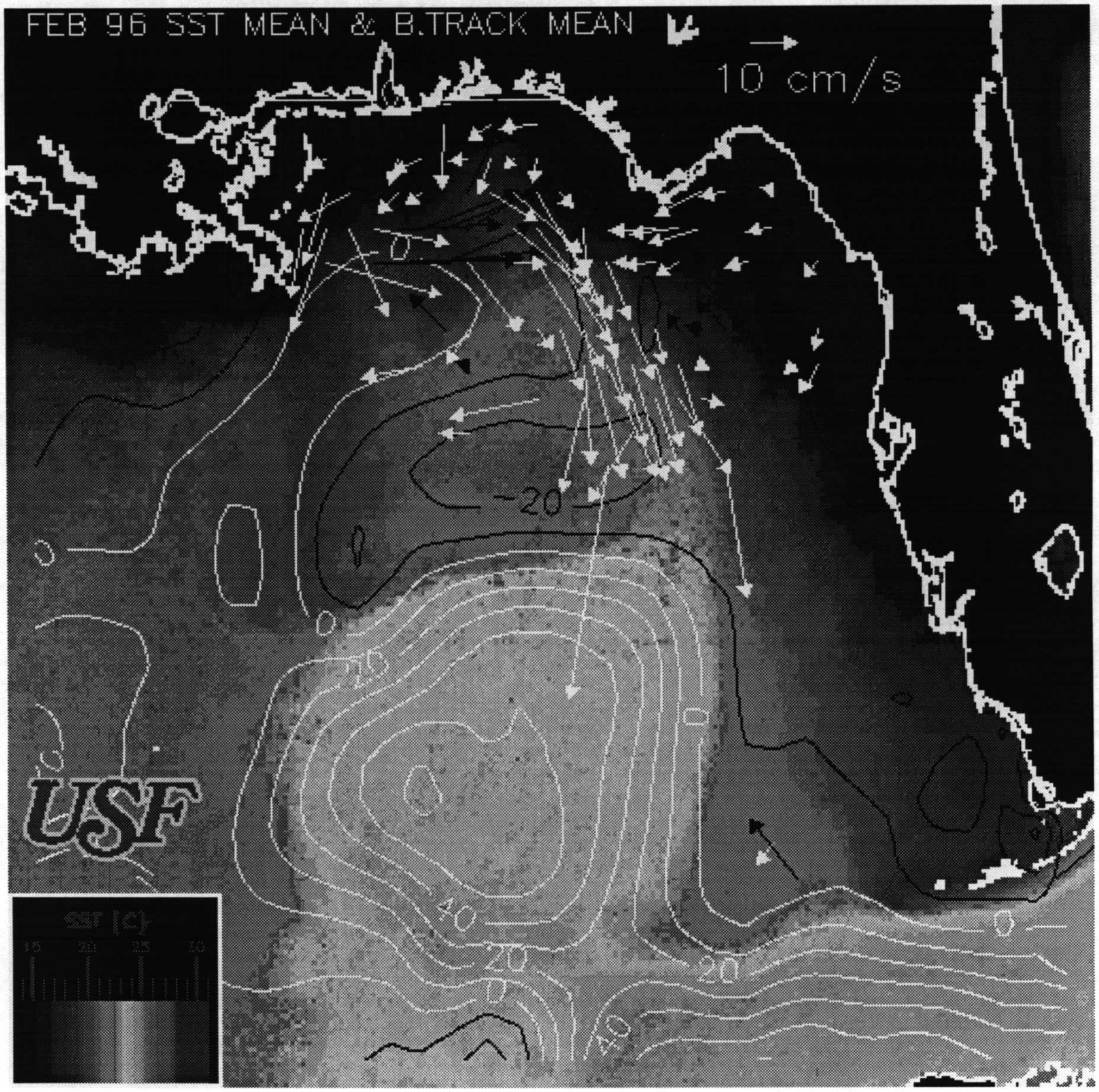


Figure 2. Dynamic Features: SST, Buoys and Altimetry (February 1996)

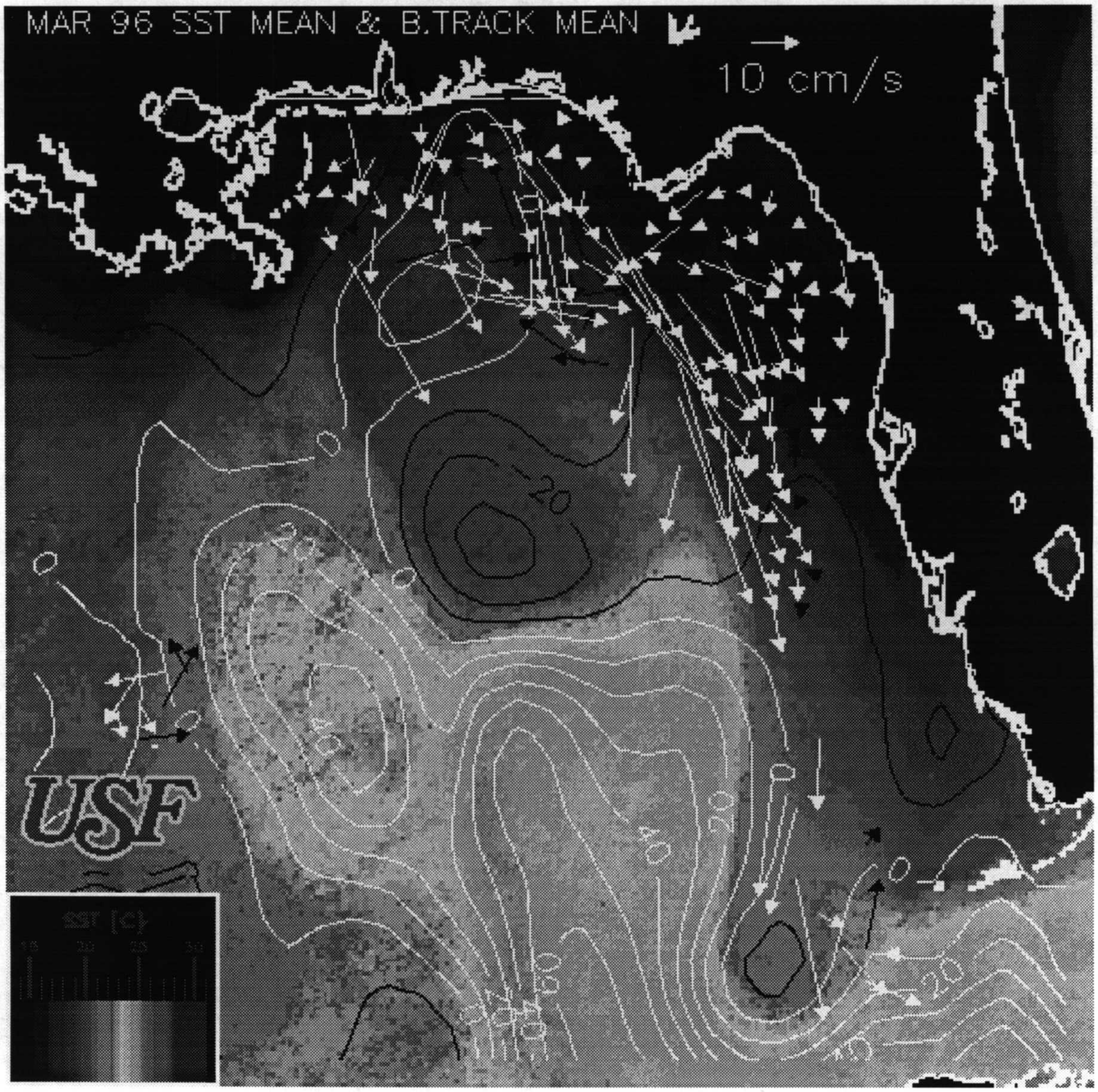


Figure 3. Dynamic Features: SST, Buoys and Altimetry (March 1996)

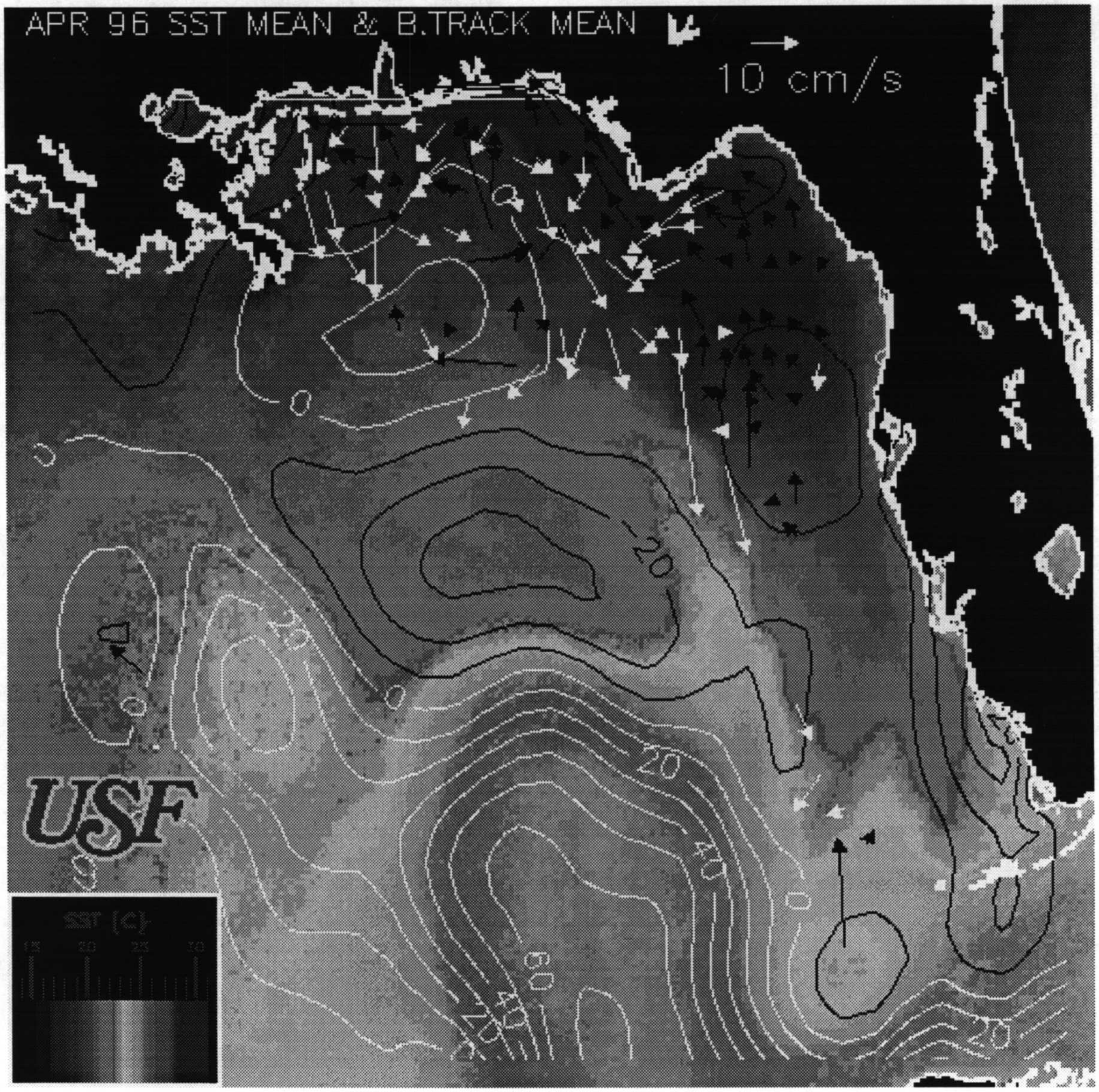


Figure 4. Dynamic Features: SST, Buoys and Altimetry (April 1996)

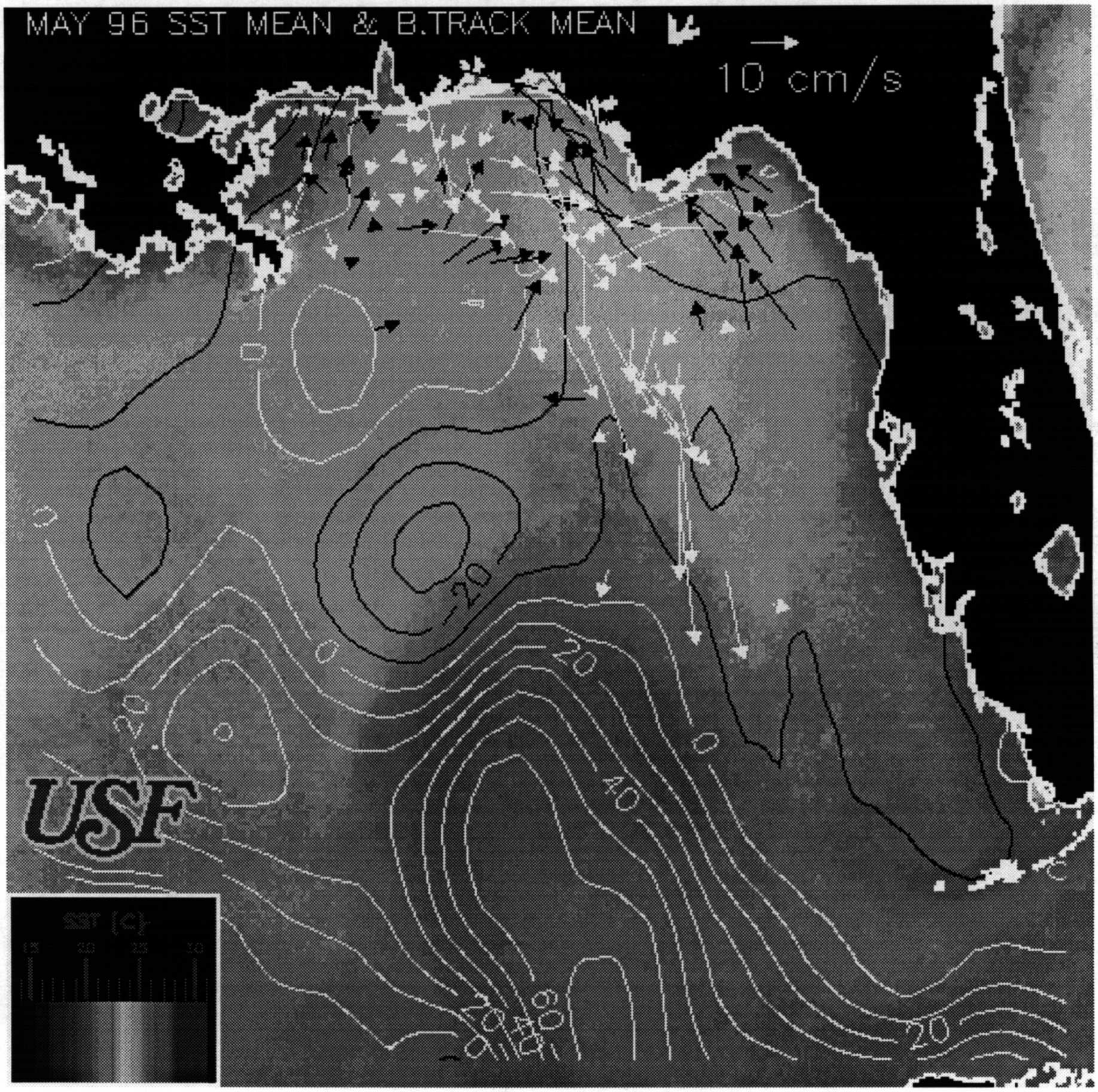
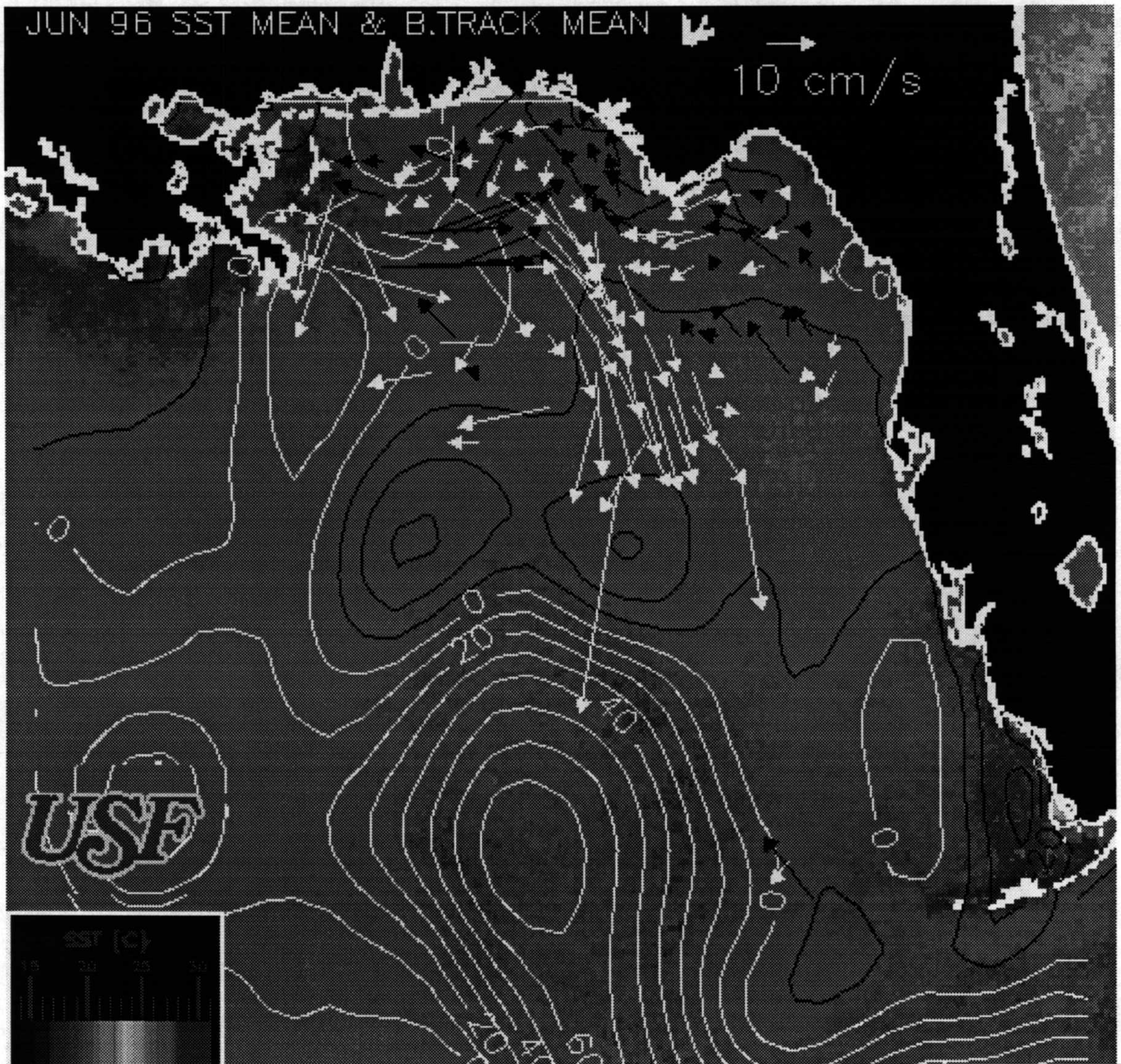


Figure 5. Dynamic Features: SST, Buoys and Altimetry (May 1996)



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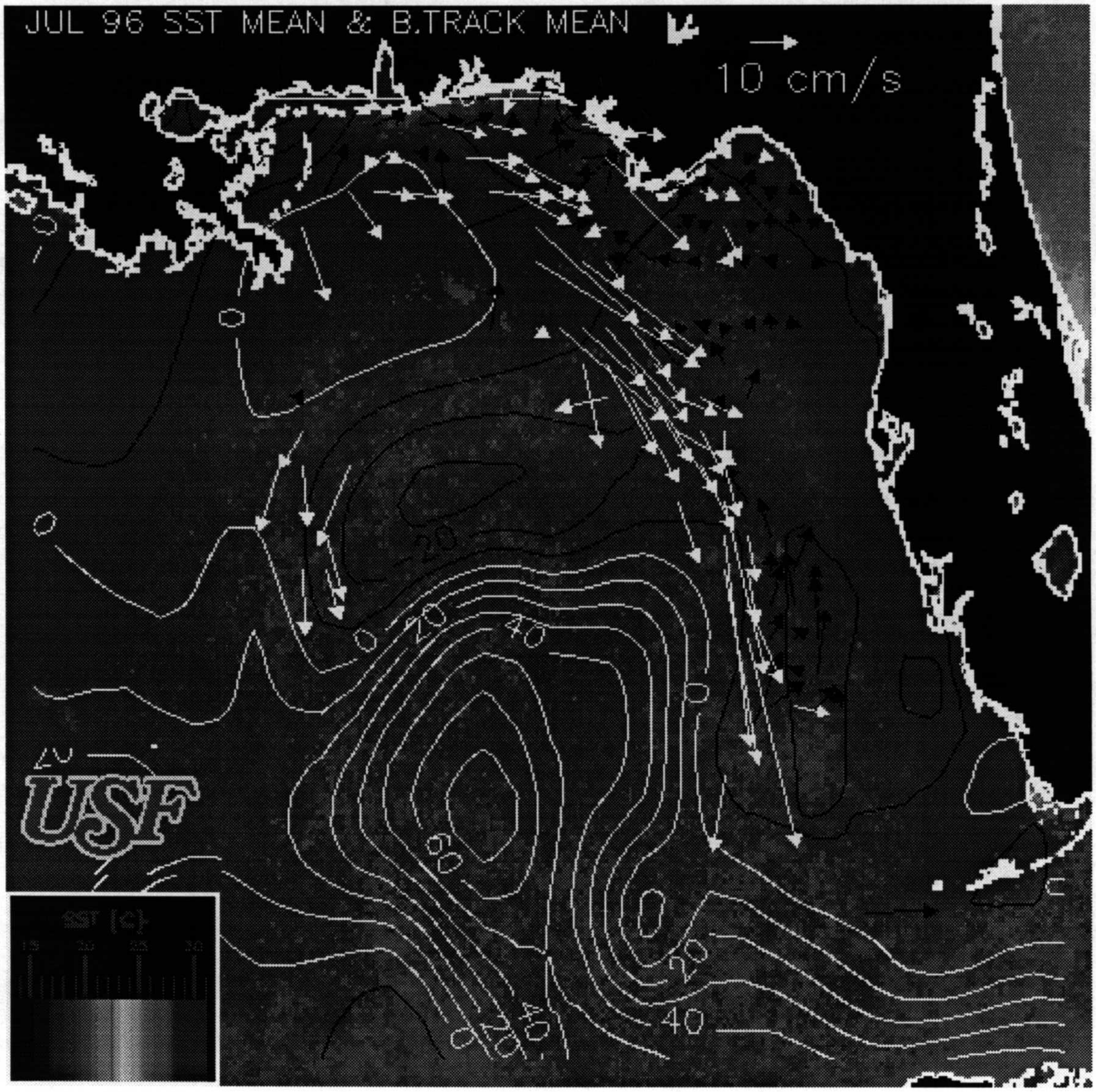

Figure 7. Dynamic Features: SST, Buoys and Altimetry (July 1996)

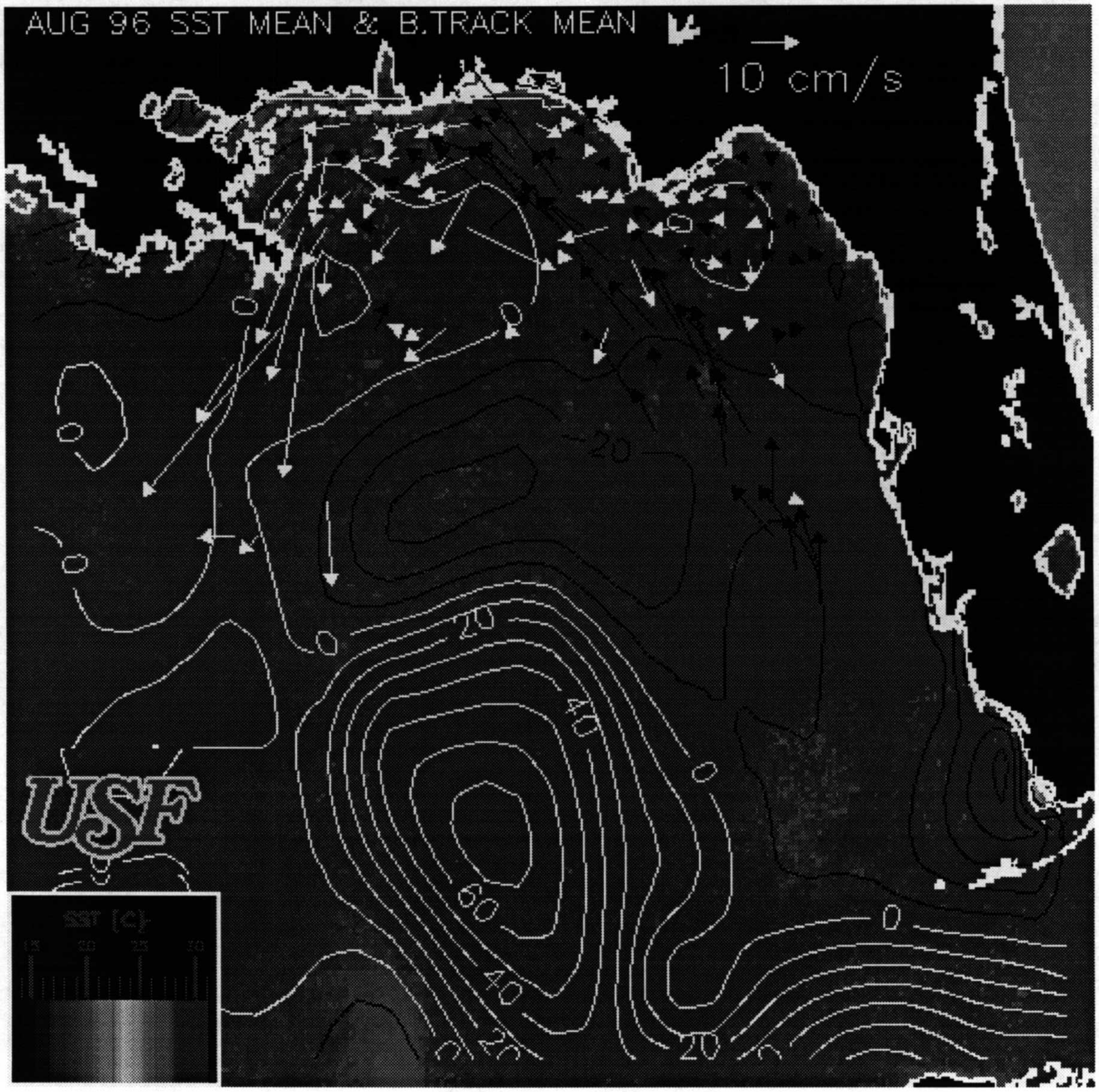

Figure 8. Dynamic Features: SST, Buoys and Altimetry (August 1996)

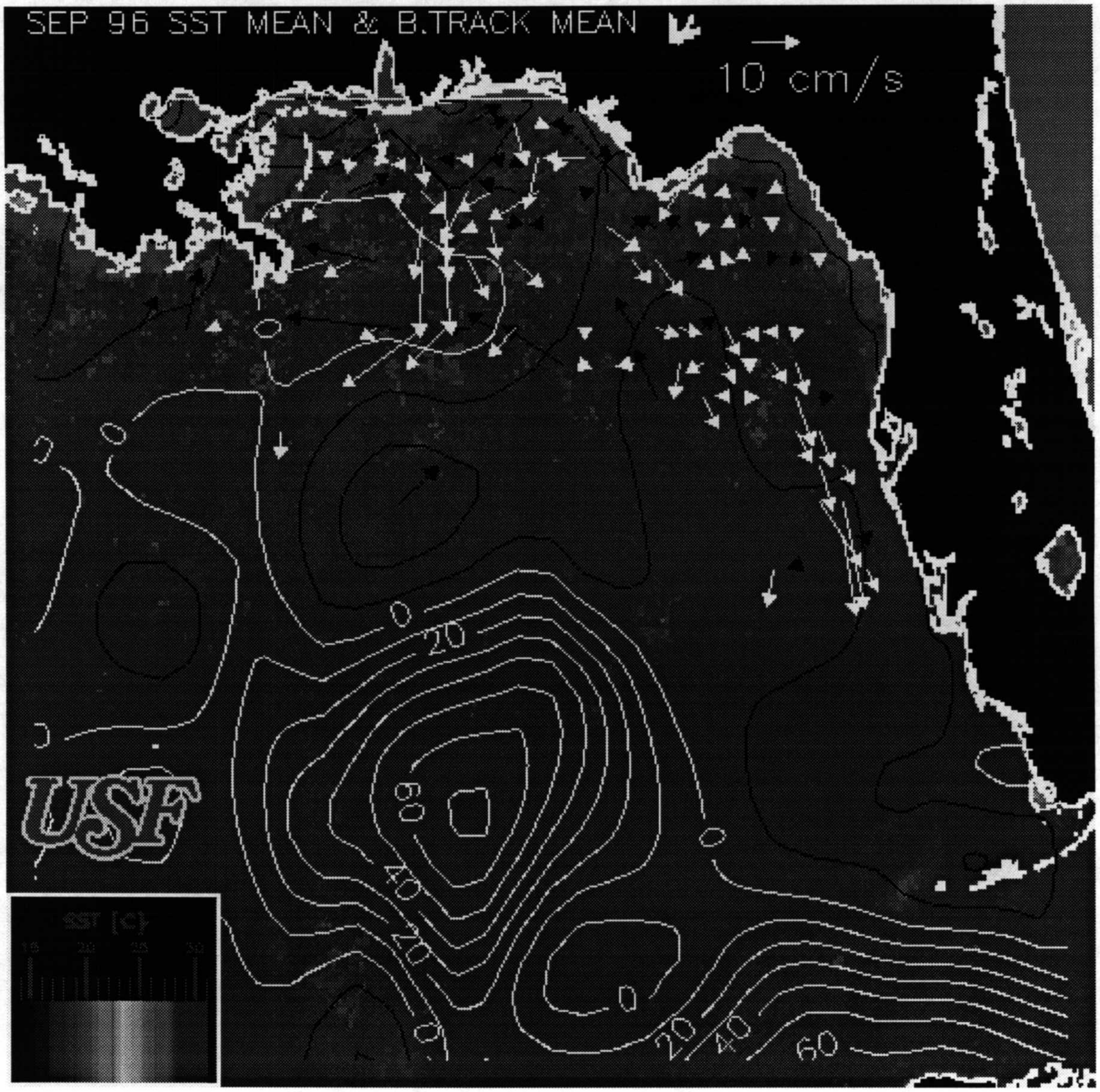

Figure 9. Dynamic Features: SST, Buoys and Altimetry (September 1996)

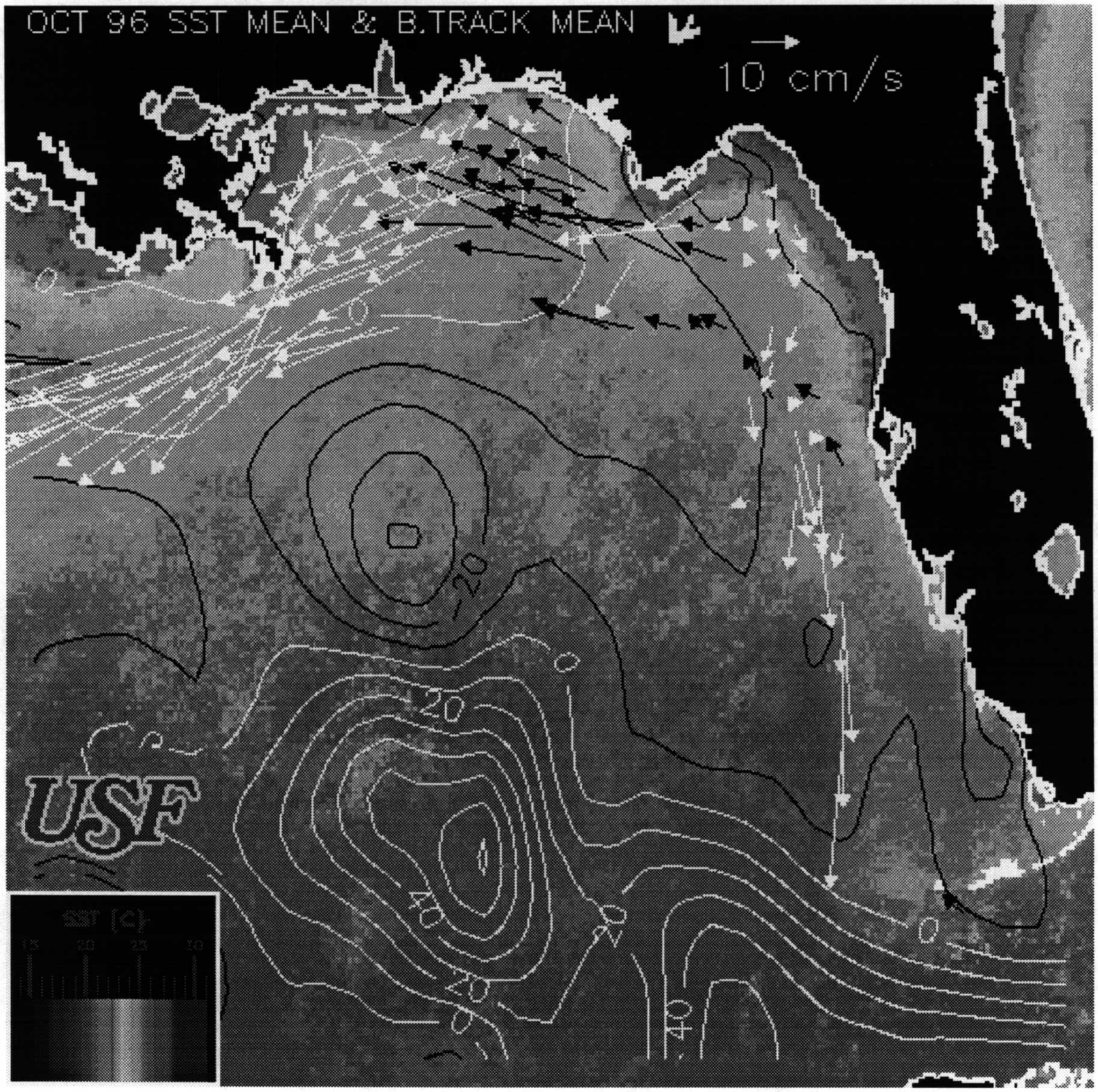

Figure 10. Dynamic Features: SST, Buoys and Altimetry (October 1996)

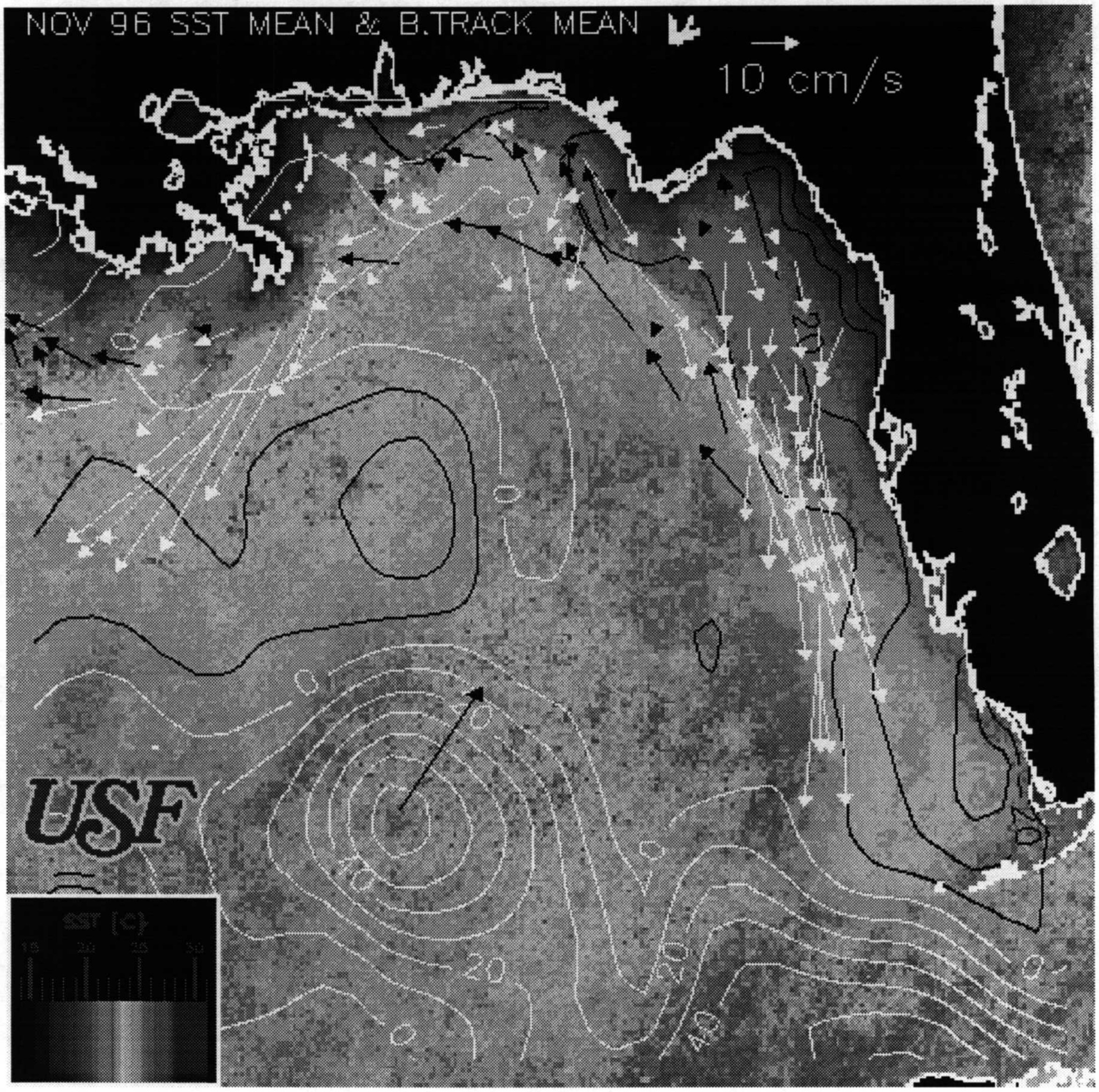

Figure 11. Dynamic Features: SST, Buoys and Altimetry (November 1996)

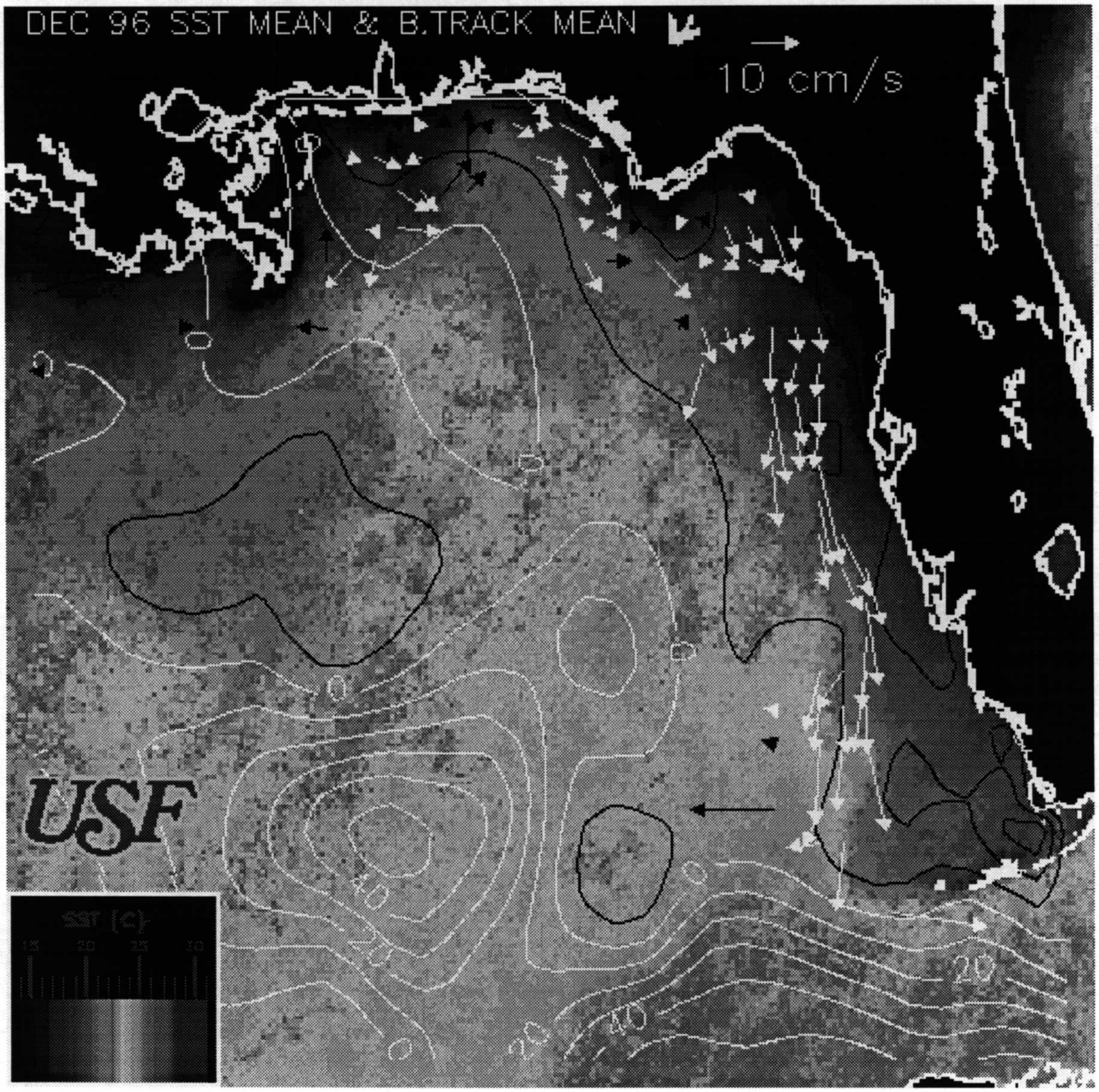

Figure 12. Dynamic Features: SST, Buoys and Altimetry (December 1996)

Appendix 1.

Satellite Remote Sensing Data Studies in the Northeastern Gulf of Mexico

By

Fred Vukovich
Science Applications International Corporation
Raleigh, NC 27605

1.0 Observations of surface flow reversal in the eastern GOM associated with the separation of a major eddy from the Loop Current

Monthly mean satellite SST and altimeter data combined with the monthly mean surface flow field that were derived from drifter data in the eastern Gulf of Mexico (GOM) were used to study the effect of Loop Current eddy shedding on the surface flow in the period June through August 1996. Figure 1 provides characteristic frontal analyses for the Loop Current for the period June, July, and August 1996 that were derived from AVHRR, altimeter, and in-situ data. Characteristic frontal analysis do, in many cases, provide a mean condition for the month, but when important events such as eddy shedding occur, the characteristic frontal analysis will focus on that event even though it does not depict the mean condition for the month. The data show that in August, a major eddy that separated from the Loop Current. That eddy actually separated at the end of August and that event is not depicted in the mean frontal analysis.

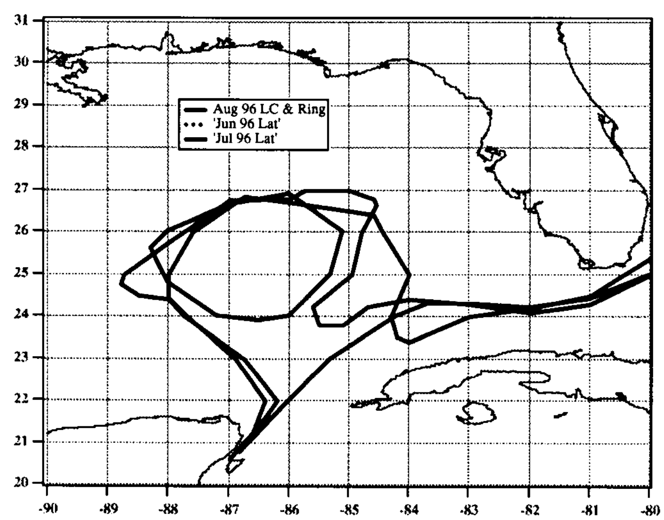

Figure 1. Frontal analyses for the Loop Current for the period June, July, and August 1996 that were derived from AVHRR, altimeter, and in-situ data.

Figure 2 shows the monthly mean AVHRR SST analysis with contours of monthly mean sea-surface height from the altimeter data and the monthly mean surface flow field that were derived from drifter data superimposed for July 1996. The figure shows a well developed Loop Current in the eastern GOM as far north as 26°N. A major cold eddy is found on the boundary of the Loop

Current in the vicinity of the Dry Tortugas. The buoy data show that the surface flow was from west to east, for the most part, in the area around the shelf break in the northeastern GOM (NEGOM) and from north to south at the shelf break along the West Florida Shelf. The surface flow had an anticyclonic curvature even though neither of these areas were directly influenced by the Loop Current since the altimeter data shows the main currents associated with the Loop Current were further south of the area around the shelf break in the NEGOM and a little further west of the area at the shelf break along the West Florida Shelf.

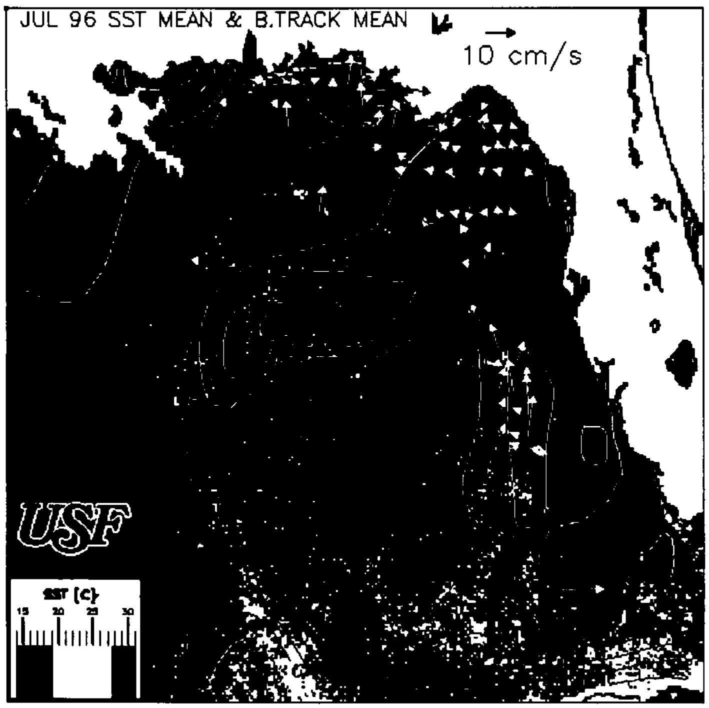

Figure 2. The monthly mean AVHRR SST analysis with contours of monthly mean sea-surface height from the altimeter data and the monthly mean surface flow field from drifter data superimposed for July 1996

While the eddy was separating from the Loop Current in August 1996, the Loop Current drifted westward (Figure 3). The monthly mean surface flow field for August had completely reversed direction from what had existed in July. The mean surface currents were south to north at the shelf break along the West Florida Shelf and east to west in the area around the shelf break in the NEGOM. Strong surface flow from north to south is noted in the Mississippi delta region. The surface flow in this case had a cyclonic curvature.

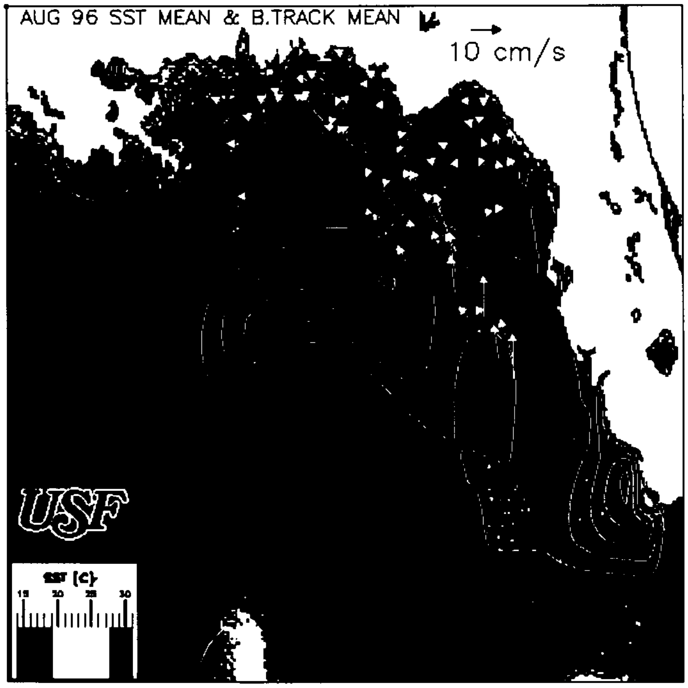

Figure 3. The monthly mean AVHRR SST analysis with contours of monthly mean sea-surface height from the altimeter data and the monthly mean surface flow field from drifter data superimposed for August 1996.

The above data provide the first document case study of this surface flow reversal feature associated with the separation of a major eddy from the Loop Current. A preliminary examination has begun using the archive of AVHRR SST data available to determine if there is any evidence that the flow feature noted at the time a major eddy separated from the Loop Current in the 1996 case may have happen before or was a persistent feature of that event. The monthly mean frontal analysis in the eastern GOM for December 1987 (Figure 4) shows that a major eddy had separated from the Loop Current. Separation actually took place in late November 1987. The feature of interest is the intrusion of shelf water into the deep GOM off the Mississippi delta that is noted in the shelf frontal analysis. It can be hypothesized that such an intrusion would require strong southward currents similar to those detected using the buoy data in August 1996. Since the 1987 case also involves a major eddy separation, it is possible that the cyclonically curving surface flow field noted in the 1996 case also occurred in this case. The evidence, however, is circumstantial at best. Further, evidence is required; but because surface flow data such as that available in the 1996 will not normally be available in the case studies using retrospective data, proof that such a feature existed in other cases when eddy separation is occurred will be statistical in nature and based on numerous case studies similar to that for December 1987.

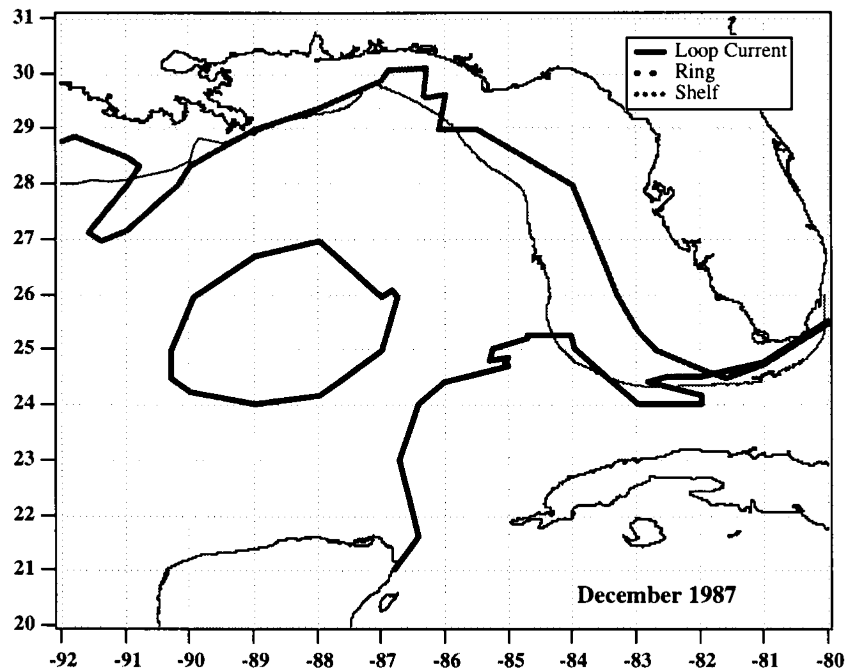

Figure 4. Frontal analyses for the Loop Current, warm core ring, and shelf region for December 1987 that were derived from AVHRR data.

2.0 Frequency that Loop Current water that is isolated from the Loop Current and/or major warm core rings is found in the eastern GOM

The spatial distribution of the frequency at which Loop Current water, which is not directly associated with the Loop Current and/or a major ring that separated from the Loop Current, is found in the eastern GOM, are being developed. The frequency analysis is being developed for the period 1976-1997 using AVHRR SST, ocean color, altimeter, and in-situ data. The Loop Current water in this case is associated with minor, short-lived rings, pools produced by the advection associated with the circulation in cold core rings found on the boundary of the Loop Current, or shallow pools of Loop Current water dragged from the Loop Current by strong winds. The objective of this analysis is to determine how often Loop current water not directly associated with the Loop Current and/or a major ring reaches the shelf break in the NEGOM.

To produce this analysis, a 0.5° latitude by 0.5° longitude grid was created for the eastern GOM. The frequency was determined at each grid-point by overlaying the grid on characteristic monthly ocean frontal analyses created for the GOM using AVHRR SST, ocean color, altimeter, and in-situ data and determining the number of times Loop Current water, which is not directly associated with the Loop Current and/or a major ring, encompasses that grid-point over the period which in this cases is 1976-1997. Figure 5 presents the preliminary results from our initial analysis. The results are considered preliminary because no quality assurance (i.e., QA) has been performed as yet.

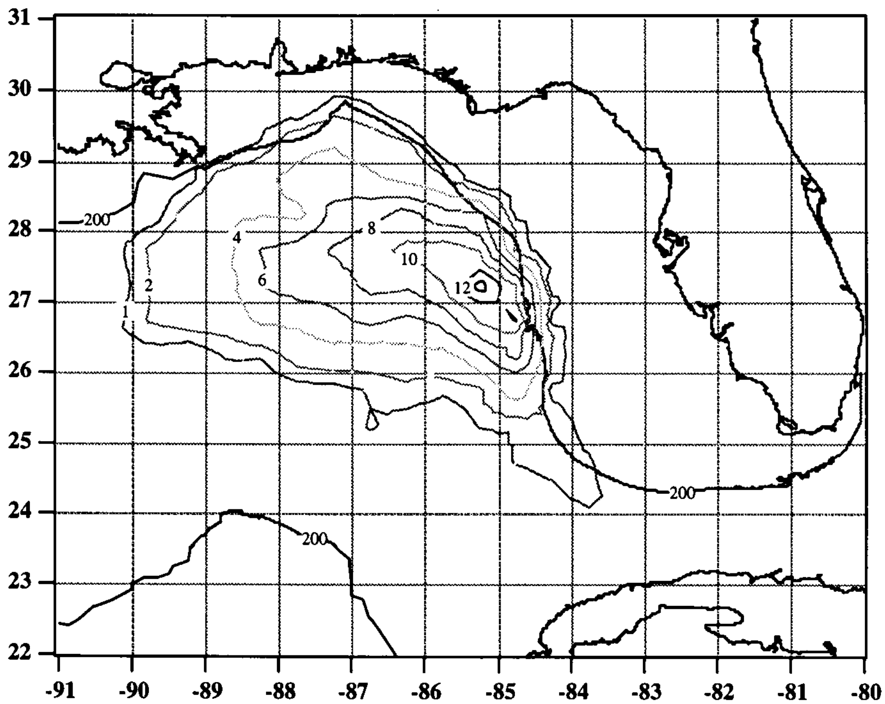

Figure 5. Frequency at which Loop Current water which is not directly associated with the Loop Current and/or a major ring is found in the eastern GOM.

Figure 5 shows that the greatest frequency (i.e., approximately 14 percent) at which Loop Current water not directly associated with the Loop Current and/or a major ring is found in the eastern GOM is located immediately west of the West Florida Shelf at 27.25°N and 85.25°W. This frequency feature is for the most part associated with pools of Loop Current water produced by the advection associated with cold core rings which are found on the boundary of the Loop Current. This feature occurred about 14 percent of the time in the period 1976-1997 or about two times every year. There is a region centered at about 28.75°N and 87.25°W which has a frequency of about 4-5 percent and which extends northward toward the shelf break in the Big Bend region of the NEGOM. That frequency feature is associated with either minor, short-lived rings which very often moved northward into DeSoto canyon and dissipated or with shallow pools of Loop Current water dragged to the north away from the Loop Current, which has made a deep northward penetration, by strong winds. Those features occurred about 4 percent of the time in the period or about once every two years.

Appendix 2.

GULF OF MEXICO ALTIMETRY ARCHIVE

By

Robert Leben

University of Colorado

Boulder, CO

Abstract

Historical and near-real-time satellite altimeter data archives for the Gulf of Mexico are being hosted at the Colorado Center for Astrodynamics Research at the University of Colorado, Boulder. Graphical access to the data archives is publically available through Web-based visualization tools. The digital data is not online, but can be accessed by ftp after obtaining permission by email. This report summarizes the data processing and products. Here is a list of theWeb-based forms with access to the Gulf of Mexico data archive:

- **Near-Real-Time Gulf of Mexico Altimetry**
  - Gulf of Mexico Near Real-Time Altimeter Data Homepage (http://www-ccar.colorado.edu/~realtime/gom/gom-nrt.html)
  - Gulf of Mexico Near Real-Time Data Viewer (http://www-ccar.colorado.edu/~realtime/gom-real-time_ssh)
  - Gulf of Mexico Near Real-Time Geostrophic Velocity Vector Viewer (http://www-ccar.colorado.edu/~realtime/gom-real-time_vel)
  - Gulf of Mexico Along-Track Data Host (http://www-ccar.colorado.edu/~realtime/gom_data_ssh/ssh.html)
  - Gulf of Mexico Along-Track Visualization (One Day) (http://www-ccar.colorado.edu/~realtime/gom_data_ssh/sshpic.html)
  - Gulf of Mexico Along-Track Visualization (Multiple Day) (http://www-ccar.colorado.edu/~realtime/gom_data_ssh/sshpic2.html)
  - Latest Gulf of Mexico sea surface height maps (http://www-ccar.colorado.edu/research/gom/html/latest_nrt.html)
- **Historical Gulf of Mexico Altimetry**
  - Gulf of Mexico Historical Data Viewer (http://www-ccar.colorado.edu/gom-historical_ssh)
  - Gulf of Mexico Historical Geostrophic Velocity Viewer (http://www-ccar.colorado.edu/gom-historical_vel)

1. Introduction

Since 1993, a continuous altimeter data stream has been available from altimeters aboard the TOPEXPOSEIDON and ERS-1&2 satellites. These data have permitted mapping of circulation variability in the Gulf of Mexico at unprecedented spatial and temporal resolution and in near-real-time. Anticyclonic and cyclonic eddies in the Gulf map are routinely detected in analyses produced by blending data from these satellites. The spatial resolution afforded by altimetric mapping with multiple satellites is especially important for mapping the smaller cyclonic features, which are frequently observed on the periphery of the larger anticyclones and the Loop Current. Another benefit of satellite altimetry for monitoring general circulation in the Gulf of Mexico is that it is an all-weather, all-season data source. This is a significant advantage over circulation monitoring with infrared imagery, which is often hampered by cloudy conditions. Also, during the months June through October, a shallow layer of warm surface water typically masks the thermal signature of the Gulf's deep circulation while the altimetric measurements remain unaffected.

The spatial resolution necessary to monitor circulation in the Gulf of Mexico requires that data from multiple satellites in a variety of orbits be processed and blended in a consistent fashion to produce accurate maps depicting the mesoscale to basin-scale circulation in the Gulf of Mexico. Fortunately, tandem sampling by the TOPEX/POSEIDON and ERS satellites during the 1990s has permitted accurate mesoscale mapping over most of the time period from 1992 to the present. In this report, we describe these altimeter missions and how data from those missions have been processed to produce the historical and near-real-time data archive hosted at the Colorado Center for Astrodynamics Research (CCAR) at the University of Colorado.

2. Altimeter Missions

The decade of the 1990s has seen a revolution in satellite-based monitoring of circulation changes in the global oceans at mesoscale to basin scales using satellite altimetry. Monitoring in the Gulf of Mexico has benefited from the increased spatial sampling afforded by satellite altimeters aboard the TOPEX/POSEIDON and ERS-1&2 satellites. Here is a brief summary of these missions.

2.1 TOPEX/POSEIDON

TOPEX/POSEIDON is a joint U.S.-France satellite mission managed in partnership by the National Aeronautics and Space Administration (NASA) and the Centre National d'Etudes Spatiales (CNES). The TOPEX/POSEIDON satellite was launched aboard an Ariane 42P launch vehicle on August 10, 1992 from Kourou, French Guiana. Two altimeters are carried aboard the satellite but only one is active at any one time because of on-board sharing of the altimeter antenna. The primary instrument is the dual-frequency NASA altimeter, commonly referred to as TOPEX. TOPEX sends microwave pulses to the ocean surface at two frequencies so that a correction can be made to the altimeter range to account for the delay caused by free electrons in the ionosphere. The CNES altimeter, commonly referred to as POSEIDON, is a single frequency, solid-state, low-power, low-mass sensor. The antenna sharing agreement between NASA and CNES provides for the POSEIDON altimeter to be turned on approximately 10% of

the time. The current operational procedure is to turn on POSEIDON for a complete cycle (10 days) approximately every 10 cycles, though not exactly every 10 cycles to prevent aliasing problems.

After an initial assessment phase, the satellite was placed into a 10-day exact repeat orbit in late September 1992 to begin operational sampling of the ocean and has remained in this orbit through the entire mission to date (Table 1). The primary science objective of the TOPEX/POSEIDON mission is to accurately observe basin-scale to global -scale circulation variability. The operational orbit, which repeats every 10 days along the ground track shown in (Figure 1), does not provide sufficient spatial sampling for accurate mapping of mesoscale circulation variability. As a result, data from TOPEX/POSEIDON must be combined with altimeter data from other satellites for mesoscale circulation monitoring. Fortunately, during a majority of the TOPEX/Poseidon misson, tandem sampling has been provided by the Euorpean Remote-Sensing (ERS) satellites.

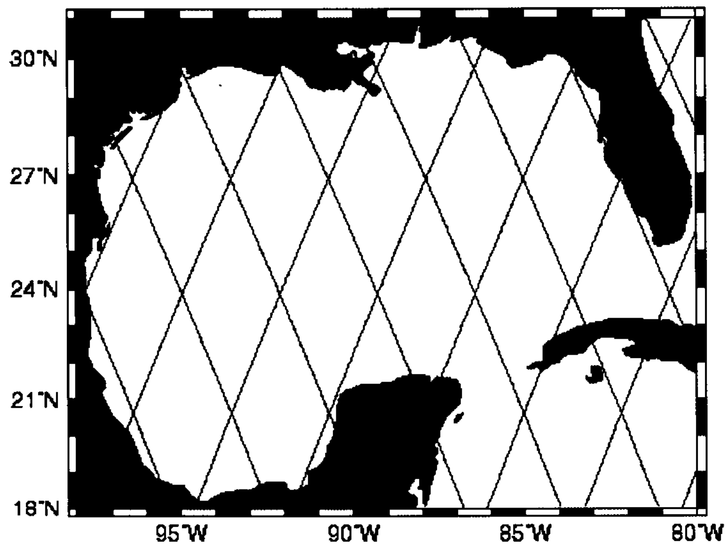

Figure 1. TOPEX/POSEIDON ground track over the Gulf of Mexico from the operational 10-day exact repeat orbit.

2.2 ERS-1&2

The first and second European Remote-Sensing satellites, ERS-1 and ERS-2, were developed by the European Space Agency (ESA) as a sequence of multidisciplinary earth observing satellites devoted to remote sensing from a polar orbit. These two satellites are nearly identical and have identical payload instruments including satellite altimeters. The only difference in the payloads is an ozone mapping instrument that was added to ERS-2, which was not available on ERS-1. By flying a sequence of identical instruments, ESA has been able to cross-calibrate and extend a very useful time series of global remote sensing observations. Both satellites are in good health, however, only ERS-2 is actively providing data. ERS-1 was placed in a safe-hold state in May 1995 and serves as a back-up for ERS-2.

ERS-1 was launched on July 17, 1991. To meet the multidisciplinary objectives of the mission several observational periods, called "mission phases", were flown in orbits selected to optimize the scientific usefulness of the data collected (Table 2). Only the 3-day repeat orbits used during the commissioning and ice mission phases are unsuitable for mesoscale mapping. Both the multidisciplinary and geodetic phases provide altimeter data at sufficiently dense spatial sampling to be useful for circulation monitoring at mesoscales. During the multidisciplinary mission phases, both ERS-1 and ERS-2 sample along the 35-day repeat ground track (Figure 2). The 168-day repeat orbits flown during the geodetic phases can also be exploited for mesoscale mapping by using the sampling afforded by the 37-day near-repeat cycles within this orbit. An example of this spatial sampling over the Gulf of Mexico is shown in the ground track/coverage map for ERS-1 during the second cycle of the first geodetic phase (Figure 3).

Table 1. TOPEX/POSEIDEN Mission

Mission phase	Duration	Repeat period	Description
Assessment	8/10/92 to 9/23/92		Initial phase to maneuver into the operational orbit and assess the performance of the satellite.
Primary and Extended Missions	9/23/92 to EOM* *End of Mission	10-day	Primary and extended mission phase dedicated to collection of an extended time series of altimeter data from the TOPEX/POSEIDON operational 10-day repeat orbit.

ERS-2 was launched on April 21, 1995 and immediately placed into the 35-day repeat orbit used for the multidisciplinary phases of the ERS missions. Current plans are to keep the satellite in this orbit throughout the entire mission. This simplifies processing of ERS-2 altimeter data since all the data coincident with the ongoing TOPEX/Poseidon mission will be collected from this orbit.

3. Historical Altimeter Data Sets

Sea surface height analysis maps are being produced from historical altimetric measurements based on the latest versions of the TOPEX and ERS geophysical data records (GDRs). TOPEX data have been obtained from the Physical Oceanography Distributed Active Archive Center (PO.DAAC) at the Jet Propulsion Laboratory, and ERS data from the "Centre ERS d'Archivage et de Traitement"(CERSAT), the French Processing and Archiving Facility for ERS-1 and ERS-2. Both data sets are processed in as consistent a fashion as possible to produce accurate analysis maps based on tandem altimetric observations.

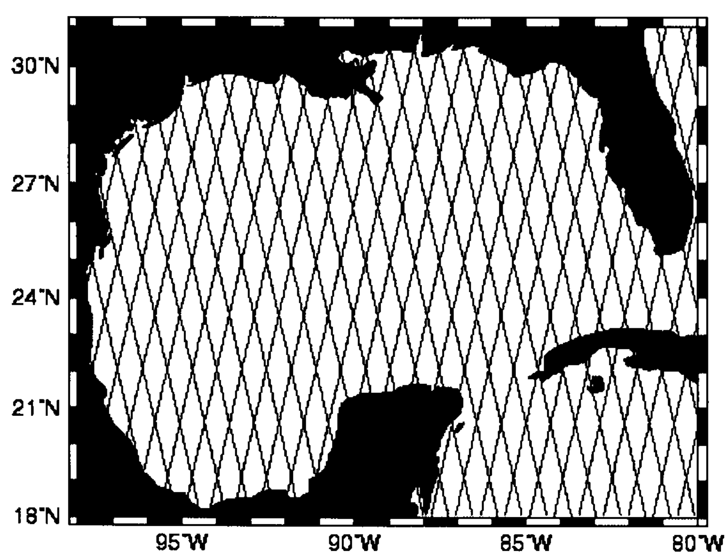

Figure 2. ERS-1 and ERS-2 ground track over the Gulf of Mexico from the operational 35-day exact repeat orbit.

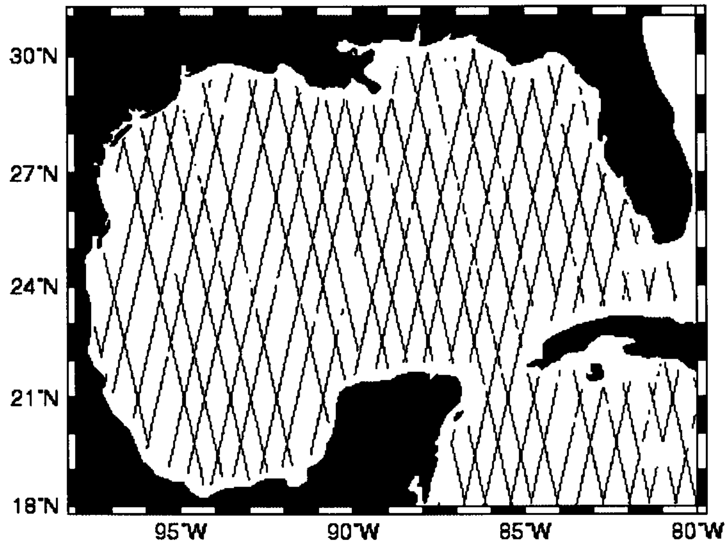

Figure 3. Sample ground track/data coverage for the first 37-day near repeat during the 168-day exact repeat orbit used in the ERS-1 Geodetic 1 mission phase.

Table 2. ERS-1 Mission

Mission phase	**Duration**	**Repeat period**	**Description**
Commissioning	7/31/91 to 12/20/91	3-day	Phase dedicated to observing very frequently the calibration sites.
Ice 1	12/28/91 to 3/30/92	3-day	Phase dedicated to observing specific ice zones.
Multidisciplinary 1	4/14/92 to 12/20/93	35-day	Multidisciplinary phase dedicated to satisfying most of the applications including land/ice mapping with SAR and ocean circulation mapping with altimetry.
Ice 2	12/23/93 to 3/10/94	3-day	Phase dedicated to resampling ice zones after a two year period.
Geodetic 1	4/10/94 to 9/27/94	168-day	Phase dedicated to providing very dense spatial observations from the altimeter for mapping the geoid.
Geodetic 2	9/27/94 to 3/21/95	168-day	Second phase of geoid mapping with the 168-day ground track shifted longitudinally by 8 km to double spatial resolution.
Multidisciplinary 2	3/21/95 to 5/16/96	35-day	Final phase to perform multidisciplinary mission and permit cross-calibration and tandem operation with ERS-2.

Table 3. ERS-2 Mission

Mission phase	Duration	Repeat period	Description
Commissioning	5/1/95 to 11/1/95	35-day	Phase dedicated to commissioning satellite and
Tandem	11/1/95 to 5/15/96	35-day	Phase flown in tandem with ERS-1 for tandem SAR
Multidisciplinary	5/16/96 to EOM	35-day	Phase dedicated to performing multidisciplinary mission. The satellite is expected to remain in the 35-day repeat orbit to the end of mission (EOM).

3.1 Data Processing

The TOPEX data are corrected using standard corrections supplied on the JPL/PO.DAAC TOPEX GDRs, including inverted barometer, electromagnetic bias, ionosphere and wet/dry tropospheric corrections, as recommended in the GDR handbook (Calahan, 1993). Data at each subsatellite point are differenced to the mean sea surface included on the GDRs (Basic and Rapp, 1992) to apply an implicit cross-track geoid correction. Several additional corrections not found on the original GDRs are also applied to the TOPEX data. These corrections include improved orbits based on the JGM-3 gravity model (Marshall et al., 1995) and a new empirical ocean tide model (Desai and Wahr, 1995) based on TOPEX altimeter data computed using the JGM-3 orbits.

The ERS-1 and ERS-2 Altimeter Ocean Products (ALTOPR) CD-ROMs were obtained from CERSAT. The ERS altimeter data are corrected using standard corrections supplied on the ALTOPR GDRs, including inverted barometer, electromagnetic bias, ionosphere and wet/dry tropospheric corrections. The data are also corrected using the Desai and Wahr (1995) tide model to be consistent with the TOPEX processing.

Each cycle of corrected 10-day repeat TOPEX and 35-day repeat ERS data are linearly interpolated to reference ground tracks based on computed emphemerides for the satellites. The TOPEX reference track is based on a ground track computed for cycle 18, with a fixed spacing of the subsatellite reference points at one second along-track which is approximately a 7 km spacing. The ERS 35-day reference ground track is based on 1/second along-track points computed for cycle 6 of the ERS-1 Multidisciplinary 1 mission phase. No gridding of the nonrepeat ERS-1 data is performed. An empirical orbit error correction is applied to the ERS along-track data, after gridding when appropriate, to remove residual ERS orbit error. An empirical correction of the TOPEX data was not needed , however, to consistently "filter" both data sets the empirical correction is also applied to the TOPEX data. This correction is based on an along-track "loess" filter, which removes a running least squares fit of a tilt plus bias within a sliding window from the along-track data. The filter window is approximately 15 degrees of latitude (200 second along-track), passing the short wavelength mesoscale signals while filtering the longer wavelength orbit and environmental correction errors.

After extracting the data from the GDRs, applying the corrections, and along-track gridding/detrending,, the corrected sea surface heights are referenced to an accurate high resolution mean sea surface based on altimeter data collected from the TOPEX/POSEIDON, ERS-1 and GEOSAT Exact Repeat missions (Yi, 1996). By referencing the altimeter data to an independent mean sea surface, the climatology based on the blended TOPEX/POSEIDON and ERS-1 data can be extended to include past, present and future climatologies referenced in the same manner, such as have been produced from the historical GEOSAT data (Berger et al., 1996a,b) and is currently being produced from the TOPEX/POSEIDON and ERS-2 data sets.

3.2 Blended T/P and ERS 1&2 Climatology

A climatology of the Gulf of Mexico sea surface height for the Gulf of Mexico has been produced from the corrected sea surface height anomalies determined from TOPEX/POSEIDON and ERS-1&2 altimetry. Daily analysis maps of height anomaly relative to the mean sea surface are created using an obective analysis procedure (Cressman, 1959) to interpolate the along-track data to a 1/4 degree grid over the gulf. The method uses an iterative difference-correction scheme to update an initial guess field and converge to a final gridded map. A multigrid procedure is used to provide the initial guess. The complete multigrid procedure is described in an appendix to Hendricks et al. (1996). Five Cressman interations are used with radii of influences of 200, 175, 150 , 125 and 100km, while employing a 100 km spatial decorrelation length scale in the isotropic Cressman weighting function. In addition to the spatial weighting, data are weighted in time using a 12-day decorrelation time scale relative to the analysis date. A 10-year climatological model mean is added the height anomaly maps to estimate the total dynamic topography. A sample of the maps produced is shown in Figure 4.

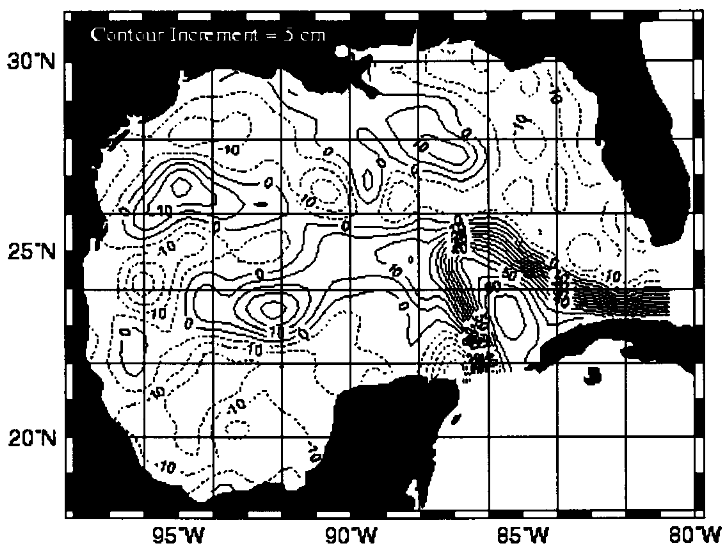

Figure 4. Gulf of Mexico sea surface height on 1 Jan 1993 from blended TOPEX and ERS-1 sea surface height anomaly plus 10-year climatological model mean.

3.3 Historical Data Archive

The daily data files for April 1992 through October 1997 are available from the CCAR archive through a password protected ftp login account on the CCAR server (shaman.colorado.edu). The login and password can be obtained by email.The files contain the daily estimated total dynamic topography over the gulf at 1/4 degree resolution and are identified by the .xyz extension. The latitude, longitude and height values at the 1/4 degree grid points are stored line by line in the file and are in ASCII format. The .xyz files have been compressed using Free Software Foundation compression software, GNU zip , and placed on the ftp archive in the data/historical directory. GNU zip and unzip (gzip and gunzip)are available for most computer systems and allow efficient transfer of the data products over the Internet.

3.4 Validation, Verification and Synthesis Studies

A number of validation, verification and synthesis studies are in progress to assess the accuracy of the historical data and improve their utility. Software to interpolate altimetric estimates of the sea surface height, geostrophic velocity, relative vorticity, radius of curvature, etc. from the daily analysis maps has been developed and tested. These estimates are being compared to measurements acquired from drifting buoy, current meter, expendable bathythermograph (XBT) and conductivity temperature depth (CTD) records. Qualitative comparisons are also being made with remote sensing imagery.

4. Near-Real-Time Altimetric Monitoring

The capability to routinely monitor ocean circulation variability in near-real-time has been a primary goal of satellite altimetry. In the late 1980s, near-real-time monitoring with altimeter data from the U.S. Navy GEOSAT Mission was an unqualified success. Various oceanographic phenomena including the north wall location and mesoscale features of the Gulf Stream system (Lybanon and Crout, 1987), sea level changes in the tropical Pacific (Cheney et al., 1989), mesoscale eddies in the North Central Atlantic (Calman and Manzi, 1989) and Loop Current eddies in the Gulf of Mexico (Forristal et al., 1990) were monitored in near-real-time. Near-real-time eddy detection in the Gulf of Mexico using satellite altimetry was first attempted in 1988 during the GEOSAT Exact Repeat Mission (ERM) (Forristal et al., 1990). Near-real-time (within 48 hours) Geosat ERM data was used for operational detection of eddies to aid in the selection of locations for in situ measurements at sea. The altimeter sea surface height (SSH) anomalies showed mesoscale circulation that was subsequently validated by coincident drifter and XBT data.

Recently, thanks to the concerted effort of a large number of individuals and organizations, near-real-time data (within 18 hours) from altimeters aboard the TOPEX/POSEIDON and ERS-1&2 satellites have been made available and are being used for circulation monitoring. The near-real-time altimeter data sets and processing are briefly described below.

4.1 Near-real-time Altimeter Data

In November 1995 the NOAA Laboratory for Satellite Altimetry began generating near-real-time altimeter data products from ERS-1, and has continued with ERS-2 since May 1996 (Lillibridge et al., 1997). These "real-time" geophysical data records (GDRs) are based on ESA's fast-delivery radar altimeter product, which is received at NOAA within 6 hours of satellite acquisition. Since the fast-delivery data contain only crude satellite state vector information, the most important step in "real-time" GDR production is the addition of orbital information from ephemerides computed by the Delft Institute for Earth-Oriented Space Research. In order to produce "real-time" GDRs on a daily basis (within 12 hours of satellite acquisition) it is necessary to use a predicted extension to the computed orbits of up to five days. The magnitude of the radial component of orbit error grows as the prediction time increases, however, even in the worst case scenario of a five-day prediction the expected orbit error remains below 50 cm. This level of error is acceptable for short-arc mesoscale studies where explicit orbit error removal is performed. After applying the predicted orbit, NOAA enhances the "real-time" GDR with improved geophysical corrections and makes the ERS data available to select real-time users.

Beginning in early 1996, near-real-time data also became available from the TOPEX/POSEIDON mission. TOPEX interim GDRs are being produced by the Altimeter Data Fusion Center at the Naval Oceanographic Office using TOPEX sensor data records obtained from the Jet Propulsion Laboratory (JPL) and include predicted orbits based on extensions of the TOPEX/POSEIDON GPS orbits computed by the JPL Earth Orbiter Systems Group. The predicted extensions are usually less than 24 hours old and are accurate to better than 50 cm (Muellershoen et al., 1996; Lichten et al., 1996). GDRs are produced every 8 hours and are usually available within 12 hours of satellite acquisition.

4.2 Near-real-time Processing

The processing of the TOPEX and ERS-2 near-real-time data over the Gulf is designed to retain mesoscale scale signals while removing the substatial orbit error that may be present in the fast-delivery products. The procedure blends the data from the two satellites , treating both data sets in a consistent fashion, as follows:

All TOPEX and ERS-2 data are referenced to the Ohio State University Mean Sea Surface 1995 (Yi, 1995). The data are treated as non-repeat tracks and are referenced directly to the mean sea surface. This saves a significant amount of computational effort during near-real-time processing.

Along-track "loess" filtering is used to remove residual orbit and environmental correction errors. The loess filter removes a running least squares fit of a tilt plus bias within a sliding window from the along track data. The window width is approximately 15 degrees of latitude (200 seconds along-track). This high pass filter acts retains the short wavelength mesoscale signals while removing the longer wavelength orbit and environmental correction errors.

A fast, multigrid preconditioned Cressman analysis with temporal weighing is used to interpolate the along-track data to a quarter-degree grid over the Gulf of Mexico (Hendricks et al., 1996). The most recent 10 days of TOPEX/POSEIDON data and 17 days of ERS-2 data are used in the analysis with a 12 day decorrelation time scale for temporal weighting.

A model mean is added to the sea surface height anomaly to produce an estimate of the total dynamic height.

An example of the dynamic topography derived from this method is shown in Figure 5. Here a clear image of sea surface temperature in the Gulf of Mexico (courtesy of Frank Muller-Karger, Univ. of S. Florida) is shown with overlaid contours of dynamic height based on the blended TOPEX and ERS-2 analysis. A large meander in the Loop Current, in the SE corner of the Gulf, is well mapped by the altimeter derived sea surface height. Even less energetic cyclones and anticyclones are evident in the topography, in excellent agreement with the sea surface temperature field.

4.3 Near-Real-Time Data Archive

A near-real-time data archive is also available by ftp. The login and password can be obtained by email.

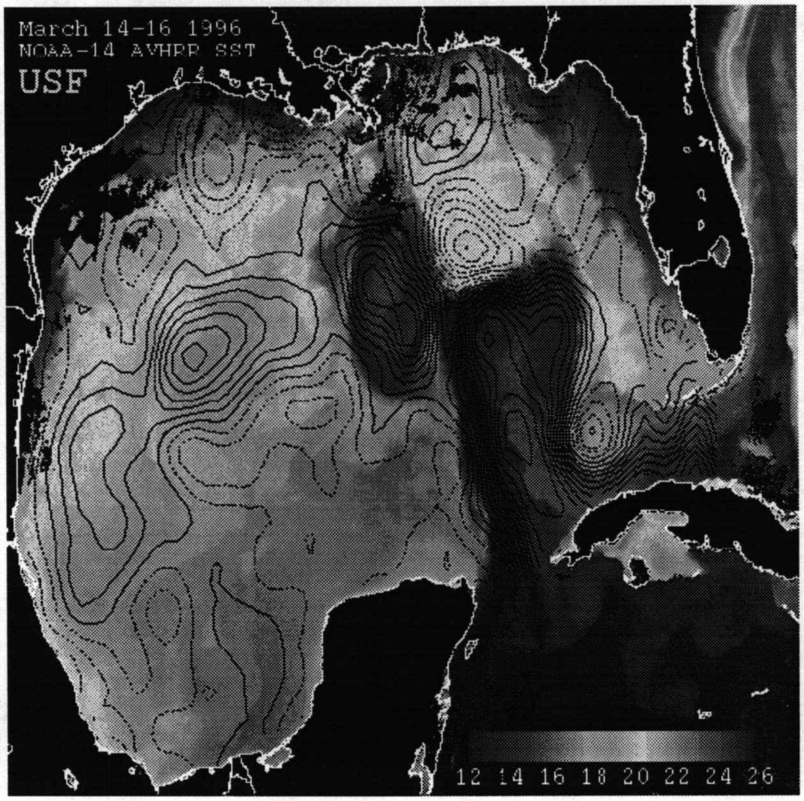

Figure 5. Composite of sea surface temperature imagery in the Gulf of Mexico for March 14 - 16, 1996 with overlaid contours of sea surface height from blended TOPEX & ERS-2 data plus model mean (10 cm contour interval).

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The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Royalty Management Program** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.